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Optimal Design of Beacon Array for Long Baseline Positioning System Used in Manned Deep-Sea Submersibles

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ABSTRACT Ultrashort baseline positioning systems are used to localize manned deep-sea submersibles. A long baseline positioning system is a significant supplement to an ultrashort baseline positioning system and provides more precise positioning. The long baseline beacon array design applied is a primary factor affecting the accuracy of long baseline positioning. However, beacon array designs have mainly been studied in autonomous underwater vehicles (AUVs). Because the characteristics and dive tasks between AUVs and manned deep-sea submersibles are different, the simple beacon array formations used in AUVs cannot be directly used in manned deep-sea submersibles. To the best of our knowledge, this study is the first to present the optimal design of a beacon array for a long baseline positioning system used in manned deep-sea submersibles. In this paper, based on the characteristics of a manned deep-sea submersible, the seven basic principles used for the optimal design of a long baseline beacon array are presented. First, the dive tasks of a JIAOLONG manned deep-sea submersible are analyzed, including the relationship between the dive survey lines, and the depth and distance of each line. Second, we explore the minimum beacon number to cover the dive site and its vicinity. Third, we adjust the beacon position based on the seven optimal design principles. The beacon array is designed to satisfy manned deep-sea submersible dive requirements during the JIAOLONG Test Applications Voyage 2013. A sea trial demonstrates that the long baseline positioning results are reliable if at least three beacons are not blocked, and the accuracy of the long baseline positioning system is better than that of an ultrashort baseline.

INDEX TERMS Performance optimization, optimal design, data processing, long baseline, beacon array.

I. INTRODUCTION

The deep sea is the lowest layer in the ocean, existing below the thermocline, at a depth of 1,800 m or more. Deep sea areas with a depth of more than 1,800 m account for 84% of the ocean area. The manned deep-sea submersibles have played an important role in human exploration and scientific discovery. Throughout history, The manned deep-sea submersible missions and expeditions have inspired mankind and fascinated society while fostering new technological advancements [1], [2].

Because the attenuation coefficients of electromagnetic waves are extremely high in oceans, we typically use acoustic waves to detect and transmit information at sea [3]–[6].

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TABLE 1. Comparison between ultrashort baseline positioning system and long baseline positioning system.

	Ultrashort baseline	Long baseline
Advantage	• Simple • Easy to operate • Easy to maneuver in a wide range	• High positioning accuracy • Good real-time performance
Disadvantage	• Calibration is needed • Positioning accuracy is related to operating distance • Large time delay	• Beacon array requires replacement • Equipment and time costs are high

An ultra-short baseline positioning system [7]–[9] is used to obtain the position of manned deep-sea submersibles relative to the support mothership. However, to ensure the safety of manned deep-sea submersibles, a long baseline positioning system [10]–[13] is also required as an independent positioning platform to provide more accurate and real-time navigation and positioning data for manned deep-sea submersibles in large areas and deep seas.

Table 1 presents the comparison of the advantages and disadvantages of a long baseline positioning system and an ultrashort baseline positioning system. Clearly, both ultrashort baseline and long baseline positioning systems are complementary. For example, if a manned deep-sea submersible needs to conduct multiple dives and continuous investigations in a specific sea area (within a few kilometers), using a long baseline positioning system for navigation and positioning is highly suitable. Conversely, if the distance between different sea areas or dive sites is long, the ultrashort baseline positioning system is often used for navigation and positioning [6].

Underwater networks provide another positioning choice [14], [15]. The methods used in cyber-physical systems and hybrid networks, such as network location-aware service recommendation [16], [17], service selection [18], [19], trust-aware recommendation [20], web service recommendation [21], particle swarm optimization [22], and composition-driven IoT service [23], [24], can be used in underwater acoustic sensor networks to improve the positioning performance. A stratification-based data collection scheme in underwater acoustic sensor networks that can combine the advantages of a multi-hop transmission scheme and an AUV-aided data collection scheme used to reduce the network consumption has recently been reported [25], [26].

Broadly speaking, the nodes used in underwater networks can be treated as beacons of a long baseline positioning system, and a beacon array of a long baseline positioning system is the simplest type of underwater network available. In this sense, a long baseline positioning system and an underwater network-based positioning system are similar. Both calculate the positioning results from the measured range from a beacon/node. However, the main purpose of a long baseline positioning system differs from that of an underwater network. A long baseline system concentrates more on high-precision positioning, whereas underwater networks, which are used for data collection, consider both data collection and positioning.

For a long baseline positioning system, a beacon array composed of underwater acoustic transponders/responders is the reference for precise positioning and navigation [27]–[29]. Numerous beacon array formations exist for a long baseline positioning system. Different beacon array formations have different applications and different levels of precision in terms of navigation and positioning. The commonly used formations of autonomous underwater vehicles (AUVs) include rectangular, triangular, star, and diamond formations, one reason for which is that the survey lines of an AUV are usually straight or in a comb shape, and are more regular than those used by manned submersibles. Another reason is that an AUV follows a pre-planned track, and travels underwater without the requirement of input from an operator.

