Shi *et al.*
EURASIP Journal on Advances in Signal Processing (2023) 2023:36
https://doi.org/10.1186/s13634-023-00986-4

EURASIP Journal on Advances in Signal Processing

RESEARCH

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ASBL: low-cost, small-sized AUV remote guidance method and experimental verification

Yang Shi[1,2,3,4], Xiao Han[1,2,3], Lin Ma[4] and Lin Guo[1,2,3,4*]

*Correspondence: guolin36@163.com

[1] Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin, China
[2] Key Laboratory of Marine Information Acquisition and Security (Harbin Engineering University), Ministry of Industry and Information Technology, Harbin, China
[3] College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin, China
[4] Shanghai Acoustics Laboratory, Chinese Academy of Sciences, Shanghai, China

Abstract

The low-cost, small-sized autonomous underwater vehicle (AUV) is the preferred carrier for seabed operations. As all know, the inertial navigation system (INS) error drifts over time. Three or more seafloor datum signals are required when error-correcting the INS using the long baseline (LBL). Typically, a seafloor datum has an acoustic ranging capability of 15 km. However, the positioning ability of the conventional LBL is limited and cannot play the role of remote guidance when there is only a single datum. The paper proposes the Acoustic Synthetic Baseline (ASBL) positioning technology, which can achieve target positioning through multi-frame acoustic distance estimates between the measured target and the underwater datum. Firstly, the positioning principle of the ASBL is introduced, and the error distribution is analyzed in the paper. Secondly, a small-sized AUV is used to carry out the verification on the lake test, and the result shows that the ASBL positioning technology can play a guiding role. According to the statistics of the positioning results, the detection probability of less than 5% positioning error can reach more than 83%. The ASBL technology can reduce the dependence on the number of seafloor datums that convenience and operation efficiency can improve only by a single datum.

Keywords: ASBL positioning, AUV remote guidance, INS error correction

1 Introduction

The AUV has become a vital tool for various seabed investigations, deep-sea resource exploration, marine scientific research, military reconnaissance mission, and other uses because of its self-contained energy, autonomous navigation, high intelligence, good concealment, and mobility [1, 2]. In addition, the AUV can perform large-scale detection missions. With the emergence of low-weight, low-power, low-cost, and small-sized AUVs, it has become the best operation carrier preferred by testers.

Generally, the INS installs on the submarine to realize the function of complex tasks, such as underwater-autonomous navigation. There is no doubt that the inertial navigation error will accumulate with time. The longer the time, the greater the error. Effective means are necessary to eliminate INS shift errors and extend the underwater working time. In previous studies, the common practice for correcting inertial navigation errors relies on acoustics equipment, especially the LBL system, because of its long baseline distance and high positioning error [3, 4]. LBL needs more than three seafloor datum signals for effective AUV positioning. Due to space constraints, small-sized AUVs can only install low-precision INS, and the error divergence degree is large and fast. It is difficult to guide the AUV into the underwater LBL navigation and positioning network composed of multiple datums for error correction only by itself under long voyages. Moreover, the acoustic ranging capability of a single seafloor datum can generally reach more than 15 km, which provides a good prerequisite for ASBL positioning technology applied to the remote guidance of the measured target.

The ASBL positioning technology uses the dynamic moving vector of the underwater measured target to construct the acoustic-synthetic baseline, which can estimate the target location through the distances of multiple sampling periods between the target and seafloor datum. Compared with the traditional LBL, by combining with the INS, the ASBL positioning system reduces the dependency on the number of the seafloor datum, and the convenience and operation efficiency can be improved only by a single seafloor datum [5]. But the accuracy is more affected by random errors compared with LBL [6–9]. In addition, ASBL does not need to use multiple array elements for reception and calibration, which reduces the installation space and weight of the measured target, thereby improving the maneuverability and reliability of the AUV.

The paper proposes the ASBL positioning technology to realize the purpose of long-distance navigation, which can guide the small-size AUV into the acoustic navigation and positioning network for error correction. Firstly, the positioning principle of the ASBL technology is described, and its error distribution is analyzed. Secondly, a small-sized AUV is used to carry out a lake test, which can verify the effectiveness of the ASBL positioning technology. Through the statistics of the test results, the detecting probability of less than 5% positioning error can reach more than 83% at the distance range of 3 km. Finally, the application prospect of ASBL positioning technology is introduced. The method proposed in the paper can reduce the design requirements for the AUV route in the remote guidance and calibration process. And the ASBL system can also reduce the number of seafloor datums deployed in the rapid positioning system.

2 Positioning principle and error analysis

The ASBL system does not need to deploy multiple seafloor datums in advance. Compared with the traditional LBL, it can complete the acoustic guidance and inertial navigation calibration for the small-size AUV at a lower cost and in a shorter time.

