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Geosynchrotron radio pulse emission from extensive air showers: Simulations with AIRES

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A full Monte Carlo simulation of the charged particles in an air shower, using a specially modified version of the AIRES software package, was used to generate radio-frequency electric field stimuli on the ground. The signal simulated is from the geosynchrotron emission of the electrons and positrons in the shower. The simulation results qualitatively agree with previous formulations and semi-analytic forms for the radiation pattern, spectra, and intensity.

1. Introduction & Theory

Although cosmic ray air showers are known to produce a radio signal in the region of 10-100 MHz, there has been disagreement as to the size and form of this signal. Experiments were carried out to detect this signal in the 1960s-1970s by several groups of researchers but the results of these studies are controversial. Reasons for skepticism included the magnitude of expected electronics-produced backgrounds and the difficulty in connecting observations to shower model properties. Cosmic ray radio emission has been largely ignored until recently. As researchers have turned their attention to higher energy cosmic rays, and consequently the large and expensive detectors required, there has been renewed interest in radio emission, which may prove to be a more practical (*i.e.*, cheaper) means of detecting and characterizing these high-energy showers. There is general agreement among researchers the radio signal from an Extensive Air Shower (EAS) is produced by the acceleration of the shower's positrons and electrons in the earth's magnetic field. In this paper we report on the study of the radio emission process by adapting AIRES, a widely used cosmic ray EAS simulator, to provide realistic particle energies and trajectories[1]. Using AIRES as a backbone for the simulation also allows the simulation of a wide spectrum of cosmic ray primary energies and the resulting signal strengths. Shower-to-shower fluctuations have also been an interesting area of measurement. Although the thinning process used by AIRES does significantly affect the results, it does so in a way that is easier to recognize and understand than in other methods of simulation. In practice, this thinning imposes limits on the regions of applicability of the calculations.

The fields we wish to calculate are produced by the acceleration of electrons and positrons in the earth's magnetic field. Effects such as Cherenkov radiation and transition radiation will be ignored, as these processes are several orders of magnitude smaller in total effect on the ground. The formula for the fields of an accelerated relativistic particle is given by:

$$\boldsymbol{E} = \underbrace{e\left[\frac{\boldsymbol{n}-\boldsymbol{\beta}}{\gamma^2\left(1-\boldsymbol{\beta}\cdot\boldsymbol{n}\right)^3 R^2}\right]_{ret}}_{Static\ Field} + \underbrace{\frac{e}{c}\left[\frac{\boldsymbol{n}\times\left\{(\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right\}}{\left(1-\boldsymbol{\beta}\cdot\boldsymbol{n}\right)^3 R}\right]_{ret}}_{Radiation\ Field} \qquad (1)$$

$$\boldsymbol{B} = \left[\boldsymbol{n}\times\boldsymbol{E}\right]_{ret} \qquad (2)$$

Where this is calculated at retarded time, μ is the relative permeability of air (~1), n is the index of refraction of air (~1), $\hat{r}$ is the unit vector from the particle to the antenna, and r is the distance from the particle to the antenna.

2. Simulation Method

The trajectories of individual particles are calculated in a stepwise fashion by AIRES which provides realistic particle trajectories and densities which can easily be adapted for our purpose. AIRES simulates each particle in the shower in a stepwise fashion, and at each step a routine has been added to calculate the radio signal produced by the particle's acceleration. The signal broadcast to each antenna is calculated using the radiative part of eqn. 1. Only the electric field is computed, although the magnetic field could be approximated to a high degree of accuracy using eqn. 2 and assuming **n** is constant. **B·v** is calculated from the expected acceleration due to the magnetic field and ignores other effects. In other words, it is calculated directly as opposed to being numerically derived from the path given by AIRES. Because the magnetic field is by far the most prominent source of acceleration, this does not significantly affect the results while avoiding the error that would be produced by calculating the acceleration numerically from the stepwise path given by AIRES. The signal delay is calculated in the obvious way (assuming, as discussed below, $\varepsilon = \varepsilon_0$ and $\mu = \mu_0$), and the signal intensity at the ground is added to a series of global bins for each antenna.

