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Seafloor geodetic network establishment and key technologies

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Abstract Seafloor geodetic network construction involves the development of geodetic station shelter, network configuration design, location selection and layout, surveying strategy, observation model establishment and optimization, data processing strategy and so on. This paper tries to present main technological problems involved in the seafloor geodetic network construction, and seek the technically feasible solutions. Basic conceptions of developing seafloor geodetic station shelters for shallow sea and deep-sea are described respectively. The overall criteria of seafloor geodetic network construction for submarine navigation and those of network design for crustal motion monitoring are both proposed. In order to enhance application performances of the seafloor geodetic network, the seafloor network configuration should prefer a symmetrical network structure. The sea surface tracking line measurements for determining the seafloor geodetic station position should also adopt an approximately symmetrical configuration, and we recommend circle tracking line observations combined with cross-shaped line (or double cross-shape line) observations for the seafloor positioning mode. As to the offset correction between the Global Navigation Satellite System antenna phase center and the acoustic transducer, it is recommended to combine the calibration through external measurements and model parameter estimation. Besides, it is suggested to correct the sound speed error with a combination of observation value correction and parameterized model correction, and to mainly use the model correction to reduce the influence of acoustic ray error on the seafloor positioning. Following the proposed basic designs, experiments are performed in shallow sea area and deep-sea area respectively. Based on the developed seafloor geodetic shelter and sufficient verification in the shallow sea experiment, a long-term seafloor geodetic station in the deep-sea area of 3000 m depth was established for the first time, and the preliminary positioning result shows that the internal precision of this station is better than 5 cm.

Keywords Seafloor geodesy, Seafloor geodetic network, Seafloor shelter, Undersea navigation, Acoustic positioning

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1. Introduction

A seafloor geodetic network is a set of geodetic stations deployed on the seafloor to form a positioning system like the Global Navigation Satellite System (GNSS) constellation, which can provide the surface and subsurface users with positioning, navigation and timing information, and monitor seafloor crustal motion and marine environment changes (Yang et al., 2018; Liu et al., 2019; Li et al., 2018). Seafloor geodetic network should be an integral part of the national geodetic network of China. It would not be a real "national geodetic network" without covering the territorial water, at

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least it is not complete to be the full-fledged one. Seafloor geodetic network is the basis for undersea positioning and navigation, and plays a key role as the fundamental infrastructure for marine security, economy development and ocean environment monitoring, and also provides important supports for marine geological researches and the exploration and exploitation of seabed resources.

The terrestrial geodetic network of China is relatively complete with centimeter level precision, and it is maintained by a long-term remeasurement (Chen et al., 2007; Yang, 2009; Wei, 2008; Wei et al., 2011). The seafloor geodetic network construction in China, however, is still underdeveloped. This is not only because the seafloor geodetic network construction is very difficult and involves high technical requirements, but also because the seafloor geodetic equipment is expensive and there is still some way from being autonomous and controllable. Additionally, the seafloor geodetic network construction will take a relatively long time while the service life of the equipment is relatively short. Besides, the theory and method of the seafloor geodetic network data processing are still immature; neither the acoustic positioning model nor the data processing model for multi-source seafloor observations is perfect. In order to solve these problems, the International Association of Geodesy (IAG) formally set up a working group in 2019 to promote the seafloor geodetic datum and undersea positioning technology development.

The United States, Canada, Russia and other developed countries have already launched the seafloor geodetic network researches for a long time and they have basically mastered the technology for establishing and maintaining the seafloor geodetic network (Spiess et al., 1998; Favali and Beranzoli, 2006; Matsumoto et al., 2008). To monitor the seafloor crustal motion and seismic activities, Japan has already established a seafloor geodetic network (Mochizuki et al., 2003; Fujiwara et al., 2011), and made a series of research achievements.

Aiming at the positioning, navigation and timing (PNT) security issues in special scenes and complex environments such as underwater positioning and navigation, the U.S. proposed a long-term plan for developing the national comprehensive PNT architecture (National Security Space Office, 2008). In 2015, the US Defense Advanced Research Projects Agency (DARPA) proposed the Positioning System for Deep Ocean Navigation (POSYDON) project to determine the precise position of the submarine vehicle by using the received passive signals or the request-response signals from a set of acoustic beacons with known coordinates, where the acoustic beacons form an acoustic array (i.e. a seafloor geodetic network) like the GNSS constellation to provide underwater positioning services (Defense Advanced Research Projects Agency, 2016). Chinese researchers have made some achievements in developing acoustic positioning models and algorithms, including underwater differential positioning based on the short-baseline positioning (Liu et al., 2006) and the long-baseline positioning (Han et al., 2017; Li, 2007; Ning et al., 2014), acoustic ray error correction (Zhao and Wang, 2015; Zhang et al., 2013) and modelling (Yan et al., 2016; Zhao et al., 2016), etc. Preliminary results were also achieved in the comprehensive PNT architecture and resilient PNT frame studies, both involving the submarine PNT service (Yang, 2016; Yang and Li, 2017; Yang, 2019). Besides, some Chinese scholars have started researches on the theory and methods of marine positioning and navigation (Wu, 2013; Yang et al., 2017; Han et al., 2017; Zhao et al., 2017; Sun et al., 2018). However, the long-term stable working seafloor geodetic network has not been established at present, and there still lacks effective underwater positioning technologies and methods (Yang et al., 2018; Yang, 2019).

There are a great number of difficulties encountered in establishing the seafloor geodetic network. Firstly we need to develop the acoustic beacon and shelter featured with good stability, measurability, pressure-resistance and anti-corrosion to adapt to the complex ocean environment, and to solve key technological problems in the power supply and device *in-situ* maintenance; secondly, we have to solve problems in optimizing the layout of large-scale seafloor geodetic network, and ensure that it is tied to the national terrestrial geodetic network to form a whole. The seafloor geodetic measurement strategy is also one of key technological issues in seafloor geodetic network construction. Besides, the involved data processing problems, including model refinement for multi-type observations obtained under different environments and data fusion of multi-source ocean observations and so on, also have to be solved in the seafloor geodetic network establishment. Although we can hardly give optimal solutions to all of the above issues in a short term, properly investigating and analyzing those problems is still significantly meaningful for constructing the seafloor geodetic network.

2. Key technologies for seafloor geodetic station shelter

2.1 Shelter design

The problems involved in developing the seafloor geodetic station shelter need to be tackled first. A seafloor geodetic station shelter includes the acoustic beacon, power supply unit, depth gauge, foundation bed unit, protective unit, balance weight structures, etc.

