Simulations of results from antennas that measure cosmic neutrinos

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Abstract: This paper provides an overview of how to manipulate data regarding neutrinos of high energy using indirect measurements. To be more precise, it is focused on the way the elementary cosmic particles interact with different mediums (in this case, salt and air) from the perspective of the electromagnetic field generated by them and captured by the antennas. Furthermore, another important aspect of this article is represented by the phenomena that occur during the transmission of the electromagnetic field from one medium to another. The interaction is measured by knowing the characteristics of the antenna (length, current, impedance and vector effective length) and the electric field generated by the particle in salt, thus resulting the voltage that gives important information about the behavior of the neutrinos.

Key-Words: antennas, cosmic neutrinos, electromagnetic field, salt detector

1 Introduction

Cosmic rays were discovered in 1936 by Austrian physicist Victor Hess [1], direct measurements of them being possible for energies up to 10^{14} eV due to detection systems installed on balloons or satellites. For higher energies, towards 10^{20} eV, the flux of these particles becomes very small. The only way to obtain information about particles that are so rare is by indirect methods, by measuring the interaction effects of these primary cosmic particles with various environments. Depending on the phenomena that can appear because of the interaction, complex detection systems can be built on the surface of Earth, in air or underground.

The primary purpose of a detector designed to observe cosmic neutrinos of high energies is identifying the extragalactic sources that produce them. Measuring neutrinos with energies higher than 10^{12} eV can determine the discovery of new astrophysical systems and possibly new physical processes. The lack of hard and electromagnetic interactions gives these particles the possibility to travel the Universe without deviations produced by magnetic fields. Thus, the direction from which they arrive is a direct indicator towards the source that generates them [2].

When a neutrino of very high energy interacts with a dielectric environment which is transparent and dense, it produces an avalanche of relativist particles. At the beginning of the ‘60s, Gurgen Askaryan predicted that this avalanche is accompanied by a strong radio electromagnetic component (up to ~ 10 GHz), lasting 1 ns [3].

A radio-detector for neutrinos is usually built in a natural formation occupying volumes of the order of km^3 (in the case of the current project – salt domes), and the experiment consists in using a large number of antenna rows that can notice the radio impulses produced at the interaction of the cosmic particle. Therefore, it is possible to determine not only the characteristics of the particle (mass, type and energy), but also its route throughout the Cosmos and its source of origin [4].

The article is organized as follows: section 2 consists of the presentation of the electromagnetic field generated by the cosmic particle in salt, section 3 consists of how the field is transmitted in air, section 4 consists of the results obtained by manipulating the voltage recorded by the antennas and the final section is reserved for the conclusions.

2 The electromagnetic field generated by the cosmic particle in salt

It is known that the cosmic particle comes from the direction (θ_{inc}, ϕ_{inc}). The angles in discussion are not absolute; they are relative to an observer who notices the angles from the direction (θ'_{inc}, ϕ'_{inc}). As a result, it is necessary to calculate the direction (θ'_1, ϕ'_1) from which the particle comes relative to the absolute coordinate system.

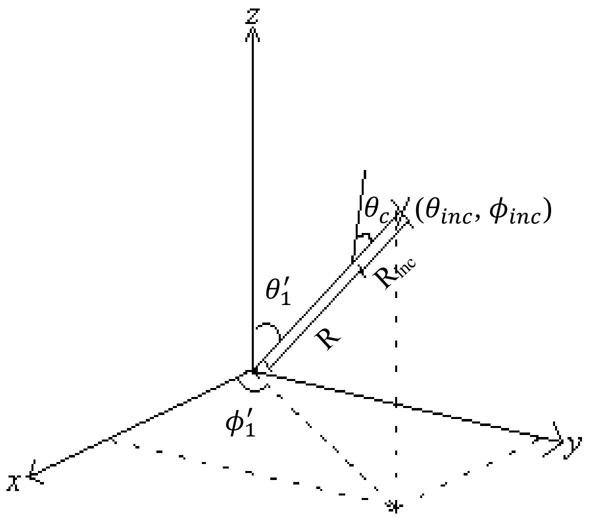

Fig.1 Direction of the particle

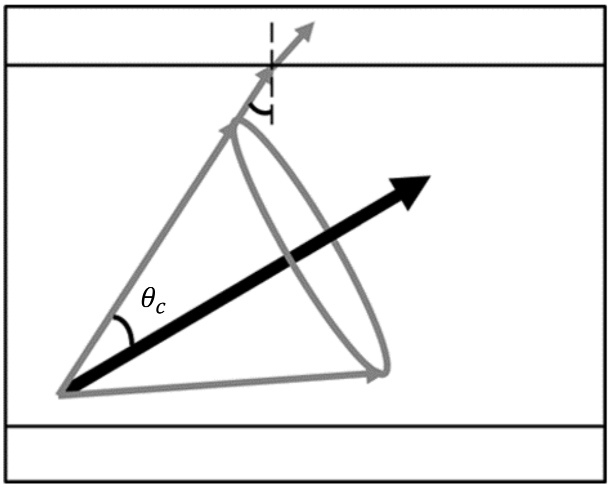

Fig.2 Cherenkov cone [5]

