Status and Recent Results of the Acoustic Neutrino Detection Test System AMADEUS

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Abstract: The AMADEUS system is an integral part of the ANTARES neutrino telescope in the Mediterranean Sea. The project aims at the investigation of techniques for acoustic neutrino detection in the deep sea. Installed at a depth of more than 2000 m, the acoustic sensors of AMADEUS are based on piezo-ceramics elements for the broad-band recording of signals with frequencies ranging up to 125kHz. AMADEUS was completed in May 2008 and comprises six "acoustic clusters", each one holding six acoustic sensors that are arranged at distances of roughly 1m from each other. The clusters are installed with inter-spacings ranging from 15 m to 340 m. Acoustic data are continuously acquired and processed at a computer cluster where online filter algorithms are applied to select a high-purity sample of neutrino-like signals. In order to assess the background of neutrino-like signals in the deep sea, the characteristics of ambient noise and transient signals have been investigated. In this article, the AMADEUS system will be described and recent results will be presented.

Keywords: AMADEUS, ANTARES, Neutrino telescope, Acoustic neutrino detection, Thermo-acoustic model

1 Introduction

Measuring acoustic pressure pulses in huge underwater acoustic arrays is a promising approach for the detection of cosmic neutrinos with energies exceeding 100 PeV. 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 [1, 2], 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 spectrum that is expected to peak around 10 kHz [3, 4, 5]. 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.

The AMADEUS project [6] was conceived to perform a feasibility study for a potential future large-scale acoustic neutrino detector. For this purpose, a dedicated array of acoustic sensors was integrated into the ANTARES neutrino telescope [7]. In the following, the AMADEUS device will be described and recent results will be presented.

2 The ANTARES Detector

The ANTARES neutrino telescope was designed to detect neutrinos by measuring the Cherenkov light emitted along the tracks of relativistic secondary muons generated in neutrino interactions. A sketch of the detector, with the AMADEUS modules highlighted, is shown in Figure 1. 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, starting at about 100 m above the sea bed and interlinked by electro-optical cables. A standard storey consists of a titanium support structure, holding three *Optical Modules* (each one consisting of a photomultiplier tube inside a water-tight pressure-resistant glass sphere) and one cylindrical electronics container

A 13th line, called *Instrumentation Line (IL)*, is equipped with instruments for monitoring the environment. It holds six storeys. For two pairs of consecutive storeys in the IL, the vertical distance is increased to 80 m. Each line is fixed on the sea floor by an anchor equipped with electronics and

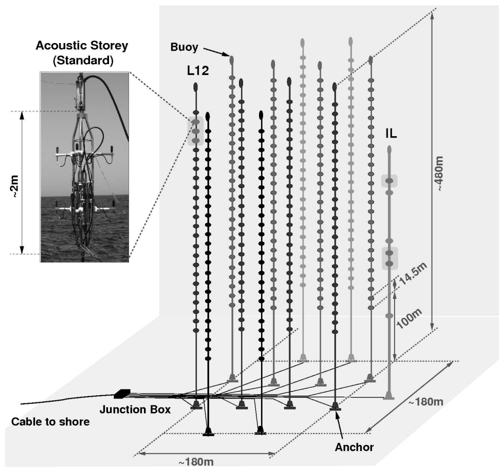

Figure 1: A sketch of the ANTARES detector. The six acoustic storeys are highlighted and a photograph of a storey in standard configuration is shown. L12 and IL denote the 12th detection line and the Instrumentation Line, respectively.

held taut by an immersed buoy. An interlink cable connects each line to the *Junction Box* from where the main electro-optical cable provides the connection to the shore station.

3 The AMADEUS System

Within the AMADEUS system [6], 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 pre-processing of the analogue signals. Figure 2 shows the design of a standard acoustic storey with hydrophones. Six acoustic sensors per storey were implemented, arranged at distances of roughly 1 m from each other. The data are digitised with 16 bit resolution and 250 k samples per second.

The AMADEUS system comprises a total of six acoustic storeys: three on the IL, which started data taking in December 2007, and three on the 12th detection line (Line 12), which was connected to shore in May 2008. AMADEUS is now fully functional and routinely taking data.

Two types of sensing devices are used in AMADEUS: hydrophones and *Acoustic Modules* [6]. The acoustic sensors employ in both cases piezo-electric elements for the broad-band recording of signals with frequencies ranging up to 125 kHz. For the hydrophones, the piezo elements are coated in polyurethane, whereas for the Acoustic Modules they are glued to the inside of standard glass spheres which are normally used for Optical Modules.