The acoustic-based seafloor geodetic station shelter and device should have capabilities of pressure-resistance, anticorrosion and long-distance signal transmission. Moreover, the seafloor geodetic station should have capabilities of location stability, long-term working and high-precision positioning, and it can be easily and rapidly deployed, recycled and maintained in most undersea areas.

As the depth of the majority of China sea areas does not exceed 4000 m and that of the global sea areas does not exceed 7000 m, the seafloor geodetic station devices should be able to withstand the water pressure at a depth over 6000 m, so they can be used for the seafloor geodetic network construction in the most of sea areas.

Taking the above-mentioned aspects into account, materials of high-strength, press-resistance and anti-corrosion, such as stainless steel or titanium alloy, are generally selected for the seafloor geodetic station shelter, and a stable foundation bed design should be added as shown in Figure 1. In addition, the design of a seafloor geodetic station shelter in deep-sea should take the effects of time-variant flow-field and seafloor sediments into account, therefore we designed an overflow structure with a stable foundation bed as shown in Figure 1a. The shallow-sea shelter needs to be anti-dragging additionally and thus an overflow-type anti-dragging structure is finally adopted to prevent it from damages caused by human or other factors as shown in Figure 1b. To reduce the number of plug-ins closely contacted with seawater, the overall structure of the shelter should adopt a penetrating design to improve the reliability. Due to the large volume of the shelter assembly, it needs to adopt separable standardized structures to assemble the shelter to effectively save the assembly space and enhance the operation efficiency.

At present, most seafloor geodetic station shelters in the world adopted structures featured with simple and easy deployment, convenient operation and high stability and reliability (David and Spiess, 2008; McGuire and Collins, 2013; Sakic et al., 2016). In the future, the *in-situ* maintenance of seafloor geodetic acoustic beacons may be realized by remotely operated vehicle (ROV) to ensure the continuity of the coordinate time series of seafloor geodetic station.

2.2 Acoustic signal design

Acoustic-based signal design requires considering the waveform, frequency selection, bandwidth design, etc. The acoustic signal waveform design needs to consider the stability and resolution. The wider the bandwidth is, the lower the spectrum level will be, and therefore for the same sound source, the spectrum level of a broadband signal is lower than that of the single-frequency and it may be disturbed by the ocean ambient noise, which means that it will be difficult to be detected. Besides, the higher temporal resolution the acoustic signal has, the more precise the acoustic ranging will be (Liu and Lei, 2010; Tian, 2010; Hui and Sheng, 2007). Moreover, the coding scheme also needs to be considered in the signal waveform design to ensure the signal detection convenience and on the other hand to increase the decoding difficulty. Direct sequences or frequency hopping coding technology is usually adopted to enhance the signal to noise ratio (SNR) of the detected signal and the encoding complexity (Liu, 2008; Han et al., 2016; Cheng, 2004).

In the respect of the frequency selection, current mature products can be classified into low frequency ones (8–16 kHz) and medium frequency ones (20–30 kHz). It is noted that, the effective range of the low frequency ones is generally limited to 10 km approximately; thus, the shelter deployment requires considering the signal reachability, signal propagation characteristics and the influence of the temporal varying ocean ambient noise (Sun et al., 2019; Li et al., 2005).

2.3 Service life design for the seafloor geodetic station

Service life is one of key indexes to indicate the long-term observability of a seafloor geodetic station. It does not only involve with the reliability design of the seafloor geodetic station shelter, but also highly relies on the continuous power supply of the shelter. At present, the lithium battery has become one of the mainstream products for the seafloor geodetic shelter power supply due to the best safety, the largest specific capacity, the lowest self-discharge rate and the best cost-effective performance. The storage life of lithium battery is usually about 5 years (capacity>90%) (The General Armaments Department of the PLA, 2011). According to the self-discharge rate and current experimental data (six-year failure rate<3%, capacity>98%), the five-year availability of the seafloor geodetic station can reach 99.9999% by connecting multi battery groups in parallel and then separately managing each battery group. The convenience of the power replacement must be additionally incorporated into the seafloor geodetic shelter design.

In the respect of the shelter development, based on the above designs, we have developed a single-beacon shelter with one acoustic transponder and a double-beacon shelter with two acoustic transponders. Shallow seafloor geodetic positioning experiments have been implemented in the surrounding sea areas of Lingshan Island and Jiaozhou Bay in Qingdao to verify the proposed deploying and recycling procedure. It shows that the positioning precision is better than 2 cm (Chen et al., 2019). The deep-sea shelter has been successfully passed the deploying and recycling tests in the deep-sea experiment performed in July, 2019, and the deep-sea overflow shelter as shown in Figure 1a was deployed on the seafloor for a long-term operation.

3. Seafloor geodetic station deployment and network optimization

Since the seafloor geodetic network deployment is costly and

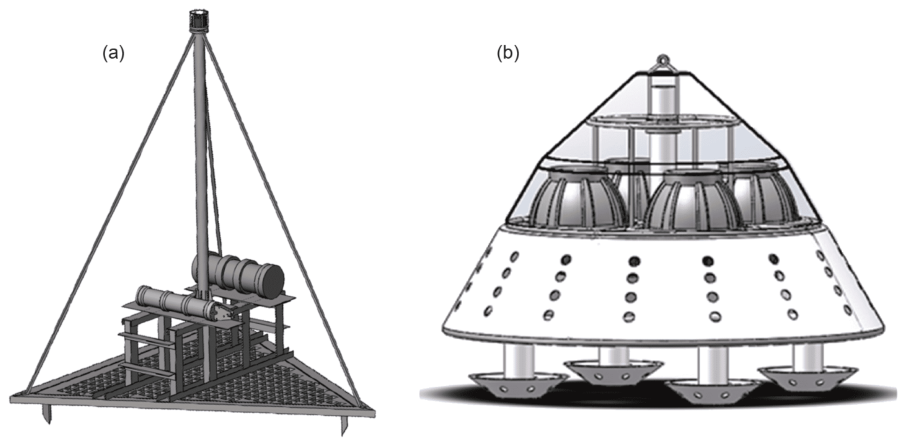

Figure 1 Deep-sea overflow structural shelter (a) and shallow-sea anti-dragging shelter (b).

involves complicated technologies, it is unrealistic to establish a continuous seafloor network like the terrestrial geodetic network. To maximize the effectiveness of the seafloor geodetic network, we need to study the precise deployment strategy for the seafloor geodetic network, and optimize the density and distribution of the seafloor geodetic stations serving as both the coordinate frame and the reference stations for undersea navigation.

