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APPLICATION OF DIFFERENTIAL MODE FOR AUV LOCATION

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Introduction: *Signals from satellite radio navigation systems cannot penetrate seawater. Therefore, autonomous underwater vehicles are located with the use of one or more support objects. Because of the layered nature of a marine environment, a sound beam goes not in a straight line as radio signals do, but along an arcuate trajectory. Therefore, the correction of the vehicle location by the differential method has a large error.* ***Purpose:*** *Assessing the requirements and conditions necessary for using the differential mode of correcting a vehicle location.* ***Results:*** *We have simulated the propagation of sound beams in a vertical plane according to Snell's law, under the condition that sound beam propagation follows the Rice distribution. We have determined the distance covered by a sound beam, evaluated its dependence on the emission direction, specified the procedure of locating a vehicle with the use of the differential mode for correcting the location, and formulated the conditions for using the differential method which are determined by the sound emission direction, by the sound speed profile and by the mutual position of the emitting buoys, the correcting base station and the underwater vehicle.* ***Practical relevance:*** *The obtained results can be used for locating vehicles in areas where you cannot use the traditional methods of precise location.*

Keywords *— Autonomous Underwater Vehicle, Route Trajectory, Current, Efficiency Evaluation.*

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Introduction

Increasing the accuracy of locating autonomous underwater vehicles (AUV), especially in the case of using them in groups, for example, when conducting seismic survey or searching for anthropogenic objects [1–10], is of paramount importance. By now, a large number of methods for positioning an underwater object have been developed [11–16], including AUV positioning, a comprehensive review of which is given in [17]. To locate an AUV under water, range-measurement hydroacoustic navigation systems [18] or systems with a single mobile beacon [19] are used. Some recent attempts have been made to conduct underwater positioning in accordance with the principles of satellite radio navigation systems [20–22].

At the same time, the peculiarity of locating an AUV in a group is that:

— the location should be conducted aboard the AUV;

— there can be no emitting devices or hydroacoustic modems aboard the AUV;

— there can be no inertial navigation system or auxiliary equipment like lags or echosounders aboard the AUV due to the limitations on weight-size parameters and power consumption.

A way to increase the accuracy of locating an object in satellite radio navigation is the use of differential corrections to pseudoranges or pseudospeeds of radio signal propagation [23]. The transfer of the differential method of object location correction into a marine environment requires taking into account the laws of sound signal propagation in water and the dependence of the propagation on the mutual position of the AUV and reference objects (other underwater or surface vessels with known coordinates, bottom beacons, surface buoys, escort vessels, etc.), as well as the dependencies on the state and parameters of the marine environment determined by the location, weather conditions, time of year and time of day.

Marine environment has the following features:

— significant attenuation of sound in water;

— sound propagation along multiple directions;

— refraction of beams causing a curvature of the trajectory along which a sound beam propagates;

— layered nature of the medium and the dependence of the sound speed on depth.

The above-mentioned studies on navigational location of AUV do not discuss the ways to apply the differential method to correcting underwater object location.

Differential Mode Description

The idea of the differential mode of correcting an object location is based on developing corrections to pseudoranges from the source of a hydroacoustic signal to its consumer. As signal sources, we will consider transmitter buoys (further referenced to as buoys). The consumer is an AUV. The prefix “pseudo-” is added because the time scales of the radiation source and the AUV are not synchronized with one another and hence the measured range value differs from the actual one. To maintain the differential mode of pseudorange correction, in a specified seabed area a base station (BS) is established in advance, whose coordinates are being determined over a long period of time by means of precise measurement of its position [24].

We will assume that the buoys on the sea surface are located using the signals of satellite radio navigation systems. The same signals are used to synchronize the time scales of the buoys with high accuracy.

The formation of differential corrections of the BS with their transfer to consumers, including AUV, goes as follows. The buoys periodically emit signals into the seawater. The period of the signals is maintained with high accuracy. The frequency of the signals is known to the BS and the AUV. Aboard the AUV, using the signal received from the buoy, the signal arrival delay is determined, counting from the moment of its emission. According to the delay, distance to the buoy is calculated. In this manner, distances to at least four buoys are found. The distances to the buoys determine the AUV position by the difference-ranging method. This method is used because of the mismatch between the time scales of the buoys and the AUV: the beginning of the AUV time scale does not coincide with the beginnings of the time scales of the buoys mutually coordinated by the signals of satellite radio navigation systems.

