ANTARES: TOWARDS ACOUSTIC DETECTION OF HIGHEST ENERGY NEUTRINOS

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Neutrinos within a wide energy range are predicted to originate from very-high-energy phenomena in the Universe. Acoustic neutrino detection is a promising option to enlarge the discovery potential for astrophysical sources in the highest-energy regime above 10^{18} eV. In order to investigate the techniques for acoustic particle detection in the deep-sea, the AMADEUS set-up has been integrated into the ANTARES neutrino telescope in the Mediterranean Sea. The research pursued with AMADEUS spans a wide range of topics, amongst them the study of the deep-sea ambient acoustic background: the characterisation of the noise level and of the location, the rate and the correlation length of transient signals.
In this article we describe the basic principles of acoustic neutrino detection and the AMADEUS array of acoustic sensors and we summarise the recent results achieved by the project.

1 Introduction

Several questions in astrophysics, cosmology and particle physics can be pursued using cosmic neutrinos of ultra-high-energies (*UHE*, $E_\nu \gtrsim 10^{18}\,\text{eV}$) as messenger particles. Among these questions are the origin of UHE cosmic rays (*UHECR*), the Greisen-Zatsepin-Kuzmin (*GZK*) effect, cosmological top-down scenarios and topological defects. New results on the particle properties, e.g. the neutrino cross section, are expected at these energies which are not reachable in particle accelerators on Earth. The faint neutrino fluxes at ultra-high energies, e.g. expected from the GZK suppression of UHECR as indicated by the results of the HiRes and Auger Collaborations[1,2], are at the edge of detectability for current or future cubic-kilometre-sized Cherenkov neutrino telescopes (e.g. IceCube and KM3Net). Hence for the study of cosmic UHE neutrinos new approaches in the detection technique are required. We discuss one of those approaches in this article: an acoustic detection method.

2 Acoustic Neutrino Detection

The acoustic detection method is based on sound emission as an effect of the propagation of neutrino-induced particle cascades in liquid and solid media[a]. The sound generation process is described by the *thermo-acoustic model*[3,4]. According to this model, the energy deposition of particles transversing the medium leads to a local heating of the water which is fast with respect to the hydro-dynamical time scale. The temperature change is accompanied by an expansion or contraction of the medium according to volume expansion coefficient and the specific heat capacity. This translates into a pressure wave or acoustic pulse which propagates through the medium. The main input to the calculation of a thermo-acoustic pulse[4] is the superposed energy deposition density in the medium of all particles in a cascade. The evolution of particle cascades resulting from neutrino interactions and their energy deposition need to be simulated with Monte Carlo particle interaction codes like CORSIKA and GEANT[5].

Due to the approximately cylindric cascade geometry, the pressure pulse is emitted in a cylindric wave pattern, i.e. its isobars are located in a disk-shape perpendicular to the cascade axis defined by the neutrino direction[b]. At each point in space within the sonic disk, the thermo-

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[a] Only sea water is regarded here.

[b] At the high energies regarded here, the neutrino direction aligns almost completely with the cascade direction.

acoustic signal is bipolar in time with a peak-to-peak amplitude of the order of 10 mPa per 1 EeV cascade energy at 200 m distance from the cascade; the signal is largely reduced outside the disc. The signal energy spectral density is peaking around 10 kHz and the signal length is several tens of microseconds. The propagation of the sonic wave through the medium is accompanied by attenuation, much lower than the one of optical Cherenkov light, and refraction. The attenuation length for sound propagation in sea water decreases with frequency; for 10 kHz (20 kHz) signals it is on the order of 5 km (1 km).

A three-dimensional array of acoustic sensors with an instrumented volume of $\gtrsim 10\,\mathrm{km}^3$ and with a sensor density of $\approx 100\,\mathrm{sensors/km}^3$ is required to detect acoustic signals for GZK neutrinos with a significant rate. In such a hypothetical detector, the signature of a neutrino-induced sound pulse has to be recognised among the ambient noise and has to be distinguished from background transients which can originate from either surface or under-sea sound sources (fauna or anthropogenic). In the frequency range of interest for acoustic detection, from 1 to 100 kHz, the ambient noise in the deep-sea is primarily generated by agitation of the sea surface – through precipitation, cavitation and spray[6].

