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Posted Date: 14 October 2024

doi: 10.20944/preprints202410.1062.v1

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Article

Analysis of Sea Surface Observation Trajectory Based on the External Coincident Accuracy of Seafloor Geodetic Station Positioning

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Abstract: Seafloor geodetic station positioning generally uses internal precision to judge the quality of the positioning result, which has many limitations. This paper proposes to use a seafloor geodetic station structure, which can obtain the external coincident accuracy of the acoustic beacon positioning, to evaluate the quality of the observation configuration. The results of the sea trial show that a circular line with a radius of $\sqrt{2}$ times the depth of the water has an internal precision and an external coincident accuracy of approximately 0.02m; this circular line path also happens to be the best trajectory.

Keywords: seafloor geodetic; acoustic positioning; external coincident accuracy

1. Introduction

A seafloor geodetic network is the basic framework for the topography surrounding a marine environmental information observation. The positioning accuracy of its reference station is required for all data measurement. Beginning in the 1980s, [1] used a combination of GPS satellites and underwater acoustics to establish a geodetic reference point at 2.6 kilometers within the Juan de Fuca plate. [2] and others also conducted GPS/acoustic experiments to accurately locate the seabed in the Japanese Trench and were able to calculate the plate motions of various Japanese Trenches. Later scholars proposed many high-precision underwater positioning methods (to assist with the deployment of acoustic beacons) such as underwater differential positioning ([3,4]) considering vertical coordinates and depth constraints ([5]), nonlinear equation based positioning ([6]), trajectory analysis based positioning, and sound ray tracking ([7]).

[8] considered symmetrical tracking with differential positioning to eliminate errors. A single-difference method can eliminate long-term system errors, while the double-difference method can eliminate most depth-related and space-related system errors. A computationally efficient method to determine absolute coordinates of traditional submarine control network points and low vertical solution precision was proposed by [9]; underwater control network points were to find the influence of waves and depth constraints on the network. [10] studied the solution of nonlinear equations that modeled intersection points between trajectories. [11] analyzed a ship's motion track and found that symmetrical circle tracks are more suitable tracks for seabed reference point measurements.

Additionally, because errors in sound velocity profiles can affect distance observation errors and can reduce hydroacoustic positioning accuracies, various sound velocity correction methods were used to reduce hydroacoustic positioning errors, including the weighted average sound velocity method [13], the equivalent sound velocity profile method, and the acoustic ray tracing method [12]. [14–18] etc. are some application examples of ocean geodetic control stations.

However, Most methods use internal precision to assess the quality of positioning results for the seafloor geodetic beacon or compare the navigation results of the reference network after positioning with GPS navigation results to indirectly evaluate the positioning accuracy[19?]. The former makes sense when using the same equipment or the same test. However, because systematic error cannot be eliminated, it cannot be used as a unified evaluation standard for different tests. Therefore, the method used to evaluate the quality of observed configurations is biased. The latter is an indirect evaluation method. The positioning precision is not only related to the coordinate position accuracy but also to the time delay estimation accuracy during navigation, and GPS itself has positioning errors. Therefore, the quality of the observation configuration can only be roughly determined, and the accuracy of the positioning results of the submarine geodetic beacon cannot be accurately or intuitively obtained.

This paper proposes a seafloor geodetic station structure, which can extend the external coincident accuracy of the acoustic beacon positioning. This paper is organized as follows. In Section 2, the basic principle of the method is presented, including the estimation of the equivalent sound velocity, the geometric premise of the seafloor geodetic station structure and the calculation of the positioning error. In Section 3, the positioning results of a sea trial, under different water surface tracking line measurement configurations, analyzed and the best seafloor geodetic observation strategy is found.

2. Method

2.1. Equivalent Sound Velocity Calculation

When calibrating a sound measurement instrument, the original measurement data is the time delay value; therefore, it is necessary to calculate an equivalent sound velocity via the sound velocity profile to calculate the distance measurement value \hat{L} . In this paper, a real-time sound ray tracking algorithm is used, and each measurement point has an independent sound ray tracking process; this approach improves the range accuracy as much as possible to eliminate any positioning interference outside the observation configuration. The calculation process is as follows ([15]).