The survey lines of a manned deep-sea submersible are shorter than those of an AUV. If a manned deep-sea submersible is required to perform multiple dives and continuous investigations within a specific sea area, using a long baseline positioning system for navigation and positioning is highly suitable. However, a beacon array requires replacement, and the equipment and time costs are extremely high. Thus, we aim to use fewer beacons to form an array to cover multiple dives. Because the characteristics and dive tasks between AUVs and manned deep-sea submersibles are different, we cannot use simple array formations for manned deep-sea submersibles. This is the problem with a beacon array design in manned submersibles.

In this study, to optimize the performance of long baseline positioning systems, seven basic principles for the optimal design of a long baseline beacon array are presented considering the characteristics of manned deep-sea submersibles. Considering the dive task of a manned deep-sea submersible and the available beacons, five steps are involved in the optimal design of a long baseline beacon array. The beacon array is designed to satisfy manned deep-sea submersible dive requirements in the JIAOLONG Test Applications Voyage 2013. To the best of our knowledge, this is the first study presenting the optimal design of a beacon array for a long baseline positioning system used in manned deep-sea submersibles.

Specifically, the following are the contributions of this work.

(1) Considering the characteristics of manned deep-sea submersibles, the basic principles for the optimal design of a long baseline beacon array are presented.

(2) Based on the basic beacon array design principles, the optimal beacon array is designed in five steps.

(3) The performance of the designed beacon array is verified based on three dives of JIAOLONG during the JIAOLONG Test Applications Voyage 2013.

The remainder of this paper is organized as follows. Section II presents the general description of the manned deep-sea submersibles and the long baseline positioning system. Section III provides seven basic principles and five steps to design an optimal beacon array, and then give a detailed design of the beacon array. Section IV discusses the sea trial of the long baseline positioning system of JIAOLONG manned deep-sea submersible at a depth of 5,200 m. Finally, a summary of the findings is presented in Section V.

II. MANNED DEEP-SEA SUBMERSIBLE AND LONG BASELINE POSITIONING SYSTEM

A. MANNED DEEP-SEA SUBMERSIBLES

The Manned Underwater Vehicles Committee divided the active manned submersibles into two groups by the depth 1,000 m. In Group 1-Hadal depth (depth >1,000 m), there are 11 active manned submersibles: DEEPSEA CHALLENGER (United States, 11,000 m, 1 crewmember), JIAOLONG (China, 7,000 m, 3 crewmembers), SHINKAI 6500 (Japan, 6,500 m, 3 crewmembers), MIR 1 (Russia, 6,000 m, 3 crewmembers), MIR 2 (Russia, 6,000 m, 3 crewmembers), Nautile (France, 6,000 m, 3 crewmembers), SHENHAI YONGSHI (China, 4,500 m, 3 crewmembers), Alvin (United States, 4,450 m, 3 crewmembers), PISCES IV (United States, 2,000 m, 3 crewmembers), PISCES V (United States, 2,000 m, 3 crewmembers), and ICTINEU (France, 1,200 m, 3 crewmembers). In Group 2-Deep Ocean (depth 250-1,000 m), there are 36 active manned submersibles. Thus, there are 47 active manned submersibles

The JIAOLONG manned deep-sea submersible developed by China can dive to depths exceeding 7,000 m [3]–[7]. There are 16 usable sonar systems for of the JIAOLONG manned deep-sea submersible [4], including two acoustic communication systems, one acoustic phone, one ultrashort baseline positioning system, one long baseline positioning system, one high-precision bathymetric side-scan sonar, one imaging sonar, one Doppler velocity log, seven obstacle avoidance sonars, and one altimeter [3].

B. LONG BASELINE POSITIONING SYSTEM

Figure 1 shows a schematic diagram of the long baseline positioning system. The coordinates of the beacons are set as (x_i, y_i, z_i), where $i = 1, 2, 3$, or 4, and the coordinates of the manned deep-sea submersible are set as (x, y, z). The influence of the ray bending is not considered here. According to the relations regarding the geometric position, we have the following equations:

$$\begin{cases} (x-x_1)^2+(y-y_1)^2+(z-z_1)^2=r_1^2 \\ (x-x_2)^2+(y-y_2)^2+(z-z_2)^2=r_2^2 \\ (x-x_3)^2+(y-y_3)^2+(z-z_3)^2=r_3^2 \\ (x-x_4)^2+(y-y_4)^2+(z-z_4)^2=r_4^2 \end{cases} \tag{1}$$

where r_i is the range between the ith beacon and the manned deep-sea submersible, where $i = 1, 2, 3$, or 4. The depth of the manned deep-sea submersible can be obtained using pressure sensors. Let the depth be h, and let the equation order be decreased. The following two-variable linear equations

