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UNDERWATER NAVIGATION AND CALIBRATION OF JIAOLONG MANNED SUBMERSIBLE IN THE SOUTHWEST INDIAN RIDGE HYDROTHERMAL VENTS

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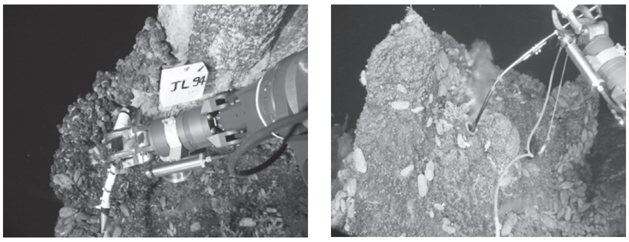
Key words: manned submersible, underwater navigation, data calibration, hydrothermal vent, Southwest Indian Ridge.

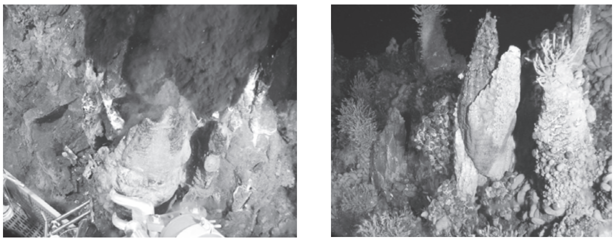
ABSTRACT

China's 7000 m manned submersible JIAOLONG carried out an exploration cruise on the Indian Ocean Ridge from late 2014 to early 2015. During the cruise, the submersible completed manned diving *in situ* investigations into hydrothermal vents in the area. One of the primary tasks of the work was to map the vents precisely. In this paper, we briefly introduce the cruise, and then focus on the submersible's underwater navigation and the positioning of five hydrothermal vents using the Ultra-Short Base Line positioning system of JIAOLONG. This study describes the positioning data of each vent from different dives, and discusses the variation in the positioning data among dives in the same location. We propose a shape-based calibration method using the trajectories of the submersible and its mother ship to correct for noted deviations in position data. This method is verified using calibration results of five typical vents and provides a promising technique that can be used for other underwater vehicles under similar conditions.



(a) Collecting the hydrothermal mussels in Dive94

(b) *In situ* temperature measurement in Dive90



(c) Collecting the hydrothermal vent in Dive89

(d) Biotic communityin low temperature hydrothermal area, shot in Dive96

Fig. 1. Underwater photos acquired by JIAOLONG submersible.

I. INTRODUCTION

From Dec. 2014 to Feb. 2015, China's 7000 m manned submersible JIAOLONG (Liu et al., 2010; Cui, 2013) carried out legs II and III of Chinese Cruise 35th at Longqi-1 (Dragon Flag) Field (49°39′E, 37°47′S) on the ultraslow-spreading Southwest Indian Ridge (SWIR) (Tao et al., 2011; Tao et al., 2014). The United Nations International Seabed Authority (ISA) granted a license to the China Ocean Minerals Research Agency (COMRA) to explore mining of polymetallic sulfide deposits in this area associated with deep sea hydrothermal vents in June 2011. Thus, the general scientific goal of this cruise was to systematically investigate geographical and biological characteristics of the hydrothermal vents using JIAOLONG.

During the 2-month expedition, the JIAOLONG submersible was deployed for 10 dives, completing numerous tasks that included: investigations on the geology, biology and fluidics of the hydrothermal vent regions; sampling of rocks, sediment, polymetallic sulfide and hydrothermal plumes fluid; and, *in situ* cultivation tests in the hydrothermal venting area (Fig. 1). The expedition team identified and documented seven new hydro-

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Table 1. The statistics of the positioning data of five typical vents in different dives.

Name of Vents	Dive	Time length of underwater investigation	Latitude		Longitude		Straight-line distance deviation (m)	Average Depth (m)
			Average Value (°)	Distance deviation (m)	Average Value (°)	Distance deviation (m)		
Jabberwocky	90	17 min	-37.78293	11.4	49.64982	23.2	25.9	2737.2
	98	6 min 50 sec	-37.78351	2.4	49.64988	7.8	8.1	2735.1
	100	39 min	-37.78360	12.9	49.64990	18.6	22.6	2738.8
JiaoLong Palace	89	98.5 min	-37.78391	29.3	49.64963	28.2	40.6	2764.3
	94	135 min	-37.78387	29.2	49.64981	27.8	40.3	2760.1
	96	24 min	-37.78356	10.5	49.64960	14.7	18.1	2760.2
	100	28.4 min	-37.78380	5.1	49.64951	2.4	5.6	2760.2
RuyiJingu Bang	90	15 min	-37.78283	9.5	49.64915	2.4	9.8	2743.9
	97	29.3 min	-37.78254	23.9	49.64918	26.3	35.5	2729.8
	100	11 min	-37.78273	3.8	49.64938	7.1	4.9	2731.0
Ryugo-jo	90	75 min	-37.78357	28.6	49.65006	19.8	34.8	2736.7
	100	21 min	-37.78325	12.4	49.65016	9.4	15.6	2736.8
Fucanglong's Furnace	94	34 min	-37.78308	11.1	49.64899	21.0	23.8	2768.6
	96	34 min	-37.78373	6.7	49.64915	12.7	14.4	2768.7
	100	30 min	-37.78339	18.0	49.64939	14.7	23.2	2768.3

