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Calculation of radio emission from high-energy air showers

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Abstract: Results of the simulation of radio signals from 10^{17} eV extensive air showers are reported. The simulations are based on a track-by-track electric field calculation using the EGSnrc Monte Carlo shower code. The lateral distribution of the predicted radio emission is compatible with the recent LOPES-10 experimental data at distances < 300 m. Perspectives of extending EAS radio emission calculations to the ultra-high energy range (up to 10^{20} eV) are also discussed.

Introduction

Radio emission accompanying extensive air showers (EAS) is considered as a promising alternative to traditional methods of high energy cosmic ray detection. Recently, first measurements from a new generation of radio antenna arrays, LOPES [1], which is co-located with the KASCADE air shower array [2], and CODALEMA [3], were published. The experimentally found, good correlation of the signal with the shower energy has also renewed the interest in theoretical predictions [1].

In general, there are two approaches of calculating the radio signal of an air shower.

The starting point of Askaryan's predictions in 1961 was the model of the motion of effective charges in EAS [4]. In [4] both electron excess and charge separation in the Earth's magnetic field were proposed as responsible for the EAS radio emission. In this picture a shower is considered as a continuous system of charges and currents. Evidently, the approach of calculating the radio emission for a system of charges and currents rather than individual particles has the potential of being numerically very efficient.

On the other hand, parametrizations of the overall charges and currents in EAS have not yet been developed. Therefore it is very useful to start with an approach that is based on following individual particle trajectories using the Monte Carlo (MC) technique. In such an approach, shower properties can be included in the most accurate and simple way, which, however, requires very large computing time at primary energies above 10^{15} eV.

Using the MC approach, EAS radio emission has been theoretically investigated most intensively within the framework of the "geosynchrotron emission" model [5] proposed by Falcke and Gorham in 2003 [6]. In this model, it is assumed that the overall radio signal of air showers is dominated by the radio emission due to the deflection of particle trajectories in the magnetic field of the Earth. In the geosynchroton model, simulations are performed in the time domain, i.e. the electric field contributions produced by shower particles are summed as function of the detection time [5, 7]. The refractive index of air is taken as unity.

In this paper, we follow a more general approach that does not explicitly distinguish between the geosynchroton or Cherenkov radio signal. We calculate the radio signal of each shower particle in Fourier space (frequency domain). Signal contributions due to start and end points of particle trajectories and localized momentum changes in Coulomb scattering and bremsstrahlung are included as well as the continuous deflection in the Earth's magnetic field. The refractive index of air is naturally accounted for in the simulation.

Electric field calculation

In the EAS case, particle trajectories are mainly governed by elementary interactions with air and also the deflection of the particles in the Earth's magnetic field. The problem then is to calculate the radiation from a charged particle having a trajectory which cannot be described by an analytic function. An important constraint is that the sum over all particles should result in an expression similar to that of the continuous charges and currents approach.

As MC simulation is a linear procedure employing a "straight-step-by-straight-step" particle transportation, it is natural to calculate the electric field from a charged particle by considering the trajectory as a sum of many leaps of the velocity $\vec{\beta} = \vec{u}/c$:

$$\vec{E}_\omega(\Sigma_N) = \underbrace{\vec{E}_\omega(\vec{0} \to \vec{\beta}_1)}_{\text{birth of the particle}} + \dots + \underbrace{\vec{E}_\omega(\vec{\beta}_s \to \vec{\beta}_{s+1})}_{\text{deflection of the particle}} + \dots + \underbrace{\vec{E}_\omega(\vec{\beta}_N \to \vec{0})}_{\text{death of the particle}} . \quad (1)$$

Here N is the total number of adjoining individual trajectory segments at which the velocities $\vec{\beta}_s$ are being constant vectors, Fig.1. Internal terms in the series (1) may describe both discrete interactions of charged particles in air (including multiple Coulomb scattering and secondary particle creation below the simulation threshold) and their "smooth" deflection in the Earth's magnetic or electric fields.

In the case of discrete interactions, the electric field can be estimated within classical radiation theory rather than quantum theory due to $\omega\Delta t \ll 1$, where ω is the observation frequency and Δt is the time of interaction.

