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Research Article

Acoustic Particle Detection with the ANTARES Detector

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The (Antares Modules for Acoustic Detection Under the Sea) AMADEUS system within the (Astronomy with a Neutrino Telescope and Abyss environmental RESsearch) ANTARES neutrino telescope is designed to investigate detection techniques for acoustic signals produced by particle cascades. While passing through a liquid a cascade deposits energy and produces a measurable pressure pulse. This can be used for the detection of neutrinos with energies exceeding 10^{18} eV. The AMADEUS setup consists of 36 hydrophones grouped in six local clusters measuring about one cubic meter each. This article focuses on acoustic particle detection, the hardware of the AMADEUS detector and techniques used for acoustic signal processing.

1. Introduction

AMADEUS [1] is a system for acoustic detection within the ANTARES [2] infrastructure. It is designed to investigate the feasibility of acoustic detection of ultra high energy neutrinos. ($E_\nu \geq 10^{18}$ eV).

The ANTARES experiment, a water Cherenkov neutrino telescope (see Figure 1), is located 25 km off the southern French coast at a water depth of 2500 m and consists of 12 vertical support structures, so called lines, of 480 m length. They are anchored to the sea floor over an area of about $(180 \times 180)\ \mathrm{m}^2$ and held vertically by immersed buoys. A line supports 25 mechanical frames, so called storeys, instrumented with three photo-multipliers each. In addition a 13th line, the Instrumentation Line (IL), is used for environmental monitoring and multidisciplinary research. The AMADEUS system is incorporated into the ANTARES detector. It consists of six local clusters with six acoustic sensors each, placed at water depths between 2000 and 2300 m. Three of these clusters are located on the 12th line with a spacing of 14.5 m, while the rest is mounted on the IL with a spacing of 14.5 m and 110 m, see Figure 1. The distances between the hydrophones within a cluster of the order of one meter.

Amongst the goals of the AMADEUS detector are the investigation of the background for acoustic detection in the deep sea (rate of neutrino-like signals, localization of background sources, and levels of ambient noise), the study of signal and background correlations on different length scales, the development and test of filter and reconstruction algorithms, the evaluation of different sensors and sensing methods, and the study of hybrid optoacoustical detection methods. These studies will allow to evaluate the feasibility of acoustic particle detection with a future large volume detector. This paper introduces the generation of acoustical signal, describes the AMADEUS detector (Section 3), and discusses the online data handling (Sections 4 and 5). In Section 6 an example for offline analysis is given and first results are presented.

2. Signal Generation

The acoustic neutrino detection method is based on a theory that implies the production of pressure waves by particle cascades passing through liquids [3]. This lead to the development of the thermoacoustic model [4, 5] according to which a sound wave is generated by a local energy deposition, produced by a particle cascade, in a medium. The energy deposition causes an increase in temperature and thus, depending on the medium properties, results in an accelerated expansion or contraction creating a detectable pressure pulse. This effect can be used to detect neutrinos; a neutrino interaction in water produces a cascade resulting in a measurable pressure pulse. A simulated exemplary bipolar pulse produced by a neutrino interaction

