THE ALGORITHM OF DETERMINATION OF COORDINATES OF UNDERWATER ACOUSTIC SOURCE USING THE CORRELATION FUNCTION OF THE SIGNAL

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Abstract: *The purpose of the work is to study the algorithm that implements the method of coordinates (distance and depth) determination of the broadband signal source using the parameters of the interference maxima in the correlation function of the signal at the hydroacoustic antenna output. The algorithm takes into account a number of negative factors affecting the accuracy of the algorithm in real conditions. By means of simulation it is shown that developed algorithm potentially provides a high-precision signal source coordinates estimates in the conditions of the deep sea at sufficiently large distances. In the conditions of shallow water, as well as at short distances in the deep sea, the estimates of the coordinates using the developed algorithm are multivalued. The dependences of the accuracy of the coordinates estimation on the number of detected interference maxima in the correlation function, the signal-to-noise ratio at the antenna output and the accuracy of the sound speed vertical distribution measurement are studied.*

Key words: *underwater acoustics, multipath channel, correlation function, coordinates of the signal source.*

1. INTRODUCTION

One of the actual practical problems of underwater acoustics is determination of the submerged sound source coordinates in the passive mode of sonar operation. A large number of methods and algorithms are proposed to solve this problem.

One of these methods is based on the processing of a wide-band multi-path acoustic signal emitted by a submerged source. There are two types of this method. The first, called "Matched field processing (MFP)" [1-4], is based on the coherent addition of signal rays at the receiving antenna output taking into account the calculated signal ray structure at the antenna input for different variants of the source location in the "range – depth" space. The second type of this method [5] operates with the total multi-ray signal at the antenna output. Since the first type of the method imposes strict requirements on the vertical wave size of the receiving antenna and the magnitude of the signal-to-noise ratio (SNR), it is difficult to implement it in practice [4]. Taking this into account, the proposed article is devoted to the second type of the method, or rather to its variant, which is based on the comparison of the measured and calculated ray interference maxima (IM) in the correlation function (CF) of the received broadband signal [5-8].

The sense of the method under consideration is to find such position of the signal source (SS) in the "range–depth" space, for which the number and the location of calculated IMs are as close as possible to the number and location of IMs in the measured CF at the antenna output.

The fulfilled studies [7, 8] have shown that there are a number of factors that lead in specific cases to the large errors of the coordinate determination. These factors are:

1) the low coherence of rays in conditions, characterized by multiple signal reflections from the boundaries of the waveguide. As a result only few IMs are detected in CF or not detected at all;

2) the real ambiguity of the signal source coordinates determined by the considered method in a number of hydroacoustic conditions;

3) the low accuracy of the signal ray structure calculation due to inaccurate knowledge of hydroacoustic conditions parameters and their casual fluctuations.

The purpose of the work is to study the algorithm that implements the considered method in view of these factors.

2. THE ALGORITHM DESCRIPTION

The algorithm implementing the considered method has the following form

$$\left(R_{opt},H_{opt}\right)=arg\ \min_{R,H}\ \sum_{k=1}^{K}\left|\hat{\tau}_k-T_{(i,j)_k}\left(R,H\right)\right|, \quad (1)$$

where R_{opt},H_{opt} are the optimal estimates of the SS distance and depth; K is the number of IMs detected in the CF at the output of the receiving antenna; $\hat{\tau}_k$ is the abscissa (delay) estimate of the k-th IM, detected in the CF; $T_{(i,j)_k}\left(R,H\right)$ is function, linking the true SS coordinates R,H with the true value of the delay between i-th and j-th signal rays forming the k-th IM.

From the formula (1) it follows that the optimal SS coordinates estimates are those for which for each IM detected in the CF can be found a pair of signal rays emitted by SS, located in the point with R,H coordinates, the interference of which forms IM with delay in the CF, closed to the delay of the detected IM. It means that to implement considered method we must define the region in $[R,H]$ space and find in this region point satisfying the condition (1). And it is necessary to take into account the above-mentioned negative factors.

The analysis showed that it is not possible to completely eliminate the reasons that reduce the accuracy of the SS coordinates determination, but they can be minimized by applying some measures. Consider these measures.

1) It is experimentally established that the accuracy of the SS coordinates determination is higher the more IMs are found in the CF. Since the coherence coefficient of each pair of rays is a random variable, varying in time, the number of IMs, detected in the CF, calculated at different time intervals, can vary. Therefore, to obtain a sufficient number of IMs to solve the problem, it is advisable to combine IMs found at different time intervals.

