

Neutrino Detection, Position Calibration and Marine Science with Acoustic Arrays in the Deep Sea

R. Lahmann

Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany

Abstract

Arrays of acoustic receivers are an integral part of present and potential future Cherenkov neutrino telescopes in the deep sea. They measure the positions of individual detector elements which vary with time as an effect of undersea currents. At the same time, the acoustic receivers can be employed for marine science purposes, in particular for monitoring the ambient noise environment and the signals emitted by the fauna of the sea. And last but not least, they can be used for studies towards acoustic detection of ultra-high-energy neutrinos. Measuring acoustic pressure pulses in huge underwater acoustic arrays with an instrumented volume of the order of 100 km^3 is a promising approach for the detection of cosmic neutrinos with energies exceeding 1 EeV . Pressure signals are produced by the particle cascades that evolve when neutrinos interact with nuclei in water, and can be detected over large distances in the kilometre range. In this article, the status of acoustic detection will be reviewed and plans for the future—most notably in the context of KM3NeT—will be discussed. The connection between neutrino detection, position calibration and marine science will be illustrated.

Keywords:

neutrinos, cosmogenic neutrinos, acoustic detection, underwater sound

1. Introduction

“Of all the forms of radiation known, sound travels through the sea the best” [1]. Hence, sound is used in the sea by marine mammals and by humans for purposes of communication and positioning. It is important for astroparticle physics that sound waves are furthermore emitted when the local medium heats up following the interaction of a neutrino in water. As will be elaborated in Sec. 2, this effect allows for the detection of ultra-high-energy neutrinos. Apart from the design of the detector, the energy threshold is essentially determined by the relatively high ambient noise in the sea and by the small signals expected from neutrino interactions.

The acoustic detection of neutrino reactions in principle is possible in any dense homogeneous medium. In addition to water and ice, which are the media of acoustic detection test experiments presently or recently conducted, acoustic detection in salt domes [2, 3] and in permafrost [4] has been discussed. In this article only the detection of neutrinos in water will be covered in detail, in particular in the context of interdisciplinary research and the use of sound in Cherenkov neutrino telescopes for the position calibration of the optical detectors. In Sec. 3 an overview of current and recent test setups for the investigation of acoustic neutrino detection techniques is given and in Sec. 4 the acoustic background present in the Mediterranean Sea will be discussed. Monte Carlo simulations required to investigate

acoustic detection of neutrinos are discussed in Sec. 5, while interdisciplinary use of the data from deep sea acoustic arrays is the subject of Sec. 6. An outlook on the use of acoustics for position calibration and the next step of neutrino detection tests in KM3NeT is given in Sec. 7 before in Sec. 8 conclusions and an outlook are given.

2. Acoustic Detection of Neutrinos

Measuring pressure pulses in huge underwater acoustic arrays is a promising approach for the detection of ultra-high-energy (UHE) neutrinos with energies exceeding 100 PeV , in particular cosmogenic neutrinos. The pressure signals are produced by the particle showers that evolve when neutrinos interact with nuclei in water. The resulting energy deposition in a cylindrical volume of a few centimetres in radius and several metres in length leads to a local heating of the medium which is instantaneous with respect to the hydrodynamic time scales. This temperature change induces an expansion or contraction of the medium depending on its volume expansion coefficient. According to the thermo-acoustic model [5, 6], the accelerated expansion of the heated volume—a micro-explosion—forms a pressure pulse of bipolar shape which propagates in the surrounding medium. Coherent superposition of the elementary sound waves, produced over the volume of the energy deposition, leads to a propagation within a flat disk-like volume (often referred to as *pancake*) in the direction perpendicular to the axis of the particle shower. After propagating several hundreds of metres in sea water, the pulse has a characteristic frequency

Email address: robert.lahmann@physik.uni-erlangen.de
(R. Lahmann)

spectrum that is expected to peak around 10 kHz [7, 8, 9]. As the attenuation length in sea water in the relevant frequency range is about one to two orders of magnitude larger than that for visible light, a potential acoustic neutrino detector would require a less dense instrumentation of a given volume than an optical neutrino telescope.

3. Test Setups for Acoustic Neutrino Detection

Current or recent test setups for acoustic neutrino detection have either been add-ons to optical neutrino telescopes or have been using acoustic arrays built for other purposes, typically for military use. In the context of the DUMAND¹ experiment, ideas about adding a large scale acoustic detector to a deep-sea optical neutrino telescope were already considered in the 1970s [10]. As the DUMAND experiment was not realised beyond a prototype phase, acoustic particle detection was subsequently pursued by the parasitic use of military arrays. In an early effort starting in 1997 by the SADCO² collaboration, a Russian Navy stationary antenna near Kamtchatka consisting of 2400 hydrophones was used for acoustic particle detection studies [11]—see also [12] and references therein.

