

Energy-Attenuation-Based Passive Localization of Acoustic Sources in Restricted Aquatic Areas

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ABSTRACT: The article is devoted to the problem of determining the coordinates of a sound emitter using a network of scalar hydrophones. The physical operating principle of such a network is that a sound wave carries energy from the source through the medium, and this energy gradually decreases with distance from the emitter. The proposed method uses several synchronized scalar hydrophones, each of which measures the total sound energy at its location. When the measured energy exceeds the ambient-noise threshold, the system interprets this as the appearance of a new acoustic source in the monitored water area. From the wave energy recorded by different hydrophones, the relative distances to the source are estimated: the greater the energy attenuation, the farther the emitter is located. Knowing the exact coordinates of the scalar hydrophones and the calculated distances, the system determines the position of the sound emitter on the horizontal plane of the water area with the required accuracy. This approach is based on a predefined model of sound-energy attenuation with distance and enables reliable localization of the emitter without any active emission from the hydrophone network.

1 INTRODUCTION

Modern coastal and port-area monitoring faces increasing demands due to the growing presence of small craft, autonomous underwater vehicles, and other mobile acoustic sources near maritime infrastructure [7]. Under such conditions, rapid and continuous monitoring of water bodies becomes an important component of maritime infrastructure management, navigation safety, and environmental acoustic observation.

The main sensor in underwater acoustic monitoring systems is the scalar hydrophone, which measures changes in acoustic pressure and provides high sensitivity and reliability [8, 15]. Recent developments in thin-cable fiber-optic hydrophone arrays have demonstrated the ability to maintain sensitivities above 120 dB over a wide frequency range (20-500 Hz)

and to achieve minimum detectable pressures below the sea-level ambient noise floor [13].

Underwater monitoring architectures range from active acoustic sensing configurations to distributed passive hydrophone arrays. Active acoustic configurations can simultaneously detect and localize multiple acoustic targets as they pass through a monitored region [7]. Passive fiber-optic arrays deployed in coastal zones can track mobile underwater and surface acoustic sources, including small vessels and large ships, over distances of tens of kilometers, providing multilayer integration with sonar and visual observation systems [8].

The integration of hydrophones with autonomous platforms and modern signal-processing algorithms further enhances acoustic detection and source-localization capabilities. For example, a Wave Glider-based system towing a hydrophone array

demonstrated an average signal-to-noise ratio gain of 15.3 dB and enabled the detection of whale vocalizations against anthropogenic noise [14]. The application of convolutional neural networks to spectral-cepstral features obtained from a single hydrophone makes it possible to estimate range and localize moving vessels at distances beyond the capabilities of classical passive acoustic monitoring methods [6]. Moreover, deep neural networks have shown high source-localization accuracy in shallow-water conditions even when information about the acoustic medium is limited [9].

A promising direction is the fusion of different sensor types (scalar and vector hydrophones), the use of distributed optical sensing, and the implementation of adaptive machine-learning algorithms to improve system robustness against acoustic interference and changing oceanographic conditions [15]. Together, these technologies form a multilayer framework for underwater acoustic monitoring that is capable of detecting, localizing, and classifying relevant acoustic sources in real time and supporting timely operational decision-making.

2 RESEARCH METHODOLOGY

2.1 Key factors influencing the selected approach

Scalar hydrophones do not generate their own acoustic pulses. They only record sound vibrations in water and use them to determine the parameters of noise sources. An acoustic wave is energy propagating from a source through the surrounding medium. Several critically important factors influence the propagation of acoustic waves, each of which changes the speed of sound in its own way.

2.2 Parameters of the water environment

Physicochemical properties of water (salinity, temperature, density). As the concentration of dissolved salts increases, as the liquid is heated, and as its density grows, the propagation speed of acoustic vibrations increases.

Internal currents in the water column. Currents disturb the rectilinear propagation of sound, causing refraction and distortions.

Sea depth and seabed characteristics (silt, sand, clay, gravel, etc.). As depth increases, hydrostatic pressure grows, which accelerates wave transmission toward the seabed. If bottom sediments have low reflectivity, a significant part of the acoustic energy is absorbed.