3.1 Level classification for seafloor geodetic network construction

Considering the economy of the construction, the established China terrestrial geodetic network is usually divided into different levels. The traditional geodetic network consists of the I-level net and II-level net, and the GNSS geodetic network is composed of the Continuously Operating Reference Station (CORS) network, I-level (A-level) net and II-level (B-level) net. We recommend that, the seafloor geodetic network should also be classified by levels according to different users' requirements in the positioning precision of the seafloor geodetic station. Thereby we can divide the seafloor geodetic network into centimeter-level net, decimeter-level net and meter-level net to satisfy different application requirements. The centimeter-level net will be mainly applied to the seafloor crustal motion monitoring, such as the US seafloor geodetic network with the north direction precision of 0.9 cm and the east direction of 3.9 cm (Spiess et al., 1998). The decimeter-level net will mainly serve the marine engineering such as the ocean oil-gas engineering and undersea cable laying engineering. The meter-level net can mainly provide reference beacons for PNT users. By the power supply mode, the seafloor geodetic station can also be classified into the cable station and non-cable station. As the cable station uses electrical wire cable and optical fiber cable to supply the power and transmit the information, it can support continuous long-term operation and huge volume information transmission. The non-cable station, however, is battery-powered, so it can be only remeasured regularly, usually once or twice per year, e.g., the Japanese seafloor geodetic net is remeasured twice a year (Mochizuki et al., 2003; Fujiwara et al., 2011).

3.2 Location selection of seafloor geodetic station

In the seafloor geodetic network construction, the location selection and layout of the seafloor geodetic station should be solved primarily. Not only the stability, but also the intervisibility between the neighboring stations need to be ensured (Fujimoto et al., 1997), so the location should be carefully selected according to the water depth, seafloor topography, seabed sediments and hydrologic conditions. In order to reasonably deploy the seafloor geodetic station, we primarily presented the main technical indicators of the location selection of seafloor geodetic station from the aspects of the seafloor topography, landforms and stability, as shown in Table 1.

A seafloor geodetic station would be laid in flat terrain area and needs to be of good stability if it is only used as a seafloor geodetic point. However, when it is applied to the seafloor crustal motion monitoring, a set of seafloor geodetic stations should be evenly distributed on the moving plates to monitor the seafloor tectonic motion with the plate tectonics, and need to keep stable within the plates. For a set of seafloor geodetic stations to monitor the seafloor spreading, they should be located on the connecting belt between two plates, and in this case the relative motion between plates can be measured by conducting seafloor acoustic ranging or by the sea surface GNSS/acoustic connection surveying with the seafloor geodetic stations located in the plates. For the power supply limitation, the seafloor geodetic station far away from mainland or island is hardly to be continuously operated, so it

Table 1 Seafloor geodetic shelter layout risk and strategies

Topographic and morphologic risks	Strategies	Geological risks	Strategies
Stability risk	No sand wave or sand ridges	Erosion and deposition risk	Low hydrodynamic force, no loose and soft sediment
Steep slope risk	No larger than 5° slope	Sliding risk	Away from old-landslide, high-steep slopes
Morphologic risk	Away from shallows, volcanos, coral reefs, submarine gullies, canyons, grooves, etc.	Subsidence risk	Away from loose sediment

should be remeasured regularly (or irregularly) to reflect the seafloor plate tectonic motion.

3.3 Seafloor geodetic network configuration design

The seafloor geodetic network configuration design should also be considered in addition to the stability and visibility of seafloor geodetic stations. If only considering the subsurface PNT service, we need to set a reasonable distance among seafloor geodetic station groups to establish a relay-type network according to the error accumulation of the inertial navigation system (INS) equipped on the underwater vehicle. If we further assume that the precision of the INS equipment is 0.1% and the maximum tolerant navigation error is 100 m, then the distance between two seafloor geodetic station groups along the shipping channel should be less than 100 km to perform a timely calibration on the INS accumulated error to ensure high-precision navigation of underwater vehicle. If the maximum tolerant navigation error of the underwater vehicle is set to be 500 m, then the distance between the seafloor geodetic station groups along the shipping channel should be less than 500 km.

Furthermore, not only the distance between different seafloor geodetic station groups, but also the observability and geometric structure of each seafloor geodetic station group need to be considered as well. Under the observability condition, generally three seafloor acoustic beacons can be used to determine the three-dimensional position of the submarine vehicle, and the regular triangle configuration should be the optimal configuration. If further considering the time synchronization requirement, we need at least four necessary geodetic stations and one backup station to form the simplest network, then the regular pentagon is the optimal configuration as shown in Figure 2a. In practice, we usually select one station as the master station located in the center of a square, and set the left as auxiliary stations distributed on the four vertexes of the square, as shown in Figure 2b. As to submarine PNT applications in special regions, the seafloor geodetic network can be realized by extending or densifying the above-mentioned basic configurations.

When the regular polygon network cannot be laid due to the limitation of the seafloor topography and sediment conditions, we can minimize the geometric dilution of precision (GDOP) at the geometric center of the predesigned network coverage, and the network optimization criterion can be expressed as:

$$\min \mathrm{GDOP} = \min\sqrt{\mathrm{tr}(\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}},$$

where $\mathbf{A}$ is the design matrix of the underwater positioning and navigation model. It is definite that the mean GDOP of the regional coverage can be used as the network optimization criterion, which might be more suitable for underwater PNT applications.

4. Seafloor geodetic observation strategy and observational error influence control

The seafloor geodetic network must be integrated with the national terrestrial geodetic network to form a whole national geodetic network, and this should be implemented by the connection measurement between the two networks, and then the terrestrial geodetic datum can be precisely transferred to the seafloor geodetic network. The datum transferring and connection measurement involve two types of observations i.e. the space radio signal and acoustic signal observations, so the different error characteristics of the both need to be considered. The seafloor geodetic positioning principle is the ranging intersection between the known surface points (like the satellite constellation) and the seafloor geodetic station to calculate the three-dimensional coordinates of the seafloor geodetic station (Matsumoto et al., 2008). The sea surface point coordinates at the GNSS antenna phase center can be determined by using GNSS signals, and then the acoustic phase center of the transducer can be obtained by combining the leverage arm vector measured by the precise engineering approach with the vehicle attitude measurements. At last, we can figure out the three-dimensional coordinates of the seafloor geodetic station by distances from the transducers to the transponder installed on the geodetic station. Obviously, the errors of this transmission type of positioning mainly come from measurement error in the surface ship tracking lines, measurement error in leverage arm vector, attitude measurement error and acoustic ranging error.