An overview of experiments in salt water, fresh water and ice that are currently taking data or have done so until recently is given in Table 1. Below, the individual projects will be discussed in some more detail.

The **SPATS (South Pole Acoustic Test Setup)** project [17, 18], deployed up to a depth of 500 m in the upper part of four boreholes of the IceCube Neutrino Observatory, has continuously monitored the noise in Antarctic ice at the geographic South Pole since January 2007. As acoustic properties, in particular the absorption length and the speed of sound, have been subject to fewer experimental studies for ice than for water, these properties have been instigated with SPATS [19, 20]. Based on 8 months of observation, a limit on the neutrino flux above 10^{11} GeV has been derived [21], see Fig. 1.

In **Lake Baikal**, an antenna consisting of four hydrophones in a tetrahedral arrangement with equal interspacings of the hydrophones of 1.5 m has been placed at 150 m depth [22]. Fresh water has the advantage over sea water in that the attenuation length is roughly one order of magnitude larger in the frequency range of 10 to 100 kHz. However, conditions in Lake Baikal are not particularly favourable for acoustic neutrino detection, since in the deep zone of the lake the water temperature is only 1.5 – 2°C higher than the maximum density at the respective depth [23, 24]. The thermal expansion coefficient hence is close to zero and the Grüneisen parameter small. The observed noise level depends mostly on surface conditions and in the frequency range of 5 to 20 kHz has a value of a few mPa.

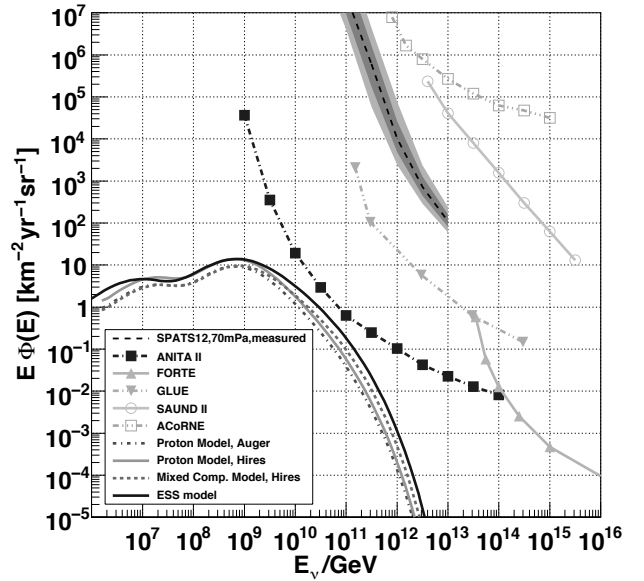


Figure 1: The neutrino flux limit of the 2009 SPATS configuration (70 mPa threshold, ≥ 5 hits per event) from [21]. The dark grey band (50 to 100 mPa threshold) around the limit considers uncertainties in absolute noise. The even broader light grey band includes additional uncertainties due to the choice of different acoustic models. Experimental limits on the flux of ultra-high-energy neutrinos are from ANITA II [26], FORTE [27], GLUE [28], SAUND II [29], ACoRNE [30]. Different models for the cosmogenic flux are shown [31, 32]. Figure adapted from [21].

The **OvDE (Ocean noise Detection Experiment)** project at the site of the NEMO³ Cherenkov neutrino detector [15] has performed long term noise studies at 2050 m depth, 25 km east of Catania (Sicily) in the Mediterranean Sea at the location 37°30.008'N, 15°23.004'E. Phase I operated from January 2005 until November 2006. It employed 4 hydrophones forming a tetrahedral antenna with side lengths of about 1 m. In an analysis carried out with data recorded during 13 months between May 2005 and November 2006 [25], the average acoustic sea noise in the band 20 to 43 kHz was measured as 5.4 ± 2.2 (stat) ± 0.3 (sys) mPa (RMS). In 2011, the deployment of a new hydrophone antenna is planned in the context of the NEMO-II project.

