PROCEEDINGS OF SCIENCE

From signal properties toward reconstruction for the Radar Echo Telescope for neutrinos

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High energy cosmic neutrinos interacting in ice will induce a particle cascade. The Radar Echo Telescope (RET) aims to detect the neutrino through probing the cascade by means of the radar echo method. In order to study this process, we simulate transmitting a radio signal to scatter off the cascade. A return radio signal will be detected at a number of user-defined receivers. Several properties in the radio signals have been observed when systematically varying the direction of the cascade, such as patterns in the intensity and fourier transform amplitudes at half, at and twice the transmit frequency. Given these patterns, it is possible to train machine-learning algorithms to reconstruct the cascade direction. As such, we simulate a simple setup of four receivers and vary the direction of the cascade, keeping the position and energy constant, and show the reconstruction accuracy that can be currently achieved.

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1. Introduction

The main aim of the Radar Echo Telescope (RET) experiment is to detect ultra-high energy cosmic ray particle cascades penetrating a high-altitude ice sheet [1, 2], and ultimately cosmic neutrinos interacting in ice [3, 4]. A shower of relativistic particles is produced following the neutrino or cosmic-ray interaction, in turn leaving behind an ionisation deposit. It is possible to reflect radio waves off this deposit and detect the scattered signal. Understanding the radar signal properties is critical as it will enable the vertex, directional, and energy reconstruction of the primary cascade-inducing particle.

The properties of the radar signals that are detected depend on the geometry of the transmitter-cascade-receiver setup as well as the direction and energy of the cascade [5]. For the current work, the cascade position and energy is fixed, and only the direction is varied. Several other factors affect the signals, such as the chosen transmitter frequency and plasma lifetime.

The signals detected are non-trivial: there are doppler, diffraction and Cherenkov-like effects adding richer features to the signal.

1.1 Geometry and simulation setup

We consider a setup composed of four receivers and one transmitter. The cascade is fixed at the origin, and we examine several signal properties, described further below, when varying the direction of the cascade systematically. The geometry is shown in Figure 1. The positions of the receivers are as follows: Receiver 1: (-250,0,0) m, Receiver 2: (250,0,0) m, Receiver 3: (0,-250,0) m, Receiver 4: (0,250,0) m.

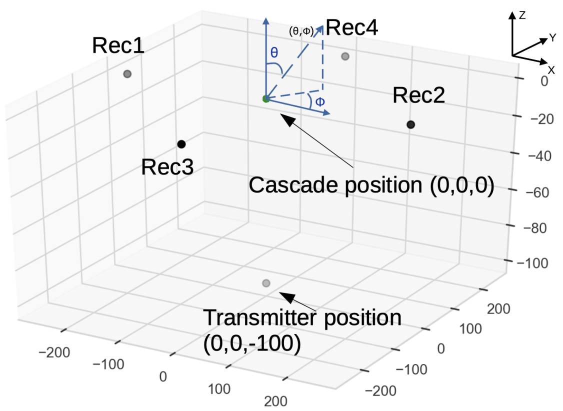


Figure 1: Geometry of the simple four receiver setup. Dimensions are in meters.

We use RadioScatter [6], a particle-based approach to simulate the particle cascade and radar scattering process[1]. It is run within Geant4 [7], a simulation toolkit for the passage of high energy particles through matter. The primary particle properties are set up in Geant4, such as the position, energy and direction, and in RadioScatter it is possible to define the locations of the transmitter and a number of receivers, placed inside the ice.

We use a 50 MHz transmit frequency and a 10 ns plasma lifetime. The transmitter power is 1kW and the polarisation is along the y-axis. No noise is currently included in the simulations.

[1]https://github.com/prchyr/RadioScatter

2. Results

We deduced several properties that show interesting patterns when changing the direction of the cascade in a systematic way; namely by rotating the cascade in the vertical (θ) and horizontal (ϕ) plane in spherical coordinates.

The properties are derived directly from the voltage-time traces, their fourier transform as well as the spectrogram, all representing the same information in a different base.

