IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 30 November 2023, accepted 26 December 2023, date of publication 1 January 2024,
date of current version 9 January 2024.

Digital Object Identifier 10.1109/ACCESS.2023.3348782

RESEARCH ARTICLE

Research on Underwater Collaborative Detection Method Based on Complex Marine Environment

CHAOFENG LAN[1], ZELONG YU[1], HUAN CHEN[2], LEI ZHANG[3], AND MENG ZHANG[4]
[1]School of Measurement and Communication Engineering, Harbin University of Science and Technology, Harbin 150080, China
[2]China Shipbuilding Research and Design Center, Wuhan 430064, China
[3]Beidahuang Industry Group General Hospital, Harbin 150088, China
[4]School of Electronics and Communication Engineering, Guangzhou University, Guangzhou 510006, China

Corresponding authors: Lei Zhang (happyzhang68@126.com) and Meng Zhang (zhangmeng@gzhu.edu.cn)

This work was supported in part by the Natural Science Foundation of Heilongjiang Province under Grant LH2020F033, in part by the National Natural Science Youth Foundation of China under Grant 11804068, and in part by the Research Project of the Heilongjiang Province Health Commission under Grant 20221111001069.

ABSTRACT In modern underwater warfare, detecting and locating enemy submarines is the primary task, but there are still many difficulties in detecting submarines. The acoustic signals may distort in the ocean channel due to the complexity of the ocean, which affects the detection of sonar. That is to say, the impact of environmental factors needs to be considered in submarine detection. Therefore, this article proposes an underwater collaborative detection method based on complex marine environments, constructs a sonar underwater detection capability analysis system to improve detection performance, analyzes the impact of marine environmental factors on sonar detection capability, evaluates sonar performance using sonar quality factor, calculates sonar detection distance, establishes polar coordinates, and explores sonar detection capability; Besides, the concept of collaborative detection is also introduced, and a collaborative detection probability distribution surface is proposed to fuse the detection capabilities of different platforms, presenting the collaborative detection capabilities of multiple platforms in the form of probability contour lines. The detection performance of different deployment methods is explored by changing the placement position and number of platforms. At last, the research has shown that the underwater detection capability of sonar is closely related to the marine environment. The square layout in underwater collaborative detection has better detection performance. The research results of this article can provide references for the layout of platforms in underwater detection tasks.

INDEX TERMS Marine environment, sound signal propagation, collaborative detection, probability distribution surface, detection capability.

I. INTRODUCTION

Underwater warfare occupies the main position in today's naval warfare due to its unique concealment and complexity. The emergence of this new form of combat has brought unprecedented challenges to naval warfare. In addition, the development and application of various new types of unmanned underwater combat equipment in recent years have put forward higher requirements for the study of underwater combat concepts [1].

Underwater combat is a typical systematical combat. With the introduction of the concept of agile underwater combat by the US military, the widespread application of unmanned clusters in underwater combat has become a research hotspot in various countries. Due to limited investment in resources and constantly changing task requirements, and different platforms have different tasks. It is necessary to coordinate the impact of the marine environment on the ability of each node platform to achieve tasks, making the planning of underwater combat missions more challenging. Submarine detection is the primary task of underwater warfare and the foundation for achieving a series of activities such as submarine

The associate editor coordinating the review of this manuscript and approving it for publication was Tao Wang.

search and attack. In the field of submarine detection, traditional platform anti submarine detection methods and tactical collaborative anti submarine detection methods have always been the most commonly used detection methods. In recent years, underwater acoustic network (UAN) [2] and unmanned underwater vehicle (UUV) technology [3] have developed rapidly, providing new directions for anti submarine detection.

In the field of anti-submarine collaborative detection, research on collaborative detection of homogeneous detection equipment has achieved relatively numerous results, while research on collaborative detection of heterogeneous sensors is currently mainly focused on tactical collaborative operations, and has not yet delved into the fusion level of detection information [4]. Although homogeneous formations can effectively improve detection efficiency, the single platform type and function within the formation limits its flexibility in application. Heterogeneous formation detection is currently a hot research direction in cluster detection. Based on the characteristics of various types of platforms, tasks on each platform are reasonably allocated to enhance strengths and avoid weaknesses, and improve overall detection efficiency [5].