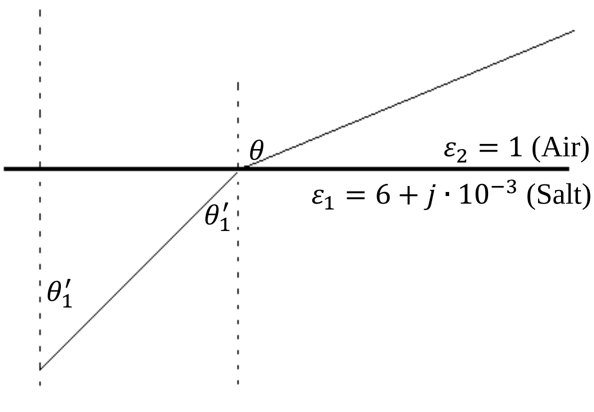

Fig.3 Transmission of the ray from salt to air

$\phi_1' = \tan^{-1}(\cos\theta_{inc} \tan t)$ (1), where it is a parameter for projecting an ellipse in the XYZ system,

$\theta_1' = \theta_{inc} - \tan^{-1}\left(\frac{R_{inc} \tan\theta_{inc}'}{R+R_{inc}}\right)$ (2)

To continue, it is mandatory to calculate the electric field that the particle generates in salt by Cherenkov effect [6]:

$$E_1(\theta_1', \phi_1', f) = \frac{3.2 \cdot 10^{-16}}{X} \frac{E_0}{E_c} \frac{X_0}{\rho} f \frac{1}{\left(1 + \frac{f}{f_L}\right)^{2.6}} \frac{\sin\theta_1'}{\sin\theta_c} j$$

$$exp\left[-\left(\frac{\theta_1' - \theta_c}{\Delta\theta}\right)^2\right] \frac{exp[jk(R+R_{inc})]}{R} \quad (3)$$

In equation (3) the following constants have been used, considering the salt as the target medium: $E_0 = 10^{19}\, eV$ – the energy of the particle; $\varepsilon_1 = 6 + j \cdot 10^{-3}$ – the relative permittivity of salt; $\varepsilon_2 = 1$ – the relative permittivity of air; $k_D = 14.95$; $k_L = 21.12$; $k_R = 1.33$; $R_M = 12.09\, g/cm^2$; $\rho = 2.05\, g/cm^3$; $c_0 = 3 \cdot 10^8\, m/s$ – the speed of light in vacuum; $X_0 = 22.16\, g/cm^2$. The refractive index of salt is $n = \sqrt{\varepsilon_1}$, the Cherenkov angle is $\theta_c = \cos^{-1}\left(\frac{1}{|n|}\right)$, the wavelength is $\lambda = \frac{c_0}{nf}$, and the wave number $k = \frac{2\pi}{\lambda}$. It has also been considered that:

$X = \frac{k_R R_M}{\rho}$ (4),

$f_L = \frac{\rho}{k_L X_0} \frac{c_0}{|1 - n\cos\theta|}$ (5),

$\Delta\theta = \frac{c_0}{f} \frac{\rho}{k_D X_0} \frac{1}{\sqrt{n^2 - 1}}$ (6)

3 The transmitted field in air

It shall be considered that the field generated by the cosmic particle in salt (medium 1) passes in air (medium 2), as described in figure 3. Several phenomena will affect the propagation.

The next step is to calculate the transmission coefficient. The reflection coefficients are initially determined; they are used to determine the transmission coefficient T and afterwards the electric field E_2 determined by the cosmic particle in air [7]:

$\rho_\perp = \frac{\sin\theta_1' - \sqrt{\frac{1}{\varepsilon_1} - \cos^2\theta_1'}}{\sin\theta_1' + \sqrt{\frac{1}{\varepsilon_1} - \cos^2\theta_1'}}$ (7),

$\rho_\parallel = \frac{\frac{sin\,\theta_1'}{\varepsilon_1} - \sqrt{\frac{1}{\varepsilon_1} - \cos^2\theta_1'}}{\frac{sin\,\theta_1'}{\varepsilon_1} + \sqrt{\frac{1}{\varepsilon_1} - \cos^2\theta_1'}}$ (8),

$R_\perp = \rho_\perp^2$ (9),

$R_\parallel = \rho_\parallel^2$ (10),

$T = \left[1 - \left(\frac{R_{\perp} + R_{\parallel}}{2}\right)\right] \frac{\cos\theta_1'}{\cos\left(\sin^{-1}\left(\frac{\sin\theta_1'}{Re\{n\}}\right)\right)}$ (11),

$E_2 = TE_1$ (12)

Using the laws of refraction, the angles will change according to Snell's law as:

$\theta = \sin^{-1}\left(\frac{\sin\theta_1'}{Re\{n\}}\right)$ (13),

$\phi = \phi_1' - \pi$ (14)

4 Voltage recorded by antennas

Simple ideal dipoles have been used in the simulations. The length of the dipoles was considered to be l = 93.75 cm (considering the frequency f = 160 MHz, and our antenna being of length equal to half the wavelength).