2.3 Parameters determined by the acoustic emitter itself

Frequency range and amplitude level of acoustic waves. As wave frequency increases, absorption in the medium grows, which leads to a decrease in transmitted energy.

Distance to the scalar hydrophone. As the source moves farther away, sound disperses in the surrounding medium, as a result of which its energy at the receiver (the hydrophone) decreases.

Scalar hydrophones based on piezoelectric elements are used to record acoustic vibrations in water. To ensure the reception of signals from all directions, a scalar hydrophone consists of an array of piezoelectric elements placed in a single housing. Hereinafter in this article, the term scalar hydrophone refers to devices designed to receive acoustic waves arriving from all directions [15].

3 PROBLEM STATEMENT

For monitoring the water areas of seaports and coastal zones in order to detect newly appearing acoustic sources, it is proposed to deploy a network of scalar hydrophones at optimal points on the seabed that do not create significant obstacles to navigation. It is assumed that the scalar hydrophones in this network have synchronized internal clocks and that the information transmitted to the server includes the precise time of signal registration.

There are several approaches to determining the position of an object in a water area on the basis of the acoustic signal it emits. The location of an object is determined from the difference in arrival times of acoustic pulses at scalar hydrophones distributed at different points of the seabed [11]. However, this method is applicable only in the case of irregular acoustic emissions; otherwise, the signal registration time becomes ambiguous.

This paper considers the problem of source localization in the case of repeated acoustic impulses. It is assumed that the internal clocks of the scalar hydrophones are precisely synchronized, that the receivers transmit information to the server with minimal delay, and that the coordinates of the receiving nodes on the seabed are known in advance. Anthropogenic acoustic sources, such as underwater vehicles, surface vessels, and port-related equipment, generate characteristic noise patterns at each point of the water area during motion and operation. Natural sounds produced by aquatic fauna (fish, marine mammals, etc.) are also present, but their level is usually substantially lower than the level of anthropogenic noise.

The principal characteristic of an acoustic wave is its energy, which decreases during propagation both with distance and depending on the properties of the medium. It is assumed that sound is absorbed by seawater in such a way that the sound intensity decreases exponentially with distance [5]. Therefore, if the acoustic-wave energy at the source is equal to E , then at a distance R its value is estimated by the formula [2]:

$$E_R = E \times R^{-2} \times e^{-\alpha R} \quad (1)$$

where α is the (average) sound attenuation coefficient in water, calculated on the basis of the sound frequency f , the (average) temperature of the medium T , and the propagation depth z :

$$\alpha = 4.9 \cdot 10^{-5} \cdot f^2 e^{-\left(\frac{T}{27} + \frac{z}{17}\right)} \quad (2)$$

According to Huygens' principle, waves propagate along straight lines in a homogeneous medium [3].

Let us assume that a closed marine area is being monitored (for example, port waters), and that its water may be considered homogeneous. Let each scalar hydrophone record the energy of acoustic waves passing through its observation point. Consequently, if the acoustic-noise sources in the area operate at a certain stable power, each hydrophone will record a stable background-noise level. In this paper, it is assumed that, at the time instants $t_j = j \cdot \Delta t$, $\Delta t > 0$, $j = 0, 1, 2, \dots$ the deviation of the background-noise energy recorded by the scalar hydrophones serves as the basis for calculating the coordinates of the newly appeared acoustic source.

4 MATHEMATICAL MODEL

Consider a conditionally bounded water area in which N scalar hydrophones are installed, indexed as $i = 1, 2, 3, \dots, N$. It is assumed that the depth of this sea region is negligibly small compared with its horizontal dimensions. In this case, a two-dimensional model is sufficient for solving the problem.

We introduce a Cartesian coordinate system and denote the position of the i -th hydrophone by the point (x_i, y_i) . At the initial time t_0 each hydrophone recorded the background-noise energy E_{0i} . At a later time t_j , $j > 0$ the recorded energy became equal to $E_{ji} \neq E_{0i}$, and the difference $\mathcal{F}_i \equiv E_{ji} - E_{0i}$ is associated with the appearance of a new acoustic source. Let the unknown source coordinates be (x, y) , and let the initial acoustic-wave energy be E . Then, based on Eq. (1), for each hydrophone we obtain the approximate relation

$$\mathcal{F}_i \cong \frac{E}{(x - x_i)^2 + (y - y_i)^2} \times e^{-\alpha \sqrt{(x - x_i)^2 + (y - y_i)^2}} \quad (3)$$

$i = 1, 2, 3, \dots, N$.