The datum unification between the seafloor geodetic network and the terrestrial geodetic network relies on the sea surface vehicle connection measurements. The vehicle po-

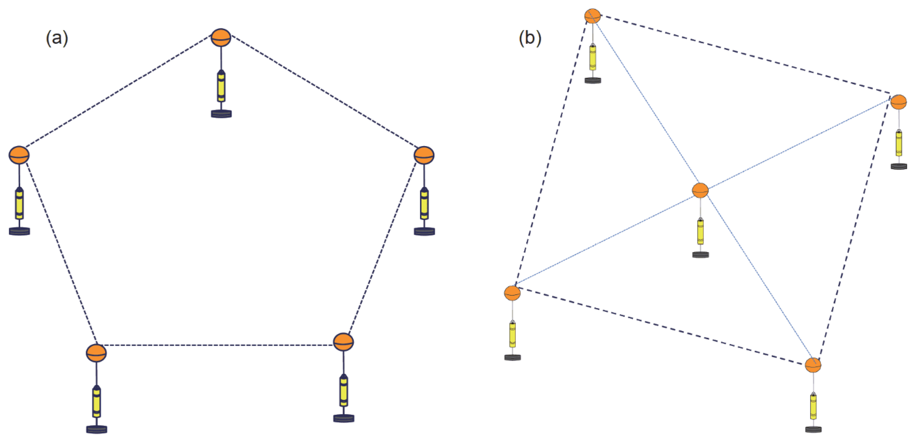

Figure 2 Regular pentagon network (a) and network with master-auxiliary stations (b).

sition is usually determined by GNSS techniques, i.e., to obtain the position of the GNSS antenna phase center by the satellite-based differential technique, precise point positioning (PPP) technique, real time kinematic (RTK) technique or post-processing differential technique, etc. Satellite-based differential technique can be used to obtain the real time position of the vehicle with 20–30 cm precision; meanwhile the positioning precision of PPP technique can be better than 10 cm by only using the vehicle receiver observations and the IGS precise orbit and clock products. The RTK or post-processing differential technique needs not only the surface vehicle receiver observations, but also the terrestrial CORS stations located on land or island to conduct a joint measurement and calculation, and thereby it can be utilized to obtain the vehicle position with precision better than 5 cm.

The seafloor geodetic beacon positioning configuration is naturally asymmetrical (Bürgmann and Chadwell, 2014; Liu et al., 2006; Zhao et al., 2018). Since the known points are located on the sea surface while the unknown point is located on the seafloor, the observations along the vertical direction is so asymmetrical that it is hardly to compensate systematic errors, resulting in a relatively low positioning precision in the vertical direction. In order to reduce the error influence on the vertical direction, the seafloor geodetic station is usually equipped with a depth gauge to obtain the water depth information to remedy the deficiency of the asymmetrical configuration. At present, the relative precision of the most precise depth gauge can reach 1/10000 (Polster et al., 2009). When double depth gauges are installed on the transducer and the transponder respectively, we can obtain the vertical distance between the transducer and transponder at each observation epoch. By using the depth information to establish an observational equation system to constrain the positioning process, the vertical positioning accuracy can be improved.

The centering correction otherwise known as leverage arm offset from the GNSS antenna phase center to the transducer needs to be solved when using the GNSS/acoustic technique to conduct the seafloor geodetic positioning. The offset correction measurement error can lead to a systematic error and then affect the seafloor geodetic positioning. The offset parameters in the ship-based coordinate system are generally constant and can be premeasured by the total station or other instruments for implementing the centering correction on the observations. The offset parameters can also be treated as unknown parameters and estimated together with the coordinate parameters of the seafloor geodetic station. However, since the vertical offset parameter is highly related to the vertical coordinate of the seafloor geodetic station, treating the offset parameters as unknowns to be estimated with the seafloor geodetic coordinates will lead to an ill-posed observational model (to be ill-conditioned and even to be rank defect). Researchers proposed a sample search algorithm, according to which the vertical offset parameter is fixed firstly, and then the horizontal offset parameters are estimated together with the three-dimensional geodetic coordinates, and this approach can significantly improve the estimation effectiveness (Chen et al., 2019). We propose a strategy that by premeasuring the offset parameters at first and treating the premeasured offset parameters and their uncertainty information as prior information, the offset parameters and geodetic coordinates can be figured out with the Bayesian estimation approach (Yang, 1991). The strategy can not only avoid the ill-posed problem caused by the strong correlation between the vertical offset parameter and the vertical coordinate of geodetic station, but also improve the precision of the estimated offset parameters.

Assuming that the offset parameters from the GNSS antenna to the transducer have been figured out and the aided depth observations from the seafloor gauge have been obtained, the left problem is to optimally determine the three-dimensional coordinates of the seafloor geodetic stations. Currently, a great number of studies show that the position precision of vehicle GNSS antenna can reach centimeter level; thus, we can ignore the influence of the GNSS positioning error and only consider the influence of the surface vehicle tracking lines' geometric configuration on the seafloor geodetic positioning. It shows that the surface vehicle tracking lines determine the geometric strength contained in the observations (Chadwell et al., 2002; Mcintyre, 1989). Theoretical studies and experimental tests show that, when the surface vehicle tracks the seafloor geodetic station to form a circle tracking line with a radius equal to $\sqrt{2}$ times the water depth, an optimized geometric structure can be obtained (Xue et al., 2014; Zhao et al., 2016; Zou et al., 2017). If further considering the systematic error influence and the requirements in the differential positioning, we need to introduce cross tracking lines right above the seafloor geodetic station. The circle plus the cross lines can further improve the positioning geometric structure and reduce the systematic error influence. The ship tracking line previously proposed by Japanese researchers still has reference values (Fujita et al., 2006; Sato et al., 2013). It should be noted that, the circle plus cross lines also belongs to symmetry-type observational configurations, which are still helpful to reduce the influences of systematic errors including the offset error, sound velocity error and acoustic ray bend error, etc.

5. Acoustic positioning model refinement and seafloor geodetic positioning

As the ocean acoustic observations are seriously affected by the ocean environmental factors such as the sea water temperature, salinity, density, currents, etc., (Osada et al., 2003; Li et al., 2016), there are great challenges in the model refinement for the high-precision acoustic positioning. Functional model and stochastic model were widely studied to tackle the high-precision underwater positioning problems. The dominant errors in acoustic positioning are the systematic error and random error from the sound speed spatial-temporal variations and the acoustic signal delay measurements. The observational model refining is however closely related to the used observational mode and the combination type of observation information. Different observation combination modes have different error influences on the seafloor geodetic positioning. Besides, the influence of linearization error on the positioning needs to be considered in shallow sea positioning (Xue et al., 2014).