2.1 Positioning principle and model

The ASBL system uses the operation mode of interrogation and response to estimate the acoustic propagation distance of underwater AUV and seafloor datum at the observation time. In the current observation period, the condition for obtaining the position coordinate of the underwater AUV is that the distance observation and datum position information meet the hyperbolic positioning principle. The ASBL is to iterate the AUV velocity estimation of multiple adjacent observation periods to the actual seafloor datum, build virtual datums, and establish equations with the distance estimation to solve the AUV coordinates.

Establish a geodetic Cartesian coordinate system $\{O - XYZ\}$ centered with an arbitrary origin that X-axis and Y-axis point to the east and north, and Z-axis is perpendicular to the sea level downward. The datum is deployed on the seafloor using the anchor structure and pre-calibrated to obtain its position $\boldsymbol{X}_{BS} = [x_{BS}, y_{BS}, z_{BS}]^T$ in $\{O - XYZ\}$ [10, 11] (Fig. 1).

At the i_{th} observation period, the coordinate of the underwater AUV is $\boldsymbol{X}_i = [x_i, y_i, z_i]^T$, and the acoustic observation distance from the seafloor datum is r_i. The target observation equation based on r_i can express as,

$$(x_i - x_{BS})^2 + \left(y_i - y_{BS}\right)^2 + (z_i - z_{BS})^2 = r_i^2 \tag{1}$$

Here, $r_i = c \cdot t_i$. t_i represents the acoustic observation time delay between the underwater AUV and the seafloor datum, and c is the sound speed in seawater. Similar to the LBL positioning system, when the number of the seafloor datum is greater than 3, the target observation equations can satisfy the full-rank condition and solve $\boldsymbol{X}_i$.

At the $(i-1)_{\text{th}}$ observation period, assuming the speed of the AUV is $\boldsymbol{v}_{i-1} = \left[v_{x(i-1)}, v_{y(i-1)}, v_{z(i-1)}\right]^T$, the observation period is T. Theoretically, the position relationship of the AUV between two adjacent observation periods is

$$\begin{cases} x_i = x_{i-1} + v_{x(i-1)} \cdot T \\ y_i = y_{i-1} + v_{y(i-1)} \cdot T \\ z_i = z_{i-1} + v_{z(i-1)} \cdot T \end{cases} \tag{2}$$

Using the motion parameter $\left[v_{x(i-N)}, v_{y(i-N)}, v_{z(i-N)}\right]^T$ and position estimation $[x_{i-N}, y_{i-N}, z_{i-N}]^T$ of AUV in the $(i-N)_{\text{th}}$ observation period, formula (3) can be obtained

$$\begin{cases} (x_i - x_{BS})^2 + \left(y_i - y_{BS}\right)^2 + (z_i - z_{BS})^2 = r_i^2 \\ \left(x_i - \left(v_{x(i-1)} \cdot T + x_{BS}\right)\right)^2 + \left(y_i - \left(v_{y(i-1)} \cdot T + y_{BS}\right)\right)^2 + \left(z_i - \left(v_{z(i-1)} \cdot T + z_{BS}\right)\right)^2 = r_{i-1}^2 \\ \left(x_i - \left(v_{x(i-1)} \cdot T + v_{x(i-2)} \cdot T + x_{BS}\right)\right)^2 + \left(y_i - \left(v_{y(i-1)} \cdot T + v_{y(i-2)} \cdot T + y_{BS}\right)\right)^2 \\ \quad + \left(z_i - \left(v_{z(i-1)} \cdot T + v_{z(i-2)} \cdot T + z_{BS}\right)\right)^2 = r_{i-2}^2 \\ \left(x_i - \left(v_{x(i-1)} \cdot T + v_{x(i-2)} \cdot T + v_{x(i-3)} \cdot T + x_{BS}\right)\right)^2 + \left(y_i - \left(v_{y(i-1)} \cdot T + v_{y(i-2)} \cdot T + v_{y(i-3)} \cdot T + y_{BS}\right)\right)^2 \\ \quad + \left(z_i - \left(v_{z(i-1)} \cdot T + v_{z(i-2)} \cdot T + v_{z(i-3)} \cdot T + z_{BS}\right)\right)^2 = r_{i-3}^2 \end{cases} \tag{3}$$

Here, taking three virtual datums as an example, that is, $N = 1, 2, 3$. It can be seen from formula (3) that the synthetic baseline positioning is equivalent to transferring the motion parameters of the AUV to the deployed seafloor datum, thereby constructing the synthetic baseline contained with three additional virtual seafloor datums $\boldsymbol{X}_{BS(i-N)} = \left[x_{BS(i-N)}, y_{BS(i-N)}, z_{BS(i-N)}\right]^T$,