Ji et al. [6] proposed a regional coverage performance evaluation model based on a multi-static sonar detection system, and verified the feasibility of improving the detection performance of the sonar system by reasonably setting the working parameters of the sonar system through experiments. Wu [7] proposed a collaborative detection method for the Anti Submarine Detection Profile (ASDP), which accurately describes the global situation distribution of the search capability of the anti submarine system through the visualization of probability distribution. This result, after practical modification, can be used to assist anti submarine system combatants in command decision-making. Zou [8] proposed a regional coverage performance evaluation model for a multi-static sonar detection system and verified the feasibility of improving the detection performance of the sonar system by reasonably setting the working parameters of the sonar system. Zhou [9] proposed a fusion detection algorithm for multi-static sonar systems based on cumulative detection probability, comparing the detection performance of different sonar arrangements, and further studying the spatial gain of vector hydrophones. In recent years, multiple scholars have conducted research on sonar deployment strategies for collaborative detection and have achieved rich results [10], [11], [12]. Based on the above research, this article further studies the area coverage capability of multi platform collaborative detection and explores the impact of platform placement on the detection coverage area.

The ocean is the combat space for submarines and anti-submarine forces, and its environmental characteristics play a decisive role in the detection and tracking of acoustic sensors. It is crucial to fully understand and master the ocean battlefield environment for submarines and anti-submarine forces. Reasonable utilization of the ocean environment and efficient performance of sonar are the basic conditions for achieving victory in underwater warfare. With the continuous deepening of research on ocean environmental effects, the impact of the underwater acoustic environment on the design and application of sonar equipment can be quantitatively described [13].

Due to the constantly changing marine environment, the impact of environmental information on marine warfare is enormous. While the underwater environment has a certain impact on the propagation of underwater acoustic signals, which can interfere with the detection probability of sonar [14]. Based on this point, domestic and foreign experts and scholars have begun to focus on studying the impact of underwater environment on sonar detection capabilities. Guo [15] explored the impact of environmental uncertainty on the prediction of sonar action distance and proposed the probability distribution of sonar action distance, providing a probability basis for the prediction of action distance. Zhang et al. [16] studied the main factors affecting the operating distance of passive sonar and conducted experimental analysis using orthogonal experimental design. The results show that the operating frequency and depth of sonar have a significant impact on the operating distance of sonar. Gao et al. [17] examined seasonal changes in the ocean and the impact of different regions on the probability of passive sonar detection, and established a mathematical model for the probability of passive sonar detection to quantitatively describe the effects of the ocean environment. Tong [18] delved deeper into the impact of the ocean environment on sonar systems. He pointed out that in addition to traditional sonar technology improvements, it is also necessary to consider the complexity of ocean environment noise and changes, and adapt sonar systems to the ocean environment to achieve better detection performance. In the complex and ever-changing marine environment, the impact of seabed topography on the propagation of sound waves is receiving increasing attention. Liu et al. [19], [20] were the first to use the BELLHOP ray model for underwater sound field calculations, analyzing the impact of seabed topography on sound field uncertainty, laying an important theoretical foundation for sound propagation and its applications in complex marine environments. In recent years, more and more scholars have begun to study the construction of sonar detection and analysis models, quantitatively analyzing the impact of the marine environment on detection capabilities, and have achieved relatively abundant results [21], [22], [23]. It can be seen that marine environmental factors have a significant impact on the performance of sonar equipment, and it is urgent to establish a suitable sonar detection capability analysis model to analyze the impact of marine environment on sonar detection capability. Therefore, in this article, suitable ocean acoustic models will be explored to analyze how the underwater detection capability of sonar changes with changes in ocean environmental conditions.

In summary, research on anti-submarine detection is becoming increasingly diversified, but a complete analysis system for sonar underwater detection capability has not yet been constructed. Therefore, this paper starts from the sonar equation, combines hydrological environments such as temperature, salinity, and depth, and using the Bellhop ray model to calculate underwater sound propagation. By introducing the sonar quality factor, a sonar detection capability analysis system is constructed, and it is introduced into the polar coordinate system to visualize the real-time detection performance of the sonar. At the same time, the concept of collaborative detection is introduced, and the detection capabilities of multiple sonar are integrated to generate a collaborative detection probability for the entire region. The impact of sonar placement position and number on the overall detection capability is also analyzed. The research results provide reference for the placement of sonar in underwater detection tasks.

II. METHODS

A. OCEAN ENVIRONMENTAL SOUND PROPAGATION MODEL

The sonar equation combines sonar equipment, detection targets, and marine environmental characteristics, and is the theoretical basis for conducting sonar detection [24]. According to the working mode of sonar, it can be divided into two types: active sonar and passive sonar. In underwater warfare, these two methods are also mainly used for detection and positioning, and thus two signal margin formulas for active and passive are established. Among them, the active sonar equation can be divided into two types based on the main interference types: reverberation background and noise background.

The signal margin when under reverberation as the main interference type can be expressed as:

$$SE = SL - TL_1 - TL_2 + TS - RL - DT \tag{1}$$

The signal margin when under noise as the main interference type can be expressed as:

$$SE = SL - TL_1 - TL_2 + TS - NL - DT + DI \tag{2}$$

In the equation, SE represents the signal margin, which is the signal strength received by the receiver, SL represents the sound source level, TL_1 and TL_2 represent the propagation loss on the transmission and reception paths, TS represents the target strength, RL represents the reverberation level, DT represents the detection threshold of the sonar device, NL represents the noise interference level, and DI represents the reception directionality index.

