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CONSIDERATIONS ON A LARGE SCALE NEUTRINO DETECTOR IN A SALT DOME*

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Abstract. 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. In the end we calculate a single receiver effective volume.

Key words: Electromagnetic shower, salt, UHE cosmic neutrinos.

1. INTRODUCTION

Over the past few decades the astronomical community has become increasingly interested in the subject of particle astrophysics. Observations have confirmed that the universe is continuously hit by highly energetic atomic nuclei collectively known as cosmic rays [1–4].

Recently particle astrophysics has begun to look for a different particle: the neutrino. Neutrinos carry the same information about the regions of the universe where the cosmic rays were formed because they are produced in the same nuclear reactions. 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 [5].

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Below the 10^{16}eV threshold, neutrinos are detected by optical Cherenkov telescopes. Above this limit, the best performances of detection can be achieved using radio technologies. Acoustic technology looks also promising.

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 [6]. The debris, consisting of an electron or hadrons depending on the neutrino type and mediation boson involved, produces a shower within the detector. Several new neutrino detectors were planed and are now being built [7–10].

As a result of Askaryan effect [11] 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 [12–15]. According to [16], the radiation is coherent and the electric field is proportional to the negative charge in the cascade. The power of radio emission grows as the square of the energy of the shower.

This paper is structured as follows: in Section II we present briefly the basic structure of the detector and in Section III we analyze the characteristics of the radio signal on its propagation from the site of the shower to the antenna. We study the pulse at the input of a realistic receiver and the behavior of the key instrument - radio antenna - in Section IV. Signal-to-noise ratio (SNR) limiting situations are presented in Section V while Section VI deals with the effective volume of a single receiver. Last section summarizes our main results.

2. BASIC GEOMETRY OF THE DETECTOR

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.

As presented in [17], we decided to select the operating frequency of 187.5 MHz and to keep the distance between antennas around 2 m in order to avoid mutual coupling. Each receiving antenna is followed by a bandpass filter to select the spectral components and two low noise amplifiers. The output is recorded in a control center.

The control center must include circuits for hardware triggering, digitization and modulation. After a hardware and a software trigger, the signals from the four receiving antennas are multiplexed and transmitted to surface for further processing. Software triggering is used for elimination of false events. In the end, signals from all antennas are correlated for event reconstruction.

Following [18–20], the detector configuration consists of strings with multiple RS. The pulse generated by the shower is a ring-shaped structure that propagates along the surface of a cone defined by the Cherenkov angle for the medium. On its way it meets the RSs that measure its characteristics. All data collected from all antennas is used to fit the energy and direction of the primary particle.

The RS spacing and also the distance between strings is given by the minimum neutrino energy to be detected, structure of the shower (given by the neutrino type) and the height of the dome. For best performances, other factors should be included in optimization programs, like: antenna characteristics, medium properties, signal to noise ratio etc. A symmetrical structure in the xOy plane would decrease the processing time.

3. CHARACTERISTICS OF THE RADIO PULSE AND PROPAGATION EFFECTS

We will consider the parameterization of the coherent radio pulses from showers given in [21], which allows us to predict the properties of radio pulses in different media without performing time-consuming Monte Carlo GEANT4 simulations. This is valid for frequencies typically below 10 GHz (at which condition for the far-field response is met – [22]. For this parameterization, the closer the observation angle is to the Cherenkov angle, wider the pulse gets, making it much easier to detect. The amplitude also increases.

The coherent waves will propagation in salt so according to [23] we can expect no scattering effects and depolarization phenomena. On the other hand, both real and imaginary parts of the permittivity are temperature and frequency dependent [24].

As we have performed no measurements of the properties of salt yet, we will assume a homogeneous, nondispersive media characterized by a dielectric constant of $\varepsilon_1 = 6 + i10^{-3}$. We have chosen this value for permittivity because studies carried out by [25] have shown that salt has a dielectric constant in the 5–7 range at 300 MHz.

The imaginary part of the permittivity is a measure of the absorptions in the medium. The absorption coefficient is given by [19].