In the framework of the Fraunhofer approximation, the Fourier-component $\vec{E}_\omega$ of the electric field at a given frequency $\omega = 2\pi\nu$ produced by a sudden leap $\vec{\beta}_s \to \vec{\beta}_{s+1}$ of an electron velocity at the time moment $t_0^{(s+1)}$ is given by

$$\vec{E}_\omega(\vec{\beta}_s \to \vec{\beta}_{s+1}) = = \frac{e}{8\pi^2\varepsilon_0 c}\frac{\mathrm{e}^{ikR_s}}{R_s}\mathrm{e}^{i\omega(t_0^{(s+1)} - n\vec{e}_{R_s}\cdot\vec{\xi}_0^{(s+1)}/c)} \times \left(\frac{\vec{\beta}_{s\perp}}{1 - n\vec{e}_{R_s}\cdot\vec{\beta}_s} - \frac{\vec{\beta}_{s+1\perp}}{1 - n\vec{e}_{R_s}\cdot\vec{\beta}_{s+1}}\right) . \quad (2)$$

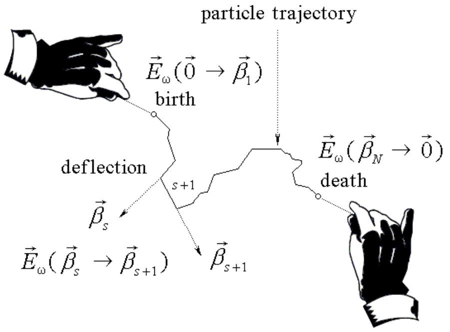

Figure 1: Illustration of the individual trajectory contributions considered in the calculation.

Here ε_0 is the permittivity of vacuum, c is the light speed in vacuum, $k = n\omega/c$, n is the refractive index of air, R is the distance between electron location and the observation point, $\vec{e}_R$ is the unit vector in the direction of observation, $\vec{\xi}_0$ is the radius-vector of electron at the time t_0 and $\vec{\beta}_\perp$ is the transverse component of $\vec{\beta}$ with respect to $\vec{e}_R$.

In comparison, in the geosynchrotron model only the terms in the series (1) which are due to the particle deflections in the Earth's magnetic field are taken into account.

Modelling

Calculations of the EAS radio emission are carried out in the "particle-by-particle" manner in a special program written for this purpose. A photon is used as primary particle and MC shower modelling is performed just for the electromagnetic part of the shower using the EGSnrc code [8]. The density and optical properties of the Earth's atmosphere are taken to be uniform within slices of 9.5 g/cm^2. The strength and declination of the Earth's magnetic field correspond to those for the LOPES experiment. The radiation field is calculated via (2) for all particle energies above the threshold 100 keV. The upper limit on step size of particle straight transport is equal to 1 m.

A straight-forward MC simulation of the full shower development is limited to energies up to

$\simeq 10^{15}$ eV. The situation may be improved by applying the "thinning" method [9], which is characterized by the parameter $\varepsilon_{th} = E_{th}/E_0$, where E_{th} is the energy at which the thinning process is started, E_0 is the energy of primary particle. The influence of thinning on the radio emission calculation quality has been studied in the $10^{12} - 10^{14}$ eV range. Unfortunately, the general conclusion is that thinning does not allow to increase the primary energy as much as would be needed to simulate showers at ultra-high energy. Namely, at the LOPES frequency range (40-80 MHz), the acceptable level ε_{th} reduces computing time by a factor of only 10-20 for a range of observation distances up to 200-300 m from a shower axis. The reason is that for radio emission the low energy particles (having energies much less than the critical energy of 81 MeV) are extremely important.

Results

In Fig.2 the longitudinal profile of one 10^{17} eV photon-initiated vertical shower is presented. The initial photon was injected at 30 km above the sea level. The simulated profile is similar to the average cascade curve at 10^{17} eV. Therefore it is reasonable to assume that the given shower is representative for a comparison of the predicted radio emission with experimental data at energies of about 10^{17} eV that is averaged over many showers.

The comparison with LOPES-10 experimental data is plotted on Fig.3, where the simulated radio emission has been averaged over north, south, west and east directions. A correlation of radio signals with distance is found for the group of events selected out of 5 months of LOPES-10 measurements [10]. All selected showers have energies in the range $E_0 \simeq 5 \cdot 10^{16} - 6 \cdot 10^{17}$ eV and zenith angles $< 50°$.

