HYDROACOUSTICS WAVES' DIRECT-OF-ARRIVAL ESTIMATION USING MUSIC ALGORITHM – SIMULATIONS RESULTS

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Paper presents simulations results of hydroacoustics waves' direction-of-arrival estimation using MUSIC algorithm. Firstly, the research problem is formulated by general description of studied case and release of simplifying assumption. Next the used to direct-of-arrival estimation MUSIC algorithm was discussed. The mathematical formulations, algorithm of calculation and some computational issues were presented. At the end of the paper the simulations results of estimation of direction-of-arrival using MUSIC algorithm for hypothetical situation were presented.

INTRODUCTION

In various applications of array signal processing such as hydrolocation, there is a great interest in detection and localization of wideband sources. But we must noticed that hydroacoustics detection and tracking of moving ship in water environment is a challenging problem. Any dominant spectral lines in the acoustic signatures are nonstationary due to engine load and RPM changes during maneuvering. Water region, hydroacoustics effects and sound wave propagation characteristic that vary with time also produce significant signal variability.

The problem of estimating the direction of arrival (DOA) of wideband sources using a sensor array has been studied extensively in the literature. A common approach to this problem, for a single source scenario, is to use the time delay estimation between two sensors to determine the DOA. More advanced approaches are so called superresolution techniques. Techniques based on the eigen-structure of the input covariance matrix including MUSIC (Multiple Signal Classification), Root-MUSIC and ESPRIT (Estimation of Signal Parameters via Rotational

Invariance Techniques) generate high resolution DOA estimation. Music algorithm proposed by Schmidt [6] returns the pseudo-spectrum at all frequency samples. Root-music [1] returns the estimated discrete frequency spectrum, along with the corresponding signal power estimates. Root-music is one of the most useful approaches for frequency estimation of signals made up of a sum of exponentials embedded in additive noise.

1. PROBLEM FORMULATION

In general the problem which should be solved is to detect and locate n-th radiating sources by using an array of m-th passive sensors (see figure 1, which shows the single emitter case) [7]. Because formulate problem will be considered as hydroloaction problem so, the radiating sources will be understood as the moving ships which are emitting hydroacoustics energy.