thermal vents, collecting positioning data and high-definition photos and videos. Further, the location of hydrothermal vents previously reported by Dr. Copley in the James Cook 67 cruise report (Copley, 2011) were updated. The vents were labeled with markers launched by JIAOLONG and positioned with the submersible's track. Geographical and biological investigations were led by chief scientists Chunhui Tao, Huaiyang Zhou, Xiang Xiao and Zongze Shao.

In this paper, we focus on the data analysis of the underwater navigation and positioning of JIAOLONG in Longqi-1 Field and discuss the constraints of the available methods, especially those that can be feasibly applied onboard (Opderbecke, 1997). As the hydrothermal vents are several meters above the sea bottom, the submersible remain stationary while completing sampling and measuring by hanging the sampling basket on a rock from the vent. Therefore, it is logical to assume the vent and the submersible share the same coordinates during the operation. JIAOLONG's tracks were obtained using the POSIDONIA Ultra Short Base Line (USBL) system developed by the IXSEA Corporation (Zhu et al., 2014; iXblue, 2015). The transponder for the system was on the back of the submersible and the array was installed on the bottom of Xiang Yang Hong 9, the mother ship of JIAOLONG. In this case study, we provide details on the analysis of the data, identify the problems, probe their cause and calibrate the result of the acquired hydrothermal vent positioning data, providing techniques that can improve underwater navigation and positioning in future studies.

II. UNDERWATER NAVIGATION RESULTS

1. Statistical Positioning Results of JIAOLONG in Longqi-1 Field

In Nov. 2011, Dr. JT Copley from the University of Southampton led Research Cruise JC67 of the Royal Research Ship (RRS) to survey the biogeography and ecology of the hydrothermal field in SWIR. Dr. Copley utilized two underwater vehicles, "Kiel6000"and "HyBIS," in the JC67 cruise. The two robots dived a total of eight times and acquired abundant data and pictures, but did not sample at the vents. The JC67 cruise report describes in detail the diving process in this area, and provides location data and pictures of the vents (Copley, 2011). This information was valuable for later cruises, but also needed to be verified.

In legs II and III of the Chinese Cruise 35th, JIAOLONG revisited most of the hydrothermal vents described in the JC67 report, including (names are those given in JC67 report): "Jabberwocky" (JW), "Jiaolong Palace" (JLP), "Ryugo-jo" (RJ), "Fucanglong's Furnace" (FF), and "Ruyi Jingu Bang" (RYJB) and deployed markers in the field. Table 1 shows positioning data for the five vents in different dives, including duration, position coordinates and distance deviation. Distance deviation is the statistical standard deviation of all the positioning dots acquired in one dive. Data segments were chosen based on the diving record of the submersible pilots and scientists and the HD video that JIAOLONG acquired. The total duration that JIAOLONG spent investigating a hydrothermal vent was approximately 13.3 h in this cruise, and the mean duration of each investigation was 30.7 min. The maximum distance deviation for all dives was 40.8 m, and the minimum was 15.0 m. Distance deviation was strongly correlated with duration. Mean latitude and longitude for each vent, along with the corresponding distance deviation from Table 1 are provided in Table 2; mean distance deviation across all five vents was 35.5 m.

Table 2. The statistics of the positioning data of the five typical vents in this cruise.