First

Calculate the glancing angle of the launch point. The position of the launch point and the position of the underwater transponder are known. The launch point, the depth of the transponder, and the horizontal distance between the two can also be obtained by measuring techniques. Combined with the sound velocity profile $c(z)$, the dichotomy method is used to find the initial glancing angle of the intrinsic sound ray. Eq.(1) expresses the relationship between the horizontal distance (between the depth of the transponder and the position of the launch point) and the initial glancing angle.

$$\hat{x} = \int_{z_0}^{z_1} \frac{\cos \alpha_0 \cdot dz}{\sqrt{n^2(z) - \cos^2 \alpha_0}} \quad (1)$$

where \hat{x} represents the horizontal distance, z_0 represents the depth of the sound source, z_1 represents the depth of the receiver, $c(z)$ represents the sound velocity distribution, α_0 represents the initial glancing angle, and $n(z) = c(z_0)/c(z)$. To find the α_0 needed to minimize $\hat{x} - x$ via the dichotomy method we use

$$\alpha_0 = \arg \min_{\alpha_0} \left(\int_{z_0}^{z_1} \frac{\cos \alpha_0 \cdot dz}{\sqrt{n^2(z) - \cos^2 \alpha_0}} - x \right). \quad (2)$$

Second

The initial glancing angle α_0 and the sound velocity distribution $c(z)$ are used to find the estimated propagation delay \hat{t}_1 from the launch point to the transponder via

$$\hat{t}_1 = \int_{z_m^s}^{z_n^B} \frac{dz}{c(z) \cdot \sin \alpha(z)}. \quad (3)$$

Third

The glancing angle α_0 from the receiving point to the transponder and the estimated propagation delay \hat{t}_2 can be obtained in a similar way.

Fourth

The equivalent sound velocity c of the whole process from transmission to reception of the signal is obtained through Eq.(4), where ${}^G X_{\text{Resp}}$ is the target position to be measured, ${}^G X_{\text{Array1}}$ and ${}^G X_{\text{Array2}}$ are the signal transmitting and receiving points, respectively.

$$c = \frac{\|{}^G X_{\text{Resp}} - {}^G X_{\text{Array1}}\| + \|{}^G X_{\text{Resp}} - {}^G X_{\text{Array2}}\|}{\hat{t}_1 + \hat{t}_2} \quad (4)$$

2.2. Acoustic Beacon Positioning Accuracy Evaluation Method

The seafloor geodetic station structure designed in this paper is shown in Figure 1. The acoustic beacons are rigidly connected, the beacons are on the same plane, and the distance between them is R . Take beacon 1 as an example, let the geographic coordinates of the shipborne transceiver be (X, Y, Z) , The initial value of the coordinate of the submarine beacon array element to be determined is (X_{01}, Y_{01}, Z_{01}) . The true value of the slope distance between the two is L . The measurement $\hat{L} = \tau \times c$, where τ is the measured delay and c is the equivalent speed of sound from Equation (4). The measurement error is $\Delta L = L - \hat{L}$ and $f(x)$ is a function of the distance between the shipborne transceiver and the array element. L is expressed as

$$L = f(x)^0 + \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} & \frac{\partial f}{\partial z} \end{bmatrix} \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} + \Delta L. \quad (5)$$

Then the error equation is

$$\begin{aligned} v &= \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} & \frac{\partial f}{\partial z} \end{bmatrix} \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} + L - f(x)^0 + \Delta L \\ &= \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} & \frac{\partial f}{\partial z} \end{bmatrix} \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} + \Delta L \end{aligned} \quad (6)$$

