Chapter

Advanced Mapping of the Seafloor Using Sea Vehicle Mounted Sounding Technologies

Tongwei Zhang, Baohua Liu and Xiaodong Liu

Abstract

A large proportion of the Earth's surface is the deep sea. Numerous fields require access to seafloor topography and geomorphology. With the emergence of different types of underwater vehicles, especially the commercialization of near-seafloor micro-topographical mapping sonars, near-seafloor micro-topographical detection in the deep sea is possible. Near-seafloor micro-topographical exploration allows accurate detection of the seafloor using multibeam echosounder, side-scan sonar, and bathymetric side-scan sonar carried on-board various vehicles, including deep-tow, autonomous underwater vehicles, remotely operated vehicles, and human-occupied vehicles. Near-seafloor micro-topographical detection can obtain more accurate micro-topography and micro-geomorphology of the seafloor compared to full sea depth topographical detection. In this chapter, the basic principles of three types of near-seafloor micro-topographical mapping sonars are analyzed. Then, four types of underwater vehicles that are suitable for near-seafloor micro-topographical mapping are briefly discussed. Factors affecting mapping and detection results are presented using the Jiaolong human-occupied vehicle and its bathymetric side-scan sonar as an example. Next, the entire data processing and mapping methods are described. Finally, two typical detection results obtained by the Jiaolong bathymetric side-scan sonar in deep-sea are given.

Keywords: topography, geomorphology, deep sea, underwater vehicle, mapping sonar

1. Introduction

The ocean accounts for about 71% of the Earth's surface area and is the largest potential resource base on the Earth that has not been fully recognized and utilized by humans. There are extremely rich biological and mineral resources in the ocean. The deep sea is the lowest layer in the ocean, existing below the thermocline, at a depth of 1800 m or more [1]. Deep sea areas with a depth of more than 2000 m account for 84% of the ocean area. Therefore, the surface of the earth is mostly deep sea. The hypsometric profile of the ocean is shown in **Figure 1**.

Scientific research, resource development, engineering construction, and military activities around the ocean usually require accurate acquisition of seafloor topographical information in the area of interest as the basis for data and support. Therefore, understanding ocean topographical information, mapping ocean

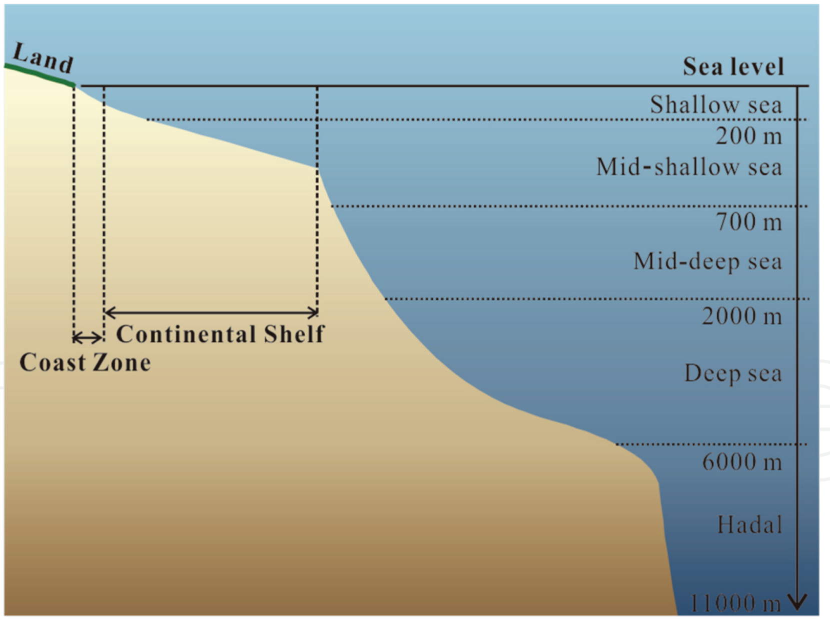

Figure 1.
Hypsometric profile of the ocean.

topographical and geomorphological information effectively, and how to obtain ocean topographical information map have become important issues in the current development of marine resources and marine space utilization [2]. In particular, marine topographical information is of immense value in marine space utilization.

Topography involves the recording of terrain, the three-dimensional quality of the surface, and the identification of specific landforms. It is often considered to include the graphic representation of the landform on a map by a variety of techniques, including contour lines, hypsometric tints, and relief shading [3]. Geomorphology is the branch of science that studies the characteristics and configuration and evolution of rocks and landforms [4]. In the ocean, seafloor topography is measured by multibeam echosounder (MBE), and seafloor geomorphology is measured by side-scan sonar (SSS).

Deep sea topographical exploration mainly includes full sea depth topographical detection and near-seafloor micro-topographical detection. The advantage of full sea depth topographical is large spatial range and rapid data acquisition, and the disadvantage is limited accuracy. In contrast, near-seafloor micro-topographical exploration provides accurate detection of the seafloor using MBE, SSS, and bathymetric side-scan sonar (BSSS) carried on-board various underwater vehicles, including deep tow (DT) [5], autonomous underwater vehicle (AUV) [6], remotely operated vehicle (ROV) [7], and human occupied vehicle (HOV) [8–10]. It can obtain more accurate micro-topography and micro-geomorphology of the seafloor compared to full sea depth topographical detection.

In this chapter, the basic principles of three types of near-seafloor micro-topographical mapping sonars are analyzed. Then, four types of underwater vehicles suitable for near-seafloor micro-topographical mapping are briefly discussed. Next, factors affecting mapping and detection results are presented using the Jiaolong HOV and its BSSS as an example. Finally, the entire data processing and mapping methods are presented.

2. Near-seafloor micro-topographical mapping sonars

Three types of seafloor mapping sonars, which can be mounted of deep sea vehicles, are the multibeam echosounder (MBE), and the side-scan sonar (SSS) and the bathymetric side-scan sonar (BSSS).

2.1 Multibeam echosounder

An MBE works by transmitting a wide-sector-covered sound wave to the seafloor using a transmitting transducer array, and the narrow-beam receives the sound wave using a receiving transducer array. The footprints of the seafloor topography are formed by the orthogonality of the transmission and reception sectors, and these footprints are properly processed. A ping can indicate the water depth values of hundreds or even more seafloor measured points in the vertical plane perpendicular to the heading. Therefore, it is possible to accurately and quickly measure the size, shape, and height variation of underwater targets within a certain width of the route, and to reliably depict the three-dimensional features of the seafloor topography. The basic principle of an MBE is shown in **Figure 2**.