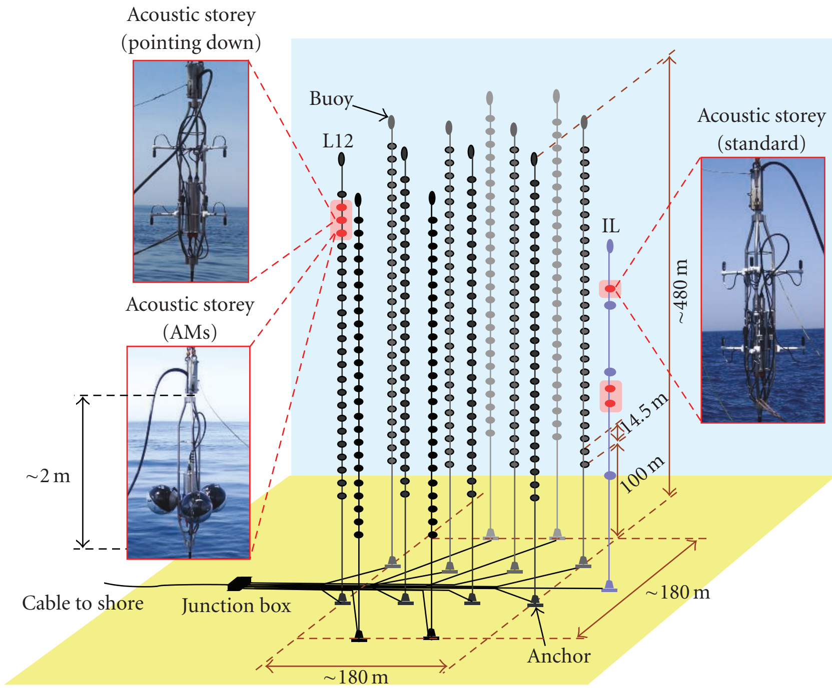


Figure 1: The ANTARES detector. The AMADEUS clusters are located on the Instrumentation Line (IL) and Line 12 (L12). Five clusters are equipped with hydrophones and one with acoustic modules (AM) using piezo ceramics glued to the inside of a glass sphere instead of hydrophones. Four of the hydrophone clusters were assembled with the hydrophones pointing upward, referred to as "standard", while one cluster was assembled with the hydrophones looking downwards.

in water for a cascade energy of 1 *E*eV [6] is shown in Figure 2.

The signal amplitude scales linearly with the energy deposited in the cascade (E_{casc}) and at 1 km perpendicular to the shower axis, is roughly given by

$$p(1\,\text{km}) \approx 1\,\text{mPa} \cdot \frac{E_{\text{casc}}}{1\,E\text{eV}}. \tag{1}$$

Its spectral density peaks at about 10 kHz.

3. The AMADEUS Detector

The acoustic system AMADEUS was integrated in the ANTARES experiment. On that account special hard- and software was designed. The idea was to keep the overall layout of the line and to modify only some stories according to the requirements of the acoustic detection. Therefore the optical modules [7], present on every standard ANTARES storey, had to be replaced by acoustic sensors and the standard data acquisition cards [8] by custom boards meeting the requirements for the acoustic sensors. In addition dedicated software needed to operate the detector was developed. Two different types of acoustic sensors were used, hydrophones and so-called acoustic modules, both using piezo-electrical ceramics to convert pressure waves into voltage signals. The hydrophones consist of a ceramic and a preamplifier coated in polymer plastics. They measure about 4 cm in diameter and 10 cm in length. Two types of hydrophones were used for the AMADEUS detector, commercial and produced by the (Erlangen Centre for Astroparticle Physics) ECAP both specifically designed for the frequency range of interest and for low inherent noise level. Storeys equipped with hydrophones consist of a frame with six arms supporting the sensors, see Figure 3(a). Three of the acoustic storeys are equipped with commercial hydrophones, two with ECAP hydrophones and one with acoustic modules.

The acoustic modules consist of a ceramic and an amplifier glued to the inside of a glass sphere, the same spheres as used for the optical modules. This enables the investigation of the possibility to combine optical and acoustical sensing. The storey equipped with acoustic modules consists of three glass spheres mounted on a frame with an opening angle of 120°. Each glass sphere houses two acoustic sensors with an opening angle of 60° thus rendering a 2π coverage in the azimuthal angle, see Figure 3(b).

In both cases the sensors are connected to a local control module (LCM) housing the readout electronics, power supply and a compass board monitoring the orientation and tilt of the storey. Figure 4 shows the LCM of an Acoustic Storey. All components except for the data acquisition card are standard ANTARES components.

The DAQ (AcouADC), shown in Figure 5, consists of an analog and a digital part. The analogue part amplifies the signal, settable to 12 different factors between 1 and 562, and applies a bandpass filter suppressing frequencies below 4 kHz, governed by the ambient noise, and above 130 kHz. The bandpass filter is essentially flat with a linear phase response. The digital part of the AcouADC digitizes and processes the acoustic data. Designed to be highly flexible it uses a micro-controller and a field programmable gate

