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Sensitivity estimates for an underwater acoustic neutrino telescope

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We present a Monte Carlo study of an underwater neutrino telescope based on acoustic detection, providing a promising approach to instrument the extremely large detector volumes needed to detect the small flux of cosmic neutrinos at ultra-high energies ($E \gtrsim 1\,\mathrm{EeV}$). Based on the thermo-acoustic model, the acoustic signature of neutrino-induced ultra-high energy cascades inside various detector setups can be simulated. Sensitivity estimates for the diffuse neutrino flux are presented.

1. Introduction

Among the ultra-high energy neutrino sources predicted by various theoretical models, a guaranteed one appears to be the GZK neutrinos [1, 2] originating from the interaction of cosmic ray protons ($E_p \gtrsim 50\,\mathrm{EeV}$) with the cosmic microwave background. Due to the smallness of these fluxes very large target masses are needed to detect them. Current (AMANDA, BAIKAL, ANTARES, NESTOR, ...) and next-generation km^3 size (IceCube, KM3NeT) water Čerenkov neutrino telescopes do not have sufficient fiducial volume to detect GZK neutrinos. Their affordable size is limited by the attenuation length of light in water or ice which determines the spacing between optical sensors.

In 1957 G.A. Askariyan described a hydrodynamic mechanism of sound generation for charged particles propagating through water [3] which can be exploited for an acoustic neutrino telescope. Neutrinos interacting in water produce a particle cascade which locally heats the medium and leads to fast expansion, giving rise to a shock wave which propagates perpendicular to the cascades axis as a bipolar acoustic signal. This unique disc-shaped event signature allows for good direction reconstruction and background suppression. The thermo-acoustic model has been verified in the laboratory several times and with high precision [4, 5, 6]. Utilising the fact that, for the frequencies considered, the sonic attenuation length in water is about ten times larger than the optical attenuation length, much larger volumes could be instrumented with the same number of sensors, thus allowing for the detection of the small neutrino fluxes at highest energies.

In the next section we describe the simulation chain used for studying acoustic neutrino telescopes. This includes the development of the cascade, the propagation of the acoustic signal through the water to the sensor, the detection of the signal taking into account a background-induced detection threshold and the reconstruction of the cascade direction and energy. After that, sensitivity estimates for an acoustic detector are derived.

2. The Monte Carlo chain

For the simulation an isotropic flux of highest-energy neutrinos ($10^8\,\mathrm{GeV} < E_\nu < 10^{16}\,\mathrm{GeV}$) is generated. Equal numbers of neutrinos are produced in each energy bin of constant width in $\log E$, with a given energy spectrum following a power law (E^{-2}) in each E bin. It is assumed that all neutrinos from above can propagate freely down to the detector. On the other hand, the earth is assumed to be opaque for all neutrinos coming from below the horizon. The distribution of the kinematic variable y describing the energy transfer from the neutrino to the hadronic final-state system is taken from the ANIS neutrino interaction simulator [7]. The median of this distribution is about 0.06, i.e. in 50% of all interactions the hadronic system takes less than 6% of the neutrinos energy. However, since the energy density, and thus the acoustic signal, produced from electromagnetic cascades is supposed to be much lower due to the LPM effect (the LPM threshold in water is at about 10^7 GeV), and there is no reliable shower simulation including the LPM effect in water so far, the leptonic branch of all neutrino interactions is discarded, even for electron-neutrino charged-current interactions. The sensitivities presented in this work may increase when this leptonic branch is included.

The three-dimensional cascade development and energy deposition were studied with GEANT4 [8] up to primary hadronic energies of 100 TeV using the QGSP interaction model. It can be seen that the shape and the spatial extension of the energy distribution vary only slightly with the primary energy. Therefore, they are assumed fixed for all energies, and the energy density scales linearly with the energy of the hadronic system. This energy distribution and the thermodynamic parameters (volume expansion coefficient, heat capacity and sound velocity) of water are then used as an input to the thermo-acoustic model which gives the acoustic signal for every sensor position and time, where the amplitude of the bipolar pulse only depends on the cascade energy. Sonic attenuation in sea water is strongly frequency dependent, where the attenuation length for the typical signal frequency of approx. 20 kHz is 1 km (compared to 50 – 70 m optical attenuation length relevant for water Čerenkov neutrino telescopes). It is accounted for by applying a FFT to the acoustic signal at a given sensor distance and using the frequency dependence of the attenuation from [4]. Figure 1 shows the parametrisation of the amplitude of the bipolar signal as a function of position used to determine the sensor response for a given hadronic cascade.

