SCIENCE CHINA
Earth Sciences

•RESEARCH PAPER•

August 2018 Vol.61 No.8: 1148–1156
https://doi.org/10.1007/s11430-017-9187-3

Use of the Jiaolong manned submersible for accurate mapping of deep-sea topography and geomorphology

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Received April 13, 2017; revised January 3, 2018; accepted March 9, 2018; published online May 17, 2018

Abstract High-resolution bathymetric side-scan sonar (BSSS) performs the functions of traditional side-scan sonar, while also providing a depth-sounding function that allows simultaneous measurement of seafloor topography and geomorphology. Submarine microtopography and microgeomorphology detection ability and advanced underwater acoustic digital communication are important technical capabilities of the Jiaolong manned submersible. High resolution BSSS achieved accurate detection of seafloor topography and geomorphology at a depth of 7000 m, and successful mapping of local microtopography and microgeomorphology in the Mariana Trench.

Keywords Microtopography, Microgeomorphology, Manned submersible, Deep sea, High-resolution bathymetric side scan sonar, Jiaolong

Citation: Zhang T, Tang J, Li Z, Zhou Y, Wang X. 2018. Use of the Jiaolong manned submersible for accurate mapping of deep-sea topography and geomorphology. Science China Earth Sciences, 61: 1148–1156, https://doi.org/10.1007/s11430-017-9187-3

1. Introduction

Numerous fields require access to seafloor topography and geomorphology (e.g., scientific research, resource development, construction, and the military); the accurate mapping of maritime spaces and interpretation of data on maritime topography and geomorphology (including full sea depth topography detection and near-seafloor microtopography detection) are increasingly important (Jin, 2007; Zhao et al., 2009). Full sea depth topography detection refers to large-area voyage measurements using shipborne deep-water multi-beam sonar. Its main features are large spatial range and rapid data acquisition, making it especially suitable for large-area exploration of seafloor topography; however, it has limited accuracy in the measurement of deep-sea seafloor topography and geomorphology. In contrast, near-seafloor microtopography exploration provides accurate detection of the seafloor using multi-beam sonar, side-scan sonar, and bathymetric side scan sonar (BSSS) carried aboard various submersible types, including deep-tow (Xu et al., 2011; Liu et al., 2015; Cao et al., 2016; Tao et al., 2016), underwater robots (Tang, 2009), remotely controlled submersible (Luo et al., 2006; Xu et al., 2011) and manned submersibles (Liu et al., 2015). Compared with full sea depth topography detection, it can obtain more accurate microtopography and microgeomorphology of the seafloor.

In this paper, we describe the development of the Jiaolong manned submersible, China's first independently designed, independently integrated operational deep-sea manned submersible. The technological features of the Jiaolong are considered, and examples of their application are given. Finally, we describe the potential sources of error in microtopography detection, and the filtering and correction processes that can be applied to the data.

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2. Jiaolong manned submersible

2.1 Design and development

According to the database of the Manned Underwater Vehicles Professional Committee of the Marine Technology Society (MTS) of the United States, there are currently 16 manned submersibles with over 1000 m depth capacity in the world (Kohnen, 2013; Liu et al., 2015; Liu, 2016); these include the Alvin (4500 m; United States), Nautile (6000 m; France), Mir I and Mir II (6000 m; Russia), Shinkai 6500 (6500 m; Japan), and Jiaolong (7000 m; China).

The development of the Jiaolong manned submersible has been one of the major goals of Plan 863 during the China's 10th Five-Year Plan period (Liu et al., 2010). Through joint research by nearly 100 scientific research institutes across the country, the Jiaolong has progressed through the research and development stages of design, manufacturing, final assembly and connection, and pool functional tests. In early 2008, it met the technical criteria for sea trials. From 2009 to 2012, the Jiaolong completed sea trial missions of 1000, 3000, 5000 m (Cui et al., 2011) and 7000 m (Cui et al., 2012). To date, the maximum dive depth reached is 7062 m, which allows access to 99.8% of the ocean-bed on Earth. After successful completion of the 7000-m sea trial, the Jiaolong entered a test application stage, completing four test application voyages from 2013 to 2017 (COMRA 31, 35, 37 and 38). During this time, it carried out more than 100 successful submarine operations in the South China Sea, Northeast Pacific, Northwest Pacific, Southwest Indian Ocean, Northwest Indian Ocean, Yap Trench, and Mariana Trench. During these voyages, it collected a wealth of biological, geological, and sediment samples, and obtained a large volume of high-definition video data, fine topographic and geomorphological data, and on-site detection data. The success of these voyages demonstrated the unique advantages of Jiaolong deep-sea operations, and effectively promoted China's deep-sea science and technology development program.

Compared with other great-depth manned submersibles, the Jiaolong has four prominent technical highlights (Liu et al., 2013; Zhu et al., 2014):

(1) maximum operation depth of 7000 m;

(2) advanced maneuverability and sailing control ability;

(3) advanced underwater acoustic communications and undersea micromorphology and microgeomorphology detection capabilities;

(4) high-security functionality.

The Jiaolong can carry three people (one pilot and two scientists). It consists of structural, hydraulic, control, acoustic, and other systems, not only capable of photography, video recording, and accurate mapping of seafloor topography and geomorphology, but also of obtaining seafloor water samples, sediments, and biological samples by use of mechanical hands and other tools.