The second propagation phenomenon to consider are reflexions at separation borders between dielectrics. We will assume that the boreholes that contain the antennas are filled with air. This way, the electromagnetic radiation from showers travels first in the salt medium and only a fraction of it will cross the interface of separation between the two media (salt/air) while the rest will be reflected backwards and regarded as loss.

For unpolarized incoming radiation, the ratio of the transmitted to incident field from salt to air is given in [26]. If $\varepsilon_1 = 6 + i10^{-3}$, we calculated $T = 0.7846$.

4. ANTENNA CHARACTERISTICS

Knowledge of antenna behavior is very important especially as in Ultra Wide Band (UWB) systems conventional methods for characterizing the antenna prove limiting. The need of UWB system is given by the broad band type of the Cherenkov pulse spectrum. In such systems, the antenna acts like a filter so a transfer function must be associated with it [27].

The antenna transfer function is the ratio of the antenna output voltage V_{rec} to the E-field at the antenna $|E_{ant}|$. Its dimension is a length, the so-called effective antenna 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_a – the angle of incidence with respect to the normal (broadside) of the antenna. For more details see [17].

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 V_L.

One can see in Fig. 1 that 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 $\theta_a = 90$ deg. An increase in the primary particle energy with a factor of 100 is producing a voltage that is one order of magnitude higher.

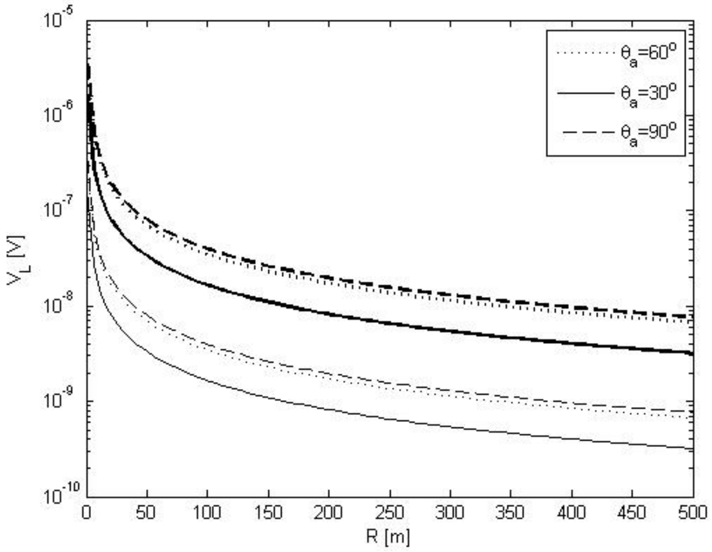

Fig. 1 – The voltage delivered to the receiver as function of the distance between antenna and the shower for a primary particle energy of 10 PeV (thinner lines) and 100 PeV (thicker lines) for three incoming angles: 30° (continuous lines), 60° (dotted lines) and 90° (dashed lines).

5. SIGNAL TO NOISE RATIO LIMITATIONS

After calculating the voltage delivered to the receiver system, we must investigate the problem of the possibility of detecting the signal under noise.

Detection of known signal in a white Gaussian noise background is a standard problem of signal processing and is maximized in the sense of maximizing the signal to noise ratio by use of a matched correlation receiver. In [28] it was suggested that:

$$\mathrm{SNR}^2 = \frac{2}{kT_n}\left(\int_{-\infty}^{\infty} \left|V_L(f)\right|^2 \mathrm{d}f\right)^2 \Bigg/ \int_{-\infty}^{\infty} \left|V_L(f)\right|^2 R_L(f)\mathrm{d}f \qquad (1)$$

where R_L is the resistive component of the load impedance Z_L and T_n – the system temperature.

We have assumed a system temperature of 450 K (based on a temperature of about 310 K for the salt and a receiver noise temperature of 140 K, 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).

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. For an observation angle equal to the Cherenkov angle, the threshold energy is given in Table 1 for two SNRs. The values are dependent on the distance R between shower and antenna and on the angle of incidence with respect to the normal (broadside) of the antenna θ_a.

