IEEE Access Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

SPECIAL SECTION ON EMERGING TRENDS, ISSUES AND CHALLENGES IN UNDERWATER ACOUSTIC SENSOR NETWORKS

Received October 28, 2018, accepted November 8, 2018, date of publication November 19, 2018, date of current version December 18, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2881390

Positioning Systems for Jiaolong Deep-Sea Manned Submersible: Sea Trial and Application

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This work was supported in part by the National Key R&D Program of China under Grant 2017YFC0305700, in part by the Qingdao National Laboratory for Marine Science and Technology under Grant QNLM2016ORP0406, in part by the Taishan Scholar Project Funding under Grant TSPD20161007, in part by the National Natural Science Foundation of China under Grant 41641049, in part by the Shandong Provincial Natural Science Foundation under Grant ZR2015EM005, in part by the Shandong Provincial Key R&D Program under Grant 2016GSF115006, and in part by the Qingdao Independent Innovation Project under Grant 15-9-1-90-JCH.

ABSTRACT A crucial issue that cannot be ignored in deep-sea resource surveys and scientific research is underwater positioning and navigation of deep-sea manned submersibles. Ultra-short baseline (USBL) is an important technical method for performing underwater positioning and tracking of manned submersibles and ensuring the safety of their underwater operations. Using USBL, the mothership can obtain the manned submersible's position in real time. Furthermore, the manned submersible can obtain its own position at longer time intervals using digital underwater acoustic communication to assist the pilot in driving. Long baseline (LBL) is a significant supplement to USBL because it is an independent positioning system that provides more accurate and real-time navigation and positioning data for manned submersibles in large areas and deep seas. In this paper, we analyzed USBL sea-trial calibration, its application in real diving, and details of LBL sea-trial using the Jiaolong deep-sea manned submersible as a case study. Data measured during 10 consecutive dives of the Jiaolong manned submersible are utilized to analyze the USBL positioning performance. We found that the positioning performance (relative slant range error, relative depth error, and data efficiency) is consistent with calibration results. Finally, a rectangular path with a length of 900 m and breadth of 300 m is designed to verify LBL performance in deep sea. The LBL sea-trial results show that the positioning accuracy of LBL is better than that of USBL. The USBL positioning performance is affected by the distance from the mothership and its heading.

INDEX TERMS Ultra-short baseline, long baseline, manned submersible, sea trial, calibration.

I. INTRODUCTION

The Jiaolong is a Chinese deep-sea research manned submersible that can dive to a depth of more than 7000 m [1]. Its maximum dive depth is 7062 m, covering approximately 99.8% of the ocean area. This manned submersible can carry three crewmembers (one pilot and two scientists) to extreme deep sea for scientific expeditions. It includes structural, hydraulic, control, sonar, and other systems [2], and can obtain water, sediment, and biological samples from the ocean bottom using a manipulator.

A crucial issue that cannot be ignored in deep-sea resource surveys and scientific research is the underwater positioning and navigation of manned submersibles. Because electromagnetic waves attenuate rapidly in seawater, sound is the primary method for detection and information transmission at sea. Positioning systems are categorized into two main types based on the application and general technical requirements of manned submersibles: ultra-short baseline (USBL) and long baseline (LBL) [3].

The USBL's transducer array is installed at the bottom of the mothership; therefore, it can be conveniently used. The advantages of the USBL are its simple structure, maneuverability, and ease of operation. As the main body of the USBL is installed on the mothership, it is suitable for use with manned submersibles, which generally dive one or multiple times in a specific area. Therefore, USBL has become the main positioning tool for manned submersibles, and it meets the navigation and positioning requirements of a manned-submersible dive.

The advantages of the LBL include high positioning accuracy (independent of the water depth) and good real-time performance (the manned submersible adjusts its own position in real time) [4]. However, the beacon array needs to be located, and the time cost is high. Obviously, the USBL and LBL complement each other. For example, if the manned submersible is to perform multiple dives and continuous investigations on a certain area (within a few km), the LBL is appropriate for navigation and positioning (the Alvin manned submersible is often used in this mode). Conversely, if the distance between different sea areas or dive sites is long, the USBL is often used for navigation and positioning.

Specially, the following are the contributions of this work.

