A Design of The Underwater Acoustic Beacon Detection and Location Method

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Abstract. Aiming at the search of the underwater acoustic beacons used in aircraft or ship parameter recorders, this paper mainly introduces the underwater acoustic beacon detection and location method of the short baseline array system. According to the signal form of underwater acoustic beacon, this paper discusses the basic algorithm and the engineering algorithm applied in this system. In theory, the basic algorithm is a necessary algorithm for short baseline array to calculate target azimuth, which including the two-element linear array direction measurement algorithm, two-direction cross-location algorithm and the virtual direction discrimination algorithm. In addition, according to the experience of offshore operations, this paper introduces the engineering practice methods such as the angle measurement, the data extraction, the location ray screening and the location ray starting point coordinate calculation. The combination of engineering algorithm and basic algorithm can effectively reduce the impact of the test equipment and environment, and improve the accuracy of underwater acoustic beacon detection and position, which has been tested in actual operation at sea.

1. Overview
The underwater acoustic beacon that automatically triggers by the water which is widely used in various marine activities because of its ease of installation and use. It is used as the emission source to indicate the position of the target in the water. Underwater acoustic beacons are widely used on "black boxes" (parameter recorders) installed on aircraft or ships. Used for "black box" search and salvage in the accidental sinking into the water. The signal form of the underwater acoustic beacon is shown in Figure 1. The transmission period is 1s, the pulse width is 10ms, and the signal frequency is 37.5kHz. The search and positioning of underwater acoustic beacons has many methods such as long baseline, short baseline, ultra-short baseline, and so on.[1] This paper mainly introduces the underwater acoustic beacon detection and location method of the short baseline array system, combining GPS positioning and navigation technology, and realize the direction finding and positioning of underwater acoustic beacons in the geodetic coordinate system.
Figure 1. The underwater acoustic beacon signal form.

2. Basic algorithm

2.1. Principle of detection and positioning

The short baseline array system consists of two underwater acoustic receiving units, this two-element line array is used to receive underwater acoustic beacon signals. Using the time difference between the signals arriving at the two receiving elements, solving the azimuth angle of the beacon relative to the two-element line array.

The two-element line array needs to be fixed on the surface ship, located on the left and right sides of the ship, the baseline formed by the two mounting points is perpendicular to the ship's rifling. The ship's bow direction is zero degrees, and calculate the azimuth of the acoustic beacon relative to the ship, obtain the azimuth of the beacon in the geodetic coordinate system by ship heading. Using a detection point to complete the beacon direction finding, using the direction finding results of the two detection points, the plane intersection method is used to realize the positioning of the underwater acoustic beacon. [2]

2.2. Two-element line array for direction finding

In Fig. 2, If the acoustic signal propagates as a plane wave, P is the sound source in the far field, and M1 and M2 are the receiving array elements.

Figure 2. Schematic diagram of two-element line array direction finding method.

The distance between M1 and M2 is d, P is the pulse acoustic wave of the underwater acoustic beacon located in the far field, sound speed is c, the time difference between reaching M1 and M2 is t, then the path difference between P and M1 M2 is:

\[ s = c \times t \]

(1)

The angle of the beacon relative to the two-element line array is:

\[ \beta = \arcsin \left( \frac{s}{d} \right) = \arcsin \left( \frac{t \times c}{d} \right) \quad \beta \in [0, \pi) \]

(2)
Convert the geodetic coordinate system using GPS and electronic compass. As shown in Fig.3, the Y-axis positive direction is the true north direction, the midpoint of the two-element line array element connection line is G1 (a1, b1), and y’ is the perpendicular direction in the two-element line array. P (x, y) is the position of the underwater acoustic beacon, and γ is the angle between the positive direction of the Y-axis and the perpendicular line in the short baseline. In the geodetic coordinate system, the Azimuth angle of the acoustic beacon is:

\[ \alpha = \gamma + \beta \]

\[ (y - b_1) = \tan(\gamma + \beta) * (x - a_1) \]

2.3. Use the intersection of two rays to positioning

In Fig. 4, in the geodetic coordinate system, the system obtains two direction finding rays at two points A and B, and the intersection point P of the two rays is the position of the acoustic beacon. \( \alpha_1 \) is the azimuth angle of the acoustic beacon when the system is at point A, and \( \alpha_2 \) is the azimuth angle of the acoustic beacon when the system is at point B.