The uncertainty of the sound speed is one of dominant error sources in acoustic positioning. The sound speed profile (SSP) measurement may contain instrument calibration error and spatial-temporal representativeness error (Yamada et al., 2002). To reduce the influence of systematic errors represented by the sound speed error on the positioning, a GNSS-like differential technique can be utilized (Xu et al., 2005; Yang et al., 2011). The differential technique can weaken the common errors in observations, but at the same time the vertical positioning information in the un-differential observations is reduced, which further decreases the vertical positioning precision. The cross lines can be used to improve the vertical positioning geometry, and the data amount is much smaller than that of the circle line. We can then develop a combination observation mode where the circle line is used to form differential observation equations while the cross line is used to form un-differential observation equations. This combination can weaken the sound speed error influence on the one hand, and provide a necessary complement to the vertical positioning information on the other hand.

Like the above discussed spatial-differential mode to weaken the spatial representativeness error, the epoch-differential mode, based on differences between the adjacent observations, can be used to weaken the temporally related systematic errors. Some researchers proposed the robust single and double differential positioning techniques by combining the epoch-differential mode with the robust estimation (Zhao et al., 2017; Gao, 2018). The robust epoch-differential can not only weaken the influence of temporally related errors, but also effectively control the influence of outliers.

The acoustic ray bend error and the sound speed error are two types of major systematic error sources of the underwater positioning. The acoustic ray bend error is related to both the spatial-temporal varying ocean environment and the incident angle of the ray. When the SSP data in the field is available, theoretically the acoustic ray bend error can be completely removed by the ray-tracing positioning method. However, as mentioned above, there are strong uncertainties and spatial-temporal representativeness errors in the SSP data. For these reasons, we recommend that, the seafloor geodetic data processing should adopt the constant velocity positioning model, and then add both the ray bend error correction and the acoustic signal delay correction, or perform modelling and parameter estimation compensation. The prior sound speed can adopt the empirical speed (Zhao and Liu, 2008) or the weighed mean speed (Yi et al., 2009). The time-varying speed error influence has become a thorny problem in high-precision acoustic positioning, and this kind of error might be significantly reduced by developing dynamic data processing model for seafloor geodetic network referring to the GNSS atmospheric error processing practice. Besides, the neural network learning approach (Nguyen and Widrow, 1990), the equivalent sound speed method (Geng, 1997), effective sound velocity method (Sun, 2007) and the acoustic ray error correction method (Wang et al., 2009) can be utilized to reduce the influence of the sound speed error.

To precisely implement the acoustic ray error correction on the acoustic ranging observations, we must obtain the sound speed field (SSF) information within the observing time interval and the sea area. The spatial interpolation and empirical orthogonal functions (EOF) are two commonly used approaches to restructure the sound speed field by utilizing the discretely distributed SSP data (Wu, 2013). EOF has been widely considered as the most effective base functions to describe the SSP (Davis, 1976), and generally 2–3 order EOF functions can be used to precisely represent arbitrary SSP within the surveying region. Combining the EOP with the genetic simulated annealing algorithm has been applied in shallow sound speed field inversion (Zhang and Liu, 2006). Using the obtained SSP, we can trace the acoustic ray to get the ray error correction value (Takahashi et al., 2000; Sakic et al., 2018; Wang et al., 2016). As one can imagine, too much layering of the SSP will lead to inefficiency in the ray tracing, and thus an adaptive SSP division algorithm was proposed (Li et al., 2015; Zhang et al., 2013). The adaptive filter algorithm may also be applied to utilize the prior sound speed model and the measured SSP data (Yang and Zeng, 2009).

In the practice of underwater positioning, as the acoustic ray bend error becomes large with the increase of incident angle, the underwater positioning regarding the incident angle becomes one of hot research topics in establishing the functional models (Yang et al., 2011). The acoustic ray error influence was also considered in the stochastic model (Han et al., 2017; Zhao et al., 2018), in which the weight of the acoustic ranging signal with larger error is decreased to weaken its influence. The stochastic model construction and parameter estimation approach will be discussed in our future works and not be presented here in details.

6. Deep-sea experiment and preliminary analysis

Applying the above-mentioned seafloor geodetic shelter development strategy, seafloor geodetic location selection criterion and geodetic network layout strategy, we conducted a deep-sea experiment in a sea areas of 3000 m depth in July, 2019. Figure 3 illustrates the seafloor geodetic network and the surface ship tracking lines, where the five seafloor stations adopt the configuration as shown in Figure 2b, and the radius of each circle tracking line is about 0.5 times the seawater depth. In addition, a circle tracking line with the radius of 1.5 times the seawater depth and a series of cross lines are laid for locating the station No.5.

Compared with the terrestrial environment, the observation condition under the ocean environment is relatively poor, resulting in more outliers in acoustic observations which have a huge impact on the least squares (LS) estimation. To control the influences of gross errors, we adopted the robust LS with IGGIII scheme (Yang et al., 2002a, 2002b) to process the data. To show the influences of different observation strategies on the positioning results, we used the following four schemes to calculate the seafloor geodetic coordinates: Scheme 1, circle tracking line with the radius of about 0.5 times the seawater depth; Scheme 2, circle tracking line with the radius of about 1.5 times the seawater depth; Scheme 3, cross tracking lines; Scheme 4, circle tracking line plus cross tracking lines.

In Tables 2 and 3, $\mathbf{m}_X$, $\mathbf{m}_Y$ and $\mathbf{m}_H$ represent the RMS of the coordinates *X*, *Y* and *H*, respectively.