With this measurement, the evaluation of the pseudoranges between the AUV and the buoys has a certain error similar to the errors in satellite radio navigation systems caused by the features of both signal propagation environment and signal delay measurement hardware. AUV onboard delay calculation is so sophisticated because marine environment is very different from aerial: the signals of satellite radio navigation systems propagate in space rectilinearly and almost without distortion, while acoustic signals propagating through water are influenced by a host of unfavorable factors. The world ocean is an inhomogeneous medium; there are warm and cold currents, whirlpools, areas with different concentrations of dissolved salts, etc. Acoustic signals propagating with a low speed relative to radio signals will physically move, shift in phase, be reflected and distorted while passing through the inhomogeneities of a marine environment. Partially, their influence can be compensated by choosing appropriate mathematical processing methods, as all the above-mentioned factors are constant [25, 26]. However, not everything can be compensated only mathematically; there are errors in the measurements as such, which also contribute to the error of pseudorange calculation.

The base station, similarly to AUV, also estimates the distance to the buoys by the delays of the received signals. Simultaneously, the BS evaluates the calculated distance to the buoy, knowing its exact and constant location and the position of the buoy at the signal emission moment. It is assumed that the emitted signal contains the coordinates of the buoy and the emission time. The BS compares the obtained distance values with the calculated ones; on the base of this comparison it produces a correction, and emits it into the water for the consumers, including the AUV. Receiving these corrections and adding them up, the AUV updates its estimation of the distance to the buoy. The updated distances to four buoys are then used in the difference-ranging method.

Mathematically, it can be described as follows. Let it be given that:

x_{BS}, y_{BS}, z_{BS} are BS coordinates known with the required accuracy;

x_i, y_i, z_i are the coordinates of the i^{th} buoy with a high accuracy; $i = 1, \ldots, M$, where M is the number of the buoys, $M = 4$.

At some instant of time t, all the M buoys emit sonar signals carrying the information about the time t and each i^{th} buoy coordinates x_i, y_i, z_i.

Let the time in which a signal from the i^{th} buoy reaches the BS be $\tau_{\mathrm{BS}\ i}$ and the time in which it reaches the AUV be $\tau_{\mathrm{AUV}\ i}$.

Then the actual distance between the i^{th} buoy and the BS is defined by the following expression:

$$R_{\mathrm{BS}\ i} = \tau_{\mathrm{BS}\ i} C,$$

where C is the speed of sound in water in this particular area.

From the i^{th} buoy coordinates x_i, y_i, z_i and the base station coordinates x_{BS}, y_{BS}, z_{BS} precisely known at the base station, the distance between the buoy and the base station is calculated:

$$R_{\mathrm{calc_{BS}}i} = \sqrt{\left(x_i - x_{\mathrm{BS}}\right)^2 + \left(y_i - y_{\mathrm{BS}}\right)^2 + \left(z_i - z_{\mathrm{BS}}\right)^2}.$$

It determines the differential correction to the distance to each ith buoy as the difference between the actual and calculated values:

$$\Delta R_i = R_{\mathrm{act_{BS}}i} - R_{\mathrm{calc_{BS}}i}.$$

The distance from the i^{th} buoy to the AUV is defined by the following expression:

$$R_{\mathrm{AUV}\ i} = \tau_{\mathrm{AUV}\ i} C.$$

Using the correction ΔR_i produced at the BS and transferred to the AUV, the distance between the buoy and the AUV is calculated:

$$R_{\text{calc}_{\text{AUV}}i} = R_{\text{act}_{\text{AUV}}i} - \Delta R_i .$$

Having these values for the distances from the AUV to four or more buoys, the AUV locates itself by the difference-ranging method through solving a system of equations

