PROCEEDINGS OF SCIENCE

Transition radiation and the anomalous events of ANITA

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Transition radiation has been proposed as a possible explanation of the anomalous events detected by the ANITA experiment. These pulses come from the ice surface and do not display the characteristic polarity inversion that the pulses produced by regular cosmic ray showers acquire as they are reflected on the ice surface. A new version of the ZHS Monte Carlo program has been developed to treat coherent transition radiation of showers that go through an interface between air and ice. This program simulates electromagnetic showers that develop through air of constant density and hit an ice surface such as the Antarctic ice sheet, taking into account the magnetic effect of the Earth as included in a recent upgrade of the ZHS code. It can also calculate the induced radio emission at any point in the atmosphere. Simulations of radio pulses with this program are used to address whether the radio pulses produced by showers intercepting the ice surface, including transition radiation, can be observed at the ANITA detector without the characteristic polarity inversion.

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1. Introduction

The search for Ultra High Energy neutrinos with the Antarctic Impulsive Transient Antenna (ANITA) detectors resulted in the serendipitous discovery of GHz radio pulses from air showers [1]. The instrument flown over the Antarctica continent detected coherent radio pulses from Ultra High Energy Cosmic Ray (UHECR) showers developing in the atmosphere, characterized by a large horizontal polarization which is attributed to the magnetic field approximately pointing in the upward direction in Antarctica. The transverse current that develops because of the Lorentz force is thus nearly horizontal. The majority of pulses coming from the ice surface (below the horizon at the ANITA location) are produced by inclined UHECRs that get reflected on the ice surface, but a few come directly from stratospheric air showers without reflection on the ice cap [1]. Reflected pulses display a characteristic polarity inversion relative to the "direct pulses".

With ANITA, several "anomalous" pulses, that point to the ice surface but do not have the expected polarity inversion, were detected in the ANITA I [2], III [3] and IV [4] flights. The first two events obtained in flights I and III correspond to large elevation angles respectively of 27.4° [2] and 35.0° [3]. These events are consistent with pulses from air showers with a large horizontal component and could be induced by particles that emerge from the Earth and produce atmospheric showers in the upward direction. The pulses point directly to the ANITA instrument and have the same polarity as direct UHECR showers. The most effective mechanism to produce such showers is with neutrinos that traverse the Earth to interact just below the ice producing a high energy lepton that exits into the atmosphere. Tau neutrinos dominate because tau leptons suffer less energy loss in the rock or ice compared to muons and can travel through tens of km of rock before exiting. However, the energy of the shower must exceed $\sim$ 100 PeV for the pulses to be detected with the ANITA instruments and their elevation angle is too high for neutrinos of such energies to be able to traverse thousands of kilometers of Earth's crust before interacting just below the ice [2]. The neutrino tau interpretation was ruled out by detailed simulation of the pulses and the detector exposure. The implied neutrino fluxes exceed current bounds from IceCube, the Pierre Auger Observatory and the ANITA detector itself, for a diffuse flux [5] and the events are unlikely to come from point sources [6, 7] without observation in IceCube or Auger. The events have been interpreted in terms of particles beyond the SM (such axions, sterile neutrinos, heavy SUSY or dark matter particles) that also induce upward-going showers in the atmosphere[8–10].

Alternative explanations suggest anomalies in the ice such as subsurface reflections that could modify the pulse polarity [11], but these explanations are not supported by subsequent studies nor by anomalies in the reflectivity data at the ice locations indicated by the pulse directions [12]. Coherent transition radiation (TR) as a shower intercepts the ice-air interface, has also been suggested as an alternative explanation. Coherent TR can be generated from showers started by neutrinos in the ice if the shower crosses the ice-air interface when it is close to shower maximum. This explanation has been ruled out using detailed simulations. A modified version of the ZHS code [13] to simulate coherent radiation in homogeneous media was developed for that purpose [14]. The results imply that the required fluxes of neutrinos also exceed current bounds from other experiments [15]. Another explanation has been put forward based on coherent TR as UHECR showers intercept the ice surface. Using an analytical approximation the contribution due to TR from a UHECR shower with zenith angle 55° intercepting the ice has been estimated. The results appear to indicate that there is no polarity inversion for observers that are located so that they can detect the pulses emitted within the Cherenkov after being reflected in the surface [16]. However, there is no detailed simulations supporting this result. This work reports on the first results of such a simulation based on pulses simulated with a newly developed version of the ZHS that calculates TR pulses in this scenario. The method used to calculate TR with a new version of the ZHS code that accounts for magnetic deflections [17] is first described. Magnetic deflections are crucial for a shower that develops in air and the calculation of TR was one of the motivations to extend the ZHS code including magnetic effects. The code is then used to simulate showers under the same conditions chosen for the calculation in [16] and to obtain the time structure of the produced pulses for the same observation directions. The obtained results do not find the claimed polarity inversion.