2.2 Bathymetric side scan sonar system

2.2.1 Applications of BSSS

As electromagnetic waves attenuate rapidly in seawater, sound waves have become the primary means of detection and information transmission in the water. The technical capabilities of the Jiaolong acoustic systems include 16 sonars in 9 categories (Zhu et al., 2014); namely, two Acoustic Communication Sonars (ACS), one Acoustic Phone, one Ultra-Short BaseLine Sonar (USBL), one Long BaseLine Sonar (LBL), one BSSS, one Imaging Sonar, one Doppler Velocity Log (DVL), seven Obstacle Avoidance Sonars (OAS), and one Altimeter (Figure 1).

BSSS is mainly used for obtaining data on microtopography and microgeomorphology; USBL and LBL provide navigation and positioning data, which are essential for topographical and geomorphological mapping; underwater acoustic communication devices transmit positioning data obtained by USBL to the supporting mother ship at the surface, allowing for determination of the initial position of the integrated navigation system; DVL provides information on submersible velocity for combined navigation. In addition, motion sensor provide data on posture and heading, which are used to supplement BSSS data; the conductivity-temperature-depth (CTD) system provides sound velocity data for correction of BSSS detection data; and the high-accuracy depth meter provides depth data of the submersible (i.e., depth of BSSS). When combined with topographic data from the BSSS, the absolute depth of the seafloor can be determined.

The BSSS setup on the Jiaolong is unique among comparable deep-sea submersibles; its transducers (Zhu et al., 2003; Zhu et al., 2006; Sun et al., 2009) are mounted on both sides of the manned submersible (Figure 1), enabling them to measure microtopography and microgeomorphology of the seafloor, and construct three-dimensional maps of chosen sites. The BSSS is capable of mapping complex areas of seafloor by determining the height of the target, making it ideal for surveying cobalt crust regions and for measuring the geometric dimensions of hydrothermal chimneys.

2.2.2 Basic principles of BSSS

BSSS was first developed by the Institute of Acoustics of the Chinese Academy of Sciences and adopts advanced multi-subarray seafloor automatic detection (i.e., signal parameter estimation technology of the signal subspace), enabling it to distinguish echoes arriving simultaneously from different directions in order to automatically detect the seafloor. BSSS was developed to realize simultaneous measurements of seafloor geomorphology and topography through a combination of side-scan and multi-beam depth-sounding tech-

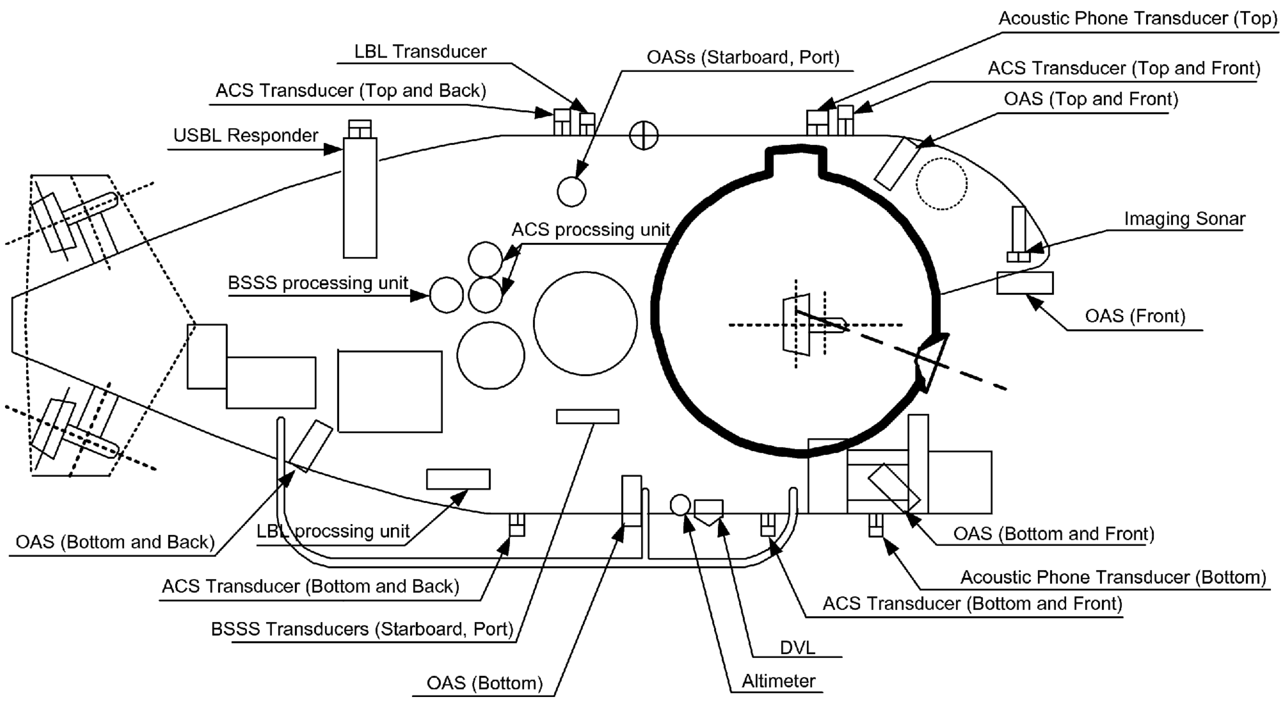

Figure 1 Layout of acoustic systems aboard the Jiaolong manned submersible (Zhu et al., 2014).

nologies. The first stage of technological development was low-resolution acoustic interference. During the second stage of development, differential phase technology provided improved resolution, but only allowed for measurement of one target at a same time, could not measure complex seafloor, and could not work under multi-path signal conditions. During the third stage of development, high-resolution three-dimensional acoustic imaging technology was introduced. By applying the subspace fitting method, simultaneous measurement of multiple targets, measurement of complex seafloor areas, and measurements under severe multi-path signal conditions was achieved; at the same time, the amplitude and phase of signal θ_m was made possible.

