Simulations of the Radio Frequency Signals Produced by Electromagnetic Showers in Ice

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Abstract

We report our recently updated study of Cherenkov signals at radio frequencies from high energy electromagnetic showers in ice using GEANT based Monte Carlo simulations. Our results are used in calibrating the ultrahigh energy neutrino detection experiment RICE at the South Pole.

1. Introduction

Ultrahigh energy electron neutrinos from cosmological sources can be detected from the shower created in dense media (ice e.g.) by the secondaries in a charged current interaction ($N\nu_e \rightarrow eX$). Shower particles travelling faster than light in the medium emit coherent Cherenkov signals at radio frequencies, which are picked up by radio antennas buried in the medium [2, 3].

We have modeled the signal contribution from the dominant ($\sim 80\%$) electromagnetic shower component using GEANT detector simulation tools. Shower simulation and electromagnetic pulse generation from shower particles are essentially two separate procedures in our study. The details of our study can be found elsewhere [4, 5]. We report here highlights of our results.

2. Shower Simulations

We have defined a cube of ice of km scale as the target medium in our GEANT simulations. Given an effective atomic number $Z = 7.2$, an effective mass $A = 14.3$ and a density 0.92 g/cm^3 of the medium, GEANT calculates internally all parameters like radiation length, absorption length and cross-sections.

The electromagnetic showers, in our analysis, are initiated by an e^- or γ with pre-specified momenta and position. GEANT gives detailed particle tracking information such as interaction points, total energy, energy lost in interaction and interaction time in output data files. These data files are used later to calculate

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Table 1. Track length and particle yield results from an averaged 100 GeV electron induced shower using different Monte Carlo shower codes. The error bars correspond to error in the mean, $s/\sqrt{N}$, where s is the standard deviation and N is the number of showers (100 for GEANT 4 and 20 in all other cases).

Shower code	Total track lengths			Particle yield at shower max	
	Absolute $(e+p)$ [m]	Projected $(e+p)$ [m]	Projected $(e-p)$ [m]	$(e+p)$	$(e-p)$
G3 (preferred)	542.74 ± 0.08	455.3 ± 0.2	125.0 ± 2.0	148 ± 5	42 ± 3
G3 (default)	389.51 ± 0.48	365.7 ± 0.5	76.3 ± 1.5	111 ± 7	20 ± 2
G4	572.58 ± 0.04	466.3 ± 0.2	135.0 ± 0.8	153 ± 3	45 ± 1
ZHS	642.17 ± 0.06	516.6 ± 0.2	135.2 ± 1.5	164 ± 6	44 ± 2

electromagnetic pulses and to diagnose shower properties.

We used GEANT 3.21 and, more recently, GEANT 4 to simulate electromagnetic showers in ice. In our original work [4], we used GEANT 3.21 with default settings to generate showers, which yields significantly less track length compared to GEANT 4 and to GEANT 3.21 with "preferred" settings [1, 5]. The reason is that, with the default setting, electrons are stopped prematurely before reaching the low kinetic energy threshold needed for accurate Cherenkov radio signal emission calculations [1, 5]. Our updated results from GEANT 3.21 with preferred settings and GEANT 4 are in reasonable agreement with each other and with the results in [6]. In the lower frequency range, the signal is significantly increased compared to the signal reported in [4]. Total track lengths and particle yields at the shower maximum are reported in Table 1 for an average 100 GeV e^- shower generated by GEANT 3.21 with the preferred and default settings and GEANT 4. Also shown are results from our copy of the Zas, Halzen and Stanev code [6] for comparison.

3. Radio Signal

We have calculated the net electric field, in the Fraunhoffer limit, by vector superposing contributions from Monte Carlo track segments of all the charged particle using the formula [4,6]:

$$R\vec{E}_\omega(\vec{x}) = \frac{1}{\sqrt{2\pi}}\left(\frac{\mu_r q}{c^2}\right) e^{ikR} e^{i\omega[t_1-(n/c)\hat{n}\cdot\vec{r}_1]}\,\vec{v}_\perp \frac{e^{i\omega\delta t(1-\hat{n}\cdot\vec{\beta}n)}-1}{1-\hat{n}\cdot\vec{\beta}n} \qquad (1)$$

where $(t_1, \vec{r}_1)$ is the initial position of a track segment and δt is the time elapsed. The refractive index of the medium is denoted by n and $\vec{v}_\perp = -\hat{n}\times(\hat{n}\times\vec{v})$, $\vec{v}$ being the particle velocity and $\hat{n}$ the observer's direction. The condition $1-\hat{n}\cdot\vec{\beta}n = 0$