Vents	Total time length of underwater investigation (min)	Mean Latitude (°)	Mean Longitude (°)	Distance Deviation (m)	Mean Depth (m)
Jabberwocky	63	-37.78335	49.64987	40.8	2737.0
JiaoLong Palace	286	-37.78379	49.64964	20.5	2761.2
Ruyi Jingu Bang	55	-37.78270	49.64924	19.7	2734.9
Ryugo-jo	96	-37.78341	49.65011	25.7	2736.7
Fucanglong's Furnace	98	-37.78340	49.64918	52.2	2768.5

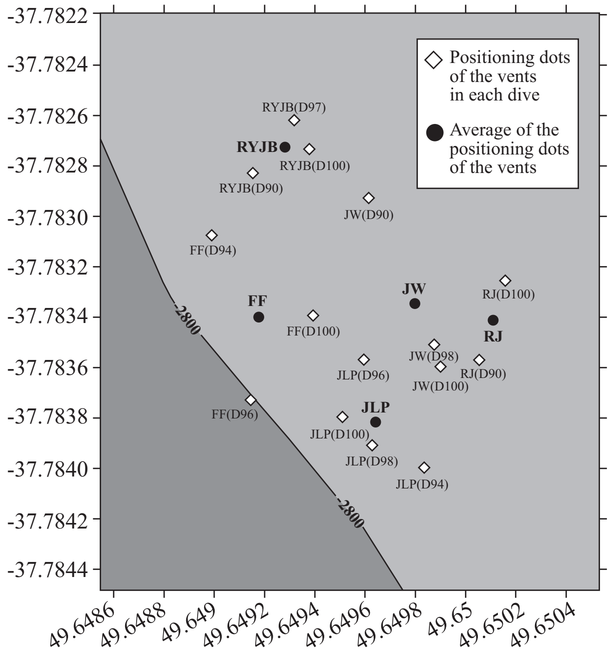

Fig. 2. Position dots and their average value of the hydrothermal vents in different dives of JIAOLONG.

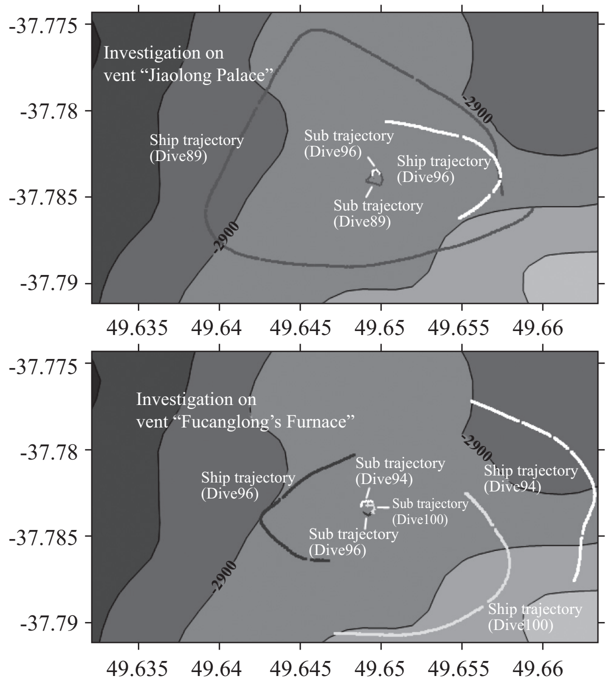

Fig. 3. The trajectories of the ship and the sub in Dive 89 and Dive 96 at the vent "Jiaolong Palace" (upper panel) and that in Dive94, Dive96 and Dive100 at the vent "Fucanglong's Furnace" (lower panel).

2. The Appearance of the USBL System Deviation and the Corresponding Verification Test

The position reading of each dive and the mean value for the vent were plotted for all vents on a single map (Fig. 2). This map reveals that the JIAOLONG's marked position varied among dives at the same vent, which is problematic in positioning the vents. This difficulty is approached by comparing the trajectories of the ship and the submersible (Fig. 3). These trajectories were captured for the time in which the submersible was stationary at the vent and the ship was moving. From this data, we noted that: 1. A line trajectory was got instead of a centralized set of dots during the time the submersible was not moving; and, 2. the trajectories of the ship and the submersible were highly correlated. Thus, it appeared that some systematic deviation in the USBL system is occurring.

To identify the deviation characteristics of the USBL system, the team of the Chinese Cruise 35th carried out a verification test of the USBL in the northwest of Longqi-1 Field. A USBL transponder was put into the water, and then the ship moved around it along designated circles and lines. three circles with radii of 600, 1000, and 1500 m were completed. Also, three straight lines were completed in the circles, as shown in Fig. 4 (upper panel). When the ship moved, the transponder seemed moving simultaneously, and formed similar trajectories as the ship but in a perpendicular direction. Accordingly, the USBL transponder's trajectory appeared as three circles and three lines (Fig. 4, lower panel). This verifies that the USBL system indeed has a systematic deviation.

