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Radio propagation environment analysis for neutrino radio detection in salt mines

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Abstract

[a] We consider a neutrino large-scale radio Cherenkov observatory in a Romanian salt mine. We include propagation effects on the radio signal generated and make a threshold analysis, taking into account how the pulse couples to a realistic receiver and signal-to-noise ratio limiting situations.

Keywords: Electromagnetic shower; salt; UHE cosmic neutrinos

1. Introduction

Neutrinos carry the information about the regions of the universe where the cosmic rays have been formed because they are uncharged, therefore not deflected by magnetic fields. As they only interact via the weak force, they are immune to almost all attenuation. A neutrino that reaches Earth came directly from its point of origin and so can, in principle, be used to determine the location of the source.

The main goal of the construction of a large volume, ultra high energy (UHE) neutrino telescopes is the detection of extra-Galactic neutrino sources [1]. Other implications are in cosmology, Big Bang scenario, particle physics, stellar physics, gravitational waves etc.

Neutrino telescopes detect the three types of neutrinos via the process of primarily upward-going or horizontal neutrinos interacting with a nucleon of the matter comprising or surrounding the detector volume [2]. The debris, consisting of an electron or hadrons depending on the neutrino type and

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mediation boson involved, produces a shower within the detector. Several detectors are built to determine high energy neutrinos propagating in different media[3]-[6].

As the particles' speed is higher than the speed of light in the medium of the detector, by depolarization of molecules will appear emission of radiation at visible and radio wavelengths. Moreover, as a result of the charge asymetry in shower (predicted by Askaryan [7]) a nanosecond pulse of coherent Cherenkov radio emission can be observed in directions corresponding to a 'spread' conical surface with the opening equal to Cherenkov angle [8]-[11]. According to [12], the radiation is coherent and the electric field is proportional to the negative charge in the cascade.

We have chosen a salt dome as natural detector because the volume is very large and it compensates for neutrino small cross section and flux. Salt is transparent to the radio frequency shower signal so the distance between antennas can be larger. Salt domes are radio-quiet area, that is no interference will appear with other radio signals. As compared to other detectors, the density of salt is higher than the density of ice so the shower dimension is smaller. This will lead to coherent radiation up to higher frequencies. The power of radio emission grows as the square of the energy of the shower [2].

Because of the large volume and high sensitivities involved, equipment will be configured in multiple radio stations (RS) deployed in a 3D grid. Each RS will include two vertical polarization antennas and two horizontal polarization ones. A pair of antennas (horizontal and vertical polarization), can detect the strengths of electrical field. The arrival time of the waves can be correlated between RS to find the incoming neutrino direction.

2. Radio pulse and antenna characteristics

The detector configuration consists of strings with multiple RS. The radio waves (generated by neutrino induced particle shower) propagate and their amplitude and phases are measured by the RSs.

The 3D detector should be able to reconstruct the energy and direction of the primary particle based on the measured properties of the electrical field generated by the initial neutrino. The reconstruction process (conversion of measured voltages to field strengths) will determine the energy and direction of the initial neutrino.

The absolute measured field strength depends on the electric field generated by the shower, receiving antenna characteristics (antenna effective area, spectral response, coupling efficiency, angular response) and propagation effects in the medium.

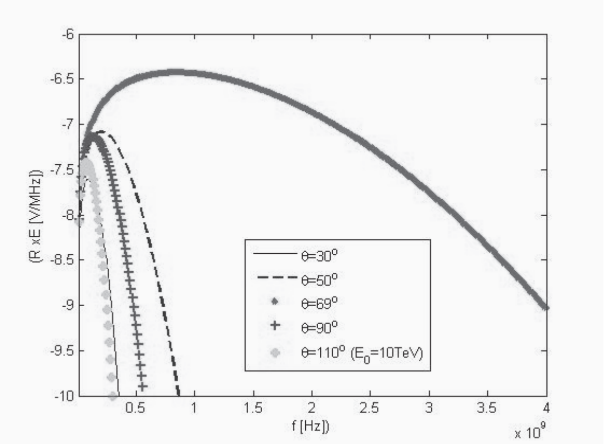

Fig. 1. Spectrum of the electrical field produced by a 10TeV particle

One can see in figure 1 that the electrical field is maximum at Gigahertz frequencies. We have decided to operate below these frequencies (at 187.5 MHz [13]) as attenuation effect decreases with frequency. The frequency corresponds to a half wave dipole of length 80 cm.

The electrical field's magnitude also depends on the observation angle and it is maximum at Cherenkov angle.