The **SAUND (Study of Acoustic Ultra-high energy Neutrino Detection)** experiment [33] employed a large hydrophone array in the U.S. Navy Atlantic Undersea Test And Evaluation Center (AUTECH) [33]. The array is located in the Tongue of the Ocean, a deep tract of sea in the Bahama islands at approximately 24°30'N and 77°40'W. In the first phase SAUND-I, 7 hydrophones arranged over an area of ~ 250 km² were used for studies of UHE neutrino detection. The hydrophones were mounted on 4.5 m booms standing vertically on the ocean floor at about 1600 m depth. The horizontal spacing between central and peripheral hydrophones was between 1.50 and 1.57

¹Deep Underwater Muon and Neutrino Detection

²Sea Acoustic Detector of Cosmic Objects

³Neutrino Mediterranean Observatory

Experiment	Location	Medium	Sensor Channels	Host Experiment
SPATS	South Pole	Ice	80	IceCube [13]
Lake Baikal	Lake Baikal	Fresh Water	4	Baikal Neutrino Telescope [14]
OvDE	Mediterranean Sea (Sicily)	Sea Water	4	NEMO [15]
AMADEUS	Mediterranean Sea (Toulon)	Sea Water	36	ANTARES [16]
ACoRNE	North Sea (Scotland)	Sea Water	8	Rona military array
SAUND	Tongue of the Ocean (Bahamas)	Sea Water	7/49 ^(*)	AUTEC military array

Table 1: Overview of existing and recent acoustic detection test sites.

(*) The number of hydrophones was increased from 7 in SAUND-I to 49 in SAUND-II, see text.

km. After the upgrade of the array, 49 hydrophones that were mounted 5.2 m above the ocean floor, at depths between 1340 and 1880 m were available. The upgraded array spans an area of about 20 km \times 50 km with spacing of 3 to 5 km. This array was used in the second phase SAUND-II. Neutrino flux limits were derived with SAUND-I for a lifetime of 195 days [34] and for SAUND-II for an integrated lifetime of 130 days [29], see Fig. 1.

The **ACoRNE (Acoustic Cosmic Ray Neutrino Experiment)** project [35] utilises the Rona hydrophone array, situated near the island of Rona between the Isle of Skye and the Scottish mainland. At the location of the array, the sea is about 230 m deep. The ACoRNE Experiment uses 8 hydrophones, anchored to the sea bed and spread out over a distance of about 1.5 km. Six of these hydrophones are approximately in mid-water, one is on the sea bed while the last one is about 30 m above the sea bed. The ACoRNE collaboration has derived a flux limit on UHE neutrinos [30] which is shown in Fig. 1.

The **AMADEUS (ANTARES Modules for the Acoustic Detection Under the Sea)** project [36] was conceived to perform a feasibility study for a potential future large-scale acoustic neutrino detector in the Mediterranean Sea. For this purpose, a dedicated array of acoustic sensors was integrated into the ANTARES⁴ neutrino telescope [16]. A sketch of the detector, with the AMADEUS modules highlighted, is shown in Figure 2. The detector is located in the Mediterranean Sea at a water depth of about 2500 m, roughly 40 km south of the town of Toulon at the French coast at the geographic position of 42°48' N, 6°10' E. ANTARES was completed in May 2008 and comprises 12 vertical structures, the *detection lines*. Each detection line holds up to 25 *storeys* that are arranged at equal distances of 14.5 m along the line. A standard storey holds three *Optical Modules*, each one consisting of a photomultiplier tube inside a water-tight pressure-resistant glass sphere. A 13th line, called the *Instrumentation Line (IL)*, is equipped with instruments for monitoring the environment. It holds six storeys.

Within the AMADEUS system [36], acoustic sensing is integrated in the form of *acoustic storeys* that are modified versions of standard ANTARES storeys, in which the Optical Modules are replaced by custom-designed acoustic sensors. Dedicated electronics is used for the amplification, digitisation and