The beamforming method of MBE can be divided into two types: beam steering method (measuring the round-trip time of the reflected signal at a specific angle) and coherent method (measuring the angle of the reflected echo signal at a specific time). There are two main variables to be measured in an MBE, namely the slant distance or the distance from the acoustic transducer to each point on the seafloor and the angle from the transducer to the bottom of the ocean. All MBEs use one or both beamforming methods to determine these variables. At present, MBE manufacturers using beam steering method include Reson, Kongsberg, ATLAS, L3, and R2Sonic, whereas manufacturers using coherent method include Teledyne Benthos and Geoacoustics.

For large-area exploration of seafloor topography, shipborne deep-water MBE can be used to obtain relatively accurate seafloor topographical data. The frequency of deep-water MBE is generally approximately 12 kHz. A typical beam width is 1°× 1°, and the corresponding beam footprint is 1.75% water depth. For example, when the water depth is 5000 m, the beam footprint is approximately 87.5 m. It can be observed that the shipborne deep-water MBE cannot obtain high-precision seafloor topographical data.

Underwater vehicles, such as DT, AUV, ROV, and HOV, can carry more high-frequency MBE to near-seafloor to achieve accurate topographical detection. The corresponding MBE is designed with a special pressure-resistant design with a pressure depth of up to 6000 m or even deeper. At present, some commercial

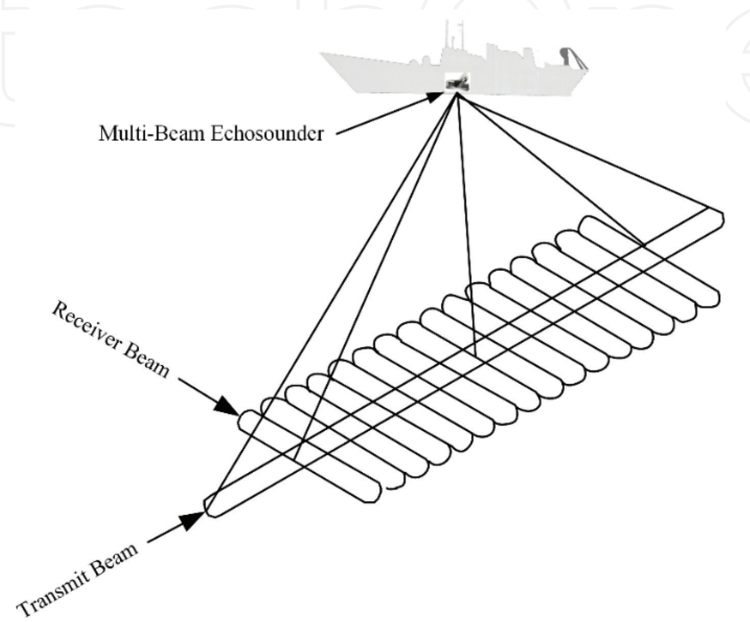

Figure 2.
Basic principle of MBE.

MBEs used for deep sea underwater vehicles are Kongsberg EM2040, Reson SeaBat 7125/T20-S, and R2Sonic 2022/4/6. They are widely used on different underwater vehicles around the world. They are widely used on different underwater vehicles around the world. Comparison of typical high-resolution MBEs for deep sea underwater vehicles is shown in **Table 1**.

2.2 Side-scan sonar

SSS generates an acoustic image by emitting an acoustic signal and receiving an echo signal reflected by the seafloor to reveal sea bottom conditions, including the position, current status, height, and shape of the target. SSS has advantages of intuitive image, high resolution, and large coverage compared to other seafloor detection technologies.

SSS can be divided into two types according to the installation position of the acoustic transducer array: shipborne type and towed type. A shipborne acoustic transducer array is mounted on both sides of the ship hull. This type of SSS operates at a generally lower frequency (below 10 kHz) and has a wider swath. On the other hand, a towed acoustic transducer array is installed in the tow body, only a few tens of meters away from the seafloor, and the speed is low. The obtained side-scan image quality is higher, and even a pipeline of 10 cm and a small volume of oil drum can be distinguished. Recently, the speeds of some deep tow type SSS systems have increased, and high-resolution side-scan images can still be obtained at 10 kn.

SSS technology has two development directions: one direction is to develop BSSS technology that can obtain the topography of the seafloor while obtaining the seafloor geomorphology and the other direction is the development of synthetic aperture sonar technology with lateral resolution theoretically equal to half the physical length of the sonar array and does not increase with increasing distance.

At present, commercial SSSs for deep-sea underwater vehicles commonly used are Klein 3000, EdgeTech 2200-M, and Kongsberg dual-frequency sonar. A comparison of typical SSSs for deep sea underwater vehicles is shown in **Table 2**.

2.3 Bathymetric side-scan sonar

In order to incorporate the advantage of MBE and SSS, the Institute of Acoustics of the Chinese Academy of Sciences (IOACAS) [11] developed BSSS. BSSS can detect seafloor geomorphology and topography simultaneous. The arrival angle

	Kongsberg, EM2040		**Reson, SeaBat 7125**		**R2Sonic, Sonic 2024**	
Frequency	200 kHz	400 kHz	200 kHz	400 kHz	200 kHz	450 kHz
Transmit beamwidth	0.7°	0.4°	2.0°	1.0°	1.0°	0.45°
Receive beamwidth	1.5°	0.7°	1.0°	0.5°	2.0°	0.9°
Depth	635 m	315 m	450 m	175 m	400 m	—
Coverage	200°	200°	165°	165°	160°	160°
Number of beams	400	400	256	512	1024	1024
Ping rate	60 Hz		50 Hz	50 Hz	60 Hz	60 Hz
Range resolution	14.2 mm	10.5 mm	6 mm	6 mm	—	10.2 mm
System depth rating	6000 m		6000 m		6000 m	

Table 1.
Comparison of typical high-resolution MBEs for deep sea underwater vehicles.

and the water depth of seafloor echoes can be measured by receiving arrays of BSSS. The advantage of BSSS is high resolution, small array, and low power. **Figure 3** shows the basic principles of BSSS.

The BSSS system's small size, lightweight, and low power consumption make it especially suitable for installation on DT, AUV, ROV, and HOV.

	Klein, 3000	EdgeTech, 2200-M	Kongsberg, dual-frequency sonar
Frequency	100/500 kHz	75/410 kHz 120/410 kHz 75/120 kHz 300/600 kHz	114/410 kHz
Horizontal beams	0.7° (100 kHz) 0.2° (500 kHz)	0.6° (120 kHz) 0.3° (410 kHz)	1.0° (114 kHz) 0.3° (410 kHz)
Beam tilt	5/10/15/20/25°	20°	10° ± 1°
Range	600 m (100 kHz) 150 m (500 kHz)	500 m (120 kHz) 150 m (410 kHz)	600 m (114 kHz) 150 m (410 kHz)
Depth rating	3000 m	6000 m	2000 m

Table 2.
Comparison of typical SSSs for deep sea underwater vehicles.