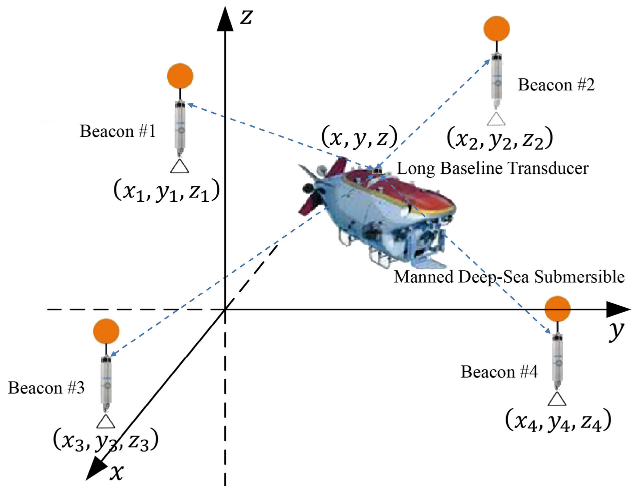

FIGURE 1. Schematic diagram of long baseline positioning system.

can then be obtained:

$$\begin{bmatrix} (x-x_1) & (y-y_1) \\ (x-x_2) & (y-y_2) \\ (x-x_3) & (y-y_3) \\ (x-x_4) & (y-y_4) \end{bmatrix} \times \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \frac{r_1^2-r_2^2+d_2^2-d_1^2}{2} - h(z_2-z_1) \\ \frac{r_2^2-r_3^2+d_3^2-d_2^2}{2} - h(z_3-z_2) \\ \frac{r_3^2-r_4^2+d_4^2-d_3^2}{2} - h(z_4-z_3) \\ \frac{r_4^2-r_1^2+d_1^2-d_4^2}{2} - h(z_1-z_4) \end{bmatrix} \tag{2}$$

where $d_i = \sqrt{x_i^2+y_i^2+z_i^2}$, where $i = 1, 2, 3$, or 4. Equation (2) can be treated as $AX = B$. When matrix A^TA is an invertible matrix, according to the least square method, the optimal solution can be obtained as follows:

$$X = \left(A^TA\right)^{-1} A^TB \tag{3}$$

Thus, we can get three-dimensional position of the manned deep-sea submersible.

The positions of the ocean bottom beacons should be measured from an initial survey. If the surface support mothership contains an ultrashort baseline positioning system, the beacons can be directly measured using an ultrashort baseline positioning system. In general, the surface support mothership sails around a beacon; subsequently, the ultrashort baseline positioning system can measure the position of the beacon in different directions. Consequently, the positional errors can be minimized. After removing outliers, the ultrashort baseline positioning data can be used to calculate the beacon positions.

III. OPTIMAL DESIGN OF BEACON ARRAY

A. BASIC PRINCIPLE

The design of a long baseline positioning system beacon array used in manned deep-sea submersibles should follow the following basic principles:

- Each beacon must achieve an effective coverage of the dive site and its vicinity to ensure positioning accuracy throughout the area.
- The beacons should remain distant from the dive sites to ensure the safety of the manned deep-sea submersible.
- The beacons should form a regular geometric shape.
- The beacons should be spread as far as possible to avoid the survey line of the manned deep-sea submersible.
- The adjacent beacon spacing should be controlled to be within the range of 2–3.5 km.
- The distance between each beacon and the farthest survey position should be as small as possible.
- The beacons should be maintained within ±100 m of the primary operation depth of the manned deep-sea submersible.

B. DESIGN STEPS OF AN OPTIMAL BEACON ARRAY

Because the characteristics and dive tasks between AUVs and manned deep-sea submersibles differ, the simple beacon array formations used in AUVs cannot be directly used in manned deep-sea submersibles. Considering the dive task of a manned deep-sea submersible and the available beacons, there are five steps required for an optimal design of a beacon array for a long baseline positioning system used in a manned deep-sea submersible, as listed in Table 2. First, the dive tasks of the JIAOLONG manned deep-sea submersible are analyzed, including the relationship between the dive survey lines and the depth and distance of each dive survey line. We then explore the minimum number of beacons to cover the dive site and its vicinity. Finally, we adjust the beacon position based on the seven optimal design principles.

C. DIVE TASK

During the JIAOLONG Test Applications Voyage 2013, three dives were conducted in the same area for scientific research. As shown in Figure 2, all three dives commenced at point O. Lines 1 (from O to A), 2 (from O to B), and 3 (from O to C) are the expected survey lines of these three dives. The distances of Lines 1, 2, and 3 are 3.3, 4.0, and 4.0 km, respectively.

Before the voyage, four beacons were available. Thus, we designed the beacon array using four beacons.

D. FIRST DESIGN

The positions of the four beacons (#1–4) are indicated by the yellow dots in Figure 2. The intersection from point A to line BC for the vertical line is the position of beacon #3. The intersection from point C to line AB for the vertical line is the position of beacon #4. Beacons #1 and #2 were obtained from beacons #4 and #3, which are perpendicular to line AC.

TABLE 2. Design steps of an optimal beacon array for a long baseline positioning system.