$$\begin{cases} \sqrt{(x_2-x)^2+(y_2-y)^2+(z_2-z)^2} - \\ -\sqrt{(x_1-x)^2+(y_1-y)^2+(z_1-z)^2} = \Delta r_{21} \\ \sqrt{(x_3-x)^2+(y_3-y)^2+(z_3-z)^2} - \\ -\sqrt{(x_1-x)^2+(y_1-y)^2+(z_1-z)^2} = \Delta r_{31} \\ \sqrt{(x_4-x)^2+(y_4-y)^2+(z_4-z)^2} - \\ -\sqrt{(x_1-x)^2+(y_1-y)^2+(z_1-z)^2} = \Delta r_{41} \end{cases},$$

where Δr_{i1} is the difference between the distances from a couple of reference points $\{O_i, O_1\}$ to the point in question; x, y, z are the AUV position point coordinates; x_i, y_i, z_i are the coordinates of the i^{th} buoy; $i = 1, \ldots, 4$.

Fig 1 explains the difference-ranging method; the symbol ρ_{bi} designates the distance from the buoy reference points to the AUV position point.

The calculation of ΔR_i corrections and their transfer to the consumers occur with a certain constant periodicity, which is why this is called a differential mode of pseudorange correction. The differential mode is successfully used in satellite navigation, improving object location accuracy.

Applying the differential mode in a marine environment requires that we consider how the marine environment affects the propagation of sound and the determination of distances between objects.

Let us assume that:

— the beam propagation follows the Rice distribution [27] with the dominance of one beam;

— a BS knows the sound speed profile (SSP) which is periodically measured with a pulsed SSP meter [28];

— the AUV also knows the SSP which can either coincide with the BS SSP or differ from it;

— signals formed by a buoy correlate with one another.

Estimating the Influence of Seawater Stratification on the Sound Beam Trajectory

The curvature of a sound beam propagation trajectory caused by seawater stratification is schematically shown in Fig. 2.

The distance to which a beam deviates from the vertical because it was emitted at an angle to the horizontal is determined by the expression [29]

$$\Delta R_j = \rho_j (\sin\alpha_j - \sin\alpha_{j-1}), \tag{1}$$

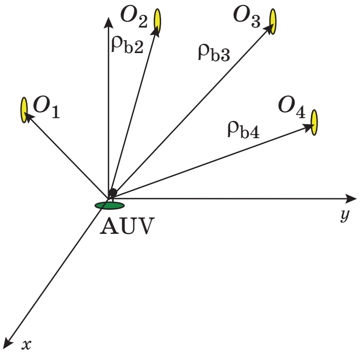
where j is a layer number $j = 1, \ldots, n$; n is the number of the layers; ρ_j is the radius of the circle whose arc is the beam trajectory in the j^{th} layer; α_j is the angle of the beam entry into the j^{th} layer; α_{j-1} is the angle of the beam entry into the $(j-1)^{\text{th}}$ layer; when $j = 1$ the direction of the signal emitted by the buoy is α_{j-1}.

The radius of the circle is determined by the expression

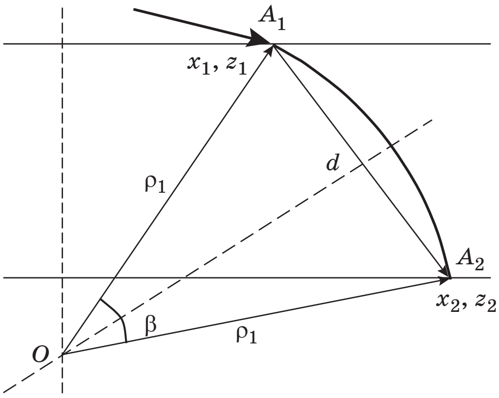
$$\rho_j = \frac{1}{a\cos\alpha_j},$$

a is a relative gradient:

$$a = \frac{G_C}{c_0},$$



■ ***Fig. 1.*** Diagram explaining the difference-ranging method



■ ***Fig. 2.*** Schematic representation of beam curvature where G_C is a gradient of the speed of sound in water determined by the expression

$$G_C = \frac{c_{j+1} - c_j}{z_{j+1} - z_j}.$$

Let us assume that $G_C = \text{const}$. Then the full horizontal distance of the beam deviation from the vertical will be determined by the following expression:

$$R_{\text{f}} = \sum_{j=1}^{n} \Delta R_j. \tag{2}$$

From triangle ΔOO_1O_2 we can express the distances between the point of the beam entry into the j^{th} layer and the point where the beam leaves the j^{th} layer:

$$d_j = \sqrt{\left(x_{j+1} - x_i\right)^2 + \left(z_{j+1} - z_i\right)^2}. \tag{3}$$

