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# Current status of the CODALEMA/EXTASIS experiments

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**Abstract.** Secondary electrons and positrons of air showers emit a coherent radio electric field in a wide frequency band. The CODALEMA experiment installed at the Nançay radioastronomy observatory since 2002 detects air showers and the associated electric field in [20;200] MHz. EXTASIS, triggered by the CODALEMA scintillators, detects since 2016 the air shower electric field in [1;6] MHz. We also expect an additional signal at low frequency: the sudden death pulse, corresponding to the sudden disappearance of the shower front particles when they reach the ground level. We present the instrumental setups, their performances and the first results of EXTASIS.

## 1. The radio signal from extensive air showers

The air showers created following the interaction of ultra-high energy cosmic ray in our atmosphere contain many information on the primary particle. The secondary particles, in particular the  $e^\pm$ , emit a detectable electric field. The emission mechanisms are understood in great details [1, 2, 3]. The principal mechanism is the geomagnetic effect that produces an electric field linearly polarized in the direction  $\mathbf{v} \times \mathbf{B}$  where  $\mathbf{v}$  is the shower axis direction and  $\mathbf{B}$  is the geomagnetic field at the location of the experiment. The second effect is the field emitted by the excess of  $e^-$  with respect to  $e^+$  [4] which produces a field with a radial polarization with respect to the shower axis. The total electric field is the superposition of both mechanisms with a possible Cherenkov-like amplification for adequate observer positions with respect to the shower axis. Various radio experiments are currently taking data all over the world [5, 6]. By the comparison of the measured electric field distribution at ground level to the expected distribution, it is possible to estimate the atmospheric depth  $X_{\max}$  of maximum development of the shower which is an excellent way to constrain the nature of the primary cosmic ray. The cosmic ray composition is the key to a much better understanding of their sources that are still unidentified.

## 2. The experimental setup

The CODALEMA/EXTASIS experiment aims, among other topics, at estimating the cosmic ray composition in the energy range  $10^{16} - 10^{18}$  eV. It covers the full area of  $1 \text{ km}^2$  of the

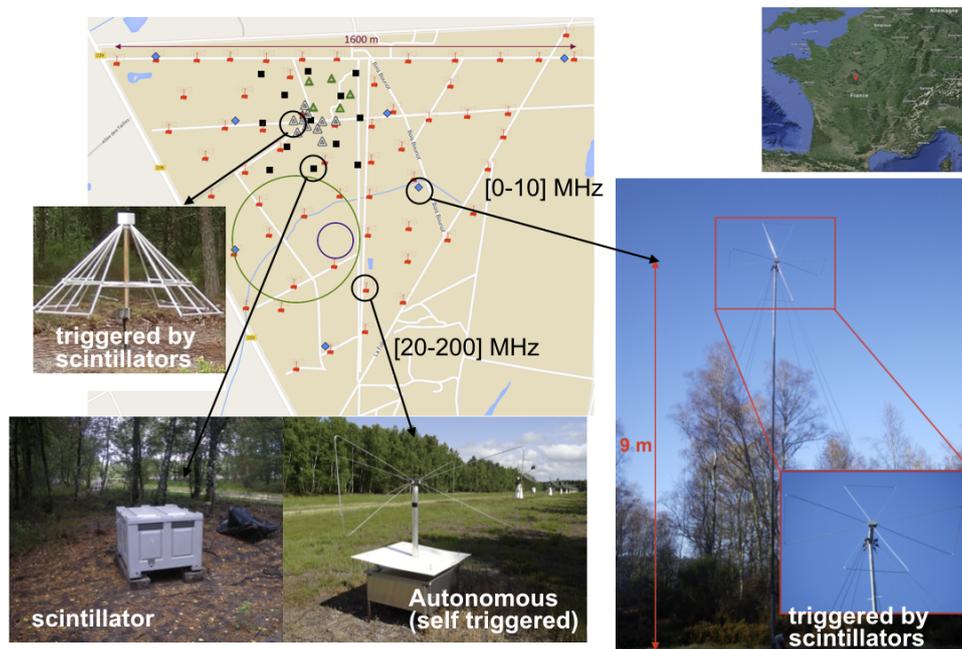


Nançay radio observatory. We have various instruments allowing a precise reconstruction of the air shower characteristics: axis direction  $\theta$ ,  $\phi$ , core position  $x_c, y_c$  and the atmospheric depth of maximum development  $X_{\max}$ . From these informations, we can estimate the primary cosmic ray properties: energy and nature.