The current iteration of BSSS uses multiple receiving arrays to measure the arrival angle of seafloor echoes, obtaining water depth from a sonar detecting site. Among its advantages are a relatively long operating distance, high-resolution, small sonar arrays, and low energy consumption. Figure 2 shows a schematic diagram of the working principles of BSSS, where T1 is the transmitting transducer, R1–R8 are eight receiving transducer units, and the sonar front normal is at a 30-degree angle above the horizontal plane. The directions of seafloor echoes are calculated by analyzing the phase difference of each received signal; the seafloor position can be obtained with combination of the two.

The BSSS system is small, light-weight, and has low power consumption, making it especially suitable for installation on deep-tow, underwater robots, remotely controlled submersibles, and manned submersibles.

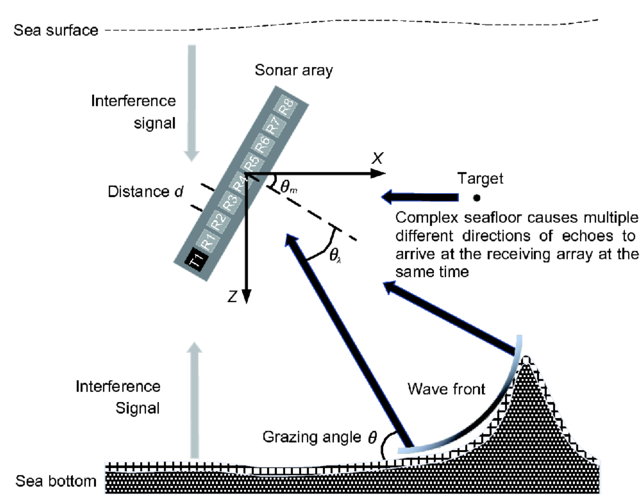

Figure 2 Schematic diagram detailing the working principles of bathymetric side-scan sonar (BSSS).

2.2.3 *BSSS system composition*

The BSSS system is divided into two parts, one installed in the manned cabin (i.e., the master controller unit) and the other installed outside of the manned cabin (i.e., the electronic cabin, port side transducer array, starboard side transducer array, and subsidiary sensors).

The major axis of the BSSS transducer array must be parallel to the major axis of the submersible. The transducer surface normal must have a 30° angle above the horizontal plane. In addition, as deformation of the mounting bracket must be minimized during lifting to avoid damaging the transducer array, it is installed between submersible stations 4 and 5. In this cylindrical part of the submersible, the transducer array has a better line-type after installation; the mounting bracket is independent of the load-bearing frame, thereby reducing the impact of the frame deformation on the transducer.

3. Factors affecting mapping and detection results

In general, when using small-carrier submersibles (e.g., deep-tow and autonomous underwater vehicles; AUV) to carry multiple-beam seafloor microtopography measurements, the factors affecting data quality fall into five categories: horizontal positioning accuracy, vertical positioning accuracy, depth-sounding accuracy, sensor time uniformity, and sensor location uniformity. Large-scale manned submarines (e.g., the Jiaolong) have different characteristics, including poor stability in posture control, BSSS transducer port and starboard installations, and wide spacing. By processing BSSS detection data collected by the Jiaolong manned submersible, we found that the factors most affecting mapping quality were submersible posture, port and starboard positions of BSSS transducers, and navigation accuracy.

3.1 Effect of submersible posture on detection mapping

According to the No. 44 Special Publication of the International Hydrographic Organization (5th ed.; IHO S-44 5th), under a condition of 95% confidence, the special-grade standards for seafloor microtopography detection and mapping require a depth-sounding accuracy of 0.25 m and a depth of 0.75%; grade 1 standards require 0.5 m and 1.3%. In addition to the sound velocimeter and BSSS, depth-sounding accuracy is also affected by the optical fiber compass, which includes three components (heading, pitch, and roll angle), of which the depth-sounding accuracy of BSSS is most sensitive to roll angle. For example, at an operating distance of 250 m and a height of 50 m, accuracy of 0.5% requires that the accuracy of the roll angle sensor should be 0.06 degree; if the roll angle sensor accuracy is 0.1 degree at 50 m height from the bottom, an overall accuracy of 0.5% requires an operating distance 143 m. Finally, the stability of submersible posture control is relatively poor, being affected by both the streamline and manual control of the submersible; therefore, submersible posture also has a significant impact on BSSS detection results.

Taking the exploration of seafloor microtopography at a cold spring area as an example, the importance of roll angle filtering to improve depth-sounding quality is illustrated in Figure 3. Figure 4 shows roll angle, pitch angle, and heading angle change curves for submersible posture recorded by BSSS. For roll angle, the periods of greatest instability show a one-to-one correspondence with the most distorted areas of the seafloor topography map (Figure 3a); however, there is no relationship between map distortion and either pitch or heading angle.