(1) An "8-shaped" pattern is designed for USBL sea-trial calibration, and two criteria for confirming the success of the calibration are presented. The USBL accuracy is 0.25% of the slant range with calibration, which meets the requirement of Jiaolong manned submersible.

(2) Data measured during ten consecutive dives of the Jiaolong manned submersible are utilized for analyzing the USBL positioning performance. Compared with the calibration results, it was found that the positioning performance (relative slant range error, relative depth error, and data efficiency) is consistent.

(3) A rectangular path with a length of 900 m and breadth of 300 m is designed for testing the LBL performance in deep sea. The LBL sea-trial showed that the positioning accuracy of the LBL is better than that of the USBL. The USBL positioning performance is affected by the distance from the mothership and its heading.

The rest of this paper is organized as follows. Section II presents the general description of the USBL and LBL used for the Jiaolong manned submersible. Section III gives a detailed discussion of the USBL sea-trial calibration, the USBL application in real diving, and the LBL sea-trial. Finally, a summary of the findings of the study is presented in Section IV.

II. ULTRA-SHORT BASELINE AND LONG BASELINE

A. ULTRA-SHORT BASELINE

The USBL includes two modes, the transponder mode, and the responder mode. In the transponder mode, an interrogation signal is sent from the surface transducer array to the seabed transponder. After this interrogation signal is received, an acknowledge signal is transmitted from the transponder. The time delay between the transmission of the interrogation signal and the reception of the acknowledge signal is used for calculating the range. In the responder mode, a pair of high precision clocks are used to trigger the responder on the manned submersible and USBL surface processing unit on the mothership synchronously. The time delay between the synchronous pulse triggering moment and the reception of the acknowledge signal is used for calculating the slant range. The sound speed profile is needed for calculating the range from the time delay. Thus, an accurate sound speed profile guarantees accurate positioning. In addition to the range, the azimuth is needed for positioning and can be computed by analyzing the phase of the received signals. Combining the GPS and USBL, the exact location of the manned submersible can be obtained.

During an actual dive operation, the manned submersible uses the responder mode. Synchronous clocks are installed on the mothership and manned submersible, and are clocked before the manned submersible is launched.

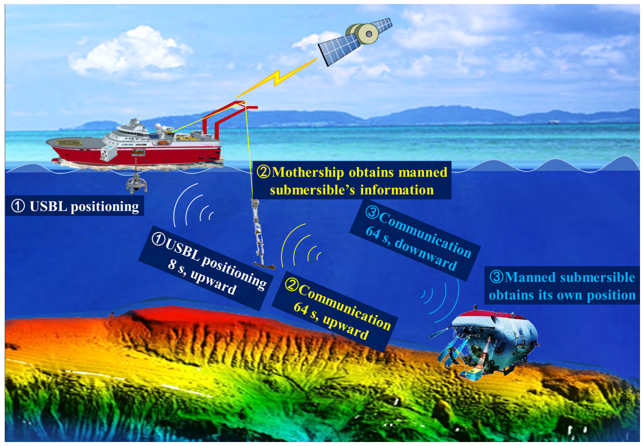

FIGURE 1. Steps required by the Jiaolong manned submersible to obtain its position using USBL.

The manned submersible obtains its position through the following three steps (as shown in Figure 1). (1) The responder beacon on the manned submersible transmits a positioning pulse at regular intervals (for example, 8 s). The position of the manned submersible can be obtained after the USBL on the mothership receives the pulse. (2) The manned submersible sends its status information to the mothership at longer time intervals (for example, 64 s) through digital underwater acoustic communication. (3) After the mothership receives this status information, it sends manned submersible position information calculated by the USBL to the manned submersible through feedback communication.

B. LONG BASELINE

The LBL system consists of two parts: a transducer and processing unit installed in the manned submersible, and a set of beacons at the bottom of the ocean. The LBL acoustic positioning converts the travel times to ranges utilizing three or more widely spaced (approximately 4 km) stationary beacons for calculating the location of a moving vehicle in two or three dimensions. The beacons are typically stationary (fixed baseline) and moored to the seafloor with tethers. Moreover, they can be held at fixed relative locations on a moving platform, such as a ship (moving baseline). At least three beacons (known positions) are required to form a specific geometry.