Table 2 presents the internal precisions of the five seafloor geodetic stations in the circle tracking observation scheme 1. The seafloor geodetic station No.5 is measured by different

Table 2 Internal precisions of the seafloor geodetic stations (Scheme 1)

No.	$\mathbf{m}_X$ (m)	$\mathbf{m}_Y$ (m)	$\mathbf{m}_H$ (m)
1	0.018	0.012	0.019
2	0.029	0.020	0.030
3	0.019	0.013	0.020
4	0.045	0.034	0.047
5	0.032	0.025	0.042

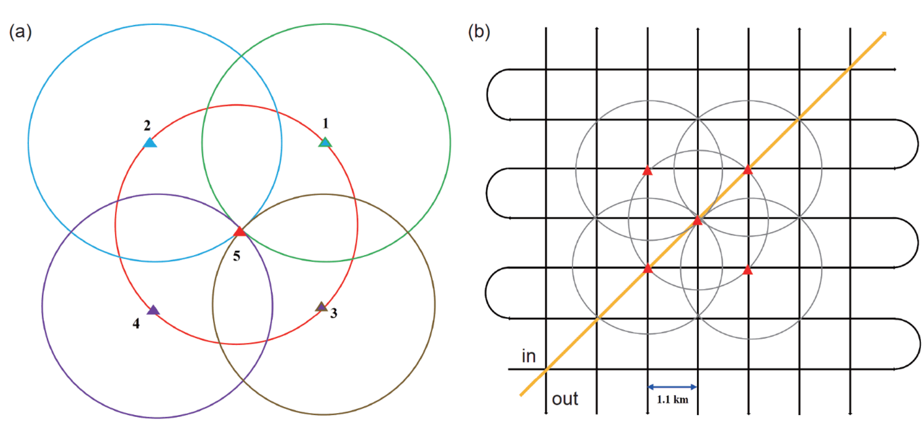

Figure 3 Illustration of the seafloor geodetic network (a) and verification line for acoustic navigation (b).

Table 3 Internal precisions of the seafloor geodetic station No.5 adopting different schemes

Schemes	Coordinates			Precision		
	X (″)	*Y* (″)	*H* (m)	$\mathbf{m}_X$ (m)	$\mathbf{m}_Y$ (m)	$\mathbf{m}_H$ (m)
Scheme 1	0.06	0.613	−72.67	0.032	0.025	0.042
Scheme 2	0.054	0.622	−72.42	0.018	0.02	0.018
Scheme 3	0.067	0.607	−72.43	0.026	0.018	0.026
Scheme 4	0.06	0.615	−72.43	0.022	0.015	0.023

Table 4 Coordinate differences under different schemes

Schemes	*X* (″)	*Y* (″)	*H* (m)
Scheme 1	0.000	−0.001	−0.182
Scheme 2	−0.006	0.008	0.068
Scheme 3	0.007	−0.007	0.058
Scheme 4	0.000	0.001	0.058

radius circles and cross lines, and the corresponding positioning results are shown in Table 3. Since external reference values with higher precision about the seafloor geodetic stations are hardly given, we used the mean of the positioning results from different schemes as a reference to show the differences between each scheme and the mean value as shown in Table 4. Table 2 indicates that the internal precision ranges from 1.2 to 4.7 cm. Tables 3 and 4 show that the maximum differences in directions of *X*, *Y* and *H* are 0.007″, 0.008″ and 0.182 m respectively. Since the different schemes are implemented independently in different days, they can be used for mutual verifying and checking. By further refining the functional model and improving the algorithm, higher accuracy results are expected to be obtained. As the optimization of data processing models and improvement in algorithms involve many aspects, we will discuss them in future works and do not present here in details.

Once the five seafloor geodetic station coordinates are obtained, we simultaneously track the five seafloor geodetic stations to conduct a sea surface vehicle navigation test. The vehicle navigation precision is evaluated by comparing with the GNSS measured results of the sea surface vehicle trajectory. The acoustic navigation testing used the grid-type figure as shown in Figure 3b, where the maximum testing distance is 11 km away from the center of the seafloor geodetic network. Testing result shows that, the navigation precision (RMS) within the seafloor geodetic network coverage is better than 3 m and in margin areas outside of the network is still better than 10 m.

7. Conclusions

(1) Seafloor geodetic network is a significant part of the marine geodetic reference frame construction. Establishing a seafloor geodetic network starts with developing the acoustic beacon device suitable for deep-sea deployment, which not only needs to be pressure-resistant, anti-corrosive, but also anti-dragging and anti-flow; meanwhile, it must possess long-term working ability. The selected frequency range should be as low-frequency and wide-band as possible. In addition, the direct sequences or frequency hopping approach should be adopted to improve the signal detection ability.

(2) The seafloor geodetic station should be laid in flat regions with good geological stability and without soft sediments. If only for underwater navigation, the overall network layout should consider the maximum tolerant accumulation error of the INS equipped on the submarine vehicle to develop a relay-type seafloor geodetic network to restrict the tolerant error effects on margin areas. If applied to the seafloor crustal motion monitoring, the distribution of seafloor plate tectonics should be taken into account in the overall network design, in order to ensure one or more relatively independent local seafloor networks for each plate. To partly compensate the influence of systematic errors, each local seafloor network should be as symmetrical as possible.

(3) Observation strategy optimization is one of effective ways to weaken the systematic error influence. In the practice of measurement, offset correction (i.e., the centering correction) parameters between the GNSS antenna phase center and the transducer should be first premeasured, and then the offset correction parameters can be treated as unknowns with prior information to implement a jointed parameter estimation with the coordinate parameters of the seafloor geodetic station. Using this recommended strategy, not only the ill-posed problem is avoided, but also the precision of the estimated offset parameters can be improved. The depth gauge observation, which should be treated as an important aided information of the seafloor positioning, can be processed together with the acoustic observations. To weaken the influence of some systematic errors, each seafloor geodetic point should be observed by a circle tracing line aided with cross tracing lines to perform a jointed data processing. This strategy can not only improve the vertical coordinate precision, but also weaken the influence of systematic errors on the horizontal coordinates.

(4) As acoustic observational error changes with the varying ocean environment, the acoustic observation model should have the abilities to compensate the influences of

relevant systematic errors. Systematic error compensation can adopt the spatial-differential and the epoch-differential approach respectively to weaken the spatial-related and temporal-related errors. Acoustic ray error correction approach is commonly used to reduce the systematic error, but the specific value of the systematic error needs to be figured out in advance to correct the observations. In contrast, the functional model error compensation approach is one of more effective methods, which treats the systematic error as unknown parameter to be estimated together with the model parameters.

In practical applications, establishing resilient functional model and resilient stochastic model for undersea multi-sensors, and resilient data fusion model for sea surface and subsurface observations, are still an important development direction in the seafloor geodetic network construction and applications.

