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Original Empirical Research

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Features of Bearing on Underwater Object Using Phase Information of a Differential Stereo Sensor

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Abstract

Introduction. Safety of navigation and development of underwater mineral deposits require the accurate detection of various underwater objects. The literature discusses the issues of tracking their motion and trajectory. Sonar methods are proposed to maintain high accuracy of underwater object positioning. High accuracy of the bearing of stereo sensors with an ultrashort base is noted. However, this equipment is sensitive to the sampling rate of the signals, which causes "sampling noise". There are no publicly available publications dedicated to the solution to this problem. The presented study is designed to fill this gap. This work is aimed to study the possibility of obtaining data clarifying information about the bearing of underwater objects through using the phase information about echoed probing signals and an additional procedure for resampling the source data.

Materials and Methods. The location of the object was determined using the experimental complex for studying hydroacoustic sensors created by V.A. Shirokov and V.N. Milich at the Udmurt Federal Research Center, the Ural Branch of the Russian Academy of Sciences. A stereo sensor with a small base (30 mm) was used compared to the distance to the object (≈800–900 mm). Digital filtering methods and mathematical apparatus of correlation analysis of return hydroacoustic signals obtained by the phase method were used for data processing.

Results. The results of comparing two methods for determining the bearing on an object are presented: by the difference in the time of arrival of the pulse-leading edges and by the maximum of the cross-correlation function (CCF). The change in bearing as the object moves, is graphically shown. The use of the leading edge of the signal caused small outliers of values along the entire bearing curve (less than 0.12 rad). At the maximum CCF, emissions were recorded only in some areas, but they were quite significant (about 0.17 rad). It showed how to select points corresponding to a smoother and more valid object trajectory, and how to work with erroneous points. The presented method of error correction can be implemented programmatically. With a quasi-harmonious signal, rare measurements of the original signal are interpolated by frequent calculated values. Thanks to this virtual increase in the sampling rate (oversampling), intermediate indicators can be recorded in the digitized source data. Interpolation of the signal values by a cubic spline allowed us to obtain 20 points for 1 period of the signal instead of 5 points in the original version. In this case, the trajectory formed with the maximum CCF is more correct.

Discussion and Conclusion. The direction-finding problem can be solved with the accuracy required for practical application. Taking into account the factor of smoothness and continuity of the object's trajectory makes it possible to qualitatively correct the selection of the maximum of the cross-correlation function of the stereo sensor signals. The proposed methods have great potential for the development of underwater vision systems.

Keywords: determination of the location of an object in a hydraulic environment, phase direction finding, pulse-leading edges, cross-correlation function, sampling noise

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Оригинальное эмпирическое исследование

Особенности определения пеленга на подводный объект с использованием фазовой информации дифференциального стереодатчика

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Аннотация

Введение. Безопасность судоходства и разработок подводных месторождений полезных ископаемых требуют точного обнаружения различных подводных объектов. В литературе рассматриваются вопросы отслеживания их перемещений и траектории движения. Предлагаются методы гидролокации, обеспечивающие высокую точность позиционирования подводных объектов. Отмечена высокая точность пеленга стереодатчиков с ультракороткой базой. Однако такое оборудование чувствительно к частоте дискретизации сигналов, что вызывает «шум дискретизации». В открытом доступе нет публикаций, посвященных решению этой проблемы. Представленное исследование призвано восполнить данный пробел. Цель работы — изучение возможности получения данных, уточняющих информацию о пеленге подводных объектов за счет использования фазовой информации отраженных зондирующих сигналов и дополнительной процедуры передискретизации исходных данных.

Материалы и методы. Местоположение объекта определяли с помощью экспериментального комплекса для исследования гидроакустических датчиков, созданного В.А. Широковым и В.Н. Милич в Удмуртском федеральном исследовательском центре Уральского отделения Российской академии наук. Использовали стереодатчик с малой базой (30 мм) по сравнению с расстоянием до объекта (≈800–900 мм). Для обработки данных применяли методы цифровой фильтрации и математический аппарат корреляционного анализа отраженных гидроакустических сигналов, полученных фазовым методом.