The shower observation is made through:

- the direct detection of the secondary particles by the scintillator array (13 detectors spread over a square of  $0.16 \text{ km}^2$ ) with an energy threshold around  $10^{15} \text{ eV}$ ;
- the detection of the electric field emitted by the secondary charged particles
  - with the 57 autonomous (self-trigger) stations covering the full area of  $1 \text{ km}^2$ , measuring the electric field in both north/south and east/west polarizations with a Butterfly antenna (in 20-200 MHz).
  - with the 10 cross-polarized antennas (in 10-200 MHz) covering a very small area to study the electric-field at short distances.
  - a single 3D antenna, triggered by the scintillator array, in order to measure the three components of the electric-field vector, allowing to check the validity of the far-field approximation.
- the detection of the electric field at low frequency (1 – 6 MHz), with the 7 radio stations spread over the area of  $1 \text{ km}^2$ .

The setup is presented in FIG. 1. The scintillator array has a very low background as



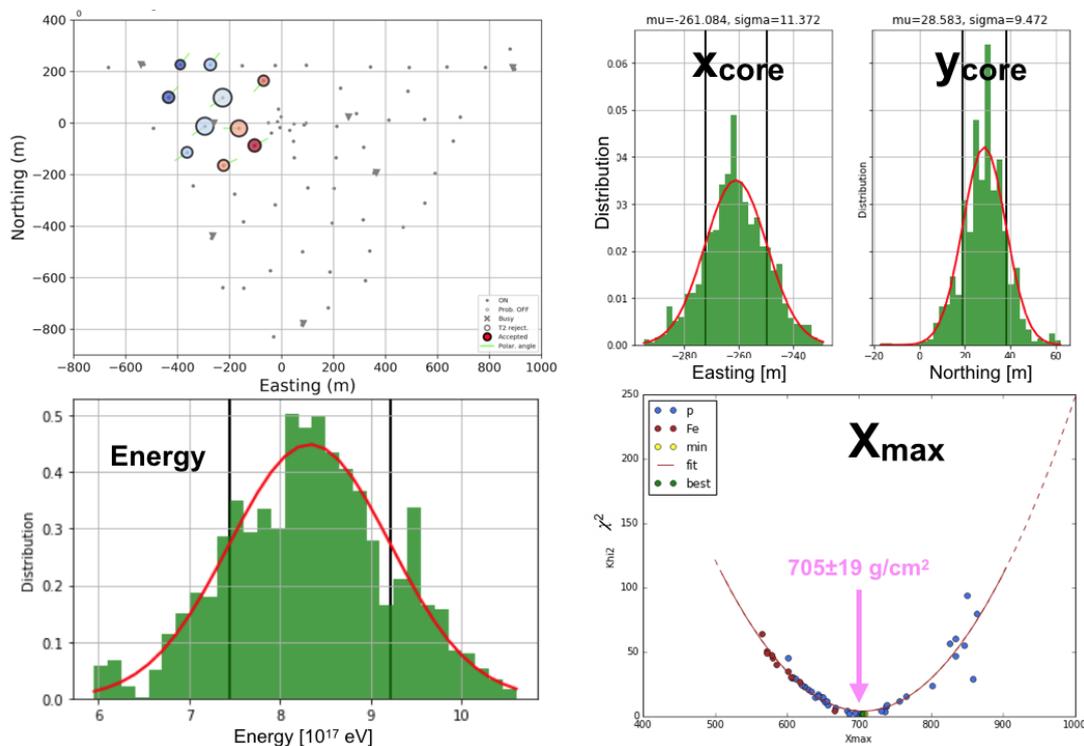
**Figure 1.** Setup of the CODALEMA/EXTASIS experiment in Nançay, France. The black squares represent the scintillators. The red symbols are the 57 autonomous radio stations. The white triangles are the antennas of the compact array and the blue diamonds are the low-frequency antennas of EXTASIS.

these detectors are sensitive to high energy particles of the shower only. The scintillator DAQ triggers in real time the radio compact array, the 3D antenna and the low frequency antennas of EXTASIS.

