Radio emission in UHECR atmospheric showers in the MHz to GHz frequency range using ZHAireS

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Abstract: We present predictions for the radio pulses emitted by extensive air showers using ZHAireS, an AIRES-based Monte Carlo code that takes into account the full complexity of ultrahigh energy cosmic ray induced shower development in the atmosphere, and allows the calculation of the electric field in both the time and frequency domains. Our results are compatible with a superposition of the emission from transverse currents induced by the geomagnetic field and from the excess charge produced by the Askaryan effect. We have characterized the features of the radio emission in the frequency range from tens of MHz up to GHz. We show that shower geometry, coupled to the relativistic effects arising when using a realistic refractive index $n > 1$, play a prominent role on the radio emission. We also address the ability of our simulations to interpret data collected at ground arrays of antennas typically working in the VHF band (30-300 MHz) and of flight experiments working in the UHF band (300 MHz - 3 GHz) such as the ANITA antenna balloon.

Keywords: Extensive air shower, cosmic ray, radio emission, simulation.

1 Introduction

The detection of radio pulses from ultra high energy cosmic rays (UHECRs) is not a new technique, but it is experiencing a resurgence in the form of several new experiments, such as AERA [1] in the context of the Pierre Auger observatory. These experiments need detailed and realistic simulations of the radio emission of extensive air showers (EAS) in order to relate the radio pulses detected at ground level with the characteristics of the primary particle that initiated the EAS high up in the atmosphere. In this work we characterize and explain the features of the emission from EAS using the ZHAireS code [2, 3] both in the very high (tens of MHz) and ultra-high (hundreds of MHz to GHz) frequency ranges.

2 The ZHAireS code

ZHAireS is a full Monte Carlo simulation of the air shower and its associated radio emission. It is based on the AIRES shower code [4]. The emission due to each individual charged particle track produced in the shower simulation is calculated using a well established algorithm [5, 6], which is obtained from first principles [7, 8, 9] and as such does not assume any specific emission mechanism. Interference effects between the emission from different tracks are carefully accounted for as is the variation of the refractive index $n$ with altitude.

3 Radio emission in EAS

3.1 Main emission mechanisms

The main radio emission mechanisms in air showers are believed to be the geomagnetic and the charge excess mechanisms. The geomagnetic mechanism is due to the deflection of electrons and positrons by the geomagnetic field, which can be thought of as a moving macroscopic dipole and a transverse current traveling through the atmosphere along with the shower front at a speed $v \sim c$. This is thought to be the dominant emission mechanism in air showers. Its characteristic polarization does not depend on antenna position and is anti-parallel to the direction of the Lorentz force, i.e. in the direction of $-\mathbf{\hat{B}} \times \mathbf{\hat{B}}$, where $\mathbf{\hat{B}}$ is the speed of the particle in $c$ units and $\mathbf{\hat{B}}$ is the geomagnetic field. Also, the strength of the geomagnetic contribution to the emission varies with $\sin \alpha$, where $\alpha$ is the angle between the shower axis and the geomagnetic field $\mathbf{\hat{B}}$. The Askaryan effect, also known as the charge excess mechanism, arises from the excess of electrons over positrons in the shower. Its characteristic polarization is radial w.r.t. the shower axis, pointing towards it. As such the polarization induced by the Askaryan mechanism depends on antenna position.

3.2 Signal asymmetries on the net electric field

The interplay between the different polarizations of these emission mechanisms makes the net field on ground asymmetric w.r.t. the shower core. E.g. for a vertical shower and a horizontal $\mathbf{\hat{B}}$ pointing North (see top panel of Fig. 1), the Askaryan and geomagnetic polarizations point in the same direction for observers East of the core, and in opposite directions for observers to the west, so we expect the EW component of the electric field to be larger in an antenna eastwards of the shower core than in an antenna at the same distance west of the core. On the bottom panel of Fig. 1 we show the North-South ($E_{NS}$) (left) and the East-West ($E_{EW}$) (right) components of the electric field as obtained in a ZHAireS simulation of a vertical shower induced by a $10^{17}$eV proton. This asymmetry of the net field is present at all frequencies. Also, since both the strength and polarization of the geomagnetic component depend on $\mathbf{\hat{B}}$, the net
field on the ground is also highly dependant on the shower azimuthal angle [2,3].

