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Reconstruction of the parameters of cosmic ray induced extensive air showers using radio detection and simulation

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Cosmic rays have a wide energy spectrum and their flux decreases quickly with the energy. For the most energetic events (above 10^{17} eV), the mass composition is not well known, due to shower to shower fluctuations. The knowledge of the mass composition would allow us to constrain theoretical models which predict different types of source and acceleration mechanism according to the mass of the particle. The only way to study such rare events is to observe the extensive air shower (EAS), composed of the secondary particles produced in the atmosphere after the interaction between the primary cosmic ray and the atmosphere's constituents. The EAS is mainly composed of electrons, positrons and photons. Different ways of detection exist to determine the EAS parameters. The fluorescence detectors receive the light emitted by the atmosphere constituents after being excited by the EAS charged particles. Cerenkov tanks and plastic scintillators sample the particles on the ground. Radio antennas record the electric field emitted by the electrons and positrons of the shower. These detection methods are able to reconstruct some of the EAS parameters such as the energy of the primary particle, its arrival direction, the EAS core position on the ground and the atmospheric depth at which the number of particles is maximum ($X_{\max}$). The radio signal is now quite well understood and its description via the simulation is successful. In this context, the reconstruction method described in this contribution is based on a detailed comparison between the simulated radio footprint and the one sampled by an array of antennas. The method is sensitive to the $X_{\max}$ value which is strongly correlated to the primary mass. We finally show how the radio detection is able to reconstruct all the EAS parameters on its own.

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1. Introduction

Cosmic rays have a wide energy spectrum and their flux decrease quickly with the energy. For the most energetic events (above 10^{17} eV), the mass composition is not well known, due to the low statistics (around one event per km^2 and per century at 10^{20} eV). The knowledge of the mass composition would allow to constrain theoretical models which predict different type of sources and acceleration mechanisms according to the mass of the particle. The only way to study such rare events is to observe the extensive air shower (EAS), composed of the secondary particles produced in the atmosphere after the interaction of the primary cosmic ray with the atmosphere's constituents. An EAS have three components: hadronic, muonic and electromagnetic. The last one, which is composed of electrons, positrons and photons, correspond to 90% of an EAS total energy. The aim of cosmic ray detection is to reconstruct the EAS parameters, which are the energy of the primary particle, its arrival direction, its core position on the ground and its nature via the atmospheric depth at which the number of particles is maximum (X_{max}), as described in Figure 1. Different ways of detection exist to study these EAS. 1) The fluorescence detectors receive the light emitted by the atmosphere constituents excited by the EAS charged particles; 2) Ground particles detectors such as Cerenkov tanks or plastic scintillators sample the secondary charged particles at the ground level; 3) Radio antennas record the electric field produced during the EAS development in the atmosphere. These detectors are currently taking data at the Pierre Auger Observatory [1], the largest cosmic ray experiment in the world. Particle detectors and radio antennas are also used on CODALEMA at the Nançay radio observatory in France [2, 3]. In this paper we will focus on the radio signal produced by the electric field emitted by the showers. Two combined main mechanisms produce this electric field [4]. First the transverse current mechanism which produces an electric field with an unidirectional polarization in the $\mathbf{v} \times \mathbf{B}$ direction, where $\mathbf{v}$ is the shower front's velocity vector and $\mathbf{B}$ is the geomagnetic field. The second mechanism is called the charge excess effect and produces a radial electric field around the shower axis. The combination of these two mechanisms leads to an asymmetry of the electric field around the shower axis (see [5] for more details). With the help of the two other methods, it is now established that the radio measurement of an EAS permits to estimate the primary cosmic ray energy, arrival direction, core position and nature [9]. In this study we introduce a method that aims to carry out a complete reconstruction of the EAS parameters (core position, nature and energy) using only radio observables. We will illustrate our method on an event detected by the CODALEMA experiment. Moreover, we intend to apply our method on the complete data set of CODALEMA. The X_{max} information (thus the nature of the particle) could then be estimated with high accuracy by the radio signals.