The signal margin under passive working mode can be expressed as:

$$SE = SL_1 - TL_3 - NL - DT + DI \tag{3}$$

In the equation, SE represents the signal margin, which is the signal strength received by the receiver, SL_1 represents the target radiation sound source level, TL_3 represents the propagation loss between the target and the receiver, DT represents the detection threshold of the sonar equipment, NL represents the noise interference level, and DI represents the receiving directionality index.

From the above equations (1), (2), and (3), it can be seen that there is a close relationship between signal margin and propagation loss when the signal source and receiving source have been determined. Therefore, for the better simulation of the underwater sound field, it is necessary to establish a comprehensive underwater sound propagation loss model.

The quantitative transmission loss describes the amount of change in sound intensity generated by sound waves as a function of their propagation distance. The propagation of acoustic signals in underwater sound fields is mainly influenced by the depth of the sound source, emission frequency, receiver depth, and various environmental parameters such as seabed depth, seawater temperature, seawater salinity, and seabed topography. Therefore, the sound field environment can be predicted based on relevant data. At present, commonly used ocean sound propagation models include Bellhop ray model, Kraken normal mode model, and RAM parabolic equation model.

The Bellhop ray model not only has fast calculation speed, but also can effectively deal with the problem of high-frequency horizontal changes. Therefore, this article selects the Bellhop ray model to calculate the propagation loss of underwater acoustic signals. Bellhop is a model that predicts the sound pressure field in marine environments through ray and Gaussian beam tracking. It calculates the sound field in a horizontally non-uniform environment using Gaussian beam tracking method. In the calculation process of this model, the important parameter of sound velocity profile is required.

The sound speed profile (SSP) refers to the vertical profile where the sound speed varies with depth. At present, the sound velocity profile of seawater is mainly calculated based on temperature, salinity, and depth. The commonly used calculation formulas are Medwin and Del Grosso. This article uses the Medwin formula to calculate the sound velocity profile. The expression for calculating the sound velocity given by Medwin [25] is:

$$\begin{aligned} v = 1449.2 + 4.6t - 0.055t^2 + 0.00029t^3 \\ + (1.34 - 0.01t)(S - 35) + 0.016d \end{aligned} \tag{4}$$

In the formula, v represents the speed of sound in m/s, d represents depth in m, t represents temperature in $^{\circ}$C, S represents salinity in ng/L.

Equation (4) shows that the calculation of sound velocity in seawater is mainly related to depth, temperature, and salinity.

B. SONAR DETECTION CAPABILITY ANALYSIS MODEL

The Figure of Merit (FOM) can combine different sonar devices and targets, and is also a comprehensive measure of sonar performance. For a given sonar system, it objectively describes the detection ability and degree of superiority and inferiority of the sonar under specific detection performance requirements. The calculation formula for the sonar quality factor is:

$$FOM = SL - NL - DT_{FOM} + DI \tag{5}$$

In the formula, SL represents the sound source level, NL represents the noise level, DT_{FOM} represents the detection threshold of the sonar device, and DI represents the receiving directivity index.

The formula for calculating the probability of sonar detection P_d can be expressed as:

$$P_{\mathrm{d}} = 1 - \frac{1}{2} erfc[\frac{SE}{\sqrt{2}}] \tag{6}$$

In the equation, $erfc[x]$ is the complementary error function, and the definition equation can be expressed as:

$$erfc[\mathrm{x}] = \frac{2}{\sqrt{\pi}} \int_{\mathrm{x}}^{\infty} \mathrm{e}^{-\eta^2} \mathrm{d}\eta \tag{7}$$

SE represents the signal margin, and by combining equations (1), (2), (3), and (5), the calculation formula for SE can be obtained, which is:

$$SE(\text{Active}) = FOM - 2TL \tag{8}$$

$$SE(\text{Passive}) = FOM - TL \tag{9}$$

In the equation, TL represents the propagation loss on the transmission and reception paths. From equation (6), it can be seen that when $SE = 0$, P_d =0.5.

