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Acoustic Neutrino Detection in Sea Water: Technical Aspects

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Abstract. The acoustic neutrino detection technique is a promising approach for future large-scale detectors with the aim of measuring the small expected flux of ultra-high-energy cosmogenic neutrinos. This article focuses on the technical aspects of the application of this technique in water. Though the technique is intriguingly simple, challenges arise from e.g. anisotropic sound propagation, ambient noise or transient background in a natural environment. We present major technical aspects of acoustic neutrino detection based on experience gained with different acoustic test arrays. Before aiming for a large-scale acoustic or hybrid (opto-acoustic) detector, the acoustic detection technique needs to be investigated further in the next generation of Cherenkov neutrino telescopes that are currently prepared. We discuss the technical implementation into those large optical detectors, primarily focussing on the KM3NeT project.

Keywords: neutrinos, cosmogenic neutrinos, acoustic detection, underwater sound, acoustic arrays

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1. INTRODUCTION

The origin and nature of ultra-high energy (UHE, $E \gtrsim 10^{18}$ eV) cosmic rays is one of the fundamental questions in astroparticle physics. From basic principles of particle physics, the production of UHE cosmogenic (Berezinsky-Zatsepin) neutrinos [1] is predicted in conjunction with charged cosmic rays via the Greisen-Zatsepin-Kuzmin mechanism [2, 3]. The detection of neutrinos in the UHE regime will provide not only important complementary information on the astrophysical phenomena and the places that accelerate particles to these extreme energies, but also on the nature of the particles themselves. In addition, neutrinos are the only viable messengers at ultra-high energies beyond the local universe, i.e. distances well beyond several tens of Megaparsecs. On these distances, all other charged and uncharged cosmic ray particles are subject to absorption or interaction, thus losing energy.

Currently several large-volume high-energy neutrino detectors are operational or in a preparatory phase in the Mediterranean Sea (ANTARES [4] and KM3NeT [5], respectively), Lake Baikal (Baikal Deep Underwater Neutrino Telescope and BAIKAL-GVD¹, respectively [6]) and at the South Pole (IceCube [7]). The currently operating detectors employ arrays of photo-sensors up to the cubic-kilometre scale to detect Cherenkov light that is emitted by charged secondary particles — mainly muons — generated in neutrino interactions. This conventional

optical technique is well advanced but will become very expensive for the instrumentation of UHE neutrino experiments, as detector volumes on the level of 100 km³ or beyond are necessary due to the expected relative scarcity of neutrinos in the UHE regime. New techniques have thus to be employed to extend the energy range of neutrino detectors towards higher energies.

Towards this goal, the complementary method of detecting UHE neutrinos via the acoustic signature of the neutrino-induced cascade is studied in the context of each of the aforementioned infrastructures. The method was extensively discussed in the 1970s within the unrealised DUMAND project [8]. Acoustic test setups have been integrated in the framework of existing Cherenkov experiments in the 2000s: AMADEUS in ANTARES [9], ONDE in NEMO [10], SPATS in IceCube [11] and a test setup in the Lake Baikal Neutrino Telescope [12]. Within the ANTARES and NEMO collaborations, these activities were in parts driven also by the know-how gained in the use of (commercial) acoustic positioning systems [13] that are necessary to accurately determine the positions of the detector elements varying in the underwater currents. In addition to the setups in Cherenkov experiments, there are projects using existing military underwater acoustic arrays: SADCO [14], SAUND [15] and ACORNE [16]. A lot of experience was gained with all these setups which have mostly been used for fundamental feasibility studies.

We want to discuss some of the “lessons learned” in this article, mainly considering major technical aspects of acoustic neutrino detection. Based on these aspects, the next step towards a large-scale acoustic neutrino

¹ Gigaton Volume Detector in Lake Baikal

detector is discussed: a large acoustic or opto-acoustic array, necessary for ultimately deciding the feasibility of an acoustic UHE neutrino detector in water. We will mainly focus on the application of the technique in sea water, however most of the discussed points are valid for fresh water as well. For a detailed discussion on the application in fresh water in the Lake Baikal Neutrino Telescope see e.g. [17]; for the application in ice see e.g. [18].