3.3 Refractive index, time compression and the Cherenkov ring

Due to the refractive index in the atmosphere being larger than unity, there are relativistic effects associated to the speed of the shower front (c) being larger than the speed of the radio waves (c/n). In Fig. 2 we show, for three different distances to the shower core, the arrival time of the signal emitted by a vertical shower as a function of atmospheric depth for several values of the refractive index n, including an n varying with the altitude. For n > 1 an observer may see two parts of the shower development simultaneously, as well as a time reversal in the shower development, as the emission from later parts of the shower arrives earlier at the detector.

The first signal that reaches an antenna (corresponding to the minimum value of $t_{det}$) is related to the part of the shower observed at the Cherenkov angle $\theta_{\text{C}} = \arccos(1/n)$. One can also see in Fig. 2, that around this region, the emission from a large portion of the shower development arrives at the detector in a very short time. This “time compression” enhances the signal from this part of the shower, and makes the frequency spectrum extend to relatively high frequencies. In fact, the intensity of the radio signal is mainly determined by three factors, namely the distance R from the emission point to the observer, the number N of charged particles at this point, and also and in a very important way by geometrical effects related to the time compression $f_c = |\partial t_{det}/\partial X|$ (with X the depth in the atmosphere), corresponding to the derivative of the curves shown in Fig. 2. Also note that as we move the antenna further away from the shower core, the part of the shower observed near the Cherenkov angle is higher up in the atmosphere. In particular, when the observer sees the shower maximum ($X_{\text{max}}$) at the Cherenkov angle, the signal will tend to be the highest. So the radio lateral distribution function (RLDF), i.e. the signal as a function of the distance $r$ from the core, will be mainly determined by a convolution of $R, N$ and $f_c$.

Inclined showers develop at larger distances to the antennas. For any given antenna the observation angles, and thus to a certain extent the compression factor $f_{\text{C}}$, will vary only slightly along the whole shower development, as will the distances $R$ between the shower and the observer. This will make the number of particles $N$ at each depth have a much greater effect on the RLDF than in more vertical showers, i.e. the RLDF will tend to mirror the longitudinal profile of the shower more closely. Also, the arrival times of the signal from the inclined shower development as a whole will tend to be closer together, leading to shorter pulses and thus a spectrum that will extend to higher frequencies if compared to vertical showers [2,3].

Our simulations of inclined showers near the south pole [3] predict strong pulses in the nanosecond scale for antennas that view $X_{\text{max}}$ at angles very close to the Cherenkov angle, i.e., antennas placed on the elliptical ring shown in the top panel of Fig. 4 defined by the intersection of a Cherenkov cone with apex at $X_{\text{max}}$ and the ground. As the observation point moves away from this region, to the inner or outer regions of the Cherenkov cone, there is a significant broadening in time of the pulse, leading to a steeper spectrum as can be seen in Fig. 3 where we show the frequency spectra for antennas lying on the ground along a W-E line that intercepts shower axis. In [3] we show that our simulations are consistent with the reflected cosmic ray events observed by ANITA [10].

From the geometry and $X_{\text{max}}$ of a specific shower, one can calculate the refractive index at the shower maximum altitude, thus defining the position and opening angle of the Cherenkov cone, which can then be projected on the ground to obtain the expected position of the Cherenkov ring for this specific shower. In the bottom panel of Fig. 4 we show the spectral component of the electric field at 300 MHz as a function of distance to the shower core for antennas along the S-N and W-E axes (see top panel of Fig. 4). The shower comes from the north and the positions of the electric field maxima are consistent with the calculated Cherenkov ring for this specific shower, making an ellipse with its major axis along the N-S direction. The ultra-high frequency (UHF) signal is maximum at the position of the Cherenkov ring, decreasing rapidly as we move away from it, illustrating the fact that the RLDF contains information on shower development. In the top panel of Fig. 5 we show the spectral components of the electric

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**Figure 1:** Top: Sketch of the projection on the ground of the electric field induced by the Askaryan and geomagnetic mechanisms in a vertical shower. Bottom: North-South $E_{NS}$ (left) and East-West $E_{EW}$ (right) component of the electric field at 60 MHz as obtained in a ZHAireS simulation of a vertical shower induced by a proton of energy $10^{18}$ eV [2].