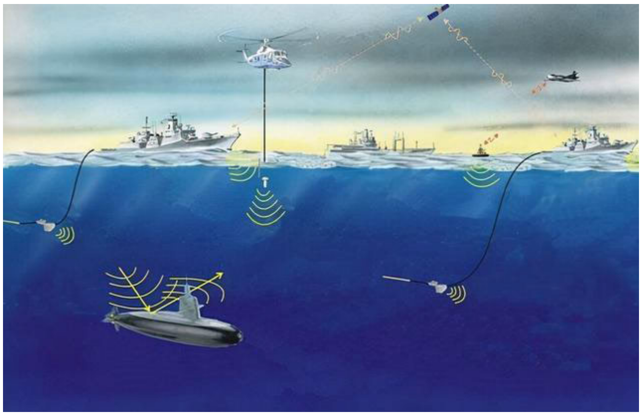
C. SONAR DETECTION CAPABILITY IN POLAR COORDINATE SYSTEM

Polar coordinate system is a coordinate system with polar diameter and polar angle as coordinate variables, which can be used to describe the direction and distance of sound waves propagating in water. In the polar coordinate system of sonar detection capability, the detection platform is used as the pole, the distance is represented by the polar diameter, and the direction is represented by the polar angle.

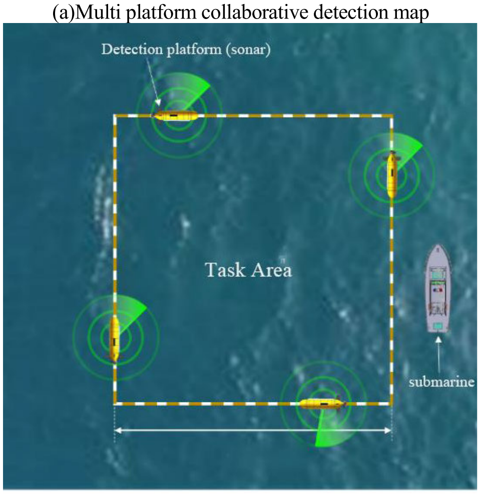
Firstly, evenly select 36 azimuth angles, with each azimuth angle spaced 10 ° apart. Then, the sonar detection capability analysis model is used to calculate the detection probability of each point in 36 directions. Finally, the detection probability of all points in the entire polar coordinate system region is obtained through multiple spline interpolation methods.

D. COLLABORATIVE DETECTION PROBABILITY DISTRIBUTION SURFACE

As shown in the Figure 1 (a), underwater collaborative detection is a multi-platform, multi-sensor collaborative detection technology aimed at improving the detection and tracking capabilities of submarines. This technology achieves rapid and accurate detection and positioning of submarines through information sharing, collaborative computing, and comprehensive analysis between multiple platforms and sensors, providing more timely and reliable decision support for underwater operations. As shown in Figure 1 (b), four detection platforms perform detection tasks in the task area, and by integrating the detection information of all detection platforms, the detection coverage task of the task area can be achieved. When an enemy submarine enters the detection area, it can successfully detect and capture the position information of the enemy submarine, providing information support for the next task.



(a)Multi platform collaborative detection map



(b)collaborative detection map

FIGURE 1. **Collaborative detection map.**

Each detection device has its own detection range, which is directly related to the target. Therefore, the probability range of detection varies for different targets. Unify the detection probabilities of each detection device using a probability surface, and fuse the detection capabilities through normalization to form a global detection capability situation map, which can reflect different degrees of detection probability distribution.

The collaborative detection probability distribution surface is centered around the detection platform, and the detection probability of each point located within the range of the detection equipment is calculated using a sonar detection capability analysis model. Therefore, the area where these points are located is called the collaborative detection probability distribution surface of the detection platform.Generally, different detection platforms have significant differences in detection range. Next, establish a mathematical model for the collaborative detection probability distribution surface.

Given the detection area A, M represents the set of detection platforms $M = \{m_1, m_2 \ldots m_n\}$, and P is the set of detection capabilities $P = \{p_1(x), p_2(x) \ldots p_n(x)\}$ for each detection platform. Therefore, the detection probability at point $r(x, y)$ on the detection probability surface of detection platform $m_i$is $p_i(r)$.

Because the detection probability of each detection platform at point $r(x, y)$ is different, it is necessary to solve the comprehensive probability, which is also the core issue of collaborative detection probability. This article uses joint probability for calculation, expressed as:

$$P_d(r) = 1 - \prod_{i=1}^{n} (1 - p_i(r)) \tag{10}$$

By calculating equation (11), the joint probability surface matrix can be obtained:

$$P_d = \begin{pmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{m1} & \cdots & p_{mn} \end{pmatrix} \tag{11}$$

Among them, m and n represent the range of probability surface values, $x \in (1, m)$, $y \in (1, n)$.

III. EXPERIMENT RESULT AND ANALYSIS

A. ACOUSTIC ENERGY ANALYSIS BASED ON MARINE ENVIRONMENT

The WOA2018 dataset is a marine hydrological dataset released by the NOAA organization in the United States in 2018, which includes data on water temperature, salinity, oxygen content, etc. The accuracy of longitude and latitude can reach 15 points [26], [27].Topo_19.1 dataset was released by Dr. Sandwell's research team in 2014 and contains global ocean depth data with an accuracy of up to 1 point [28]. This article selects the statistical average dataset of spring water temperature and salinity from WOA2018 data from 2005 to 2017, combined with the topo_19.1 sea depth dataset is used to calculate the sound velocity profile at a selected location.