Step 1	The dive task of the JIAOLONG manned deep-sea submersible should be analyzed, including the relationship between the dive survey lines and the depth and distance of each dive survey line.
Step 2	The number of available beacons should be known. The minimum number of beacons that can cover the dive site and its vicinity should be calculated.
Step 3	Based on the optimal design principles, one commonly used beacon array formation is chosen, such as a rectangular, triangular, or star formation; in addition, the distances between each beacon and the farthest survey position are analyzed, as is the height of each beacon relative to the common start point of the dive survey lines.
Step 4	If the distance is larger than the operating range of the beacon, or if there is a large difference in height between the beacons, one beacon is chosen as the center whereas the other beacons are rotated to adjust the distance between each beacon and the farthest survey position, and the beacon depth.
Step 5	The beacon position is adjusted until all seven optimal design principles are met.

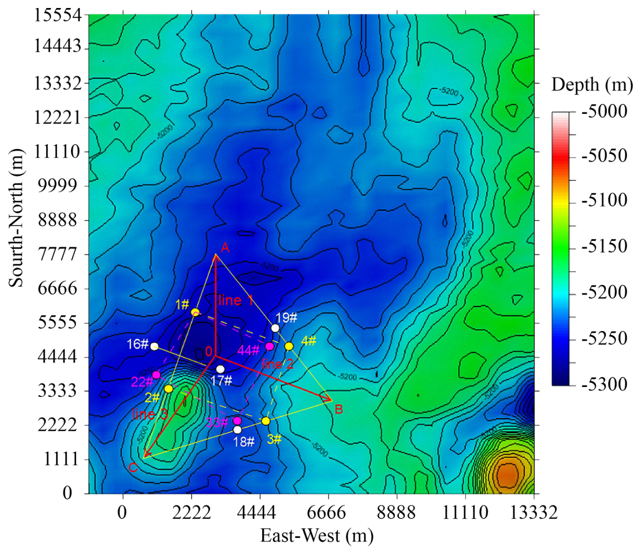

FIGURE 2. Three manned deep-sea submersible survey lines and three designed beacon arrays.

The distances between each beacon and points A, B, and C are as follows:

$$\begin{cases} \#1A = 2.0km \\ \#2A = 4.6km \\ \#3A = 5.6km \\ \#4A = 3.8km \end{cases}; \begin{cases} \#1B = 5.2km \\ \#2B = 5.2km \\ \#3B = 2.2km \\ \#4B = 2.2km \end{cases}; \begin{cases} \#1C = 5.0km \\ \#2C = 2.4km \\ \#3C = 4.1km \\ \#4C = 5.8km \end{cases} \quad (4)$$

The distances between the beacons are as follows:

$$\begin{cases} \#1-2 = 2.6km \\ \#2-3 = 3.3km \\ \#3-4 = 2.5km \\ \#4-1 = 3.2km \end{cases} \quad (5)$$

The heights of points A, B, and C, and those of beacons #1–4 relative to point O are as follows:

$$\begin{cases} h_A = 28m \\ h_B = 87m \\ h_C = 80m \end{cases} ; \begin{cases} h_{\#1} = 19m \\ h_{\#2} = 79m \\ h_{\#3} = 51m \\ h_{\#4} = 55m \end{cases} \tag{6}$$

Thus, large differences are found in the heights between the four beacons.

E. SECOND DESIGN

To adjust the depth of the other three beacons, beacon #1 is defined as the center whereas the other three beacons are rotated. The positions of the four beacons after the adjustment are denoted by the pink dots in Figure 2.

The distances between each beacon and points A, B, and C are as follows:

$$\begin{cases} \#1A = 2.0km \\ \#22A = 4.4km \\ \#33A = 5.6km \\ \#44A = 3.5km \end{cases} ; \begin{cases} \#1B = 5.2km \\ \#22B = 5.8km \\ \#33B = 3.2km \\ \#44B = 2.8km \end{cases} ; \begin{cases} \#1C = 5.0km \\ \#22C = 2.8km \\ \#33C = 3.4km \\ \#44C = 5.6km \end{cases} \tag{7}$$

In addition, the distances between the beacons are as follows:

$$\begin{cases} \#1-22 = 2.5km \\ \#22-33 = 3.1km \\ \#33-44 = 2.7km \\ \#44-1 = 2.7km \end{cases} \tag{8}$$

Finally, the heights of points A, B, and C, and those of beacons #1, #22, #33, and #44 relative to point O are as follows:

$$\begin{cases} h_A = 28m \\ h_B = 87m \\ h_C = 80m \end{cases} ; \begin{cases} h_{\#1} = 19m \\ h_{\#22} = 33m \\ h_{\#33} = 40m \\ h_{\#44} = 33m \end{cases} \tag{9}$$

From (4) and (7), we can see that there are two beacons exceeding 4 km or even 5 km to the end of each survey line in the first two designs.

F. THIRD DESIGN

The following design is adopted to arrange the beacons (shown as white dots in Figure 2) in a manner such that each survey line is guaranteed to have three beacons within a distance of 3.8 km.