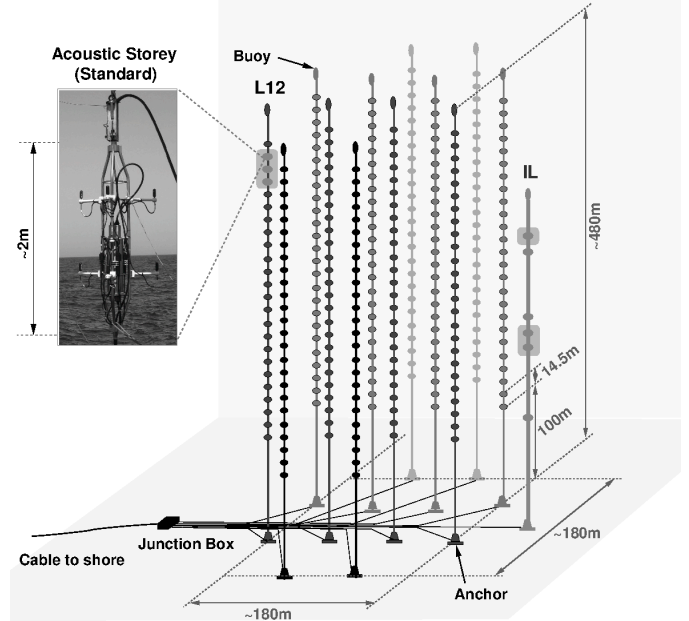


Figure 2: A sketch of the ANTARES detector. The six acoustic storeys are highlighted and a photograph of a storey in standard configuration is shown. L12 and IL denote the 12th detection line and the Instrumentation Line, respectively.

pre-processing of the analogue signals. Six acoustic sensors per storey were implemented, arranged at distances of roughly 1 m from each other. The AMADEUS system comprises a total of six acoustic storeys: three on the IL and three on the 12th detection line (Line 12). In the following, results from the AMADEUS device will be presented.

As the upper part of each line is not fixed but instead moves with undersea currents, ANTARES also contains a dedicated acoustic positioning system to continuously monitor the positions of the Optical Modules. Efforts for KM3NeT are going in the direction of designing one common acoustic system for both applications, as will be discussed in Sec. 7.

4. Acoustic Background in the Mediterranean Sea

4.1. Ambient Background

Ambient noise, which can be described by its characteristic power spectral density (PSD), is caused by environmental processes and determines the minimum pulse height that

⁴Astronomy with a Neutrino Telescope and Abyss environmental Research

can be measured, if a given signal-to-noise ratio (SNR) can be achieved with a search algorithm. To measure the ambient background at the ANTARES site, data from one sensor on the IL taken from the beginning of 2008 until the end of 2010 were evaluated. After quality cuts, 27905 minimum bias samples (79.9% of the total number recorded in that period) remained for evaluation, each sample containing data continuously recorded over a time-span of ~ 10 s. For each of these samples, the noise PSD (units of V^2/Hz) was integrated in the frequency range $f = 10\text{--}50$ kHz, yielding the square of the ambient noise for that sample, as quantified by the output voltage of the hydrophone. Preliminary studies using the shower parameterisation and algorithms from [8] indicate that this range optimises the SNR for the expected neutrino signals.

The frequency-of-occurrence distribution of the resulting noise values, relative to the mean noise over all samples, is shown in Fig. 3. Also shown is the corresponding cumulative distribution. For 95% of the samples, the noise level is below $2\langle\sigma_{\text{noise}}\rangle$, demonstrating that the ambient noise conditions are stable.

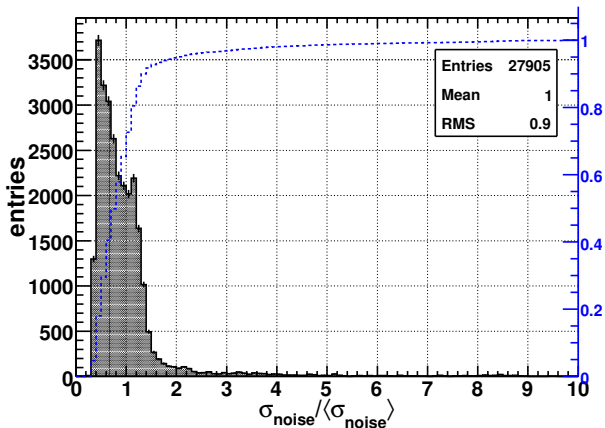


Figure 3: Frequency-of-occurrence distribution for the ambient noise in the range 10 – 50 kHz, relative to the mean ambient noise recorded over the complete period of three years which was used for the analysis (left scale, filled histogram). Also shown is the cumulative distribution, normalised to the total number of entries of the distribution (right scale, dotted line).

All sensors have been calibrated in the laboratory prior to deployment. The absolute noise level can be estimated by assuming a constant sensor sensitivity⁵ of -145 ± 2 dB re $1\text{V}/\mu\text{Pa}$. With this value, the mean noise level is $\langle\sigma_{\text{noise}}\rangle = 10.1_{-2}^{+3}$ mPa with the median of the distribution at 8.1 mPa.