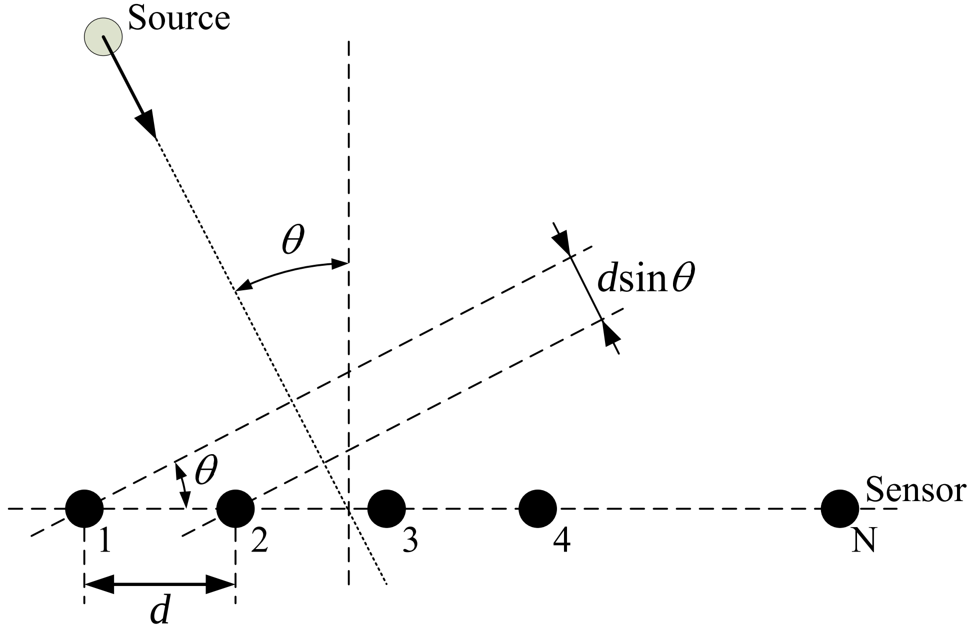

Fig.1. Schematic presentation of problem

As passives sensors will be understood, the array of hydrophones which mutual orientation is well known. As a basic approach to solve such described problem we use the spatial spectral analysis, so other words it will be determine the distribution of energy over space. Because considerations, has basic research character it is possible to make some simplifying assumptions [7]. First of all let's assume that sources which are radiating hydroacoustics energy are in the same plane as the array of sensors. More over let's assume the non-dispersive model of sound wave propagation. Hence the generated waves are planar and the only location parameter is direction of arrival (DOA) or angle of arrival (AOA). Of course, to determine the position of ship we have to calculate, beside the DOA, also the distance form array of sensors to the sound source. It can be done by calculation of DOAs for few (at least two) positions of sensors' array and then using for example triangular method calculation the distance to the source. So the main objectives, is to calculate the estimator of direction of sound wave arrival. Next assumption in conducted consideration is that the number of sources n is known. This assumption can be done because in this paper we do not treat the detection problem, but only the problem of DOA estimation. The last assumption is that the sensors are linear dynamic elements with known transfer characteristics, so the array of used passive sensors is calibrated.

2. MUSIC ALGORITHM

To estimate the DOA of a wave from the signals received at the array, the super-resolution algorithm MUSIC can be used. The feature of this is less sensitive to noise and applicable to the frequency band where the antenna distance is smaller than a half of a wavelength. This algorithm is based on the ensemble-averaged correlation matrix for the antenna outputs. The MUSIC spectrum is computed by performing an eigenanalysis on the correlation matrix. The space spanned by the eigenvectors consists of two disjoint subspaces: signal and noise subspaces. For the antenna array comprised of two antennas, the larger and the smaller eigenvalues belong to the signal and noise subspaces, receptivity. In terms of the orthogonal characteristics of eigenvectors in the signal and noise subspaces, the MUSIC spectrum in the frequency domain is given by the following [2, 10]:

$$P(f_m,\theta) = \frac{1}{\left|\mathbf{a}(f,\theta)\mathbf{v}\right|^2} \tag{1}$$

where:

$$\mathbf{a}(f_m,\theta) = [1, \exp(-j\pi\cos\theta)]^T \tag{2}$$

where: $\mathbf{a}$ and $\mathbf{v}$ denotes the eigenvector corresponding to noise space and the scanning vector,
f_m is a Fourier frequency ($m = 1, 2, 3,...$),
θ is the estimated direction of wave arrival (see figure 1).

The direction of wave arrival θ and phase difference $\varphi(f_m)$ at each Fourier frequency are in relation described by the following equitation [2]:

$$\theta(f_m) = \cos^{-1}\left(\frac{c\varphi(f_m)}{2\pi f_m d}\right) \tag{3}$$

where: c is sound speed in water,
d is a distance between sensors.

Note that this is equivalent to that of the Min–Norm method for the antenna array comprised of two antennas. In addition, it is noteworthy that the mutual coupling of antennas affects the correlation matrix, resulting in a broaden MUSIC spectrum or less resolution of DOA estimation.

Figure 2 shows the steps for implementing incoherent wideband MUSIC algorithm [4, 5]. To overcome the nonstationary nature of the hydroacoustic source, the data is segmented before processing into fixed blocks, and stationarity is assumed over each data block. Over each processing interval, it is assumed that a single frequency bin is occupied by only a single source. This takes advantage of the nonstationarity of the sources, and simplifies the MUSIC algorithm.

Although a source may be masked in a particular processing interval, this effect is unlikely to continue because the sources are changing frequencies as a function of time. Preprocessing is required to adaptively select the operating frequencies ω_k. Let $x_i(n)$ denote the output of the i th sensor from an array of M sensors, and let $Y_i(\omega)$ denote the Discrete Fourier Transform DFT of signal $x_i(n)$. The average sum of $|Y_i(\omega)|^2$ is then obtained to adaptively select frequency bins of interest. This can be performed in a variety of ways, from simple thresholding based on frequency bin signal-to-noise ratio (SNR), to more complex schemes, such as harmonic association.