The Vector Effective Length ($\overrightarrow{VEL}$) component of the antenna is calculated using the typical formula [8]:

$VEL_\theta = j\frac{2c_0}{I_0 Z_0 f} E_\theta$ (15), where E_θ is calculated for a dipole antenna as in [9]

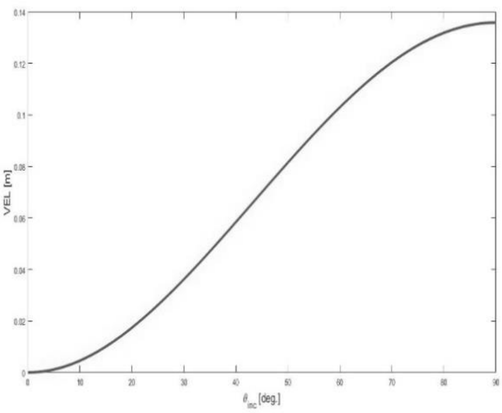

Fig.4 Vector Effective Length plotted versus θ_{inc} angle

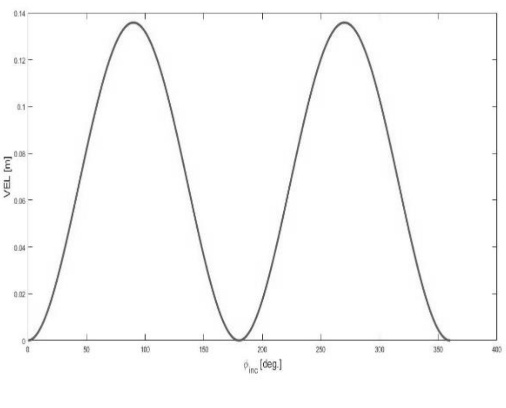

Fig.5 Vector Effective Length plotted versus ϕ_{inc} angle

In formula (15) I_0 represents the current (considered to be 1A), Z_0 is the antenna's impedance (considered to be 50Ω) and c_0 is the speed of light in vacuum and was mentioned earlier in the article. These figures have been used in the simulations.

In the end, the voltage recorded by each antenna is calculated with the formula [10]:

$V = \overrightarrow{E_2} \cdot \overrightarrow{VEL}$ (16)

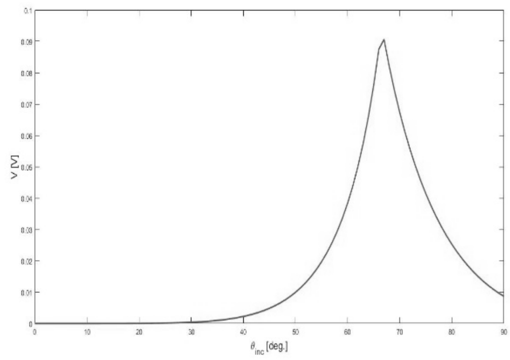

Fig.6 The voltage plotted versus θ_{inc} angle

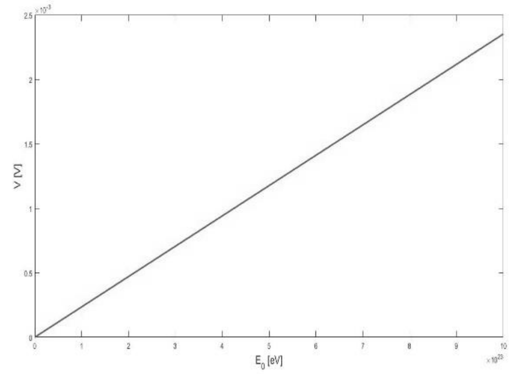

Fig.7 The voltage plotted versus the elementary energy of the particle E_0

5 Conclusions

First of all, it is noticeable from figure 4 that the Vector Effective Length of the dipole tends to rise while the angle θ_{inc} varies from 0 to 90 degrees. Second of all, figure 5 implies that the angle ϕ_{inc} has no influence over the way that the antenna acts, most of all because of the antenna's behavior which has a null component in the ϕ_{inc} direction and also because of the electric field in salt which does not depend whatsoever on the ϕ_{inc} angle (formulas (1), (2) and (3) are edifying concerning this matter).

Regarding the voltage of the antenna, figure 6 shows a slow rise, before a spike in voltage near the Cherenkov angle ($\theta_c \cong 66°$) and afterwards it steeply declines.

Figure 7 implies that the voltage has a nearly perfect linear dependency on the energy of the particle (which in this case varies from 10^{18} eV to 10^{24} eV) whilst the angles are constant ($\theta_{inc} = \theta_c \cong 66°$ and $\phi_{inc} = 135°$). This behavior is normal, considering that E_0 only intervenes in formula (3).

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