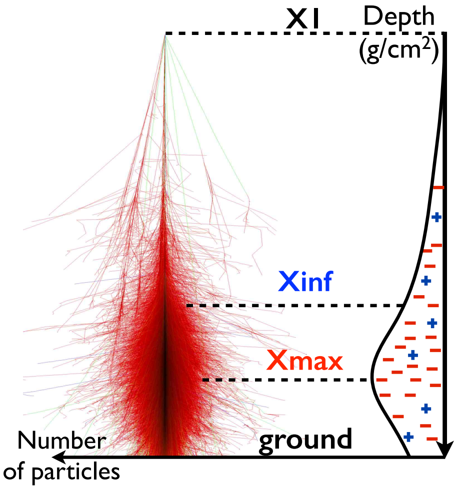
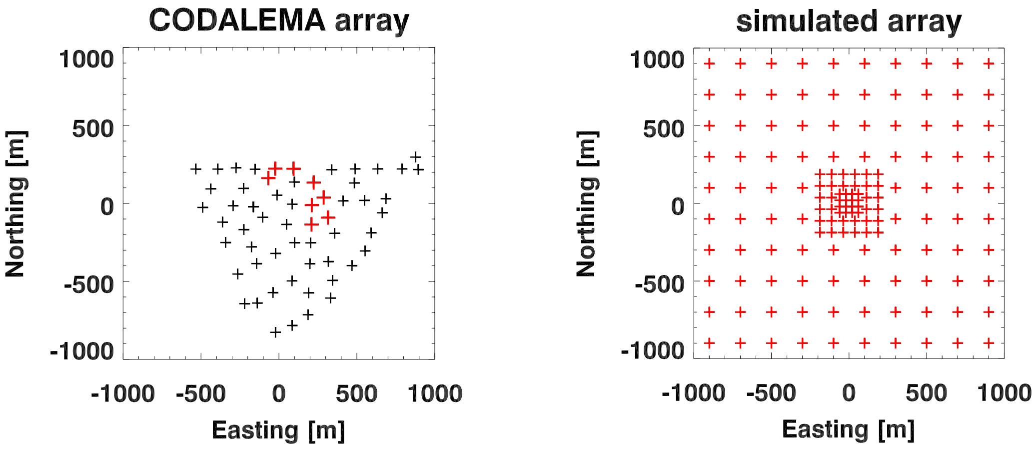


Figure 1: The geometry of an EAS.

2. Simulation and observables

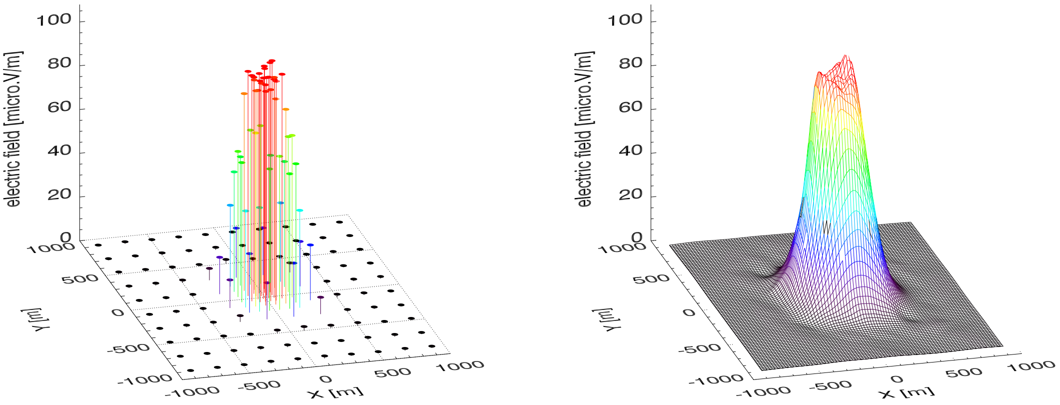
We use SELFAS [5], a code computing the electric field generated by the development of an EAS in the atmosphere, based on a microscopic description of the shower. Several frequency bands are available at the CODALEMA experiment (from 20 MHz to 200 MHz, excluding [80 - 130] MHz). In the following, the experimental and simulated signals are filtered in the [20 - 80] MHz frequency band. The choice of this particular band width is explained in Section 3.4. Only the reconstructed arrival direction (θ, ϕ), using the radio data, is known precisely [7] and used for the simulations. The event is simulated using a dense antenna array presented Figure 2b.



(a) (b)

Figure 2: (a): the CODALEMA antennas array, the red crosses are the antennas that have recorded the event - (b): the antenna array used for the simulations.

SELFAS compute the electric field at each antenna location. We extract and display in Figure 3a the electric field maximum value as a function of the position on the ground. Then, we can estimate the electric field value at any position using interpolation (Figure 3b).



(a) (b)

Figure 3: (a): the maximum of electric field of each simulated antenna - (b): interpolation of the maximum electric field distribution.