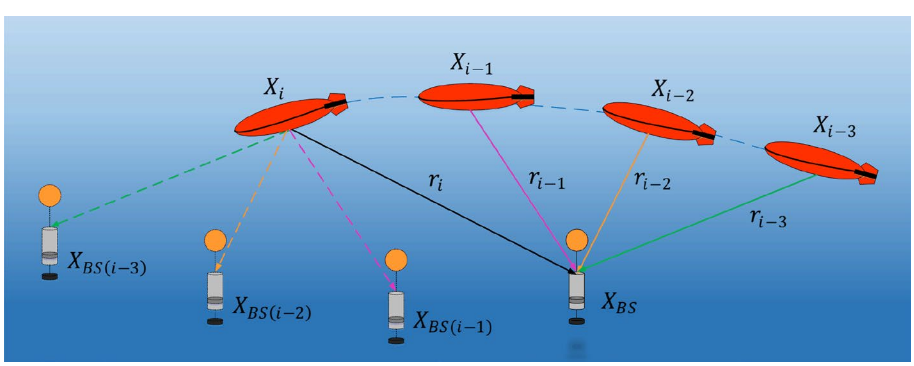


Fig. 1 Schematic diagram of ASBL positioning principle

$$\begin{cases} \boldsymbol{X}_{BS(i-1)} = \left[x_{BS} + v_{x(i-1)} \cdot T, y_{BS} + v_{y(i-1)} \cdot T, z_{BS} + v_{z(i-1)} \cdot T\right]^T \\ \boldsymbol{X}_{BS(i-2)} = \begin{bmatrix} x_{BS} + \left(v_{x(i-1)} + v_{x(i-2)}\right) \cdot T, y_{BS} + \left(v_{y(i-1)} + v_{y(i-2)}\right) \\ \cdot T, z_{BS} + \left(v_{z(i-1)} + v_{z(i-2)}\right) \cdot T \end{bmatrix}^T \\ \boldsymbol{X}_{BS(i-3)} = \begin{bmatrix} x_{BS} + \left(v_{x(i-1)} + v_{x(i-2)} + v_{x(i-3)}\right) \cdot T, y_{BS} + \left(v_{y(i-1)} + v_{y(i-2)} + v_{y(i-3)}\right) \\ \cdot T, z_{BS} + \left(v_{z(i-1)} + v_{z(i-2)} + v_{z(i-3)}\right) \cdot T \end{bmatrix}^T \end{cases} \tag{4}$$

Based on the hyperbolic positioning principle, using the least square method (LSM) to obtain the estimation of $\boldsymbol{X}_i$. From formula (4), the positions of the N virtual datums are related to the accuracy of the target velocity estimation obtained from the $(i-N)_{\text{th}}$ to the $(i-1)_{\text{th}}$ observation periods and are not affected by the historical AUV positioning accuracy. The DTM algorithm in [12] is used to filter and predict the time delay information for ensuring the effectiveness of distance estimation in each observation period. In addition, the depth of the AUV can be obtained from the depth sensor. Therefore, formula (3) can reduce to the binary linear equations.

2.2 Positioning accuracy analysis

Theoretically, if there is no error in the measurement of underwater AUV motion parameters, the positioning error of the ASBL is the same as that of the traditional LBL. For the complete differential of formula (1),

$$\begin{aligned} &(x_i - x_{BS})\mathrm{d}x_i + \left(y_i - y_{BS}\right)\mathrm{d}y_i + (z_i - z_{BS})\mathrm{d}z_i = (x_i - x_{BS})dx_{BS} + \left(y_i - y_{BS}\right)\mathrm{d}y_{BS} \\ &\quad + (z_i - z_{BS})\mathrm{d}z_{BS} + c^2 t_i dt_i + ct_i^2 \mathrm{d}c \end{aligned} \tag{5}$$

From formula (5), the positioning accuracy of ASBL is related to the seafloor datum position errors $\mathrm{dx_{BS}}$, $\mathrm{dy_{BS}}$, $\mathrm{dz_{BS}}$, time delay measurement error $\mathrm{dt_i}$, and sound velocity error dc. The position accuracy of the virtual datum is affected by the velocity measurement error of the underwater target, so the sources of the ASBL positioning error include the position error of the underwater datum, time delay measurement error, sound velocity error, and velocity measurement error.

In addition, different baseline distributions have inconsistent positioning errors under the same error condition. Figures 2 and 3 describe the possible range of the positioning result under different datum distribution types. The right parts in the figures similarly show two circular solid lines centered with two seafloor datums and the acoustic distance as the radius. The gray dotted line represents the theoretical distance between the seafloor datum and the target. The width between two circular solid lines centered on the same seafloor datum represents the measurement error. The overlapping area (shaded area) formed by four circular solid lines is the possible range of the positioning result due to the measurement error. The larger the shaded area, the greater the maximum positioning error.