To proof this hypothesis the Table 1 shows the values of IMs abscissa, detected in the 6 CF, calculated on the 10 sec interval each. From Table 1 it follows that the IM sets in CF, measured at the different time intervals, differ. The last line of the Table 1 contains all IMs, found in at least one CF.

CF number	IM abscissa, ms
1	7.5 19.3 42.0
2	6.9 71.8
3	7.0 49.4 79.3
4	6.8 49.5
5	7.6 41.9 49.3 71.9
6	7.4 6.8
1-6	6.9 7.5 19.3 42.0 49.4 71.8 79.3

Table 1: The values of IMs abscissa, detected in the 6 CF sequentially calculated on the 10 sec intervals

The Table 2 shows the results of the SS coordinates determination with the use of IMs detected in each CF and with the use of combined IMs. It should be noted that when using IMs from a single CF the result of the SS coordinates determination in all six cases was multi-valued. But in the case of the use of the combined IMs the result was single-valued, which shows the high accuracy of the SS coordinates determination.

CF number	Number of IMs, detected in CF	Distance estimate standard error, km	Depth estimate standard error, m
1	3	7,4	28
2	2	17,1	42
3	3	9,2	31
4	2	21,1	39
5	4	4,4	12
6	2	15,3	35
1-6	7	0,3	8

Table 2: The results of the SS coordinates determination

2) The influence of fluctuations of the ray parameters caused by fluctuations of the propagation channel can be reduced by trace analysis in time of the SS coordinates estimates.

Fig.1 shows 12 estimates of the SS coordinates (square blue markers) obtained in the experiment described above. Each estimate is obtained by applying the algorithm (1) using the combined IMs, found in six CF, sequentially measured at intervals of 10 seconds. The circle red marker indicates the true SS position.

From Fig.1 it follows that 10 estimates are located tight in the range from 45 to 51 km in distance and from 170 to 220 m in depth, and two estimates are far away. It is clear that the algorithmic elimination of such discharge estimates will not be difficult.

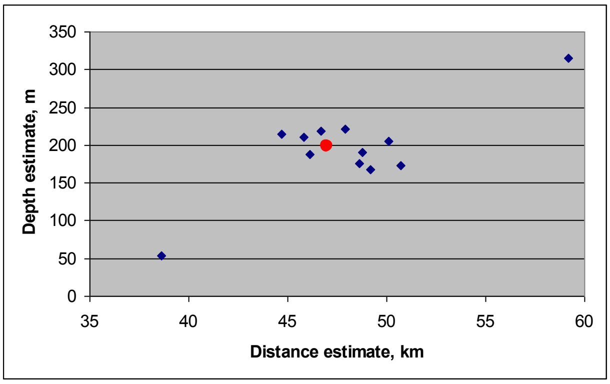


Fig.1: 12 estimates of the SS coordinates (square blue markers) and the true SS position (circle red marker)

3) Since the implementation of the algorithm (1) is based on the search of the expected points of the SS in the selected area in the space "range – depth", it is natural to assume that the uncertainty of the result will depend on the size of the this area: the smaller this area, the less uncertainty of the solution. In addition, narrowing the area reduces the time to solve the problem and the requirements to the calculator.

To determine the area of the solution, it is advisable to use one of the known SS coordinates determination methods, which give a less accurate but unambiguous result. Most simply it can be done by identifying the SS type and taking advantage of using appropriate probability density functions (PDF) of the SS depth and the signal intensity.

4) Taking in account the variability of hydroacoustic conditions in time, measurement of the environment parameters should be performed immediately before the implementation of the method.

3. THE ALGORITHM SIMULATION

The simulation was carried out in 2 steps. At the 1st step, the potential accuracy of the considered method was estimated under typical hydroacoustic conditions with precisely known parameters and with a large SNR at the antenna output. At the 2nd step, the influence of the different factors on the method accuracy was estimated.

Modeling was carried out for three types of signal propagation (Fig.2):

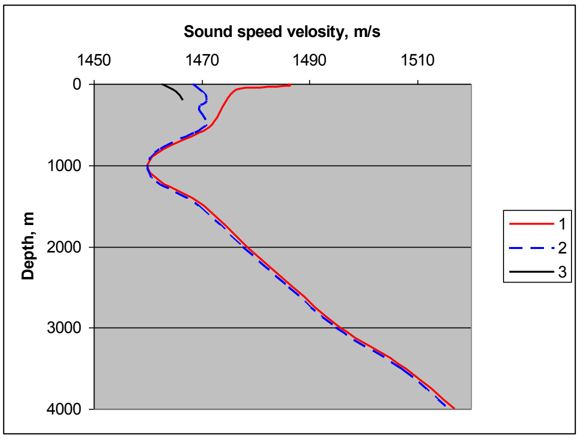


Fig.2: Types of the sound speed vertical distribution

1) the zone conditions. This type is the most favorable for the considered method, since the signal propagation in them is characterized by a small number of rays reaching the receiving antenna, and a small number of their reflections from the waveguide boundaries;