Currently, the detection threshold for bipolar signals corresponds to a SNR of about 2 for an individual hydrophone. For this SNR, the median of the noise distribution corresponds to a signal amplitude of ~ 15 mPa, equivalent to a neutrino energy of ~ 1.5 EeV at a distance of 200 m [7]. By applying pattern recognition methods that are more closely tuned to the expected neutrino signal, this threshold is expected to be further reduced.

⁵The ambient noise originates mainly from the sea surface and hence displays a directivity which has to be folded with the variations of the sensitivity over the polar angle to obtain an effective average sensitivity. For the results presented here, the noise has been assumed to be isotropic.

4.2. Transient Sources

Transient sources, e.g. from sea mammals and shipping traffic, may create signals containing the characteristic bipolar pulse shape that is expected from neutrino-induced showers. In order to reduce the data volume, the AMADEUS system employs an online pulse-shape-recognition trigger which is sensitive to the bipolar pulse expected from neutrino interactions. This trigger selects events with a wide range of shapes. For further offline data reduction, a classification scheme is being developed which allocates triggered events to one of four classes: genuine bipolar events that are compatible with signals expected from neutrinos (“neutrino-like events”), multipolar events, reflections of signals from the acoustic emitters of the ANTARES positioning system, and random events, where the latter class contains all events that do not fit into any of the other classes. For the classification, simulated signals representing the four classes in equal proportions were produced and a set of features extracted which are highly discriminatory between the classes. This feature vector is then fed into a machine-learning algorithm [37]. Classification is performed for the signals from individual hydrophones. Subsequently, the results from individual hydrophones are combined to derive a classification for a given acoustic storey. Several algorithms were investigated, the best of which yielded a failure rate (i.e. wrong decision w.r.t. simulation truth) at the 1%-level when applied to the two signal classes “neutrino-like” and “not neutrino-like”. After selecting neutrino candidates on the level of a storey, measurements from multiple storeys can be combined to search for patterns that are compatible with the characteristic “pancake” pressure field resulting from a neutrino interaction.

5. Monte Carlo Simulations

Monte Carlo simulations based on [7, 8] are currently being implemented for the AMADEUS detector setup. The pressure pulse received by a hydrophone resulting from the energy deposition of a 10^{10} GeV is shown in Fig. 4. The corresponding neutrino interaction was generated such that the centre of the hadronic shower for a vertically downgoing neutrino lies within the same horizontal plane as the storey denoted “Storey 2”, at a distance of 200 m. This way, the storey lies within the “pancake” of the pressure field. On a storey 14.5 m below that storey, denoted “Storey 1”, no signal is observed. This configuration corresponds to two adjacent acoustic storeys on L12 or the two lowermost storeys on the IL, see Fig. 2. This simulation illustrates the characteristic three-dimensional pattern expected from neutrino-generated pressure waves. A more detailed discussion can be found in [38].

6. Interdisciplinary Cooperation

Signals from marine mammals and other environmental sources constitute background for the acoustic detection of neutrinos. In particular, dolphins emit whistles with frequency spectra that resemble those expected from neutrino interactions.

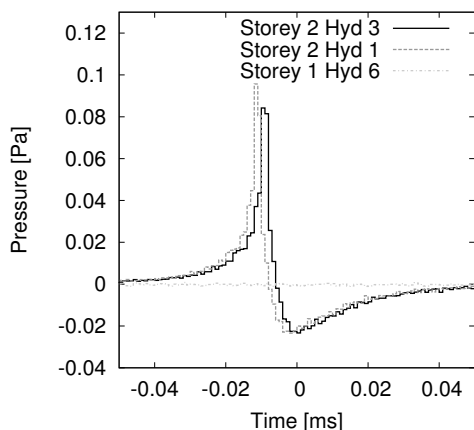


Figure 4: Simulated acoustic signals as recorded with hydrophones in two acoustic storeys with a vertical spacing of 14.5 m. See text for details. For Storey 2, signals from two different hydrophones are shown.

Dolphins can dive to depths of ~ 500 m and their whistles constitute the main background of transient signals recorded by the AMADEUS pulse shape recognition trigger. On the other hand, these signals are of great interest to environmental and marine science and the acoustic monitoring of the deep sea has a large potential for interdisciplinary research. As a consequence, efforts for acoustic detection of neutrinos are pursued in cooperation with marine scientists who are using the acoustic data for the study of marine mammals [39, 40]. For the acoustic detection of neutrinos, this cooperation helps to understand and reduce the background from marine mammals. As the AMADEUS device provides a constant stream of acoustic data to shore—currently a unique feature in the Mediterranean Sea—marine scientists are already using the AMADEUS data for dedicated research. A live stream of the data from an AMADEUS hydrophone combined with a real-time analysis focused on marine science is available on the Internet [41].