The LBL transducer sends an interrogation signal to each beacon and receives acknowledge signals from the beacons, which are rendered uniquely identifiable by generally assigning unique coded pulses or frequencies to each beacon. The time delay can then be measured, and the ranges between the LBL transducer and each beacon can be calculated. A schematic diagram of LBL is shown in Figure 2.

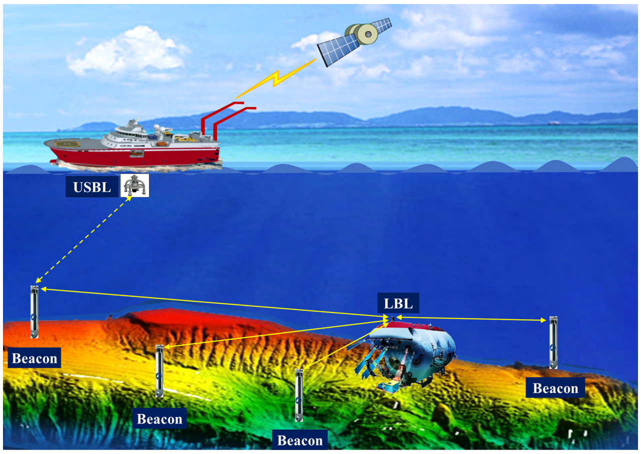

FIGURE 2. Schematic of LBL and beacon position measurement by USBL.

The beacon locations must be determined during an initial offline survey. The receiver actively interrogates the beacons acoustically during operation and measures the round-trip travel time between each beacon. The travel times are converted to slant ranges that yield the spherical constraints of the vehicle position, or they can be measured by the USBL directly if the mothership contains a USBL (as shown in Figure 2). To minimize the position error of each beacon, the mothership should run in a circular path. The USBL can then ping the beacon from any relative angle. An accurate beacon position can be obtained by removing the outlier data points and averaging the beacon positions.

The exact position of the manned submersible can be obtained using the ranges between the LBL transducer and each beacon. Additional information, such as an independent estimate of the receiver depth, can also constrain the determined position. To prevent signal blocking, the LBL transducer is mounted at the back of the manned submersible.

However, in practical applications, the LBL is limited by several factors. On the one hand, it is difficult to meet the requirements of rapid investigations because considerable time is required for beacon array deployment and recycling (e.g., during the Pacific Tuberculosis Survey). On the other hand, acoustic signals are easily blocked and are unsuitable for use in complex terrain areas such as the Indian ocean hydrothermal zone and the Pacific ocean mountain zone.

III. USBL SEA-TRIAL AND APPLICATION

A. USBL CALIBRATION

The measurement equipment of the USBL is generally installed separately, leading to inevitable installation deviations between the onboard transducer array and peripheral auxiliary sensors (particularly the attitude sensors). These deviations considerably degrade the USBL positioning performance [5]. For example, a 1° installation angle deviation produces a 1.7% slanting range error. Therefore, the installation deviations must be corrected through sea-trial calibration.

This calibration includes the following four steps:

(1) Deployment of the transponder beacon.
(2) Sailing of an ‘‘8-shaped’’ pattern and data acquisition.
(3) Calculation of the calibration matrix.
(4) Entering the calibration matrix into the USBL processing unit.

An ‘‘8-shaped’’ pattern is performed by following a particular radius of curvature, depending on the transponder's depth. As 1000–2000 m depth includes typical characteristics of deep-sea sound speed profile, calibration is usually performed at 1000–2000 m depth. The radius of curvature for a depth within these values can be estimated by interpolating between the following two values:

(1) 700-m radius of curvature with a depth of 1000 m;
(2) 1400-m radius of curvature with a depth of 2000 m.

Once the radius of curvature has been estimated, data acquisition is performed.

There are two criteria for confirming the success of the calibration:

Criterion 1: The number of points used for calculating the calibration matrix should be more than 80% of the total number of points.