Here α is the attenuation coefficient, and the symbol " $\cong$ " means that the equality holds with a certain measurement error. This approximation is sufficiently accurate provided that the source is detected by at least four hydrophones.

Thus, the problem reduces to finding (x, y) such that the set in Eq. (3) is satisfied simultaneously, where $\mathcal{F}_i$, E and α are known positive quantities.

Equations (3) are transcendental equations. If we denote

$$\lambda_i = \frac{\alpha}{2} \sqrt{\frac{E}{\mathcal{F}_i}}$$

then after substitution

$$w_i = \frac{\alpha}{2} \sqrt{(x - x_i)^2 + (y - y_i)^2}, \quad i = 1, 2, 3, \dots, N, \quad (4)$$

they can be written as

$$w_i \exp z_i \cong \lambda_i,$$

and its positive solution can be expressed "explicitly" in terms of the Lambert W function [4]:

$$w_i \equiv W(\lambda_i) \quad i = 1, 2, 3, \dots, N. \quad (5)$$

However, in practice it is preferable to use iterative numerical methods, for example Newton's method [1], since the function W itself is also evaluated iteratively.

Thus, we shall assume that for each $i = 1, 2, 3, \dots, N$ the values λ_i have been computed by one method or another, and the problem reduces to finding x, y such that the set in Eq. (4) is satisfied simultaneously.

Finding an approximate solution (x, y) that best satisfies this system can be formulated as minimizing the following functional by the least-squares method [10]:

$$\mathcal{J} = \mathcal{J}(x, y) \equiv \sum_{i=1}^N \left[\frac{2w_i}{\alpha} - \sqrt{(x - x_i)^2 + (y - y_i)^2} \right]^2 \quad (6)$$

which is a positive nonlinear function of the unknowns. Finding its minimum reduces to finding the common zeros of the functions $\frac{\partial \mathcal{J}}{\partial x}$ and $\frac{\partial \mathcal{J}}{\partial y}$, typically using iterative numerical algorithms:

$$\sum_{i=1}^N \left(\frac{2w_i}{\alpha} - \sqrt{(x - x_i)^2 + (y - y_i)^2} \right) \frac{x - x_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2}} = 0,$$

$$\sum_{i=1}^N \left(\frac{2w_i}{\alpha} - \sqrt{(x - x_i)^2 + (y - y_i)^2} \right) \frac{y - y_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2}} = 0.$$

5 EXAMPLE OF CALCULATING THE COORDINATES OF AN ACOUSTIC SOURCE

Let four scalar hydrophones be installed in the monitored shallow-water area, and let their coordinates be given in nautical miles:

$$A_1(-1.00, -0.20), \quad A_2(0.90, -0.10) \\ A_3(0.20, 1.00), \quad A_4(-0.70, 0.85)$$

Assume that the acoustic source is located at the point

$$A_0(0.15, 0.25).$$

For the numerical example, let the initial acoustic-wave energy and the attenuation coefficient be equal, respectively, to $E = 1.00$, $\alpha = 0.12$ nautical miles⁻¹. According to the adopted energy-attenuation model, the additional energy recorded by the i -th hydrophone is computed by the formula

$$\mathcal{F}_i = \frac{E}{r_i^2} \exp(-\alpha r_i),$$

where the distance from the source to the i -th hydrophone is determined by the expression

$$r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}.$$

For the true source position $A_0(0.15, 0.25)$, the distances to the hydrophones and the corresponding ideal values of the recorded additional energy are given in Table 1.

