Position reconstruction of acoustic sources with the AMADEUS Detector

C. Richardt G. Anton K. Graf J. Hößl U. Katz R. Lahmann M. Neff

Universität Erlangen ECAP (Erlangen Centre for Astroparticle Physics), Erwin Rommel Str. 1, 91058 Erlangen, Germany

Abstract
This article focuses on techniques for position reconstruction of acoustic point sources with the AMADEUS setup consisting of 36 acoustic sensors in the Mediterranean Sea. The direction reconstruction of an acoustic point source utilizes the information of the 6 small-volume hydrophone clusters of AMADEUS individually. Source position reconstruction is then done by combining the directional information of each cluster. The algorithms for direction and position reconstruction are explained and demonstrated using data taken in the deep sea.

Key words: acoustic particle detection, UHE neutrinos, neutrinos, beamforming

1. Introduction

AMADEUS [1] (Antares Modules for Acoustic Detection Under the Sea) is a system for acoustic detection within the ANTARES [2] (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) infrastructure. The former is designed to investigate the feasibility of acoustic detection of ultra high energy neutrinos. The ANTARES experiment 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 \((180 \times 180)\) m\(^2\), held vertically by buoys and support a total of \(\sim 900\) photo-multipliers. An additional line, the Instrumentation Line, is used for environmental monitoring and multidisciplinary research. The AMADEUS system consists of six local clusters of six sensors each. Three of these clusters are located on the 12th line while the other three clusters are located on the Instrumentation Line (IL07), see Fig. [1].

Fig. 1. The ANTARES detector. The AMADEUS clusters are located on the Instrumentation Line (IL07) and Line 12 (L12).
the feasibility of acoustic particle detection with a possible future large volume detector. Using local clusters allows for correlation studies ranging from about 1 m to 350 m, and also offers the advantage of quick direction reconstruction, thereby simplifying source position reconstruction.

2. Direction reconstruction

Each of the six local clusters of AMADEUS comprises six hydrophones. The hydrophones within a local cluster have typical distances of 1 m between the sensors and thus a transit time of $<1$ ms for an acoustic wave front. This allows for quick direction reconstruction of a passing pressure wave. Two methods for direction reconstruction with the individual clusters will be discussed. One of the methods is beamforming and the other one uses the time differences of the detected signals in the individual acoustic sensors of a storey.

2.1. Beamforming

This method requires the knowledge of the hydrophone positions, within a cluster, as well as synchronized data. Beamforming is done by creating a sound intensity plot scanning all directions in space $(4\pi)$ for the actual source direction. Given the six hydrophone coordinates $\mathbf{r}_n\ (n = 1, 2, ..., 6)$, the signal $p_n$ of every hydrophone will be shifted in time corresponding to the difference in path length of the sound wave reaching the respective hydrophone. Hence every direction in space corresponds to a set of time differences $\Delta t_n$ in the data. For a direction $\mathbf{k}$, the beam-forming output at time $t$ is given by

$$b(\mathbf{k}, t) = \sum_{n=1}^{N} w_n p_n(t - \Delta t_n(\mathbf{k})),$$

where $w_n$ represent weighting factors for every individual hydrophone. These factors are adjusted to match the directional sensitivity of each hydrophones. For the following calculations $w_n \equiv 1$ was used. The time differences $\Delta t_n$ are computed assuming a plane wave. The algorithm scans $4\pi$ with a predefined step size in $\theta, \varphi$ 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. The application of the algorithm increases the signal to noise ratio for the direction the signal comes from, creating the mentioned maximum. Figure 3 shows the output of the beam-forming algorithm applied to the signal shown in Fig. 2.

The beam-forming output (Fig. 3) shows a well defined maximum at $\theta = 59^\circ$ and $\varphi = -29^\circ$. The error is governed by the binning of the algorithm and not by the algorithm itself. Local maxima and the visible patterns in Fig. 3 correspond to directions where the time shift results in the constructive addition of two or more signals.

![Fig. 2. Signals recorded by one local cluster, consisting of six hydrophones.](image)

![Fig. 3. Output of the beam-forming algorithm applied to the signal shown in Fig. 2. The maximum, indicating the signal direction, can be identified at $\theta = 59^\circ$ and $\varphi = -29^\circ$.](image)

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1 The assumption of a plane wave is a sufficiently good approximation if the distances are large compared to the dimensions of the hydrophone antenna.
The advantage of this method is that it can be applied to untriggered data. A disadvantage of this method is that it is rather time consuming.

