Probing air-shower physics by Cherenkov effects in radio emission

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Abstract: The last decade has seen a rapid progress in measuring as well as theoretical modeling radio-wave emission from cosmic-ray-induced air showers. The main mechanisms are now known to be the geomagnetic emission due to deflection of electrons and positrons in Earth’s magnetic field and the charge-excess emission due to a net electron excess in the air shower front. Recently it was shown that Cherenkov effects play an important role in the radio emission from air showers. Here we show the importance of these effects to extract quantitatively the position of the shower maximum from the radio signal, which is a sensitive measure for the mass of the initial cosmic ray.

Keywords: Radio detection, Air showers, Cosmic rays, Coherent radio emission, Geomagnetic Cherenkov radiation, Mass determination.

1 Introduction

In several recent experiments (LOPES [1 2], CODALEMA [3 4]), it was shown that radio emission can be used as a new complementary technique for measuring cosmic-ray-induced air showers. These in turn have triggered several new experiments at the Pierre Auger Observatory [5 6 7 8], and LOFAR [9]. Already in the early days of cosmic-ray radio-detection the basic emission mechanisms were suggested [10] but recent years have seen a rapid convergence between microscopic models, such as ZHAires [12] and CoReas [14], and macroscopic ones such as MGMR [11], SELFAS [13], and EVA [15], leading to a consistent picture [17 16].

In a Microscopic approach the tracks of the individual electrons are followed and the emitted radiation of each is summed to yield the total radiation of the extensive air shower. In the alternative, Macroscopic approach the velocity distribution of the electrons is summed locally to yield the macroscopic charge and current density distribution in the shower. The main advantage of a macroscopic approach is that it clearly indicates the aspects of the shower dynamics that are responsible for certain features of the detected radio signal. The macroscopic approach requires a parametrization of the position and time dependence of the four-currents in the shower which can be performed at various levels of sophistication. In the following we use the Macroscopic approach. Since radio emission is basically governed by wave mechanics any features in the frequency spectrum of the pulse are directly related to the geometry and the critical length scales in the distribution of the particles in the shower [13].

In [19] it was shown that even though the deviation of the index of refraction from unity, the refractivity, is small (O(10^{-3})), this deviation gives rise to Cherenkov effects. The importance of these effects were discussed in [12 14 20 21] for a simplified shower geometry, where the LDF was shown to have a distinct peak. In [15] we showed the first results of the EVA-code based on realistic charge and current distributions in the air shower which are obtained from Monte-Carlo simulations.

Here we show that due to Cherenkov effects it is possible to accurately extract from the radio signal the position where the shower profile reaches its maximum. This is closely related to the mass of the initial cosmic ray. In addition Cherenkov effects have a large effect on the relative magnitude of the charge-excess emission with respect to the geomagnetic emission. The calculations presented are done using the EVA simulations to which we give a short introduction.

2 The Macroscopic model

Particles in the cosmic-ray shower move through the magnetic field of Earth with the light velocity c. The lighter ones, electrons and positrons, will receive a substantial acceleration due to the action of the Lorentz force. This acceleration is counteracted by the collisions with the ambient air molecules and results in an (air-pressure dependent) drift velocity with opposite directions for electrons and positrons, \( \nu_d \approx 0.023 c \). As a result a net electric current develops which is proportional to the number of particles in the shower and oriented in the direction of the Lorentz force, \( \hat{x} = -\hat{v} \times \hat{B} \), where \( \hat{v} \) is the direction of the original cosmic ray and \( \hat{B} \) is the Earth magnetic field. This varying current is responsible for so-called geomagnetic radiation which is polarized along the direction of the emitting current, \( \hat{x} \).

In addition to the electric current there is also a net charge excess in the shower due to the knock-out of electrons from air molecules by elastic positron-electron collisions and Compton scattering. In shower simulations the charge excess is approximately equal to 20% of the number of particles and is thus substantial, and, equally important, varies with shower height z (the distance, measured along the shower, to the point of impact on Earth). Because of this variation there is also charge-excess radiation which...
is radially polarized and as such distinguishable from geomagnetic radiation \[ [22, 23, 24, 25, 26]. \]

The treatment of Cherenkov effects needs special care due to a square-root divergence in the expression. By making use of the finite extent of the particle distributions in the shower a non-singular expression is obtained by safely integrating the square-root divergence over the finite extent of the charge and current distributions. Due to the small refraction of air the Cherenkov angle is small, typically of the order of 1 degree, and dependent on air density. To understand the ground-pattern from Cherenkov radiation is should be realized that in principle Cherenkov radiation is emitted from any part of the shower but this arrives at different distances from the core. If emitted from the part near the ground it is observed at short distances from the core, if from larger heights it is observed at greater distances. The fact that beyond a certain distance Cherenkov emission can not be observed anymore is related to the dependence of the refractivity on air density. The strength of the Cherenkov radiation at a certain distance from the shower core is directly related to the current density at the emission height which makes this a very sensitive measure to determine the position of the shower maximum \( X_{\text{max}}(g/cm^2) \). Care should be taken with the fact that the maximum charge-excess current may occur at a different height as the maximum geomagnetic current. Since the polarization of Cherenkov radiation is determined by the same mechanisms that determine the polarization of the normal emission, also for Cherenkov radiation the polarization may be used to unravel geomagnetic and charge excess.