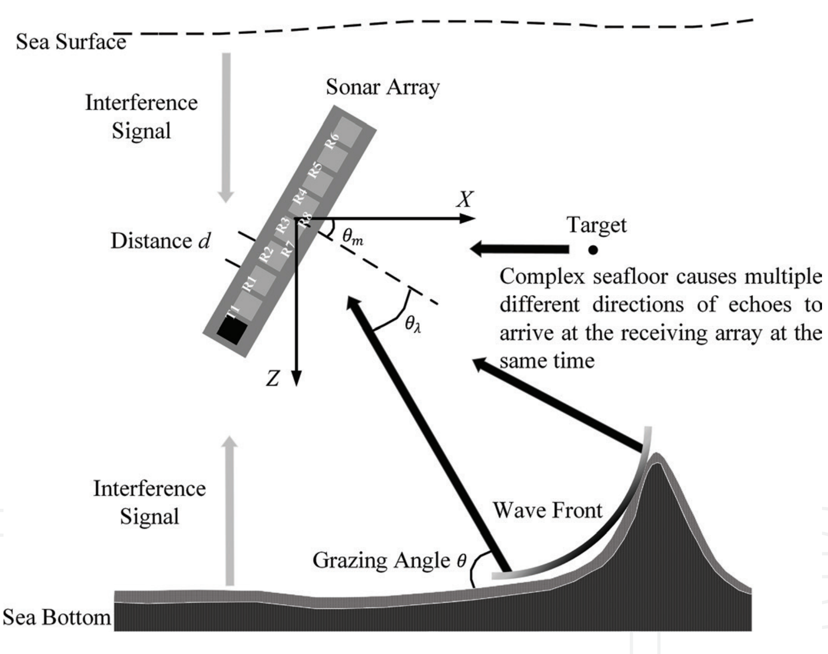

Figure 3.
Basic principle of BSSS.

	IOACAS HRBSSS	Teledyne, Benthos C3D	Kongsberg, GeoSwath Plus
Frequency	150 kHz	200 kHz	125–500 kHz
Bathymetry coverage	2 × 300 m	10–12 × depth	100 m
Side-scan coverage	2 × 400 m	2 × 300 m	200 m
Speed	2.5 kn	3–5 kn	3 kn
Depth rating	7000 m	6000 m	4000 m

Table 3.
Comparison of typical BSSSs for deep sea underwater vehicles.

At present, commercial BSSS for deep-sea underwater vehicles mainly includes IOACAS HRBSSS, Teledyne Benthos C3D, and Kongsberg GeoSwath Plus. The high-resolution BSSS developed by IOACAS can simultaneously obtain high-resolution seafloor topography and geomorphology, and is suitable for use in complex conditions in the deep sea. HRBSSS has been successfully applied to various deep-sea underwater vehicles such as Jiaolong HOV, DTA-6000 acoustic DT, and Qianlong I/II AUV. A comparison of typical BSSSs for deep sea underwater vehicles is shown in **Table 3**.

3. Deep sea vehicles

Four types of vehicles, on which seafloor mapping sonars can be mounted of deep sea surveys are the deep tow, the automated underwater vehicle (AUV), the remotely operated vehicle (ROV), and the human occupied vehicle (HOV).

3.1 Deep tow

A deep tow (DT) system is a large-scale marine equipment used for surveying the characteristics of the seafloor in the deep sea. It is generally placed near-seafloor using a towing cable to investigate high-precision topography, superficial geological structures, flow fields, and other physical and chemical parameters. A DT system consists mainly of a deck control unit, a winch, cables, a depressor, and a tow body, as shown in **Figure 4**. The A-shaped frame on the mothership is used to drop the tow body into the sea. The towing speed is less than 5 kn. In general, the distance between the tow body and the seafloor is controlled to approximately 50 m, and the mothership moves to pull the DT for topographical and hydrological data collection. The collected data are transmitted to the deck control unit of the shipboard laboratory for processing using a winch and armored photoelectric composite cable. The mothership supplies power to the tow body using the armored photoelectric composite cable. Therefore, the DT system can be used for long-term continuous operation and is widely used in deep-sea survey, target search, and other fields.

The tow body can be used as a carrier to carry topographical or hydrological survey equipment as needed. Micro-topographical mapping sonars (such as MBE, SSS, BSSS, and sub-bottom profiler) installed on the DT can detect seafloor topography near the seafloor and obtain more accurate topography and geomorphology of the seafloor.

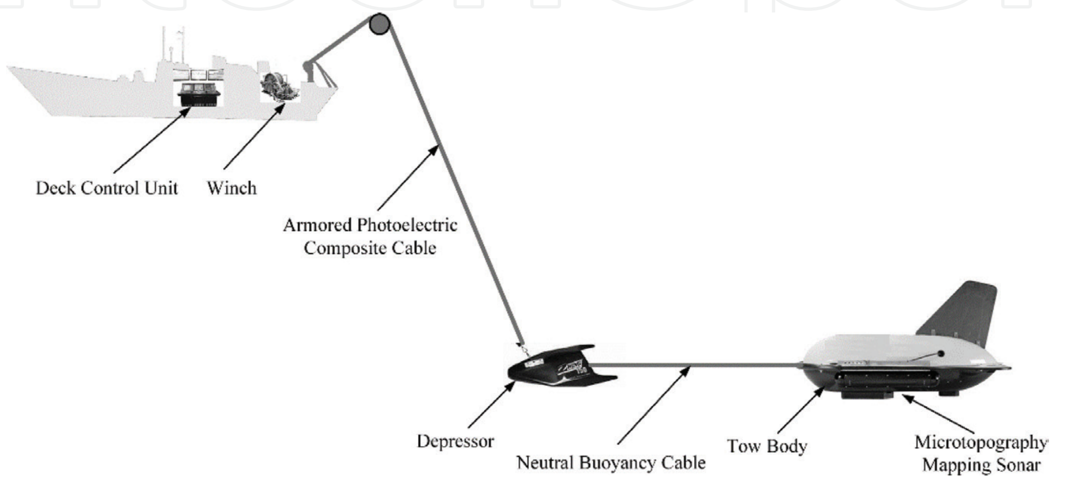

Figure 4.
Deep tow system

3.2 Autonomous underwater vehicle

AUVs (**Figure 5**) are autonomous underwater vehicle that can move in the ocean without real-time control by human being. The AUV itself carries energy and detection equipment and can achieve autonomous navigation and detection operations, less manual intervention, and low mother ship requirements. It is very suitable for large-area underwater exploration and data acquisition operations. The AUV is equipped with relevant sensors for different detection purposes, including acoustic, chemical, hydrological, and geophysical sensors. With the maturity of AUV technology, the AUV is currently equipped with micro-topographical mapping sonars, such as MBE, SSS, and BSSS to near-seafloor to measure underwater terrain as a new option.

