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Recent Results of the Acoustic Neutrino Detection Test System AMADEUS

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Abstract: The technique of acoustic neutrino detection is a promising approach for future large-scale ultra-high-energy neutrino detectors in water. To investigate this technique in the deep sea, the AMADEUS system has been integrated into the ANTARES neutrino telescope in the Mediterranean Sea. Installed at a depth of more than 2000 m, the 36 acoustic sensors of AMADEUS are based on piezo-ceramics elements for the continuous broadband recording of signals with frequencies ranging up to 125 kHz. In order to assess the background for acoustic neutrino detection in the deep sea, the characteristics of transient signals, which can mimic the acoustic signature of a neutrino interaction, and of the ambient noise have been investigated. In this context, an offline analysis package was developed, including signal classification and acoustic source reconstruction algorithms. In addition, a complete simulation chain was developed. It comprises the generation of acoustic pulses produced by neutrino interactions and their propagation to the sensors within the detector, ambient and transient noise models for the Mediterranean Sea and the response functions of the AMADEUS data acquisition hardware. In this article, the AMADEUS system will be introduced and the procedures for offline event selection and Monte Carlo simulations will be described. Recent AMADEUS results will be discussed and first conclusions concerning the feasibility of acoustic detection of ultra-high-energy neutrinos in the Mediterranean Sea presented.

Keywords: Acoustic Particle Detection, Neutrino Detection, Ultra-High-Energy Neutrinos

1 Introduction

Measuring acoustic pressure pulses in huge underwater acoustic arrays is a promising approach for the detection of ultra-high-energy (UHE, $E_\nu \gtrsim 10^9$ GeV) neutrinos. These are expected to be produced in interactions of cosmic rays with the cosmic microwave background [1]. The pressure signals are produced by the particle showers that evolve when neutrinos interact with nuclei in water. The resulting energy deposition within 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 [2, 3], 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 [4, 5, 6]. 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 [7] 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 [8].

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 Fig. 1. The detector is located in the Mediterranean Sea at a water depth of 2475 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 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 [7], 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.

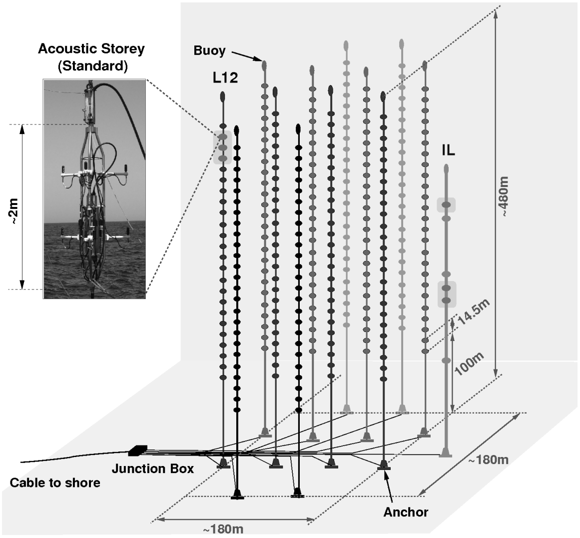

Figure 1: A sketch of the ANTARES detector. The six acoustic storeys are highlighted and a photograph of a storey in standard configuration is shown. L12 and IL denote the 12th detection line and the Instrumentation Line, respectively.

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. Six acoustic sensors per storey were implemented, arranged at distances of roughly 1 m from each other.

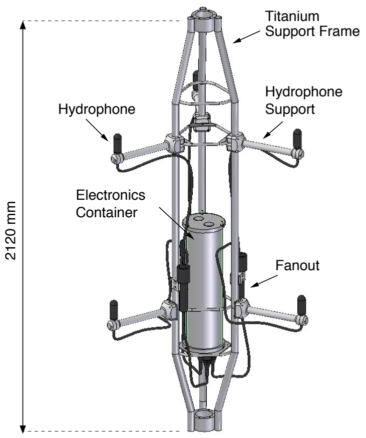

Figure 2: Drawing of a standard acoustic storey.