In the comparison, it has been taken into account that experimentally measured and theoretically calculated field strengths are not absolutely identical. In the simulation, the Fourier-component at a given frequency (2) is calculated, whereas in the experiment a field strength over the frequency range from 40 up to 80 MHz is measured. Such uncertainty introduces some fudge factor A, that does not influence essentially on the functional form

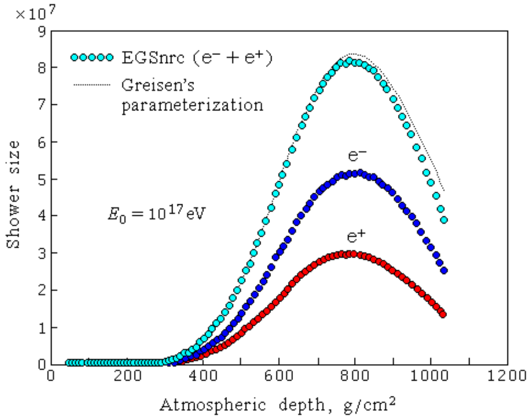

Figure 2: Number of charged particles of a 10^{17} eV photon-initiated vertical shower as a function of atmospheric depth. Thinning level $\varepsilon_{th} = 2 \cdot 10^{-7}$ or $E_{th} = 20$ GeV. The model results are compared to Greisen's parameterization for a radiation length of 36.8 g/cm^2 and an critical energy of 81 MeV.

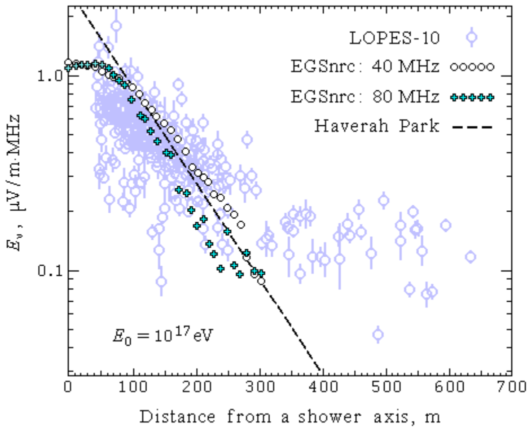

Figure 3: Lateral distribution of EAS radio emission. Results of the present work (EGSnrc), LOPES-10 experimental data [10] and Haverah Park experimental data approximation, taken from the same report [10], are compared.

of the lateral dependence of radio emission. In fact, we obtain that in the observed bandwidth of the LOPES experiment the field strength does not change substantially at the distances less than 300 m. On Fig.3 $A = 1$ has been adopted, but this value may have to be changed once the absolute calibration of the LOPES antennas is known.

It is seen that the calculated radio emission reproduces the experimentally found dependence on the lateral distance rather well. The deviation at larger lateral distances beyond 300 m is not unexpected. It is related to the detection threshold of the LOPES-10 array, since only showers with a detected radio signal were included in the LOPES data analysis. At large lateral distance, the detection probability falls below unity and showers without detected radio signal have to be included to allow a comparison with our calculation.

The parameterization of the data obtained with the old Haverah Park radio experiment [11] is also shown in the same figure. The presented approximation was fitted for the range $E_0 \simeq 10^{17}-10^{18}$ of EAS with zenith angles $< 35°$ [11] (the curve has been taken from [10]). The Haverah Park approximation (fitted for 55 MHz) corresponds to the field calculated at the range 100-300 m. Results differ significantly only for $R < 100$ m, where the exponential fit $\sim \exp(-R/(110\,\mathrm{m}))$ seems not to be valid. Note that there is considerable uncertainty regarding the absolute calibration of the pioneering radio measurements of the 60ies and 70ies.

Conclusions

Calculation of radio emission from an air shower with $E_0 = 10^{17}$ eV has been performed. The lateral distribution of simulated radio signals is compatible with the recent LOPES-10 experimental data [10] and the old Haverah Park data [11].

The presented calculation should be considered just as a demonstration since 1 month and 50 processors have been required for its realization. At present time the real limit of the straight-forward MC simulation of EAS radio emission is $10^{15} - 10^{16}$ eV.

Our present hopes of calculating EAS radio emission at ultra-high energy are based on some specific features of the radio emission. It has been mentioned that only two pure collective effects in the EAS development initiate their radio emission: an electron excess and a geomagnetic polarization. Thus, a full "particle-by-particle" shower modeling is something that is too detailed for efficient radio emission calculations.

The energy of the simulations could be considerably increased within the framework of the EAS macroscopic consideration, in which the shower is treated as a system of the electric moments and currents (due to an excess of electrons and systematic charge separating in the Earth's magnetic field). Still MC simulations will be needed for calculating the overall shower properties and generating realistic shower-to-shower fluctuations.

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