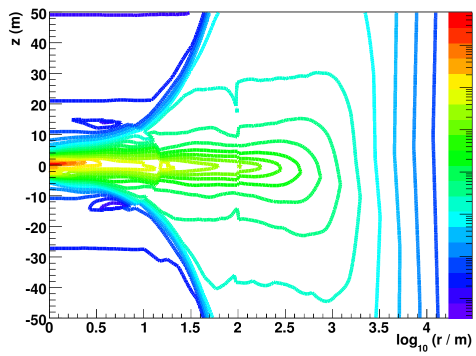


Figure 1. Parametrisation of the amplitude of the sonic field for a hadronic cascade centred at the origin. The cascade has a length of approx. 15 m and develops in positive z direction. The colour coding gives the amplitude in $\mathrm{mPa/EeV}$.

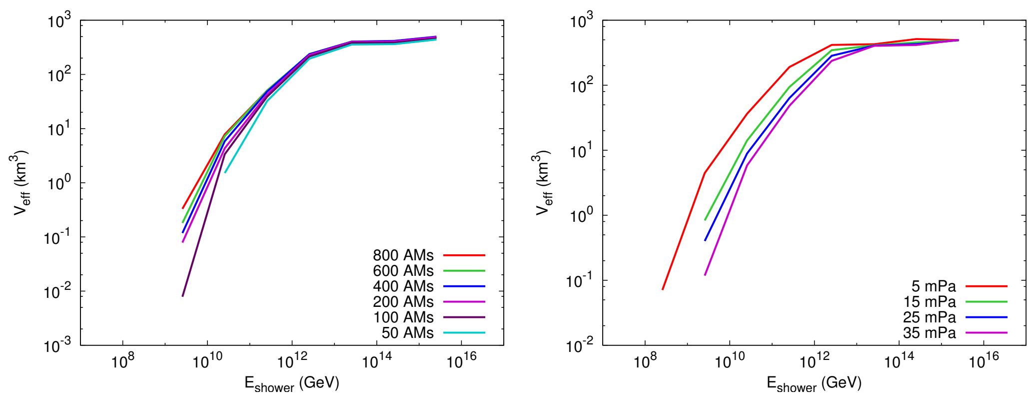
The smallest unit of the simulated acoustic detector is an "acoustic module" (AM) which is a device that can detect bipolar acoustic signals above a given detection threshold, p_{th}, determined by the background noise in the sea. Such an AM might be realized as a local array of hydrophones allowing the suppression of background with short correlation length. According to [9], for a single hydrophone a threshold of $35\,\mathrm{mPa}$ has to be used if one allows for one false signal in 10 years at a five-fold coincidence. Using AMs with multiple hydrophones should allow to lower this threshold to approx. $5\,\mathrm{mPa}$.

Our detector consists of AMs that are arranged randomly inside the instrumented volume in order to avoid geometrical effects on the sensitivity estimates. Neutrino events are generated homogeneously and with 2π sr angular distribution in a volume with a height of 2.5 km (corresponding to typical depths in the Mediterranean Sea), and a radius of 10 km; the resulting generation volume will be denoted by $V_{\mathrm{gen}} = 785\,\mathrm{km}^3$. Each AM records the arrival time and amplitude of the signal if it is above the threshold p_{th}. An event is triggered if four or more AMs detect a signal. For our study a timing resolution of 10 μs (100 kHz sampling frequency), a positioning accuracy of 10 cm for the AMs and an amplitude resolution of 2 mPa are implied, which are all realized by Gaussian smearing.