The antenna transfer function is the ratio of the antenna output voltage to the E-field at the antenna. It is called effective antenna length because its dimension is a length. For a dipole antenna (that are cheap and easy to use in such a detector), the transfer function depends on the intrinsic impedance of free space, the receiver input impedance, radiation resistance, the speed of light in medium (here, air), the length of the dipole and θ - the angle of incidence with respect to the antenna axis (presented in figure 2). The maximum efficiency is in the direction perpendicular to the axis of the antenna.

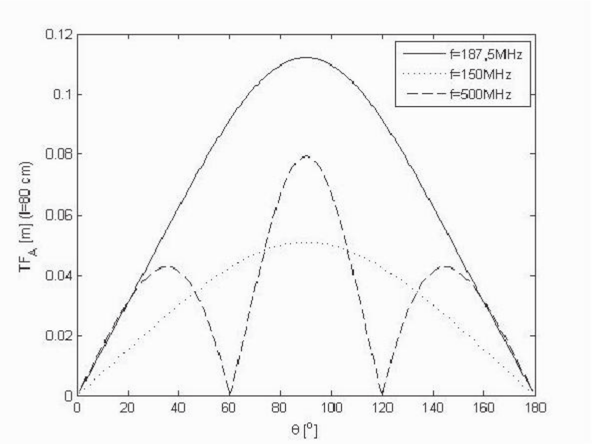

Fig. 2. Angular response of a dipole antenna of 80cm at 3 frequencies.

3. Propagation effects

The salt deposit is the result of layers of dried solutes (evaporites) from ancient seas [14]. The layers have different characteristics (though different dielectric constants) which are not normally known.

For millimetric and longer wavelength the permittivity should be independent of frequency and temperature and equal to its static value. Non-polar ionic dielectric materials (as salt) should have complex permittivities only in IR and UV.

Impurities in dielectrics affect their properties. According to [15], most common impurities in Slanic Prahova salt mines are Al, Ca, Ti, Fe, V, Mn, Cu and Br.

When an incident wave interacts with a particle, a part of its power is absorbed and the direction is changed. The simplest scattering theory is when the particle is assumed spherical.

The scattering effects of the main impurities in salt have been evaluated. Compared to the absorption, scattering is 40 orders of magnitude smaller and can be easily ignored. The higher frequencies are more scattered as the corresponding wavelength are smaller and approach the size of impurities. Another effect associated with impurities is the absorption. The imaginary part of the permittivity is a measure of it. In [16] we found the dielectric permittivity to be $\varepsilon_r=5.7+j0.0012$ at 200MHz and $\varepsilon_r=5.98+j0.083$ at 800MHz.

The third propagation phenomenon to consider are reflexions at separation borders between layers of dielectric. Each layer has different characteristics according to deposited sediments, which are not normally known. Starting with that, one can consider a toy model of the vertical variations in which each layer is ideally considered to be a non-dispersive, isotropic, linear and homogeneous medium.

The reflections will result in a decrease of the amplitude of the waves and phase shifts.

The electromagnetic radiation crosses one layer and only a fraction of it will enter the following one. The rest will be reflected backwards and regarded as loss. In order to prove that the loss assumption in well justified, the power of the transmitted waves that resides from multiple reflections has been calculated. It is more than three orders of magnitude smaller.

4. Threshold analysis

The power delivered to the receiver is maximum if the antenna is followed by an adapted filter with a matched load impedance. This gives the voltage delivered to the load.

The voltage drops almost exponentially with the distance between the shower and antenna. As expected from the transfer function of the dipole antenna, the maximum voltage is recorded for waves coming at an angle of θ=90 deg. An increase in the primary particle energy with a factor of 100 is producing a voltage that is one order of magnitude higher.

After calculating the voltage delivered to the receiver system, we must investigate the problem of the possibility of detecting the signal under noise. The signal to noise ratio (SNR) was calculated according to [17]. We have assumed a system temperature of 450K (based on a temperature of about 310K for the salt and a receiver noise temperature of 140K, consistent with low-noise amplifiers available commercially). We have taken into account just Johnson thermal noise as background noise is neglectable (salt in domes is covered by thick soil which absorbs completely radio electromagnetic waves, natural or artificial).

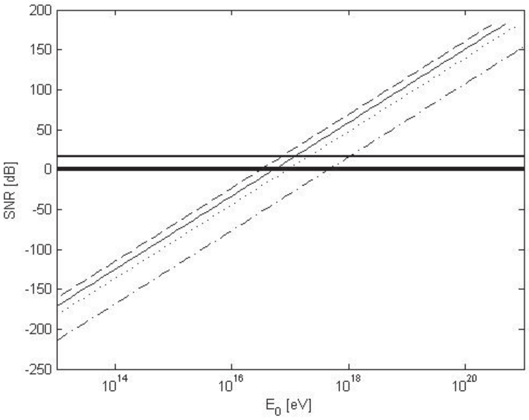

Fig. 3. SNR as function of the primary neutrino energy. With continous line we presented the situation when the distance between shower and antenna is d=100m and θ=60 deg.; with dash dotted line- d=500m and θ=30 deg.; with dotted line- d=100m and θ=60 deg.; with dashed line d=60m and θ=60 deg.