3 The AMADEUS Project

The main goal of the AMADEUS (**A**ntares **M**odules for **A**coustic **DE**tection **U**nder the **S**ea) project[7] is to conclude on the feasibility of acoustic UHE neutrino detection in large, sea-based acoustic detector arrays. This study is carried out by means of a dedicated acoustic sensor array constantly operated during several years in a detector environment. The research topics span a wide range: under study are e.g. the distribution, the rate and the correlation length of background events and the level of background noise which determine the achievable acoustic detection sensitivity for UHE neutrinos. In addition, by integrating AMADEUS into the ANTARES neutrino telescope (cf. Sec. 3.1), we will have the opportunity to study hybrid opto-acoustical detection possibilities. For all studies mentioned above, adapted filtering, triggering and reconstruction algorithms are developed and tested on the acoustic data.

3.1 AMADEUS Set-Up

The AMADEUS set-up[c] is part of the ANTARES Cherenkov neutrino telescope[8] (cf. Fig. 1). ANTARES is located off-shore in the Mediterranean Sea about 40 km south of Toulon (France) at a water depth of about 2500 m. It comprises 12 vertical structures, the detection lines labelled *L1 – L12*; the additional line *IL07* is instrumented with several apparatus for environmental monitoring. Each detection line holds 25 *storeys*, the main active part of the detector housing the optical sensors and read-out hardware. The storeys are vertically separated by 14.5 m starting at a height of about 100 m above sea floor. Each line is fixed to the sea floor by an anchor and held vertically by a buoy.

Acoustic sensing is fully integrated into the detector in form of six *Acoustic Storeys* (*AS*) which are modified versions of standard ANTARES storeys. At the AS, the three PMTs are substituted by six acoustic sensors and custom-designed electronics are used for the digitisation and preprocessing of the analogue signals. The distances between sensors in the AMADEUS set-up vary from ≈ 1 m within the storeys to a maximum of ≈ 350 m between two storeys. At the storeys, the sensor data are by default amplified to a sensitivity of ≈ 0.5 V/Pa, filtered with an $\approx 1 - 100$ kHz bandpass and digitised with 250 kSamples per second with a 16bit sampling over the input voltage range from -2 to $+2$ V. All data (up to 1.5 TByte/day) is sent to an on-shore server cluster for filtering and storing. On-line filters are implemented for all goals stated in Sec. 3: a minimum bias filter, recording 10 s samples of data every hour for each sensor, a

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[c] For a detailed description cf.[7].

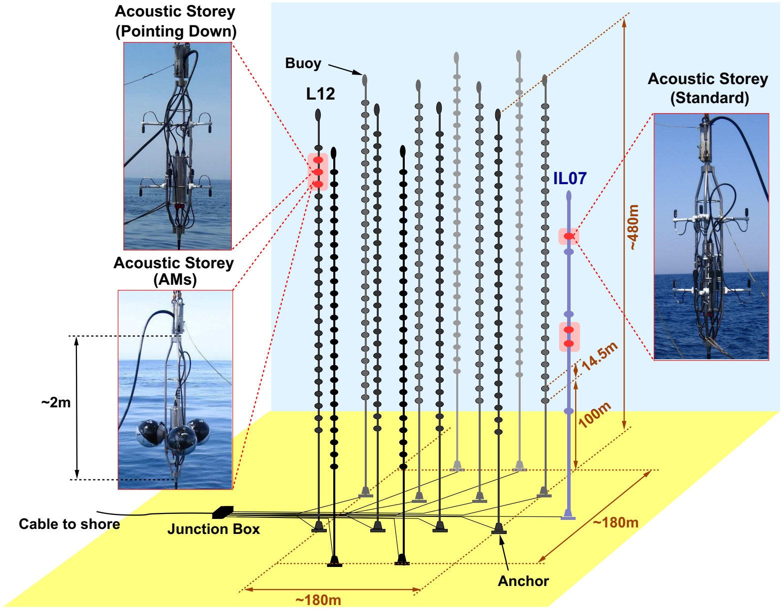

Figure 1: A sketch of the ANTARES detector[7]. The six Acoustic Storeys are highlighted and their three different set-ups, implemented to test acoustic detector designs and sensing methods, are shown.

threshold based filter, and a matched filter based on cross correlation with the expected bipolar signal; the latter two require coincidences between the sensors in a storey. These filters reduce the data volume by a factor of more than 100, constituting the data sample for off-line analysis.

The three acoustic storeys on the IL07 started operation in December 2007, the ones on L12 with the completion of ANTARES in May 2008. AMADEUS is now fully functional with 34 out of its 36 sensors active. After the first year 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. The excellent characteristics can be illustrated using the minimum bias data: the noise levels (root-mean-square of the signal amplitudes in each 10 s sample) recorded at the same time with any two active sensors are highly correlated with coefficients between 93% and 100%. The stability of the data-acquisition electronics is illustrated by the low standard deviation of the distribution of the mean signal amplitude of each sample which is only ≈ 1/10 000 of the input range.

