Sensitivity estimates of the TREND radio detection array to Ultra High energy cosmic neutrinos


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Abstract: The Tianshan Radio Experiment for Neutrino Detection (TREND) is a radio array performing the autonomous detection of Extensive Air Showers (EAS). It is being deployed at 2700m asl on the site of the 21CMA radio-interferometer, in a remote valley of the Tianshan mountain range (XinJiang province, China). This site benefits from excellent radio conditions, the Galactic plane emissions being the dominant background source in the 25-200MHz frequency range, and is surrounded by high mountains, peaking at 5 km asl. This topology could be very well suited for the detection of cosmic tau neutrinos of ultra high energy, through the observation of the nearly horizontal EAS generated by the decay in the air of the converted tau. In this work, we present prospective studies of TREND’s sensitivity to such cosmic neutrino fluxes. As a compromise between accuracy and speed, the simulation chain relies on a dedicated hybrid Monte-Carlo scheme for the propagation of the $\tau$ through rocks, rendering energy loss fluctuations. Various antenna array layouts are considered.

Keywords: Ultra High Energy Neutrinos; Radio Detection.

1 Introduction

The search for high energy (HE, $E > 10^{12}$ eV) neutrinos of cosmic origin is extremely challenging. The expected astronomical fluxes are low [1], and since neutrinos are purely weak interaction particles their cross section with matter is extremely small even at the highest energies [2]. However, if detected, the same purely weak interacting nature allows probing the very distant Universe, in the light of neutrinos. Various detection techniques have been considered over the last decades with a particular interest in Ultra High Energies (UHE, $E > 10^{18}$ eV), where the transferred energy to the medium becomes macroscopic, allowing for new detection means [3]. In the present work we focus on one of these prospective techniques, exploiting the coherent radio emission of extensive air showers (EAS), enhanced in the Earth geomagnetic field.

At UHE, tau neutrinos converting to $\tau$ leptons in rock can initiate EAS. Indeed, at those energies the $\tau$ lepton is long lived enough such that it can escape the rocks and disintegrate in the Air. However, this scenario is viable only in the case of Earth-skimming neutrinos with intercepted rock depths of 10-100 km. For downward going neutrinos, the atmosphere is not deep enough to allow neutrino conversion, while for upward going trajectories the $\tau$ disintegrates in the rock. Therefore the induced EAS will develop following a quasi-horizontal trajectory. The recently developed radio detection tech-
nique [4, 5] is potentially an efficient way to detect such EAS, since antenna detectors are able to detect radio emission even at large zenith angle. Nevertheless, quasi-horizontal EAS developing in a constant atmosphere density have never been studied experimentally until now since most of the radiodetection arrays are particle-triggered experiments which usually limit the detectable EAS to zenithal angle under 60°.

The TREND experiment is a self-triggering radio detection experiment deployed since 2009 in the Ulastai valley (Tianshan Mountains, Xinjiang autonomous province, China). The complete setup of the experiment is described in another proceeding of this conference [6], but as a self-triggering experiment using omni-directional antennae, TREND is designed to detect EAS coming from all zenithal angle, including the horizon. Moreover, the Ulastai valley is surrounded by high mountains, offering an additional target for neutrino interaction, as well as shielding for high zenithal angle EAS induced by cosmic ray particles. Thanks to its remote location in high altitude (2650m a.s.l.), the experiment site finally offers a thunderstorm free area [7].

For all these reasons, TREND can be considered as a perfect opportunity to estimate the potentiality of high energy neutrino radiodetection.

The purpose of this work is to provide an end-to-end estimation of the TREND sensitivity to cosmic neutrinos, starting from a τ neutrino down to the electric signal recorded at output of the TREND electronics. The computation is divided in two main steps. First, we consider the neutrino converting to τ in rocks, escaping the latter and decaying in air. For this we rely on a dedicated Monte-Carlo simulation scheme analogous to the one developed by the Pierre Auger Observatory in [8]. The simulation is based on a C++ high level layer embedding standard FORTRAN algorithms. The specific topology of the Ulastai valley as well as the Earth curvature is taken into account.