The measurements presented in this article were done with the hydrophones. Their calibration will be discussed in Sec. 4.

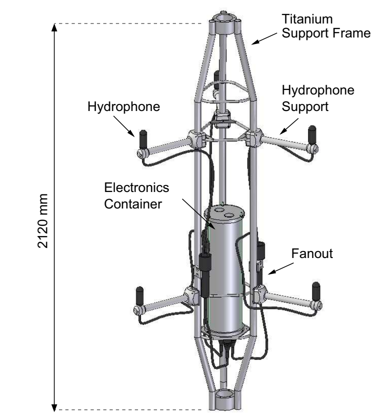

Figure 2: Drawing of a standard acoustic storey, or acoustic cluster, with hydrophones.

The AMADEUS on-shore trigger[1] searches the data by an adjustable software filter; the events thus selected are stored to disk. This way the raw data rate of about 1.5 TB/day is reduced to about 10 GB/day for storage. Currently, three trigger schemes are in operation [6]: A minimum bias trigger which records data continuously for about 10 s every 60 min, a threshold trigger which is activated when the signal exceeds a predefined amplitude, and a pulse shape recognition trigger. For the latter, a cross-correlation of the signal with a predefined bipolar signal, as expected for a neutrino-induced shower, is performed. The trigger condition is met if the output of the cross-correlation operation exceeds a predefined threshold. For the latter two triggers, the thresholds are automatically adjusted to the prevailing ambient noise and the condition must be met in at least four sensors of a storey.

4 Ambient Noise

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 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 IL07 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) were remaining for evaluation, each sample containing data continuously recorded over a time-span of $\sim$10 s. For each of these samples, the noise PSD (units of V^2/Hz) was integrated in the frequency range $f = 10 - 50$ kHz, yielding the square of the ambient noise for that sample, as quantified by the output voltage of the hydrophone. Preliminary studies using the

1. While this functionality might be more commonly denoted as filtering, it is ANTARES convention to refer to the "on-shore trigger".

shower parametrisation and algorithms from [4] 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 $2\langle\sigma_{\rm noise}\rangle$, demonstrating that the ambient noise conditions are stable.

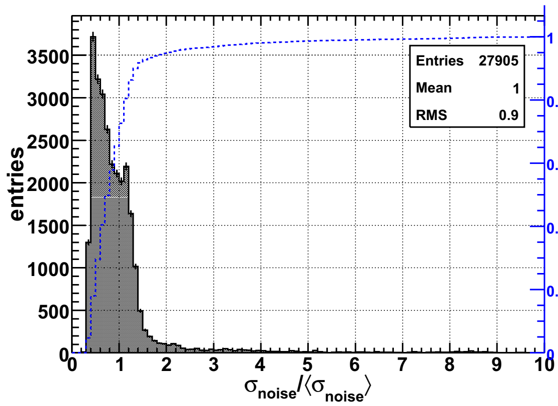

Figure 3: Frequency of occurrence distribution for the ambient noise in the range $10-50$ kHz, relative to the mean ambient noise recorded over the complete period of three years that was used for the analysis (left scale, filled histogram). Also shown is the cumulative distribution, normalised to the 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 sensitivity[2] of -145 ± 2 dB re 1V/µPa. With this value, the mean noise level is $\langle\sigma_{\rm noise}\rangle = 10.1^{+3}_{-2}$ 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 $\sim$15 mPa, equivalent to a neutrino energy of $\sim$1.5 EeV at a distance of 200 m [3]. By applying pattern recognition methods that are more closely tuned to the expected neutrino signal, this threshold is expected to be further reduced.

5 Transient Sources

Transient sources, e.g. from sea mammals, may create signals containing the characteristic bipolar pulse shape that is expected from neutrino-induced showers. Furthermore, the pulse shape recognition trigger (see Sec. 3) selects events with a wide range of shapes. Therefore, a classification scheme is being developed that selects neutrino-like events and suppresses background events with high efficiency. 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.