The matrix I consists of N error equations

$$I = BX. \quad (7)$$

Then,

$$X = (B^T B)^{-1} B^T I. \quad (8)$$

where,

$$\begin{aligned} f(x)_i^0 &= \sqrt{(X_i - X_0)^2 + (Y_i - Y_0)^2 + (Z_i - Z_0)^2} \\ \Delta L_i &= \Delta l_i + L_i - f(x)_i^0. \end{aligned} \quad (9)$$

$$\mathbf{B} = \begin{bmatrix} \frac{-(x_1-x_0)}{f(x)_1^0} & \frac{-(y_1-y_0)}{f(x)_1^0} & \frac{-(z_1-z_0)}{f(x)_1^0} \\ \dots & \dots & \dots \\ \frac{-(x_n-x_0)}{f(x)_n^0} & \frac{-(y_n-y_0)}{f(x)_n^0} & \frac{-(z_n-z_0)}{f(x)_n^0} \end{bmatrix},$$

$$\mathbf{I} = \begin{bmatrix} \Delta L_1 \\ \vdots \\ \Delta L_n \end{bmatrix}, \mathbf{X} = \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix}.$$
(10)

Therefore, the coordinates of beacon 1 (X_{P1}, Y_{P1}, Z_{P1}) are found via

$$\begin{bmatrix} X & Y & Z \end{bmatrix}_P^T = \begin{bmatrix} X_0 & Y_0 & Z_0 \end{bmatrix}_P^T + \begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \end{bmatrix}_P^T.$$
(11)

The positioning results of beacons 2 and 3 can be obtained as (X_{P2}, Y_{P2}, Z_{P2}) and (X_{P3}, Y_{P3}, Z_{P3}) in a similar way. To obtain an estimate of the baseline length $\hat{R}_{1-2}, \hat{R}_{2-3}$, and \hat{R}_{3-1} , the baseline length R (for the beacon) must be determined via

$$\Delta R_{i-j} = \hat{R}_{i-j} - R (i, j = 1, 2, 3).$$
(12)

where ΔR_{i-j} is the difference between the estimated value of the corresponding baseline L_i and the true value, which is used as the external coordinate accuracy of the beacon i to evaluate the quality of the beacon positioning result.

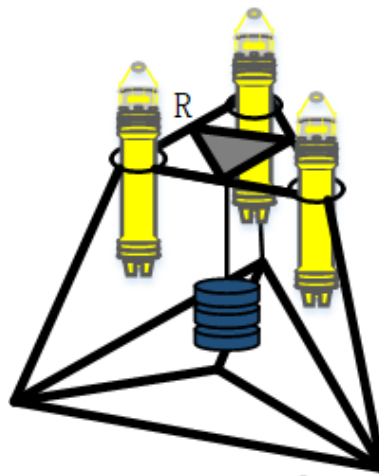


Figure 1. seafloor geodetic station structure.

3. Experimental Analysis

3.1. Experiment Overview

From 28 May to 10 June 2021, a sea surface tracking line measurement test was carried out in 300 meter waters of the South China Sea to verify the positioning accuracy of the seafloor geodetic station. The actual station design is shown in Figure 2a. A total of three reference beacons were deployed at the reference station. The acoustic transducers of the 3 beacons were designed at the top of the fixed station, and the arrangement is shown in Figure 2b. This is an equilateral triangle with a side length of 800 mm.

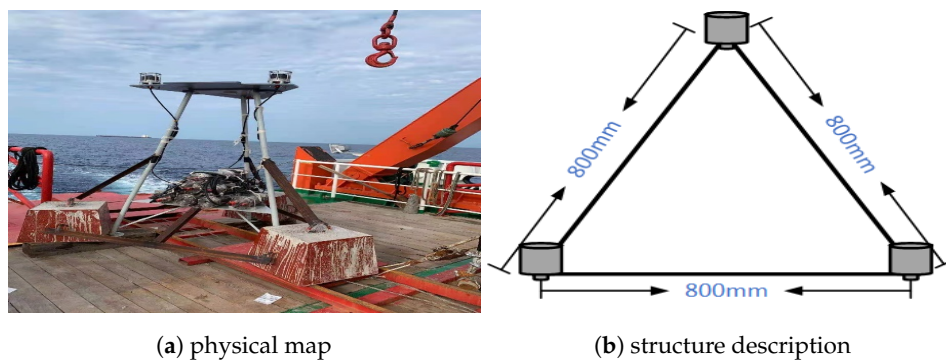


Figure 2. seafloor geodetic station physical map and structure description.