Table 1. True distances and ideal energy values

Hydr.	Coordinates	True distance r_i	Ideal energy $\mathcal{F}_i^0$
A_1	(-1.00, -0.20)	1.23491	0.565422
A_2	(0.90, -0.10)	0.82765	1.321832
A_3	(0.20, 1.00)	0.75166	1.617254
A_4	(-0.70, 0.85)	1.04043	0.815360

Taking into account random deviations not exceeding 1%, we simulate the following scalar-hydrophone data:

$$\mathcal{F}_1 = 0.569945 \quad \mathcal{F}_2 = 1.313901$$

$$\mathcal{F}_3 = 1.625340 \quad \mathcal{F}_4 = 0.808022$$

These values correspond to the following relative errors

$$+0.8\%, -0.6\%, +0.5\%, -0.9\%.$$

To reconstruct the distances from the source to the hydrophones, we use the transformation through the Lambert W function. First, denote

$$\lambda_i = \frac{\alpha}{2} \sqrt{\frac{E}{\mathcal{F}_i}},$$

and then compute

$$w_i = W(\lambda_i), \quad \hat{r}_i = \frac{2w_i}{\alpha}.$$

Table 2. True and reconstructed distances

Hydr.	Measured energy $\mathcal{F}_i$	True distance r_i	Estimated distance $\hat{r}_i$
A_1	0.569945	1.23491	1.23034
A_2	1.313901	0.82765	0.83002
A_3	1.625340	0.75166	0.74987
A_4	0.808022	1.04043	1.04487

After the distances have been reconstructed, the source coordinates are found by minimizing the residual functional

$$\mathcal{J}(x, y) = \sum_{i=1}^4 \left[\hat{r}_i - \sqrt{(x - x_i)^2 + (y - y_i)^2} \right]^2.$$

Solving this least-squares problem gives the following estimate of the acoustic-source coordinates:

$$A(0.14863, 0.24875).$$

Let us compare the obtained point with the true source position:

$$A_0(0.15, 0.25).$$

The distance between the true and calculated positions is equal to

$$d(A, A_0) = \sqrt{(0.14863 - 0.15)^2 + (0.24875 - 0.25)^2} = 0.00186$$

Since 0.00186 nautical miles ≈ 3.44 m, the obtained error can be considered acceptable for the demonstration numerical example. Therefore, even in the presence of small random errors in energy measurements, the proposed method makes it possible to estimate the coordinates of an acoustic source in a restricted water area with sufficient accuracy.

Table 3. Summary of the comparison between the true and calculated source positions

Indicator	Value	Comment
True point	$A_0(0.15, 0.25)$	Specified in the computational experiment
Calculated point	$A(0.14863, 0.24875)$	Obtained by the least-squares method
Error	$0.00186 \text{ nmi} \approx 3.44 \text{ m}$	Approx.

It should be noted that in a full-scale implementation, the values E and α should be refined based on calibration measurements, and the obtained coordinates should be checked for robustness to noise, multipath propagation, and spatial heterogeneity of the water medium.

6 RESULTS

In real monitoring of a shallow-water marine area, mobile or newly appearing acoustic sources can often be identified by the spectrum of the acoustic waves they emit. After the source coordinates are determined using the hydrophone network, the signal frequency is calculated, and then, using Eq. (4) (for example, at $i=N$), the attenuation coefficient α is refined:

$$\alpha \approx \frac{2w_N}{\sqrt{(x - x_N)^2 + (y - y_N)^2}}.$$

For a shallow-water region, it is convenient to take the water level as $z=0$. Given the known average water temperature T and using Eq. (2), one can determine the oscillation frequency f of the sound wave emitted by the source.

7 DISCUSSION

The numerical example obtained above shows that the proposed energy-based localization scheme is computationally feasible and can produce a small error under moderate energy-measurement inaccuracies. At the same time, this result should be regarded not as a field validation of a ready-to-use system, but as a demonstration of the internal consistency of the model in a controlled computational scenario. The example uses a known hydrophone geometry, a specified attenuation coefficient, a single source, and a relatively small measurement error. Therefore, the main conclusion is that the selected mathematical apparatus is suitable for further experimental verification, while its practical accuracy must be evaluated under real hydroacoustic conditions.

A significant advantage of the considered approach is its passive nature. Scalar hydrophones do not generate their own acoustic pulses and do not increase the acoustic load on the water environment. This makes the method potentially convenient for long-

term monitoring of restricted water areas, port zones, and sites with increased requirements for environmental and operational safety. In addition, the method uses the spatial distribution of measured energy and therefore can be applied as an additional localization channel in cases where methods based solely on the difference in signal arrival times become ambiguous due to repeated, continuous, or poorly separable acoustic impulses.