To reduce the influence of roll angle instability on mapping quality, median filtering and smoothing are performed (Figure 3b), removing some (but not all) of the distortion in the seafloor maps.

3.2 Effect of port and starboard positions on detection and mapping

Seafloor microtopography detection involves multiple sensors, including the long baseline, ultra-short baseline, Dop-

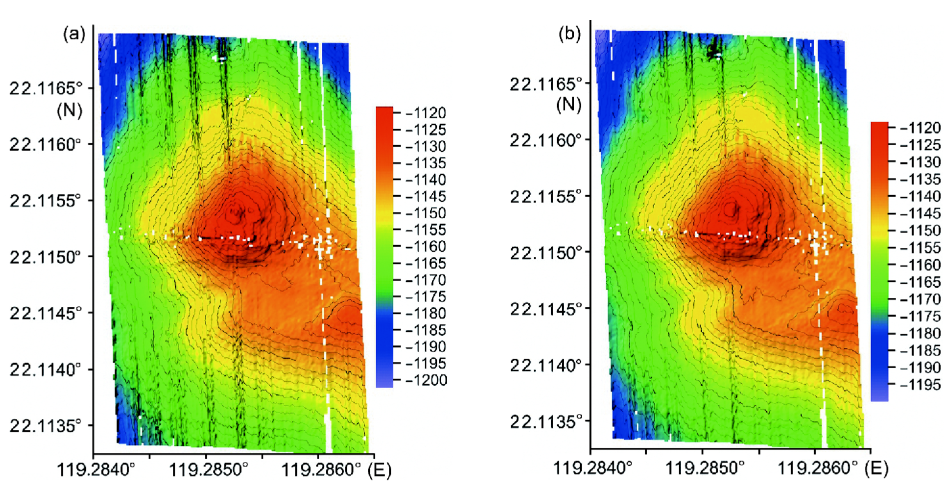

Figure 3 Seafloor topography around the peak of a cold spring area. (a) Map using raw data; (b) map using data to which filtering and smoothing have been applied to the roll angle.

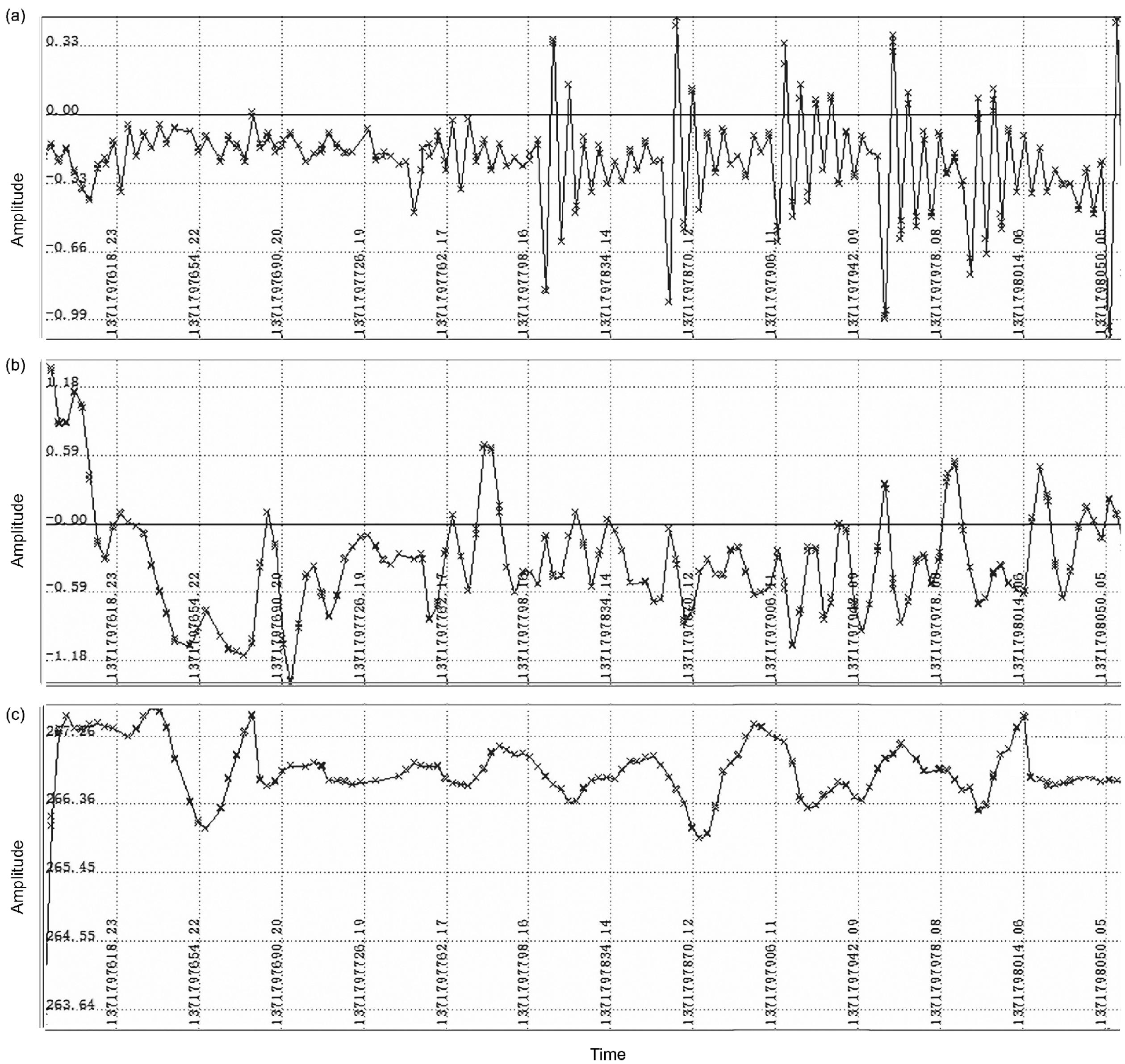

Figure 4 Temporal change curves for (a) roll angle, (b) pitch angle, and (c) heading angle. Recorded by BSSS.