If the coordinates of point A are (a1, b1), the coordinates of point B are (a2, b2), and the angle between the true north direction and ray AP and BP are \( \alpha_1 \) and \( \alpha_2 \) respectively, then the coordinate values X and Y of point P can be calculated by the intersection of ray AP and BP. [3]
\[ \begin{align*}
Y &= k_1 \times (X - a_1) + b_1 \\
Y &= k_2 \times (X - a_2) + b_2 \\
k_1 &= \tan(\pi / 2 - \alpha_1) \\
k_2 &= \tan(\pi / 2 - \alpha_2)
\end{align*} \quad (5) \]

The simplification of the formula above can be obtained as follows.

\[ \begin{align*}
X &= \frac{\tan(\alpha_1) \times \tan(\alpha_2) \times (b_2 - b_1) + \tan(\alpha_2) \times a_1 - \tan(\alpha_1) \times a_2}{\tan(\alpha_2) - \tan(\alpha_1)} \\
Y &= \frac{a_1 - a_2 + b_2 \times \tan(\alpha_2) - b_1 \times \tan(\alpha_1)}{\tan(\alpha_2) - \tan(\alpha_1)}
\end{align*} \quad (6) \]

2.4. Judgment of virtual direction

According to the method of calculating the target azimuth by using the sound path difference of the two-element line array, two target directions are calculated in the range of 360°, symmetrically distributed on both sides of the two-element line array, as shown in FIG.5.

\[ \begin{align*}
\angle PAB &= \theta = \arccos(s / d).
\end{align*} \]

In the figure 5, A and B are two detection elements, and the baseline length is d. The target is located at the far field point P, and the sound path difference is PA-PB=s. It can be calculated that \( \angle PAB=\theta=\arccos(s / d) \). Due to the value domain property of the inverse trigonometric function, there are two values in the plane, and the symmetric distribution is on both sides of AB. One of them is a false direction, which we consider to be a false target. In order to judge the true target direction, the system needs the third array element C as the auxiliary array element, and uses the sound pulse signal to reach the order of the array elements to judge the target direction and eliminate the false direction.

If the sound source is located in the far field, the auxiliary array element C is located on one side of the line array AB, CA \( \perp \) AB. As shown in Fig. 6, the azimuth angle of the vertical line direction to the underwater acoustic beacon is \( \beta \).
Figure 6. Three-element array for direction finding.

Set the following rules to eliminate the false direction value generated by the two-element array direction finding:

a. If $TA \leq TC$, then $\beta \in [0, 0.5\pi) \cup [1.5\pi, 2\pi)$

b. If $TA > TC$, then $\beta \in (0.5\pi, 1.5\pi)$

$TA$, $TB$, and $TC$ are the propagation times of acoustic signals from the sound source to A, B, and C, respectively.

Actually, the judgment rule has a scope that is not applicable. In Fig. 7 ①, ②, ③ are the three parts of the plane that are separated by the perpendicular lines in AB and AC.

![Diagram](image)

Figure 7. The applicable area of judgment method.

In the vertical line theory in the line segment shown in Fig. 7, if the acoustic signal first arrives at the array element A and then reaches the array element C, the target is located in the area ① or ②, that is, the side of the vertical line in the AC; otherwise, the target is located in the area ③.

In the above judgment method, if the acoustic signal first arrives at the array element A and then arrives at the array element C, the discrimination target is located in the area ①; otherwise, the target is located in the area ② or ③.

So The discriminating rules apply to areas ①, ③, and not to area ②.