For recent overviews on the acoustic neutrino detection technique see e.g. [19, 20, 21] and references therein.

2. ACOUSTIC NEUTRINO DETECTION: SIGNAL AND MEDIUM PROPERTIES

The acoustic detection method is based on the reconstruction of characteristic sound pulses that are generated by neutrino-induced particle cascades. The thermo-acoustic model [22, 23] describes the generation mechanism in water, connecting the energy deposition by the cascade particles to a local heating of the medium, accompanied by an expansion. A cascade induced by a UHE neutrino has a length on the order of 10 m and radial dimensions on the order of 1 cm, i.e. a line-like geometry. 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 main axis. As sound can travel several kilometres in water, the cylindrical pattern is that of a flat disc, usually referred to as acoustic “pancake”. The thermo-acoustic signal, as measured with a sensor within the pancake (cf. Fig. 1), is bipolar in time with a peak-to-peak amplitude of the order of 10 mPa (5 mPa) per 1 EeV cascade energy at a vertical distance of 200 m (500 m) from the cascade [24]. The peak-to-peak signal length is several tens of microseconds, resulting in a spectral energy density peaked at about 10 kHz.

Note that attenuation, dispersion and refraction change the signal path — deforming the pancake — and the signal shape during the propagation of the sound wave through the medium, see e.g. [20] for an in-depth discussion.

3. ACOUSTIC BACKGROUND

There are two main sources of background for acoustic neutrino detection in sea water: the persistent ambient noise and transient background pulses from point sources (fauna or anthropogenic). The persistent ambient noise is governed by the agitation of the sea surface (effects of wind, precipitation, bubbles and spray) and thermal

FIGURE 1. Simulated thermo-acoustic signal [24] of a 1 EeV hadronic particle cascade at a distance of 500 m perpendicular to the cascade main axis. Water properties as in the Mediterranean Sea are assumed.

noise [25], idealised spectra for shallow water are shown in the left plot of Fig. 2. The spectra have to be slightly modified for deeper sites, as the high-frequency noise components from the sea surface are attenuated². In addition, refraction due to a depth-dependent sound-velocity-profile can channel surface noise towards the detector. Measurements show however that a simplified model — using the Knudsen curves and attenuation depending on the depth — is accurate enough to generally describe the spectral shape and spectral density of the ambient noise [9, 26, 27]. The persistent ambient noise governs the frequency range of interest, i.e. the frequency range with the best signal-to-noise ratio, which is in the range 10 to 50 kHz (cf. right plot of Fig. 2). The RMS of the noise in this frequency range is 7.1, 17, 53 and 130 mPa for sea state 0, 1, 3 and 6, respectively. The rate of occurrence for these conditions is site dependent. For the ANTARES site near Toulon, France, those or better conditions (wind speeds) occur roughly at 1%, 10%, 50% and 95% of the time, respectively.

There is a variety of sources for transient background which is mimicking neutrino-induced signals, e.g. signals from cavitation of ship propellers and sea mammals [29]. Especially dolphins generate bipolar signals with their echolocation clicks. The transient background is very variable in rate of occurrence and spatial density, its composition is site-dependent. These background signals have to be discriminated from neutrino-induced signals (cf. Sec. 4.6).

² The attenuation length for acoustic waves in sea water is of the order of 5 km (1 km) at 10 kHz (20 kHz).

FIGURE 2. Left: Noise power spectral density for shallow sea water (Wenz or Knudsen curves, see e.g. [28]) for sea states 0, 1, 3 and 6 (calm to very rough sea). Right: Comparison of noise power and signal energy density within 1 kHz bins indicating that the best signal-to-noise ratio is present in the frequency range 10 to 50 kHz. The noise power is calculated for sea state 1, the neutrino-induced signal is simulated [24] for a 1 EeV hadronic cascade in a distance of 500 m, perpendicular to the cascade main axis.

4. DETECTOR HARDWARE

In Sections 2 and 3 the basic requirements were discussed that an acoustic neutrino detector needs to comply with. Possible technical implementations, based on the experience gained with the test setups introduced in Sec. 1, are described in this section.