pler odometer, optic fiber compass, and BSSS transducer arrays. Accurate knowledge of sensor coordinates relative to the origin of the coordinates is critical, as is awareness of the installation errors. For multi beams, a T-type transducer array is generally used; it is installed right below the underwater mobile carrier. For BSSS, two parallel transducer arrays are generally used; they are installed on port and starboard positions of the underwater mobile carrier. Owing to the small radial dimension of AUV or deep-tow vehicles, when BSSS transducer arrays are installed, the spacing between the two transducer arrays is relatively small (~0.5 m). However, the Jiaolong manned submersible is significantly larger and the two BSSS transducer arrays installed on its abdomen are ~2.46 m apart. The BSSS searches for the seafloor via both the port and starboard arrays, and uses these data as the baselines for calculating depth-sounding results. When BSSS is used to detected angled terrain (i.e., slope), a large spacing between transducer arrays results in significant differences in seafloor detection results (Figures 5 and 6).

Figure 5 shows depth-sounding results from a single-frame line measurement of sloped terrain in a cold spring area, with and without a compensation for the 30° mounting angle of port and starboard sonar array. It is clear that seafloor data from the port and starboard sides are not the same. Directly combining these data would result in poor quality seafloor topography maps for areas directly beneath the sonar arrays; therefore, accurate mapping requires a data correction step to compensate for the difference.

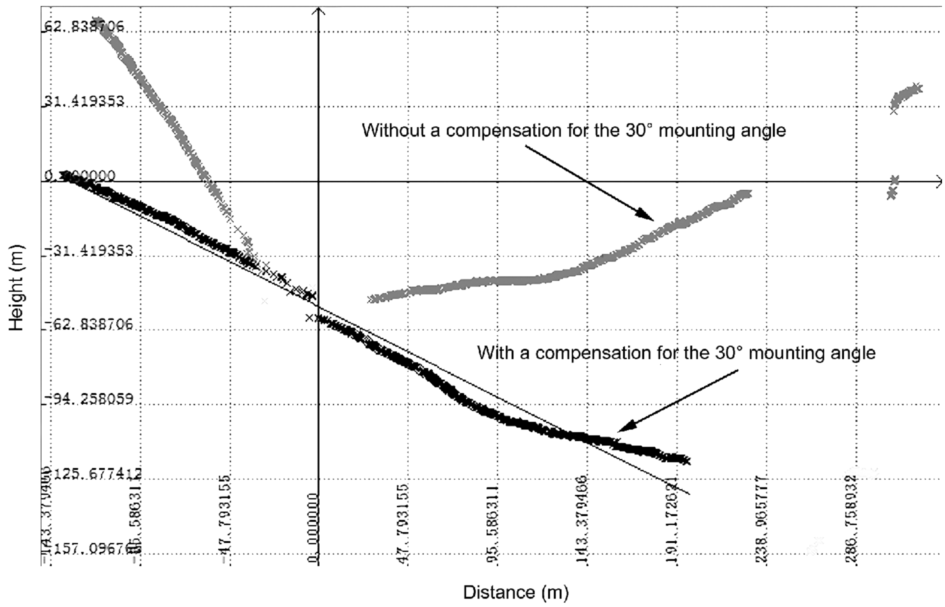

Figure 5 Depth-sounding results for a single-frame line measurement along sloped terrain in a cold spring area. The gray dotted line indicates data for which without a compensation for the 30° mounting angle of port and starboard sonar arrays, respectively; the black dotted line indicates data for with a compensation for the 30° mounting angle.