Criterion 2: The accuracy after calibration must be approximately 0.3% of the slant range. Other types of errors must be considered because they directly reduce the USBL positioning accuracy. These errors may include GPS errors, inaccurate sound velocity profiles, and ship noise. The last two errors are finally transferred to acoustic error. The global error is a combination of the GPS and acoustic errors:

$$global\ error = \sqrt{GPS\ error^2 + acoustic\ error^2} \quad (1)$$

Figure 3 shows the measurement results of the ‘‘8-shaped’’ pattern, where the mothership trajectory is obtained by GPS measurement (as shown in Figure 3a). There are 532 measurement points. The beacon depth measured by the USBL is shown in Figure 3b. Table 1 presents the calibration matrix calculated using 508 measurement points, which is approximately 95% of the total points, and meets criterion 1. After calibration, the USBL accuracy is 0.25% of the slant range, which meets criterion 2.

TABLE 1. Calibration matrix.

H_iH_j (mm)	H_1H_2	H_2H_3	H_3H_4
X	-499.54	239.07	21.39
Y	21.38	-260.45	499.53
Z	-2.28	-2.80	-3.32

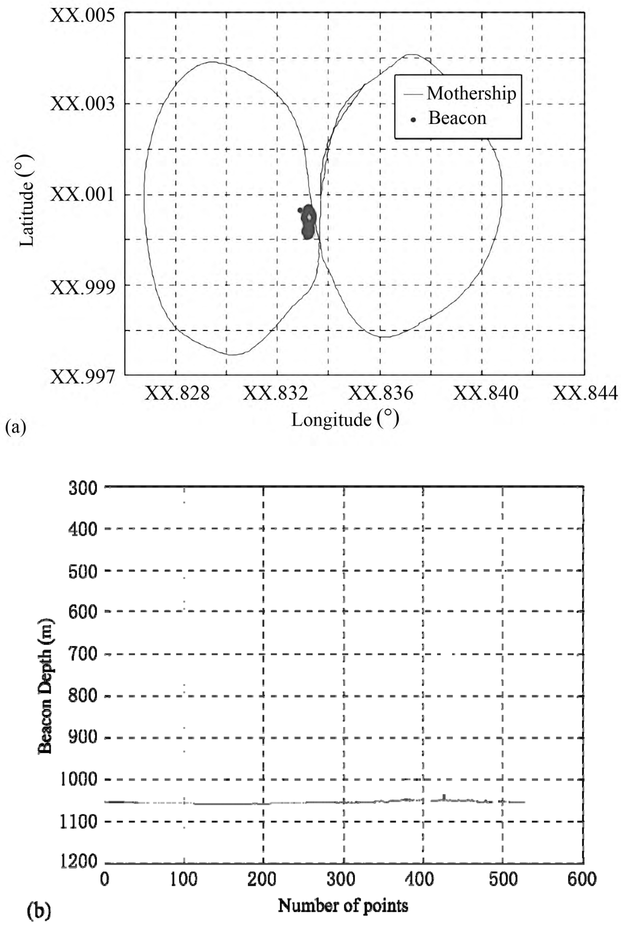

FIGURE 3. "8-shaped" pattern measurement results. (a) Mothership trajectory and beacon horizontal position; (b) Beacon depths of all measurements.

B. USBL APPLICATION

The data measured during ten dives in the first leg of the 2014–2015 Jiaolong application voyage were used to analyze the USBL positioning performance. The USBL can accurately track the Jiaolong during the descending, cruising, and ascending stages of each dive. The positioning performance (relative slant range error, relative depth error, and data efficiency) is consistent with the calibration result.

Figure 4 shows the relative slant range error of the USBL in a dive. The descending, cruising, and ascending stages are labeled in different colors. The black dotted line indicates the cone angle of the Jiaolong with respect to the USBL transducer array installed on the mothership. The relative slant range error of the USBL is greater than 0.3% in the initial stage of the Jiaolong's descent and the final stage of its ascent. This is mainly due to the large cone angle of the Jiaolong with respect to the USBL transducer array, which exceeds 30°, thereby degrading the positioning performance. When the cone angle is less than 30°, the total number of data points is 1594; the percentages of data points corresponding to relative slant range errors of <=0.1%, <=0.2%, <=0.3%, <=0.4%, and <=0.5% are 71.5%, 94.0%, 97.9%, 98.7%, and 99.0%, respectively, as listed in Table 2.

TABLE 2. Percentage of data points corresponding to relative slant range error.