Besides, from triangle ΔOO_1O_2 we can derive an expression for finding the angle β_j at a vertex as a half-angle between the directions to the point of the beam entry into the j^{th} layer and the point where the beam leaves it (see Fig. 2). This expression looks like

$$\frac{d_j}{2} = \rho_j \sin\frac{\beta_j}{2},$$

from which it follows that

$$\beta_j = 2\arcsin\left(\frac{d_j}{2\rho_j}\right). \tag{4}$$

Then, knowing the vertex angle β_j and radius ρ, we can determine the length of the arc l, along which the beam propagated:

$$l_j = \beta_j \rho_j. \tag{5}$$

The angle β_j is expressed in radians.

The above expressions (1)–(5) allow us to estimate the distance covered by the beam in the j^{th} layer.

Then, depending on the AUV immersion depth, the beam path trajectory length is estimated as a sum of the beam trajectories through the layers:

$$L = \sum_{j=1}^{n} l_j.$$

If the AUV does not know the speed of sound, the following averaging formulas can be used:

— weighted average speed of sound

$$C_{\text{w}} = \frac{\sum_{j=1}^{n} \left(c_j - c_{j-1}\right)\left(z_j - z_{j-1}\right)}{2\left(z_{\text{AUV}} - z_i\right)},$$

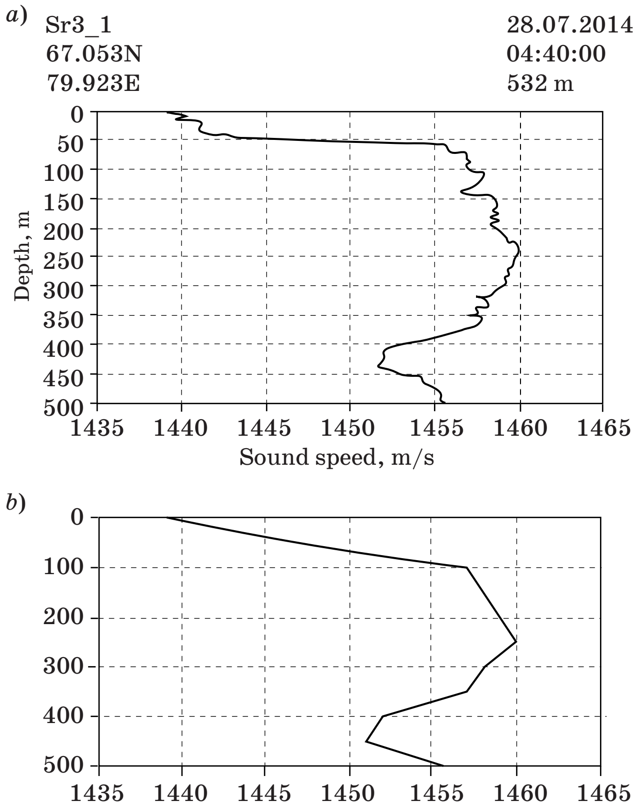
where z_i is the i^{th} buoy antenna immersion depth; in the problem under discussion $z_i = 0$;

— harmonic mean of the speed of sound

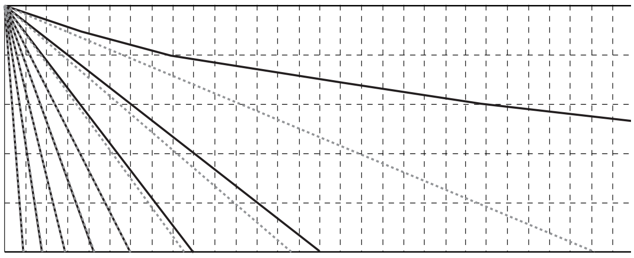
$$C_{\text{h}} = \frac{\left(z_{\text{AUV}} - z_i\right)}{2\sum_{j=1}^{n} \frac{\left(c_j - c_{j-1}\right)}{\left(z_j - z_{j-1}\right)}}.$$