The second step is purely analytical, and was numerically implemented in MATLAB. Candidate τ decays are selected from this simulation and the radiated electric field from the resulting EAS is estimated on the basis of the MGMR radio emission model [9, 10]. The simulated antenna response as well as the measured response of the whole electronics chain allows the computation of the output antenna signal. Furthermore, the electromagnetic background level measured on site is taken into account in order to determine a realistic trigger condition on these EAS.

2 Sensitivity Computation

2.1 Monte-Carlo simulation scheme: from the neutrino to the EAS

The simulation chain is subdivided in C++ packages handling the geometry and physics of the interactions. Concerning the geometric description of the rocky detector medium, the detailed topology of the site is modeled according to the data published by the NASA SRTM survey [11]. The data point cover a grid of ~90 m steps out of which we selected an area of 200×200 km², centered on the TREND setup. We assume standard rock composition [12] over the whole area with an average density of 2.65 g/cm³. The Earth curvature is taken into account by using a Cartesian coordinate frame throughout the whole simulation. The altitude profile is deformed consequently according to the local vertical direction. Candidate neutrinos are injected at the boundaries of the simulation medium, targeting the TREND region. Whenever a neutrino trajectory starts in rocks, it is back-propagated to the atmosphere.

The simulation of the physics starts with the neutrino interaction in rocks. Interactions length for both Charged Current (CC) and Neutral Current (NC) interactions are randomized according to the integrated cross-sections from [2]. The dynamics of the interaction, and consequently the inelasticity, are delegated to PYTHIA. We use PYTHIA 6 [13] together with CTEQ5D (DIS) partons distribution functions from “Les Houches Accord PDF” (LHAPDF). The native FORTRAN code was interfaced to the general simulation scheme as an independent package by embedding it in a C++ layer. The neutrino is further tracked down until (1) its energy falls below a threshold of $E_{\text{min}} = 10^{15}$ eV from NC interactions; (2) it escapes the simulation medium or (3) it converts to a τ lepton by CC interaction.

The proper lifetime of newborn τ leptons is first randomized out of an exponential distribution. Then, the τ is propagated through rock and air until (1) it lives its whole lifetime as computed in its rest frame and disintegrates; (2) its energy falls below the threshold, or (3) it escapes the simulation medium. The τ energy loss and proper time spent in rock are simulated with a hybrid Monte-Carlo scheme based on parameterizations of statistical distributions obtained from detailed simulations with GEANT4 [14]. This method allows rendering fluctuations in energy loss while being fast enough. At UHE, photonuclear interactions are the dominant energy loss process for τ lepton. It was coded in GEANT4 following [15]. The other processes considered are multiple scattering, pair production and bremsstrahlung. Due to the large τ mass, they however contribute to lesser extent than photonnuclear reactions.

We define the energy loss factor, $t_{\tau}$, and proper time loss factor, $\tau_{\tau}$, as:

$$E(d) = E_0 e^{-d/\tau_\tau},$$

$$t_\tau(d) = d/c_0 e^{-d/\tau_\tau},$$

where $E_0$ is the initial energy of the $\tau$, $E(d)$ its energy at a depth $d$ in the rocks and $t_\tau(d)$ the proper time spent in its rest frame. We write $c_0$ the speed of light in vacuum and $\tau_\tau = E_0/m_\tau$ the initial boost of the $\tau$. For travelled depths shorter than 60 km, the energy loss factors obtained from GEANT4 distributions where found to be gamma distributed, as illustrated in Figure 1. The distribution parameters $a$ and $b$ for a normalized gamma distributions are taken as:
\[ \gamma(x,a,b) = \frac{b(hx)^{a-1}e^{-hx}}{\Gamma(a)} \]

(2)

Figure 1 – Loss factors for a \( \tau \) of primary energy \( 10^{19} \) eV at a rock depth of 10 km. Dots are GEANT4 simulation results. The solid line stands for the fit of the energy loss factor by a gamma function while the dotted one is for the fit of the proper time factor.