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References

Bürgmann R, Chadwell D. 2014. Seafloor geodesy. Annu Rev Earth Planet Sci, 42: 509–534

Chadwell C D, Hildebrand J A, Spiess F N. 2002. Seafloor geodetic monitoring with the plate boundary observatory. http://www.scec.org/news/00news/images/pbominiproposals/Chadwellpbo24.pdf

Chen G, Liu Y, Liu Y, Tian Z, Liu J, Li M H. 2019. Adjustment of transceiver lever arm offset and sound speed bias for GNSS-Acoustic positioning. Remote Sens, 11: 1606

Chen J Y, Yang Y X, Wang M. 2007. Establishment of 2000 national geodetic control network of China and its technological progress. Acta Geod Cartogr Sin, 36: 1–8

Cheng W H. 2004. A study of increasing the precision of navigation position for submerged body. Ocean Eng, 31: 693–707

Davis R E. 1976. Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean. J Phys Oceanogr, 6: 249–266

David C C, Spiess F N. 2008. Plate motion at the ridge-transform boundary of the south cleft segment of the Juan de Fuca Ridge from GPS-acoustic data. J Geophys Res, 113: B04415

Defense Advanced Research Projects Agency. 2016. Department of Defense Fiscal Year (FY) 2017 President's Budget Submission. February 2016[EB/OL]

Favali P, Beranzoli L. 2006. Seafloor observatory science: A review. Ann Geophys, 49: 515–567

Fujimoto H, Kanazawa T, Murakami H. 1997. Seafloor acoustic ranging and the effect of temperature variation. In: Segawa J, Fujimoto H, Okubo S, eds. Gravity, Geoid and Marine Geodesy. Tokyo. 690–695

Fujita M, Ishikawa T, Mochizuki M, Sato M, Toyama S, Katayama M, Kawai K, Matsumoto Y, Yabuki T, Asada A, Colombo O L. 2006. GPS/Acoustic seafloor geodetic observation: Method of data analysis and its application. Earth Planet Space, 58: 265–275

Fujiwara T , Kodaira S , No T, Kaiho Y, Takahashi N, Kaneda Y. 2011. The 2011 Tohoku-Oki Earthquake: Displacement reaching the trench axis. Science, 334: 1240

Gao R. 2018. Research on key techniques of underwater acoustic positioning algorithm. Dissertation for Master's Degree. Xi'an: Chang'an University

Geng X. 1997. Precise acoustic bathymetry. Dissertation for Master's Degree. Victoria B C: University of Victoria

Han Y, Zheng C, Sun D. 2016. Signal design for underwater acoustic positioning systems based on orthogonal waveforms. Ocean Eng, 117: 15–21

Han Y F, Zheng C, Sun D J. 2017. An optimized estimation method in long baseline acoustic positioning systems (in Chinese). Acta Acustica, 42: 14–20

Hui J, Sheng X. 2007. Underwater Sound Channel (in Chinese). Beijing: National Defense Industry Press

Li L. 2007. Study on array measuring & calibration for long base line array (in Chinese). Dissertation for Doctoral Degree. Harbin: Harbin Engineering University

Li L Y, Lu Z P, Cui Y. 2018. Summary of the research progress of seafloor geodetic control network (in Chinese). Bull Surv Map, (1): 8–13

Li S X, Wang Z J, Nie Z X, Wang Y, Wu S Y. 2015. A self-adapting division ray-tracing method in the long baseline acoustic positioning (in Chinese). Mar Sci Bull, 34: 491–498

Li S J, Bao G S, Wu S G. 2005. A practical overview and prospect of acoustic positioning technology (in Chinese). Ocean Technol, 24: 130–135

Li Z, Dosso S E, Sun D. 2016. Joint inversion for transponder localization and sound-speed profile temporal variation in high-precision acoustic surveys. J Acoust Soc Am, 140: EL44–EL49

Liu B. 2008. Research on generation of orthogonal waveform and signal processing for MIMO Rader (in Chinese). Dissertation for Doctoral Degree. Chengdu: University of Electronic Science and Technology of China

Liu B S, Lei J Y. 2010. Principles of Underwater Acoustics (in Chinese). Harbin: Harbin Engineering University Press

Liu J N, Chen G X, Zhao J H, Gao K F, Liu Y X. 2019. Development and trends of marine space-time frame network (in Chinese). Geoma Inform Sci Wuhan Univ, 44: 17–37

Liu Y X, Peng L, Wu Y, Zhou X H. 2006. Calibration of transducer and transponder positions (in Chinese). Geoma Inform Sci Wuhan Univ, 31: 610–612

Matsumoto Y, Ishikawa T, Fujita M, Sato M, Saito H, Mochizuki M, Yabuki T, Asada A. 2008. Weak interpolate coupling beneath the subduction zone off Fukushima, NE Japan, inferred from GPS/Acoustic seafloor geodetic observation. Earth Planet Space, 60: 9–12

McGuire J J, Collins J A. 2013. Millimeter-level precision in a seafloor geodesy experiment at the discovery transform fault, east pacific rise. Geochem Geophys Geosyst, 14: 4392–4402

Mcintyre M C. 1989. Design and Testing of a Seafloor Geodetic System. San Diegom C A: University of California

Mochizuki M, Sato M, Katayama M. 2003. Construction of seafloor geodetic observation network around Japan. Tokyo: Recent Advances in Marine Science and Technology. 591–600

National Security Space Office. 2008. National positioning, navigation, and timing architecture study. The executive summary of the PNT architecture study final report. National Security Space Office. https://rosap.ntl.bts.gov/view/dot/16923/dot_16923_DS1.pdf

Nguyen D, Widrow B. 1990. Improving the learning speed of 2–layer neural networks by choosing initial values of the adaptive weights. San Diego: International Joint Conference on Neural Networks. 21–26

Ning J S, Wu Y T, Sun D J. 2014. The development of LBL acoustic positioning system and its application (in Chinese). Hydrogr Surv Chart, 23: 72–75

Osada Y, Fujimoto H, Miura S, Sweeney A, Kanazawa T, Nakao S, Sakai S, Hildebrand J A, Chadwell C D. 2003. Estimation and correction for the effect of sound velocity variation on GPS/Acoustic seafloor positioning: An experiment off Hawaii Island. Earth Planet Space, 55: 17–20

Polster A, Fabian M, Villinger H. 2009. Effective resolution and drift of Paroscientific pressure sensors derived from long-term seafloor measurements. Geochem Geophys Geosyst, 10: 1–19

Sakic P, Piété H, Ballu V, Royer J Y, Kopp H, Lange D, Petersen F, Özeren M S, Ergintav S, Geli L, Henry P, Deschamps A. 2016. No significant steady state surface creep along the North Anatolian Fault offshore Istanbul: Results of 6 months of seafloor acoustic ranging. Geophys Res Lett, 43: 6817–6825

Sakic P, Ballu V, Crawford W C, Wöppelmann G. 2018. Acoustic ray tracing comparisons in the context of geodetic precise off-shore positioning experiments. Mar Geodesy, 41: 315–330