To estimate the change in the calculated range when the curvilinear trajectory of the sound propagation is taken into account, we estimated the deviations of an arcuate beam trajectory from the rectilinear path connecting these points. As initial data, a real SSP was considered (Fig. 3, *a* and *b*). In the calculations, the width (thickness) of a step layer was equal to 50 m. The size of the chosen sampling interval was determined by the data error [30]. The beam pattern representation is shown in Fig. 4.

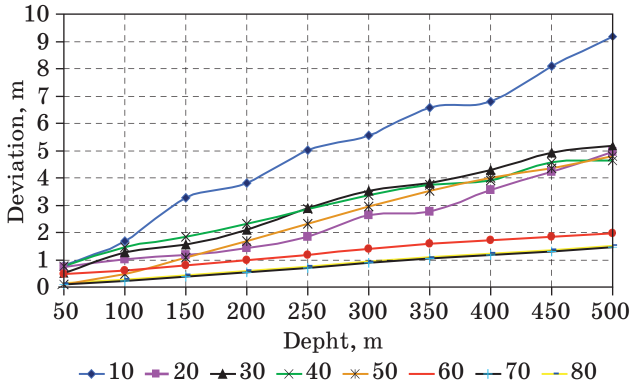
The results of the calculations (Fig. 5) showed that the deviation of an arcuate trajectory from the rectilinear one is about 9 m. This value was obtained for near-surface emission of an acoustic beam at an angle of 10° to the horizontal. When the emission direction changed to 80°, the deviation decreased from 9 down to 1.5 m.



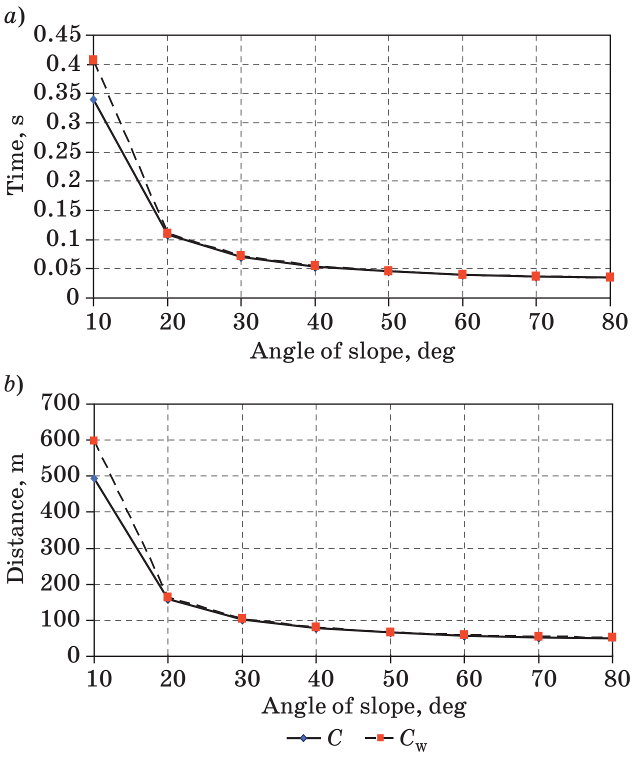
■ ***Fig. 3.*** The sound speed profile for the Kara Sea: *a* — data of the source [30]; *b* — digital representation for use in modeling



■ ***Fig. 4.*** Beam pattern representation



■ ***Fig. 5.*** Deviation of an arcuate beam propagation trajectory from the straight line connecting the points of the buoy position on the sea surface and the position of the receiver (AUV)



■ ***Fig. 6.*** An estimate of signal travel time (*a*) and covered distance (*b*) along the beam, at a known sound speed *C* (dashed line) and a weighted average C_w (solid line)

Besides, we estimated the duration of the beam travel and the distance it covers for the case when the speed of sound is considered weighted average (Fig. 6, *a* and *b*).