2. The ZHS-TR code

The ZHS code is a Monte Carlo first designed to propagate electromagnetic particles (electrons, positrons and photons) through ice and compute the coherent radio emission from them [13]. This first version accounted for the main discrete electromagnetic interactions: bremsstrahlung, pair production, Compton , Bhabba, Møller scattering and electron-positron annihilation. A negative charge excess, the Askaryan effect [18], is generated due to interactions with matter electrons as the shower develops, which is responsible for the radio emission in dense media. Particle propagation is used to account for multiple elastic scattering and energy loss as continuous processes, using Molière's theory for the former.

The code was later expanded to deal with different media [19]. In 2015, an extension was developed to run a shower in two homogeneous media separated by a planar interface. The first part of the shower runs in one media, until it encounters the interface when the particles are stored for further processing. The second run starts with particles at the interface and develops in the second medium [14]. This version was made to calculate coherent TR pulses produced in the second medium, such as for a shower generated by a neutrino interaction in ice that exits to the atmosphere, and served to rule out this as an explanation of the ANITA anomalous events [15]. The new code developed here calculates the pulse in the first medium which requires a different treatment.

The TR calculation is based on the ZHS algorithm [13]. The original method calculates the electric field in the frequency domain produced by a charged particle track moving at constant speed in an homogeneous medium. When taking the far-field approximation in the Fraunhofer regime it is possible to derive from Maxwell's equations that the corresponding electric field is given by:

$$\boldsymbol{E}(\omega,\boldsymbol{x}) = \frac{e\mu_r}{2\pi\epsilon_0 c^2} i\omega \frac{e^{ikR}}{R} e^{i(\omega t_1 - \boldsymbol{k}\cdot\boldsymbol{x_1})} \boldsymbol{v}_\perp \left[\frac{e^{i(\omega-\boldsymbol{k}\cdot\boldsymbol{v})\delta t} - 1}{i(\omega - \boldsymbol{k}\cdot\boldsymbol{v})}\right], \tag{1}$$

where $\boldsymbol{v}$ is the particle velocity, R is the distance from the track to the observer, $\boldsymbol{k}$ is the wave vector, $\boldsymbol{v}_\perp = -\boldsymbol{k}\times(\boldsymbol{k}\times\boldsymbol{v})$ and t_1, $t_2 = t_1 + \delta t$ are the absolute time at the beginning and end of the track. The total electric field from a particle shower is then calculated by the superposition of all the electric fields from the particle tracks. We have in addition incorporated the options of using the time domain calculation [20], and to calculate pulses in the Fresnel regime. In the time-domain approach we calculate the contributions from each particle track to the vector potential given by:

$$\mathbf{A} = \frac{\mu e}{4\pi R}\mathbf{v}_\perp \frac{\Theta[t - \frac{nR}{c} - (1-n\beta\cos\theta)t_1] - \Theta[t - \frac{nR}{c} - (1-n\beta\cos\theta)t_2]}{(1-n\beta\cos\theta)}, \tag{2}$$

where θ here is the angle of emission w.r.t. the track direction. After all particle track contributions are summed up, the total electric field from the shower is obtained by taking the minus time derivative of the total vector potential. Since we are not necessarily in the Fraunhofer regime, here R represents the distance from the center point of the track to the observer. If the condition $\lambda R >> D^2$, where λ is the wavelength of the radiation and D the length of the particle tracks, is not satisfied, the track is further subdivided into sub-tracks until the condition is met.