### 3. Analysis of the radio signal

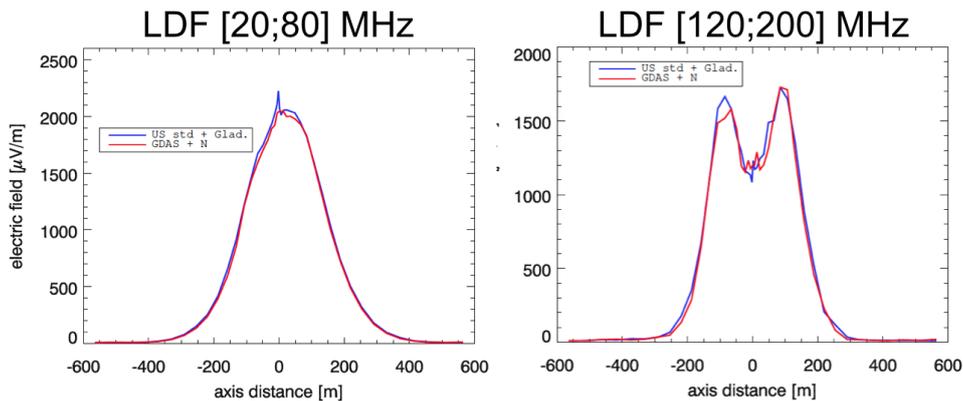
The expected electric field is obtained with the code SELFAS3, developed at Subatech. It is based on the SELFAS2 version of the code [7, 8] but we significantly improved the computation in 2018. First, we are not using anymore the common US Standard model for the description of the atmosphere. This model is static and does not include day/night effects nor seasonal effects. We are now using the data from the GDAS [9] to estimate the precise atmospheric status at the time of the detection of our events at the location of Nançay. These data allow us to compute the air density and air refractive index which are key ingredients to obtain with high precision the electric field emitted by the secondary particles [10]. We also use the exact formula for the electric field estimation, valid at all frequencies [11]. We don't rely anymore on the far-field hypothesis ( $kR \gg 1$ ) which is wrong in particular for the wavelengths of interest for EXTASIS (1-6 MHz, ie some hundreds of meters). For instance, at 100 m from the source and at a frequency of 1 MHz, we have  $kR \sim 2$  which is clearly not satisfying the far-field condition.

For each shower detected in CODALEMA/EXTASIS, we compute the arrival direction with a resolution of half a degree or so. Using SELFAS3, we simulate 40 protons showers and 10 iron showers at  $10^{17}$  eV with the same arrival direction, on a virtual array of 300 antennas. Then we compare the measured values of the electric field in 20-80 MHz to the simulated ones and the best agreement is the estimated shower core; the procedure also provides the scaling factor we must apply to correct from the arbitrary choice of the primary energy of  $10^{17}$  eV [12]. The typical accuracy we obtain at the end of the analysis chain is 15 m on the core position, 20% on the primary energy and  $20 \text{ g/cm}^2$  on the  $X_{\text{max}}$ . FIG. 2 shows the reconstruction performances on an event detected by CODALEMA on March 9<sup>th</sup>, 2017. As the CODALEMA radio stations are



**Figure 2.** Reconstruction of an event detected by CODALEMA. The ground footprint is on the top left. The color scale indicates the arrival time of the transient signal in each antenna (blue: early, red: late). The other plots indicates the accuracy on the shower parameters.