At the same time, the proposed method should not be regarded as a universal replacement for TDOA, vector hydrophones, or active hydroacoustic tools [12, 15]. Its applicability is determined by the type of source, the signal-to-noise ratio, the stability of spectral features, the density of sensor placement, and the degree of homogeneity of the water medium. The most natural role of energy-based localization is to complement other methods: it may serve as a preliminary estimation mechanism, a confirmation channel, or part of a hybrid system combining energy features, time delays, spectral classification, and, when appropriate sensors are available, the direction of arrival of the signal.

The accuracy of the method depends substantially on the physical assumptions adopted in the sound-propagation model. This work uses a two-dimensional approximation for a shallow-water area and an effective energy-attenuation model that includes the dependence on distance. In a real environment, the recorded energy is influenced not only by geometrical spreading and absorption, but also by reflections from the surface and the bottom, scattering by inhomogeneities, bottom losses, refraction, water motion, and spatial variations in temperature and salinity. Therefore, in practical implementation, the attenuation parameter should preferably be treated as an effective or locally calibrated parameter rather than as a constant quantity that is identical for the entire water area.

The acoustic background is of particular importance. In restricted water areas it is rarely stationary: it is affected by navigation, port equipment, wind, rain, biological sources, reflections from structures, and short-term anthropogenic noise. Consequently, the detection of a new acoustic component should be based not on a fixed threshold, but on an adaptive assessment of the background level in selected frequency bands. A practically useful approach is preliminary spectral or spectral-cepstral extraction of ranges characteristic of the type of source under consideration, followed by the calculation of energy features precisely in these ranges. This approach can reduce the number of false alarms and improve the robustness of coordinate estimation.

The stability of the solution is also affected by the geometry of hydrophone placement. Although the model requires detection of the source by several spatially distributed receivers, the mere presence of four hydrophones does not guarantee good conditioning of the problem. If the sensors are arranged almost along one line, if the source lies outside the covered zone, or if the measured energies differ only slightly, the residual functional may have a broad minimum region. Therefore, when designing the network, it is necessary to analyze the sensitivity of the solution to measurement errors, control the residual

discrepancy, estimate the confidence region of the coordinates, and choose the hydrophone placement so as to minimize geometric uncertainty in the most important zones of the water area.

A separate limitation is associated with the possible presence of multiple sources. The energy recorded by a scalar hydrophone is a total quantity; therefore, when several objects operate simultaneously, a simple single-source model may yield biased or physically incorrect estimates. In such cases, additional signal-separation procedures are required: clustering by spectral features, temporal tracking of sources, extraction of dominant frequency components, use of several time windows, or integration with vector-hydrophone data [12, 15]. Without such separation, energy-based localization should be applied with caution and accompanied by an uncertainty indicator.

From a practical point of view, the proposed approach should be developed in stages. At the first stage, calibration experiments should be carried out with sources of known power and known coordinates in order to estimate the effective attenuation parameters and the influence of sensor geometry. At the second stage, series of computational and field tests are required at different noise levels, depths, temperature conditions, and seabed types. At the third stage, energy-based localization can be included in a multilayer monitoring system in which the result is presented not only as a single calculated point, but also as a probable-position region, a confidence level, and a recommendation on the need for additional verification. Such a cautious approach makes the proposed method more realistic and increases its value for future systems of passive monitoring of restricted water areas.

8 CONCLUSION

The article presents a method for detecting and localizing acoustic sources in restricted water areas, including port water areas, using a network of scalar hydrophones. The proposed solution provides continuous monitoring of the acoustic background of the water area: when a new source appears, a sharp jump is observed in the acoustic energy measured by the scalar hydrophones. Since the amplitude of the received signal at each hydrophone depends on its distance from the source, the system accounts for these differences during data processing. The method is based on fundamental physical laws, which makes it possible not only to detect a new acoustic source but also to determine its coordinates. The deployment of the proposed scalar-hydrophone network is particularly relevant for improving continuous acoustic monitoring and operational safety in port zones: it can effectively detect newly appearing acoustic sources within water-area boundaries and thereby support timely technical assessment and operational response.

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