2.1 Thinning

A practical problem in using AIRES is that one needs to contend with the effects of the Hillas Thinning Algorithm[2]. The Hillas Thinning Algorithm is standard in Monte Carlo simulations of cosmic ray air showers. It operates by randomly removing certain particles from the simulation and giving the remaining particles a statistical weight. Because high-energy showers contain so many particles (roughly 10^8 for a 10^{17} eV shower) this is the only practical way to simulate them. In normal simulations, where one is only concerned with particle densities at ground level, this produces satisfactory results. For simulation of radio emission, however, the problem of coherency between signals from different particles is raised. The obvious way to deal with the thinning algorithm is to multiply the signal of each surviving particle by its statistical weight, but this in effect assumes all the particles that have been approximated by the survivor are emitting coherent radiation. In practice, this places limits of applicability on my simulation. Although in principle this problem could be corrected if one had a reliable way of calculating the effective spread of the particles simulated by each remaining particle, this is not easily done in practice.

To determine the regime in which the radiation is primarily coherent we can assume that all of the radiation comes from a horizontal pancake of particles with characteristic radius r_0 at height h. If we observe the particles at some distance d from the location where the center of the shower would impact the ground, we find that the difference in arrival times of the signal from various parts of the shower is given by:

$$\Delta t \approx \frac{r_0 d}{hc} \tag{3}$$

If we observe at some frequency f, the approximate distance at which the radiation is coherent is given by:

$$d_{coherent} \approx \frac{hc}{r_0 f} \tag{4}$$

For a typical 10^{17}eV shower, the developmental maximum occurs at about 3000 m, and the average distance of the particles from the shower core is on the order of 100 m. This means the radiation is coherent out to about 200 m at 50 MHz. In practice, the shower is not simulated by one thinned particle but by many, and so we should be able to replace r_0 in eqn. 4 with the average separation between thinned particles at the shower maximum. Thus one expects a significant improvement in the distance at which the simulation is valid. In practice, the region in which the signal becomes incoherent is apparent in plots of the RF signal on the ground. As one might expect, the signal becomes quite noisy in the region in which it is incoherent.

2.2 Adaptive Pathlength Routine

Because all of the particles of interest are highly relativistic, the signal from an individual particle will peak strongly when it is moving toward the antenna. Since the length of this peak is far less than the time between default path steps in AIRES, to achieve accurate results one must reduce the step time of the simulation. However, a universal decrease in step size will produce a corresponding increase in simulation time. A more satisfactory approach is to find the quantity in eqn. 1 which produces the most rapid signal variation and adjust the path length in response to it. The most obvious choice is:

$$\xi = 1 - \boldsymbol{\beta} \cdot \boldsymbol{n} \qquad (5)$$

Which is found cubed in the denominator of eqn. 1 and will in general be different for each observing antenna. This quantity approaches 0 when the particle points near the observer and in effect accounts for the radiation beaming effect observed for relativistic particles. After some experimentation the following prescription was found adequate: When ξ increases by more than 15% between any two steps in the simulation for any of the observing antennas, the step size is decreased by a factor of 2.5. Whenever ξ changes by less than 5% for *all* observing antennas, the step size is decreased by the same factor. In practice, this greatly reduces the amount of uncertainty in the output of the simulation while resulting in minimal effects on the length of the simulation.

2.3 Index of Refraction of Air

Throughout the simulations it is assumed $\varepsilon = \varepsilon_0$ and $\mu = \mu_0$, which corresponds with an index of refraction, n, of exactly one. In actuality, for sea level air, n = 1.0003. Although this might seem like a relatively inconsequential difference, it can be quite important for highly relativistic particles. If one rewrites eqn. 1 to take into account situations for which $n \neq 1$, β will be replaced by n β. The result is that for highly relativistic particles ξ may pass through zero, which causes the signal to rapidly diverge. When simulated in a stepwise fashion, this produces nonsensical results. This divergence can be attributed to Cherenkov radiation, which is predominately at much higher frequencies than those with which we are concerned. In addition, the Cherenkov radiation is confined primarily to the region around the core of the shower. For example, a 50 MeV electron, typical of the maximum of a 10^{17} eV shower, has a Cherenkov cone of ~1.5 degrees, which corresponds to a spread of only 75 m at ground level from an altitude of 3000 m.