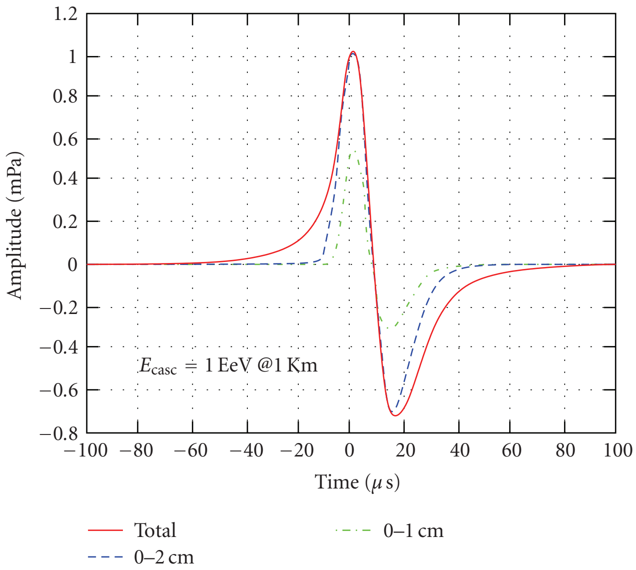
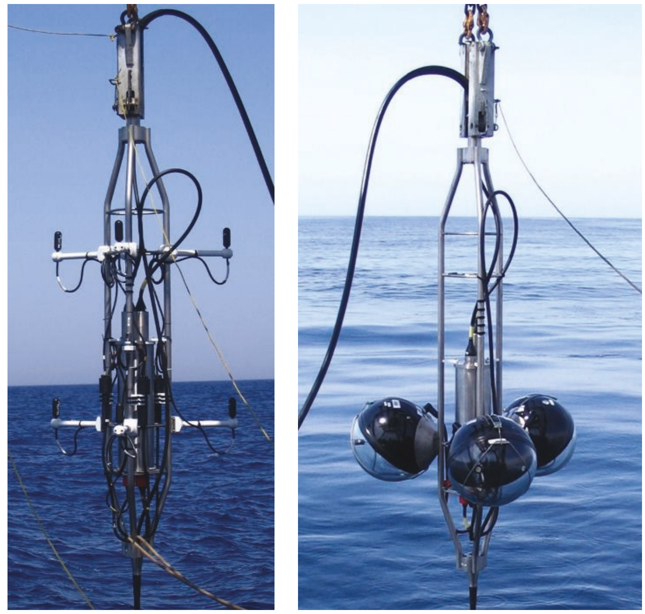


Figure 2: Simulated bipolar pressure pulse from a 10^{18} eV hadronic cascade at a radial distance of 1 km. Roughly half of the pressure pulse is produced within a radius of 1 cm (dash-pointed line) of the cascade, whereas the energy distribution within a radius of 2 cm (dashed line) is nearly completely responsible for the final signal shape (solid line). Figure adapted from [6].



(a) (b)

Figure 3: An Acoustic Storey of the IL (a), equipped with hydrophones, and the lower most Acoustic Storey of L12 (b) equipped with Acoustic Modules, shown during their deployment.

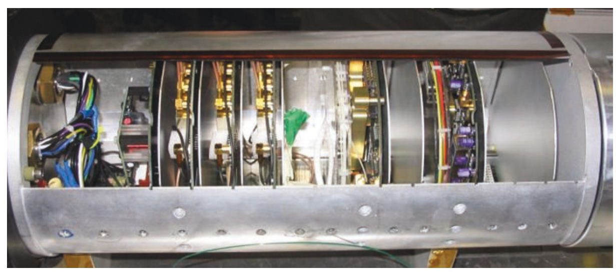


Figure 4: An LCM crate equipped with AcouADC boards before insertion into its titanium housing. From the left to the right, the following boards are installed. The Compass board, 3 AcouADC boards, a Data Acquisition (DAQ) board that sends the data to shore, and a Clock board that provides the timing signals to correlate measurements performed in different storeys.

array. The micro controller can be programmed from the shore station (with the so called "on shore software") and is used to adjust the setting of the analogue part and the data processing.

4. Data Acquisition

The AMADEUS data acquisition is based on the ANTARES DAQ [7] consisting of an off-shore and an on-shore part. On-shore, digitization and data transfer is handled by the LCMs present on every storey. The ANTARES DAQ is capable of handling several ten Mbits/s for each storey and is thus capable of sending all data to shore in order to be processed there.

Although the AcouADC cards are capable of prefiltering the data stream currently all data is being sent to shore resulting in a data stream of 144 Mbit/s for all 36 acoustic sensors.

Time synchronization between the sensors is achieved by the ANTARES clock system with a time resolution of 50 ns.

On shore the data is handled by a dedicated computer cluster consisting of four servers. Two are used for the signal triggers, one for the system control and one for storing the data. For an overview of the DAQ, see Figure 6.