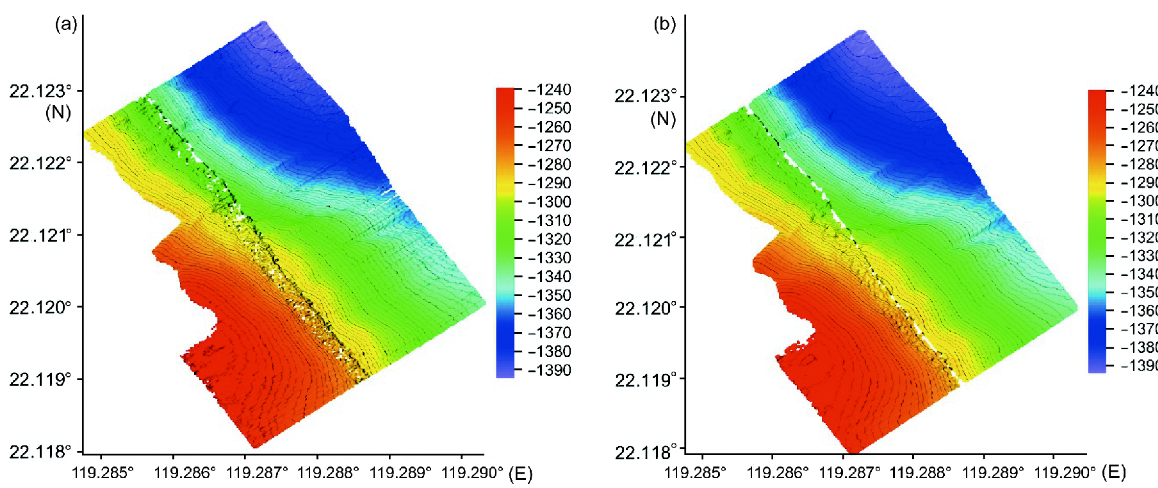

Figure 6 Seafloor microtopography maps of sloped terrain in a cold spring area. (a) Map constructed using data where the spacing between the port and starboard sonar arrays is not taken into account; (b) map constructed using data where the spacing between the port and starboard sonar arrays is taken into account.

Figure 6 shows seafloor microtopography around the cold spring area with and without a correction for the spacing between port and starboard sonar arrays. When the spacing is not considered, mapping quality of depth-sounding results for regions directly beneath the BSSS transducer arrays is poor, and the transition between the port and starboard is not ideal (Figure 6a). To compensate, during post-processing, the installation spacing of the port and starboard transducer arrays are considered, and the port and starboard results are first extracted separately and then combined (Figure 6b); this ensures that the transition between port and starboard seafloor microtopography maps is relatively smooth, which in turn improves the mapping quality.

3.3 Effect of navigation accuracy on detection and mapping

The mean horizontal positioning accuracy (i.e., the vertical track resolution) is 5 cm, and the track resolution is related to the angle, which ranges from 0.5 to 5 m. Taking this into account, and according to the No. 44 Special Publication of the International Hydrographic Organization (5th ed.; IHO S-44 5th), under a condition of 95% confidence, the special-grade standards for positioning accuracy of seafloor microtopography detection and mapping require 2 m, and grade 1 standards require 5 m+5% depth. The main sensors involved in horizontal positioning are long baseline, ultra-short baseline, Doppler log, and the optic fiber compass. The static positioning accuracy of the long baseline is 2.5 to 5 m; the dynamic positioning accuracy is lower than the static positioning accuracy and is related to the sound velocity profile, topography, calibration, signal-to-noise ratio, and other factors. The positioning accuracy of ultra-short baseline is about 0.2–0.5% the slope distance and is related to the sound velocity profile, GPS, and signal-to-noise ratio, among other factors. The accuracy of the Doppler log depends on the sound velocity, the installation declination angle, the speed deviation, and the signal-to-noise ratio; the accuracy of optic fiber compass is related to latitude and speed.

The effect of navigation accuracy during BSSS detection is illustrated in Figure 7, which shows a map produced by combining data from the two measuring lines for the peak area of a cold spring area. In this map, no long-baseline positioning system was used; instead, ultra-short baseline positioning data was used as the navigation data. The results show that seafloor topography could not be well defined because the ultra-short baseline does not satisfy the data combination requirements of BSSS.

To further analyze the navigation accuracy of submersibles, it is necessary to choose data from a dive where the long baseline positioning system was working normally. For this purpose, data from another dive were chosen as being representative because: (1) during the dive, the long baseline positioning system was working normally and the positioning accuracy was high; (2) during the normal working process of the long baseline positioning system, the sailing track of the submersible was relatively diversified with straight line and turning. Figure 8 shows the results of LBL, USBL, Shenyang Institute of Automation (SIA) navigation and dead reckoning navigation during the dive operation. According to the sea trial, LBL provided the most reliable positioning results for the submersible under the water. The navigation results from USBL did not meet the

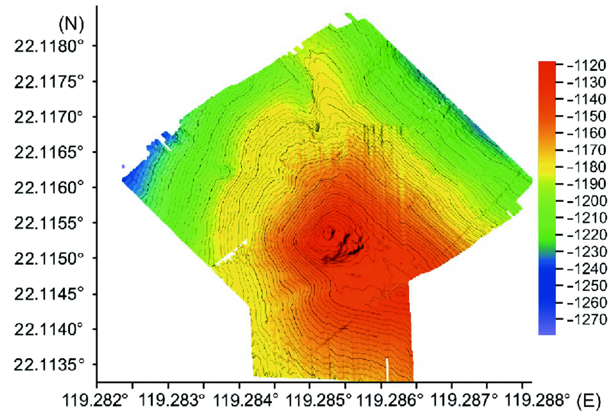

Figure 7 Map produced by combining data from two measuring lines around the peak of a cold spring area.

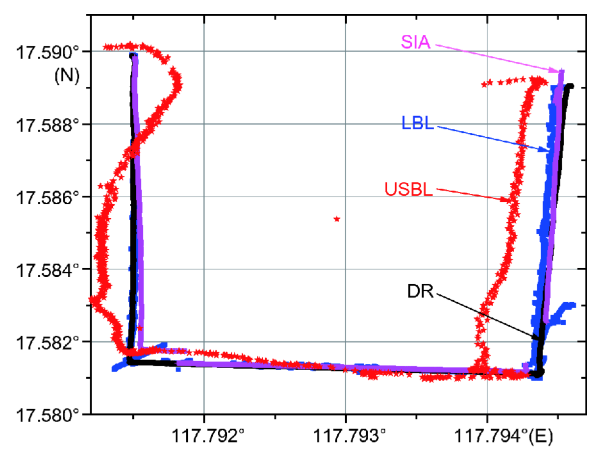

Figure 8 LBL, USBL, SIA, and dead reckoning navigation during a dive operation.