- Beacon #16 is placed 0.9 km to the west of, and along the normal from, the center point of line AC.
- Beacon #17 is set at 150 m east and 430 m south of point O, and the distances between this beacon and point A, point B, and point C are 3.7 km, 3.6 km, and 3.8 km, respectively.
- Beacon #18 is set at the center of the line BC.
- Beacon #19 is set at the center of the line AB.

The distances between each beacon and points A, B, and C are as follows:

$$\begin{cases} \#16A = 3.6km \\ \#17A = 3.7km \\ \#18A = 5.7km \\ \#19A = 3.0km \end{cases} ; \begin{cases} \#16B = 5.9km \\ \#17B = 3.6km \\ \#18B = 3.2km \\ \#19B = 3.0km \end{cases} ; \begin{cases} \#16C = 3.7km \\ \#17C = 3.8km \\ \#18C = 3.2km \\ \#19C = 6.0km \end{cases} \tag{10}$$

In addition, the distances between the beacons are as follows:

$$\begin{cases} \#16-17 = 2.3km \\ \#16-18 = 3.8km \\ \#16-19 = 3.9km \\ \#17-18 = 2.0km \\ \#17-19 = 2.2km \\ \#18-19 = 3.5km \end{cases} \tag{11}$$

Finally, the heights of points A, B, and C, and those of beacons #16, #17, #18, and #19 relative to point O are as follows:

$$\begin{cases} h_A = 28m \\ h_B = 87m \\ h_C = 80m \end{cases} ; \begin{cases} h_{\#16} = 23m \\ h_{\#17} = 17m \\ h_{\#18} = 38m \\ h_{\#19} = 35m \end{cases} \tag{12}$$

In this design, beacon #17 is close to point O. In order to avoid colliding with beacon #17, this design imposes stricter requirements on the deployment of the manned deep-sea submersible. Prior to deployment, it is necessary to measure the ocean current velocity/direction and find a reasonable deployment point.

G. FOURTH DESIGN

On the way to the dive destination, we tested the four beacons, and found that one beacon was malfunctioning. To encompass all three diving lines, beacon #17 was placed in the middle of line AC, beacon #18 was placed in the middle of line BC, and beacon #19 was placed in the middle of line AB, as shown in Figure 3.

The distances between each beacon and points A, B, and C are as follows:

$$\begin{cases} \#17A = 3.5km \\ \#18A = 5.7km \\ \#19A = 3.0km \end{cases} ; \begin{cases} \#17B = 5.0km \\ \#18B = 3.2km \\ \#19B = 3.0km \end{cases} ; \begin{cases} \#17C = 3.6km \\ \#18C = 3.2km \\ \#19C = 6.0km \end{cases} \tag{13}$$

In addition, the distances between the beacons are as the following:

$$\begin{cases} \#17-18 = 3.0km \\ \#17-19 = 3.1km \\ \#18-19 = 3.5km \end{cases} \tag{14}$$

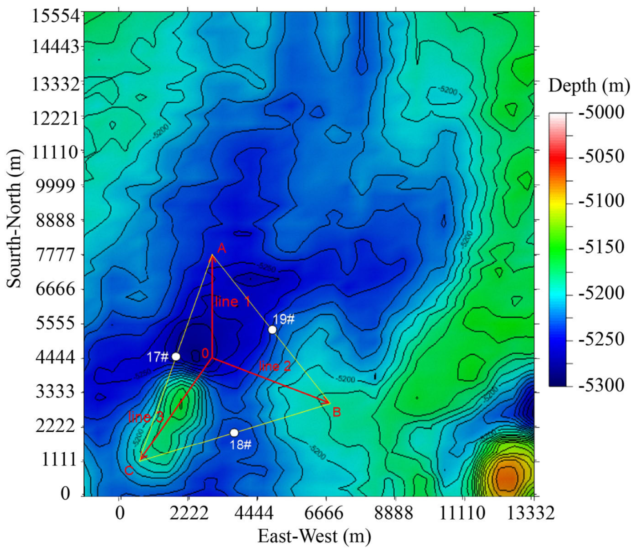

FIGURE 3. Three manned deep-sea submersible survey lines and the final designed beacon array.

The heights of points A, B, and C, and those of beacons #17–19 relative to point O are as follows:

$$\begin{cases} h_A = 28m \\ h_B = 87m \\ h_C = 80m \end{cases}; \begin{cases} h_{\#17} = 6m \\ h_{\#18} = 38m \\ h_{\#19} = 35m \end{cases} \tag{15}$$

Finally, the depths of beacons #17–19 are as follows:

$$\begin{cases} D_{\#17} = -5,207m \\ D_{\#18} = -5,185m \\ D_{\#19} = -5,188m \end{cases} \tag{16}$$

Thus, if there are four beacons, we will adopt the third design. However, as only three beacons can be used, the fourth design is adopted for the sea trial.