5. Trigger Concept

Since the raw data flow of the AMADEUS detector would result in 1.5 TByte of data per day the incoming data stream has to be filtered before storage. The data is sent to the filter processes in timeslices of 104.864 ms length. Currently 12 processes running in parallel filter the data by applying three different trigger algorithms, consisting of a minimum bias, a threshold, and a cross-correlation trigger. Once a trigger has identified a signal, a coincidence check is performed to see if a predefined number of sensors on one storey recorded the same signal. If both criteria are met a time window with raw data including the signal is stored for all triggered sensors. Following a brief overview of the filters used is given.

5.1. Minimum Bias Trigger. In order to study ambient noise in the sea a minimum bias trigger was implemented. This trigger stores the complete input stream of the sensors for about 10 seconds every hour. This results in 4 GB of noise data per day, sufficient to perform noise studies, such as noise weather correlations.

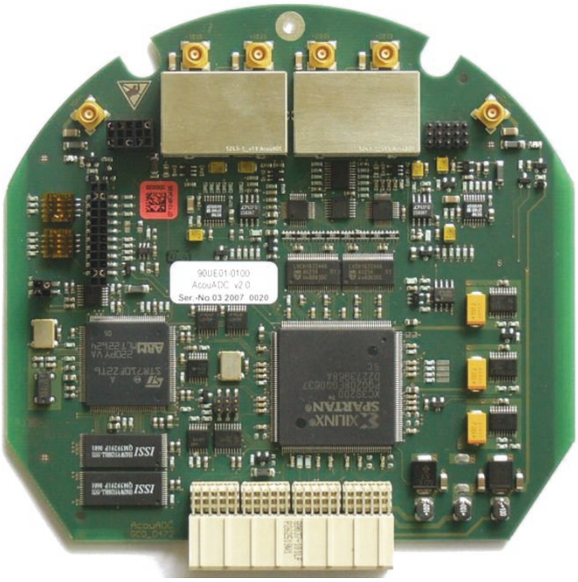


Figure 5: An AcouADC board. Metal covers on the analog part are for shielding.

5.2. Threshold Trigger. To investigate transient signals in the vicinity of the detector a simple threshold trigger is applied. In this case an adaptive trigger is required because of varying noise conditions in the deep sea, mainly caused by sea agitation due to weather conditions. A transient signal has to exceed the RMS of the current timeslice ($\approx$104 ms) by a predefined factor. To avoid statistical fluctuations a predefined consecutive number of samples in the timeslice have to exceed the threshold. If all criteria are fulfilled the waveform of the detected signal is stored. Advantages of a threshold trigger are that no knowledge of the signal characteristics is needed and that little computational power is required.

A known source for transient signals are the transducers (also called pingers) of the ANTARES acoustic positioning system [9]. As only the anchors of the 13 lines are fixed to the sea floor the rest of the detector is able to move in the sea current, see Figure 1. Since precise knowledge of the storey positions within the ANTARES detector are needed for event reconstruction, an acoustic system consisting of transducers on the anchor of every line and receivers along the lines is used to triangulate their positions. The signals are high in amplitude, have a sinusoidal shape and narrow bandwidth and thus easily identified in the data stream.

5.3. Cross-Correlation Trigger. The filters discussed above do not take into account the signal shape. To use this additional information, a pattern recognition based on a cross correlation of the data with a predefined bipolar pulse, characteristic of a neutrino-induced acoustic signal, is used. The cross correlation for two discrete functions f and g is defined as

$$(f \circ g)(i) := \sum_{k=-N/2}^{N/2} f(i+k)g(k). \tag{2}$$

It results in a peak if the template g best matches the function f. To improve computational time the operation is done in the frequency domain using the convolution theorem of the Fourier-transform F:

$$F[(f \circ g)(i)] := F[f(i)]F[g(i)]^{\star}, \tag{3}$$

where $\star$ denotes conjugation. A perfect match between the data and an expected signal would result in a δ-like peak with an amplitude corresponding to the template amplitude. Variations in central frequency result in a broadening of the output signal. Detected signals are analyzed for further characteristics as every bipolar signal similar to the expected signal will create a peak in the cross correlation. A measure for the quality of the signal is the ratio between the width and the height and the integral of the resulting peak. This information is recorded along with the wave form.

The operations introduced can be executed in real time, with the current system.

Although a matched filter is slightly better than the cross correlation function the increase in efficiency would cost a lot of computational power.

5.4. Further Trigger Techniques. Besides the filter methods introduced above a number of other techniques are currently being investigated. Among them are Singular Value Decomposition for noise removal and artificial neural networks for pattern recognition.