In Fig. 2, due to the scattered orientation of the baseline, the overlapping area caused by measurement error is small and concentrated. In Fig. 3, although the error is similar, the overlapping area caused by four circles increases significantly because of the more centralized distribution of the baseline.

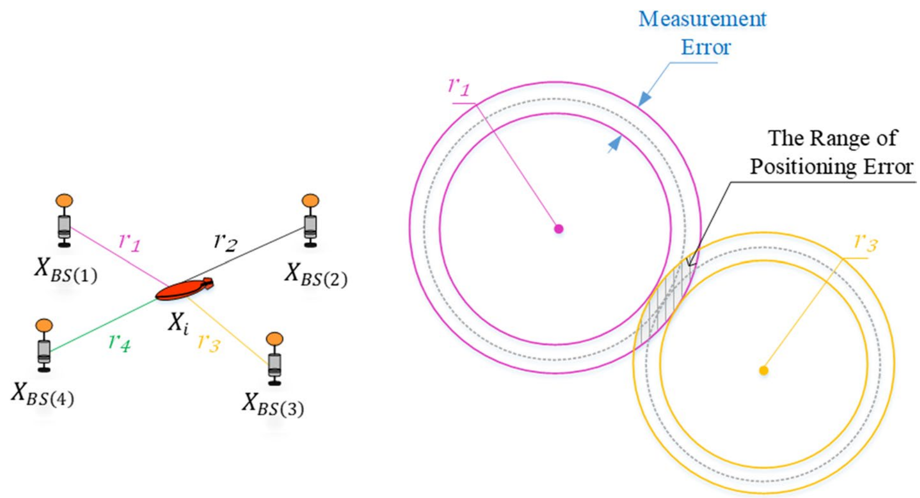


Fig. 2 Decentralized baseline and positioning error

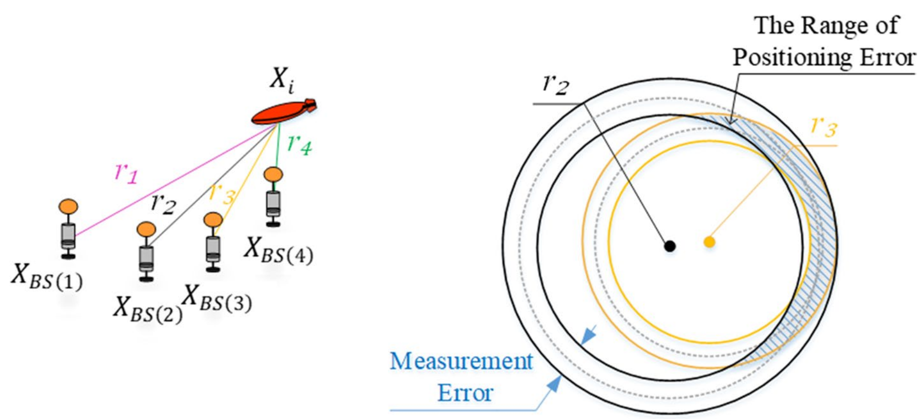


Fig. 3 Centrally distributed baseline and positioning error

Therefore, the positioning error is related to the baseline distribution. When the baseline is densely distributed (especially on a straight line), the accuracy of the positioning results will significantly reduce. In addition, if the angle between the target and the baseline in the horizontal direction is small, the LSM may incorrectly estimate the target position change, and the value of the positioning error is proportional to the distance between the target and the datum [13].

Generally, the moving speed of the AUV is small, the maximum is not more than 10 knots, and the moving distance of two adjacent observation periods is not more than 100 m, so the distance between two virtual datums is small. Although the error of a single datum is equivalent, the positioning error increases significantly due to their concentrated distribution in azimuths [14].

Assuming that the depth of the seafloor datum is 1000 m, the AUV moves in a uniform linear motion from south to north and then from north to south at the speed of 4 knots, and its depth is 100 m. The sampling interval is 50 m until AUV covers the area of 6 km × 6 km. The sound speed measurement error is 3‰, the velocity