able to measure the electric field up to 200 MHz, we can improve the 20-80 MHz reconstruction by taking into account the high frequency data. For geometrical reasons, the electric field emitted by inclined showers has an important high frequency component. The electric field amplification due to Cherenkov-like effects is clearly visible on inclined events. FIG. 3 shows the expected lateral distribution functions for the frequency band 20-80 MHz (left) and 120-200 MHz (right). For inclined showers, all stations are roughly at the same axis distance and



**Figure 3.** Expected lateral distribution functions (LDF) for an inclined shower, between 20-80 MHz (left) and 120-200 MHz (right) using SELFAS3. The LDF looks like a Gaussian, as a function of axis distance, in 20-80 MHz. The shape is more complicated at high frequency as the Cherenkov-like amplification of the electric field is visible at 140 m of the axis. The two curves correspond to the profiles obtained using two different atmospheric models.

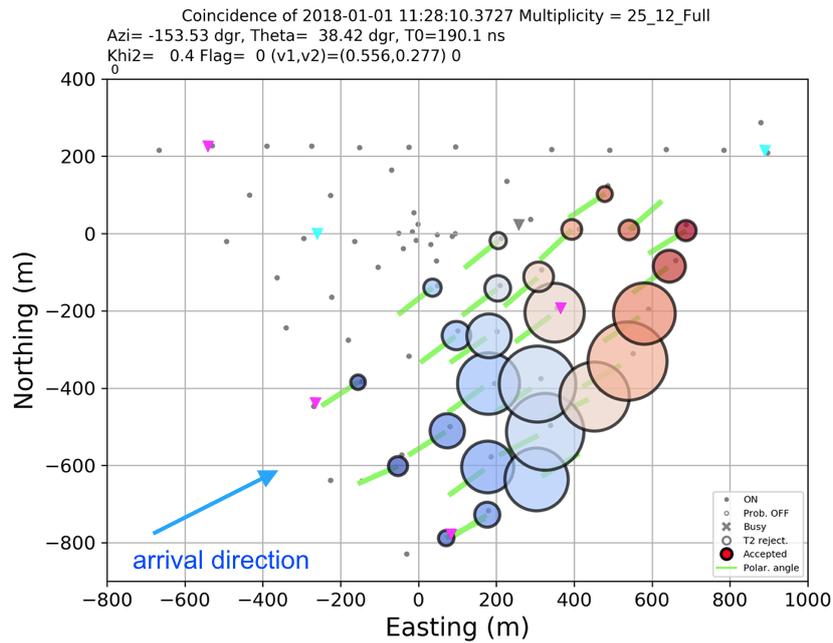
the electric field gradient in 20-80 MHz is very small: the shower parameters reconstruction is not well constrained by these data alone. At higher frequency (120-200 MHz), the electric field variations are much stronger due to the Cherenkov-like amplification at  $\sim 140$  m of the shower axis. This permits a much better shower reconstruction.

#### 4. EXTASIS: air showers observed at low frequency

There are several motivations for the study of the low frequency radio emission of air showers. Air showers develop within some  $\mu\text{s}$  so that we expect some contribution at some hundreds of kHz. The simulation also predicts an emission at some MHz comparable to that of the 20-80 MHz band but the range is expected to be larger. We also aim to detect the emission from the air shower sudden death: it is the coherent emission from the sudden deceleration of  $e^\pm$  when the shower front reaches the ground level [13, 11]. This emission is directly related to the shower front lateral dimensions, implying a contribution at the MHz level. We installed in Nançay 7 Butterfly antennas, 9 m above the ground level, as suggested by NEC2 simulations for the antenna response at these frequencies. These low frequency antennas are triggered by the scintillator array and data are produced by a scope with a sampling rate of 500 MHz on 8 bits, in a time window of 2 ms. The associated amplifier is a modified version of the LONAMOS used in the 57 radio stations of CODALEMA.