Relative slant range error	Data number	Percentage of data points
<= 0.1%	1139	71.5%
<= 0.2%	1498	94.0%
<= 0.3%	1560	97.9%
<= 0.4%	1573	98.7%
<= 0.5%	1578	99.0%

Figure 5 shows the relative depth error of the USBL in a dive; the relative depth error of the USBL is greater than 0.2% during the initial stage of the Jiaolong descent and the final stage of its ascent. This is mainly due to the large cone angle of the Jiaolong with respect to the USBL transducer array, which exceeds 30°, thereby degrading the positioning performance. When the cone angle is less than 30°, the total number of data points is 1594; the percentages of data points corresponding to relative depth errors of <=0.1%, <=0.2%, <=0.3%, <=0.4%, and <=0.5% are 97.8%, 99.2%, 99.6%, 99.7%, and 99.8%, respectively, as listed in Table 3.

TABLE 3. Percentage of data points corresponding to relative depth error.

Relative depth error	Data number	Percentage of data points
<=0.1%	1559	97.8%
<=0.2%	1581	99.2%
<=0.3%	1588	99.6%
<=0.4%	1590	99.7%
<=0.5%	1591	99.8%

Figure 6 shows the statistical results of the slant range errors for cone angles within 30° in 10 dives (dive 75–84). Except for dive 75, the data efficiency for relative slant range errors less than 0.3% is above 90%. During dive 75, there were some problems with the mothership engine, resulting in large radiation noise and degradation of the positioning performance.

Figure 7 shows the statistical results of the depth errors for cone angles within 30° in 10 dives. Except for dive 75, the data efficiency for relative depth errors less than 0.2% is above 95%. During dive 75, there were some problems with the mothership engine, resulting in large radiation noise and degradation of the positioning performance.

C. LBL SEA TRIAL

Four transponder beacons (16#, 17#, 18#, 19#) deployed individually were used for LBL positioning, as shown in Figure 8. After all the transponder beacons have been deployed, the USBL was used to measure their positions. As the transponder beacon depths were nearly 3850 m, the mothership was required to run 1600-m circles (the cone angle was approximately 11.7°) around each beacon at a speed of 3 kn. An accurate beacon position can be obtained by removing the outlier data points and averaging the transponder beacon