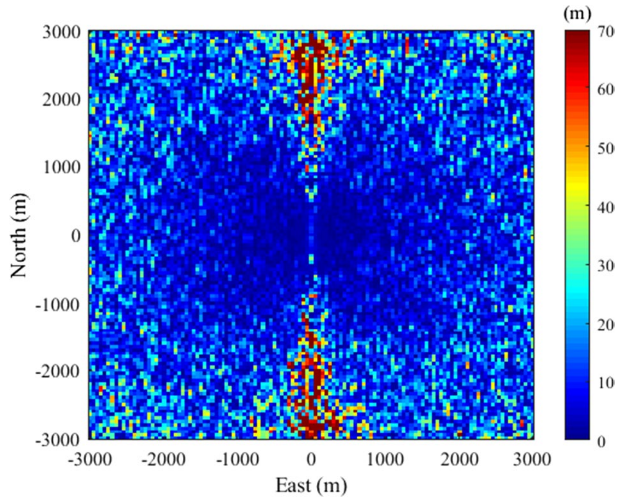
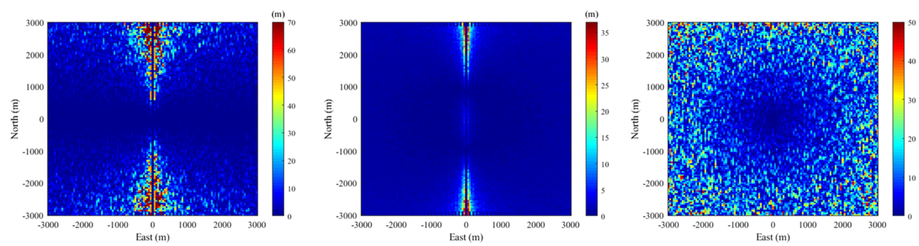


Fig. 4 The positioning error of ASBL



(a) Velocity Error (b) Sound Speed Error (c) Heading Error

Fig. 5 Influence of each error for ASBL positioning error

measurement error is 3‰, and the heading measurement error is 0.5°. After 100 times Monte Carlo statistics, the positioning error of ASBL caused by the above errors is shown in Fig. 4.

Here, the influence of each error on the positioning accuracy of the underwater AUV is as follows:

From Figs. 4 and 5, the positioning error of the ASBL is mainly affected by the velocity measurement error and is related to the motion trajectory of the AUV. As the horizontal angle between the target and the datum increases, the positioning error decreases. The overall change characteristics of sound speed measurement error and velocity measurement error are consistent with the comprehensive error. The influence of heading error on positioning error is related to the distance between the target and the datum.

Consider that the Dead Reckoning System (DRS) is the standard method for navigation and positioning, which is used to compare with the ASBL method proposed in the paper. Figure 6 shows the comprehensive error results of traditional LBL and DRS.

From Fig. 6, under the same error condition, the velocity measurement error of the AUV is transferred to the position error of the virtual datum, and the comprehensive