The Lateral Distribution function (LDF) for signal power in various frequency bands is shown in Fig. 1 for a vertical proton induced shower. The LDF strongly depends on frequency. At the highest frequency the only coherent contribution to the signal is created by Cherenkov radiation since the air-density profile, is directly related to the position of the shower maximum, \( x_{\text{max}} \), which, through the air-density profile, is directly related to \( X_{\text{max}} \). In Fig. 2 we plot \( X_{\text{max}} \) as a function of \( d_p \). Showers for which \( d_p \) is less than 30 meters have been omitted from the analysis.

Fig. 1: The signal power as function of the distance to the core in different frequency bands. The quoted results are for a \( 10^{13} \) eV shower induced by a proton primary particle moving perpendicular to Earth’s surface.

and Dale. To test the applicability of Eq. (1) in realistic cases we simulated a set of 100 showers with a \( 10^{13} \) eV proton as primary shower-inducing particle as well as a set of 20 showers with iron as a primary. The cosmic ray is taken perpendicular to Earth’s surface. For each we determine the distance to the shower core, \( d_p \), where the maximum of the power in a certain frequency band occurs as well as the position of the shower maximum, \( x_{\text{max}} \), which, through the air-density profile, is directly related to \( X_{\text{max}} \). In Fig. 2 we plot \( X_{\text{max}} \) as a function of \( d_p \). Showers for which \( d_p \) is less than 30 meters have been omitted from the analysis.

Fig. 2: The value of \( X_{\text{max}}(g/cm^2) \) as a function of \( d_p(m) \) for different frequency bands for 100 proton (circles) and 20 iron (squares) induced showers.

3 Determining \( X_{\text{max}} \) from the radio signal

For an index of refraction equal to unity it has been shown that one can distinguish between different shower-inducing primary particles \[ [25, 27] \] by calculating a ratio of signal strengths at different distances from the shower core. Here we show that also in the presence of Cherenkov emission the earlier method still applies, but for higher frequencies there is an alternative that yields accurate results for \( X_{\text{max}} \).

In [25], it was noticed that the observer position \( d = \sqrt{(x^2)^2 + (x^2)^2} \), corresponding to the Cherenkov angle, can be linked to the emission height by,

\[
d_c = \sqrt{n^2 \beta^2 - 1} \, x_{\|},
\]

for a constant index of refraction \( n \). In a more realistic model, the index of refraction depends on the air density and thus atmospheric height as given by the law of Gladstone...
Such a linear dependence is sufficient to extract $X_{\text{max}}$ with an accuracy of $10 - 15$ g/cm$^2$ from the determined values of $d_p$, for the higher frequency bands ($> 200$ MHz). The linear dependence is independent of energy as shown in Fig. 3 for the 200-500 MHz band for three different energies of $10^{17}$, $10^{18}$, and $10^{19}$ eV. For each energy a set of 20 proton-induced and 20 iron-induced are calculated.

Fig. 3: The value of $X_{\text{max}}$ (g/cm$^2$) as a function of $d_p$ (m) in the 200-500 MHz band. The line shows the fit using Eq. (2) with $\alpha = 916$ g/cm$^2$ and $b = 4.6$ g/cm$^2$/m resulting in a standard deviation of 14.2 g/cm$^2$.

For the low frequency bands ($< 200$ MHz), the sensitivity to $X_{\text{max}}$ is small, as is evident from Fig. 4. As a result of the competition between Cherenkov and normal emission a two peak structure is seen in Fig. 1 for the $120 - 200$ MHz band. This results in a jump in $X_{\text{max}}$ as a function of distance for this band. For this more complicated situation we follow the approach proposed earlier [23, 27] where in Fig. 3 we plot $X_{\text{max}}$ as a function of $Q_{300/100}$ defined as

$$Q_{d_2/d_1}^{BW} = \frac{p_{BW}^{BW} (\mu V^2/m^2/\text{MHz}; d = d_2 \text{m})}{p_{BW}^{BW} (\mu V^2/m^2/\text{MHz}; d = d_1 \text{m})},$$

(3)

the ratio of power in a certain frequency and observed at two distances, $d = d_2$ m and $d = d_1$ m from the shower axis. One of the simulated showers where $X_{\text{max}}$ lies very close to Earth’s surface has been excluded from the analysis. The results show a clear logarithmic dependence which can be parameterized as

$$X_{\text{max}} = \alpha - \eta \log(Q_{d_2/d_1}^{BW}),$$

(4)

with an accuracy of $\sim 10 - 15$ g/cm$^2$. This construction emphasizes the importance of shower geometry. For two showers that have the same profile but just differ in energy the LDF will only differ in an overall scale factor. This scale factor is divided out by considering the power-ratio and this thus focusses on the shower profile.

4 Conclusions

We have shown that Cherenkov effects due to a finite refractivity of the atmosphere strongly modify the structure of the lateral distribution of radio signal strength. For the high-frequency bands ($> 200$ MHz), it is shown that the distance with respect to the shower core where the signal power shows a maximum can be linked to $X_{\text{max}}$ with an accuracy of $10 - 15$ g/cm$^2$. For the low frequency bands ($< 200$ MHz), a power ratio can be defined which correlates to $X_{\text{max}}$ with a similar accuracy of $10 - 15$ g/cm$^2$. The fact that different energies show the same distance dependence shows that shower geometry is the determining factor and thus that the results are not dependent on the particular model that is used. These values are obtained for a simplified geometry of vertical air showers, and instrumental errors have not been included into the analysis. In comparison, the Fluorescence detection technique employed at the Pierre Auger Observatory [29], determines the shower maximum with an approximate accuracy of 20 g/cm$^2$.

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