After the ω_k 's have been selected, the next step is formation of the estimated spatial correlation matrix for each ω_k, over each data block, given by:

$$\hat{R}_Y(\omega_k) = \hat{Y}(\omega_k)^H \hat{Y}(\omega_k) \tag{4}$$

where: $\hat{Y}(\omega_k) = [Y_1(\omega_k), Y_2(\omega_k), ..., Y_M(\omega_k)]^T$

H is the Hermitian operator (complex conjugate transpose).

Once $\hat{R}_Y(\omega_k)$ is formed for each ω_k, the narrowband MUSIC algorithm is applied repeatedly [4, 5]. The first step is eigenanalysis of $\hat{R}_Y(\omega_k)$ to obtain the noise subspace. Taking $\hat{R}_Y(\omega_k)$ w to be $M \times M$ then, by the assumption that only one source can occupy a frequency bin over a processing interval, the noise subspace consists of the $M-1$ eigenvectors corresponding to the $M-1$ smallest eigenvalues of $\hat{R}_Y(\omega_k)$, and these form $\hat{U}_n(\omega_k)$. The MUSIC beampattern is then computed. For each look angle θ, the beampattern is given by

$$\hat{P}_{MUSIC}(\theta) = [E(\omega_k,\theta)^H \hat{U}_n(\omega_k)\hat{U}_n(\omega_k)^H E(\omega_k,\theta)]^{-1} \tag{5}$$

The array manifold or steering vector, $E(\omega_k,\theta)$, is defined as

$$E(\omega_k,\theta) = [e^{2\pi f_k \Delta t_1}, e^{2\pi f_k \Delta t_2}, ..., e^{2\pi f_k \Delta t_M}]^T \tag{6}$$

where:

$$\Delta t_i = \frac{d}{c}\sin(\theta - \alpha_i) \tag{7}$$

where: α_i is the relative angle to the normal for sensor $i = 1, 2, ..., M$.

After the beampatterns are calculated for all ω_k 's, they are incoherently averaged together to form a resulting MUSIC beampattern [3, 4, 9]. Finally, the source DOA's are estimated by selecting the angles corresponding to the peaks in the resulting averaged beampattern. For each update, the raw DOA estimates from the sensor arrays are transmitted to the gateway for tracking. The tracker correlates the DOA estimates from the sensor arrays, and maintains a tracking history for each acoustic source.

The computational complexity of MUSIC is governed mainly by the eigen-analysis calculation, which is $O(N^3)$. However, this can be reduced by applying methods that calculate the signal subspace only, as opposed to the full eigenanalysis, because in our implementation the signal subspace is assumed to consist of one component only. By further assuming that only one source occupies a frequency bin, the algorithmic complexity and the estimation of the number of sources are simplified. The complexity can be reduced even further by precomputing $E(\omega_k,\theta)$

for all the frequency bins in the range of interest at an additional memory cost. An alternative method is to use a coarse beamformer (e.g., DS) during preprocessing to reduce the number of look angles. Therefore, $\hat{P}_{MUSIC}(\theta)$ is computed for fewer values of θ. Other more complex forms of $E(\omega_k, \theta)$ can be used to incorporate the sensitivity and gain calibration of the sensors. However, the response of the sensors can change over time due to changes in the environment, requiring the sensors to be recalibrated, and the parameters used in $E(\omega_k, \theta)$ to be updated and stored periodically.

Other methods (e.g., harmonic line association (HLA)) can be used to limit the number of operating frequencies. The HLA algorithm detects the frequency bins that are above a set SNR threshold level. The bins are then sorted and combined into harmonic groups. Each harmonic group contains frequency bins that are harmonically related to a fundamental frequency of an engine rate. The HLA will declare a harmonic group valid (i.e., a source is detected) if there are at least m ($m = 2, 3, 4$ *or* 5) components in that group; otherwise, there is no source detected. The use of HLA in this way, however, requires that the acoustic sources belong to a group of known sources [4, 5].