2.1 Properties

2.1.1 Sum of voltage squared (intensity)

One property that was found to be useful is the intensity, defined by integrating the squared voltage over time, $I = \int V^2(t)dt$. Figure 2 shows the pattern across all four receivers in ϕ and θ respectively. In the geometry shown in Figure 1, receivers 1 and 2 are located opposite each other along the x-axis, whereas receivers 3 and 4 are located opposite each other along the y-axis.

Both geometries consistently show a higher magnitude for the receivers 1 and 2 since the antenna polarisation is set along the y-axis for all antennas. The same features are observed across the pairs of receivers, but shifted by 180 degrees due to their placement. Looking at receiver 1, one can see that the maximum magnitude occurs when the cascade is oriented at 90 and 270 degrees multiples for both θ and ϕ.

There are diffraction effects observed when rotating θ, where the magnitude appears to fluctuate significantly between 0 and 90 degrees. The observed features originate from a complex interplay of polarization, Cherenkov and diffraction effects, which are difficult to separate.

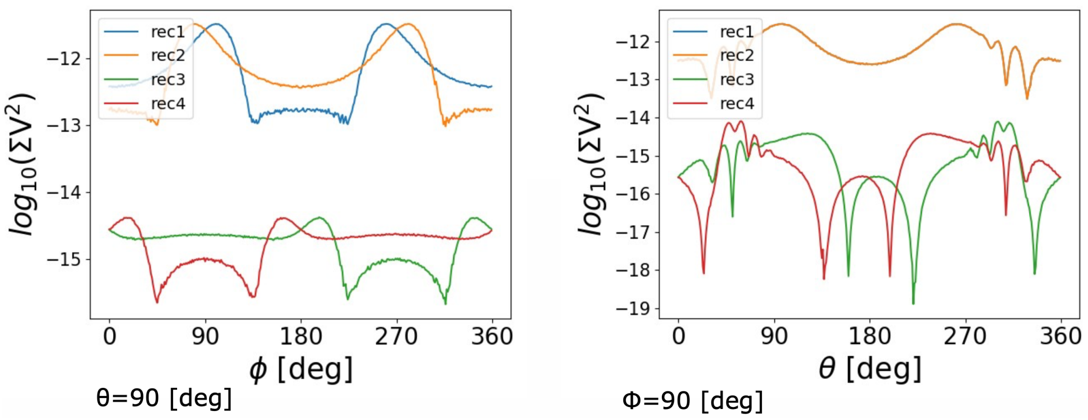


Figure 2: Intensity versus ϕ and θ across all four receivers.

2.1.2 FFT amplitudes: Half, full, and twice the transmit frequency (f_t)

Another set of interesting properties that was found is given by the amplitude at multiples of the transmit frequency, referred to as f_t from hereon in. Specifically, we consider the amplitude occurring at half f_t, at f_t and twice f_t. The plots overlaid in Figure 3 show these multiples of f_t across receiver 1.

One observation is that the largest amplitudes, as well as the range of high amplitude values over θ and ϕ occur at f_t. Here the amplitude is maximised at 90 and 270 degrees in both θ and ϕ, as was observed in the sum of voltage squared. These maxima are pushed to the left and right when at half and twice f_t respectively.

Generally, the features appear most spread out at half f_t, becoming increasingly compressed as the frequency is increased to f_t and the highest compression occurs at twice f_t.

Considering the rotation in ϕ, similar features are observed. Furthermore, a local minimum occurring at roughly halfway between 90 and 180 degrees is observed across all three frequencies. The diffraction effects in θ are most obvious at half f_t.