The AMADEUS system comprises a total of six acoustic storeys: three on the IL and three on the 12th detection line (Line 12). The analysis presented in this article was done with the standard acoustic storeys which are equipped with hydrophones. These acoustic sensors employ piezo-electric elements, coated in polyurethane, for the broadband recording of signals with frequencies ranging up to 125 kHz. The lowest acoustic storey on Line 12 is equipped with alternative sensing devices, so-called *acoustic modules* which are described elsewhere [7].

All data from the 36 acoustic sensors is transmitted to the shore station. Here an adjustable software filter selects events from the data stream for storage on disk and further offline analysis. Currently, three filter schemes are in operation [7]: 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 Acoustic Background in the Deep Sea

To assess the feasibility of acoustic neutrino detection in a natural body of water, transient and ambient noise at the site of the installation have to be investigated. The ambient noise is broadband and is mainly caused by agitation of the sea surface [9], i.e. by wind, breaking waves, spray, and cavitations. Thus it is correlated to the weather conditions, mainly to the wind speed, see e.g. [10]. It is predominantly the ambient background that determines the energy threshold for neutrino detection. Transient noise signals have short duration and an amplitude that exceeds the ambient noise level. These signals can mimic bipolar pulses from neutrino interactions. Sources of transient signals can be anthropogenic, such as shipping traffic, or marine mammals. In particular dolphins emit short signals with a spectrum similar to that of acoustic emissions from neutrino interactions. Given the expected low rate of cosmogenic neutrinos of the order of 1 per year and km^3, the transient background must be *completely* suppressed, which poses a major challenge.

5 Suppression of Transient Background

To suppress signals from transient sources which are not consistent with acoustic signals of neutrino interactions, a classification strategy is employed [11]. This strategy stems from machine learning algorithms trained and tested with data from a simulation (see Sec. 6). Random Forest and Boosted Trees algorithms have achieved the best results for individual sensors and clusters of sensors. For individual sensors, the classification error is of the order of 10 % for a well trained model. The combined results of the individual sensors in an acoustic storey are used as new input for training. This method obtains a classification error below 2 %.

Using the six hydrophones of an acoustic storey, direction reconstruction of point sources is possible with an accuracy of $1.6^\circ \pm 0.2^\circ$ in azimuth and $0.6^\circ \pm 0.1^\circ$ in zenith [12]. If the directions were reconstructed for at least two of the acoustic storeys, the best approximation of the intersection point of the rays starting from the sensor clusters and pointing into the reconstructed direction is searched for. In principal, a powerful method to reduce ambient background is to restrict neutrino searches to a fiducial volume that excludes the topmost part of the sea above a depth of about 500 m. This eliminates signals from ships and from dolphins, which do not dive below 500 m. However, given the geometry of AMADEUS, the small angular errors of the zenith angle reconstruction translate into large uncertainties of the position reconstruction at large distances. Hence the more effective approach of suppressing sources using a

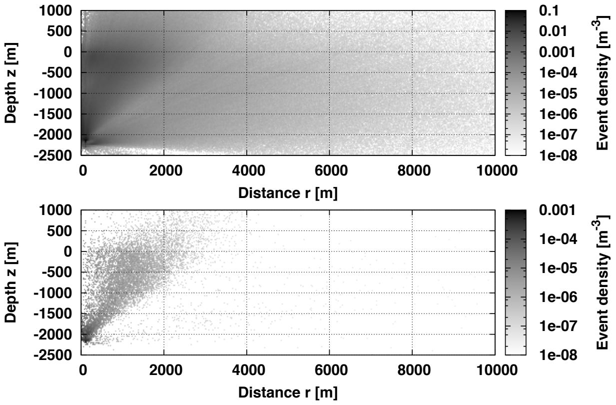

Figure 3: Spatial density of transient signals as a function of the depth z and the distance r from the centre of the AMADEUS detector. Top: the density of transient signals as selected by the AMADEUS online filter; bottom: events remaining after the offline cuts described in the text.

clustering algorithm was chosen: since neutrino interactions are rare and isolated events, a number of events clustering temporally and spatially can be assumed to stem from a single source such as a ship or a sea mammal. To avoid the aforementioned problems with the position reconstruction, for each event the intersection of the reconstructed direction with the sea surface was used as input for the clustering algorithm.