According to Section 3.2 of this paper, the measured opening angle of the system is ±60°, as shown in Figure 8.

![Diagram](image)

Figure 8. The not-applicable area of judgment method in actual testing.
In Fig. 8, the shaded area is the effective measurement range of the two-element line array in the target area ②. When the target is located in the shaded area of the figure, the discriminating method is invalid; when the target is located in the non-shaded area in the area ②, the system does not perform measurement. In the actual test, the baseline AB, AC distance is short, and the target is located in the far field, not in the shadow area, so the set discriminant rule is reasonable.

3. Engineering algorithm

3.1. Purpose of the engineering algorithm
The basic algorithm is the necessary algorithm to theoretically solve the target orientation by using the short baseline system. In the implementation process, due to the influence of test equipment and test environment, more methods are needed to break the limitation of the application range of the test system to reduce the influence of measurement error, thereby improving measurement efficiency and test accuracy. This chapter describes the engineering processing algorithms used by the system. These methods effectively improve the performance of the test system during the actual measurement process [4].

3.2. Measuring the appropriate angle
In order to reduce the influence of measurement error, the system designs a suitable angle for measurement. When the measured target is outside the suitable angle of measurement of the array, if the measurement result is large, the data is discarded. Due to the existence of the appropriate angle of measurement, one measurement cannot cover the entire plane. As shown in Fig.9, the shaded area in the figure 9 is a single-measure single-measurement coverage area, calculated at a suitable angle of 120°, and the effective measurement coverage area is the entire plane. 66.7%.

![Figure 9](image)

Figure 9. The open angle of the two-element line array measurement.

In order to eliminate the virtual direction value that occurs when the dual-line array is oriented, the test system uses a two-element array and a subsidiary array element to measure the target direction. To improve the efficiency of marine surveying, the three element array consisting of two mutually perpendicular linear measuring range as shown in Fig.10.

![Figure 10](image)

Figure 10. Two mutually perpendicular linear measuring range.
Main line array: array elements A and B form the main baseline, and C is the auxiliary array element.

Sub-line array: array elements A and C form the secondary baseline, and B is the auxiliary array element.

After the two line arrays are combined, the measurement range covers most of the area of the plane, improving the efficiency of marine measurements. When the target is within the main baseline measurement opening angle, the primary baseline measurement data is used; otherwise, the secondary baseline measurement data is used.

3.3. Data extraction method

3.3.1. Data Structure. The signal form of the underwater acoustic beacon is a periodic single-frequency rectangular pulse. Three array elements A, B, C received target pulse signal, reception timing as shown in Fig.11.

![Figure 11. Schematic diagram of three-channel data timing.](image1)

In the figure, the horizontal axis represents the time axis, and the three horizontal lines correspond to the array elements A, B, and C, T is the emission period of the single-frequency pulse signal, and \( \tau \) is the time difference between the same single-frequency pulse signal reaching any two array elements. Underwater acoustic beacon at a fixed cycle single frequency pulse transmitter T, assume that the channel stability, and the receiving end is no relative motion transmitting end, the receiving end receives the pulse signal period T is fixed.

With a single-frequency pulse signals of any two array elements to achieve a time difference determined by the two array elements and the acoustic path difference between the sound source, sound path difference does not exceed the maximum distance between the two array elements.

When the system works, using a fixed length time window at the receiving end receives the segment signal received during each time window of data is a set of data, as shown in Fig.12.

![Figure 12. Schematic diagram of segmentation reception at the receiving end.](image2)

\( Tw \) is the length of time of a time window, \( Tw \geq 2T \). There are 2 to 3 pulse signals in one time window.