This observable is called the lateral distribution function (LDF), the maximum value of the electric field as a function of the distance to the shower axis (displayed in Figure 3a in three dimensions as a fonction of the position of the antenna). A set of events is simulated to study the influence of the nature of the primary cosmic ray on the EAS geometry and the induced electric field. A total number of 150 events (100 protons, 50 iron nuclei) are simulated and their first interaction depths are calculated by EPOS [11], an hadronic interaction model, according to the interaction cross section. As protons and iron nuclei have different interaction cross sections with the constituants of the atmosphere, an EAS initiated by a proton will not occur at the same atmospheric depth, compared to an EAS initiated by an iron nucleus. Thus, this atmospheric depth difference leads to differences in the electric field seen by antennas and its quantification is a measurement of the nature of the primary particle. We decide to simulate all events at 2×10^{17} eV. The simulated events allow to predict the most suitable EAS parameters describing the experimental event.

3. Event reconstruction

3.1 Core position

In order to reconstruct the event's core position (x_c, y_c), a comparison is made between the observed electric field distribution to the ones predicted by the simulations. The core position of a simulated EAS, giving the best agreement between the observed electric field distribution and the simulated one, gives the most probable core position of the experimental event. To do so, a χ^2 calculation will be made at every steps (i.e. every possible (x_i, y_j) positions with a 5 meters step in both directions):

$$\chi^2_{ij} = \chi^2(x_i, y_j) = \frac{1}{n}\sum_{k=1}^{n}\left(\frac{\frac{E^{\text{sim}}_{ijk}}{C_{ij}} - E^{\text{exp}}_{k}}{E^{\text{exp}}_{k}}\right)^2 \tag{3.1}$$

where (x_i, y_j) is a core position being tested within the CODALEMA coordinates frame, E^{exp}_{k} is the maximum electric field of the antenna number k, E^{sim}_{ijk} is the expected electric field obtained by the simulation for the antenna k (from the set of antennas triggered by the experimental event). In this work, we would like to compare only the shape of the LDFs. That is why, before the χ^2 calculation a scaling factor (C_{ij}) is determined at each tested core position (x_i, y_i) for every simulated event. The scaling factor is calculated as the mean ratio between simulation and data and is taken into account in the χ^2 calculation. The relation between the scaling factor and the energy of the simulated showers (in this case 2×10^{17} eV) will be developed in Section 3.3. Once χ^2_{ij} has been determined at each (x_i, y_j) position a χ^2 density map of all tested core positions is made (see Figure 4). The red crosses are the CODALEMA antennas and the green cross is the core position giving the best agreement between the simulated and the experimental LDF (the one where the χ^2 value is the smallest). To give an accurate core position, the errors

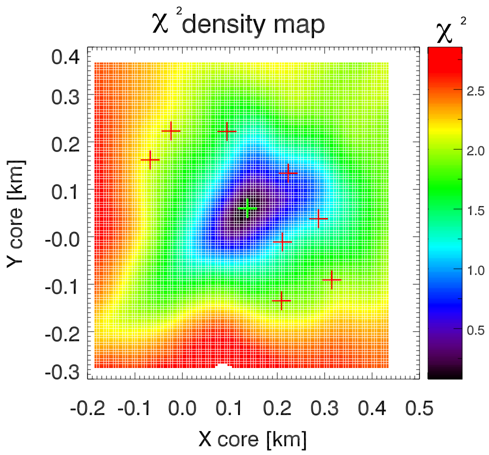
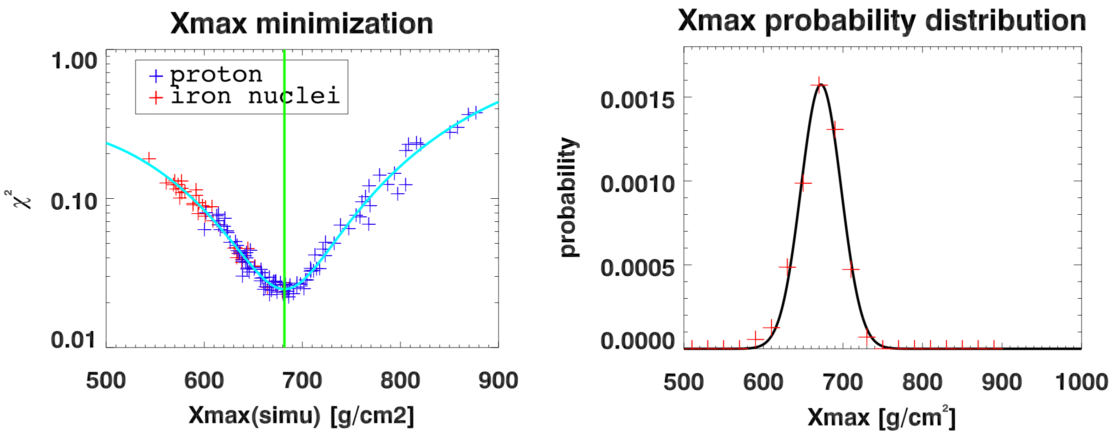