Результаты исследования. Представлены итоги сопоставления двух способов определения пеленга на объект: по разности времени прихода передних фронтов импульсов и по максимуму кросс-корреляционной функции (ККФ). Графически показано изменение пеленга при движении объекта. Использование переднего фронта сигнала обусловило небольшие выбросы значений вдоль всей кривой пеленга (менее 0,12 рад). При максимуме ККФ выбросы фиксировались лишь в некоторых областях, но были довольно значительными (около 0,17 рад). Показано, как выбрать точки, соответствующие более гладкой и валидной траектории объекта, и как работать с ошибочными точками. Представленный метод устранения ошибки можно реализовать программно. При квазигармоничном сигнале редкие измерения исходного сигнала интерполируются частыми вычисленными значениями. Благодаря такому виртуальному увеличению частоты дискретизации (передискретизации) можно фиксировать промежуточные показатели в оцифрованных исходных данных. Интерполяция значений сигнала кубическим сплайном позволила получить 20 точек на 1 период сигнала вместо 5 точек в исходном варианте. В этом случае более корректна траектория, сформированная с максимумом ККФ.

Обсуждение и заключение. Задачу пеленгации можно решить с точностью, необходимой для практического применения. Учет фактора гладкости и непрерывности траектории движения объекта позволяет качественно корректировать выбор максимума кросс-корреляционной функции сигналов стереодатчика. Предложенные методы обладают большим потенциалом для разработки систем подводного видения.

Ключевые слова: определение местоположения объекта в гидросреде, пеленгация фазовым методом, передние фронты импульсов, кросс-корреляционная функция, шум дискретизации

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Introduction. Safety of navigation and work in underwater mineral deposits require high-quality detection of underwater objects and tracking their movements [1]. Hydroacoustic sensors are used in underwater surveillance systems. They capture the signal reflected from the object and provide for the calculation of its location using the trilateration method [2]. In this process, each sensor provides information about the time interval of the probing signal reflected from the object. In the case of using several sensors [3], it becomes possible to solve the problem of spatial resection and determine the coordinates of the observed object [4]. To increase the accuracy of measurements, it seems promising to use stereo sensors with an ultrashort base as a receiver [5], which allow obtaining phase information [6] and determining the bearing on an object [7]. The possibilities of using sonar data on remote underwater targets, as well as on the bearing of underwater objects [8] through the use of phase [9] or frequency [10] information of reflected probing signals have been studied.

At the same time, it is known that the signal sampling procedure causes errors in determining the parameters of the trajectory of underwater objects [11]. This applies to both distance measurements and bearing determination procedures. Digitization of the analog sensor signal, which is required for further digital processing, introduces the so-called "sampling error". The error caused by the signal amplitude quantization is estimated by the number of quantization levels of the analog-to-digital converter. The error caused by time sampling is proportional to the range of the quantization time interval and the stress rate. Therefore, the sampling frequency of the signal is sought to be as high as possible above the upper frequency of the signal itself. However, increasing the sampling rate in a number of cases is limited by the capabilities of recording equipment: processor, analog-to-digital converter, data transmission channels, data storage devices. The limited possibilities of sampling in time when performing trajectory measurements do not allow for accurate recording of the extreme values of the trajectory (range and bearing). As a result, the accuracy of measurement results decreases, and outliers appear on the fixed trajectories. To eliminate this disadvantage, it is necessary to study the potential of oversampling the digitized sonar signal. There are no publicly available publications dedicated to solving this problem. The materials of this article fill in the existing gap.

The objective of the presented study is to evaluate the possibilities of determining the bearing on an object using phase information, and to develop a phase method of bearing using the resampling of a digitized sonar signal.

Materials and Methods. An algorithm for determining coordinates using the direction-finding phase method is considered. The results of its testing for an object moving along a circular trajectory in an experimental pool are presented.