Figure 3 shows the distribution of events over an integrated measurement time of about 156 days without any offline suppression and after applying the signal classification and clustering cuts described above. The background from transient signals is reduced from $15 \times 10^3\,\mathrm{km}^{-3}\,\mathrm{yr}^{-1}$ to $100\,\mathrm{km}^{-3}\,\mathrm{yr}^{-1}$. Figure 3 shows the limitations of the reconstruction of the z-coordinate, which is smeared out and even extends to positive values which would imply a source above the sea surface.

The background rate was reduced significantly by applying the cuts described above, but as mentioned in the previous section, basically a complete reduction of the transient background is required. The characteristic propagation of the signal within a flat disk-like shape (the "pancake") is another important feature to classify neutrinos. This feature however cannot be exploited with AMADEUS due to its small size and two-dimensional arrangement of acoustic storeys. With the software framework developed and the data collected with the AMADEUS detector, designs of large acoustic neutrino detectors can be investigated using Monte Carlo techniques in order to optimise the detector layout with respect to the potential for the reconstruction of the source position and the three-dimensional shape of the acoustic emission pattern.

6 Simulation Chain

The simulation chain [10] consists of the following modules, which build upon each other to create a simulated neutrino event:

1. An interaction vertex is located at a random position in a given volume around the detector and the energy and direction of the incident neutrino are set randomly within predefined ranges.
2. The Monte Carlo hadronic shower is produced from a parametrisation, valid up to a total shower energy of 10^{12} GeV, which is based on work by the ACoRNE collaboration [4, 5]. The fraction of energy of the neutrino energy that is deposited in the shower is calculated according to parametrisations from [13].

   After the cascade has been simulated, the acoustic pulse and its propagation to the sensors within the detector are calculated following [4, 5]. This comprises the disk-like propagation pattern and the bipolar pulse recorded by the sensor.
3. A realistic model of both the ambient and transient background, reproducing the characteristics measured with AMADEUS have been implemented. Signal and noise are then superimposed.
4. The inherent noise of the sensor is added and the resulting waveform is convoluted with the system transfer function of the sensor. Subsequently, the same steps of adding noise and applying the system transfer function are applied for the read-out electronics.
5. The output is directed to the simulation of the online filter system described in Sec. 3.

The complete chain allows for the investigation of the neutrino detection efficiency of AMADEUS or any other existing or potential acoustic neutrino detection device.

7 Effective Volume

A measure of the sensitivity of the AMADEUS device to neutrino interactions is its effective volume. While the AMADEUS layout will not allow for an effective volume sufficient to set a competitive limit on the flux of ultra-high-energy neutrinos, an estimate of the energy detection threshold can be derived and the effects of various cuts and environmental conditions can be quantified. The simulation and analysis chains described above were used to simulate the data required for this study. An effective volume V_{eff} for the AMADEUS detector can be defined as:

$$V_{\mathrm{eff}}(E_\nu) = \frac{\sum_{N_{\mathrm{gen}}} \delta_{\mathrm{sel}} p(E_\nu, \mathbf{r}, \mathbf{e_p})}{N_{\mathrm{gen}}} V_{\mathrm{gen}}, \qquad (1)$$

where N_{gen} is the number of generated neutrino interactions in a volume V_{gen} and $p(E_\nu, \mathbf{r}, \mathbf{e_p})$ is the probability that the neutrino reaches the interaction vertex set in the simulation. $\delta_{\mathrm{sel}} \in \{0,1\}$ accounts for the fact that the probability only contributes to the effective volume if the pressure pulse corresponding to the neutrino interaction was selected by the online filter within a time window of $128\,\mu$s around the expected arrival time. The probability that the neutrino reaches the interaction vertex is given by:

$$p(E_\nu, \mathbf{r}, \mathbf{e_p}) = e^{-d_{\mathrm{WE}}(\mathbf{r}, \mathbf{e_p})/\lambda_{\mathrm{water}}(E_\nu)}, \qquad (2)$$

where $\mathbf{r}$ is the position of the interaction vertex, $\mathbf{e_p}$ is the unit vector of the direction of the flight trajectory. The mean free path $\lambda_{\mathrm{water}}(E_\nu)$ of the neutrino in water is antiproportional to the total cross section of the neutrino. The total cross section as a function of the neutrino energy E_ν was parametrised using values from [14]. The distance d_{WE} is the water equivalent of the distance travelled through matter of varying density encountered by the neutrino along its flight path. For the determination of the density distribution