7. Acoustic Sensing for KM3NeT

The planned towers⁶ of the KM3NeT detector will be free to sway and twist in the undersea current with an expected displacement of up to 150 m at the top for sea currents reaching 30 cm per second [42]. In order to determine the relative positions of the storeys with a precision of not worse than 20 cm the detector will be equipped with an acoustic positioning system. The system employs acoustic transceivers on the sea floor and acoustic receivers (hydrophones) in each storey. By performing multiple time-delay measurements and using these to triangulate the positions of the individual hydrophones, the hydrophone positions can be reconstructed relative to the positions of the emitters. Reliable, low-power and cost-efficient emitters operating in the range 20 – 40 kHz are under development [43].

⁶The vertical structures of the KM3NeT detector holding optical sensors are called towers.

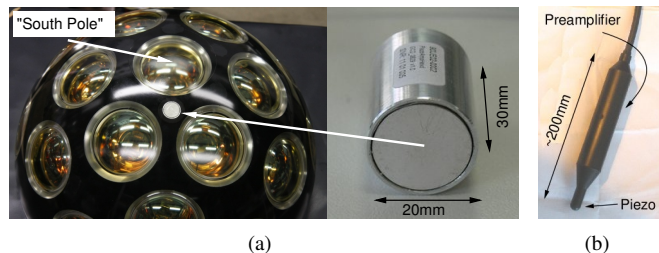


Figure 5: (a) Acoustic piezo sensor for installation inside a DOM and a DOM with installed sensor. (b) Prototype of a hydrophone for KM3NeT, to be mounted on the bar structure near the DOM.

The KM3NeT positioning system is based on experience of the systems developed for ANTARES, see [44, 45] and references therein. Sampling will be done at about 200 k samples per second and all data will be written to shore. This way, algorithms for the position calibration, running on an on-shore computer farm, can be adapted to in-situ conditions that may affect the shape of the received signal. Furthermore, the data can be used for additional analyses, such as acoustic detection of neutrinos, see e.g. [12] and references therein, or marine science investigations.

Two types of acoustic sensors, both based on the piezoelectric effect, are currently tested. They are shown in Fig. 5. The first kind are standard hydrophones, i.e. a piezo ceramic and a preamplifier coated with polyurethane for high pressure water tightness. The second kind are compact units of a piezo ceramic and a preamplifier, glued to the inside of the glass sphere of the DOM near its “South Pole”. This design has been tested within AMADEUS. The advantages w.r.t. to standard hydrophones are lower costs and a reduction of the number of failure points: no additional cables and junctions are required and the sensor is not exposed to the aggressive environmental conditions. Disadvantageous on the other hand is a reduced angular acceptance and the vulnerability of the system to electric interferences with the PMTs in the same sphere. A KM3NeT prototype Detection Unit planned to be deployed in 2012 will contain both types of sensors and will allow for a design decision, see also [46].

8. Conclusions and Outlook

Acoustic detection is a promising approach for a future large volume detector of UHE neutrinos. To investigate the feasibility and potential of such a detector, several experiments have been performed or are underway. These experiments use either existing military acoustic arrays or are additions to Cherenkov neutrino telescopes. Their sizes are far too small to yield competitive limits on the flux of UHE neutrinos but they allow for the investigation of experimental techniques for a future acoustic neutrino detector and for the investigation of background conditions, which are the essential factor that determines the feasibility of such a device. At the same time, the continuous stream of data from the deep sea provided by deep-sea acoustic arrays is of great interest for marine scientists for the study of sea mammals.

Background conditions in the Mediterranean Sea have been monitored by the AMADEUS system within the ANTARES neutrino telescope. The ambient background was found to be stable at the expected level. The transient background is very diverse and stems mainly from dolphins and shipping traffic. Methods for its suppression are under development, as are Monte Carlo simulations and algorithms for neutrino selection.

For the proposed KM3NeT neutrino telescope, a combined system for acoustic position calibration of the photomultipliers and neutrino detection is planned. For the latter purpose, it would be an intermediate step towards an even bigger acoustic detector for UHE neutrinos.

9. Acknowledgements

The author wishes to thank the organizers of the VLVnT workshop for the invitation to give a presentation. The AMADEUS project is supported by the German government (Bundesministerium für Bildung und Forschung, BMBF) through grants 05A08WE1 and 05A11WE1.