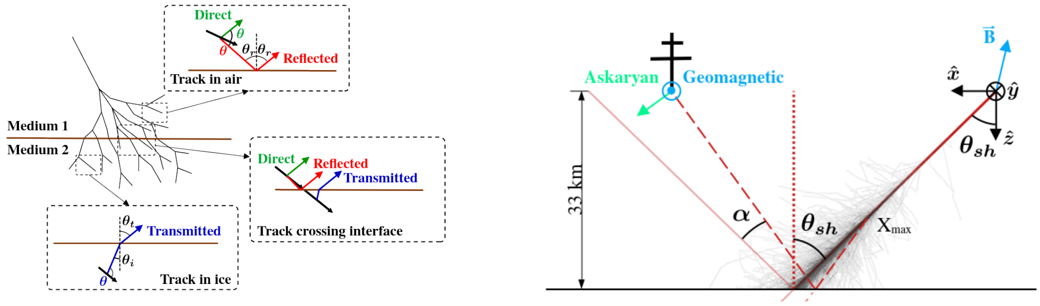


Figure 1: Left: Sketch of the three contributions to the pulse from different particles tracks in a shower: a particle track contained in air (medium 1), a particle track contained in ice (medium 2) and a particle track crossing the interface. The latter is subdivided into two tracks each fully contained in a single medium. Right: Sketch of the chosen simulation setup. The observer and the magnetic field are in the **xz** plane while the transverse current and the geomagnetic component are orthogonal to it.

To account for coherent TR we follow the procedure described in [14]. The shower develops first in air (medium 1) and then traverses to ice (medium 2) with the observer placed in the air (medium 1). Particle tracks fully contained in medium 1 have two contributions, due to direct and reflected emission (see Fig. 1 left). The direct emission simply follows Eq. (2). The reflected contribution is calculated using the same expression but now the relevant emission angle, θ, and total path length, R, are calculated with ray tracing. The relevant light ray reaches the observer after reflection at the interface, θ is the emission angle before reflection and R accounts for the total path length. The contribution to each polarization of the electric field must be multiplied by the Fresnel coefficient for reflection. For the tracks that are fully contained in the second medium only the transmitted contribution must be calculated. Again the angle θ and the distance R must be calculated using ray tracing. Also the factor nR/c that serves to calculate the retarded time must be adapted to the actual time taken by light that follows the light ray. The Fresnel coefficient for transmission must be finally applied and it must be multiplied by $n_1 \cos\theta_{tr}/n_2 \cos\theta_i$ (see Fig. 1) to account for angular dispersion of the transmitted rays [21]. Tracks that cross the interface are split so that they belong to either medium 1 or 2.

3. Radio emission from an air shower intersecting the ice

We have chosen the geometry shown in Fig. 1 (right), trying to reproduce the same setup as in De Vries et al. [16]. We choose the observer location so that the geomagnetic component is in the $\hat{\boldsymbol{y}}$ direction (perpendicular to the shower axis and the magnetic field), while the Askaryan component is orthogonal to it, in the $\hat{\boldsymbol{x}}\hat{\boldsymbol{z}}$ plane. The angle α is the emission angle w.r.t. shower axis of the light ray starting at shower maximum that reaches the observer after reflection. It serves to define the observer's position for a fixed detector altitude.