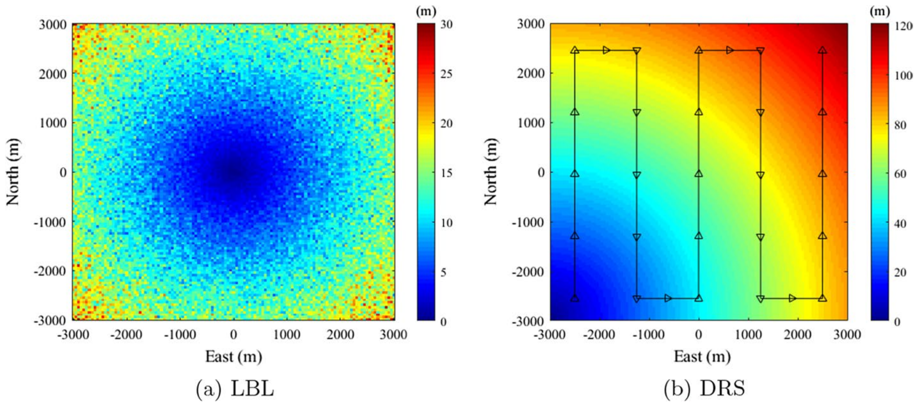


Fig. 6 Comprehensive error results of LBL and DRS

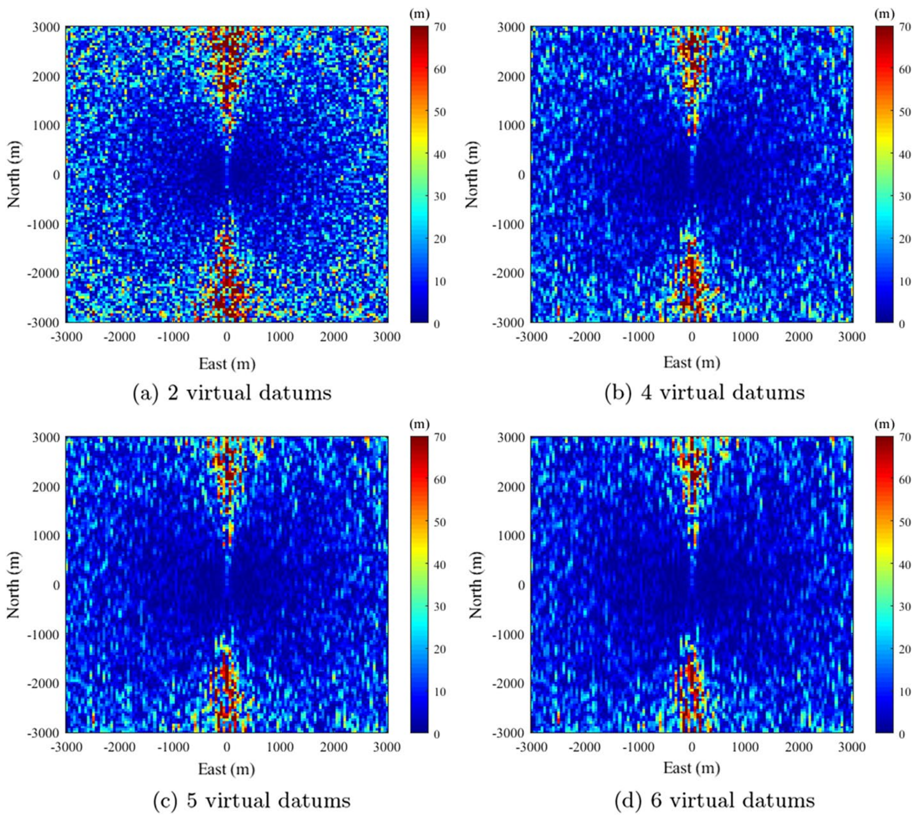
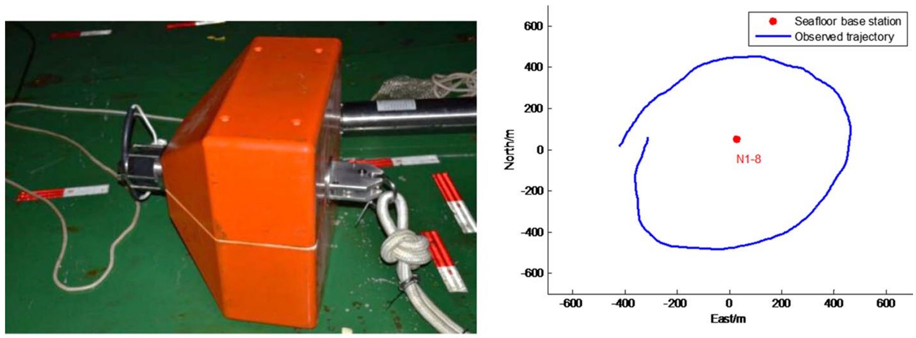


Fig. 7 Positioning error under different virtual datums

error of the ASBL is more than twice that of the LBL. The DRS can maintain good positioning accuracy in short range. With the increase in working time, due to the accumulation of speed estimation error and heading measurement error, AUV positioning error increases significantly, and the reliability of positioning results decreases gradually. In Fig. 6b, the vertex direction of the triangle indicated the direction of AUV movement roughly.



(a) The seafloor datum (b) The observed trajectory

Fig. 8 Seafloor datum and the observed trajectory of position estimation

Table 1 Seafloor datum measurement result

Seafloor Datum	East (m)	North (m)
N1-8	27.98	51.61 .

Figure 7 shows the positioning error of underwater AUV under different combinations of 1 seafloor datum and 2, 4-6 virtual datums.

The overall positioning error of the AUV under 2 virtual datums is the largest, and under 3 to 6 virtual datums is similar. However, increasing the number of virtual datums would put forward higher requirements for system computing ability.

3 Test Verification

3.1 Seafloor datum deploy and survey

The lake test is carried out to verify the ASBL technology proposed in the paper. The test is carried out in open water, and the selected area meets the conditions of the flat lake bottom and no shelter around. The average water depth is about 40 m, and the lake coverage is about 12 km in the north–south direction and about 3 km from east to west. In the test, the single seafloor datum was deployed in the lake center area and fixed at 35 m underwater.

After the seafloor datum was deployed and stabilized, the ship was to measure its positioning [15, 16]. The acoustic array was rigidly installed on the survey ship, extending 3 m downward from the keel, and no ambient occlusion. The Global Navigation Satellite System (GNSS) antenna and attitude sensor were also fixedly installed above the acoustic array. During the survey, the ship carrying the measurement device takes the seafloor datum as the center, circles around a certain radius and speed, and the acoustic distance measured from the acoustic array to the seafloor datum through the interaction of the inquiry and response signals. The seafloor datum position is estimated by combining ranging information, GNSS information, and attitude sensor data. Figure 8b shows the ship observation trajectory. Table 1 presents the datum measurement results.