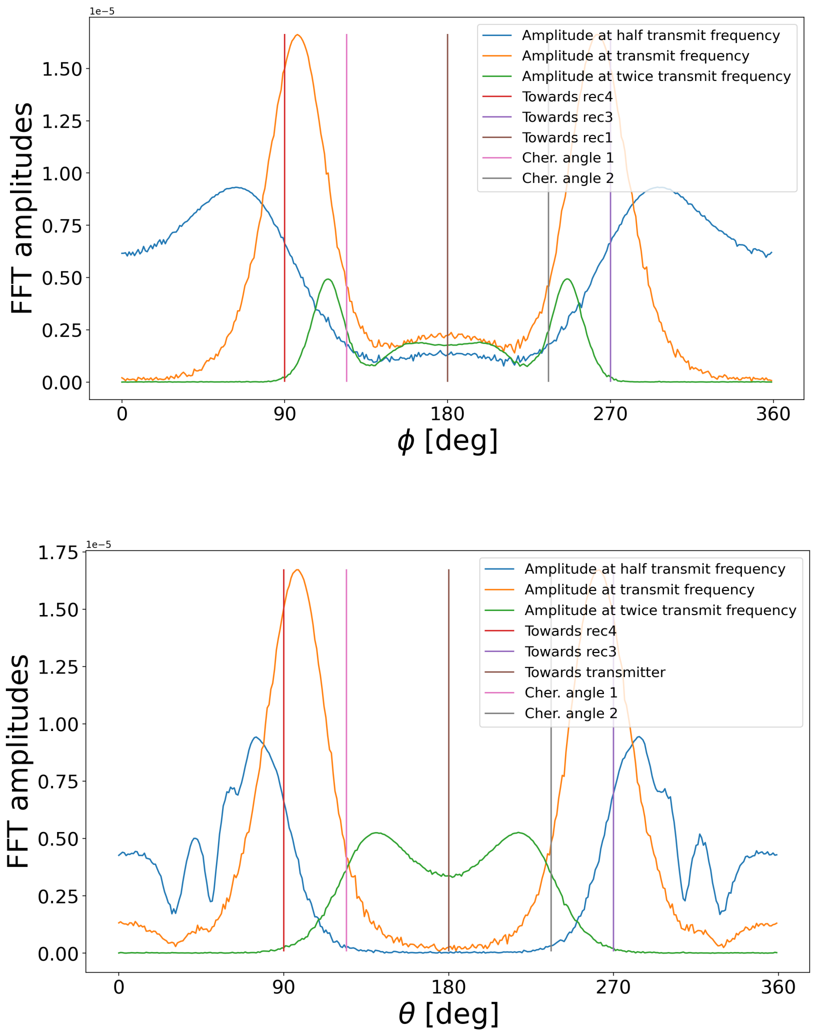
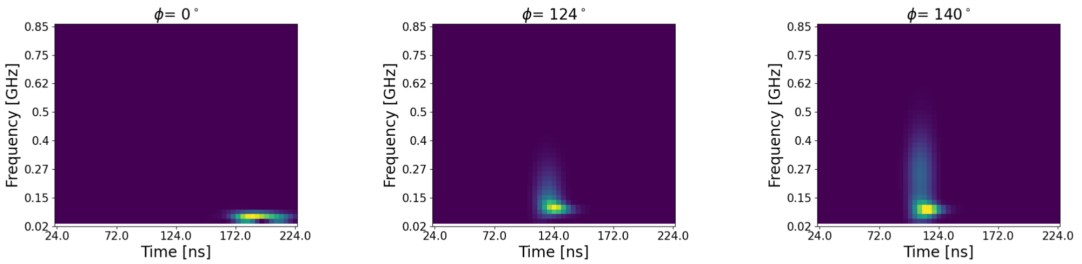


Figure 3: FFT amplitudes at half f_t, occurring at f_t, and twice f_t, vs ϕ (top) and θ (bottom). Moving towards higher frequencies tends to shift the peaks toward the Cherenkov angle.

2.2 Signal spectrograms

Converting the voltage-time trace into spectrograms enables a simultaneous representation of both time and frequency information. Considering only the signals detected in receiver 1, Figure 4 shows how the spectrograms appear at different orientations of the cascade. The zenith angle is set to be constant at 90 degrees and the azimuth angle is varied.

The signal is most compressed in frequency but spread out in time when the cascade is directed away from the receiver, as shown in Figure 4(a). Increasing the angle ϕ results in a broadening of frequency and compression in time, as well as occurring earlier. In theory, the Cherenkov angle occurs at around 124 degrees as shown in Figure 4(b), which should result in the broadest range of frequencies, however this appears to be shifted, most likely due to different phase coherence conditions for the transmitter-cascade-receiver set-up as compared to the configuration without a transmitter, and instead occurs at around 140 degrees as shown in Figure 4(c).



(a) Cascade directly away from receiver 1

(b) At the calculate Cherenkov angle with respect to receiver 1

(c) Broadest range of frequencies appears at a shifted location

Figure 4: Showing appearance of spectograms at some chosen angles.