3.3 Remotely operated vehicle

A remotely operated vehicle (ROV, **Figure 6**) is an unoccupied underwater robot that is connected to a mother ship by a series of cables. A load-carrying umbilical cable is used along with a tether management system (TMS) when the ROV works in rough conditions or in deeper water.

Before the ROV dives, it requires a relatively accurate understanding of the topography of the working area. Usually, the topographical map of the working area is obtained by a shipborne deep-water MBE. However, for deep sea areas, the accuracy of shipborne deep-water MBE is limited. To ensure safety of the ROV when the topography of the seafloor is complex, it is necessary to use micro-topographical

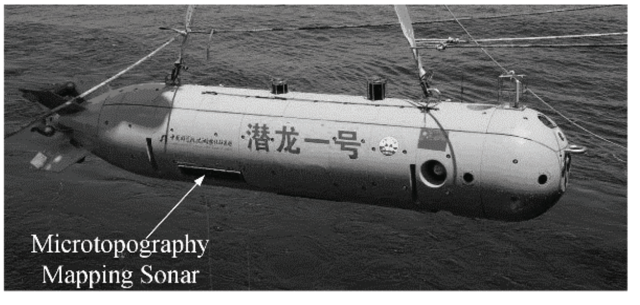

Figure 5.
Autonomous underwater vehicle.

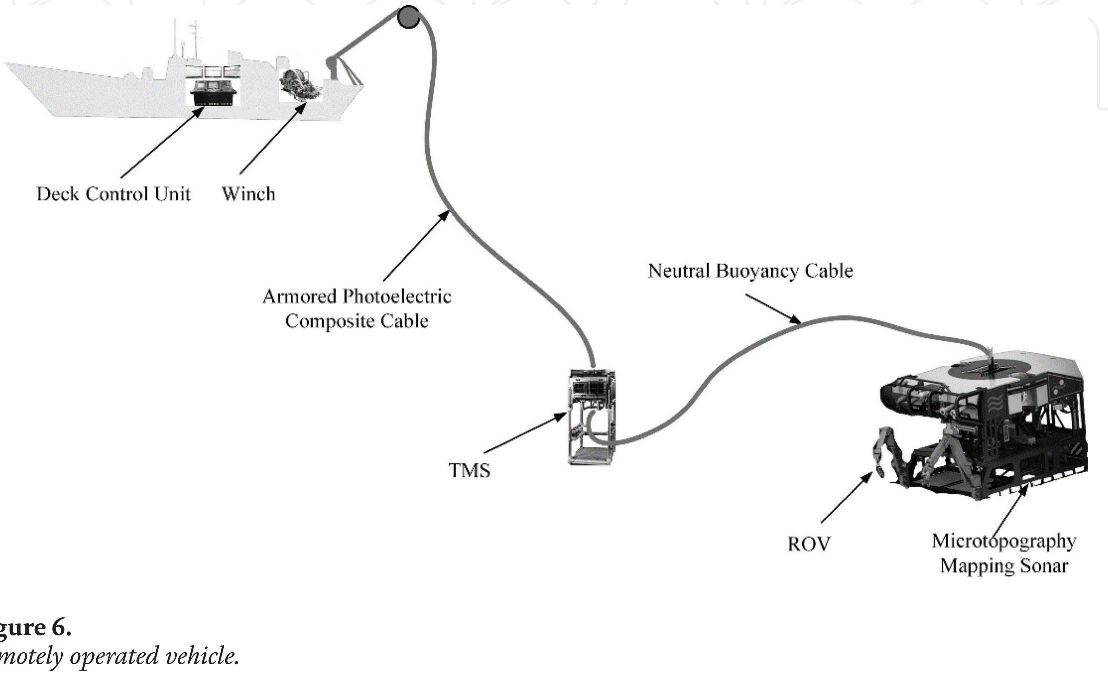

Figure 6.
Remotely operated vehicle.

mapping sonars mounted on the ROV to obtain fine topographical map of the working area. However, unlike DT and AUV, ROV is not suitable for large-area mapping surveys.

3.4 Human occupied vehicle

HOV is similar to a small submarine; however, a submarine is not submersible. Equipment on an HOV typically includes a manipulator, a camera system, and a special lighting system. HOV is a more versatile underwater vehicle than a submarine, which is reflected in several applications. An HOV is designed to dive to greater depths, just like a submarine. Due to enormous pressures in the deep sea, it requires a special pressure-resistant design that carries no more than two or three people and limited food, water, and oxygen.

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 HOVs worldwide with a depth capacity of over 1000 m [12]. 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).

Jiaolong is equipped with a BSSS system to obtain accurate mapping of seafloor topography and geomorphology, similar to other great-depth HOVs, as shown in **Figure 7**. The BSSS system consists of two parts: one part is installed in the manned cabin (i.e., the master controller unit), whereas the other part is installed outside 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 HOV. The transducer surface normal must have an angle of 30° above the horizontal plane. In addition, the transducer array is installed between HOV stations 4 and 5 as deformation of the mounting bracket must be minimized during lifting to avoid damaging the transducer array. In this cylindrical part of the HOV, 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 frame deformation on the transducers.