As a major analysis example, the reconstruction of arrival direction of acoustic signals is presented in the following.

3.2 Reconstruction of Arrival Directions

Position reconstruction of acoustic point-like sources is implemented by reconstructing first their arrival direction from individual storeys, taking advantage of these local sensor groups. The combination of reconstructed directions from three or more storeys in a second step results in the source position. For the first step, the direction is identified from the differences in the arrival times of the acoustic wave in the sensors of one storey[9].

Fig. 2 shows a qualitative mapping of the arrival directions of transient acoustic signals originating in the vicinity of the ANTARES detector for the second storey from the bottom on IL07. The data sample has been collected with the minimum bias filter during the time period 29.01. to 05.06.2008. The figure shows the directions of all reconstructed signals (≈ 200 000) which have an amplitude greater than eight times the standard deviation of the ambient noise. As expected, the majority of the sources are received from directions in the upper hemisphere, including all kinds of transient signals, e.g. dolphins click and shipping noise. In the lower

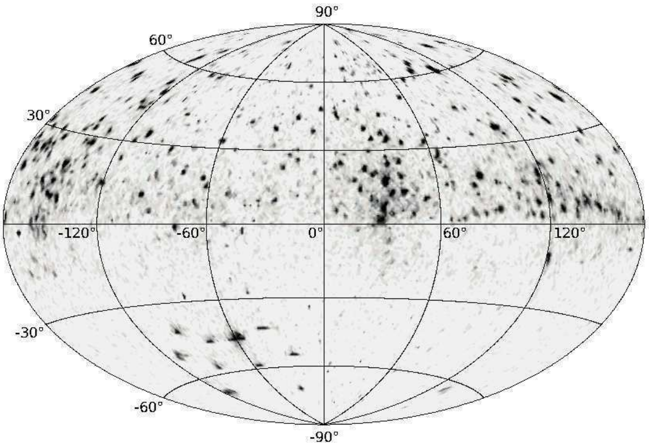

Figure 2: A qualitative mapping in Aitoff projection of the arrival directions of transient acoustic signals[9] for the second storey from the bottom on IL07, 180 m above the sea-bed. The centre direction is defined by the westward direction towards the horizon of that storey. 90° (−90°) in longitude corresponds to north (south), 90° (−90°) in latitude to vertically upwards (downwards).

hemisphere only few sources are observable with the layout pattern of the ANTARES detector evident on the lower left part of the figure. Those sources constitute the ANTARES acoustic positioning system[10], emitting signals from acoustic beacons at the bottom of each line.

4 Conclusions

The acoustic neutrino detection technique is a promising option to extend the study of cosmic neutrinos to the ultra-high-energy regime. The AMADEUS system, dedicated to the investigation of this technique, has been successfully installed together with the ANTARES neutrino telescope. Except for size, the system has all features required for concluding on the feasibility of neutrino detection with a potential future acoustic neutrino telescope. AMADEUS can also be used as a multi purpose device, e.g. for studies of hybrid opto-acoustical neutrino detection techniques, marine acoustic source distributions, and marine research.

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References

1. HiRes Coll., R.U. Abbasi *et al.*, preprint *arXiv:astro-ph/0703099v2* (2007).
2. Auger Coll., A. Watson *et al.*, *Nucl. Instrum. Methods* A **588**, 221 (2008).
3. G.A. Askariyan, B.A. Dolgoshein *et al.*, *Nucl. Instrum. Methods* **164**, 267 (1979).
4. J.G. Learned, *Phys. Rev.* **19**, 3293 (1979).
5. Acorne Coll., S. Bevan *et al.*, preprint *arXiv:astro-ph/0903.0949v1* (2009).
6. R.J. Urick, *Ambient Noise in the Sea*, Peninsula Publishing, Los Altos, USA (1986).
7. R. Lahmann, *et al.*, *Nucl. Instrum. Methods* A , doi:10.1016/j.nima.2009.03.058 (2009).
8. N. Cottini, these proceedings.
9. C. Richardt, *et al.*, *Nucl. Instrum. Methods* A , doi:10.1016/j.nima.2009.03.074 (2009).
10. M. Ardid, *Nucl. Instrum. Methods* A **602**, 174 (2009).

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Summary