Figure 4: χ^2 density map.

on the reconstruction have to be calculated by taking into account the errors on the electric field of the data and also the influence of the nature of the primary cosmic ray (thus the influence of the $X_{\max}$ value on the LDF). To do so, the method is applied to the whole set of simulated events.

3.2 $X_{\max}$ reconstruction

We now use the influence of the shower geometry on the electric field topology, to find the most probable $X_{\max}$ value. The previous method is applied to the 150 simulated events, each one of them has been associated to a best χ^2 value corresponding to a best reconstructed core position, on their respective density map (Figure 4). On Figure 5a, we show the best χ^2 of each simulated event as a function of its $X_{\max}$ value.



(a) (b)

Figure 5: (a): best χ^2 of each simulated event as a function of its $X_{\max}$ value - (b): $X_{\max}$ distribution (see text for details).

Two distinct populations appear (protons and iron nuclei) due to the generation of realistic first interaction depths, here using EPOS [11] as hadronic interaction model, included in SELFAS. The minimum χ^2 gives the most probable value of $X_{\max}$. Mostly protons fit into experimental $X_{\max}$ uncertainties. To estimate the effect of the error on the electric field on the $X_{\max}$ reconstruction, a 10% gaussian error is added to each antenna electric field measurement. A Monte Carlo method is then applied on the 150 simulated events. The procedure permits to construct the $X_{\max}$ probability density function of the experimental event (Figure 5b). At this point, we can propose an estimation of the most probable $X_{\max}$ depth and its uncertainties due to the errors on the electric field, using a gaussian fit of the $X_{\max}$ distribution. We finally obtain:

$$X_{\max} = 673 \pm 26 \text{ g/cm}^2.$$

This result suggests that the method is able to reconstruct the $X_{\max}$ depth of an experimental event using only radio data and radio simulation. We now have a set of χ^2 density maps taking into acount errors on the electric field, giving a new set of most probable core positions with their errors. Each of these best positions is weighted by its corresponding $X_{\max}$ probability taken from the $X_{\max}$ distribution of Figure 5b, giving an histogram of the core positions from which the most likely core position and its uncertainty is calculated:

Easting: 80.2 ± 9.0 m
Northing: -10.5 ± 8.0 m

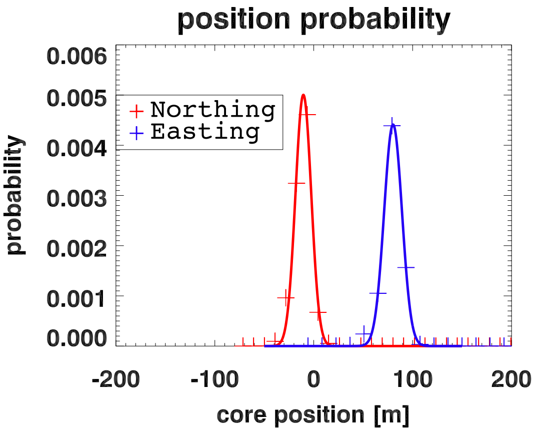
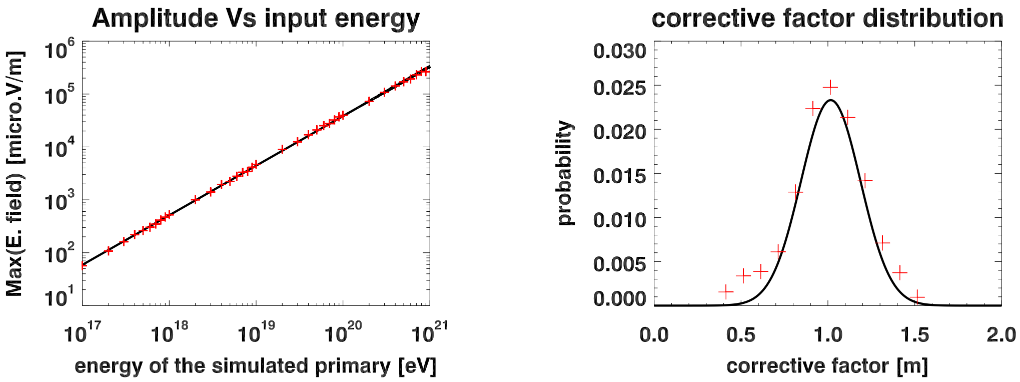


Figure 6: Core position probability.