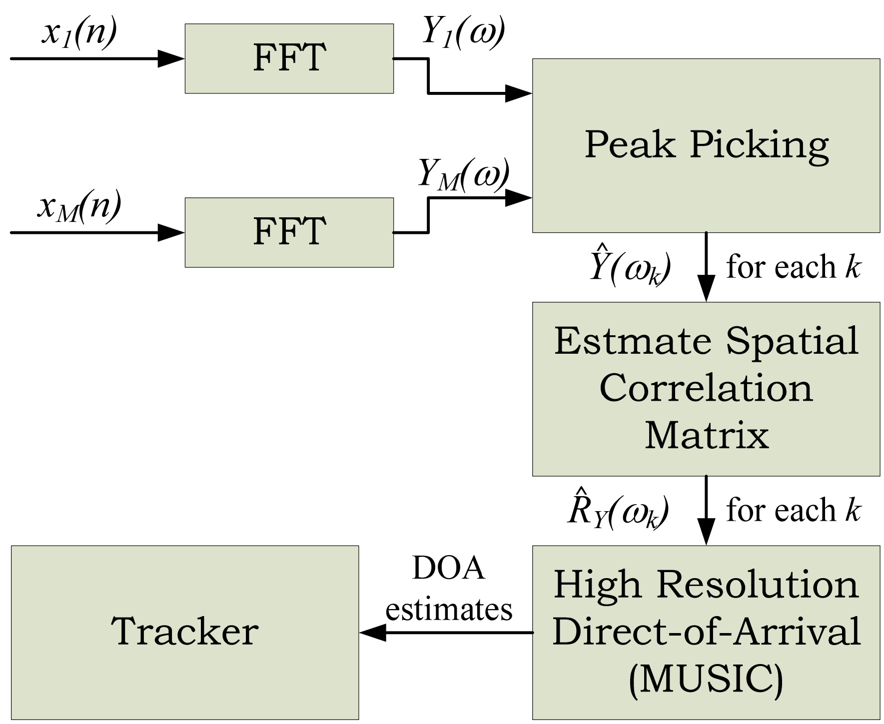

Fig.2. Implementation of the MUSIC algorithm [4, 5]

3. NUMERICAL RESULTS

During simulation experiment it was assumed that we have two ships, which are moving along the appointed track. Every ship is generating hydroacoustic signals, which has the same pressure levels. The distance between hydrophones in antenna is equal the half of wave length.

Taking into account signals has length of 4096 samples. During simulation research firstly, it was checked the influence of number of hydrophones on precision of DOA estimation. During second part of research the influence of variance of noise on precision of DOA estimation was checked. On the figures below it was presented the estimates DOA versus real angle of wave arrival depending on quantity of sensors. On figure 4 it was presented the results of MUSIC spectrum calculated depending on variance of noise for the situation when both ships are in position at $t = 600[sek]$. At this time the assumed angles of arrival were for first ship $\theta_1 = -39.8336[\deg]$ and second $\theta_2 = 50.1978[\deg]$.