2.2. Time difference method

Another method for directional reconstruction is using the time differences between signals, detected by the hydrophones in a cluster, of a passing pressure wave. This method requires, in addition to the knowledge of the hydrophone position and synchronized data, a signal identification. Once a signal is identified, e.g. by a simple threshold trigger for large signal amplitudes, the signal arrival times are used for the direction reconstruction. Direction reconstruction is done by comparing the measured signal times to expected signal arrival times. The expected time \( t_{\text{expected}}(\theta, \phi) \) for an arriving wave front is taken from a lookup table and subtracted from the measured time. That is done for \( 4\pi \) in the desired angular resolution, where the minimum indicates the reconstructed direction:

\[
\min \left\{ \tau^2 := \sum_{n=1}^{6} \left( t_{n,\text{measured}} - t_{n,\text{expected}}(\theta, \phi) \right)^2 \right\}.
\]

This technique is similar to beam-forming, but much faster. Applied to the data in Fig. 2, the algorithm produces the \( \tau^2 \) data shown in Fig. 4 and 5. A clear minimum can be identified in both \( \theta \) and \( \phi \). The values match the ones obtained by the beam-forming algorithm. The error is again governed by the binning of the algorithm.

Fig. 5. Cut through the \( \theta - \phi \) plane at \( \varphi_{\text{min}} \) of the minimum computed with the time difference method.

Though the time difference method is much faster, beam-forming has the advantage of not having to identify a signal.

Figure 6 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 is from the time period 29.01.2008 to 05.06.2008\(^2\), using a minimum bias trigger which is taking unfiltered data for 10 seconds every 30 minutes. Taking this data set, the directions of all included signals with an amplitude greater than 8-RMS (about 200000 signals) were reconstructed. The RMS was calculated for a 0.1 s time interval around the signal time. A virtual observer residing on the second cluster from the bottom of the IL07, about 180 m above the sea bed, looking westward towards the horizon of the storey, is defining the origin of the coordinate system, see Fig. 6. Thus \( 90^\circ \) (\( -90^\circ \)) in longitude (\( \phi \)) is north (south), while \( 90^\circ \) (\( -90^\circ \)) in latitude (\( \theta \)) is looking upwards (downwards). As expected, the majority of the signals is coming from above the detector, including all kinds of transient signals, as e.g. produced by dolphins. In the lower hemisphere a few sources can be seen amongst which a clear structure can be identified. The Signals between \( 0^\circ \) and \( -120^\circ \) in \( \phi \) and \( -30^\circ \) to \( -70^\circ \) in \( \theta \) originate from the ANTARES acoustic positioning system, emitting signals at the bottom of each string.

\(^2\) Most of the data was taken when the detector consisted of 10 lines.
Fig. 6. 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.

3. Source reconstruction

For a given local cluster such as in the AMADEUS setup, directions are the prime observables of acoustic signals. The identified directions then allow for a simple source position reconstruction. After the successful direction reconstruction, each antenna that detected a signal will point to a direction \( \vec{k}_i \) identifying where an event came from. Since the cluster positions \( \vec{a}_i \) are known, one obtains a line pointing to the event for each cluster,

\[
\vec{d}_i = \vec{a}_i + n_i \vec{k}_i , \quad n_i \in \mathbb{R} .
\]

(3)

The source position of a signal is theoretically given by the intersection point of the lines \( \vec{d}_i \). Due to inherent uncertainties in the direction reconstruction, mainly due to the one degree grid, the source location is where the lines are closest to each other. Localising the point of closest approach for all lines is realized by calculating the square distance from a point \( \vec{s} \) to the reconstructed lines,

\[
L_i^2(\vec{s}) = \left( \vec{s} - (\vec{a}_i + n_i \vec{k}_i) \right)^2 \quad \text{with} \quad n_i = (\vec{s} - \vec{a}_i) \cdot \vec{k}_i ,
\]

(4)

and minimising the sum of these distances.

Since the cluster positioning and orientation was not yet implemented, a full source position reconstruction was not possible at the time of this analysis. However, as the tilts of the local clusters, induced by the sea current, are small, in the order of one degree, it is possible to reconstruct the \( \theta \) angle with that uncertainty. The circles in Fig. 7 represent the possible solutions of a source given by the reconstructed \( \theta \) angle and the distance of each storey to the sea floor. The signal origin can clearly be identified as the acoustic positioning emitter of the 7th line (L7), as can also be deduced from the signal properties.

Fig. 7. Layout of ANTARES on the sea floor in UTM coordinates. Each point indicates the position of a line. The positions of the Instrumentation Line (IL07), Line 12 (L12) and Line 7 (L7) are labeled.

4. Summary

Techniques for source reconstruction using localized clusters have been presented. Source location is done by using the local clusters for direction reconstruction. For direction reconstruction two methods were investigated. One is a beam-forming algorithm only requiring the hydrophone positions, within a local cluster, and synchronized data. The other method additionally requires a signal identification and uses time differences. Although both methods work well, using time differences proved to be much faster. A technique for source reconstruction, based on the directional information of the local clusters, was explained and its potential demonstrated.

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References

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