BSSS is mainly used to obtain data on micro-topography and micro-geomorphology: ultra-short baseline (USBL) and long baseline (LBL) provide navigation and positioning data, which are essential for topographical and geomorphological mapping; underwater acoustic communication devices transmit positioning data obtained by USBL on the supporting mothership at the surface to HOV, allowing the

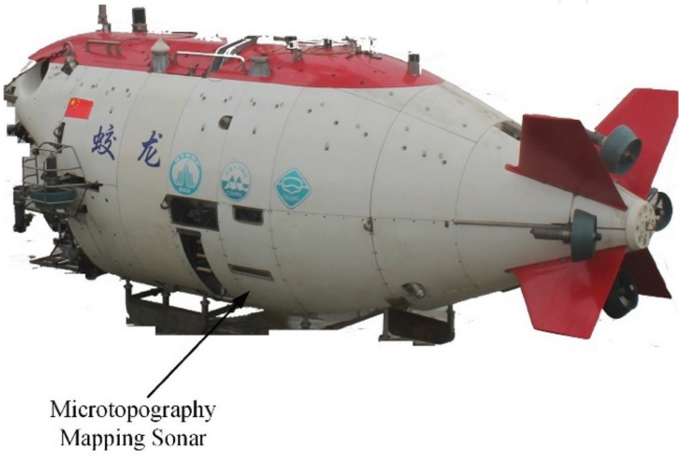

Figure 7.
Human-occupied vehicle Jiaolong.

determination of the initial position of the integrated navigation system; the HOV speed is measured by Doppler velocity log (DVL). The attitude and heading are measured by optical fiber compass. The sound speed is provided by the conductivity-temperature-depth (CTD). The depth of HOV is measured by a high-accuracy depth sensor, which combined with topographical data measured by BSSS, the absolute depth of the seafloor can be obtained.

4. Factors affecting mapping and detection results

In general, factors affecting data quality when using small underwater vehicles (e.g., DT and AUV) to carry near-seafloor micro-topographical mapping sonars fall into five categories: horizontal positioning accuracy, vertical positioning accuracy, depth accuracy, sensor time uniformity (time requirements of the sensor are uniform, the attitude sensor time is accurate to 50 ms, the transmission time is accurate to 50 ms, and the other sensors are accurate to 1 s), and sensor location uniformity (it requires precise knowledge of the coordinates of each sensor relative to the origin of the coordinates origin and installation errors). Large-scale underwater vehicles (e.g., ROV and HOV) not only have the above five features but also have other additional characteristics, including poor stability in attitude control, acoustic transducer array port and starboard installations, and wide spacing. Hence, detailed discussion on factors affecting mapping and detection results is presented using Jiaolong HOV and its BSSS as an example. By processing the BSSS detection data collected by the Jiaolong HOV, we found that factors that mostly affect mapping quality are the HOV attitude, port and starboard positions of BSSS transducer array [7].

4.1 Effect of HOV attitude

Because the streamline of HOV and manual control, the attitude control stability of HOV is relatively poor; therefore, HOV attitude is a main factor that effect BSSS detection and mapping. **Figure 8** shows the seafloor micro-topography around the peak of a cold spring area. **Figure 8a** uses raw data; **Figure 8b** uses data in which filtering and smoothing have been applied to the roll angle.

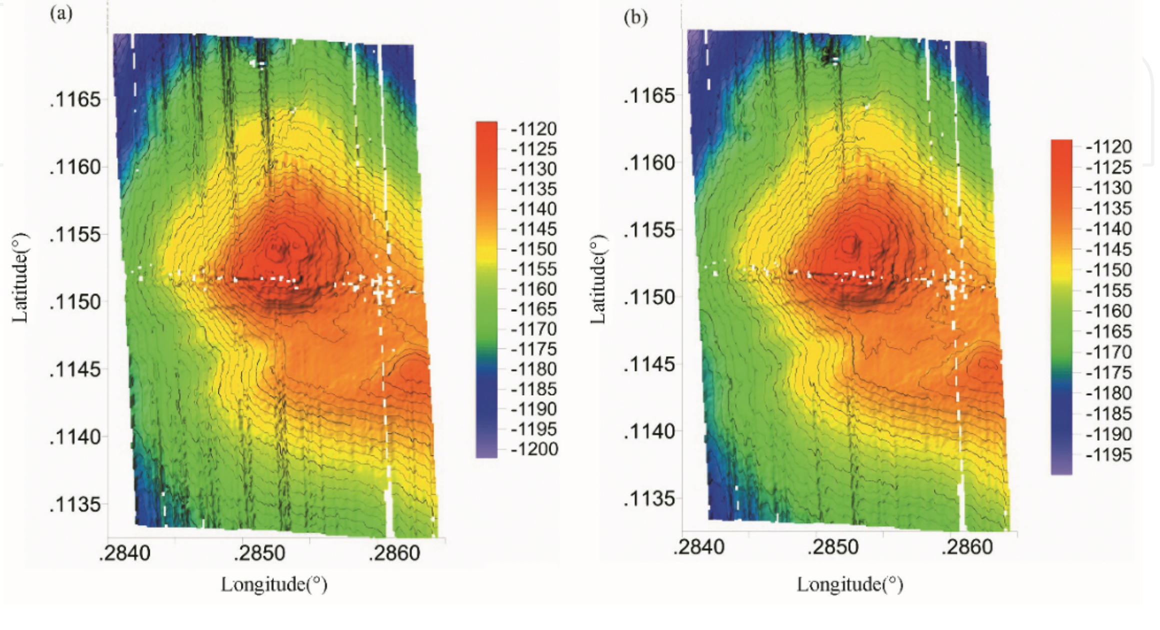

Figure 8.
Seafloor micro-topography around the peak of a cold spring area: (a) map using raw data and (b) map using data in which filtering and smoothing have been applied to the roll angle.

Figure 9 shows the temporal change curves recorded by BSSS for (a) roll angle, (b) pitch angle, and (c) heading angle. It can be found that there is a strong correlation between map distortion in **Figure 8a** and roll angle in **Figure 9a**.

4.2 Effect of port and starboard positions

Seafloor micro-topographical detection involves multiple sensors, including LBL, USBL, DVL, fiber optic compass (FOC), and BSSS arrays. The distance of the two