They depend on the initial \( \tau \) energy, \( E_0 \), and the length, \( d \), traveled in the rocks. Furthermore the two loss factors distributions are almost 100% correlated. Consequently, the hybrid simulation scheme resumes to the drawing of a single number out of a gamma distribution in order to randomize both the energy loss and proper time spent by the \( \tau \) lepton as it reaches a depth \( d \) in the rocks. For rock depths larger than 60 km this procedure is repeated iteratively by slicing the path in steps of 60 km. Whenever the \( \tau \) proper lifetime reaches zero or less within the rocks, a decay vertex is set following [17]. Finally, the additional factors \( f_\tau \) of electrons and positrons in the shower, from which the 3 source terms are derived. We model \( f_\tau \) by a gamma function, following [17] with parameters and normalization taken according to averaged air shower simulation results for primary protons. Those are in agreement with recent measurements considering uncertainties on the extrapolation of hadronic models [18, 19]. Averaging over QGSP-II, SIBYLL 2.1 and EPOS 1.99 we consider \( X_{\text{max}} = 158 + 27.5 \ln(E) \) and \( N_{\text{max}} / E = 0.47 \cdot E^{0.0142} \), where \( X_{\text{max}} \) is in unit g cm\(^{-2}\) and \( E \) in GeV. The longitudinal distribution peak value is normalized to \( N_{\text{max}} \) and we further set \( b = 0.53 / X_0 \) which is consistent with simulated air shower profiles in the PeV to EeV energy range. The parameter \( a \) falls as

\[ a = b X_{\text{max}} + 1. \]

The transverse drift distance, \( x_d \), and drift velocity, \( v_d \), at a given shower age are computed following [8], as:

\[ x_d = \frac{C}{e_0} \frac{1}{\langle K \cdot L \rangle} \]

\[ v_d = \frac{C}{2} \frac{1}{\langle K \cdot L \rangle} \]

with \( K = eB/(\beta m_\tau) \) and \( L = \gamma(\gamma^2 + \gamma_0^2)X_0 / \rho \), where \( X_0 = 367 \) g cm\(^{-2}\) is the radiation length in air and \( \rho \) the local air density. The air atmosphere was modeled according to data from [20] with mid-latitude winter conditions. The magnetic field at Uluistai is \( B = 56.5 \) \( \mu T \) oriented North and making an angle of 26° with the local vertical. We further recall that the averages in Eq. 3 run over the energy distribution of electrons and positrons in the shower with spectrum modeled following [21]. The factor \( \gamma_0 = 13.6 \) MeV/m, \( c_0 \), rendering multiple scattering, is set following [17]. Finally, the additional factors \( C_{x} = 6.7 \) and \( C_{v} = 0.6 \) are tuned in order to reproduce the results of [9] for the quoted conditions. Note that the latter relies on Monte-Carlo description of the source terms from shower simulation. We achieve agreement on electric field amplitude within 10% which is satisfactory considering uncertainties introduced by the shower profiles and atmosphere model. Further assuming a pancake thickness of \( L_\rho = 3.9 \) m [22] we get a 10-20% agreement with [23].

The charge excess source term was parameterized according to [22]. We get perfect agreement with results shown in [10, 23] without any tuning. Collecting all terms, Figure 2 shows the expected electric field for a \( 10^{19} \) eV horizontal shower developing at 200 m above TREND, at various observation depths down the shower axis. It can be seen that for a given distance to the shower

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axis the signal strength actually increases as one gets farther from the shower start, along the shower development direction. This result, which is a priori counter intuitive, results from the fact that the unfiltered radio emission is strongly collimated in the forward region due to the strong Lorentz boost of emitters. Hence, the signal strength is dominated by the angular aperture from which an observer sees the shower axis.

Comparison of various radio antenna designs is beyond the scope of this work. We performed our study with the antennas presently used by TREND, and inspired by the so-called "Butterfly" antennas designed by CODALEMA [24]. The detailed response of theses antennas is simulated with EZNEC, assuming a system bandwidth of 25-250 MHz, and is used to estimate the EAS induced voltage at antenna level. The signal at acquisition level is determined according to the system frequency response, and the standard triggering condition used in TREND (signal amplitude higher than a multiple of the average noise standard deviation) is finally applied. If 5 antennas or more trigger on the shower, the simulated event is considered as a neutrino radio candidate.

**References**