Other properties used for reconstruction but not mentioned here include the peak frequency, bandwidth and signal arrival time.

2.3 Preliminary reconstruction

Given the complex nature of the signal, which is an interplay between diffraction, Cherenkov and polarization effects that are observed when varying the direction of the cascade in a systematic way, it is possible to utilise this behaviour to help perform reconstruction. Machine learning techniques can be employed in this context.

To demonstrate the use of machine learning for reconstruction, we simulate 990 runs of the cascade with isotropically varying direction. The primary is given a constant energy of 10 PeV, and the cascade is set to be at the origin (0,0,0). The geometry of the antennas is shown in Figure 1. The signal properties used in performing the reconstruction are the intensity, arrival time, peak frequency, rise and fall time, bandwidth, maximum FFT amplitude, and amplitude at half, at and twice the transmit frequency.

We use gradient boosted machines (GBM), also known as boosted decision trees, to help reconstruct the direction of the cascade. 80% of the data is used for training and validation, 20% is used for testing. Five iterations of training and testing are performed, shuffling the data in between iterations to generate different samples for training and testing.

The quality of the reconstruction on the test set iterations is gauged using the opening angle α as shown by equation 1, which can be understood as the angle between the true and reconstructed direction. The smaller the opening angle, the better the reconstruction. The distribution peaks at a median opening angle of 2.17 deg. It should be noted that the simulation represents a far from ideal scenario for reconstruction, given the symmetry of antenna setup and the fact that all receivers are in the same plane. The results of the reconstruction are shown in Figure 5, which shows the combined results following 5 iterations, where the data is shuffled for each iteration.

$$\alpha = cos^{-1}(\vec{x}_{real} \cdot \vec{x}_{reco}), \tag{1}$$

where $\vec{x}_{real}$ and $\vec{x}_{reco}$ denote the true and reconstructed directions respectively.

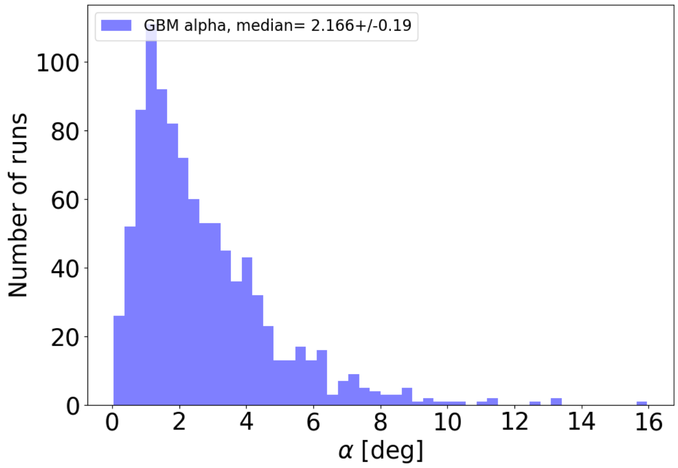


Figure 5: Opening angle α showing reconstruction performance using boosted decision trees.

3. Conclusion

In the current work we have investigated several properties found by exploring the radar echo off a high-energy neutrino-induced particle cascade. The signal is detected at a number of user-defined receivers, using a simulation for the scattering of a radio signal from a particle cascade in ice. Patterns in the signal properties have been observed when varying the direction of the cascade in a systematic way. The properties are not trivial, and contain many features, that arise due to the geometry of the setup, relativistic effects and polarization effects and diffraction. For example, peaks and troughs occur at some evenly spaced intervals when varying the zenith angle, that are likely due to diffraction. Intensity patterns are observed to change as function of frequency, indicating relativistic boosting effects become more prominent at high frequencies. These effects are currently under investigation.

The signal properties investigated serve as useful reconstruction variables, that can be provided as the input to a machine-learning approach to reconstruction, with the direction as the output. While considering a rather symmetric, non-ideal, configuration and by simulating random directions, we have shown promising preliminary results for reconstruction, where the direction of the cascade is reconstructed to a median opening angle of ~ 2 degrees. Full reconstruction efforts are currently in progress, including optimising the machine learning algorithms and approaches, such as using spectrograms or raw signals as input for the reconstruction.

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