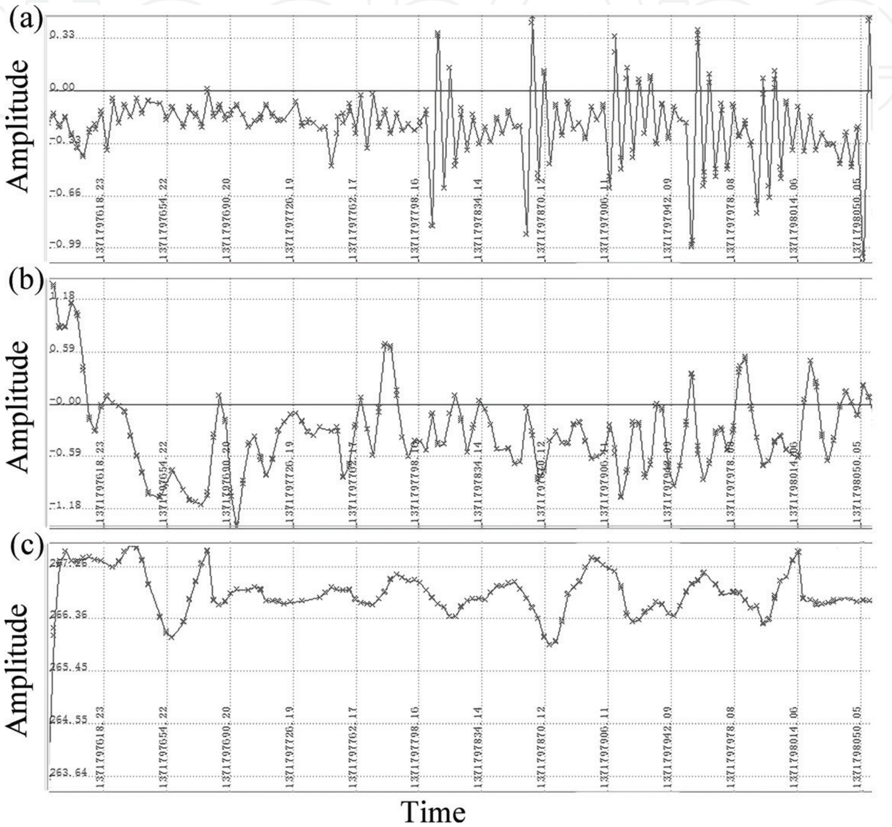

Figure 9.
Temporal change curves recorded by BSSS for (a) roll angle, (b) pitch angle, and (c) heading angle.

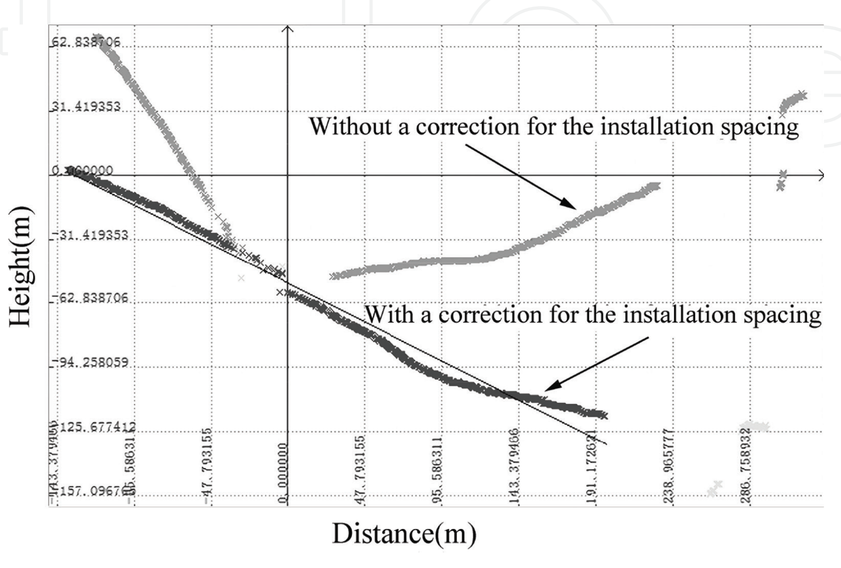

Figure 10.
Depth-sounding results for a single ping measurement along sloped terrain in a cold spring area. The gray dotted line indicates data without correction for the installation spacing between the port and starboard transducer arrays, whereas the black dotted line indicates data with correction for the installation spacing.

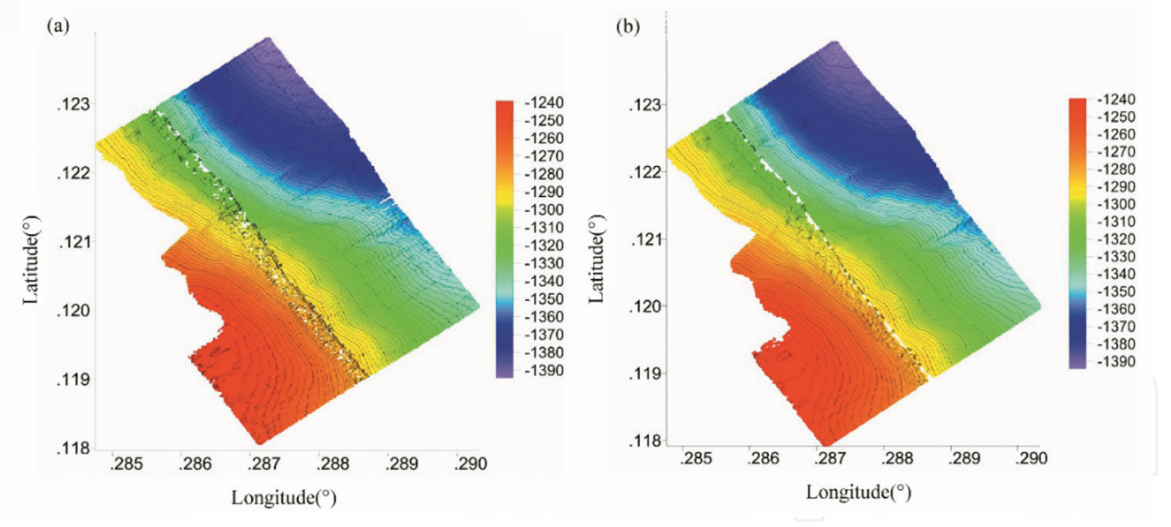

Figure 11.
Seafloor micro-topographical maps of sloped terrain in a cold spring area: (a) without compensation of the array spacing (b) with compensation of the array spacing [10] (permissions obtained to reprint).

BSSS array is about 2.46 m. As BSSS detect the bottom by the two BSSS array separately, so when the bottom has a large slope, the bottom detection results are different.

Figure 10 shows depth results from a single ping measurement of sloped terrain in a cold spring area, with and without correction for the installation spacing. The detection results of two BSSS arrays are different. If there is no compensation, the quality of seafloor topographical map will be poor.

Figure 11a shows that when the spacing of two BSSS arrays is not taken into account, the quality of the mapping result is poor. After compensation of the spacing, the transition of the mapping result is relatively smooth, and the mapping quality is improved, as shown in **Figure 11b**.

5. Data processing and mapping method

The raw data, including BSSS mapping data, HOV attitude data, acoustic positioning data, sound velocity data, are processed in two steps (pre-processing and post-processing) to obtain topographical and geomorphology map. Data pre-processing mostly consists of five steps: navigation data processing, rewriting navigation data, coarse error elimination, angular deviation correction, and port/starboard position correction. Data post-processing mostly consists of 12 steps, namely installation angle correction, sound velocity correction, attitude data filtering, bathymetric data filtering, fine error elimination, field correction, side-scan data filtering, bottom tracking, angle variation gain, equalization gain, data export, and mapping. **Figure 12** shows the flow diagram of data processing and mapping.