4.1. Sensors

The requirements for the sensor characteristics are governed by the neutrino-induced signal and the ambient noise (cf. Secs. 2 and 3). The maximum signal-to-noise ratio is in the frequency band between 10 and 50 kHz. To fully reconstruct the signal shape, the sensors should thus be sensitive starting from a few kHz up to about 100 kHz. At lower and higher frequencies, the background dominates the signal. It could even saturate the data acquisition hardware, especially for lower frequencies. In addition, the dynamic range of the sensor needs to span the range from a few millipascals (ambient noise) to several tens of pascals (calibration signals and strong sources). To facilitate the full reconstruction of an event, i.e. the neutrino direction and its energy, a sensor with flat angular response is preferable. For a fully calibrated sensor, inhomogeneities in the response can be corrected during data processing, however.

Up to now, all acoustic sensors that were employed in the acoustic test setups are based on piezo-ceramics, varying however concerning housings, sensor shapes and sizes. There are developments of optical hydrophones that are promising [30, 31], but apparently there have been no extensive *in situ* tests. As several acoustic test

setups have been integrated in the infrastructure of existing Cherenkov experiments, the combination of acoustic and optical sensors into one sensor module is pursued [32]. This is mainly driven by the need of acoustic sensors for position calibration of the optical sensor modules (cf. Sec. 5), but such acoustic sensors can be used in a variety of acoustic tasks including acoustic neutrino detection. Combined modules have the advantage of simplified mechanics and electronics, however the angular sensitivity and signal fidelity is not as good as with dedicated hydrophones.

4.2. Acoustic Antennae

In most test setups, the acoustic sensors are grouped to clusters or acoustic antennae, each with a volume in the range of a cubic metre and four to six sensors. The data of all sensors is digitised individually but the proximity of sensors is utilised in the processing strategies for the data [33]. This concept has several advantages: Random coincidences of noise mimicking a neutrino-induced signal can be suppressed by a factor of one over the square root of sensors in the antennae. For coincidence test and comparison of the signals between different sensors, only small time scales on the order of milliseconds have to be analysed, thus reducing the necessary computational effort (cf. Sec. 4.6). In addition, the direction to the source can be reconstructed on the antenna level and by combining several antennae the source position can be triangulated.

4.3. Calibration Devices

As there is no physical background that can be used for calibrating an acoustic neutrino detector, calibration devices are essential to determine the sensor sensitivity and the efficiency of the whole data taking chain. These calibration devices are required to operate reliably and stably at high emission levels due to the distances in a large-scale detector. Versatility — i.e. the ability to emit acoustic pulses of divers types — is advantageous as well. Such pulse types would include: pulses mimicking neutrino interactions (bipolar pulses with flat disk geometry); pulses for position calibration (short, distinguishable pulses); and sensor calibration pulses (broad-band pulses of well-known signal shape). Several calibration sources with such features have been developed, e.g. phased emitter arrays [34] or parametric source arrays [35].

4.4. Acoustic Array

Due to the predicted small fluxes of cosmogenic neutrinos at energies above the EeV scale, a first detection of UHE neutrinos is expected with detectors of $\sim 100 \text{ km}^3$ size, see e.g. [36]. A large percentage of events in such a big detector will occur within the instrumented volume. This facilitates the reconstruction of the full geometry of the neutrino-induced sound pattern, and consequently a good reconstruction of the event. Events occurring near the edges or outside of the detector are harder to reconstruct, as only parts of the deformed pancake can be detected and information is lost.

The dimensions of a $\sim 100 \text{ km}^3$ -sized detector are necessarily asymmetrical, while $\sim 10 \text{ km}$ in horizontal direction, it will only be $\sim 1 \text{ km}$ high. These dimensions are primarily given by the properties of the open sea and technical aspects (pressure tightness of detector elements), but also the fact that only “down-going” neutrinos (with a zenith-angle $\lesssim 95^\circ$) can be detected as the Earth is opaque to UHE neutrinos. The geometry of the sensor array and primarily the spacing of active elements is not governed by the attenuation length of sound (as it is for light in Cherenkov detectors) but by the geometry of the sound emission: the pancake, with dimensions of 10 to 100 m parallel to the cascade axis and several kilometres perpendicular to it (depending on the initial energy of the cascade). This translates into an asymmetric spacing of adjacent acoustic sensors or antennae: the horizontal spacing can be on the order of several hundred metres; the vertical spacing should be denser with sensors/antenna every few ten meters. It is also easier to install a detector with these spacings, as it will in all likelihood consist of vertical structures.