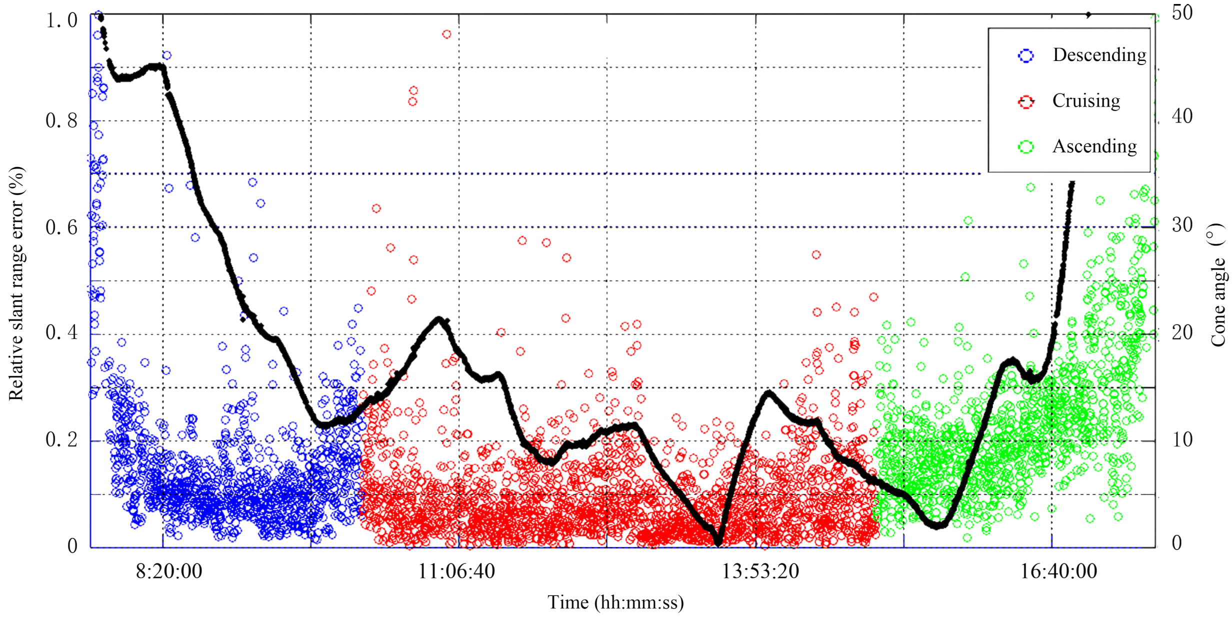

FIGURE 4. USBL relative slant range error in a dive.

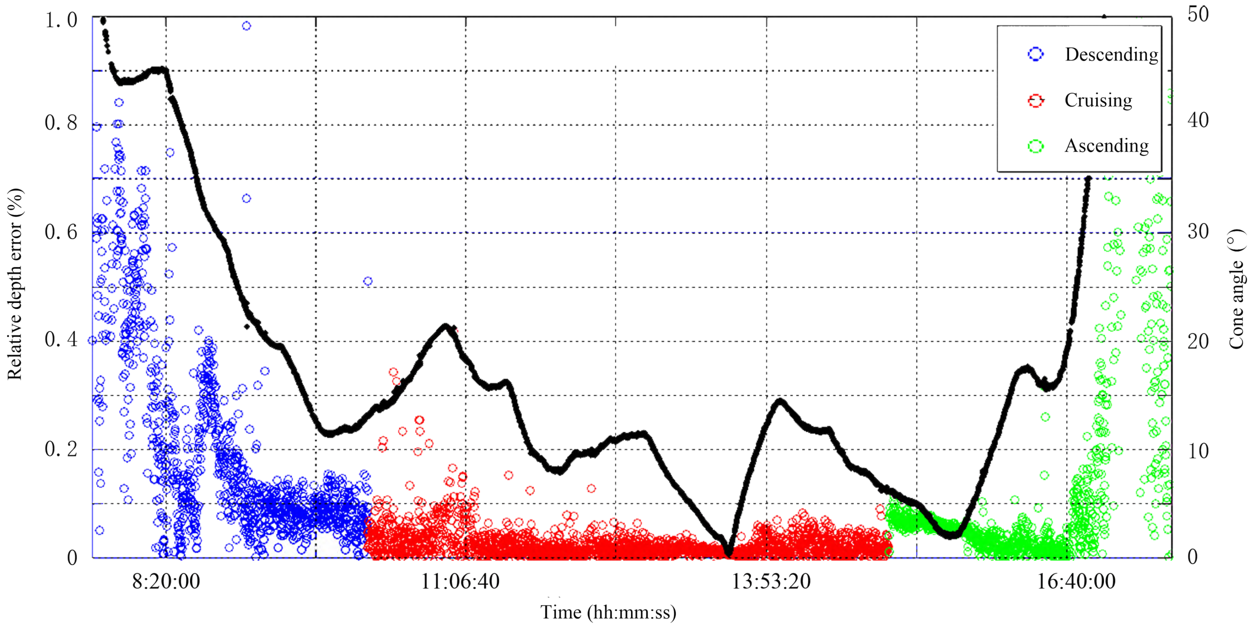

FIGURE 5. USBL relative depth error in a dive.

positions measured by the USBL. The statistical results of the measured data for the four transponder beacons are listed in Table 4. Compared to the preset transponder beacon positions, the offsets of the real positions of the four transponder beacons with respect to the seabed are 160 m, 130 m, 80 m, and 80 m, respectively.

Figure 8 also shows the Jiaolong diving position (indicated by a star) and landing position (indicated by a diamond). During long-duration diving, the Jiaolong drifted approximately 160 m to the south and 18 m to the east due to ocean currents.

To assess the LBL tracking continuity of the Jiaolong, the effect of propeller noise, and the difference with the USBL, the Jiaolong sailed along a rectangular path with a length of 900 m and breadth of 300 m, as shown in Figure 8. Figure 9 shows a comparison of the positioning results of LBL and USBL. It can be observed that both LBL and USBL can depict the trajectory of the Jiaolong on the seabed,

TABLE 4. Statistical results of measured data for four transponder beacons.