- [1] R.J. Urick, Principles of Underwater Sound, Peninsula publishing, 1983. ISBN 0-932146-62-7.
- [2] G. Manthei, J. Eisenblätter, and T. Spies, in: Proceedings of the 1st International Workshop on Acoustic and Radio EeV Neutrino detection Activities (ARENA 2005), Zeuthen, Germany, May 17–19, Int. J. Mod. Phys. A21S1, World Scientific, 2006, p. 30. ISBN 981-256-755-0.
- [3] P.B. Price, J. of Geophys. Res 111 (2006) B02201. arXiv:astro-ph/0506648v1.
- [4] R. Nahnhauser, A.A. Rostovtsev, and D. Tosi, Nucl. Inst. and Meth. A 587 (2008) 29. arXiv:0707.3757v1 [astro-ph].
- [5] G.A. Askariyan, B.A. Dolgoshein, A.N. Kalinovsky, and N.V. Mokhov, Nucl. Inst. and Meth. 164 (1979) 267.
- [6] J.G. Learned, Phys. Rev. D 19 (1979) 3293.
- [7] S. Bevan et al. (ACoRNE Coll.), Astropart. Phys. 28 (2007) 366. arXiv:0704.1025v1 [astro-ph].
- [8] S. Bevan et al. (ACoRNE Coll.), Nucl. Inst. and Meth. A 607 (2009) 398. arXiv:0903.0949v2 [astro-ph.IM].
- [9] V. Niess and V. Bertin, Astropart. Phys. 26 (2006) 243. arXiv:astro-ph/0511617v3.
- [10] A. Roberts, Rev. Mod. Phys. 64 (1992) 259.
- [11] L.G. Dedenko et al., Sadco: Hydroacoustic Detection of Super-High Energy Cosmic Neutrinos, 1997. arXiv:astro-ph/9705189v1.
- [12] R. Nahnhauser, in: Proceedings of the 4th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2010), Nantes, France, June 29–July 2, Nucl. Inst. and Meth. A 662, p. S20. arXiv:1010.3082v2 [astro-ph.IM].
- [13] A. Achterberg et al. (IceCube Coll.), Astropart. Phys. 26 (2006) 155. arXiv:astro-ph/0604450.
- [14] A. Avrorin et al., in: Proceedings of the 4th International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea (VLVnT 2009), Athens, Greece, 13–15 Oct. 2009, Nucl. Inst. and Meth. A 626–627, p. S13.
- [15] M. Taiuti et al., in: Proceedings of the 4th International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea (VLVnT 2009), Athens, Greece, 13–15 Oct. 2009, Nucl. Inst. and Meth. A 626–627, p. S25.
- [16] M. Ageron et al. (ANTARES Coll.), Nucl. Inst. and Meth. A 656 (2011) 11. arXiv:1104.1607v1 [astro-ph.IM].
- [17] T. Karg, for the IceCube Coll., in: Proceedings of the 4th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2010), Nantes, France, June 29–July 2, Nucl. Inst. and Meth. A 662, p. S36. arXiv:1010.2025v1 [astro-ph.IM].
- [18] Y. Abdou et al. (IceCube Coll.), Nucl. Inst. and Meth. A 683 (2012) 78. arXiv:1105.4339v1 [astro-ph.IM].
- [19] R. Abbasi et al. (IceCube Coll.), Astropart. Phys. 33 (2010) 277. arXiv:0909.2629v1 [astro-ph.IM].
- [20] R. Abbasi et al. (IceCube Coll.), Astropart. Phys. 34 (2011) 382. arXiv:1004.1694v2 [astro-ph.IM].
- [21] R. Abbasi et al. (IceCube Coll.), Astropart. Phys. 35 (2012) 312. arXiv:1103.1216v1 [astro-ph.IM].
- [22] K. Antipin et al. (BAIKAL Coll.), in: Proceedings of the 30th International Cosmic Ray Conference (ICRC2007), Merida, Mexico, July 3–11. arXiv:0710.3113 [astro-ph].
- [23] V. Aynutdinov et al., in: Proceedings of the 4th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2010), Nantes, France, June 29–July 2, Nucl. Inst. and Meth. A. Doi:10.1016/j.nima.2010.11.153.
- [24] V. Aynutdinov et al., in: Proceedings of the 31st Int. Cosmic Ray Conf. (ICRC2009), Lodz, Poland, July 7–15. arXiv:0910.0678v1 [astro-ph.HE].
- [25] G. Riccobene for the NEMO Coll., in: Proceedings of the 3rd International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2008), Rome, Italy, June 25–27, Nucl. Inst. and Meth. A 604, p. 149.