Select a location ($22°N$, $132°E$) and extract water temperature, salinity, and sea depth data for that location. According to the basic knowledge of acoustics, it can be seen that most environmental factors related to sonar can be displayed using sound velocity profiles [29]. Based on equation (4), this article draws a sound velocity profile at the selected location, and the results are shown in Figure 2.

From Figure 2, it can be seen that different marine environments exhibit significant changes in sound velocity with increasing depth. During the transition of sound velocity from negative gradient to positive gradient, there are significant differences in sonar detection distance and performance. Besides, the depth with the lowest sound speed is beneficial for detection, while the depth with the highest sound speed is advantageous for concealment. Therefore, sonar is generally deployed at the location with the lowest sound velocity for detection, which is beneficial for detecting enemy targets.

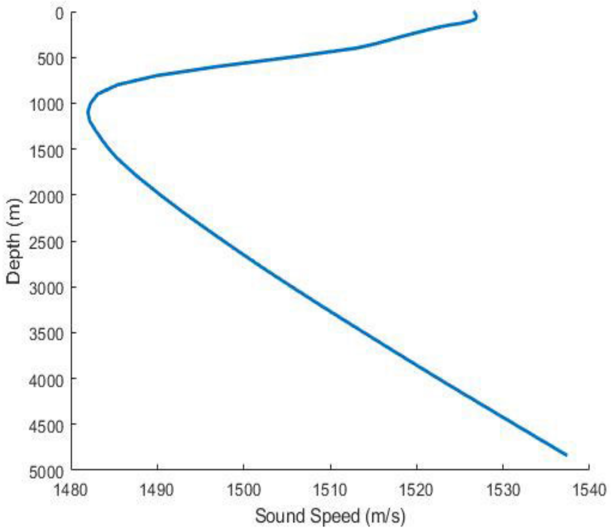


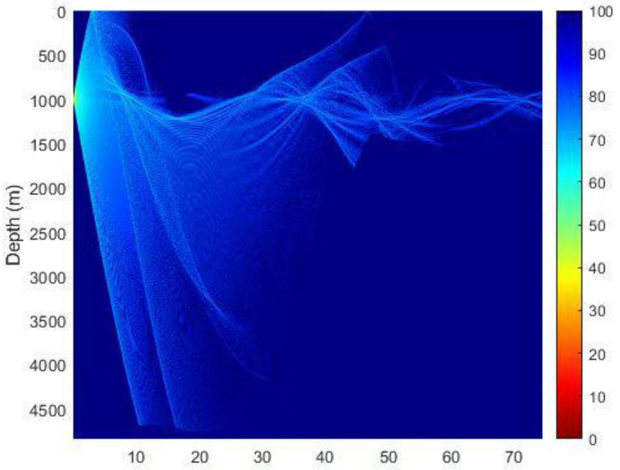
FIGURE 2. **Sound velocity profile.**

According to the calculated sound velocity profile in Figure 2, the Bellhop calculation model and extracted sea depth data are used to set the positions of the detection sonar and the detected target, by the way, the sound field energy distribution and sound line propagation curve at this position are also plotted. The results are shown in Figure 3. During the simulation process, both the sound source and receiver depths were set to 1000m, and the emission frequency of the emission source was 1.2kHz. The Bellhop calculation model has a calculation depth of 6000m, a depth calculation step of 1m, a horizontal calculation distance of 100km, and a horizontal calculation step of 5m.

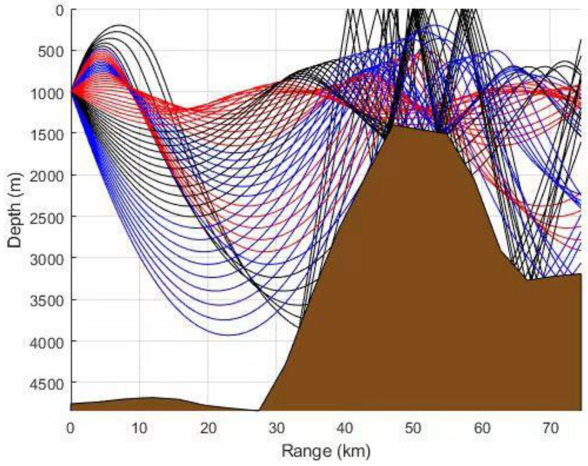
As shown in Figure 3 (a), the abscissa represents the transmission distance in units of km, while the ordinate represents the depth in units of m. As the transmission distance increases, the propagation loss gradually increases, and there is a significant jump at 30 km points. Based on Figure 3 (b), it can be seen that an underwater mountain exists here, which will affect the propagation of underwater acoustic signals. In addition, it can be concluded that underwater sound can propagate further near the sound channel, which also indicates that the detection ability of sonar is closely related to the marine environment.