Table 2 Parameters of the AUV

Parameters	Values
Size	φ 220 mm × 2000 mm
Weight	60 kg
Maximum depth	300 m
Maximum velocity	5 knots
Velocity measurement error	3–4‰
Heading measurement error	0.5°
Acoustic ranging error	1‰ Slant distance

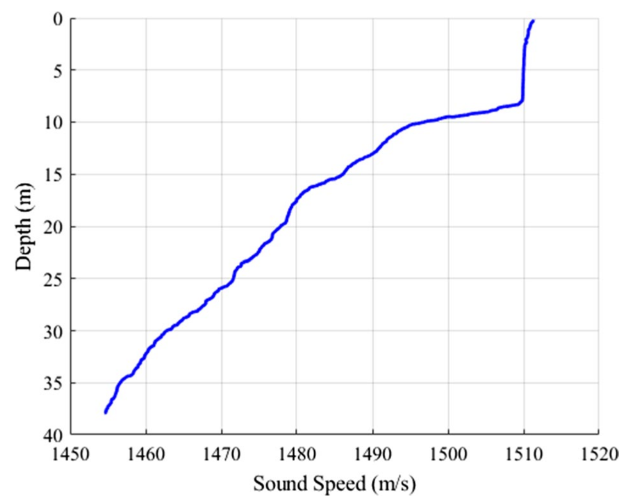


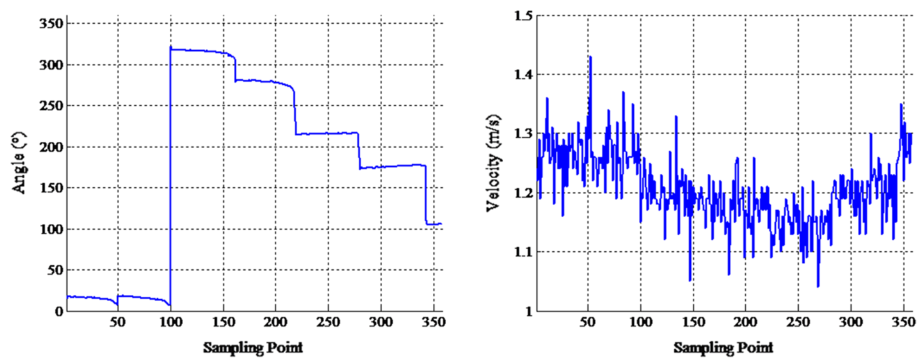
Fig. 9 Sound speed profile

3.2 AUV remote guidance test verification

After the seafloor datum survey, carry out the remote guidance test. The underwater target is a small-size AUV equipped with a combined Doppler velocity log (DVL), INS, and GNSS navigation system. The parameters are shown in Table 2. The synthetic baseline acoustic positioning sensor is installed on the head of the AUV, away from the propeller, and the electronic part installs inside the AUV. The AUV route planning refers to the application requirement of remote navigation, therefore the route from far to near at first, and then far away from the seafloor datum, to verify the positioning capability of the ASBL. The sound speed profile during the test is shown in Fig. 9. The AUV voyage parameters are shown in Fig. 10. The route divides into six sections, the AUV travels in a straight line with a relatively stable heading, and the speed maintains at 2-3 knots.

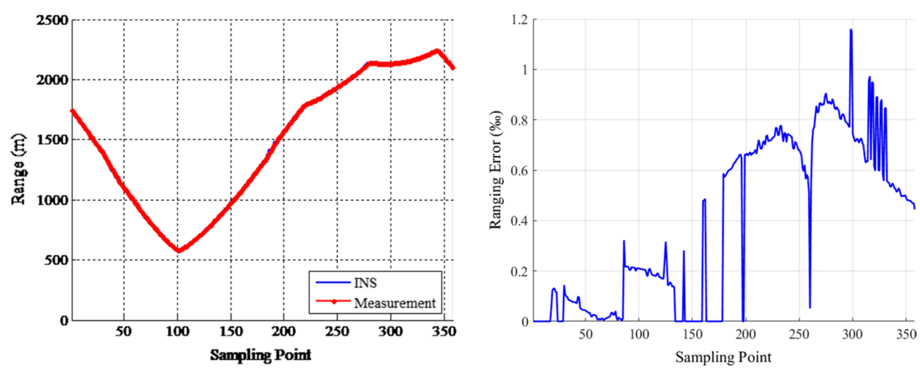
Figure 11a presents the measured results of acoustic ranging, and Fig. 11b shows the ranging error.