- [26] P.W. Gorham et al. (ANITA Coll.), Phys. Rev. D 82 (2010) 022004. arXiv:1003.2961v3 [astro-ph.HE]; Erratum: arXiv:1011.5004v1 [astro-ph.HE].
- [27] N.G. Lehtinen, P.W. Gorham, A.R. Jacobson, and R.A. Roussel-Dupré, Phys. Rev. D 69 (2004) 013008. arXiv:astro-ph/0309656v2.
- [28] P.W. Gorham et al., Phys. Rev. Lett. 93 (2004) 041101. arXiv:astro-ph/0310232v3.
- [29] N. Kurahashi, J. Vandenbroucke, and G. Gratta, Phys. Rev. D 82 (2010) 073006. arXiv:1007.5517v1 [hep-ex].
- [30] S. Bevan, in: Proceedings of the 3rd International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2008), Rome, Italy, June 25–27, Nucl. Inst. and Meth. A 604, p. 143.
- [31] R. Engel, D. Seckel, and T. Stanev, Phys. Rev. D 64 (2001) 093010. arXiv:astro-ph/0101216v2.
- [32] D. Seckel, Internet, 2005. <ftp://ftp.bartol.udel.edu/~seckel/ess-gzk/>; “Proton model, Auger”: file 2008/export_data/ss_135.a.txt; “Proton model, HiRes”: file 2008/export_data/ss_135.h.txt; “Mixed comp model, HiRes”: file 2008/export_data/ss_151.h.txt.
- [33] N.G. Lehtinen et al., Astropart. Phys. 17 (2002) 279. arXiv:astro-ph/0104033v1.
- [34] J. Vandenbroucke, G. Gratta, and N. Lehtinen, Astrophys. J. 621 (2005) 301. arXiv:astro-ph/0406105v2.
- [35] S. Danaher for the ACoRNE Coll., in: Proceedings of the 2nd International Workshop on Acoustic and Radio EeV Neutrino detection Activities (ARENA 2006), Newcastle, UK, 28–30 June, volume 81 of *J. Phys. Conf. Ser.*, IOP Publishing, Philadelphia, 2007, p. 012011.
- [36] J.A. Aguilar et al. (ANTARES Coll.), Nucl. Inst. and Meth. A 626-627 (2011) 128. arXiv:1009.4179v2 [astro-ph.IM].
- [37] M. Neff et al., in: Proceedings of the 4th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2010), Nantes, France, June 29–July 2, Nucl. Inst. and Meth. A 662, p. S242. arXiv:1104.3248v1 [astro-ph.IM].
- [38] M. Neff, in: Proceedings of the 5th International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea (VLVnT 2011), Erlangen, Germany, 12–14 Oct. 2011, Nucl. Inst. and Meth. A, to be published.
- [39] N. Nosengo, Nature 462 (2009) 560. News Feature.
- [40] H. Rietz, Walgesang als Beifang, published in the German newspaper “Die Zeit” on March 14th, 2011. <http://www.zeit.de/2011/11/N-Neutrindetektoren>.
- [41] Web page of the LIDO (Listening to the Deep-Ocean Environment) project, 2011. <http://listentothedeep.org/>.
- [42] P. Kooijman for the KM3NeT Consortium, in: Proceedings of the 32nd Int. Cosmic Ray Conf. (ICRC2011), Beijing, China, Aug. 11–18.
- [43] M. Ardid et al. for the KM3NeT Consortium, in: Proceedings of the 4th International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea (VLVnT 2009), Athens, Greece, 13–15 Oct. 2009, Nucl. Inst. and Meth. A 626–627, p. S214.
- [44] M. Ardid for the ANTARES Coll., in: Proceedings of the 3rd International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea (VLVnT 2008), Toulon, France, April 22–24, Nucl. Inst. and Meth. A 602, p. 174.
- [45] F. Ameli et al. for the KM3NeT Consortium, in: Proceedings of the 4th

International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea (VLVnT 2009), Athens, Greece, 13–15 Oct. 2009, Nucl. Inst. and Meth. A 626–627, p. S211.

- [46] A. Enzenhöfer, in: Proceedings of the 5th International Workshop on a Very Large Volume Neutrino Telescope for the Mediterranean Sea (VLVnT 2011), Erlangen, Germany, 12–14 Oct. 2011, Nucl. Inst. and Meth. A, to be published.