B. VERIFY THE INFLUENCE OF WORKING FREQUENCY ON THE ENERGY DISTRIBUTION OF THE SOUND FIELD

According to the research in section III-A, a sound channel can be formed at the lowest underwater sound velocity, allowing the sonar to detect farther distances. Therefore, this article sets the depth of the sonar to 100 mand explores the impact of frequency on sound energy. Select a location ($21°N$, $122°E$) and extract water temperature, salinity, and sea depth data for that location. By using equation (4), the



(a)Sound field energy distribution map



(b)Sound ray propagation diagram

FIGURE 3. **Sound energy distribution and sound line propagation curve.**

sound velocity profile at this location can be obtained, and then the energy distribution of the sound field at different frequencies can be calculated using the Bellhop model, as shown in Figure 4.

Figure 4 shows the sound energy distribution of signals with frequencies of 800Hz, 1.2kHz, 2kHzand 5kHz at a sound source depth of 1000m. The horizontal axis represents the transmission distance, in units of m, and the vertical axis represents the depth, in units of m. Comparing the four figures (a), (b), (c), and (d), it can be seen that if the difference in operating frequency is not significant, changing the signal operating frequency has a relatively small impact on the sound energy distribution, and the characteristics of the sound energy distribution have no significant change. That is, when the difference in operating frequency is small, the influence of the signal operating frequency on the sound energy distribution is limited. Therefore, when selecting the working frequency of sonar for simulation, the impact of different frequencies on detection ability can be ignored, as long as it is limited in the commonly used working frequency band of sonar.

TABLE 1. **Calculation of sonar detection capability in polar coordinate system.**

```
Input: Layout position of a single detection platform
Output: Sonar detection capability polar coordinate system
Algorithm:
1. Take the input coordinate point as the center and evenly select 36 orientations, with each orientation spaced 10 ° apart;
2. Calculate the sound velocity profile for each direction according to equation (4);
3. Calculate the sound energy distribution in each direction using the Bellhop model, as shown in Figure 4;
4. Use equation (10) for multiple spline interpolation to obtain the distribution of sound energy in the entire polar coordinate system;
5. Calculate the detection capability of the entire polar coordinate region according to equations (5), (6), (7), and (8);
6. Generate a polar coordinate system diagram of sonar detection capability, as shown in Figure 5.
```

C. SIMULATION OF SONAR DETECTION CAPABILITY IN POLAR COORDINATE SYSTEM

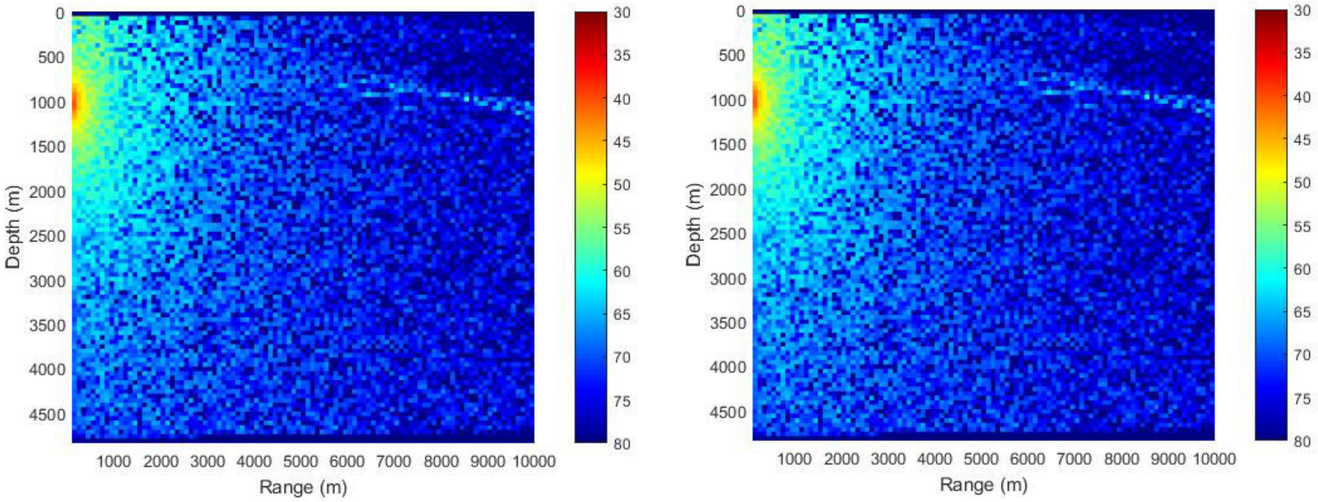
The ocean environment data is the same as the ocean environment parameters in section III-B ($21°N,\ 122°E$), and the sonar's working state is selected as passive by default. The main steps and parameters for calculating the polar coordinate system of sonar detection capability are shown in Table 1, the propagation loss results are shown in Figure 5, and the polar coordinate system of detection capability is shown in Figure 6.