Setting up an experiment. During the experiments, an experimental assembly created by V.A. Shirokov and V.N. Milich at the Udmurt Federal Research Center of the Ural Branch of the RAS was used to determine the location of an object in the hydroenvironment with the direction finding by the phase method [12]. This is a laboratory measuring complex with a linear aqua medium in the form of an extended cylindrical tank (hydro waveguide) and a basin equipped with a system for generating test sonar signals. The installation elements used in the experiments are described in detail below.

1. Hydroacoustic signal emitter with known coordinates *S* (Fig. 1). An amplitude-modulated signal is used in the work [13].

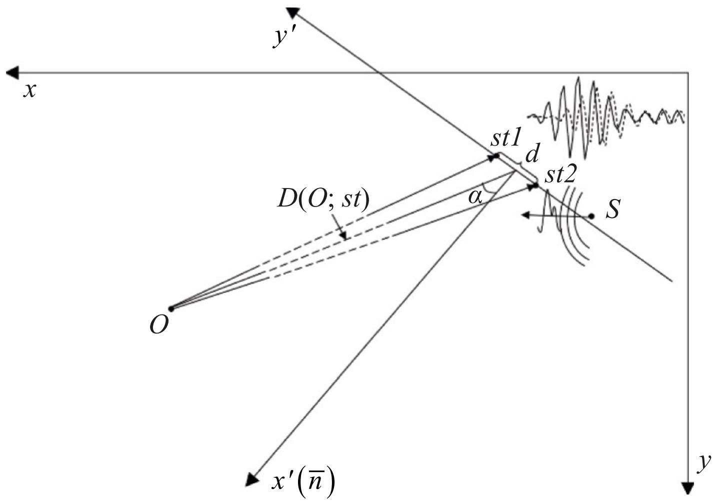

Fig. 1. Location of the receiving sensors (stereo sensor with two receivers *st*1 and *st*2) and emitter (*S*) in the plane of experimental tank (*xy*). Here, *d* — stereo sensor base; *D*(*O*; *st*) — distance between the stereo sensor and the object; α — bearing on the object; plate (*x'y'*) is formed by the plane of the stereo sensor and normal *n* to it

2. Reflecting object. In the experiment, an extended cylindrical object is used as a test object — a copper wire whose diameter (0.15 mm) is significantly less than the acoustic wave length (1.5 mm). In the presented work, the problem is solved on a plane; therefore, for the compilation of computational procedures for calculating coordinates, this object can be considered a point.

3. Stereo sensor that converts a sonar signal into an electrical one. The coordinates of each of the two receivers of the stereo sensor are known (see *st*1, *st*2 in Fig. 1).

4. Hardware-software complex that performs amplification, digitization and processing of sensor signals.

The measurement result is a recording file of the received two-channel signal.

Algorithm for processing measurement results. Using a stereo sensor with a small base (30 mm) compared to the distance to the object (≈ 800–900 mm) allows us to apply simplified formulas.

Now then, we calculate the coordinates of the object under study in the system *x'y'*, formed by the plane of the stereo sensor and the normal to it. To do this, we use the algorithm that includes five stages.

1. Preprocessing:

– removal of the blind zone (the first N counts);

– signal filtering.

High-frequency filtering is used in the work.

2. Selecting informative fragments *imp*1, *imp*2 (in two channels) containing pulses reflected from the object under study. To do this, thresholding is performed according to amplitude *A* of the signal. The threshold is assumed to be equal to $p \times max(A)$ ($p = 0.5$).

This processing allows for determining the leading edge of the pulse (*BeginIndex*), reflected from the object. Sections [*BeginIndex*–0.5×*LenSignal*; *BeginIndex*+*LenSignal*] are cut from two signal channels. Here, *LenSignal* — length of the input signal. As a result, we get two signals *imp*1 and *imp*2 with a length of 1.5×*LenSignal*. Each of them contains the pulse reflected from the object.