6. Offline Data Analysis

The off-line analysis consists of a wide range of activities ranging from noise weather correlation to signal source location reconstruction. Direction reconstruction is one of the off-line signal processing algorithms. It is used for source location reconstruction. To simplify reconstruction the detector was designed with clusters of hydrophones. A cluster of small size, in this case six hydrophones in a volume of about one cubic meter, greatly reduces the time window necessary to be analyzed and simplifies signal selection at high background rates. Following two methods currently employed for direction reconstruction will be discussed, beamforming and the difference method.

6.1. Beamforming. This method requires the knowledge of the hydrophone positions, within a cluster, synchronized data, and comparable sensor responses. Beamforming is realized by creating a sound intensity plot scanning all directions in space (4π) for the actual source direction. Given the six hydrophone coordinates $\vec{r}_n$ ($n = 1, 2, \ldots, 6$), the signal p_n of every hydrophone is shifted in time corresponding to the difference in path length of the sound wave reaching the respective hydrophone from a given direction. Hence every direction in space corresponds to a set of time differences Δt_n in the data. For a direction $\vec{k}$, the beamforming output at time t is given by

$$b\left(\vec{k}, t\right) = \sum_{n=1}^{N=6} w_n p_n\left(t - \Delta t_n\left(\vec{k}\right)\right), \tag{4}$$

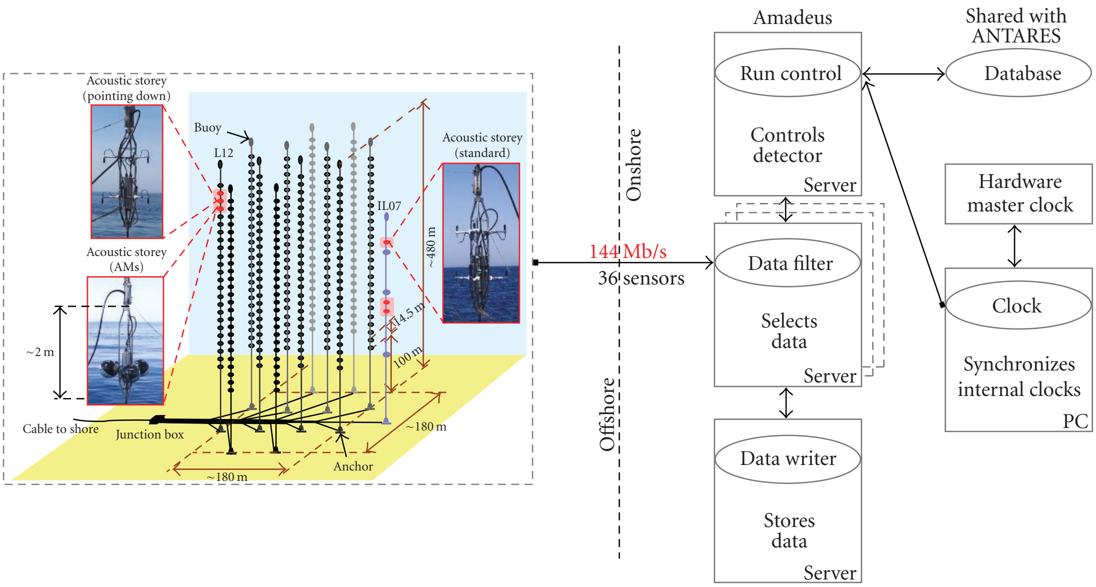


Figure 6: Overview of the AMADEUS DAQ system.

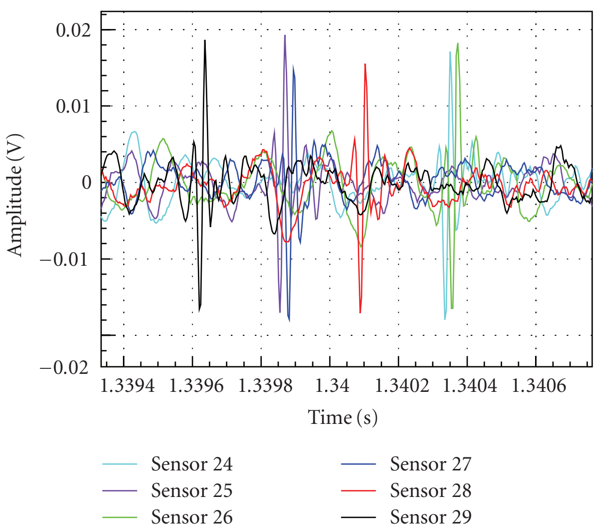


Figure 7: Signals recorded by one local cluster, consisting of six hydrophones.