In principle acoustic detection would also be possible near the water surface, however the major background sources are located near the surface (ships and mammals), so to reduce the background sources contained in the instrumented volume of the detector, a deep-sea installation is preferable.

These considerations can be used to determine a rough estimate for the energy threshold of the acoustic detection method: We assume a signal-to-noise ration of 1, where a neutrino-induced signal can be clearly identified online in the background (cf. Sec. 4.6) which is on the 10 mPa level (cf. Sec. 3). The discussed array geometry leads to a typical distance between cascades and neighbouring sensors inside the array on the order of 200 m. Consequently, cascades with signal amplitudes of 10 mPa at the sensors and with energies above 1 EeV can be detected (cf. Sec. 2). If an external trigger is available, e.g. from the optical part in an opto-acoustic detector, the threshold would be significantly lower as additional information (interaction vertex and event time) would be utilised to search for the acoustic signal inside the background.

4.5. Data Acquisition

The data acquisition hardware has to be adapted to the sensor properties to maximise the dynamic range and to avoid effects deteriorating the signal, such as aliasing. Accordingly, analogue processing of the sensor signal — like amplification and filtering — might be necessary. The digitisation of the individual sensor signals can be achieved with standardised commercial, off-the-shelf components — sampling rates of several hundred kHz with 16 or 24 bit sampling place no high requirements on hardware. The amount of data per sensor is in the range of one MB/s, for an estimate of one hundred to one thousand antennae per cubic kilometre that would amount to 10 GB/s to 1 TB/s in a 100 km^3 detector — a data rate manageable by modern network technology. A challenging task is the identification of the signals and events of interest in the data stream, i.e. the online filtering (cf. Sec. 4.6). That can be done at the level of the acoustic antennae using e.g. DSP boards [17]. The data handling principle employed successfully e.g. by the ANTARES and IceCube neutrino telescope seems the more flexible solution, however. In that scheme, the data is only digitised and prepared for data transmission in the detector. The digitised data is sent to a central filter system — in the case of acoustic data that would be an onshore computer farm. Such a farm needs to house thousands to tens of thousands of cores, as the data of several sensors can be analysed online with one computing core. New developments in parallel processing can be fully exploited, so

computing for acoustic detection is feasible already and will become less and less of a challenge in the coming years.

4.6. Filtering

The filtering of the digital acoustic data is a challenging task — not only small signals have to be found in the ambient noise at a signal-to-noise ratio near or even below unity, but also neutrino-induced signals have to be distinguished from neutrino-like background signals. For the first task, digital signal processing techniques (usually matched filters or related techniques) are employed [16]. The second task can be approached on two levels: First, for the signal classification of data from one sensor or an antenna, machine learning algorithms (primarily boosted decision trees or random decision forests) show promising results. When those algorithms are used for features extracted from antenna data, classification errors in the percent range are achieved [37]. The second level is given by the angular emission characteristic of a neutrino interaction: the pancake. All other sources are expected to show a different geometry: either a point source or an extended source, but not a cylindrical one. With the existing small test setups, taking advantage of this last point is not possible, as the number of acoustic antennae is too low. However, clustering algorithms can help here, looking for aggregations of signals that are causally connected, e.g. emitted on a straight line or from the same point in space over a sequence in time.

5. STEPS FORWARD

None of the test setups listed in Sec. 1 reaches the three-dimensional size necessary to ultimately decide on the feasibility of a future large-scale neutrino detector: the reconstruction accuracy is deteriorated by the small size or unfavourable geometry. In addition technical aspects like data acquisition or calibration could not be tested on a large scale. The natural next step towards a future large-scale detector in (sea) water is an intermediate-scale detector. This step will most probably be taken within existing infrastructures — and possibly the only fitting projects are the KM3NeT project in the Mediterranean Sea, which will be discussed in the following, and the GVD project for fresh water in lake Baikal which is discussed in [17].