3.3 Energy reconstruction

The last EAS parameter to be derived from radio data is the energy of the primary cosmic ray. The ratio between the scaling factor (C) described in Section 3.1 and the energy of the primary particles simulated (E_p) is used to estimate the energy of the primary cosmic ray. Figure 7a shows the simulated electric field amplitude as a function of the energy of the simulated primary cosmic ray for an antenna at 100 meters from the shower axis in the East direction.



(a) (b)

Figure 7: (a): The maximum signal received by an antenna (at 100 m from the shower axis in the East direction) as a function of the energy the primary particle. - (b) Distribution of the values of the corrective factors used to scale the data

The relation between these parameters is a power law, which can be approximated as a linear relation in our case. From the distribution of the scaling factor presented Figure 7b, we obtain:

$$\text{primary energy: } 2.0 \pm 0.7 \times 10^{17} \text{ eV}$$

This result shows that an arbitrary energy can be used to generate the set of events simulated to reconstruct an event like this one, regardless of the true primary energy.

3.4 Influence of frequency band width on the reconstruction quality

The electric field emitted by the development of an EAS in the atmosphere is highly focused toward the direction of propagation of the shower. Considering this characteristics, the distance (directly related to X_{max}) to the detection array at which the EAS emits the maximum electric field, changes its topology at the ground level. The method described in this contribution is able to constrain X_{max} only if the experimental antennas are located at a position where the decreasing part of the electric field distribution is recorded. The topology of the electric field depends strongly on the considered frequency band at which it is observed. Due to geometrical considerations, antennas close to the shower axis are more sensitive to high frequencies, while antennas far from the axis are more sensitive to low frequencies. It is therefore important to be able to mesure the electric field in a wide frequency band as it is the case for the CODALEMA experiment. Typically we use frequencies from 20 MHz to 200 MHz after exclusion of the band [80 - 130] MHz.

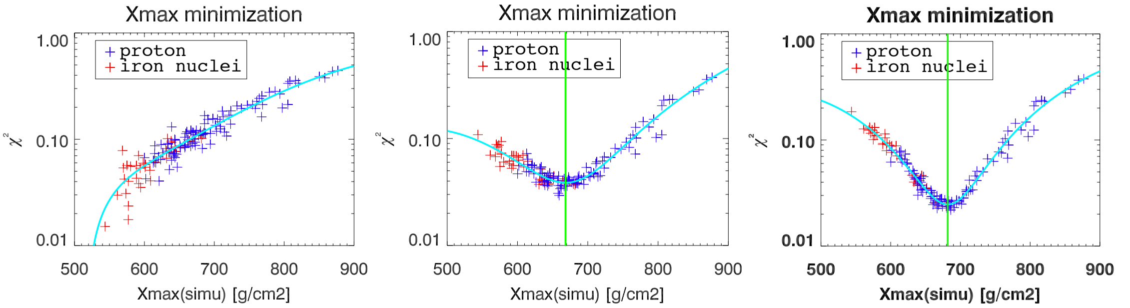


Figure 8: quality of X_{max} reconstruction for different frequency bands, from left to right: [20-200] MHz, [20-150] MHz and [20-80] MHz .

Figure 8 shows how the selected frequency band influences the quality of X_{max} reconstruction. A clear optimal X_{max} appears in both [20 - 150] MHz and [20 - 80] MHz bands but it is not the case for the [20 - 200] MHz band, these differences are due to the finite number of antennas and their pattern. The frequency band [20 - 80] MHz is the most sensitive to the shower geometry (for this antennas pattern) and has less χ^2 fluctuations than the [20 - 150] MHz band. Thus the frequency band [20 - 80] MHz has been chosen to reconstruct the event. Second order effects at high frequencies could lead to second order corrections between antennas. A more quantitative study is in progress for the frequency band [130 - 200] MHz. We have checked the validity of the method with a simulated event with a blind X_{max} and we found the same X_{max} value with 3% errors.

4. Conclusions

The experimental event has been fully reconstructed with good accuracy. It has now to be tested on other events to prove its robustness in order to be applied routinely. This reconstruction method is currently under study on the complete CODALEMA data set.

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