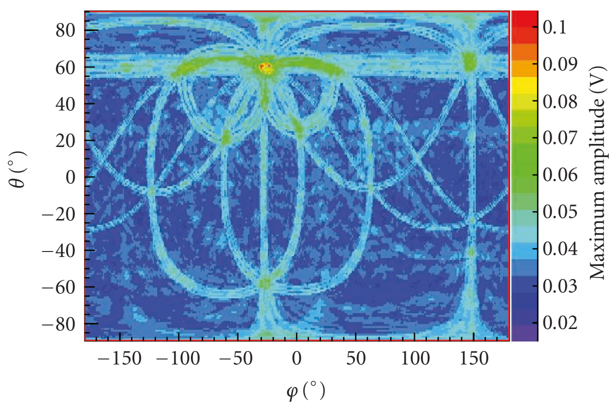


Figure 8: Output of the beamforming algorithm (4) applied to the signal shown in Figure 7. The maximum, indicating the signal direction, can be identified at $\theta = 59^\circ$ and $\varphi = -29^\circ$.

where w_n represent weighting factors for every individual hydrophone. These factors are adjusted to match the directional sensitivity of each hydrophone. Following $w_n \equiv 1$ was used. The time differences Δt_n are computed assuming a plane wave (The assumption of a plane wave is a sufficiently good approximation if the distances are large compared to the dimensions of a cluster). The algorithm scans a solid angle of 4π with a predefined step size in θ, φ by applying the calculated time differences to the data, assuming a constant speed of sound. Once all directions are scanned, the maximum value of the produced output identifies the direction of the signal. For this direction all signals are shifted such that they add up constructively. Figure 8 shows the output of the beamforming algorithm applied to the signal in Figure 7.

The beamforming output (Figure 8) shows a well-defined maximum at $\theta = 59^\circ$ and $\varphi = -29^\circ$. The error in θ is less than one degree, while the error in φ is about three degrees due to correction of the orientation of the storey. Local maxima and the visible patterns in Figure 8 correspond to directions where the time shift results in the constructive addition of two or more signals.

The advantage of this method is that it can be applied to untriggered data. The disadvantage is that it is time consuming compared to the method described next.

6.2. Time Difference Method. The second method described here uses time differences between signals, detected by the hydrophones in a cluster, for direction reconstruction. It

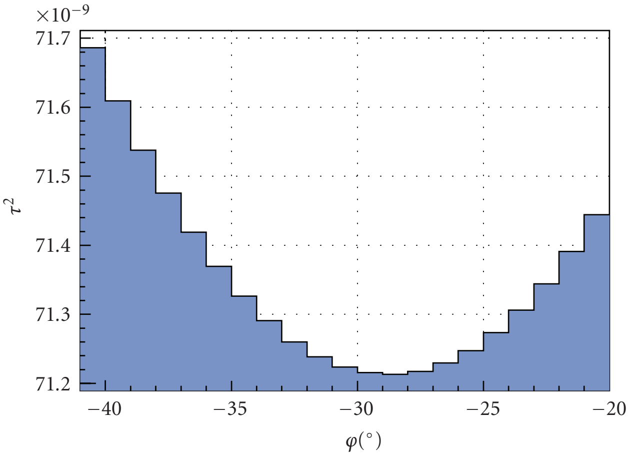


Figure 9: Cut through the $\theta - \varphi$ plane at $\theta_{\min}$ of the minimum computed with the time difference method.

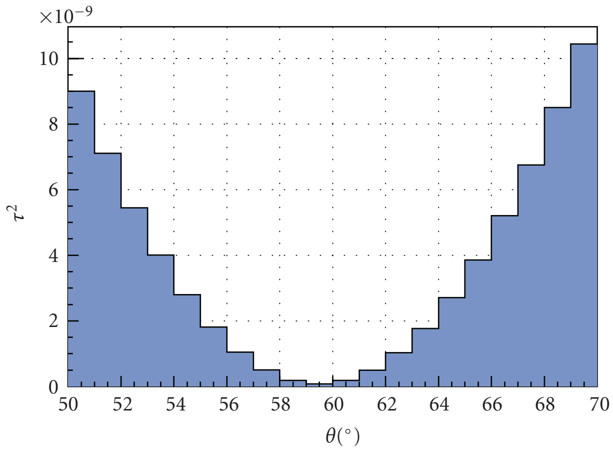


Figure 10: Cut through the $\theta - \varphi$ plane at $\varphi_{\min}$ of the minimum computed with the time difference method.