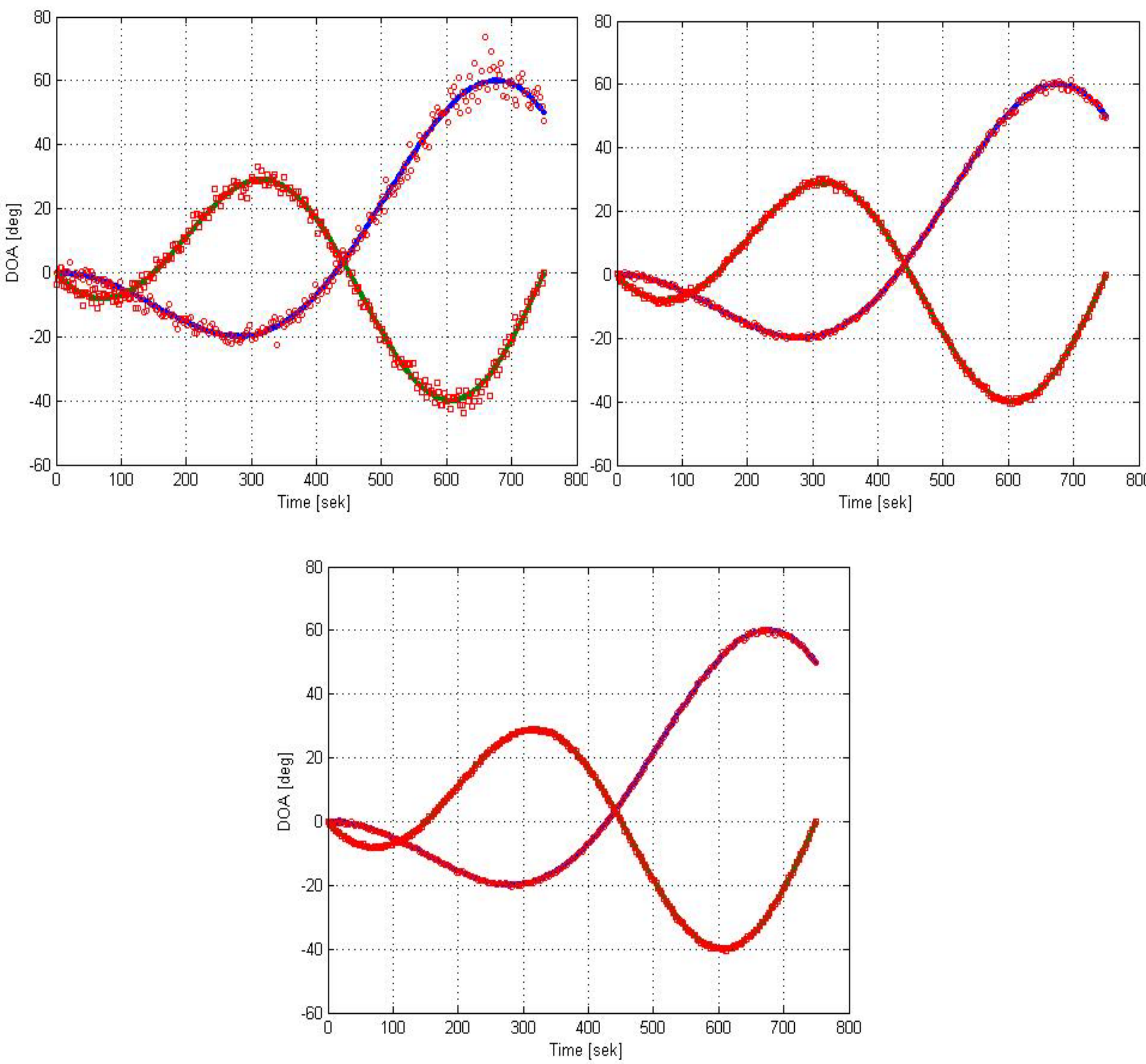

Fig.3. DOA estimates versus real angle of arrival. Assumed variance of noise is equal 20. A) using 3 hydrophones, B) using 6 hydrophones, C) using 9 hydrophones

As it is shown on figure above the number of sensors has a great significant to precision of DOA calculation. As we see if the number of hydrophones is increasing the precision of DOA estimation is increasing too at the same level of assumed variance of noise.