The obtained results allow us to state that when the emission angle relative to the water surface is 20° or more, we can use the weighted average value of the sound speed, rather than counting it literally by layers, because the results for the time and distance at $\alpha \geq 20°$ nearly coincide.

Determining a Distance Covered by a Beam Along an Arcuate Trajectory by Layers

As discussed above, a beam propagation trajectory can be sophisticated. Therefore, when you calculate the length covered by a beam using the measured delay between the emission of a signal and its reception in a certain point, you have to take into account the complex curvilinearity of its trajectory. To use the formulas (1)–(5), you need to know the direction in which the buoy emits the beam, i. e. the beam angle α in the top layer. Since the trajectory is curvilinear, the emission direction is not obvious, requiring a special approach to its determination.

Mathematically, the problem of determining the emission direction α can be formulated as follows:

Let the beam arrive to an AUV point whose coordinates are unknown and need to be found. We know the time necessary for the signal to cover the curvilinear trajectory, and we know the SSP.

We need to find the coordinates of the AUV point to which the beam arrives.

This means we need to find a triplet of coordinates which would meet the following criterion:

$$\left(x_{\mathrm{AUV}}, y_{\mathrm{AUV}}, z_{\mathrm{AUV}}\right) = \\ = \left\{ \begin{matrix} \left(x, y, z\right) \in K : \Delta T\left[\left(x, y, z\right); \left(x_{\mathrm{AUV}}, y_{\mathrm{AUV}}, z_{\mathrm{AUV}}\right)\right] = \\ = \sum_{j=1}^{n} \Delta t_j \end{matrix} \right\},$$

where *K* is the set of all points of possible AUV position in the given area, and ΔT [(1); (2)] is the time of sound travel between points 1 and 2.

In order to determine the emission direction, let us consider two cases. In the first case, the AUV has the information about its immersion depth; in the second case, it has not.

1. *The AUV has the information about its immersion depth.*

Let us assume that the AUV measures the depth by a special pressure gauge. Aboard the AUV, the delay is determined between the moments of emission and reception of the sound. To determine the

AUV position, you need, for various values of α, to go through all the variants for the time of signal travel through the layers and to calculate the total signal travel time. The value closest to the measured time will be the problem solution. It will allow you to uniquely determine the emission direction for the signal accepted by the AUV.

Mathematically, this approach is called a net method: we build a net and find a solution in its knots. A net is characterized by its cell size.

The result of modeling the beam travel time for different emission directions from 10 to 80° is shown in Fig. 7.

Knowing the depth of the AUV position and the duration of the sound signal travel from a buoy to the AUV, we estimate the distance and, according to the chart (see Fig. 7), find the beam angle at the moment of its emission.

For example, the time of signal travel along the arc from the surface to the depth of 270 m is 0.5 s. For this conditions, the following variants are possible:

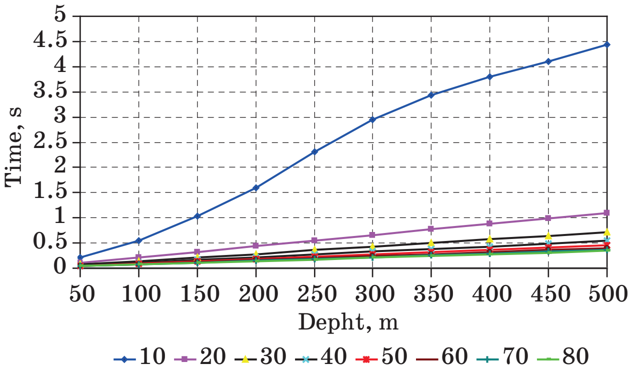
— the emitted signal inclination angle is 10°, and the depth of the AUV is $H = 105$ m;

— the emitted signal inclination angle is 20°, and the depth of the AUV is $H = 270$ m.

Out of these two variants, the more suitable one is the second ($\alpha = 20°$), because the actual depth coincides with the calculated one. This variant is chosen as a solution. To find the AUV coordinates, the coordinates of the signal reception point are used.