To verify the influence of the observation trajectory on the beacon positioning, the fixed station acoustic beacons (No. 1, No. 2, and No. 3) were positioned in a circle line with a radius of 4.3 km, a cross trajectory with a radius of 4 km, a diamond trajectory with 3 km, a square trajectory with 3 km, and a diamond trajectory with 1.5 km. The observation trajectories are shown in Figure 3, and the positioning results are shown in Table 1, expressed in local coordinates.

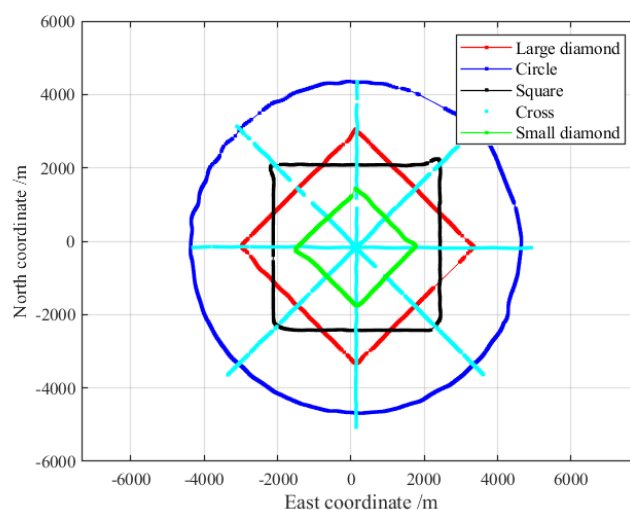


Figure 3. Observation trajectory when the test ship locates the acoustic beacon.

Table 1. Comparison of positioning results of different observation strategies.

Observation Trajectory	Beacon Number	North Coordinate (m)	East Coordinate (m)	Elevation (m)
Circle	1	0.5195	-0.4822	-0.200
	2	1.2382	-0.2153	-0.129
	3	1.0951	-1.0095	-0.137
Cross	1	1.2671	-0.1215	2.862
	2	1.8375	1.6804	2.870
	3	1.7036	-0.5058	2.937
Large diamond	1	1.2609	-0.0200	3.499
	2	2.0535	1.7783	3.421
	3	1.9166	-0.5626	3.416
Square	1	1.1502	-1.1955	1.001
	2	1.8704	-0.9398	2.897
	3	1.7664	-1.7356	2.891
Small diamond	1	1.0900	1.5812	2.333
	2	1.8114	1.3134	2.254
	3	1.6363	-0.0102	2.233

3.2. Positioning Accuracy Analysis

Subtracting the result of the calculation of the basic element of the reference station on each trajectory with the standard baseline length of 0.8 m is considered the external coincident accuracy, and the error of the positioning point of each elementary element is used as the internal precision, as shown in Figure 4.