**Figure 2:** Arrival time $t_{det}$ of the signal as a function of atmospheric depth for a vertical shower and for different values of the index of refraction $n$ and different distances to the shower core (curve labels). Also shown is the longitudinal profile of a 100 PeV proton shower in arbitrary units.
field at 300 MHz for a $10^{19}$ eV proton shower with three different zenith angles. The scaling of the major axis of the ring with sec $\theta$ is illustrated. The axes of the elliptical ring, as well as the UHF illuminated area increase as the zenith angle rises because the shower maximum is more distant from the antennas. In the bottom panel of Fig. 5 we show the RLDF for a fixed zenith angle of $\theta = 70^\circ$ and for several frequencies. As the frequency drops the width of the Cherenkov ring broadens (as expected from Fig. 3), and eventually the peaks on each side of the core merge, making a plateau near the shower core. This can be mostly appreciated in the 50 MHz frequency line shown in Fig. 5. There is evidence of this behavior in the flattening of the lateral distribution of the signal close to the shower core in showers detected by the LOPES [11] and LOFAR [12] experiments.

### 3.4 Time delays and coherent emission

In order to interpret the frequency dependence of the radio signals we have calculated, for a given observer, the arrival time of the emission originated at different positions of the shower w.r.t. the arrival of the earliest signal. In Fig. 6 we show the calculated delays up to 1 ns for a vertical shower (left) and a shower with $\theta = 60^\circ$ (right) for observers located in their respective Cherenkov rings. For these observers the earliest part of the signal originates from $X_{\text{max}}$ (origin of the plots). The vertical axis is the longitudinal distance w.r.t. the position of $X_{\text{max}}$ (positive values higher in the atmosphere), and the horizontal axis is the lateral distance to the shower axis. Also shown is a representative Gaisser-Hillas curve for each (10 EeV proton) shower.

In order to contribute coherently at a given frequency the magnitude of the delays must be below the period of that frequency. So we expect coherent emission above $\sim 1$ GHz from the regions shown in Fig. 6 which have delays smaller than 1 ns. One can see that in both cases only a region very close to the shower axis emits coherently at these higher frequencies, due to the large delays induced by the curvature of the shower front as we move away from the axis. In the case of inclined showers this small coherent region around the axis spans almost the whole shower development (longitudinal dimension), while only a much smaller region of the shower development emits coherently in vertical showers. This time delay interpretation has been confirmed in full Monte Carlo simulations and is very useful to interpret the characteristics of the emission spectrum [3].

### 3.5 Vertical vs. inclined showers

In contrast to inclined showers, more vertical showers ($\theta \lesssim 30^\circ$) develop closer to the antennas on the ground. The lateral dimensions of these showers become impor-
We have shown that the RLDF, especially in the case of more inclined showers, contains information about the longitudinal profile of the shower using the radio technique, obtaining similar results as fluorescence detectors, but with a duty cycle close to 100%. Using inclined showers for this purpose may prove to be easier for several reasons. More inclined showers have wider Cherenkov rings, thus a higher resolution can be achieved with the same antenna density. Also the RLDF of these showers follow the longitudinal profile more closely than less inclined ones, making any reconstruction that relates it to the shower development easier to accomplish.

4 Discussion and Conclusion

We have shown that the $n > 1$ of the atmosphere leads to several important effects on the net electric field on the ground, and that the geometry of the shower/observer system plays a prominent role on the radio signal. The emission due to the Askaryan and geomagnetic mechanisms can have a sizeable intensity well into the GHz frequency range in an elliptical region defined by the intersection of the Cherenkov cone centered at $X_{\text{max}}$ with the ground, i.e. the Cherenkov ring. We have also shown that delays related to the curvature of the shower front makes only regions very close to the shower axis contribute coherently to the signal at higher frequencies.

We have shown that vertical and inclined showers have different emission regimes: while inclined showers can be approximated as one-dimensional, the lateral spread of more vertical showers becomes important, smearing the signal on the ground, although this importance is diminished by observation at higher frequencies. We have also shown that the RLDF, especially in the case of more inclined showers, contains information about the longitudinal development of the shower. In the future it may prove to be possible to reconstruct not only $X_{\text{max}}$ but the whole longitudinal profile of the shower using the radio technique, obtaining similar results as fluorescence detectors, but with a duty cycle close to 100%. Using inclined showers for this purpose may prove to be easier for several reasons. More inclined showers have wider Cherenkov rings, thus a higher resolution can be achieved with the same antenna density. Also the RLDF of these showers follow the longitudinal profile more closely than less inclined ones, making any reconstruction that relates it to the shower development easier to accomplish.

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