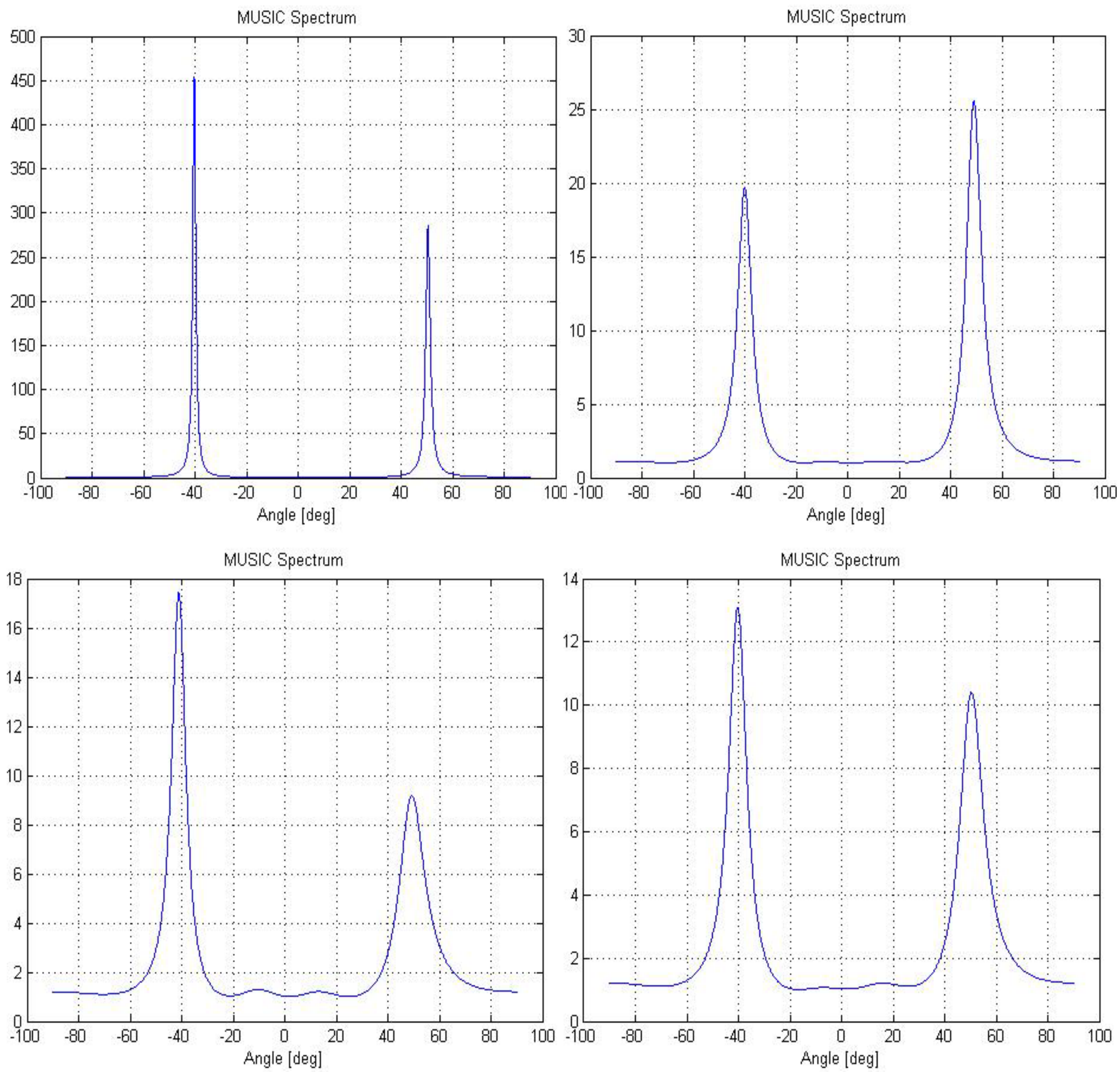

Fig.4. MUSIC spectrum for objects positions at t = 600 [sek] using 6 hydrophones. A) variance of noise equal 10, B) variance of noise equal 30, C) variance of noise equal 50 D) variance of noise equal 70

Analyzing the figures above, it can be concluded that increasing variance of noise, cause not only the decreasing of levels of MUSIC spectrum, but also influence on peaks' base width which grow according to variance of noise increasing. At the same it causes the increasing of error in DOA estimation.

4. SUMMARY

In this paper, it was proposed a DOA estimation algorithm, which allows for the calculation of hydroacoustic energy source position. The effectiveness of proposed method was demonstrated through numerical examples. This method can found application not only in underwater surveillance but also in radar systems, sonar systems, communications and seismology. Future work of interest includes highresolution coherent wideband array processing to achieve higher processing gain during time intervals of low SNR [4, 5, 8]. But firstly suitability of proposed in paper method of DOA estimation will be checked for real signals acquired during sea measurements.

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