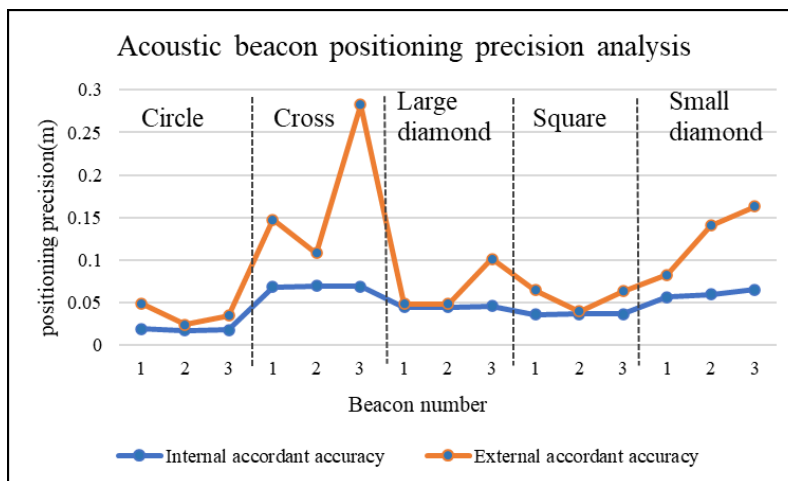


Figure 4. Acoustic beacon positioning accuracy analysis.

Figure 4 shows that, in terms of shape, the circle line is better than the other line in terms of the internal precision and the external coincident accuracy. When measuring the baseline length, the accuracy is better than 3 cm. The square-line and large diamond-line trajectories do not demonstrate obvious advantages when calculating the external coincident accuracy. The advantage is mainly reflected in the higher internal precision, which is also the recognized advantage of the circle line. The small diamond and the large diamond trajectories have an internal precision difference of less than 1 cm, whereas the maximum external coincident accuracy difference can reach 8 cm. The latter is more than ten times the former. The reason for this difference is that the radius of the small rhombus is half the depth of the water, while the radius of the large rhombus is equal to the depth of the water.

So, we can assume that for an observation trajectory used for positioning, when the radius is equal to $\sqrt{2}$ times the depth of the water or one-time the depth of the water, it is much better than $1/2$ the depth of the water. Thus, the circle line is superior to other shapes due to its rotational symmetry.

4. Discussion

The deployment of a marine geodetic control network is an important foundation and guarantee for the development of the current ocean industry. Scholars have always proposed many high-accuracy positioning methods. However, most methods are limited by the underwater environment. The quality of the benchmark positioning result is also to judge. Most of the time, it can only be judged via indirect methods, such as internal precision or a comparison of navigation and positioning results.

This paper proposes a multi-element fiducial station structure, which can obtain the external coincident accuracy of acoustic beacon positioning. The pros and cons of various observation trajectories are compared through sea trials and the feasibility of the method proposed in this paper is verified. The testing used for validation was a sea test with a water depth of about 3000 m, the base element spacing of the geodetic station was 0.8 m, the internal precision of the circle in the positioning result was about 0.02 m, and the accuracy of the remaining configuration was about 0.05 m. Thus, when comparing the external coincident accuracy, the accuracy of the trajectory with a trajectory radius of 1500 m is about 0.06 m. The trajectory with a trajectory radius of 3000 m has an accuracy of about 0.02 m except for the meter type. The trajectory with a trajectory radius of 4300 m has an accuracy of about 0.018 m. Therefore, whether determining the best internal precision or the best external

coincident accuracy, a circular observation trajectory with a radius equal to $\sqrt{2}$ times the depth of water has the best positioning results.

Author Contributions: Conceptualization, Y.O. and Y.H. (Yunfeng Han); methodology, Y.O.; software, Y.O.; validation, Y.O., Z.W. and Y.H. (Yifei He); formal analysis, Y.O.; investigation, Y.O.; resources, Y.H. (Yunfeng Han); data curation, Y.O.; writing—original draft preparation, Y.O.; writing—review and editing, Y.O., Z.W. and Y.H. (Yifei He); visualization, Y.O.; supervision, Y.H. (Yunfeng Han); project administration, Y.H. (Yunfeng Han); funding acquisition, Y.H. (Yunfeng Han). All authors have read and agreed to the published version of the manuscript.

Funding: Please add: This research was funded by the marine elastic PNT test system (national key research and development plan). Project No.: 2020YFB0505805.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: Data cannot be made publicly available due to privacy restrictions. Data are available from [Harbin Engineering University] for researchers who meet the criteria for access to confidential data.

Acknowledgments: This paper is the result of the construction and application demonstration of the marine elastic PNT test system (national key research and development plan). Project No.: 2020YFB0505805.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GPS Global Positioning System

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