EXTASIS: Radio detection of cosmic rays at low frequencies

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Abstract. The detection of cosmic rays via the electric field (the so-called radio detection) is nowadays a fully operative technique. With the aim of exploring the low-frequency part of the emission spectrum (below 10 MHz), the EXTASIS experiment has been conceived. Located within the CODALEMA experiment at the Nançay radio-observatory, EXTASIS measures the low-frequency emission coming from the extensive air showers created by cosmic rays. Being able to calculate the electric field at low frequency is crucial in order to correctly interpret our results. We present some results from the EXTASIS experiment and discuss the calculation of the low-frequency radio signal. We also present a new formula for the electric field of a particle track within two semi-infinite media (air and soil).

1 Introduction

Radio detection of cosmic rays is a well-established technique [1] that allows the determination of the relevant properties of the primary cosmic ray by measuring the electric field radiated by the extensive air shower (EAS) induced by the primary cosmic ray. Its arrival direction, primary energy and composition can be measured with uncertainties similar to those obtained with a surface array or a fluorescence telescope. Radio detection is also able to induce by the primary cosmic ray. Its arrival direction, electric field radiated by the extensive air shower (EAS). Low frequency implies a large wavelength, so the shower is expected to emit more coherently at these frequencies, from 1.7 to 3.7 MHz. In this work, we discuss the emission of an EAS at low frequency, introduce a new formula for the electric field that takes into account the air-soil boundary and present some results from the EXTASIS experiment.

2 Simulations of the electric field at low frequency

Standard codes for the calculation of the electric field (SELFAS2, ZHAireS or CoREAS) work in the far field, meaning that they calculate the electric field under the approximation that the measuring antenna is located in the radiation zone, or equivalently, that the wavenumber \( k \) times the distance between the emitter and the observer \( R \) is much greater than 1: \( kR = 2\pi R/\lambda \gg 1 \). If an important contribution from the tail of the shower is expected (sudden death mechanism), and the antennas are at a distance smaller than 100 m from the shower core, at 1 MHz, \( kR = 2\pi \cdot 100/300 \sim 2 \), so near-field effects can be expected to be important.

2.1 Direct emission from a particle track at all frequencies. Sudden death pulse

As a first approximation, we will ignore the effect of the soil in our calculations. When working in the far-field, this is usually sufficient since the effect of the soil can be taken into account with the reception pattern for the antenna. When calculating in the near-field regime, this is not necessarily true but such an approximation seems reasonable at first order.

Let us define a particle track as the trajectory of a particle that begins at rest, and is suddenly accelerated gaining a velocity \( v \) at \( t = t_1 \). Then, it travels at constant speed for a time and stops suddenly at a time \( t = t_2 \). Monte Carlo
The SDP is indicated by the arrows. One observer is placed at 200 m from the shower core and the other one at 500 m. The SDP is indicated by the arrows.

The field for each track is calculated and the total field is obtained as the sum of the field of all the tracks thanks to the superposition principle.

A complete formula for the direct electric field of a track at all frequencies can be found in [9]. This formula is embedded in the MC code SELFAS3, which has been used to elucidate the properties of the low-frequency emission from EAS. In Fig. 1 we show the time trace of the electric field created by a 1 EeV proton shower, filtered with a low-pass filter below 5 MHz. There is a difference between the far-field approximation and the exact formula, as well as a bump after the main pulse. This pulse corresponds to the SDP, the emission created by the sudden deceleration of the shower front at ground level. The SDP pulse is received by the antenna at a time directly proportional to the distance between the antenna and the shower core. Moreover, the amplitude of the SDP decreases with the dependence 1/R, with R the distance to the shower core. The arrival times and the amplitudes, measured by several antennas, would constitute a new method of direct measurement of shower core position, freed from the use of extensive MC simulations. The SDP pulse disappears at high frequency, since it is created by the coherent deceleration of the shower front, and coherence is most present at large wavelength.

Another feature of the low-frequency field, as predicted by the SELFAS3 code, is that the amplitude of the electric field on the ground does not decrease as fast as with high frequency. Due to the larger wavelength, the increased coherence of the emission creates a much wider profile on the ground. This implies that, if the low-frequency field is detectable, we expect it to have a larger detection range compared to the standard [20 – 80] MHz band.

In Fig. 2 we show the calculated amplitude of the SDP as a function of the shower zenith angle and its energy. For the EXTASIS setup, we do not expect showers above 10 EeV and we speculate that the detection threshold should be several µV/m, which leaves with a small window for detecting the SDP. At a higher altitude, the SDP emission is enhanced and should be easier to detect.

\[ \int_0^\infty f \left( \sqrt{k_1^2 - k^2} \right) e^{\sqrt{k_1^2 - k^2} J_n(kp) k^{3-n}} dk, \]  \( (1) \)

where \( k_1 \) is the wavenumber in the medium where the particle is (air, in our case), \( p \) is the radial distance to the observer and \( f \) is a function that arises from solving Maxwell’s equations in Fourier space. \( J_n \) is a Bessel function of the first kind of order \( n \). With these three contributions we can know the field of a perfect dipole, \( \mathbf{E}_{\text{dipole}} \), which can be then used to obtain the field from a particle track upon integration:

\[ \mathbf{E}_{\text{track}}(\omega) = q \int_{k_1} \mathbf{v} \cdot \mathbf{E}_{\text{dipole}} \]  \( (2) \)
We can write as an example the radial field emitted by a vertical track:

\[
\vec{\rho} \cdot \vec{E}_{\text{track}} = \frac{\sin \theta}{4\pi^2} \int_0^{\infty} dt \, e^{i\omega t} \times \\
- e^{ikz} \left( k_2^2 - \frac{3k_1^2}{r^2} - \frac{3i}{r^2} \right) \frac{\vec{\rho} \cdot \vec{d}}{r \cdot k_2^2} \\
+ e^{ikz} \left( \frac{\vec{\rho}}{r_{\text{image}}} \cdot \frac{\vec{d}}{r_{\text{image}}} - \frac{3i}{r_{\text{image}}} \right) \frac{\vec{\rho} \cdot \vec{d}}{r \cdot k_2^2} \\
+ 2ik_2^2 \int_0^{\infty} \frac{\vec{\rho}}{k_2^2 - k_1^2 - k_2^2 + i\omega k_2^2} \sqrt{k_2^2 - k_1^2} J_1(kp) k_2^2 \, dk,
\]

where \( k_2 \) is the wavenumber in the lower medium (soil), \( z \) is the height of the antenna, \( d \) is the height of the particle track, and \( r \) (\( r_{\text{image}} \)) is the distance from track (image) to the observer. The second line in Eq. (3) indicates the direct field, while the last two lines indicate the surface wave contribution, expressed as the superposition of the image field and the lateral field. The integral possesses no analytic form or approximation that we are aware of (without making approximations that do not correspond to the EXTASIS experimental setup), and it revealed itself to be quite difficult to compute numerically. In fact, the oscillatory nature of the Bessel functions requires a method for integration known as the Extrapolation Method [11] if we want to reduce the computation time to reasonable levels.

Formulas similar to Eq. (3) exist for the other polarizations and also when the track is underground. We have found that the field underground is always very attenuated for a standard soil, as we expected. We show in Fig. 3 the comparison of the direct, direct plus reflected and exact field for a vertical track 10 m above ground. We have chosen an atmosphere with a refractive index of \( n_{\text{air}} = 1.0001 \) and a standard soil with \( n_{\text{soil}} = 13 \) and conductivity \( \sigma_{\text{soil}} = 5 \text{ mS/m} \). We see that the exact field at high frequencies agrees with the direct plus reflected field, as it should be. It is also patent that the surface wave present in the exact calculation amplifies the emission between 1 and 5 MHz, the frequency band of EXTASIS. For a track at 100 m of height, the far-field calculation and the exact calculations match better (Fig. 4). These calculations have yet to be implemented in a Monte Carlo code so as to have a realistic estimation of the boundary effect in air showers.

3 The EXTASIS experiment

The EXTASIS experiment has been conceived as an extension to the already existing CODEMA experiment, located in the Observatory of Nançay, France. CODEMA [3] is an experiment dedicated to the measurement of cosmic rays, and it is constituted by 13 scintillators acting as a surface detector, 57 self-triggered antennas acting as autonomous stations and 10 antennas forming a compact array. The autonomous stations measure the North-South and East-West components of the electric field in the [20 – 200] MHz band. With the help of this setup, cosmic rays are routinely detected and their arrival direction, energy and composition known with the help of MC simulations.

EXTASIS (EXTinction of Air Shower Induced Signal) is the most recent detector in the Nançay observatory. It was designed to detect the low-frequency electric field coming from EAS and, in particular, the SDP emitted when the shower front hits the ground. EXTASIS operates in the [1 – 10] MHz band, which is flooded with anthropogenic and atmospheric noise, which restricts the data taking to daytime only, since the noise is highly dependent on the ionosphere temperature.

The current EXTASIS configuration consists of 7 antennas located 9 m above ground. These antennas measure the vertical and the East-West component of the electric field in the [1 – 10] MHz band. They are triggered by the scintillator array of CODEMA.

So far, EXTASIS has detected several low-frequency events, all of them detected in the [20 – 200] MHz band by CODEMA. We show one these events in Fig. 5, plotted on a map of the CODEMA/EXTASIS setup with information on the electric field measured by the antenna array. The arrival directions ((\( \theta, \phi \)) re-
constructed by the scintillators (32.4°, 144.1°), the autonomous stations (40.6°, 145.2°), and the low-frequency array (31.1°, 146.1°) are compatible with each other. We see in Fig. 5 that the EXTASIS antennas have detected the signal farther away when compared to the standalone antennas. This hints that the detection range may be indeed larger at low frequencies.

On the downside, we have only had ~ 15 low-frequency events since April 2017, meaning that the efficiency is quite low. Besides, no sudden death signal has been observed so far.

Some of the detected events are correlated with large values of the atmospheric electric field (stormy weather). It is possible that the atmospheric electric field accelerates the particles in the shower similarly to the geomagnetic effect, a process that can be called the *geoelectric* effect. This effect has been seen by LOFAR [12], and it changes the polarisation of the electric field on the ground inducing an homogeneous polarisation. We show in Fig. 6 an event measured during the Carmen storm, on the 1st of January, 2018. The green arrows that indicate the polarisation reveal that the pattern is quite uniform, and is incompatible with the standard geomagnetic polarisation.

### 4 Outlook and conclusions

EXTASIS is a experiment that measures the low-frequency ([1 – 10] MHz) electric field from EAS. In this work we have studied the expected properties of such an emission, including the SDP. We have introduced a new way of calculating the electric field taking into account the influence of the ground, valid at all frequencies. We have presented some events measured by EXTASIS, that are the low-frequency counterpart of standard radio events. One of this events shows that the detection range seems to be larger at low frequencies. Another of this events shows that the atmospheric electric field can have an important influence on the emission at low frequencies. However, the low number of events detected would suggest that the EXTASIS band is not as exploitable as the standard [30 – 80] MHz band. The SDP has not been detected so far.

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