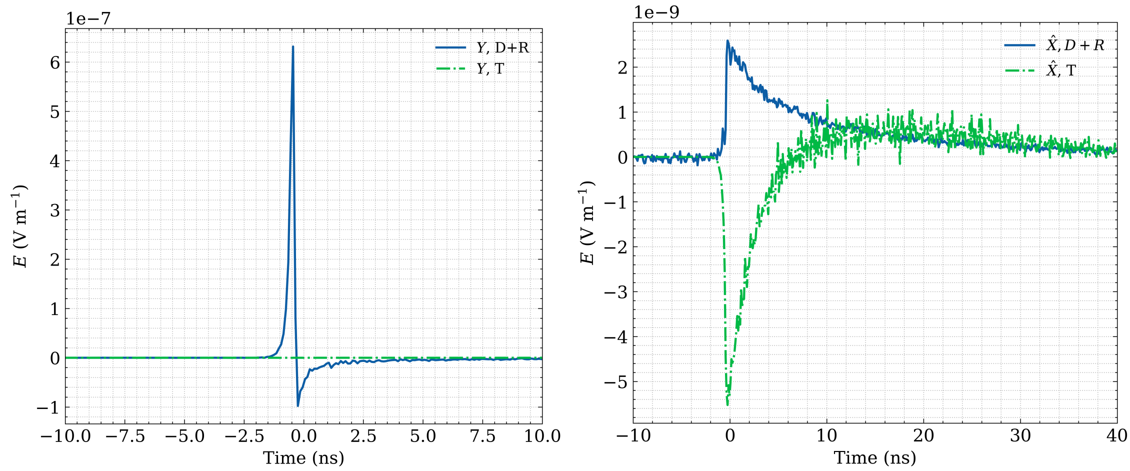
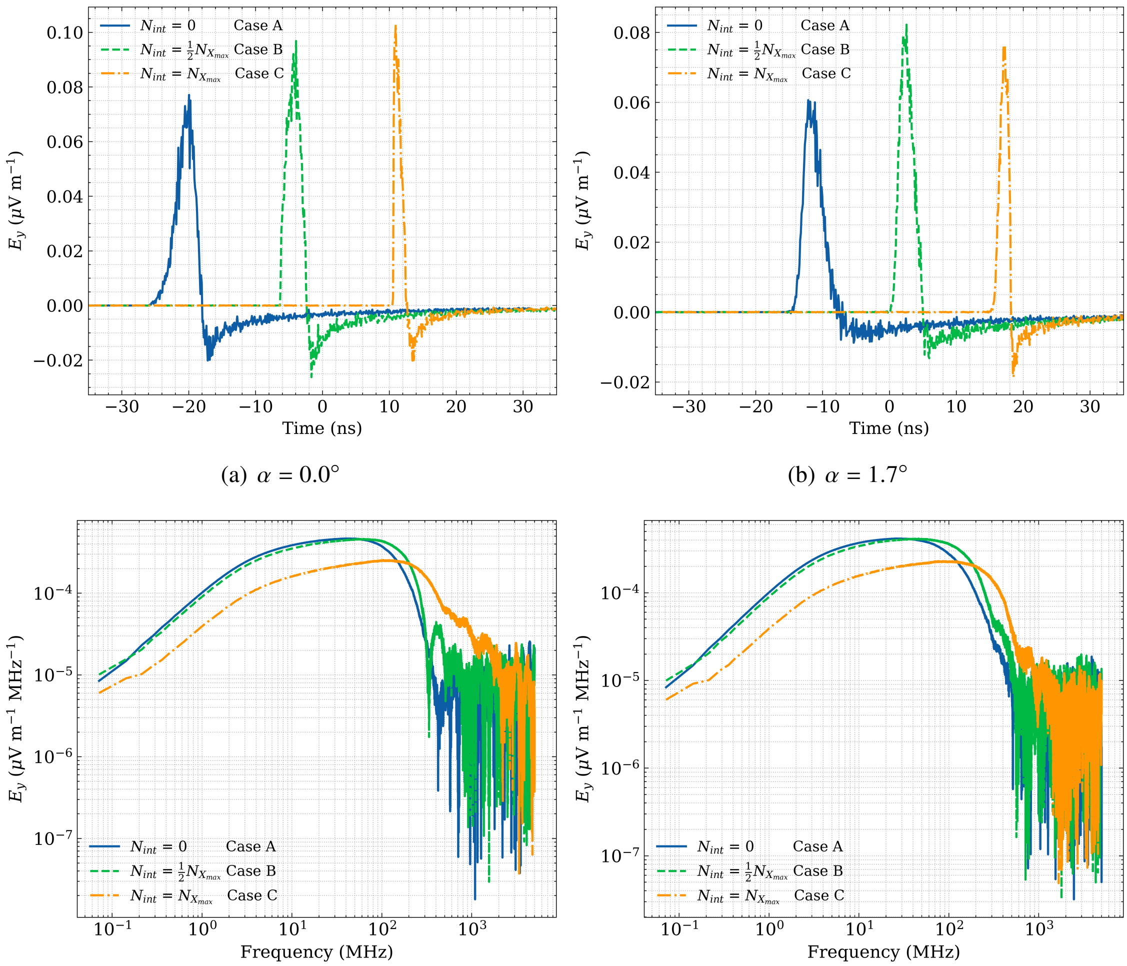