2) the conditions of continuous acoustic illumination (CAI) in the deep sea. This type is less favorable for the considered method, since the signal propagation in them is characterized by a large number of signal reflections from the sea surface, which leads to loss of signal rays coherence;

3) CAI in a shallow water. This type is even less favorable, since reflections from the bottom are added to the reflections from the sea surface, which leads to an even greater loss of signal rays coherence.

The results obtained at the 1st step of simulation are given in Table 3. The search of SS coordinates for all variants was carried out: on depth – in the range of 5-300 m; on distance – on the interval of ±30% from the true distance.

True SS coordinates		Area boundaries for solution search		SNR at antenna output, dB	Number of IMs in CF	SS coordinates estimations standard errors	
R, km	H, m	R, km	H, m			R, km	H, m
The zone conditions, receiving antenna depth 300 m							
a) near zone							
7	200	1-11	5-300	20	3	0,01	2
					3	0,02	10
					3	0,5	40
					3	0,3	100
b) 1st zone							
50	200	35-50	5-300	20	7	0,02	3
50	200	35-120	5-300	20	7	0,021	3
c) 2nd zone							
97	200	85-120	5-300	20	8	0,01	2
Continuous acoustic illumination in the deep sea, receiving antenna depth 300 m							
50	200	35-65	5-300	20	7	0,02	3
97	200	85-115	5-300	20	9	0,01	2
Continuous acoustic illumination in the shallow water, receiving antenna depth 50 m							
30	100	20-40	5-180	20	4	0,4	2
					4	9,8	3
					4	6,7	40
30	5	20-40	5-180	20	5	5,2	2
					5	4,4	5
					5	5,7	15
					5	6,3	55
					5	4,5	95
					5	3,8	115

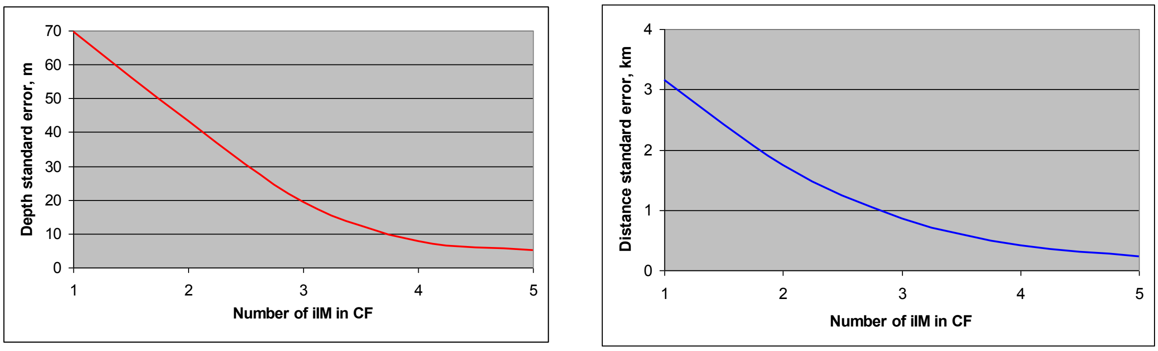
Table 3: The results obtained at the 1st step of simulation

The analysis of Table 3 leads to the following conclusions:

1) In the zone conditions, when SS is located in one of the far zones, as well as in the continuous acoustic illumination in the deep sea, the SS coordinates can potentially be determined unambiguously and with negligible errors. However, it should be noted that this conclusion is true if the number of IMs in CF is large enough (more than 3). At lower values, the solution of the problem becomes multi-valued and, as a result, the errors in the SS coordinates determination increase significantly (see Fig.3);

2) In the zone conditions, when SS is located in the near zone, as well as in a shallow water, the SS coordinates estimates are multi-valued with large standard deviation.