3. Calculation of distance *D*(*O*; *st*) between the object and the stereo sensor.

– Determination of the distance traveled by the pulse from the emitter to the object and from the object to the reception sensor, using formula *D*(*S*,*O*,*st*)=BeginIndex×<u>*dt*</u>×*C*. Here, *C* = 1475 m/s — acoustic wave velocity, *dt* = 0.2×10–6 s — sampling interval.

– Calculation of value

$$D(O,st) = \frac{D(S,O,st) - D(S,st)}{2}. \quad (1)$$

4. Determination of bearing α on object [14]:

$$\alpha = arcsin\left(\frac{\lambda \times F \times dt \times m}{d}\right), \quad (2)$$

where λ — wavelength; *F* — signal frequency; *dt* — sampling interval; *m* — difference in the arrival of the reflected pulse to two stereo sensors (in counts); *d* — base of the stereo sensor (in the presented study λ = 1.5 mm, *F* = 1 MHz, *dt* = 0.2 µs, *d* = 30 mm).

5. Calculation of the coordinates of the analyzed object in the system formed by the plane of the stereo sensor and its normal (Fig. 1), according to the formulas: $x' = D(O, st) \times \cos(\alpha)$; $y' = D(O, st) \times \sin(\alpha)$.

Determining the bearing on an object. Assume the condition of the smallness of the stereo base compared to the distance from the sensor to the object. In this case, the stereo sensor allows us to determine the bearing on the object using information about the phase difference of the received pulses previously reflected from the object, as well as the difference in the time of arrival of the leading edges of the pulses received by the stereo sensor (Fig. 2).

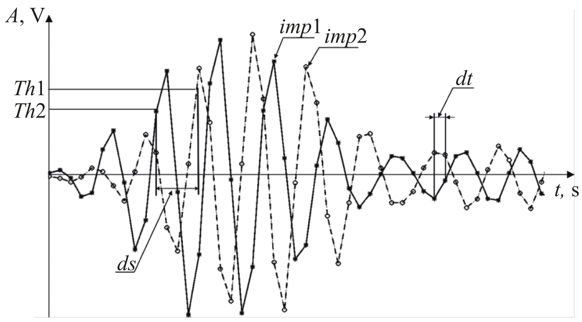

Fig. 2. Determination of difference in the moments of arrival of stereo signals ds, which are indicated by solid *imp*1(*t*) and dotted *imp*2(*t*) lines. *Th*1, *Th*2 — thresholds for the first and second stereo pair signals, respectively; *dt* — sampling interval; *A* — signal value in volts; *t* — time

To implement this approach, the following procedures are performed.

1. Identification of the moments of arrival of the leading edges of stereo signals using thresholding [15] with threshold $p \times max(A)$. In this paper, coefficient p is assumed to be 0.5 [16].

2. Calculation of difference ds (number of intervals dt) between the leading edges of the pulses registered in two receivers of the stereo sensor.

3. Calculation of bearing α by formula (1). We take value d for m.

With this method of calculating the phase shift, the leading edge of the signal is the main indicator of the pulse reflected from the object. The internal structure of the signal is not taken into account, which may be crucial for the correct determination of the bearing on the object. We take into account the similarity of the received signals and consider another approach to calculating the bearing — based on the cross-correlation function (CCF) of stereo signals. It is logical to determine the phase shift by the CCF maximum. The elements of the bearing calculation algorithm using CCF are described below.

1. Calculation of the CCF pulses arrived at two receivers of one stereo sensor: $r = xcorr(imp1, imp2)$. The value of function $xcorr$ at the shift of m of the second signal relative to the first is calculated as follows:

$$\mathrm{xcorr}_{imp1,imp2}(m) = \begin{cases} \sum_{n=0}^{N-m-1} imp1_{n+m} \times imp2_n, & m \geq 0, \\ \mathrm{xcorr}_{imp2,imp1}(-m), & m < 0. \end{cases}$$

Here, N — length $imp1$ and $imp2$, $-N<m<N$.