Figure 2: Comparison of different contributions to the E_y (left) and $E_{\tilde{x}}$ (right) polarization of a radio pulse for a 1 PeV electron shower that crosses the ice-air interface at shower maximum ($X_{\max}$). The direct and reflected (D+R) are separated from the transmitted (T) contribution. The observer is located to receive the reflection of the pulse emitted in the Cerenkov angle at $X_{\max}$ (corresponding to $\alpha = \alpha_C$ in Fig. 1 right).

We have chosen $0.9095 \cdot 10^{-3}\,\mathrm{g\,cm^{-3}}$ for the air density with a refractive index of 1.0002255 (Cherenkov angle $\alpha_C = 1.22°$) which correspond to the values of the atmosphere at an altitude of about 3 km. For the surface of the ice we use a density of $0.42\ \mathrm{g\,cm^{-3}}$ and a refractive index of 1.36 $\alpha_I = 42.67°$) [22]. The radio pulses for an observer located so that $\alpha = \alpha_C$, for a 1 PeV electron-induced shower with zenith angle 55° that starts in air and intersects the ice at shower maximum, are shown in Fig. 2. In Fig. 2a we show the E_y component of the electric field, dominated by the geomagnetic effect, as a function of time. The pulse is very sharp because we are mostly observing the emission in air in the Cherenkov direction (after reflection). The pulse is enhanced by the suppression of the vector potential as the shower intercepts the ground. The transmitted contribution is negligible because it is produced in a high density medium (ice) where the particles are barely deflected by the magnetic field and the E_y polarization is practically null. In Fig. 2b we show the $E_{\tilde{x}}$ polarization in the time domain, dominated by the Askaryan emission. The E_y (geomagnetic) component is more than two orders of magnitude larger than $E_{\tilde{x}}$. The dominant transmitted contribution is very suppressed with respect to the reflected one and this justifies approximating transition radiation only accounting for the direct and reflected contributions [16]. The shape of the reflected component in $E_{\tilde{x}}$ is broader than in E_y. One could expect similar coherence properties for the reflected component in $E_{\tilde{x}}$ compared to E_y but this is not the case by accident. The incidence angle of the reflected contribution is very close to the Brewster angle (53.66°) and as a consequence the $E_{\tilde{x}}$ reflected contribution is almost completely suppressed. As the reflected component is negligible, most of the contribution from the air (blue) in Fig. 2b is due to direct emission that gets abruptly suppressed as the shower reaches the ice. That transmitted from the ice (green) is mostly due to the abrupt start of the shower in ice.

To continue evaluating the effect of TR we show the radio pulses for two more observers located



(a) $\alpha = 0.0°$ (b) $\alpha = 1.7°$

(c) $\alpha = 0.0°$ (d) $\alpha = 1.7°$

Figure 3: E_y components of the radio pulse emitted by 1 PeV showers in three cases: not intercepting the air-ice interface (case A in blue), intercepting after $X_{\max}$ such that roughly half of the particles at X_{max} cross the interface (case B in green), and intercepting at $X_{\max}$ (case C in orange). Pulses are compared for observation at $\alpha = 0°$ (left) and $\alpha = 1.7°$ (right) (see Fig. 1 right). Plots in the time (frequency) domain are shown in the upper (lower) panels.

at $\alpha = 0°$ and $\alpha = 1.7°$ (also chosen in[16]) in Fig. 3, respectively inside and outside the Cherenkov cone. The pulses are shown for three cases in each panel: a shower that does not intersect the air-ice interface (case A, blue), a shower that intersects the interface after $X_{\max}$ such that roughly half of the particles at $X_{\max}$ cross the interface (case B, green), and a shower that crosses it at $X_{\max}$ (case C, orange). The frequency spectra of the corresponding pulses shown in panels (c) and (d) illustrate how the cases with enhanced transition radiation (B and C) have larger amplitudes at high frequencies. This is expected since the interface causes a rapid increase or decrease of the vector potential magnitude depending on α being smaller or larger than α_C. This is also observable in panels (a) and (b) for the cases B and C. The first pulse rises faster for $\alpha < \alpha_C$ because the observer "sees" first the end of the shower. When $\alpha > \alpha_C$ the pulse decreases faster because radiation from the interface arrives later. There is no polarity change when the shower intercepts the ice (cases B and C) relative to the reflected pulses from showers that fully develop in air and do not induce TR (case A). When an air shower intercepts the ice the pulses do not show any polarity inversion for $\alpha < \alpha_C$ compared to $\alpha > \alpha_C$ (as in cases with no TR [23]). This is in contrast to the results in [16].