The KM3NeT design [38] consists of slender vertical structures (lines, cf. left picture in Fig. 3) supporting optical modules to detect the Cherenkov light of neutrino-induced charged secondaries. Each optical module hosts 31 3" phototubes, readout electronics and instrumenta-

tion. One instrument included in each optical module will be an acoustic sensor either as external hydrophone or as piezo-ceramic sensor glued into the module's housings cf. right picture in Fig. 3. Though primarily designed for position calibration, these broadband sensors can also be used for different acoustic studies, e.g. monitoring of the sea fauna; the anthropogenic acoustic pollution; or — relevant in this context — for acoustic neutrino detection. The sensor recordings will be digitised in the module and all digital data will be sent to a computing farm at the shore station where the acoustic data will be subject to different filtering processes adopted to the specific analyses mentioned above.

FIGURE 3. Left: Artist's view of a KM3NeT line, available from <http://www.km3net.org>. Right: Picture of the lower hemisphere of an KM3NeT optical module prototype, taken from [39]. The acoustic sensor is visible as small light-coloured circle in the centre, located between the 3" phototubes.

The KM3NeT collaboration has recently initiated the KM3NeT phase 1 project towards a large neutrino observatory in the Mediterranean Sea. The presently available budget is sufficient to start the construction of prototype lines and a detector with several tens of lines. The layout of the lines and the sea-floor layout of the detector are

under investigation. Two different setups are considered: ORCA³, a dense Megaton layout primarily designed to determine the neutrino mass hierarchy (with ~ 20 m horizontal spacing between adjacent lines and 20 optical modules per line with approximately 5 to 10 m vertical spacing between adjacent modules); and a high-energy neutrino detector (with ~ 100 m horizontal spacing and 20 optical modules per line with ~ 40 m vertical spacing). A decision whether to opt for ORCA as the phase 1 of the KM3NeT project is aimed for later in 2013. KM3NeT phase 2 will consist of a multi-cubic-kilometre high-energy neutrino and sea science observatory.

As acoustic detector, KM3NeT phase 1 will lack some of the features that were described above as adapted to this detection technique: e.g. the sensors (in case of combined optical and acoustic modules) will be not perfectly suited, see Sec. 4.1; there will be no genuine acoustic antennae, however those can be formed in software during data processing albeit with larger extensions than described in Sec. 4.2; and the array layout will be rather dense when the ORCA layout is realised. However, the detector size and amount of sensors in phase 1 will be at least one order of magnitude larger than for the existing acoustic test setups — thus all the drawbacks mentioned above can be overcome and the feasibility of acoustic neutrino detection ultimately decided. In addition, such a detector would have the combined features of an optical and an acoustic detector.

KM3NeT phase 2 could then be regarded as a hybrid detector⁴. It would not only have the advantage of co-deploying and co-using the mechanical, digital and power infrastructures, but also to highly improve the understanding of systematic uncertainties in the detection methods that use complementary information gained from the particle interactions.

6. CONCLUSIONS

Cosmic neutrinos are the only viable UHE messengers beyond our “local” universe. The acoustic neutrino detection technique is a promising option to extend neutrino astrophysics to the extreme energy range, either in stand-alone detectors or as complementary technique in combined opto-acoustic sensor arrays. All major technical challenges have been intensively studied in the last one and a half decade and solutions have been provided.

³ Oscillation Research with Cosmics in the Abyss

⁴ In such a combined detector, the optical part could trigger the acoustic part. Using the informations about an event provided by the optical part, it seems feasible to lower the energy threshold for acoustic detection to a range, where the two highly energetic events seen by IceCube [40] might be detectable.

So the basic concept for a future, large-scale acoustic detector for UHE neutrinos can be defined, preferably in a hybrid detector with a smaller central optical part. However, some techniques may not have reached the required level of maturity and need further development. For this technical development, but also for the ultimate decision whether it is feasible to reliably detect the small acoustic signals in the ambient noise and distinguish it from transient background, a next, intermediate step is necessary. For sea water, the natural step should be using the acoustic system of the KM3NeT phase 1 project as an acoustic detector.

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