5.1 Data pre-processing

1. Navigation data processing

   Post-process navigation and acoustic positioning data, such as FOC, DVL, USBL, and LBL, to obtain high-precision navigation data.

2. Rewriting navigation data

   Rewrite high-precision navigation data to the BSSS raw data file to replace original navigation data.

3. Coarse error elimination

Set a reasonable threshold for the side-scan data energy. If the energy of side-scan data is lower than the threshold, it indicates a bad ping and should be deleted.

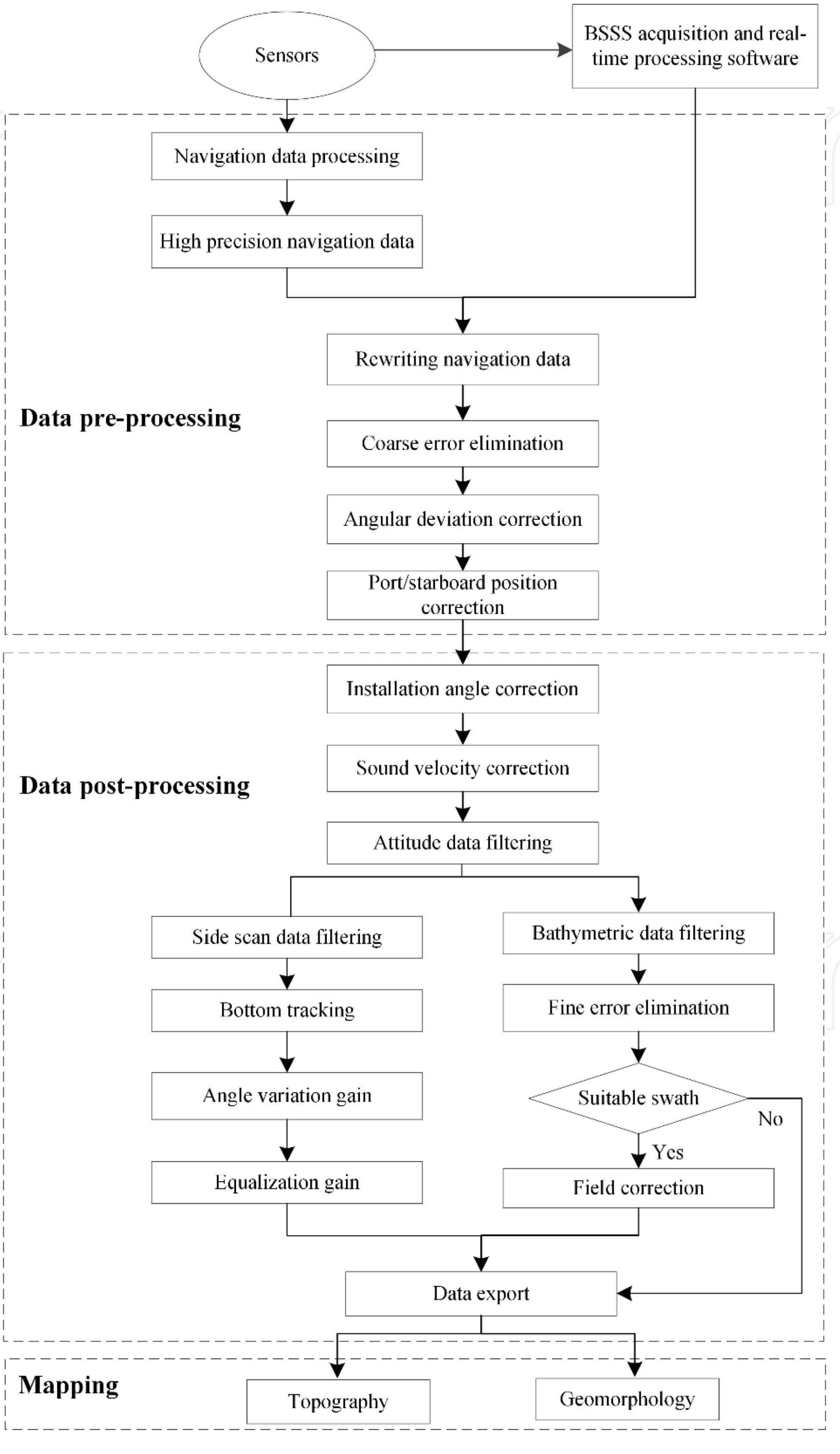

Figure 12.
Flow diagram of data processing and mapping.

4. Angular deviation correction

   Analyze existing BSSS data and select data corresponding to the seafloor with a constant slope. Let the slope pass the point just below the sonar array to find the optimal slope of the seafloor; use this slope to obtain the angle correction curve of bathymetric data. Next, use median filter to filter the obtained angle correction curve, filter out high-frequency components, and retain only low-frequency components to reflect the larger change trend. Finally, use the angle correction curve to perform angle correction on each ping data.

5. Port/starboard position correction

   Read ping data in the BSSS data file, obtain the delay and angle of each ping, and convert to slant range and angle. Calculate the horizontal distance and the vertical height of each ping according to the triangular geometric relationship (taking the installation angle of the sonar array into consideration). Add the port/starboard position to the horizontal distance while maintaining the vertical height. Recalculate the corresponding slant range and angle according to the triangular geometric relationship and convert to delay and angle.

5.2 Data post-processing

1. Installation angle correction

   Correct the installation angle with 30°, which is measured.

2. Sound velocity correction

   Input the measured sound velocity by CTD.

3. Attitude data filtering

   Perform median filtering and smoothing for roll, pitch, and heading.

4. Bathymetric data filtering

   Filter bathymetric data by setting the height, horizontal coordinates, depth, and slant distance.

5. Fine error elimination

   Trim the pings manually to realize fine error elimination.

6. Field correction

   If there is a suitable swath, select the swath that meets the requirements, carry out the corresponding error test, and make corresponding corrections to suppress deviation of the roll, navigation latency, and pitch.

7. Side-scan data filtering

   Filter side-scan data by setting the height, horizontal coordinates, depth, and slant distance.

8. Bottom tracking

   Side-scan data processing requires bottom tracking to delete the water column and generally selects automatic bottom tracking. If the effect is not appropriate, bottom tracking can be manually set.

9. Angle variation gain

   Angle variation gain is used to compensate for backscattering variations due to system beam pattern irregularities and incident angle changes.