2. Determination of the maximum CCF and the corresponding shift dc (in counts).

3. Calculation of bearing α from formula (1) taking into account that value dc is taken as m.

Research Results

Testing the bearing determination methods. The presented methods for determining the bearing on an object (by the difference in the time of arrival of the pulse-leading edges and by the CCF maximum) were tested for an object moving along a circular trajectory in the experimental pool. A harmonic signal with a duration of 7 periods and a frequency of 1 MHz was used. Digitized stereo signals were recorded at 256 points of the object's trajectory. The digitization frequency was 5 MHz.

Figure 3 shows the change in bearing values as the object moves around the circle for the two proposed approaches (difference of the leading edges, CCF maximum).

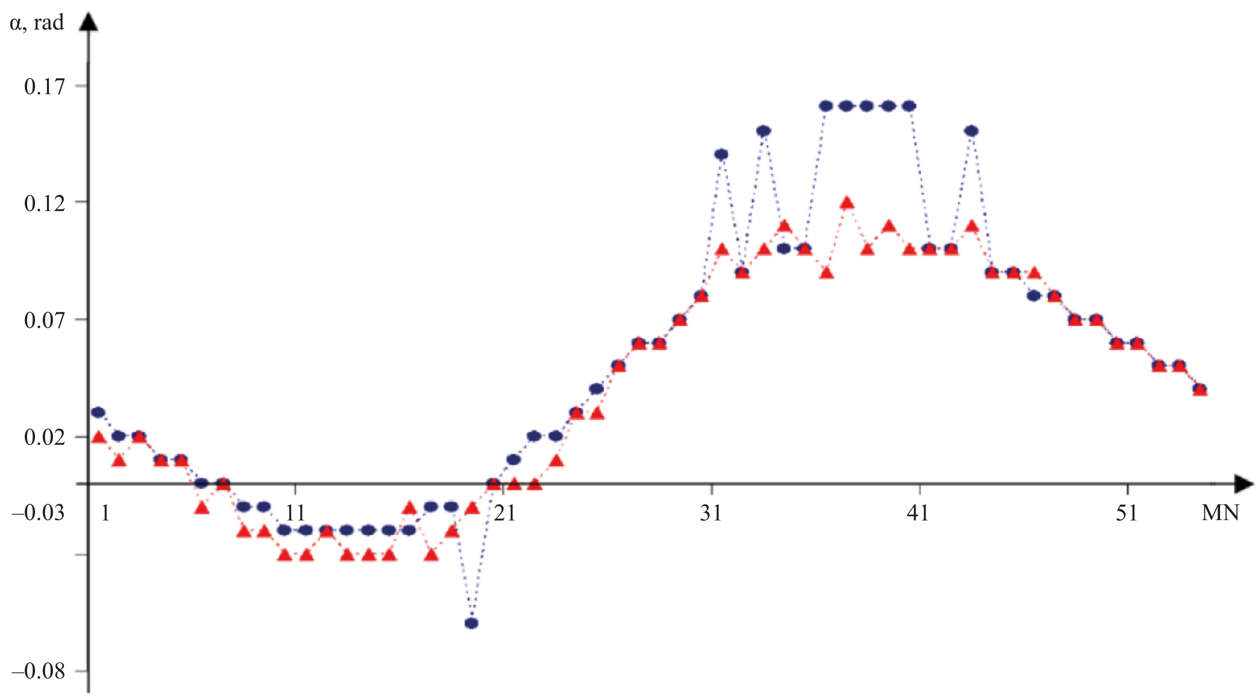

Fig. 3. Deviation of bearing α on the object making a circular motion. Indicators were obtained using two approaches (red marker — difference in the time of arrival of the leading edges of stereo signals, blue marker — CCF maximum). MN — measurement number, α — bearing on the object

When using the signal-leading edge (Fig. 3, red marker), small outliers of values are observed almost along the entire curve of the bearing on the object. When using the CCF maximum (Fig. 3, blue marker), only in some areas there are outliers of bearing values, but they are quite large. Perhaps this is due to the peculiarities of the object's movement in the area where the probing and reflected signals cross the zone of turbulence caused by the object's movement. When finding the phase shift of stereo signals using the CCF maximum, additional errors occur, which is then reflected in the calculated trajectory of the object. Also, outliers in the calculated bearing values may be due to an insufficiently high sampling rate. The values of these errors are significantly higher than the emission values observed for the method using the pulse-leading edge.