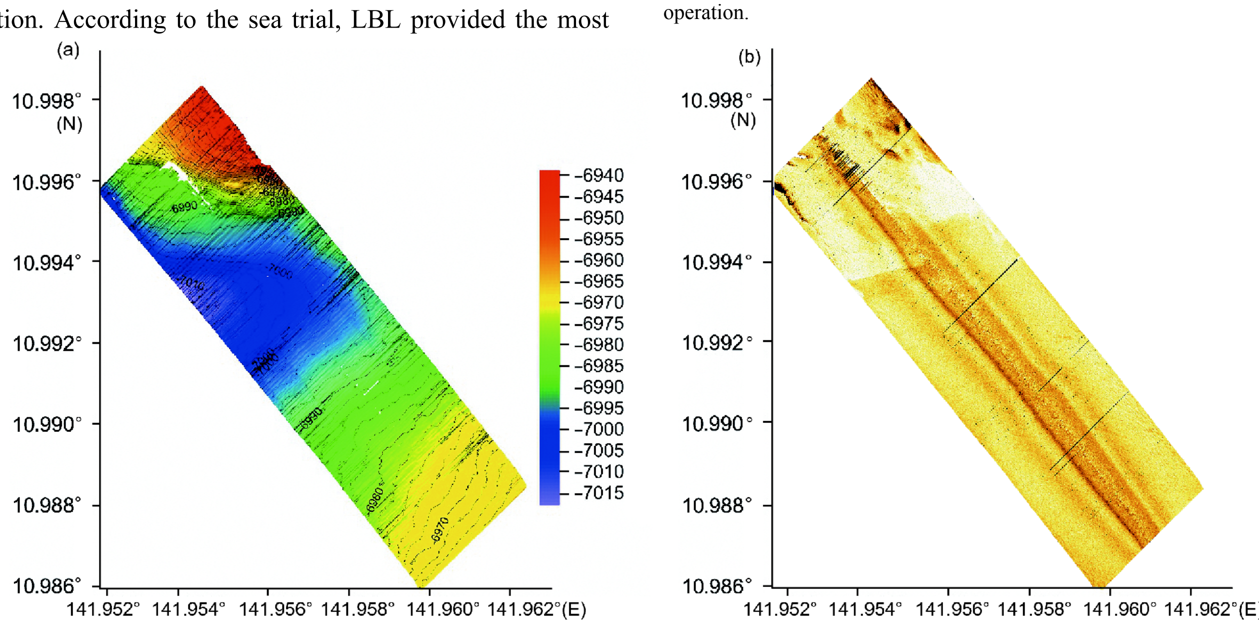

Figure 9 Seafloor (a) microtopography and (b) microgeomorphology maps obtained by the Jiaolong BSSS on a 7000-m sea trial.

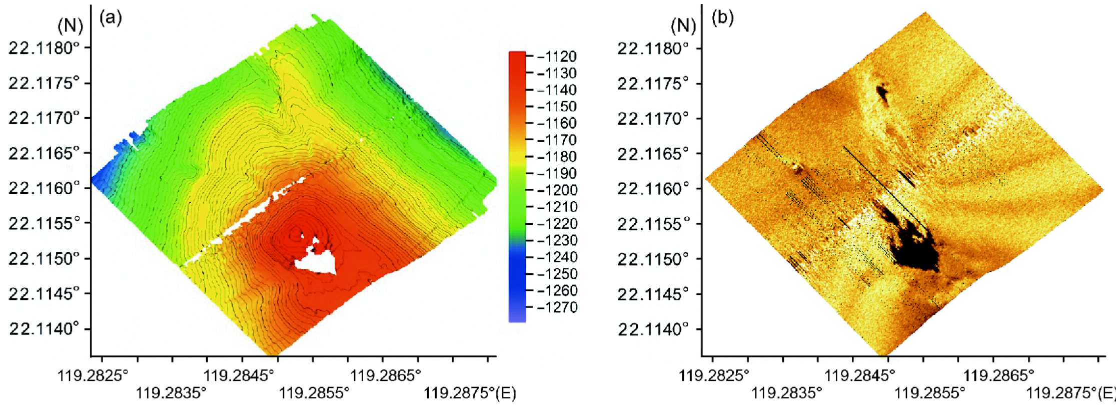

Figure 10 Seafloor microtopography (a) and microgeomorphology maps (b) obtained by the Jiaolong BSSS on a dive around the peak of a cold spring area.

requirements for BSSS. The SIA and dead reckoning method described the submersible track with considerable accuracy; however, the error gradually increased with time, especially after the second turning point.

4. Typical detection results

Sea-trials have shown that the Jiaolong BSSS can produce high-resolution microtopography and microgeomorphology data; isobaths can be displayed at 2 m intervals, and many seafloor details are clearly distinguished (Figures 9 and 10). Furthermore, comparison of side-scan and topography maps can yield additional information.