Beacon number	16#	17#	18#	19#
Number of USBL data	155	164	152	158
Effective number	149	157	152	141
Data efficiency	96.1%	95.7%	100.0%	89.3%
East-West error (m)	13.6	13.0	12.6	14.1
North-South error (m)	12.3	12.2	11.9	14.9
Depth error (m)	0.8	0.6	0.6	0.9
Relative slant range accuracy	0.47%	0.45%	0.45%	0.50%
Longitude (°)	117.803867	117.792771	117.774253	117.790842
Latitude (°)	17.581463	17.598518	17.584756	17.567053
Depth (m)	3856.6	3848.4	3806.6	3856.3

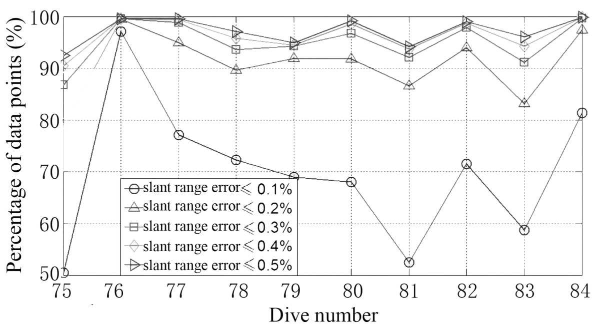

FIGURE 6. Statistical results of the relative slant range errors for cone angles within 30° in each dive.

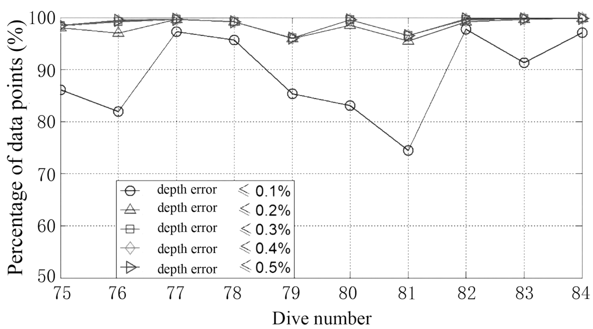

FIGURE 7. Statistical results of the relative depth errors for cone angles within 30° in each dive.

but the trajectories do not coincide. The LBL trajectory is relatively straight and consistent with the actual sailing of the Jiaolong, whereas the USBL trajectory is more distorted. Figure 10 shows the horizontal positioning differences between the LBL and USBL. The root mean square of the positioning difference is 31 m. It can be observed that the difference between the two is a circle with a diameter of 60 m, and most points are concentrated at the ±45° position. This is because the entire USBL trajectory is biased toward the southwest.

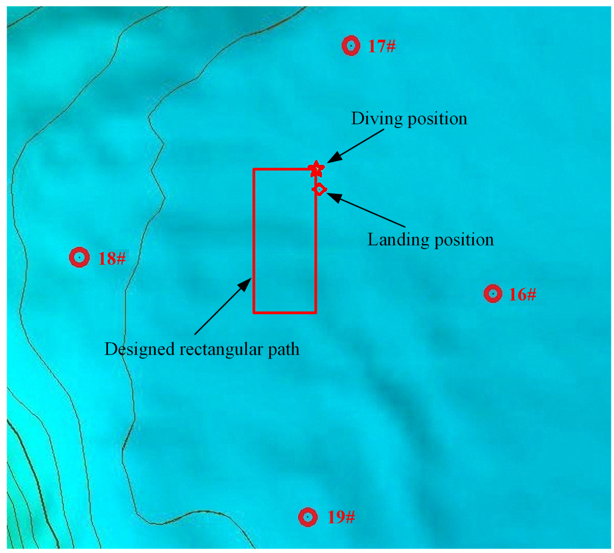

FIGURE 8. LBL sea trial design.