From Figure 5, it can be seen that the propagation losses vary depending on the marine environment (water temperature, salinity, etc.) at different locations.

From Figure 6, it can be seen that the detection ability of sonar is estimated by the detection probability. The detection probability of each point on polar coordinates represents the detection probability of the point when the sonar is deployed at the center position ($21°N,\ 122°E$). The higher the detection probability, the higher the detection accuracy of the sonar. According to equation (7), when $SE = 0$, P_d =0.5. This article assumes that sonar can detect when the detection probability P_d is greater than 0.5; When the detection probability P_d is less than 0.5, the sonar cannot detect it. Using this method to determine the sonar detection capability in Figure 6, the results are shown in Figure 7.

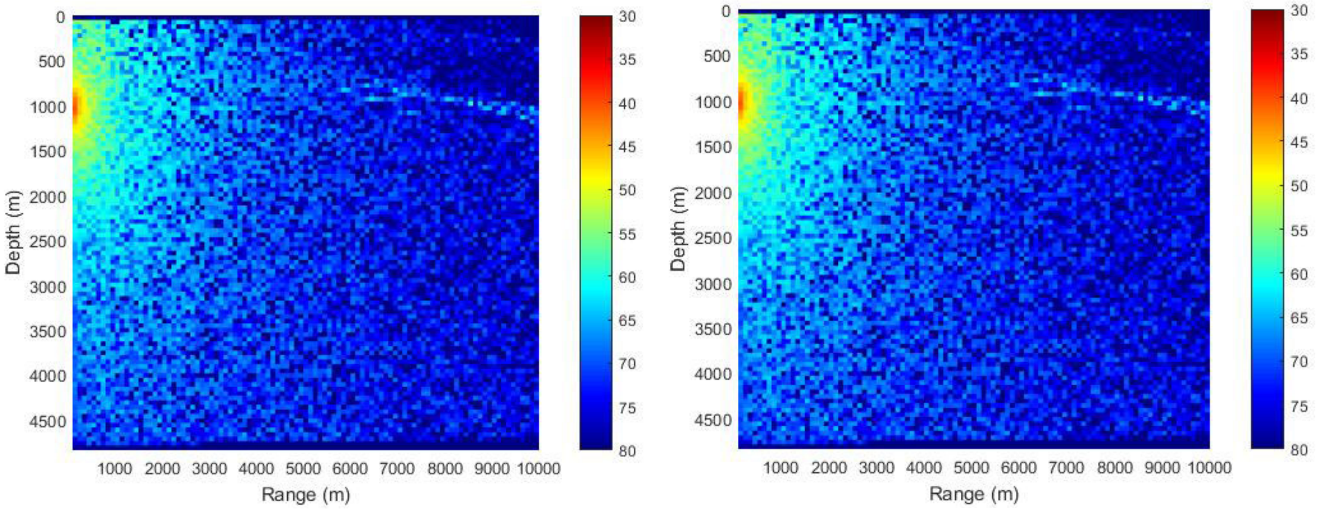
From Figure 7, it can be seen that the yellow area represents the positions that sonar can detect, while the blue area represents the positions that sonar cannot detect, indicating that this is closely related to marine environmental factors.

To verify the correctness of the selection of sonar deployment depth in section III-A, we placed the sonar at depths of 500mand 1500m, and calculated the propagation loss polar map, detection capability polar map, and detection distance polar map at that depth. The results are shown in Figure 8.



(a) Energy distribution map of sound field at 800Hz

(b)Energy distribution map of sound field at 1.2kHz



(c)Energy distribution map of sound field at 2kHz

(d)Energy distribution map of sound field at 5kHz

FIGURE 4. **Energy distribution map of sound field at different frequencies.**

From Figure 8, it can be seen that when the sonar is placed at depths of 500m and 1500m, the detection performance of the sonar decreases significantly compared to when the sonar is placed at a position of 1000m. It verifies the conclusion proposed in section III-A, that the sonar should be placed at the position with the lowest sound velocity.