However, as shown above, at emission angles bigger than 20° we can use weighted average value of the sound speed. In this case, we estimate the distance covered by the beam immediately by the delay. Knowing the depth H (cathetus) and inclined range of the beam travel L (hypotenuse), we can find the emission direction angle

$$\alpha = \arccos\left(\frac{H}{L}\right).$$



■ *Fig. 7.* Calculated time of signal travel along the arc for different emission angles

2. *The AUV has no information about its immersion depth.*

In this case, we need to simultaneously use two measurements from two buoys, because one measurement can only provide a multivalued solution.

If the depth is unknown, we will take into account the fact that everything happens in one vertical plane: the two buoys and the AUV are three points through which one and only one plane passes. Since the buoys emit sound in all directions, and the arc length does not depend on the direction in the horizontal plane, depending only on the inclination angle in the vertical plane, the solution will be the intersection point of two arcs whose length depends on the inclination angle and the AUV depth.

In the same way as described above, the emission direction is determined for the signal from the first buoy. For the buoy signal arrival delay measured aboard the AUV, several variants come out which differ from each other in the signal arrival depths and emission directions. These variants form a set of solutions for the first buoy.

After that, the same procedure is applied to the delay of the second buoy signal. The solution variants form a set of solutions for the second buoy.

Out of the two solution sets related to the first and second buoys, an element is found which is an intersection of the two. This element is the solution. It is uniquely associated with the emission direction of the first and second buoys and the AUV position coordinates which correspond to the arrival point of the signal from the first and second buoys.

Similarly to the known depth variant, we get expressions to determine the inclination angles α_1 and α_2:

$$\alpha_1 = \arccos\left(\frac{H_1}{L_1}\right);$$

$$\alpha_2 = \arccos\left(\frac{H_2}{L_2}\right),$$

$$H_1 = H_2.$$

The given expressions can be used for inclination angles α_1 and α_2 bigger than 20°.

Finding AUV Coordinates with the Difference-Ranging Method

The arcuate curvilinear trajectory of the beam travel from two spatially separated buoys gets into a certain point at a certain depth where the AUV is positioned which has received a sound signal from both the buoys. In the same way as if they were rectilinear inclined trajectories, after determining the point to which the beams from both the buoys come, inclined straight line segments are calculated. The set of possible solutions for two buoys form a hyperbola. By the intersection of three hyperbolas formed by four buoys using the difference-ranging method, the AUV determines its coordinates.

Differential Method Description

The mutual position of the AUV, BS and one of the four buoys in the marine environment is shown in Fig. 8. The AUV location is adjusted using the differential mode as follows.

A buoy emits a navigational hydroacoustic signal into the seawater. The BS receives it. Knowing its precise location, SSP and the precise location of the buoy, the BS estimates the signal travel time: calculated T_{calc} and actual T_{act}. The calculated time is determined taking into account the refraction which depends on the current SSP in this area according to Snell's law, so that the beam comes to the BS point. For that, all possible positions of the beam arrival to the BS area are considered and the best one is chosen for various emission directions α by the criterion how close the beam arrival point is to the BS location. Finally, the actual beam travel time from the buoy to the BS is found, and the distance $R_{\text{act BS}}$ is determined which differs from the calculated distance $R_{\text{calc BS}}$ by ΔR:

$$R_{\text{act BS}} = R_{\text{calc BS}} + \Delta R.$$

On this basis, the correction ΔR is determined on the BS as the difference between the calculated beam travel distance $R_{\text{calc BS}}$ and the actual distance $R_{\text{act BS}}$ which is precisely known at the BS:

$$\Delta R = R_{\text{act BS}} - R_{\text{calc BS}}.$$

When estimating the rectilinear range of the beam travel between the emission point and the BS position, you can use not only the average value of the sound speed according to the SSP, but also any other value, provided that this value is used by the AUV. This should be agreed upon in advance when you perform a differential correction of the AUV location. Besides, it is desirable that the processing principles of the navigation receivers at the BS and the AUV are similar; ideally, the receivers should be identical. The signal travel correction ΔR calculated at the BS is then emitted from the buoy to the consumers in the marine environment, including the AUV. Such corrections are emitted to the signals of all the four buoys.