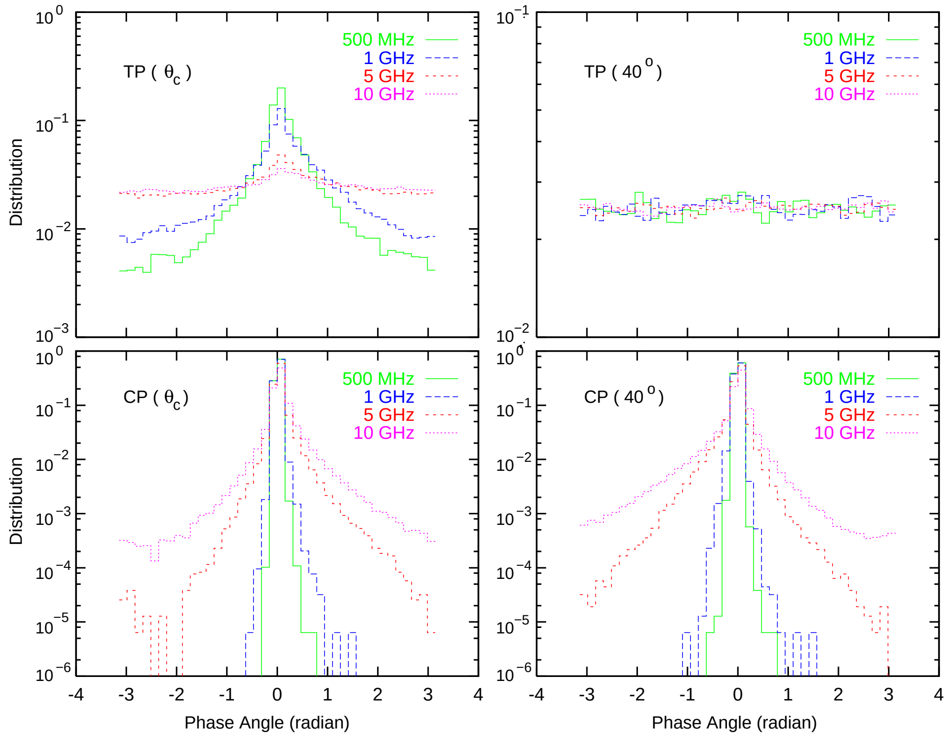

Fig. 1. Translational phase (TP) [top panels] and the Cherenkov phase (CP) [bottom panels] distributions at the Cherenkov [left panels] and 40° angle [right panels] for a 100 GeV shower. The TP is the determining factor in coherent signal emissions.

defines signal emission at the Cherenkov angle $\theta_c = \cos^{-1}(1/n\beta)$. At or close to this angle Eq. (1) reduces to

$$R\vec{E}_\omega(\vec{x}) = \frac{i\omega}{\sqrt{2\pi}} \left(\frac{\mu_r q}{c^2}\right) e^{ikR} e^{i\omega[t_1-(n/c)\hat{n}\cdot\vec{r}_1]}\, \vec{v}_\perp \delta t\,. \qquad (2)$$

A study of the phase angles: $\omega[t_1 - (n/c)\hat{n}\cdot\vec{r}_1]$ and $\omega\delta t(1-\hat{n}\cdot\vec{\beta}n)$, the translational phase (TP) and the Cherenkov phase (CP) respectively, shows that coherent signal emission is dominated by TP (see Fig. 1). These uncorrelated phases allow one to factorize the field equations and calculate the electric field semi-analytically by parametrizing the shower with a form-factor [4]. This serves as a check of our understanding of the frequency spectrum of the electric field at the Cherenkov angle calculated by the direct Monte Carlo method. The form-factor itself is derived from a fit to the transverse distribution (see Fig. 2) of the excess charge in the shower [4]. The agreement between the Monte Carlo and analytic spectra are good at low frequencies (< 10 GHz). Fig. 2 shows the Monte Carlo frequency spectrum from a 100 GeV shower.

There are several subtleties at high frequency end of the spectrum. The linear coherence with shower energy does not translate to higher frequencies but

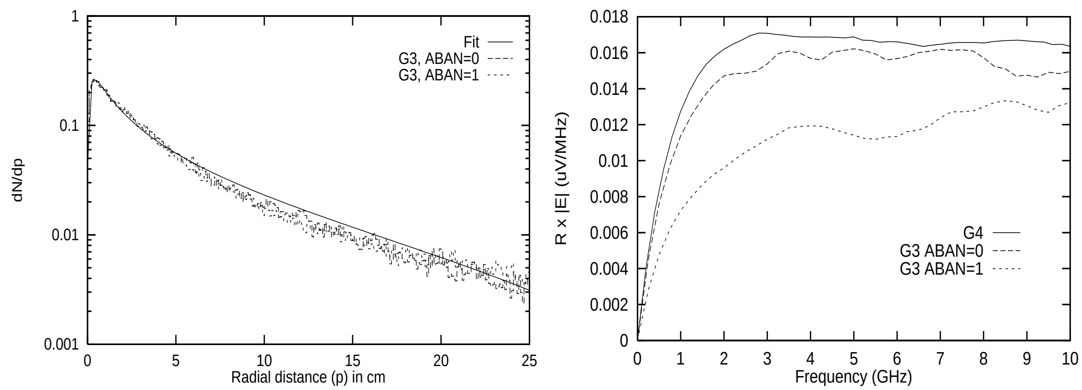

Fig. 2. Transverse excess charge distribution of a 100 GeV shower at the maximum [left panel] and the Monte Carlo frequency spectrum [right panel].

some degree of coherence is retained [3]. The scale of coherence is influenced by the peak ($\sim$ 0.1 cm) of the transverse distribution of the excess charge in the shower which is much smaller than the Moliere radius ($\sim$ 10 cm). However, understanding the high frequency behavior may involve addressing questions of the role played by the high energy particles at the beginning of the shower and the statistics of the signal phase relationships from different tracks in the later stages of the shower, for example.

4. Summary and Outlook

We have updated our calculations previously done with the GEANT 3.21 default settings by using the preferred settings of GEANT 3.21 and GEANT 4. The new results yield considerably higher track lengths, number of particles and electromagnetic signal strength. Antenna response is directly proportional to the electric field amplitude, which in turn affects the effective volume of the experiment.

We conclude that, for purposes of scaling radio signals from lower to higher energy showers, one can reasonably rely on linear scaling for frequencies below a few GHz. Clearly there is some interesting physics to explore in the domain above a few GHz. This important topic and the topic of signal contributions from the hadronic shower component are currently under study.

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