5. Conclusions

The Jiaolong is China's first independently designed, independently integrated operational deep sea manned submersible; it has a maximum dive depth of 7000 m, the deepest of any manned submersible in the world. Jiaolong is equipped with high-resolution BSSS developed by the Institute of Acoustics of the Chinese Academy of Sciences; together with an underwater acoustic communication device, the BSSS represents one of four technical strengths of the Jiaolong manned submersible.

The BSSS combines the functionality of traditional side scan sonar with a depth-sounding function, allowing simultaneous measurement of seafloor topography and geomorphology. In combination, side-scan and topographical maps of marine features can provide a wealth of information.

The Jiaolong BSSS mapping quality for seafloor microtopography and microgeomorphology measurements is mainly influenced by the posture of submersible, the installation position of the transducer arrays on the port and starboard sides, and by the navigation accuracy.

Acknowledgements *This work was supported by the National Key R&D Program of China (Grant No. 2017YFC0305700), the Qingdao National Laboratory for Marine Science and Technology (Grant No. QNLM2016ORP0406), the National Natural Science Foundation of China (Grant No. 41641049), the Taishan Scholar Project Funding (Grant No. TSPD20161007), the Shandong Provincial Natural Science Foundation (Grant No. ZR2015EM005), the Shandong Provincial Key R&D Program (Grant No. 2016GSF115006), and the Qingdao Independent Innovation Project (Grant No. 15-9-1-90-JCH).*

References

Cao J L, Liu X D, Zhang F S, Li Q, Zhang D S, Wang H Y. 2016. Application of DTA-6000 acoustic deep-tow system to cobalt-rich crust investigation (in Chinese). Mar Geol Quat Geol, 36: 173–181

Cui W C, Liu F, Hu Z, Zhu M, Guo W, Liu C G. 2012. 7000 m sea trials test of the deep manned submersible "Jiaolong" (in Chinese). J Ship Mech, 16: 1131–1143

Cui W C, Liu F, Hu Z, Zhu M, Guo W, Wang C S. 2011. 5000 m sea trials test of the deep manned submersible "Jiaolong" (in Chinese). Shipbuilding of China, 52: 1–14

Jin X L. 2007. The development of research in marine geophysics and acoustic technology for submarine exploration (in Chinese). Prog Geophys, 22: 1243–1249

Kohnen W. 2013. Review of deep ocean manned submersible activity in 2013. Mar Technol Soc J, 47: 56–68

Liu B H, Ding Z J, Shi X P, Yu K B, Li D W, Li B G. 2015. Progress of the application and research of manned submersibles used in deep sea scientific investigations (in Chinese). Acta Oceanolog Sin, 37: 1–10

Liu F. 2016. Technical status and development trend of the deep-sea manned submersible (in Chinese). J Eng Stud, 8: 172–178

Liu F, Cui W C, Li X Y. 2010. China's first deep manned submersible, JIAOLONG. Sci China Earth Sci, 53: 1407–1410

Liu K Z, Zhu P Q, Zhao Y, Cui S G, Wang X H. 2013. Research on the control system of human occupied vehicle "Jiaolong". Chin Sci Bull, 58: 40–48

Liu X D, Zhao T H, Cao J L, Wang Z B, Hou D Y, Zhang D S. 2015. General scheme analysis of the lightweight acoustic deep-tow system for gas hydrate exploration (in Chinese). Mar Geol Front, 31: 8–16

Luo B W, Pao Y Y, Zhou Z J, Liu J. 2006. Explorative study on short range exploration method for deep-sea cobalt crust tiny terrain (in Chinese). Metal Mine, 41: 15–19

Sun Y J, Liu X D, Zhang F S, Qiu Z Q. 2009. High resolution bathymetric side scan sonar system in shallow water and its application on the sea (in Chinese). Ocean Eng, 27: 96–102

Tang M Q. 2009. New technology of deep sea mapping based on AUV (in

Chinese). National Surveying and Mapping Science and Technology Information Exchange Conference and the First Survey Blog Essay Awards Proceedings. 856–863

Tao H, Luo J H, Li Y J, Nie M T. 2016. Research of deep-tow operation in deep-sea of rough seabed (in Chinese). J Waterway Harbo, 37: 213–216

Xu J, Zheng Y L, Bao G S, Wu X W, Zhang K, Jin X B. 2011. Research of seamount micro-topography based on acoustic deep-tow system investigation: A case from the Marcus-Wake Ridge area (in Chinese). J Mar Sci, 29: 17–24

Xu J K, Wang Y J, Hou B K, Yang L H. 2011. Technical status and development trend of ROV (in Chinese). J Ord Equip Eng, 32: 25–27

Zhao J H, Li J J, Li M. 2009. Progress and future trend of hydrographic surveying and charting (in Chinese). J Geomatics, 34: 25–27

Zhu M, Zhang T W, Yang B, Liu Y Y, Tang J L. 2014 Sonar system of Jiaolong human-occupied vehicle (in Chinese). Chin Sci Bull, 59: 3462–3470

Zhu W Q, Liu X D, Zhang D S, Zhang F S, Qin G L, Liao Z, Fang C L. 2006. High resolution bathymetric side scan sonar (in Chinese). Ocean Technol, 24: 29–35

Zhu W Q, Zhu M, Liu X D, Pan F, Zhang X J, Wang Y L. 2003. The survey system for detailed relief on sea floor (in Chinese). Hydrographic Survey Chart, 23: 27–31

(Responsible editor: Xixi ZHAO)