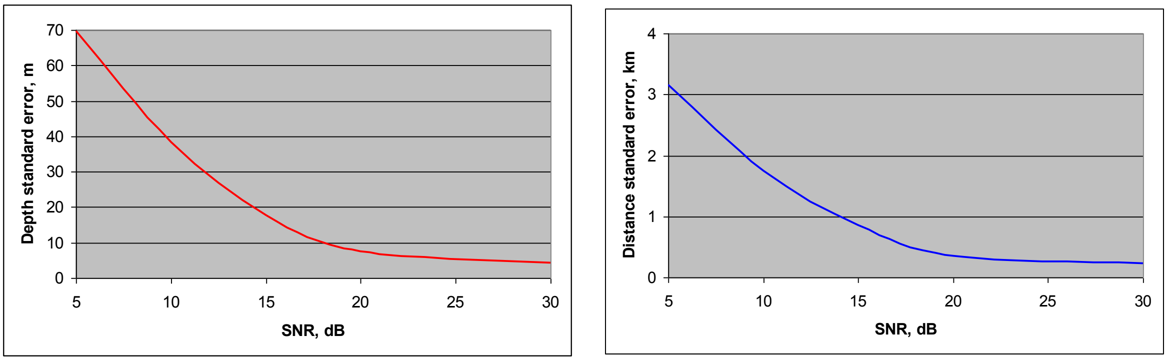
Thus, it can be concluded that the considered method is potentially applicable only in deep sea conditions and only at relatively large distances.



a) depth standard error *b) distance standard error*

Fig.3: The dependence of the SS coordinates estimates standard errors on the number of IM in CF

The results obtained at the 2nd step of simulation are given in Fig.4 and Fig.5. Fig.4 shows the dependence of the SS coordinates estimates standard errors on the SNR at antenna output when the SS locates in the 1st far zone in zone conditions. When the SNR less then 15 dB, the estimates become multi-valued and coordinate errors increase rapidly.



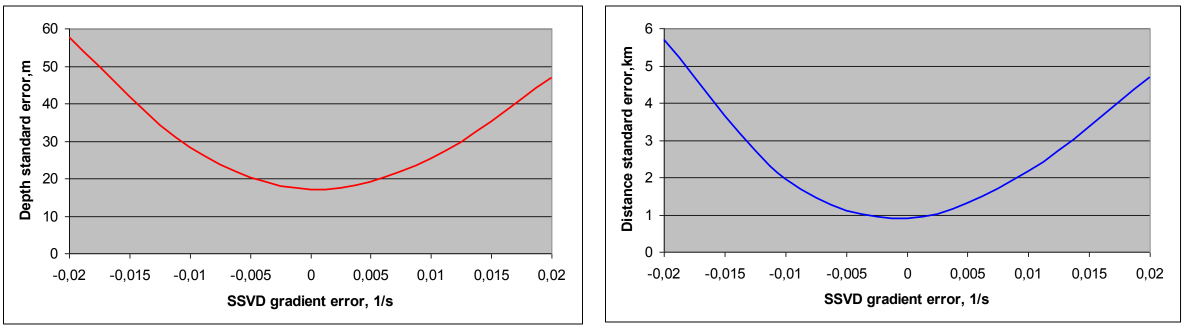
a) depth standard error *b) distance standard error*

Fig.4: The dependence of the SS coordinates estimates standard errors on the SNR at antenna output

Fig.5 demonstrates the dependence coordinates estimates standard errors on the sound speed vertical distribution (SSVD) errors for the SS, located in the 1st far zone. The true SSVD was distorted simultaneously in two ways:

– by use of sound speed and depth fluctuation errors with zero mean and RMS equal to 1 m/s and 1 m, respectively;

– by distort SSVD gradient in the interval from -0,02 to +0,02 1/s.



a) depth standard error *b) distance standard error*

Fig.5: The dependence of the SS coordinates estimates standard errors on the sound speed vertical distribution error

The consideration of Fig.5 shows:

1) if you make only the fluctuation errors (points on Fig.5, corresponding to zero abscissa) SS depth standard error increases up to 17 m and SS distance standard error increases up to 0,9 km;

2) in case of distortion of the true SSVD gradient in addition to the fluctuation errors the SS coordinates estimates standard errors increase significantly.

It follows a natural conclusion that for the application of this method in practice, the SSVD should be measured accurately.

4. CONCLUSION

An algorithm of the distance and depth of the broadband signal source (SS) determination is considered. The algorithm bases on the use the parameters of interference maxima (IM) in the correlation function (CF) of the signal at the output of the receiving hydroacoustic antenna. A number of algorithmic measures to partially overcome the negative factors affecting the accuracy of the algorithm when working in real conditions are proposed.

By means of simulation it is shown that developed algorithm potentially provides a high-precision SS coordinates estimates in the conditions of the deep sea at sufficiently large distances. In the conditions of shallow water, as well as at short distances in the deep sea, the estimates of the coordinates using the developed algorithm are multi-valued.

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