IV. SEA TRIAL AND DATA ANALYSIS

A. BEACON POSITIONS

The ultrashort baseline positioning system was used to measure three beacon positions. The depths of the beacons were approximately 5,200 m. A precise beacon position can be calculated by removing the outliers and averaging the data measured using the ultrashort baseline positioning system. Table 3 presents the process in detail using a MATLAB code. Table 4 lists the statistical results of the three beacons measured using the ultrashort baseline positioning system.

B. RANGING ANALYSIS

The long baseline positioning system distance measurements for one dive corresponding to line OA are shown in Figure 4. The blue line indicates the depth of the manned deep-sea submersible measured using a high-precision pressure sensor. The corresponding horizontal axis represents the time in hours/minutes/seconds, and the vertical axis

TABLE 3. Algorithm used to calculate the beacon position by removing outliers and averaging the data measured by ultrashort baseline positioning system.

Algorithm Calculate Beacon Position (Using MATLAB Notation)

Input:

```
USBLData % Data measured by ultrashort baseline
D = USBLData(16, :); % Beacon depth measured by ultrashort
        baseline
Lat = USBLData(9, :)*60+USBLData(10, :);% Latitude measured by
        ultrashort baseline
Lon = USBLData(12, :)*60+USBLData(13, :);% Longitude measured
        by ultrashort baseline

% Remove outliers by depth
I = find(5000<D<5500); % we know the general depth of each beacon
Z0 = mean(D(I));
I = find(abs(D - z0)<100); %Remove outlier whose depth is 100
        meters larger than the average depth
Lon = Lon(I);
Lat = Lat(I);
D = D (I);

% Remove outliers by XY error
x = (Lon-Lon(1))*1852.*cos(Lat/60/180*pi);
y = (Lat-Lat(1))*1852/1.05;
x0 = mean(x);
y0 = mean(y);
e = sqrt((x-x0).^2+(y-y0).^2+(D-z0).^2);
I2 = find(e<=100); %Adjust as needed
```

Output:

```
% Average the data
Latitude = mean(Lat(I2)); % Latitude of the beacon
Longitude = mean(Lon(I2)); % Longitude of the beacon
Depth = mean(D(I2)) % Depth of the beacon
```

TABLE 4. Statistical results of the three beacons measured using ultrashort baseline positioning system.

Beacon number	#17	#18	#19
East–West error	39.8 m	34.6 m	39.9 m
North–South error	36.2 m	34.0 m	36.0 m
Depth error	1.4 m	3.7 m	1.8 m

represents the depth in meters. The red, black, and pink dot points correspond to the distances between the manned deep-sea submersible and beacons #17–19, respectively. The corresponding horizontal axis represents the time in hours/minutes/seconds, and vertical axis represents the distance in meters.

When the manned deep-sea submersible dives to 2,870 m at 9:20, the long baseline positioning system receives the distance at beacons #18 and #19 nearly simultaneously. This is because the transducer is mounted on top of the manned deep-sea submersible. Compared with beacon #17,

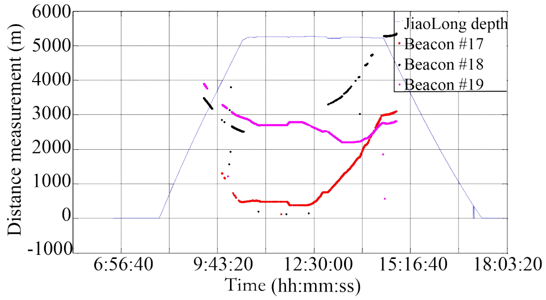

FIGURE 4. Long baseline distance measurement results for one dive corresponding to line OA.

beacons #18 and #19 exhibit greater horizontal separation from the manned deep-sea submersible; thus, their interrogation signals are easier to capture. Because the horizontal distance between beacon #17 and the manned deep-sea submersible is small, beacon #17 is almost below the manned deep-sea submersible. The long baseline positioning system obtains the distance to beacon #17 when the manned deep-sea submersible dives to 3,900 m at 9:48.

The manned deep-sea submersible ended up at 800 m west of the base point, immediately below the scheduled dive point O shown in Figure 3. The manned deep-sea submersible fell into a depression and obscured the signal between the submarine and beacon #18. After the manned deep-sea submersible landed at the ocean bottom (about 5265 m in depth), it performed *in situ* geotechnical measurements without moving, which is why no data are available for beacon #18 from 10:25 to 12:55.

At 12:55, the manned deep-sea submersible lifted to approximately 40 m and began cruising at a fixed depth (about 5215 m), and conducted a bathymetric side-scan sonar seafloor mapping survey for approximately 20 min. In Figure 4, we can see that when the manned deep-sea submersible left the depression, the three beacons worked well, and the measured distances between the manned deep-sea submersible and three beacons were correct.

C. POSITIONING ANALYSIS

Figure 5 shows a comparison between the long baseline and ultrashort baseline positioning results during the descending. The ultrashort baseline positioning results (red points) are obtained using the ultrashort baseline positioning system on the surface support mothership, whereas the long baseline positioning results (blue points) are obtained using the long baseline positioning system on the manned deep-sea submersible.