The SNR depends on more than one factors but the most important is the energy of the primary particle. Due to that, an imposed SNR will give the minimum (threshold) energy that can be detected.

We plotted the variation of SNR with the energy of the primary neutrino for different angles and distances between shower and antenna (figure 3). In this configuration, particles with energies below 1PeV cannot be detected. Particles with energies of 10^{16}eV can be detected only if the distance *R* is less than 6m (for an imposed SNR equal to 5) and less than 16m if SNR=1 (the Glashow resonance can be observed only if R<1m when SNR=5 and at R<11m when SNR=1). The minimum distance becomes much larger at higher energies (at 10^{17}eV, R=80m respectively 187m for a SNR equal to 5, respectively 1).

Some detector simulations have been also performed. Results are presented in figure 4. We show results for SNR=5 (left side of each graph) and SNR=1 (right side of each graph). The case when the frequency is 800MHz is also shown (lower side). The initial neutrino has an energy of 10^{21} eV, assumed to be all transferred to the new produced lepton.

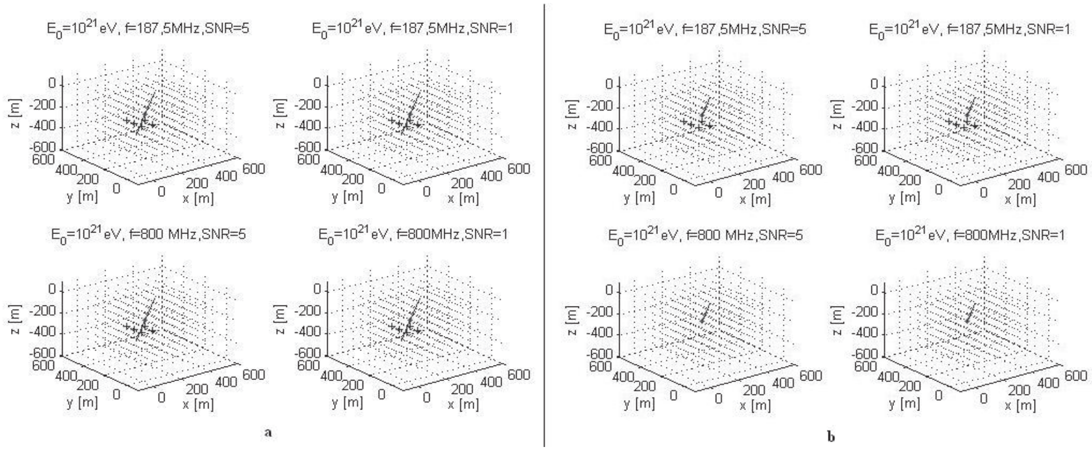

Fig. 4. Antennas that measure a signal higher than the threshold (marked by '+'). A volume of 500x500x500 m3 is filled with antennas (8 on each dimension, represented by points). The line indicates the direction of the neutrino. In (a) εr=6+j0.001. In (b) the frequency dependent permittivity is as given in [16]

The false triggers generated by thermal noise have been also calculated. It was assumed that a hardware trigger in a radio station requires that three out of four antennas to measure a threshold voltage (given by the SNR). For an event we require a trigger given by a cluster of three neighbor station and also causality. It was found that the SNR that guarantees a number of false triggers smaller than unity is about 9. The values for SNR considered in [12] and [17] are much smaller.

5. Conclusions

We found that reflections at each layer crossing not only decrease the measured voltage with at least 10%, but also produce phase shifts. Due to latter effect, information about incoming direction is lost.

By neglecting reflections at separation border between dielectrics and assuming a distance between shower and antenna of 100m, a SNR=9 and an observation frequency of f=187.5MHz, the measured voltage exceeds the threshold only if the imaginary part of permittivity is less than 0.01.

It was found that the minimum energy of an incoming neutrino that can be detected is 100PeV if the signal to noise ratio is 5 and the distance between interaction point and antenna is 80m.

In order to keep the global false trigger rate per year smaller than 1, the SNR should be at least 9. In this case the energy detection limit is $10^{19.5}$ eV and the distance between stations of 60m.

Acknowledgements

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