The other effect produced by $n \neq 1$ is a change in signal arrival time. For a rough estimate of this, we note that at a distance of 3000 m the difference in arrival times between sea level air and vacuum is only about 3 ns. In practice we only care about the *relative* difference in signal arrival times for various parts of the shower, which should be far less. From simple geometry we expect an overall characteristic time spread of about 10 ns for each 100 m of distance from the shower core at ground level (for a typical 10^{17} eV shower), which corresponds closely with the simulation results. Thus it seems reasonable to ignore this effect away from the shower core.

2.4 Results

The results for radio emission simulations from 10^{16} to 10^{21} eV are shown in a series of sample plots: Figure 1, Single shower of primary energy 10^{16} eV, East-West 10 MHz signal components with contour lines set at 1.75 μV/m/MHz apart; Figure 2, 10^{16} eV showers (averaged) observed at 300m from the core (coherence requires subshowers of the corresponding scale); Figure 3, East-west signal component vs. frequencies for a primary energy of 10^{19} eV with signals measured at (top to bottom) 10m, 30m, 100m, 300m and 1000m; Figure 4, East-west 10 MHz signal components vs. primary energies, 24 showers average out shower-to-shower fluctuations at each energy with signals measured as in figure 3, the fitted power-law slopes are 0.96, 0.95, 0.94, 0.92 and 0.80. These are in substantial agreement with other recent simulation work [3,4] though this Monte Carlo simulation includes all shower-to-shower fluctuations. These simulations have been also directly compared to experimental observations of radio pulses in coincidence with a small ground array[5].

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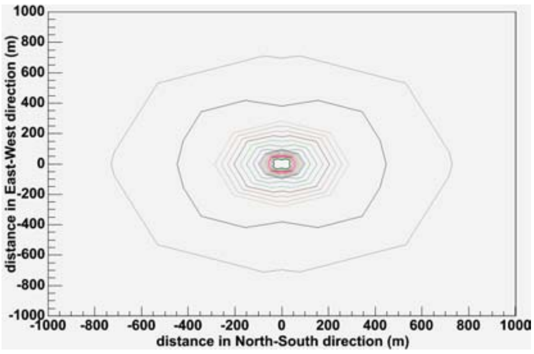

Figure 1: Shower foot-print geometry (10^{16} eV shower). Contours are 1.75μV/m/MHz apart.

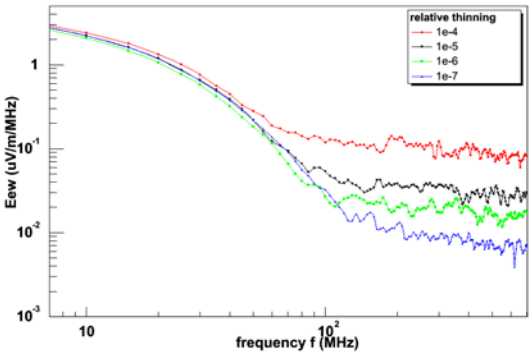

Figure 2: Thinning-dependence on maximum coherent frequency. Small subshowers contribute at higher f.

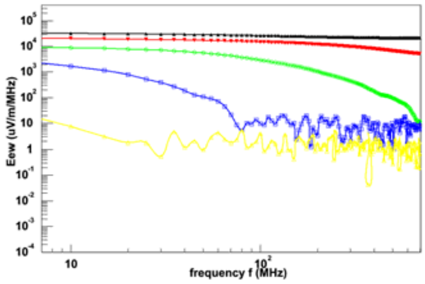

Figure 3: East-west signal component vs. frequency a primary energy of 10^{19}eV with signals measured at (top to bottom) 10m, 30m, 100m, 300m 1000m.

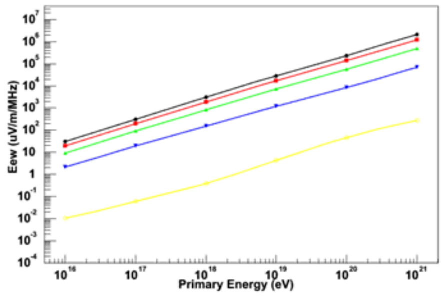

Figure 4: East-west 10MHz signal component vs. for primary energies, 24 showers average out shower-to-shower fluctuations at each energy with signals and measured as in figure 3, the fitted power-law slopes are 0.96, 0.95, 0.94, 0.92 and 0.80.