Table 1

Minimum energy that can be detected by a dipole antenna for given SNRs

$\theta_a [^o]$	R [m]	E_{thres}[eV] (for SNR = 5)	E_{thres}[eV] (for SNR = 1)
30	100	$1.32\cdot10^{17}$	$6.28\cdot10^{16}$
30	500	$1.02\cdot10^{18}$	$4.86\cdot10^{17}$
60	100	$2.31\cdot10^{17}$	$1.09\cdot10^{17}$
60	60	$7.56\cdot10^{17}$	$3.59\cdot10^{16}$

We plotted the variation of SNR with the distance between shower and antenna for θ_a = 60 deg. (Fig. 2). One can see that 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 6 m (for an imposed SNR equal to

5) and less than 16 m if SNR=1 (the Glashow resonance can be observed only if $R < 1$m when SNR = 5 and at $R < 11$m when SNR = 1). The minimum distance becomes much larger at higher energies (at 10^{17}eV, $R = 80$ m respectively 187 m for a SNR equal to 5, respectively 1).

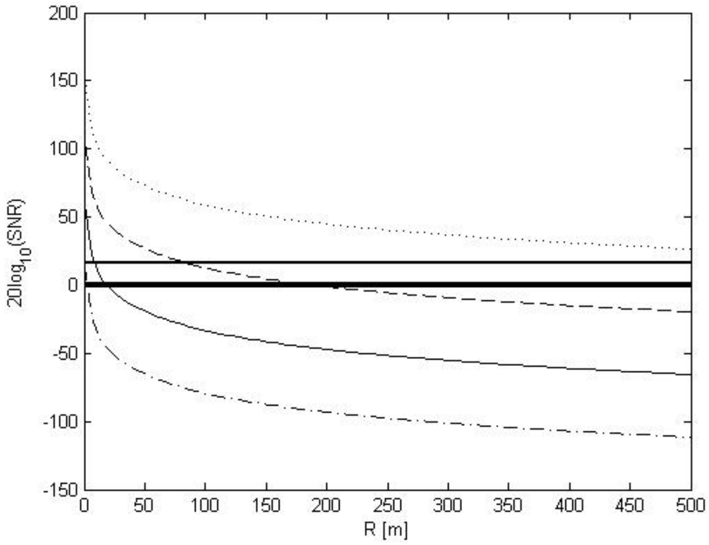

Fig. 2 – The signal to noise ratio as function of the distance between the shower and the antenna for different energies of the primary neutrinos: with a dash-dotted line was represented an energy of 10^{15}eV, with continuous line - an energy of 10^{16} eV, with a dashed line an energy of 10^{17} eV and with a dotted line an energy of 10^{18}eV. The two vertical lines represent the dB representation of a SNR=5 (thin line) and a SNR=1 (thick line).

6. EFFECTIVE VOLUMES

An effective volume for events with energies of primaries E_0 and incident direction θ is defined by [28] as the collection of potential shower positions that satisfies a signal to noise ratio greater than a given value (we have fixed $\theta = \theta_C$).

For each variable position of the electromagnetic shower, the sensitive detector is an ellipse with the major axis parallel to the dipole antenna (maximum distance is reached as expected when θ_a=90 deg. – Fig. 3). Its value is given by the signal to noise ratio condition and the angle relative to the antenna. Each combination of E_0 and θ has its own ellipse shaped volume that is the effective volume of the receiver for a particular energy and flux direction. At energies of 1 EeV, the region that can be detected by antennas extends for more than 1 km from the antenna.