3.3.2. Signal miss or error detection. Interference and noise ratio at low ambient noise in the receiving end will be missed detection signal, the error detection of the phenomenon. As shown in Figure 13, ①, ②, ③ the water acoustic signals received by the three array elements.
There is a signal missed or error detection in blocks (1), (2), only two channels receive valid data in the same signal cycle, and block (3) is a normal condition in which all three channels receive valid data. In addition, as shown in the figure, there is also a misdetection phenomenon in the data, that is, erroneous data. The data structure corresponding to the blocks (1) and (2) in the figure is referred to as dual channel data, and the data structure corresponding to the block (3) is simply referred to as three channel data. When calculating the target direction using two-channel data, a double value occurs, one of which is the false direction, that is the error value.

3.3.3. Data processing method.

(1) Three-channel data screening method
In order to reduce the influence of data misdetection on calculation and improve the reliability of data, a three-channel pulse data extraction method is designed according to the pulse signal emission period and the maximum sound path difference.

a. If there is data on a channel that satisfies the transmission period of the beacon signal, the data with the difference of the sound path difference is smaller than the spacing of the elements on the other two channels based on the data.

b. If there is no data on the three channels that satisfies the pulse signal transmission period, then the first set of sound path differences in the sequence is selected to match the array spacing data.

(2) How to use two channels of data
During the sea measurement, the ship sails at low speed or drifts. At this time, due to the influence of the environment, the ship's heading changes greatly, while the position of the underwater acoustic beacon changes little relative to the ship's position. Therefore, the target has a large change with respect to the direction value of the two-element array, but in the geodetic coordinate system, the azimuth angle of the target is substantially unchanged.

Under normal circumstances, using the measurement principle of the two-element line array, the two-channel data cannot solve the unique target real direction. According to this problem, in order to make full use of the data in the case of missed detection, and correctly solve the problem, and improve the data utilization rate, the two-channel data is processed as follows: the two direction values calculated by the two-channel data are retained and converted into geodetic coordinates. The azimuth angle of the system, after multiple measurements, select the angle interval with the highest probability of occurrence, and the average value as the target azimuth angle.

(3) Set the single channel data volume threshold
To improve data reliability, set a single-channel data volume threshold for a fixed period of time. When the amount of data received on the channel exceeds the set number of thresholds within a fixed period of time, it can be determined that the amount of erroneous data is too large, and the data of this section is discarded.

For example, according to the signal transmission period of the underwater acoustic beacon 1s, a single channel can receive up to three valid signals within a fixed time of the receiving end 2.2s. The
data threshold of the single channel can be set to 6. If the channel receives more than 6 valid signals and the data is considered to be low in accuracy, the data is discarded.

3.4. Positioning ray screening and averaging during fixed-point detection

3.4.1. Positioning ray measurement data. In the actual measurement process, due to the existence of measurement error, in order to obtain more accurate measurement data, it is usually used to reduce the influence of random error in the measurement process by using multiple measurements and then averaging.

When measuring the target direction, the system performs multiple measurements in a short time. Each measurement acquires a positioning ray containing a system’s geodetic coordinate value and a target azimuth. Since the relative positional relationship between the target and the measurement system changes little in a short time, the averaging method can be designed to average the locating rays in the time period, thereby reducing the influence of the measurement error.

The starting point coordinates of the set ray are:

$$(x_i, y_i), \quad i = 1, 2, 3, \ldots$$

The azimuth angle of the set ray is:

$$\theta_i, \quad i = 1, 2, 3, \ldots$$

3.4.2. Positioning ray averaging method. (1) Location point screening and averaging

If the geodetic coordinate value of the system changes greatly, the measured underwater acoustic beacon will have a large change relative to the orientation of the system, and it cannot participate in the averaging operation. Therefore, according to the starting point of the positioning ray, that is the position of the test system in the geodetic coordinate system, the scattered ray of the starting point is excluded, and the remaining coordinate points are arithmetically averaged. [5]

The arithmetic mean of the ray origin coordinates is:

$$
\begin{align*}
\bar{x} &= \frac{1}{N} \sum_{i=1}^{N} x_i \\
\bar{y} &= \frac{1}{N} \sum_{i=1}^{N} y_i
\end{align*}
$$

Sequentially deleted point furthest point average, deviation parameter design reasonable distance $R$, the average of remaining data again after each deleted farthest point, until all points the average distance point is less than the parameter $R$. The average value of the remaining coordinate values are taken as the starting point of the positioning ray obtained in this period.