The shower reconstruction is performed in two steps. First, the shower position is reconstructed by minimisation of the residuals of the arrival times assuming an isotropic sonic point source (which is a valid assumption since the typical inter-AM distance is large compared to the shower extension). With this method the position can be reconstructed with a RMS of 14 cm in each Cartesian coordinate. Based on this position and the parametrisation of the sonic field (figure 1) the direction and energy of the cascade are reconstructed by minimising the amplitude residuals. Without applying any selection cuts the median of the direction error is $7°$ (where due to the direction ambiguity of the disc shaped signal direction errors $\Delta\alpha > 90°$ are accounted for as $180° - \Delta\alpha$). For some events the reconstruction seems to fail completely. The energy can be determined up to a factor of 3.

3. Sensitivity estimates

Based on the detector simulation chain presented above it is possible to derive sensitivity estimates for various detector configurations. We use the effective volume defined as $V_{\text{eff}} = \frac{N_{\text{reco}}}{N_{\text{gen}}} V_{\text{gen}}$ as a measure for the sensitivity of a detector, where N_{reco} is the number of reconstructed events without any selection cuts obtained from N_{gen} events generated inside the volume V_{gen}. Figure 2(a) shows the effect of varying the instrumentation density of the detector between 50 and $800\,\mathrm{AM/km^3}$. For densities lower than $200\,\mathrm{AM/km^3}$ the effective volume drops dramatically at lower energies, and the lower energy threshold rises for less than $100\,\mathrm{AM/km^3}$. In figure 2(b) the detection threshold p_{th} was varied at a constant instrumentation density of $400\,\mathrm{AM/km^3}$. With smaller p_{th} the lower energy threshold of the detector drops and the effective volume rises continuously.



(a) Influence of instrumentation density.

(b) Influence of threshold.

Figure 2. Effective volume V_{eff} of a $1\,\mathrm{km^3}$ detector as a function of cascade energy for (a) different instrumentation densities (threshold $p_{\text{th}} = 35\,\mathrm{mPa}$) and (b) different detection thresholds p_{th} (density $400\,\mathrm{AM/km^3}$).

Therefore it is essential for a future acoustic detector to have a pressure threshold p_{th} as low as possible, where the lower limit is given by the intrinsic background noise in the sea which is $\approx 1\,\mathrm{mPa}$ (sea state 0). On the other hand, a density of only $200\,\mathrm{AM/km^3}$ seems sufficient which allows to instrument very large volumes with only a few channels read out at low frequencies (100 kHz), leading to manageable data rates.

In figure 3 we show that, with a detector with $3 \cdot 10^5$ DAQ channels ($30 \times 50 \times 1\,\mathrm{km}^3$, $200\,\mathrm{AM/km}^3$, $p_{\mathrm{th}} = 5\,\mathrm{mPa}$), several theoretical models that predict neutrinos above $1\,\mathrm{EeV}$ could be verified within 5 years of runtime.

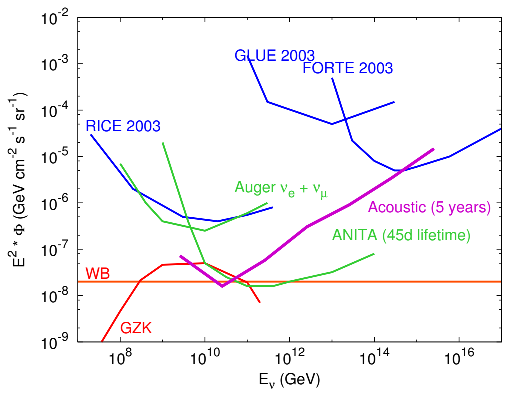


Figure 3. Flux limit derived from this work for a $30 \times 50 \times 1\,\mathrm{km}^3$ detector with a lifetime of 5 years. Red curves are theoretical models (extrapolated Waxman-Bahcall flux and GZK neutrinos from [2]). Blue curves are experimental flux limits; green curves are expected flux limits from future experiments.

4. Conclusions

Acoustic detection is a promising approach to detect cosmic neutrinos at highest energies. Detectors build of "acoustic modules" that can detect bipolar acoustic signals above $5\,\mathrm{mPa}$ are able to reconstruct neutrinos with energies above $1\,\mathrm{EeV}$ with as few as $200\,\mathrm{AM/km}^3$. This allows for the instrumentation of a volume of 10^3 – $10^4\,\mathrm{km}^3$, which is necessary to detect the small neutrino fluxes predicted by theoretical models within a reasonable measurement time.

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