III. THE ON-BOARD PROCESS AND CALIBRATION OF POSITIONING DATA

As none of the manufacturing staff or developers of the USBL system was on the ship, we could not recalibrate and debug the equipment for immediate correction. In addition, the cruise schedule did not permit taking time to resample the positioning data for each dive. So we had to find some calibration

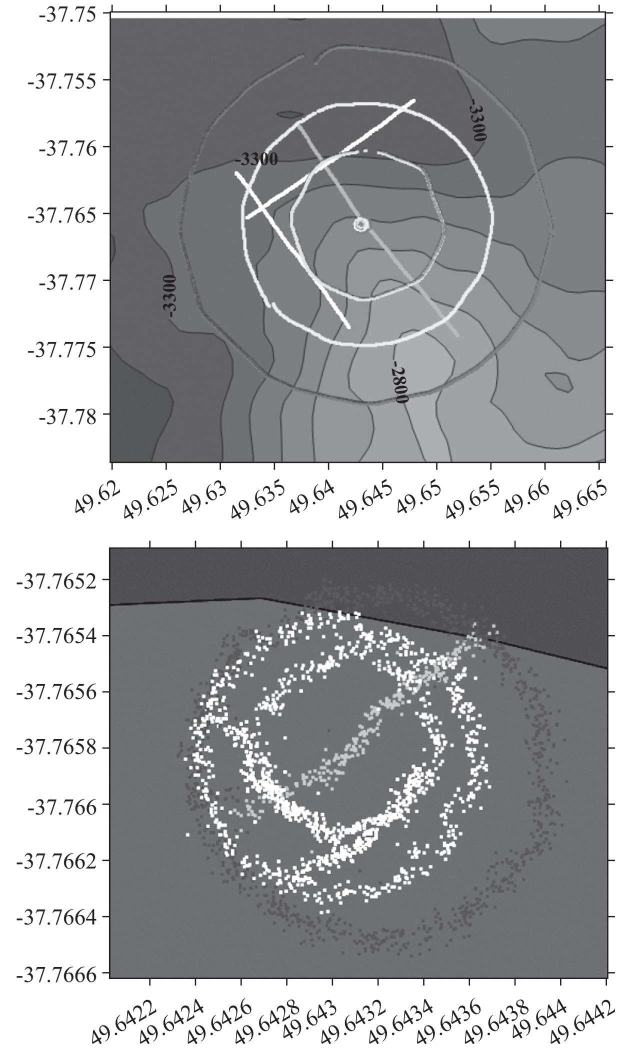

Fig. 4. The trajectories of the ship (upper panel) and the sub (lower panel) in the USBL verification test.

methods based on the data acquired already.

We calibrated the USBL positioning data using two steps. First, the calibrating direction was determined, and second, the calibrating distance was calculate.

1. The Calibrating Direction.

As shown in Fig. 3, the ship moved around the submersible during diving operation, and the ship trajectories approximately reflected the shape of an arc. An arc is a part of a circle or an ellipse, and an ellipse is a universal form of a circle. the submersible trajectories could be considered as corresponding to the segments of ellipses, with the center point of the ellipse as the true position of the submersible, which remains at the same location during vent sampling.

The center of an ellipse could be determined by fitting the ellipse using the trajectory dots. Denote the dots of the submersible trajectory as (x, y) and the center point of the ellipse as (x_0, y_0).Then, the analytic expression of the ellipse is:

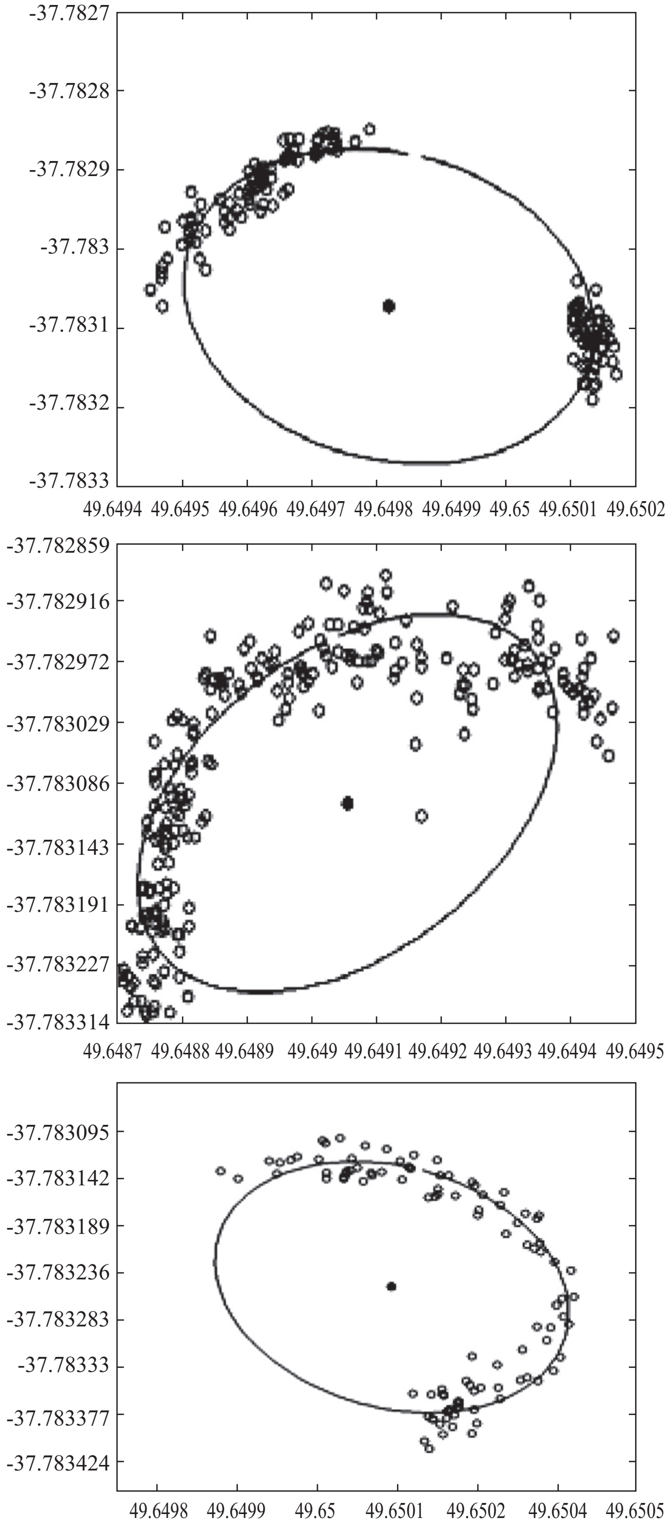

Fig. 5. The trajectory dots and their fitted ellipses in Dive90, Dive94 and Dive100.

$$\frac{(x-x_0)^2}{a^2}+\frac{(y-y_0)^2}{b^2}=1 \qquad (1)$$

Table 3. The radius of the trajectory circles in the USBL verification test.

The circle trajectory of the ship	Mean radius of the ship trajectory (R)	Mean radius of the transponder trajectory (r)	Radius difference between the ship and the transponder (d)
radius of 600 m	608.29 m	33.82 m	574.47 m
radius of 1000 m	1005.92 m	52.75 m	953.17 m
radius of 1500 m	1478.36 m	67.21 m	1411.15 m

where *a* and *b* are the long axis and short axis of the ellipse.

To fit the submersible's track, we used direct least square fitting of ellipses (Fitzgibbon, 1990), an ellipse fitting algorithm from image processing, to find the center point of the ellipse (x_0, y_0). Fig. 5 shows the trajectory dots, their fitted ellipses and the corresponding center point of "Jabberwocky" in Dive90, "Fucanglong's Furnace" in Dive94 and "Ryugo-jo" in Dive100.

The positioning dots collected were not always sufficient to map the full ellipse, providing a trajectory that is only a part of an ellipse. In actual situation, the shape of the ellipse could be easily disturbed by the ship trajectory and the calibrating distance was insufficient for calibration if we took only the center point of the ellipse. To solve this problem, the straight line that runs along the axis was used to decide the direction of the calibration, and then we took a second step to estimate the distance of the calibration.

2. The Calibrating Distance

In this step, we used the data acquired in the USBL verification test. The trajectory of the ship and the submersible in the test could be modeled by the big circle with the radius, *R* and the small circle with the radius, *r* (Fig. 6). Let the difference between them be $d = R - r$. In actual situation, we did not know the *R* and *r*, but knew the trajectories, and could get the difference *d*. Thus, the problem turned into finding the radius of the small circle *r* using *d*, which is the difference between the ship and submersible trajectories.

The verification test on the radius of the trajectory circles in the USBL is shown in Table 3. From the table, we found the correlation of *r* and *d* through numerical fitting according to the 4 dots (0, 0), (574.47, 33.82), (953.17, 52.75), (1411.15, 67.21). For simplicity, quadratic fitting was used, as shown in Fig. 7. Quadratic fitting of the 4 points in Fig. 7 leads to the following expression:

$$r = -d^2 \times 1.48772 \times 10^{-5} + 0.06889 \times d - 0.16189 \qquad (2)$$

The horizon distance between the ship and submersible was typically 400-500 m and the corresponding *r* was calculated according to the equation above. The calculation result was 25.01-53.85 m, which matched the range of the standard deviation on the horizon distance in different vents (25.7-52.2 m).

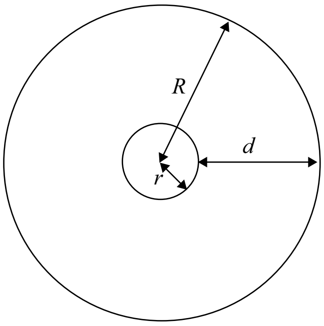

Fig. 6. The diagram of the trajectory circles of the ship and submersible.