It can be seen from the figures that the acoustic-ranging results are stable and reliable. Compared with the theoretical distance, the mean measurement error is 0.37‰, and the maximum measurement error is 1.16‰ by noise. According to the obtained AUV heading, speed, and acoustic-ranging information, the trajectory of the AUV



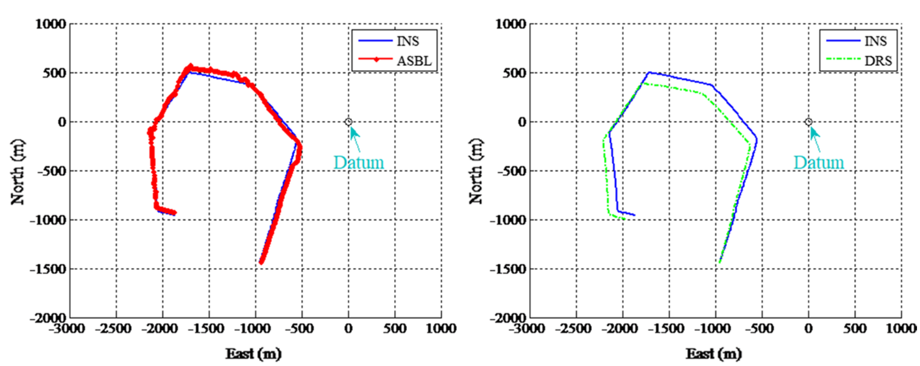
(a) AUV Heading (b) AUV Velocity

Fig. 10 AUV heading and velocity data



(a) AUV Acoustic Ranging (b) AUV Acoustic Ranging Error

Fig. 11 AUV acoustic ranging and acoustic ranging error data



(a) INS+DVL and ASBL (b) INS+DVL and DRS

Fig. 12 Comparisons of INS+DVL, DRS, and ASBL positioning results

can be obtained, as shown in Fig. 12. Here, the ASBL consists of one seafloor datum and three virtual datums.

Due to the short time and short voyage, the INS+DVL trajectory is viewed as the reference. From Fig. 12a, b, the trajectory of ASBL (red line) is stable and coincides with the INS trajectory. Although the result of the DRS (green line) is smoother than

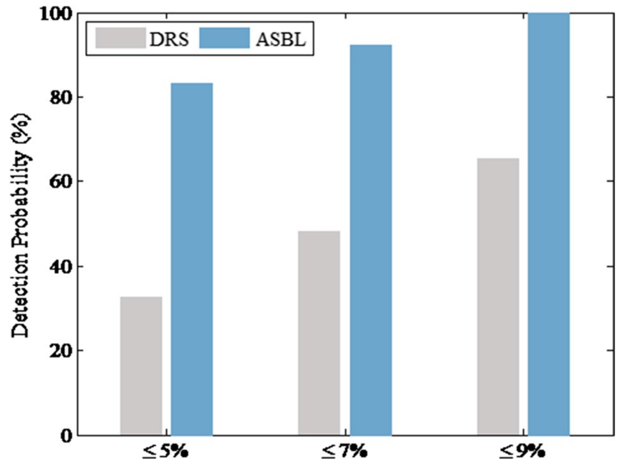


Fig. 13 ASBL and DRS positioning probability distribution

ASBL, due to the heading and speed errors accumulated over time, the positioning error of DRS tends to increase gradually. The error distribution shows in Fig. 13.

Figure 13 shows the probability under the positioning error of less than 5% is 83.24% by using ASBL, which increases by more than 50% compared with the 32.68% of the DRS method. Similarly, the probability under the positioning error of less than 9% is 100%, which increases by more than 30% compared with the 65.36% by using the DRS method. Therefore, the ASBL can use as an auxiliary positioning means, which achieves a relatively stable and reliable remote guidance function for the AUV. In addition, compared with underwater navigation using a single beacon based on the time delays of the direct signals and the surface-reflected signals proposed in [5], although the ASBL technology needs data under different periods to participate in underwater target position, with the reliability of time delay estimation increases, the effectiveness of positioning results is also improved.

4 Conclusion

The positioning result of the low-cost, small-sized AUV is rapidly divergence under long working hours only by own loads. It is hard to provide effective navigation when requiring error correction. The ASBL positioning technology is proposed in the paper to realize the remote guidance function. The reason for the lower positioning accuracy compared with the conventional LBL is analyzed from the detailed theory. Through error analysis of the model, verify the effectiveness of the ASBL positioning. Through the lake test by the small-size AUV, the positioning probability is that the error of less than 5% can reach more than 80% in a distance of 3 km, and the positioning probability of less than 7% error is more than 90%. The design difficulty of guidance trajectory can reduce, and the number of deployed seafloor datums can decrease through the ASBL technology. The influence of heading, velocity, and sound speed errors on positioning accuracy is considered in the paper. Compared with the conventional LBL positioning accuracy, it is necessary to analyze more errors and find various means to suppress the positioning error in the future.

Author contributions

YS, LG conceived the idea of the study; XH, LM analyzed the data and interpreted the results; YS, LG, LM wrote the paper; all authors discussed the results and revised the manuscript. All authors read and approved the final manuscript.

Funding

The National Key Research and Development Program of China under Grant 2021YFC2801204. Goal-Oriented Project Independently Deployed by Institute of Acoustics, Chinese Academy of Sciences (MBDX202117).

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 8 October 2022 Accepted: 31 January 2023
Published online: 17 March 2023

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