4. Conclusion and discussion

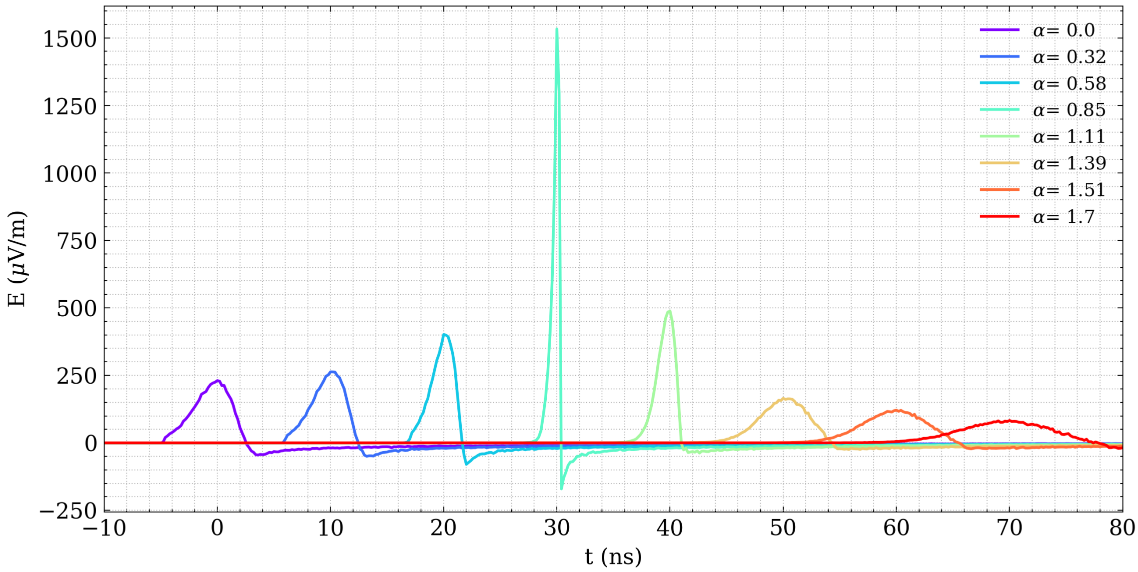


Figure 4: Radio pulses obtained using the ZHAireS Monte Carlo for different off-axis angles α, for a 1 EeV proton-induced shower with zenith angle 55° injected at 100 km of altitude and intersecting an ice core at 3 km altitude. The observer was placed at 33 km of altitude.

We have developed a program based on ZHS to obtain coherent radio pulses including TR as a shower crosses two homogeneous media for an observer located in the first medium. The program is used to simulate pulses from air shower intercepting the ice surface at Antarctica as seen by a detector like ANITA located at $\simeq$ 33 km altitude. The geometry is chosen to match the example used to justify a change of polarity for observers at different locations as an explanation of the anomalous ANITA events [16]. Our results do not confirm that interpretation. However, they confirm the approximation made in [16] that the emission from the shower that develops in ice is negligible. As the code use requires a homogeneous medium the question can be raised whether more realistic conditions could change this conclusion. Approximate results have been obtained with ZHAireS neglecting the last part of the shower that develops in ice. These results are shown for a variety of observation angles including those used in [16] in Fig. 4. The results obtained support the previous conclusion, no polarity change is observed as the observing angle α changes gradually from $\alpha = 0°$ to $\alpha = 1.7°$ passing through the Cherenkov angle $\alpha_C \sim 0.9°$. This is consistent with the behavior of pulses in a single medium.

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