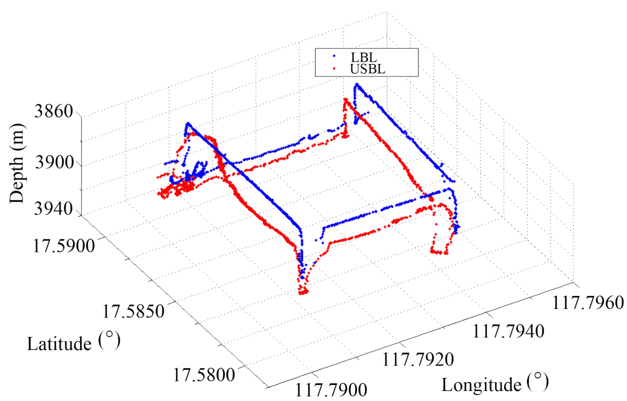

FIGURE 9. Comparison of LBL and USBL positioning results.

Figure 11a shows the East-West and South-North differences between the LBL and USBL, whereas Figure 11b shows the East-West and South-North ranges between the mothership and the manned submersible. There is a synchronous change between the East-West difference and East-West range; the same change exists between the

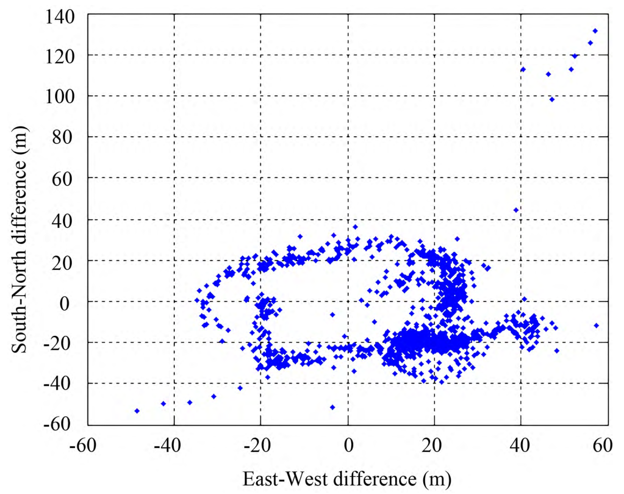

FIGURE 10. Horizontal positioning differences between LBL and USBL.

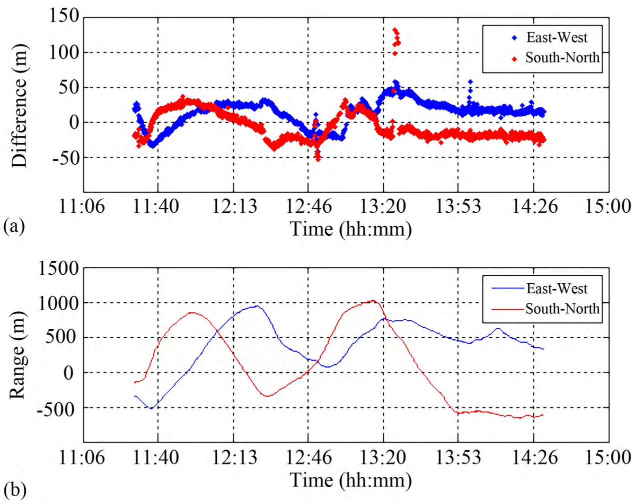

FIGURE 11. Relationship between the LBL–USBL positioning differences and the mothership–submersible range.

South-North difference and South-North range, indicating that the USBL positioning error is affected by the distance from the mothership and its heading. Furthermore, the USBL positioning error is the main source of the difference between the LBL and USBL.

IV. CONCLUSIONS

The USBL is used by the mothership to position manned submersibles. The mothership can monitor the position of the manned submersible relative to its own position. The mothership can obtain the exact location of the manned submersible by combining GPS and USBL. It can then send the positioning results to the manned submersible by digital underwater acoustic communication at longer time intervals (approximately 64 s). To ensure the accuracy and reliability of the USBL, sea-trial calibration must be performed to correct USBL installation deviations. The mothership needs to sail an "8-shaped" pattern to enable measurement of the seabed transponder beacon by the USBL in different directions. Data collected during the real dives of a manned submersible demonstrated that the USBL can track the Jiaolong during its descending, cruising, and ascending stages. The LBL sea-trial showed that the positioning accuracy of the LBL was better than that of the USBL.

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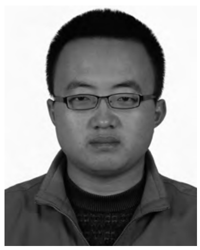

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