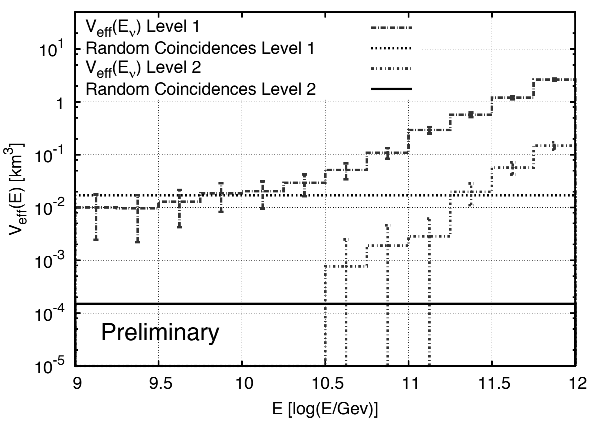

Figure 4: The effective volume of the AMADEUS detector as a function of the logarithmic neutrino energy for the two different levels, as described in the text. Also shown are the random coincidence rates for the levels 1 and 2.

along the flight path, the PREM[1] [15] was used to model the density profile of the earth. In addition, it is assumed that the earth is covered by water of 2.5 km depth and the detector is placed on the sea floor. For the calculation of the effective volume, 10^7 neutrinos with energies uniformly distributed between 10^9 GeV and 10^{12} GeV were simulated. With the uniform energy distribution, a sufficient number of events over the entire energy range is available. The interaction vertexes of these neutrinos were chosen in a cylindrical volume of 1200 km^3 around the AMADEUS detector. The heading of the flight path was ranging from $0-360^\circ$ in azimuth and from $0-100^\circ$ in zenith[2]. Neutrinos entering the volume V_{gen} from below the horizon will traverse an increasing amount of matter. For a zenith angle greater than 100°, the probability of a neutrino in the energy range under consideration to reach the interaction vertex is practically zero. To determine random coincidences formed by the ambient noise, a separate set of simulated data was created not containing any signals. The effective volume has been calculated for two different "levels" describing increasingly realistic conditions:

Level 1: Ambient noise is assumed to be minimal, always corresponding to a perfectly calm sea, and the coincidence requirement for the filter simulation is that at least two sensors on one storey need to respond.

Level 2: The complete ambient noise model and the standard online filter of AMADEUS are used, requiring a signal in at least four sensors on two storeys each.

The results of this study are shown in Fig. 4. For levels 1 and 2, the effective volume is at least one sigma above the "fake flux" from random coincidences for energies exceeding 1.8×10^{10} GeV and 1.8×10^{11} GeV, respectively. The requirements of level 1 are minimal, so this can be seen as an idealised detection threshold of the AMADEUS detector. The effective volume for level 1 exceeds 2 km^3 at 10^{12} GeV, while for level 2, it is about 0.1 km^3 at this energy.

Note that for a potential future large-scale acoustic neutrino detector with a three-dimensional arrangement of acoustic sensors, the effective volume cannot be easily derived from the results for AMADEUS by simple scaling. For neutrinos with energies near the detection threshold, the effective volume will be mainly determined by the instrumented volume (assuming sufficiently dense instrumentation). For rising energies, the water volume monitored around the detector will become increasingly important. The energy threshold as estimated in this study presumably can be decreased if a larger number of sensors is used to trigger events, as the effect of random coincidences will be reduced. Applying pattern recognition methods on the triggered signals might further reduce the threshold.

8 Conclusion and Outlook

Recent results from the acoustic neutrino detection test system AMADEUS, an integral part of the ANTARES detector in the Mediterranean Sea, have been presented. The suppression of the transient background was discussed and a full simulation chain, starting from the interaction of the neutrino in water and ending with the electric signal registered in the acoustic sensors, was applied to calculate the effective volume of AMADEUS. For realistic conditions, the effective volume is around 0.1 km^3 at 10^{12} GeV and the detection threshold was estimated as about 1.8×10^{11} GeV. The latter is expected to decrease for a larger device. The data recorded with AMADEUS can be used for Monte Carlo simulations to optimise the design of a potential future large-scale acoustic neutrino detector.

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1. Preliminary Earth Reference Model
2. A zenith angle of 0° corresponds to a neutrino coming from above.