Figure 4 *a* presents the trajectories of the object, calculated using the global CCF maximum and its neighboring local maxima.

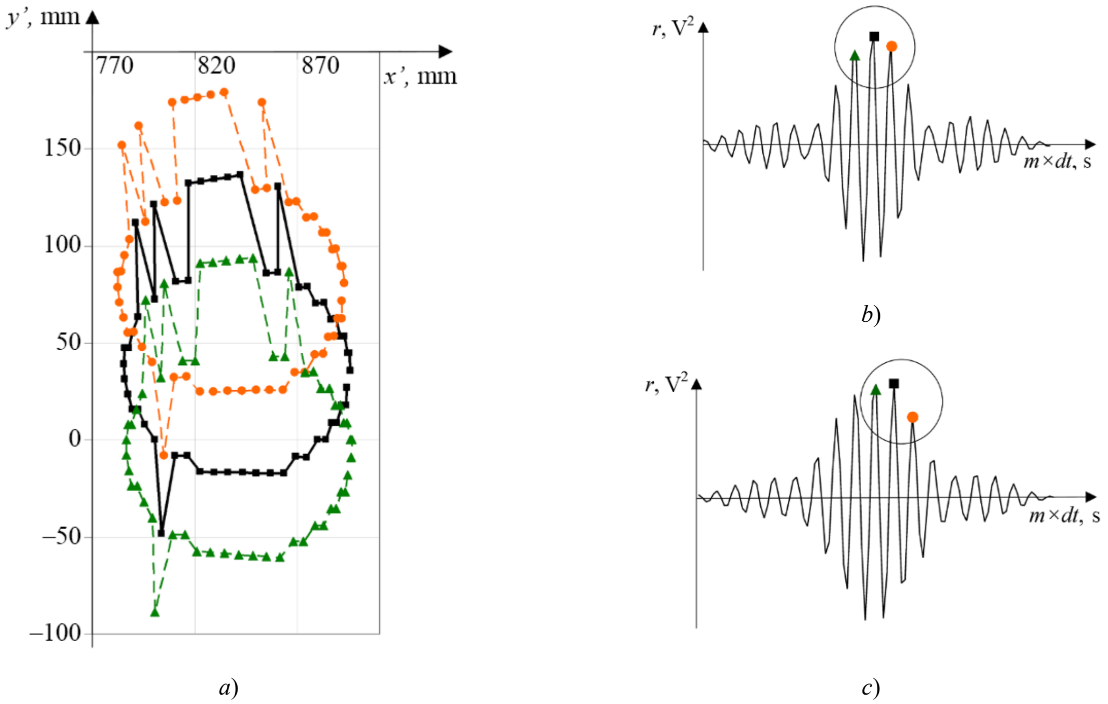

Fig. 4. Analysis of the trajectories of the circular motion of the object:
a — trajectories calculated using the global CCF maximum (black marker),
local nearest right CCF maximum (orange marker), local nearest left CCF maximum (green marker);
b — example of CCF, whose global maximum corresponds to the correct value of the coordinates of the object;
c — example of CCF, in which the left local CCF maximum corresponds to the correct value of the coordinates of the object

Using aprior information about the smoothness of the movement of the experimental object, it is possible to select points that correspond to a smoother and more valid trajectory. This approach is used in other works [17]. In Figure 4 *a*, at $x'\epsilon[800;870]$, $y'>0$, the correct values are on the curve for the trajectory calculated from the left local CCF maximum. There are also erroneous points. If they are replaced by the points of the trajectory obtained as a result of using the right local CCF maximum, the correct value of the trajectory point can be calculated ($x'\approx800$, $y'<0$ in Fig. 4 *a*). This graphical method of error correction can be implemented programmatically.

