Studies of Acoustic Neutrino Detection Methods with ANTARES

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Abstract

The emission of neutrinos within a wide energy range is predicted from very-high-energy phenomena in the Universe. Even the current or next-generation Cherenkov neutrino telescopes might be too small to detect the faint fluxes expected for cosmic neutrinos with energies exceeding the EeV scale. The acoustic detection method is a promising option to enlarge the discovery potential in this highest-energy regime. In a possible future deep-sea detector, the pressure waves produced in a neutrino interaction could be detected by a $\gtrsim 100$ km$^3$-sized array of acoustic sensors, even if it is sparsely instrumented with about 100 sensors/km$^3$. This article focuses on the AMADEUS set-up of acoustic sensors, which is an integral part of the ANTARES detector. The main aim of the project is a feasibility study towards a future acoustic neutrino detector. However, the experience gained with the ANTARES-AMADEUS hybrid opto-acoustic set-up can also be transferred to future very large volume optical neutrino telescopes, especially for the position calibration of the detector structures using acoustic sensors.

Keywords: UHECR, Neutrino detection, Acoustic detection method, ANTARES, AMADEUS

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1. Introduction

At ultra-high energies (UHE, $E \gtrsim 10^{18}$ eV), neutrinos are the only viable messengers beyond the “local” universe. Photons interact with the microwave and infrared background light. Protons suffer energy losses due to photoproduction of pions (GZK mechanism [1, 2]) and of $e^+e^-$ pairs; nuclei are additionally subject to photo-nuclear reactions. All these reactions confine undisturbed propagation of UHE cosmic rays to distances below 100 Mpc [3]. UHE neutrinos, on the other hand, are undisturbed and “guaranteed” by the GZK mechanism. The interaction rate of neutrinos originating from the propagation of UHE protons in 1 km$^3$ water equivalent has been estimated to be about 0.2 per year [4]. Consequently, target masses exceeding 100 km$^3$ are required to obtain a few neutrino events per year. Such detector sizes are not reachable with current technologies and new detection techniques have to be considered for the study of UHE cosmic neutrinos, e.g. the acoustic method discussed here.

The investigation of acoustic neutrino detection has historically evolved in the context of Cherenkov neutrino telescopes. The method was discussed in the 1970s within the DUMAND project [5]. Acoustic set-ups have been integrated in the framework of existing Cherenkov experiments in the 2000s: AMADEUS in ANTARES, ONDE in NEMO, SPATS in IceCube and acoustic test set-ups in the lake Baikal neutrino telescope [6]. A next step towards an acoustic neutrino detector could be the integration of acoustic sensors into a next-generation neutrino telescope like KM3NeT [7].

2. Acoustic Neutrino Detection

The acoustic detection method is based on the reconstruction of characteristic sound pulses that are generated by neutrino-induced particle cascades in water. The generation mechanism is described by the thermo-acoustic model [8, 9], which connects the energy deposition by the cascade particles to a local heating accompanied by an expansion of the medium. This translates into a pressure wave which propagates in a wave pattern of cylindrical symmetry through the medium, expanding in time perpendicular to the cascade axis. The thermo-acoustic signal is bipolar in time with a peak-to-peak amplitude of the order of 10 mPa per 1 EeV cascade energy at a vertical distance of 200 m from the cascade [10]. The peak-to-peak signal length is several tens of microseconds, resulting in a spectral energy density peaked at about 10 kHz.

The attenuation length of the sonic wave in sea water is of the order of 5 km (1 km) at 10 kHz (20 kHz), much longer than the one of the Cherenkov light used in optical detectors. A sensor density of the order of 100 sensors/km$^3$
is sufficient for event reconstruction in an acoustic detector. This density is driven by the geometry of the sound emission and not by the attenuation length. The simulated effective volume for an array of 200 acoustic storeys (cf. Sec. 4), randomly distributed in 1 km$^3$, reaches 1, 10 and 100 km$^3$ at 20, 60 and 600 EeV, respectively [11]. The effective volume for cascades of the 1 km$^3$-sized IceCube neutrino telescope with roughly 5000 optical sensors is $\approx 3$ km$^3$ at 1 EeV and rises by $\approx 0.15$ km$^3$ per decade in energy [12]. A direct comparison of these numbers is not fully justified as the first simulation is without quality cuts on the reconstruction of the acoustic wave and for a detector size that is comparable to the sound range and therefore unfavourable for acoustic detection. The numbers can, however, be regarded as a guideline. The breakpoint is at about 50 EeV, so below the EeV-scale an optical detector is more sensitive. At the EeV-scale a hybrid opto-acoustic detector could combine the advantages of both detection methods; in ice the radio technique could add to the sensitivity [13]. However, to measure neutrinos in water with energies beyond the EeV-scale an extremely large acoustic detector would be necessary.

In a hypothetical $\gtrsim 100$ km$^3$ acoustic detector, the signature of a neutrino-induced sound pulse has to be recognised in the abundant ambient acoustic noise; the noise level of the order of 10 mPa (at calm sea) in the frequency range of the acoustic pulse sets the energy threshold for acoustic detection in the EeV range. In addition to the persistent noise, neutrino-generated signals have to be distinguished from transient background pulses which can originate from either surface or under-sea sound sources (fauna or anthropogenic). The AMADEUS project has been launched for the investigation of these points.