It can be observed that the ultrashort baseline positioning system can depict the descending trajectory of the manned deep-sea submersible, whereas the long baseline positioning results are not reasonable. The main reason for this is that, when the depth of the manned deep-sea submersible exceeds 3900 m, the update rates of ranging data from beacon #17 and beacon #18 are very low and intermittent, making it difficult to ensure that all three beacons have signals.

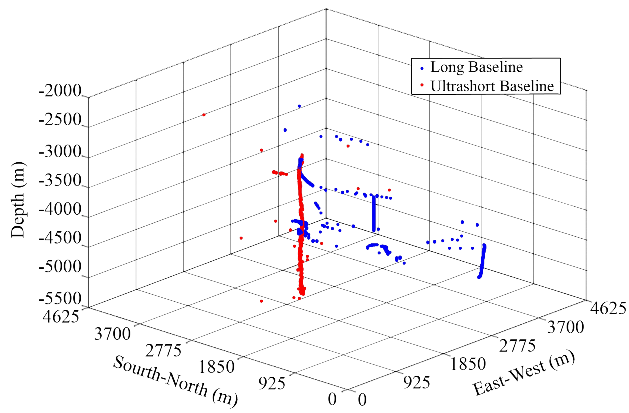

FIGURE 5. Comparison between the long and ultrashort baseline positioning results during the descending.

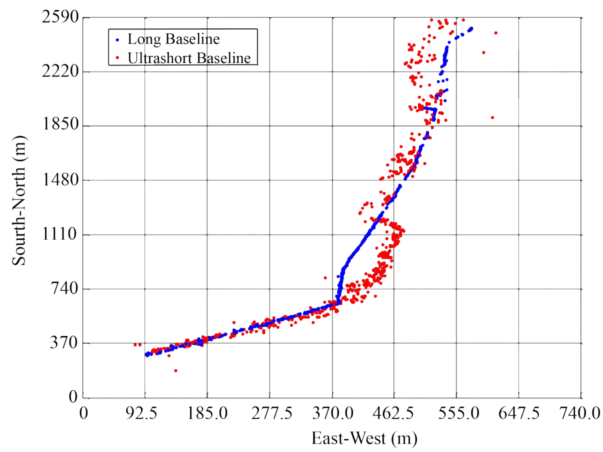

FIGURE 6. Comparison between the long and ultrashort baseline positioning results after 12:55.

The transducer of the long baseline positioning system is mounted on top of the manned deep-sea submersible, and the corresponding beacons are on the ocean bottom. The acoustic signals between the long baseline transducer and beacons are easily blocked by the manned deep-sea submersible. When there is no updated ranging data from one or two beacons, the long baseline positioning results are not credible. Therefore, this configuration is not suitable for positioning for the manned deep-sea submersible during its descending and ascending.

Figure 6 shows a comparison between the long baseline and ultrashort baseline positioning results after 12:55. After lifting 40 m (at 12:55), the manned deep-sea submersible began cruising along a straight line at a depth 5,215 m for approximately 20 min. This shows that the long baseline positioning results coincide with the real manned deep-sea submersible trajectory (straight line), whereas a deviation appears in the ultrashort baseline positioning. It demonstrates that, by ensuring that at least three beacons were not blocked (after 12:55), the long baseline positioning results obtained are deemed reliable, and the accuracy is much higher than that using the ultrashort baseline positioning system.