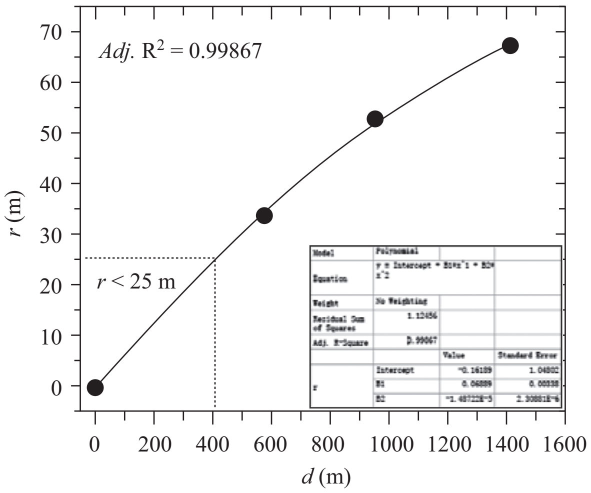

Fig. 7. The trajectories of the ship and the sub in the USBL verification test.

3. Calibration Procedure

Calibration requires the following five steps:

(1) Fit the ellipse using the positioning dots of the submersible.
(2) Calculate the direction of the major axis and minor axis of the ellipse; select the axis that is along the open direction of the trajectory of the dots, as the calibrating direction.
(3) Take the intersection of the selected axis and the ellipse as the start point; this point should be covered by, or close to, the positioning dots.
(4) Calculate the calibrating distance *r* of the start point using Eq. (1).
(5) Determine the calibrated point according to the starting point in step 3, the calibrating direction in step 2 and the calibrating distance *r* in step 4.

IV. RESULTS AND CONCLUSIONS

Applying the method described above, all the positioning dots of each vent in this leg of the cruise that had trajectories