3. The AMADEUS project

The main goal of the AMADEUS (Antares Modules for Acoustic DEtection Under the Sea) project [14] is to conclude on the feasibility of acoustic UHE neutrino detection in large, sea-based acoustic detector arrays. In addition, the integration of AMADEUS in the ANTARES neutrino telescope [12, 13] allows for studying hybrid opto-acoustic detection techniques.

The ANTARES experiment (Fig. 1) is located off-shore at a water depth of about 2500 m in the Mediterranean Sea, about 40 km south-east of Toulon (France). The detector comprises 12 detection lines labelled L1–L12; an additional line (IL07) is instrumented with devices for environmental monitoring. A detection line holds 25 storeys, each housing three PMTs [17, 18], auxiliary sensors and read-out hardware. Each line is fixed to the sea floor by an anchor and kept vertically by an undersea buoy. The acoustic set-up is integrated into the detector as a set of six Acoustic Storeys (ASs), which are modified versions of standard ANTARES storeys, at depths from 2050 to 2300 m. In an AS, the three PMTs are substituted by six acoustic sensors and custom-designed electronics is used for the digitisation and pre-processing of the analogue signals. Once digitised at the storey level, the acoustic data are fed into the detector data stream and are further processed by the data-acquisition hard- and software of ANTARES [15]. On-line filters using acoustic signal processing algorithms like matched filters [20] select and store events of interest on a dedicated server cluster on-shore. These filters reduce the data volume by a factor of more than 100, from 1.5 TByte per day arriving from the ASs to about 10 GByte per day stored on hard-disk for off-line analysis. Both filter and analysis algorithms are implemented in standard ANTARES software.

The three acoustic storeys on the IL07 started operation in December 2007, those on L12 with the completion of ANTARES in May 2008. AMADEUS is now fully functional with 34 active sensors. After two years of operation, the system has demonstrated excellent long-term stability and data-taking characteristics. During the ANTARES data-taking periods, the AMADEUS set-up has been continuously active for about 85% of the time. Studies of ambient noise features, of the calibration of the set-up and of source position reconstruction have been conducted [17]. Current studies cover e.g. temporal and spatial source distributions, signal classification and mammal tracking.

4. Acoustic Positioning and Opto-Acoustic Modules

The positioning of the sensors of an under-sea neutrino detector is essential, as its structures cannot be rigid and
thus move in the deep-sea currents. To achieve best pointing accuracy, a precision of the order of 1 cm is needed for acoustic detection and of 10 cm for optical systems. The positioning in ANTARES is performed via acoustic triangulation using acoustic emitters at the bottom of each line and acoustic sensors\(^4\) at every fifth storey, supported by compass and tilt-meter data recorded at each storey.

The ability to position the acoustic storeys is shown in Fig. 2 where the heading measured by the compass in one storey is compared to the heading derived from the individually reconstructed position of the acoustic sensors on that storey. The RMS of the deviation (1.7\(^{\circ}\)) can be converted to a positioning uncertainty of a few centimetres.

Based on the positive results gained in the operation of one storey equipped with acoustic modules (AMs\(^3\), the idea of combined opto-acoustic modules (OAMs), housing both PMTs and acoustic sensors, has evolved. The acoustic sensors in OAMs can be used for various purposes: for the positioning of the optical sensors in a future optical neutrino telescope, but also for acoustic detection and marine science (e.g. mammal tracking\(^2\)).

First laboratory tests of a parallel operation of a PMT with its high-voltage supply and acoustic sensors within one glass sphere have shown no significant degradation of performance of either of the two devices. The advantages of OAMs, as compared to separate optical and acoustic sensors, are a simplified data-acquisition hardware, the use of the optical data handling also for the acoustic data (as demonstrated with AMADEUS) and no need for components outside the sphere, thus avoiding potentially problematic penetrators through the glass and additional containers. However, the signal quality when coupling acoustic sensors to the inside of a glass sphere is reduced compared to dedicated acoustic sensors. First-principle considerations show that in combined OAMs the orientation could be reconstructed with uncertainties of $10^{\circ}$ when using two acoustic sensors per OAM at a distance of 25 cm. The resulting precision for positioning is in agreement with the requirements for an optical detector.

5. Conclusions

Cosmic neutrinos are the only viable UHE messengers beyond the “local” universe. The acoustic neutrino detection technique is an option to extend neutrino astrophysics to the extreme energy range, either in stand-alone detectors or in combined opto-acoustic sensor arrays. The AMADEUS system, dedicated to the investigation of this technique, has been successfully integrated into the ANTARES neutrino telescope. Except for size, the system has all features required for an acoustic detector and thus allows for deciding on the feasibility of neutrino detection with a potential future large acoustic sensor array. In the context of AMADEUS it is currently being investigated whether an integrated opto-acoustic sensor configuration has the potential to combine the position calibration of an optical detector with acoustic detection studies and marine science applications.

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\(^{3}\)Specialised sensors not suitable for acoustic detection.

\(^{4}\)An AM consists of two piezo-ceramic sensors with preamplifiers, glued to the inside of a glass sphere usually housing a PMT.
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