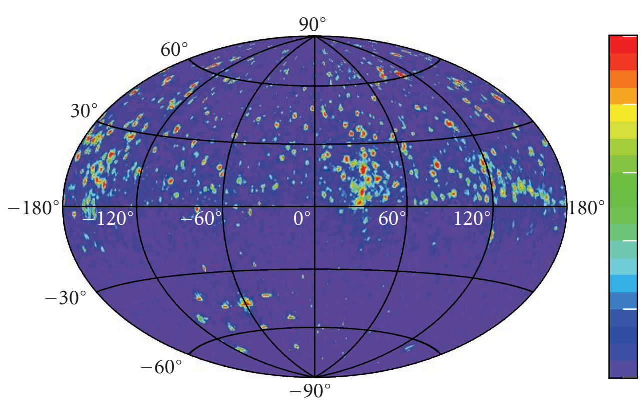


Figure 11: A qualitative mapping of the arrival directions of transient acoustic signals. The majority of the signals come from above. In the lower hemisphere the ANTARES acoustic position system can be identified.

requires, in addition to synchronized data and the knowledge of the hydrophone positions, a signal identification. The signal arrival times are determined once a signal passes the threshold trigger. Direction reconstruction is done by comparing the measured to the expected signal arrival times. The expected time $t_{n_{\text{expected}}}(\theta, \varphi)$ for an arriving wave front from direction (θ, φ) is taken from a lookup table and subtracted from the measured time. That is performed for a 4π solid angle in the desired angular resolution, where the minimum indicates the reconstructed direction:

$$\min(\theta, \varphi)\{\tau^2(\theta, \varphi)\} \quad (5)$$

with

$$\tau^2(\theta, \varphi) := \sum_{n=1}^{6} \left(t_{n_{\text{measured}}} - t_{n_{\text{expected}}}(\theta, \varphi)\right)^2. \quad (6)$$

This technique is similar to beamforming, but much faster. Applied to the data in Figure 7 the algorithm produces the τ^2 data shown in Figures 9 and 10 for the different angles. A clear minimum can be identified in both θ and φ. The values match the ones obtained by the beamforming algorithm. The error for the direction reconstruction is about two to three degrees in the azimuthal and about one degree in the zenith angle. Errors in the azimuthal angle result from the compass calibration and the dimensions of the antenna while errors for the zenith angle are mainly governed by the binning of the direction reconstruction algorithm.

The time difference method is roughly a hundred time faster than the beamforming method introduced earlier.

Figure 11 shows a qualitative mapping of the arrival directions of transient acoustic signals originating in the surrounding of the ANTARES detector. The direction reconstruction was done using the time difference method. The data was collected in October 2008 and includes all types of transient signals, biological, technical, and neutrino-like. The virtual observer resides on a storey of the ANTARES detector, about 400 m above the sea bed, looking north towards the horizon, thereby defining the origin of the coordinate system. Recurring tracks in this "marine-map" indicate that most transient signal originate from ship traffic, leaving the lower hemisphere with comparably few signals except for the positioning system of the ANTARES detector.

7. Summary

The AMADEUS system for acoustic particle detection was introduced. The purpose of the detector is to investigate the feasibility of detecting acoustic signals produced in neutrino particle interactions. The particle interaction results in a pressure pulse detectable by acoustic sensors. To assess the feasibility, acoustic sensors were developed in form of hydrophones and acoustic modules both making use of piezo-electric sensors. All data detected by the sensors is filtered by a bandpass filter, digitized and sent to shore. On shore the data is subject to a signal processing passing a minimum bias, a threshold and a cross correlation filter. The triggered signals are classified and their wave forms recorded. Synchronization of the 36 sensors is achieved by a 50 ns clock. Off-line data analysis includes more advanced techniques like beam forming and time delay methods for signal direction reconstruction. Triggering efficiency is currently under investigation. Direction reconstruction for source location is showing promising results. For the search of neutrino-like background signals the detected signals have to be analyzed in respect to their bipolar shape. This is an ongoing analysis.

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