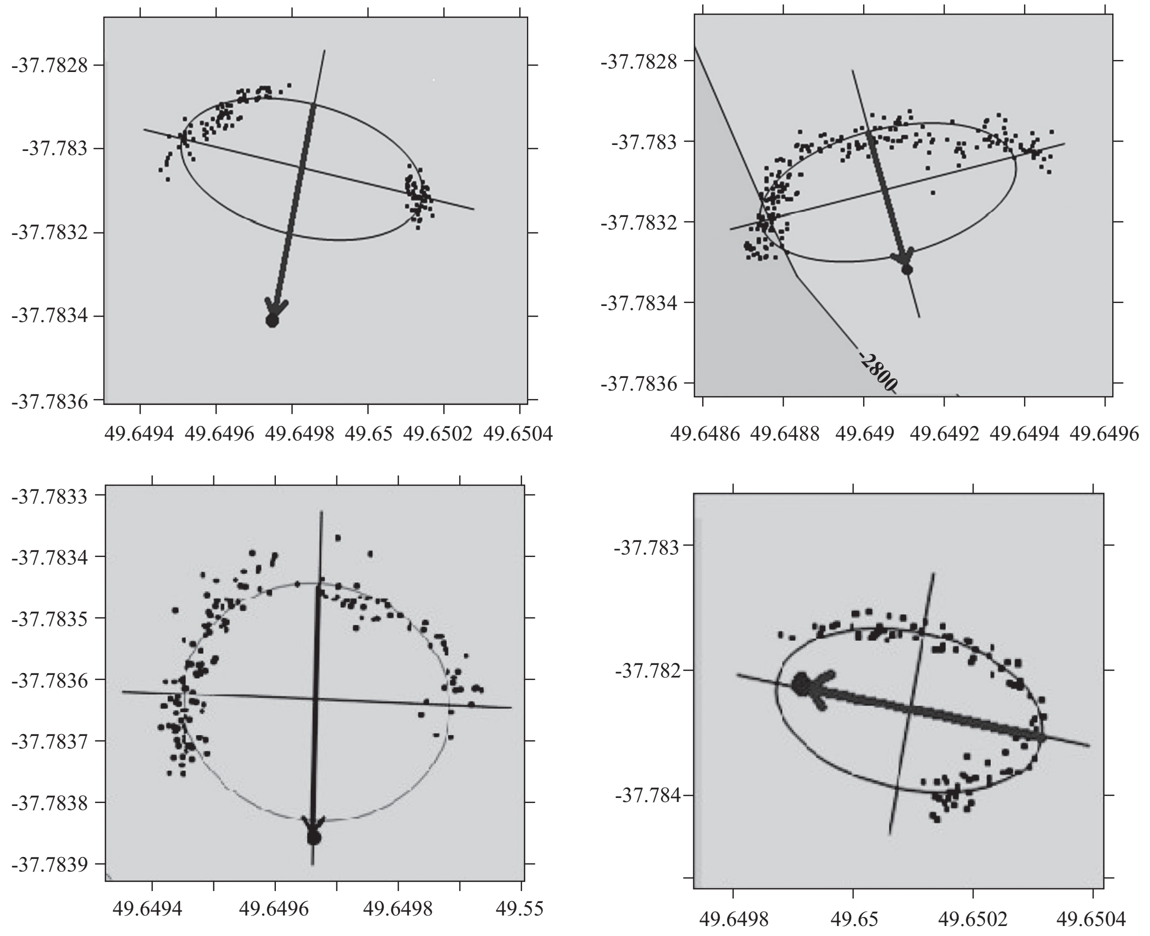

Fig. 8. The calibration process and result for "Jabberwocky" in Dive90, "Fucanglong's Furnace" in Dive90, "JiaoLong Palace" in Dive96 and "Ryugo-jo" in Dive100.

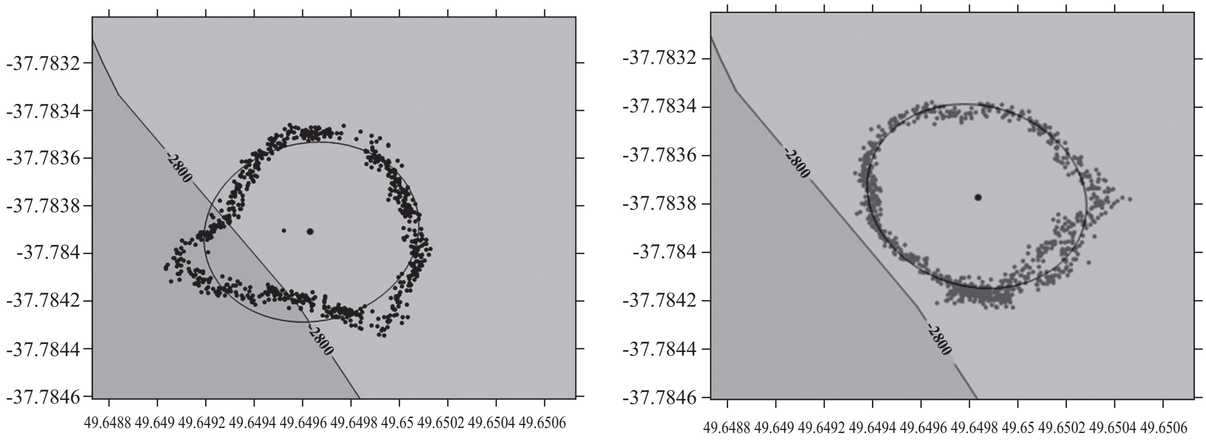

Fig. 9. The closed trajectories of "JiaoLong Palace" in dive 89 and dive 94.

were calibrated to form clear parts of ellipses. Fig. 8 demonstrates some examples of these calibration results, e.g., "Jabberwocky" in Dive90, "Fucanglong's Furnace" in Dive94 and "Ryugo-jo" in Dive100. We fit ellipses using direct least square, calculated the calibration distances using Eq. (1), and used the points at the end of line segments as the calibrated values of each vent position.

Two special cases should be noted here:

(1) the positioning data for "JiaoLong Palace" formed two separate closed curves for dive 89 and dive 94 (Fig. 9). Therefore, we used the center points of the two fitted ellipses as

Table 4. The coordinates and standard deviation of the calibrated positioning data.

Name of Vents	Positioning Result after Calibration		Comparison of Standard deviation	
	Latitude	Longitude	Before calibration	After calibration
Jabberwocky (JW)	-37.78329	49.64991	40.8m	19.1m
JiaoLong Palace (JLP)	-37.78383	49.64966	20.5m	13.6m
RuYi Jingu Bang (RYJB)	-37.78267	49.64930	19.7m	--
Ryugo-jo (RJ)	-37.78340	49.64985	25.7m	9.6m
Fucanglong's Furnace (FF)	-37.78356	49.64909	52.2m	16.1m
Average Value	--	--	31.8m	11.7m