(2) Target azimuth angle screening and averaging

The arithmetic mean of the target azimuth angle is:

$$\bar{\theta} = \frac{1}{N} \sum_{i=1}^{N} \theta_i$$

The angle value with the largest difference from the average value is deleted in turn, and the reasonable azimuth deviation parameter $\delta$ is designed. After each angle value is deleted, the remaining data is re-averaged until the difference between all angle values and the average value is smaller than
the parameter \( \delta \). The average value of the remaining angle values is taken as the azimuth of the positioning ray obtained in this period.

### 3.5. Positioning ray starting point coordinate calculation

The test system is installed on a surface ship, and the actual installation position of the GPS is difficult to coincide with the theoretical position. To improve the precision, the fibrous structure during installation data, using the GPS measurement data calculate the theoretical geodetic coordinate values of the mounting position.[6]

![Diagram](https://via.placeholder.com/150)

**Figure 14.** GPS installation position and theoretical position.

As shown in Fig. 14, in the geodetic coordinates, fix the GPS to the bow, bow and stern positioned ship line, the point A geodetic coordinates can be obtained in real time. The GPS theoretical installation position is point B, point B is located at the rear side of the ship, BC is perpendicular to the squall line, and the ship's heading is \( \theta \).

A mathematical model is built according to Figure 15:

1. Coordinates of point A in the geodetic coordinate system \((m, n)\);  
2. Upside of the Y-axis as a reference azimuth angle \( \theta \) CA radiation;  
3. \( AC = a, BC = b, AC \perp BC \);  
4. BF, AD and Y axis are parallel, BG\//CA.

Find: Point B coordinates \((x, y)\).

(1) When point B is on the port side of the ship

When point B is on the port side of the ship, the mathematical model is shown in Figure 15.
The azimuth angle $\angle FBA$ of the ray BA is:

$$\angle FBA = \theta + \beta = \theta + \arctan(b/a)$$ (9)

The length of the line segment BA is:

$$BA = \sqrt{a^2 + b^2}$$ (10)

When the $\angle FBA$ value falls within the first quadrant, the coordinates of point B are:

$$\begin{cases} x = m - BA \times \sin(\angle FBA) = m - \sqrt{a^2 + b^2} \times \sin(\theta + \arctan(b/a)) \\ y = n - BA \times \cos(\angle FBA) = n - \sqrt{a^2 + b^2} \times \cos(\theta + \arctan(b/a)) \end{cases}$$ (11)

When the FBA value falls in the other quadrants, it is known from a simple calculation that the calculation formula is the same as (11).

(2) When point B is on the starboard side of the ship

The azimuth angle $\angle FBA$ of the ray BA is:

$$\angle FBA = \theta + \beta = \theta - \arctan(b/a)$$ (12)

The coordinates of point B are:

$$\begin{cases} x = m - \sqrt{a^2 + b^2} \times \sin(\theta - \arctan(b/a)) \\ y = n - \sqrt{a^2 + b^2} \times \cos(\theta - \arctan(b/a)) \end{cases}$$ (13)

4. Conclusion

The underwater acoustic beacon detection and positioning method discussed in this paper designs the positioning method based on the two-element line array direction finding, and adopts engineering algorithms to make it suitable for offshore measurement. In order to obtain more accurate positioning accuracy, it is also possible to set a reasonable target test angle by error analysis and perform multi-point test, and take the geometric center of the direction finding intersection area to reduce the test error.
The system has been tested in the actual measurement, and the accuracy of the direction finding accuracy of the underwater acoustic beacon is not more than 3.5 °, and the positioning error is less than 10% of the detection distance. The algorithm adopted by the system effectively reduces the influence of the test equipment and the test environment, and improves the accuracy of the system for the direction and positioning of the underwater acoustic beacon.

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