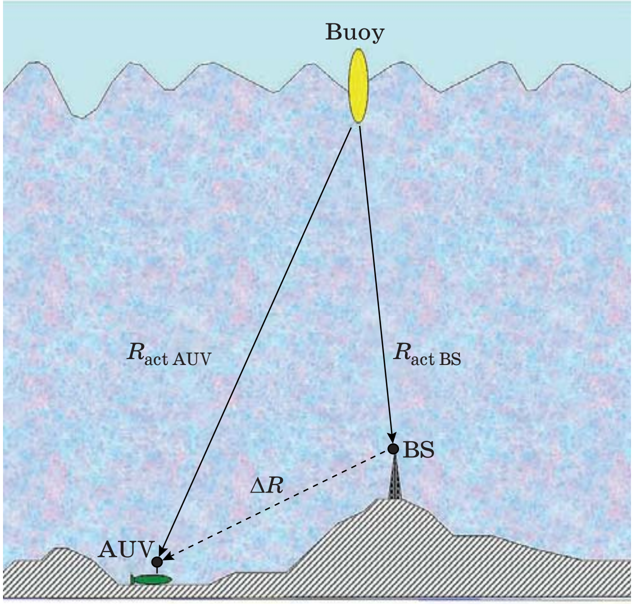
The autonomous underwater vehicle near the BS measures the delays of the signals from the four buoys. The obtained delays are converted into the ranges to the buoys as discussed above. Based on these ranges, the beam trajectory projections are determined. An obtained range is a sum of the calculated range and the correction:

$$R_{\text{act AUV}} = R_{\text{calc AUV}} + \Delta R.$$

Simultaneously with the measurement of the actual range, the AUV receives from the BS the information about the pseudorange corrections ΔR for each of the four buoys, and then specifies the pseudoranges to the buoys:

$$R_{\text{calc AUV}} = R_{\text{act AUV}} - \Delta R,$$

using them for locating itself by the difference-ranging method.



■ ***Fig. 8.*** General scheme of differential mode

Conclusion

The work is aimed at finding the ways of using the differential method to locate an AUV in a marine environment. Our research was focused on the parameters which considerably affect the usage of difference-ranging method for AUV location: sound emission direction, vertical distribution of the sound speed, sound travel trajectory, and the distance covered by a sound beam. The paper discusses an approach to applying the differential method of correcting an AUV location in a marine environment. The obtained results can be used for a more precise location of AUV or other underwater objects.

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Исследование возможности применения дифференциального режима уточнения местоположения АНПА под водой

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Постановка проблемы: ввиду отсутствия под водой сигналов спутниковых радионавигационных систем позиционирование автономных необитаемых подводных аппаратов происходит с использованием одного или нескольких опорных объектов. Слоистость морской среды является причиной распространения звукового луча не по прямой, как у радиосигналов, а по дугообразной траектории, из-за чего корректировка местоположения аппарата дифференциальным методом происходит с большой погрешностью. **Цель:** оценка требований и условий, необходимых для использования дифференциального режима уточнения местоположения аппарата. **Результаты:** проведено моделирование распространения звуковых лучей в вертикальной плоскости согласно закону Снеллиуса при условии подчинения распространения звуковых лучей распределению Райса, определен пройденный звуковым лучом путь, оценена его зависимость от направления излучения звукового сигнала, а также определен порядок оценки местоположения аппарата с использованием дифференциального режима уточнения его местоположения. Установлены условия использования дифференциального метода корректировки местоположения аппарата, определяемые направлением излучения; профилем распределения скорости звука; взаимным положением излучающих буев, корректирующей базовой станции и подводного аппарата. **Практическая значимость:** полученные результаты могут быть использованы для уточнения местоположения аппарата в районах с отсутствием возможности применять традиционные методы точного позиционирования аппарата.

Ключевые слова — автономный необитаемый подводный аппарат, маршрутная траектория, течение, оценка эффективности.

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