In 18 months, we detected 18 showers. We observed that the detection range is higher than in the 20-80 MHz band as predicted by the SELFAS3 simulation [14]: in these events, the maximum distance between any pair of low frequency antennas is always larger than for the CODALEMA antennas. We did not detect the sudden death signal so far. This could be due to the fact that the Nançay observatory has an altitude of 180 m: the atmospheric depth at this altitude is of the order of  $1000 \text{ g/cm}^2$  for vertical showers and the number of

$e^\pm$  reaching the ground level is not sufficient to emit a measurable sudden death electric field. The detection threshold for EXTASIS is around  $5 \mu\text{V}/\text{m}$  which corresponds in the best case to vertical showers of  $2 \times 10^{18}$  eV, making candidate showers quite rare. The situation would be much more favorable for a site at higher altitude. For instance, at 1400 m above sea level (the Auger site for instance) candidate showers have an energy of some  $10^{17}$  eV, the flux would be multiplied by a factor of  $\sim 130$ . We also observed that the probability to detect showers at low frequency is significantly improved when there is a high atmospheric electric field, as it is the case in thunderstorm conditions. In FIG. 4, we present an event detected on January 1<sup>st</sup>, 2018. The shower is coming from the south-west, as indicated by the blue arrow. The



**Figure 4.** Ground footprint of an air shower detected by 6 EXTASIS antennas (trinagles) and 25 CODALEMA antennas (circles). The shower arrival direction projected in the horizontal plane is indicated by the blue arrow. The electric field polarization measured by the CODALEMA antennas is indicated by the green lines. See text for details.

radio stations of CODALEMA that detected the shower are indicated by the colored circles, with the same color code than in FIG. 2. The 6 EXTASIS antennas involved in the event are indicated by the colored triangles; the arrival direction estimated using the low-frequency data only is in very good agreement with the direction obtained by the CODALEMA data. We see that the ground pattern of the EXTASIS antennas has a much larger area than the pattern of the CODALEMA stations: this confirms the more extended lateral width of the signal at low-frequency compared to the signal in the 20-80 MHz band. It is very interesting to focus on the polarization angle of the electric in all triggered CODALEMA stations. This linear polarization is indicated with the green lines. We see that these lines are roughly parallel to the incoming direction (in the horizontal plane) which is not what we expect from the geomagnetic effect. We should have observed an electric field orthogonal to the incoming direction as it is polarized at first order along  $\mathbf{v} \times \mathbf{B}$ . The discrepancy is due to the presence of a thunderstorm: the strong atmospheric electric field overtakes the geomagnetic effect and we observe a polarization that could be parallel to  $\mathbf{E}_{\text{storm}} + \mathbf{v} \times \mathbf{B}$  with  $\|\mathbf{E}_{\text{storm}}\| \gg \|\mathbf{v} \times \mathbf{B}\|$ . The amplitude of the signal

is also strongly amplified by the presence of  $\mathbf{E}_{\text{storm}}$ . This storm is not a regular one: it is the storm Carmen; at the time of the detection of the cosmic ray, the atmospheric electric field had a value at  $20\sigma$  of its value in quiet conditions.

## 5. Conclusion

CODALEMA/EXTASIS is a multi-wavelength experiment that observes cosmic-ray induced air showers in 1-6 MHz, 20-80 MHz and 120-200 MHz. This allows us to use the information at all frequencies allowing improved reconstruction of the primary cosmic ray characteristics. We observe showers in 1-6 MHz: the detected signal is the counterpart at low frequency of the regular emission when the shower develops in the atmosphere. But the number of events detected is small (18 only in 1.5 years) and the detection is favored when the atmospheric electric field is high (thunderstorm conditions). We did not detect yet the sudden death signal, corresponding to the electric field emitted when the shower front hits the ground. We believe the reason for this is the low altitude of the site of Nançay, making the number of secondary particles reaching the ground level too small to produce an electric field that would be above the detection threshold. It would be very interesting to try the sudden death pulse detection at higher altitudes. Our analysis relies on the code SELFAS3 which uses a formula of the electric field valid at all frequencies.

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