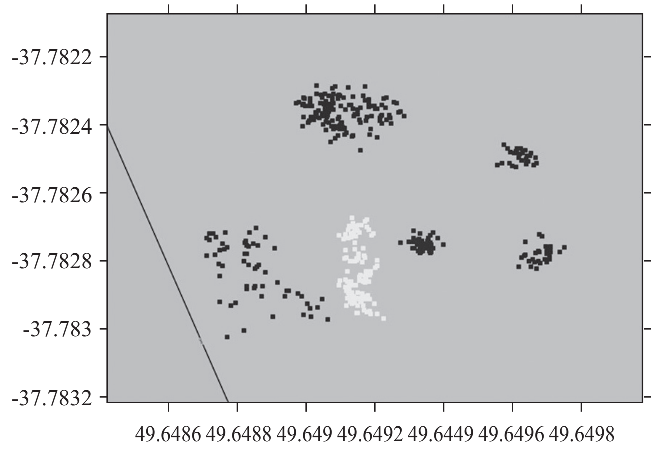

Fig. 10. The scattered trajectories of "Ru Yi Jingu Bang" in all the dives.

the final result instead of the direction and distance calibration method.

(2) For the vent "Ru Yi Jingu Bang," the JIAOLONG submersible did not maintain a stationary position over the vent during sampling and only hovered around it, so we had to use the time segment according to the diving record of the pilots/scientists and the videos/photos from the submersible. The dots selected are shown in Fig.10, and they are composed of some scattered dots or line segments. In this situation, we had no curve to use, so we calculated the average value of the dots, and did not carry out calibration for the position of "Ru Yi Jingu Bang."

All submersible trajectories of the dives for vents in Table 2 were calibrated; the mean value and standard deviation for all calibrated results are shown in Table 4. We also compared the location of the five vents between JIAOLONG's detection and JC67 report (Fig. 11). Although systematic and random errors existed in every measurement and every positioning system, the result of JC67 report provided us with a good reference for comparison with our calculation.

From Fig. 11 we can see that, the position of "Jabberwocky" and "JiaoLong Palace" did not change remarkably after calibration. "Fucanglong's Furnace" got closer to the location given in the JC67 report but in an different direction. The position of "Ryugo-jo" varied the most: it moved from east to west about

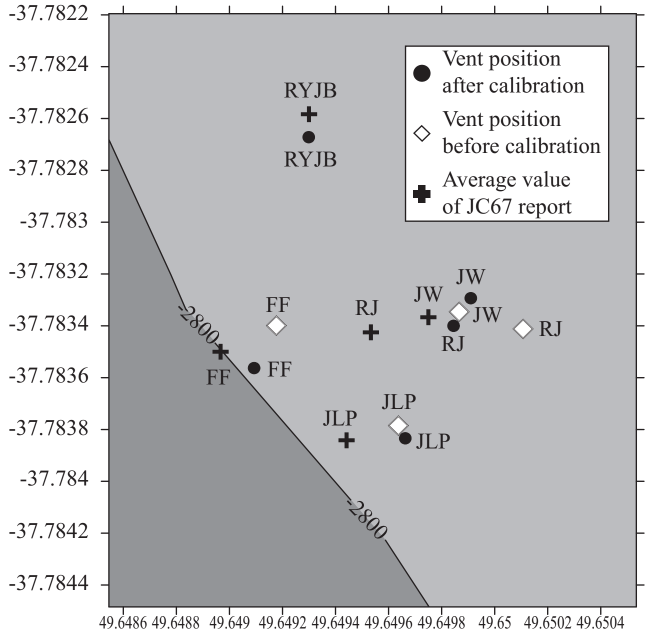

Fig. 11. Comparison of the 5 vents between the calibrated result of JIAOLONG and JC67 report

25 m, and, notably, changed its relative location with "Jabberwocky." According to the pilot and diving scientists that had personally visited the vent, "Ryugo-jo" is west of "Jabberwocky" and nearby. Moreover, Table 4 shows that the standard deviations for each vent in all dives become smaller after calibration, which indicates a better concentration of the same vent positioning dots across different dives. In this way, the estimated position range of the vent was reduced. In other words, the positioning became more precise after calibration, at least for the five vents discussed above. However, there was still an mean deviation of approximately 20 m between JIAOLONG's data and the JC67 report, which might be a result of both systematic and random errors in different USBL positioning systems and different diving operations. In fact, both results were observation values rather than the true values and they both carried bias.

This paper describes analysis of data obtained on the position of hydrothermal vents from the JIAOLONG manned submersible on the Southwest Indian Ridge. Although optimization on data processing was applied, certain technical constraints remain: Firstly, the statistical analysis was conducted after all 10 dives were finished, leaving us no ability to recollect positioning data for vents where the deviation of the positioning system was pronounced. Secondly, it was not possible to recalibrate, debug or make any changes to the positioning system during the cruise. Thus, the quality of our investigation results relied on the calibration method we applied. The work we present in this paper provides a valuable method for improving underwater positioning data in a similar scenario.

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