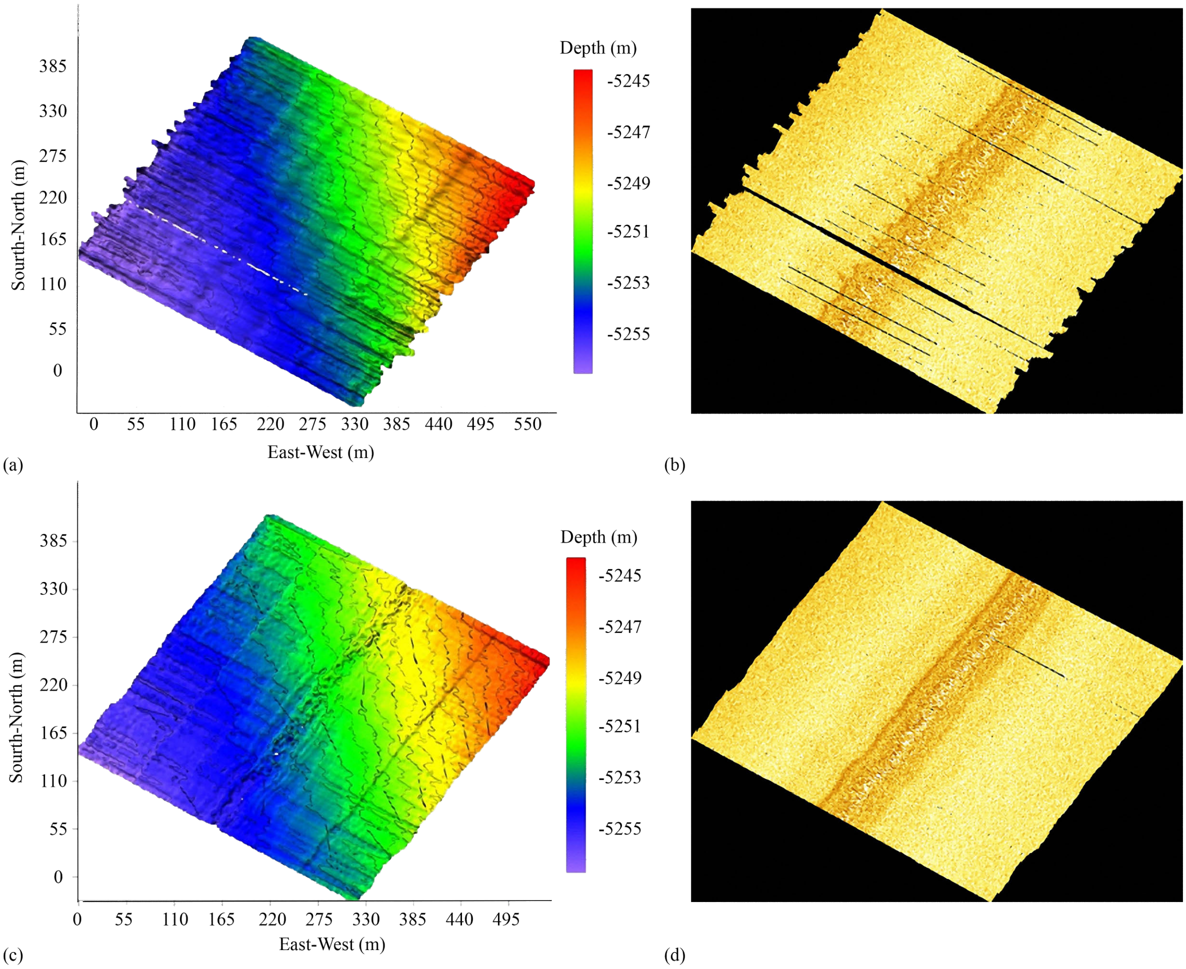

FIGURE 7. Seafloor microtopography and microgeomorphology maps obtained by the bathymetric side-scan sonar equipped on JIAOLONG manned deep-sea submersible. (a) Microtopography and (b) microgeomorphology maps using ultrashort baseline positioning data for navigation; (c) microtopography and (d) microgeomorphology maps using long baseline positioning data for navigation.

D. LONG BASELINE AND ULTRASHORT BASELINE USED IN SEAFLOOR MAPPING

In order to better understand the difference between the ultrashort baseline and the long-baseline positioning performance, the ultra-short baseline and the long-baseline are used as navigation data to map the detection data obtained by the bathymetric side-scan sonar installed on the JIAOLONG manned deep-sea submersible. To obtain smooth navigation data, digital filtering and data smoothing are carried out on the ultra-short baseline and long-baseline positioning data. The ultrashort baseline and long-baseline positioning data after processing are rewritten into the bathymetric side-scan sonar data files as navigation data. After completing the subsequent processing, seafloor microtopography and microgeomorphology maps can be obtained, as shown in Figure 7.

Figures 7(a) microtopography and (b) microgeomorphology maps use ultrashort baseline positioning data for navigation. It can be seen that there are many track burrs. Figures 7(c) microtopography and (d) microgeomorphology maps use long baseline positioning data for navigation. Compared to Figures 7(a) and (b), the microtopography and microgeomorphology maps in Figures 7(c) and (d), respectively, are much better. The reason for this is that the positioning accuracy of a long baseline is much better than that of an ultrashort baseline.

V. CONCLUSION

For a long baseline positioning system, a beacon array composed of underwater acoustic transponders/responders is the reference for precise positioning and navigation. Because the characteristics and dive tasks between AUVs and manned deep-sea submersibles are different, the simple beacon array formations used in AUVs cannot be directly used in manned deep-sea submersibles. Considering the characteristics of manned deep-sea submersibles, the basic principles for the optimal design of a long baseline beacon array are presented. Based on the basic beacon array design principles, the optimal beacon array is designed in five steps.

The performance of the designed beacon array is verified based on three dives of JIAOLONG during the JIAOLONG

Test Applications Voyage 2013. The distances between the transducer and each beacon were measured and analyzed, and the positioning results were compared with those of the ultrashort baseline positioning system. The results indicate that (1) the long baseline positioning system was suitable for operations near the depth of the beacon array, whereas the submersibles relied primarily on the ultrashort baseline positioning system for positioning during the ascent and descent processes, and (2) the positioning accuracy of the long baseline positioning system was much better than that of the ultrashort baseline positioning system, if at least three beacons are not blocked, particularly in deep sea waters.

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