Thus, at some points of the trajectory, the correct phase shift of the stereo signals required for calculating the bearing may correspond not to the global CCF maximum, but to one of the neighboring local extremes (Fig. 4 *b*, *c*). This shift of the CCF maxima may be due to an insufficiently high sampling rate of the signals. This also explains the stepwise nature of the resulting trajectory.

Taking into account the quasi-harmonicity of the signal, it is proposed to use interpolation of rare measurements of the original signal with frequent calculated values. This virtual increase in the sampling rate (oversampling) makes it possible to fix intermediate values in the digitized source data. Interpolation of the signal values by a cubic spline allowed us to obtain 20 points for 1 period of the signal instead of 5 points in the original version. Figure 5 shows the calculated trajectories of the object, formed with preliminary resampling of the signals.

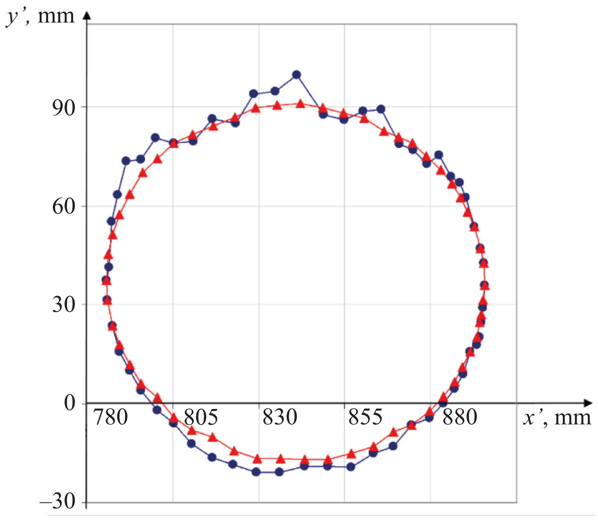

Fig. 5. Calculated object motion trajectories obtained for stereo signals with a virtually increased sampling rate:
blue marker — difference in the time of arrival of the signal-leading edges is used;
red marker — CCF maximum is used

The red line is the object's trajectory, obtained using the CCF maximum to calculate the bearing from pre-interpolated data. It seems to be more correct compared to a similar trajectory obtained using the difference in the leading edges of reflected pulses (blue line).

Discussion and Conclusion. Analysis of the features of determining the bearing on an underwater object using the mutual phase information of the differential stereo sensor signals makes it possible to draw the following conclusions.

– The difference in the arrival time of the pulse-leading edges recorded by the stereo sensor allows us to obtain bearing values indicating the direction of the object. The quality of the result depends on the accepted threshold value (used in determining the pulse-leading edge) and the variability of the amplitudes of the received signals.

– The application of the approach using the maximum of the cross-correlation function at an insufficient sampling rate of the initial signals leads to significant outliers in the calculated trajectory (Fig. 3).

– Resampling of signals through interpolation of the original quasi-harmonic signals using the CCF maximum for the calculation of the bearing and coordinates of the object provides obtaining a smooth trajectory (Fig. 5), corresponding to the smooth movement of the object in a circle. This approach requires significantly higher computational costs compared to the others discussed in this article. This may affect the speed of real-time signal processing.

Thus, the investigated possibilities of refining the phase direction finding method (resampling of digitized signals and using the CCF maximum) make it possible to effectively assess the trajectory of an underwater object.

The conditions for obtaining a smooth correct trajectory of the tracked object are described. The oversampling of interpolated quasi-harmonic stereo signals digitized with insufficient sampling rate serves this goal. At the same time, the bearing calculation method is used with the maximum of the cross-correlation function of the stereo sensor signals.

The data in Figure 5 confirm that the direction-finding problem can be solved with the accuracy required for practical application. Taking into account the factor of smoothness and continuity of the object's trajectory allows for the unique adjustment of the selection of the maximum of the cross-correlation function of the stereo sensor signals (Fig. 4).

The proposed methods are of great importance for the development of underwater vision systems.

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