10. Gain equalization

    Gain equalization can be used to address the unevenness of side-scan data due to hardware gain changes or excessive pitch angles during data acquisition.

11. Data export

    Export processed data for mapping.

12. Mapping

    Use Surfer software to perform topographical and geomorphological mapping.

6. Typical detection results

Ten years sea-trial and application have shown that the Jiaolong BSSS can produce high-resolution micro-topographical and micro-geomorphological maps; isobaths can be displayed at 2-m intervals, and many seafloor details are clearly distinguished (**Figure 13**). Furthermore, comparison of micro-topographical and micro-geomorphological maps can yield additional information.

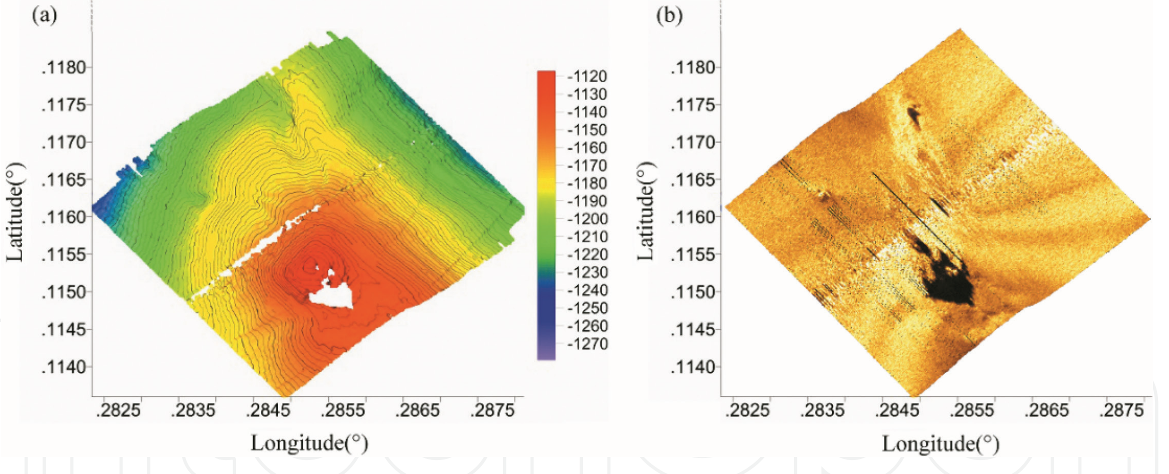

Figure 13.
Seafloor (a) micro-topographical and (b) micro-geomorphological maps obtained by the Jiaolong BSSS on a dive around the peak of a cold spring area [10] (permissions obtained to reprint).

7. Conclusions

Numerous fields require access to seafloor topography and geomorphology. The onboard deep-sea multi-beam sounding system should be used to map the area and obtain a relatively accurate topographic map of the seabed to provide basic terrain data. Although a shipborne deep-sea multibeam sounding system can detect a wide range of deep seabed terrains, its detection accuracy is limited, and it cannot search for small objects on the seafloor.

Near-seafloor micro-topographical mapping is a significant supplement to full sea depth topographical detection. It combines micro-topographical mapping sonars with underwater vehicles and can dive to near-seafloor to achieve accurate topographical detection. DT and AUV are more suitable for large-area micro-topographical mapping survey owing to their good streamline and control stability. However, although the mapping and detection results are affected by other factors, ROV and HOV are still needed for small-site micro-topographical mapping. BSSS and MBE can be mounted on ROV and HOV.

Acknowledgements

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

Conflict of interest

The authors declare that they have no conflict of interest.

Author details

Tongwei Zhang[1,2,3]*, Baohua Liu[1,2] and Xiaodong Liu[4]

1 National Deep Sea Center, Qingdao, China

2 Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

3 Joint Laboratory for Ocean Observation and Detection, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

4 Ocean Acoustic Technology Center, Institute of Acoustics, Chinese Academy of Sciences, Beijing, China

*Address all correspondence to: tongwei.zhang@outlook.com

References

[1] Wikipedia contributors. Deep sea. Wikipedia, the free encyclopedia. October 19, 2018, 19:17 UTC. Available from: https://en.wikipedia.org/w/index.php?title=Deep_sea&oldid=864831273. [Accessed: 2018-12-11].

[2] Jin XL. The development of research in marine geophysics and acoustic technology for submarine exploration. Progress in Geophysics. 2007;**22**:1243-1249

[3] Wikipedia contributors. Topography. Wikipedia, the free encyclopedia. December 5, 2018, 14:47 UTC. Available from: https://en.wikipedia.org/w/index.php?title=Topography&oldid=872158696 [Accessed: 2018-12-11]

[4] Wikipedia contributors. Geomorphology. Wikipedia, the free encyclopedia. November 2, 2018, 12:52 UTC. Available from: https://en.wikipedia.org/w/index.php?title=Geomorphology&oldid=866921872. [Accessed: 2018-12-11]

[5] Liu XD, Zhao TH, Cao JL, Wang ZB, Hou DY, Zhang DS. General scheme analysis of the lightweight acoustic deep tow system for gas hydrate exploration. Marine Geology Frontiers. 2015;**31**:8-16

[6] Li YM, Li Y, Sheng MW, Sun YS, Zhang GC. Application and development of topographic survey using multibeam echosounder equipped on AUV. Hydrographic Surveying and Charting. 2016;**36**:7-11

[7] Luo BW, Pao YY, Zhou ZJ, Liu J. Explorative study on short range exploration method for deep sea cobalt crust tiny terrain. Metal Mine. 2006;**41**:15-19

[8] Liu BH, Ding ZJ, Shi XP, Yu KB, Li DW, Li BG. Progress of the application and research of manned submersibles used in deep sea scientific investigations. Haiyang Xuebao. 2015;**37**:1-10

[9] Zhu M, Zhang TW, Yang B, Liu YY, Tang JL. Sonar system of Jiaolong human-occupied vehicle. Chinese Science Bulletin. 2014;**59**:3462-3470

[10] Zhang TW, Tang JL, Li ZG, Zhou YB, Wang XX. Use of the Jiaolong manned submersible for accurate mapping of deep sea topography and geomorphology. Science China Earth Sciences. 2018;**61**:1148-1156

[11] Zhu WQ, Liu XD, Zhang DS, Zhang FS, Qin GL, Liao Z, et al. High resolution bathymetric side scan sonar. Ocean Technology. 2006;**24**:29-35

[12] Kohnen W. Review of deep ocean manned submersible activity in 2013. Marine Technology Society Journal. 2013;**47**:56-68