5.1 Source Position Reconstruction

The sensors within a cluster allow for efficient triggering of transient signals and for direction reconstruction. The combination of the direction information from different acoustic storeys yields the position of an acoustic source. Figure 4 shows the reconstructed directions of all sources

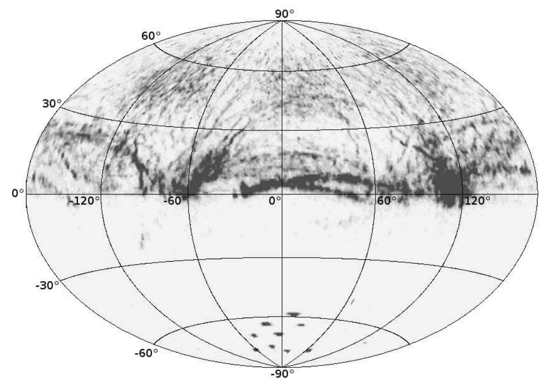

Figure 4: Map of directions of sources as reconstructed with an acoustic storey on Line 12. Zero degrees in azimuth correspond to the north direction, the polar angle of zero corresponds to the horizon of an observer on the acoustic storey. At the bottom, the signals of the emitters of the ANTARES positioning system are visible.

that were triggered during a period of one month. The dark bands of increased acoustic activity can be associated with shipping routes and points of high activity with the directions of local sea ports. It is obvious from Fig. 4 that a fiducial volume for the determination of the background rate of bipolar events must exclude the sea surface.

5.2 Signal Classification

The pulse shape recognition trigger described in Sec. 3 selects a wide range of events each of which can be allocated 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

2. The ambient noise is originating 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.

the classification, simulated signals representing the four classes in equal proportions were produced and a set of features extracted which are highly discriminant between the classes. This feature vector is then fed into a machine learning algorithm [8]. 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”.

6 Monte Carlo Simulations

Monte Carlo simulations based on [3, 4] are currently being implemented for the AMADEUS detector setup. Figure 5 shows the simulated density of the energy deposition of a 10^{10} GeV hadronic shower, projected into the xz-plane. The z- and x-coordinates denote the directions along the shower axis and a direction orthogonal to the shower axis, respectively. It is mostly the radial energy distribution within the shower which is responsible for the shape and amplitude of the acoustic pulse that is observed in the far field. The resulting pulse is shown in Fig. 6. 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 a 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 IL07, see Fig. 1. This simulation illustrates the characteristic three-dimensional pattern expected from neutrino-generated pressure waves.

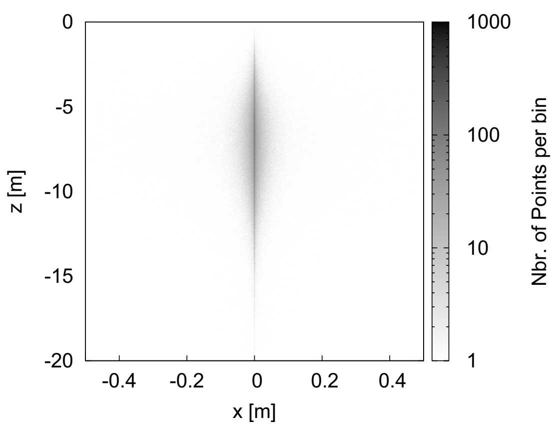

Figure 5: Density of the energy deposition of a 10^{10} GeV hadronic shower resulting from a neutrino interaction, projected from a three-dimensional distribution upon the xz-plane. Bin sizes are 0.01 m in x and 0.1 m in z.

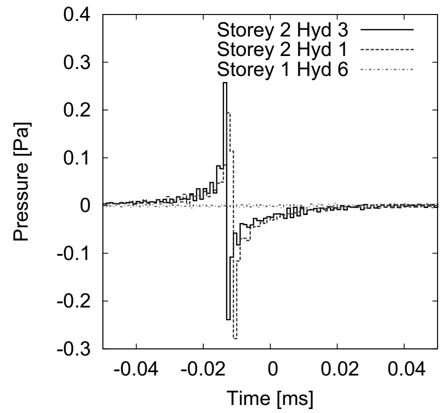

Figure 6: Simulated acoustic signals as recorded with hydrophones in two acoustic storeys with a vertical spacing of 14.5 m. See text for details. For Storey 2, signals from two different hydrophones are shown.

7 Summary and Conclusions

Recent results from the acoustic neutrino detection test system AMADEUS, an integral part of the ANTARES detector in the Mediterranean Sea, have been presented. Measurements of the ambient noise at the ANTARES site show that the noise level is very stable and at the expected level, allowing for measurements of neutrino energies down to $\sim$1 EeV. The current focus of the analysis work is on the classification of transient bipolar events to minimise the irreducible background for neutrino searches. In addition, Monte Carlo Simulations are under development. AMADEUS is excellently suited to assess the background conditions for the measurement of bipolar pulses expected to originate from neutrino interactions.

8 Acknowledgements

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