Sato M, Fujita M, Matsumoto Y, Saito H, Ishikawa T, Asakura T. 2013. Improvement of GPS/acoustic seafloor positioning precision through controlling the ship's track line. J Geodesy, 87: 825–842

Spiess F N, Chadwell C D, Hildebrand J A, Young L E, Purcell Jr. G H, Dragert H. 1998. Precise GPS/Acoustic positioning of seafloor reference points for tectonic studies. Phys Earth Planet Inter, 108: 101–112

Sun D, Zheng C, Cui H, Zhang J, Han Y. 2018. Developing status and some cutting-edge issues of underwater sensor network localization technology. Sci Sin-Inf, 48: 1121–1136

Sun D J, Zheng C E, Zhang J C. 2019. Development and prospect for underwater acoustic positioning and navigation technology (in Chinese). Bull Chin Acad Sci, 34: 331–338

Sun W Q. 2007. Studies on underwater acoustic localization technique in shallow water and its application (in Chinese). Dissertation for Doctoral Degree. Qingdao: Ocean University of China

Takahashi N, Futa K, Tsuchiya T, Kikuchi T. 2000. Calculation of eigenray with equi-sound-speed division of sound speed profile. Acoust Sci Technol, 21: 153–161

The General Armaments Department of the PLA. 2011. General specification for military lithium primary batteries (in Chinese). National military standards of the People's Republic of China, GJB916B-2011, 2011-11-25

Tian T. 2010. Sonar Technology. 2nd ed (in Chinese). Harbin: Harbin Engineering University Press

Wang Y, Lin W S, Liang G L. 2009. The influence and revision of ray bending in synchronous underwater acoustic positioning system (in Chinese). Tech Acoust, 28: 123–124

Wang Z J, Li S X, Nie Z X, Wang Y, Wu S Y . 2016. A Large Incidence Angle Ray-Tracing Method for Underwater Acoustic Positioning (in Chinese). Geoma Inform Sci Wuhan Univ, 41: 1404–1408

Wei Z. 2008. China geodetic coordinate system 2000 and its comparison with WGS84. J Geodesy Geody, 28: 1–5

Wei Z Q, Liu G M, Wu F M. 2011. China geodetic coordinate system 2000: Velocity field in mainland China (in Chinese). Acta Geod Cartogr Sin, 40: 403–410

Wu Y T. 2013. Study on theory and method of precise LBL positioning and development of positionig software system (in Chinese). Dissertation for Doctoral Degree. Wuhan: Wuhan University

Xu P, Ando M, Tadokoro K. 2005. Precise, three-dimensional seafloor geodetic deformation measurements using difference techniques. Earth Planet Space, 57: 795–808

Xue S Q, Yang Y X, Dang Y M. 2014. A closed-form of newton iterative formula for nonlinear adjustment of distance equations (in Chinese). Acta Geod Cartogr Sin, 43: 771–777

Yamada T, Ando M, Tadokoro K, Sato K, Okuda T, Oike K. 2002. Error evaluation in acoustic positioning of a single transponder for seafloor crustal deformation measurements. Earth Planet Space, 54: 871–881

Yan J, Zhang H M, Zhao J H. 2016. Study on improvement of multibeam backscatter angular response model (in Chinese). Acta Geod Cartogr Sin, 45: 1301–1307

Yang F, Lu X, Li J, Han L, Zheng Z. 2011. Precise positioning of underwater static objects without sound speed profile. Mar Geol, 34: 138–151

Yang Y X. 1991. Robust Bayesian estimation. Bull Geod, 65: 145–150

Yang Y X, Song L, Xu T H. 2002a. Robust estimator for correlated observations based on bifactor equivalent weights. J Geodesy, 76: 353–358

Yang Y X, Song L J, Xu T H. 2002b. Robust parameter estimation for geodetic correlated observations (in Chinese). Acta Geod Cartogr Sin, 31: 95–99

Yang Y X. 2009. Chinese geodetic coordinate system 2000. Chin Sci Bull, 54: 2714–2721

Yang Y X, Zeng A M. 2009. Adaptive filtering for deformation parameter estimation in consideration of geometrical measurements and geophysical models. Sci China Ser D-Earth Sci, 52: 1216–1222

Yang Y X. 2016. Concepts of comprehensive PNT and related key technologies (in Chinese). Acta Geod Cartogr Sin, 45: 505–510

Yang Y X, Xu T H, Xue S Q. 2018. Progresses and prospects in developing marine geodetic datum and marine navigation of China. J Geodesy Geoinfor Sci, 1: 1–9

Yang Y X, Li X Y. 2017. Micro-PNT and comprehensive PNT (in Chinese). Acta Geod Cartogr Sin, 46: 1249–1254

Yang Y X. 2019. Resilient PNT concept frame. J Geodesy Geoinfor Sci, 2: 1–7

Yi C H, Ren W J, Wang C. 2009. Analysis on error of secondary acoustic positioning system (in Chinese). Oil Geophys Prospec, 44: 136–139

Zhang J C, Zheng C E, Sun D J. 2013. A self-adapting division method for ray-tracing positioning (in Chinese). J Harbin Eng Univ, 34: 1497–1501

Zhang Z M, Liu B S. 2006. Simulation study of sound speed profile inversion in shallow water using genetic simulated annealing algorithm (in Chinese). J Harbin Eng Univ, 27: 505–508

Zhao J, Zou Y, Zhang H, Wu Y, Fang S. 2016. A new method for absolute datum transfer in seafloor control network measurement. J Mar Sci Technol, 21: 216–226

Zhao J H, Liu J N. 2008. Multibeam Bathymetry and Image Data Processing (in Chinese). Wuhan: Wuhan University Press

Zhao J H, Wang A X. 2015. Precise marine surveying and data processing technology and their progress of application (in Chinese). Hydrogr Survey Chart, 35: 1–6

Zhao J H, Chen X H, Wu Y T, Feng J. 2018. Determination of absolute coordinate of underwater control point taking waves and depths constraint into account (in Chinese). Acta Geod Cartogr Sin, 47: 413–421

Zhao S, Wang Z J, Liu H M. 2018. Investigation on underwater positioning stochastic model based on sound ray incidence angle (in Chinese). Acta Geod Cartogr Sin, 47: 1280–1289

Zhao S, Wang Z J, Wu S Y. 2017. A ship-board acoustic difference positioning method based on selection weight iteration (in Chinese). Oil Geophys Prospect, 52: 1137–1145

Zou Y, Wang C, Zhu J, Li Q. 2017. Optimal sensor configuration for positioning seafloor geodetic node. Ocean Eng, 142: 1–9

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