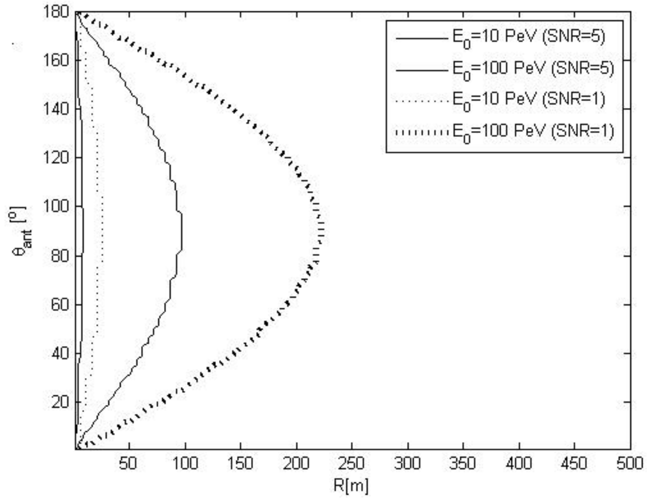

Fig. 3 – Sensitive volume for events with energies of primaries E_0 and incident direction $\theta = \theta_C$. The contour indicate SNR = 5 (continuous line) and SNR = 1 (dashed lines) for energies of 10 PeV and 100 PeV with the incoming direction fixed $\theta = \theta_C$.

For each energy of the primary, the total volume of one detector is obtained by rotating the ellipse around the *Ox* axis. The volume that one antenna can 'see' reaches tens of cubic kilometers at the highest energies (Fig. 4). This effect of the overall very large, km-scale detection volume will compensate for the small neutrino cross sections and the small expected fluxes of high-energy cosmic neutrinos.

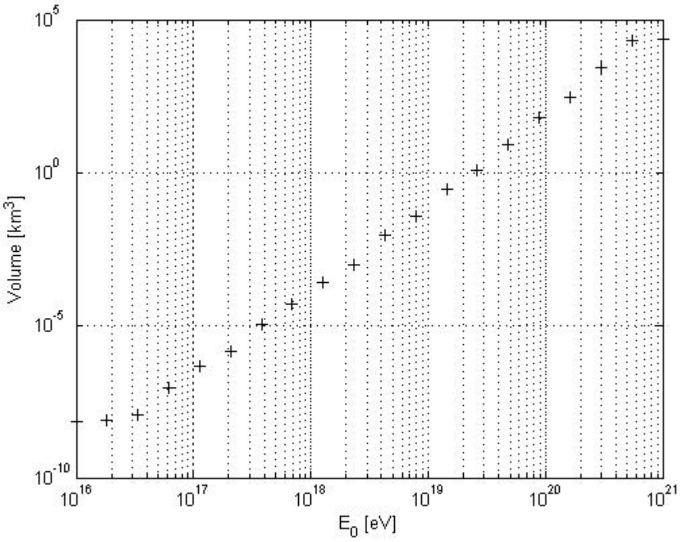

Fig. 4 – Total volume that an antenna can observe as function of the energy of the primary particle.

7. CONCLUSIONS

In this study we investigated the performances of a radio Cherenkov neutrino detector in natural salt. We presented the basic structure of the detector and we analyzed the characteristics of the radio signal on its propagation from the site of the shower to the antenna. We also studied the pulse at the input of a realistic receiver. The behavior of the key instrument – radio antenna – was briefly characterized and signal-to-noise ratio (SNR) limiting situations were also presented.

In this configuration, the Glashow resonance can be observed only if the distance between the shower and antenna is less than 11 m, but only if reconstruction of the pulse is possible with a SNR equal to 1. One has to keep in mind that our analysis included the behavior of the antennas that in this case where considered to be simple dipoles. Other more performant types (as broadband conical ones) will lead to much better performances.

At higher energies of the primary particles, detection of the showers is possible at larges distances (e.g. for a particle of 10^{17} eV, detection of radiation is possible 80 m away from the shower when SNR = 5, respectively 187 m when SNR = 1).

Due to this limitation, detection of neutrino induced radio electromagnetic radiation becomes feasible only if the geometry of the detector guarantees separation between RS smaller than 80 m. From the value imposed on the SNR we concluded that only particles with energies higher than 100 PeV can be detected in this configuration.

Our results show poorer performances than the ones presented in related work. The main reason to that is, as already discussed, the antenna behavior. More to that, other propagation effects that lower the electromagnetic field amplitude (like absorptions and reflections) have been included here.

The volume that only one receiver operating at 187.5 MHz can sense is at an order of km^3 for particles with energies of 10^{19} eV. For lower primary energies, just a few receivers will be enough to cover for the same volume. This number indicates that enormous target masses for ultra high energy neutrinos are feasible using radio as detection mechanism.

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