D. CALCULATION AND SIMULATION OF COLLABORATIVE DETECTION PROBABILITY DISTRIBUTION SURFACE

The basic idea of calculating the collaborative detection probability distribution surface proposed in this article is to separately calculate the detection capabilities of different detection platforms at different positions, generate detection capability distribution maps for each position, then fuse the detection capability distribution maps of all detection platforms at all positions, calculate the probability distribution of the overlapping part, and finally obtain the collaborative detection probability distribution surface of the entire region. Due to the rapid changes in the marine environment, in order to facilitate experimen-tal solutions, the following assumptions are made: during the simulation process, the sonar is set to use active working mode; The detection area is a rectangular area and the area is scaled; Sonar can be deployed with certainty, and once deployed, its position will no longer change.

When conducting collaborative detection tasks, the location of platform deployment has a significant impact on the overall detection performance. If the distance between platforms is too close, it will cause overlap in the coverage areas of each platform, reducing coverage efficiency; If the platforms are too far apart, it will affect the collaborative effect and also reduce coverage efficiency. Therefore, reasonable planning of placement positions can improve the area coverage capability of the detection system. This article

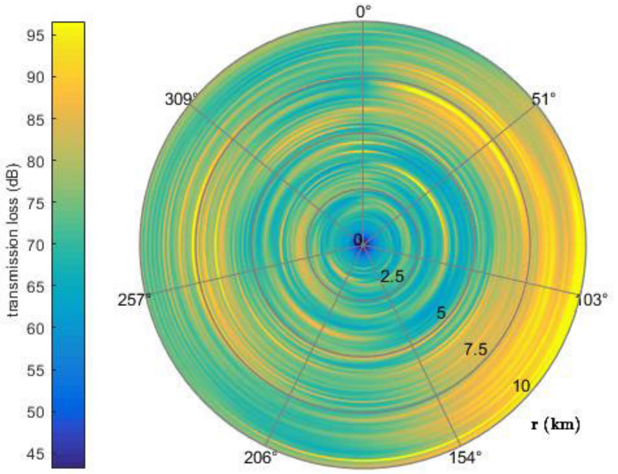


FIGURE 5. Polar plot of propagation loss.

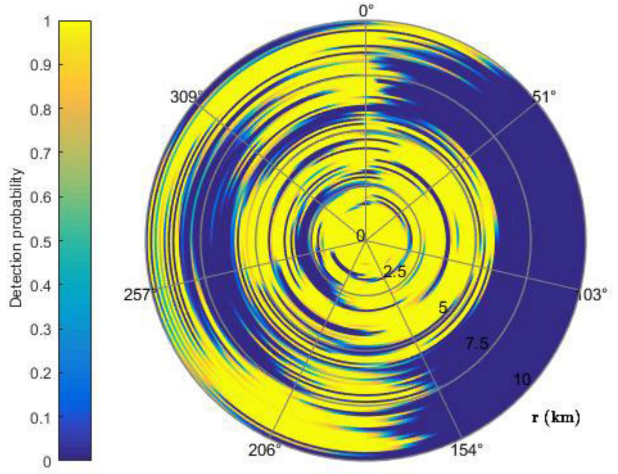


FIGURE 6. Polar plot of detection capability.

proposes a collaborative detection probability distribution surface to demonstrate regional detection performance. Based on this, the detection performance of five sonar node deployment forms, namely center deployment, horizontal uniform deployment, vertical uniform deployment, equilateral triangle deployment, and square deployment, was studied.

During the simulation process, the simulation generates 500 × 500 task areas.And the sonar is uniformly distributed, assuming a detection threshold of 0.8, that is, when the detection accuracy at each point in the area is higher than 0.8, it is considered to meet the detection task requirements. The main steps and parameters for calculating the collaborative detection probability distribution surface are shown in Table 2, and the collaborative detection probability distribution surface is shown in Figure 8.

As shown in Figure 9, taking Figure (a) as an example, the collaborative detection probability distribution surface

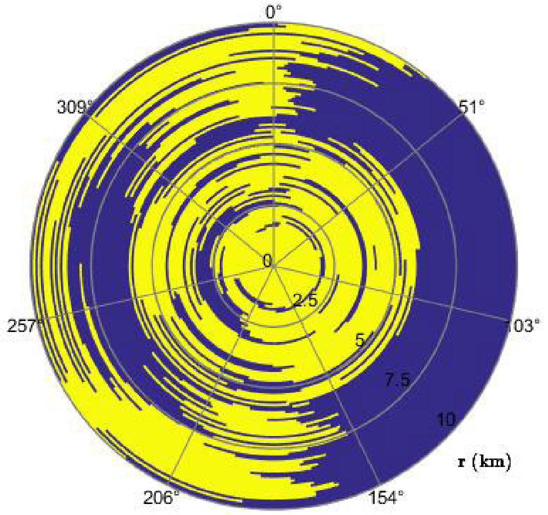


FIGURE 7. Polar coordinate map of detection distance.

TABLE 2. Calculate collaborative detection probability distribution surface.

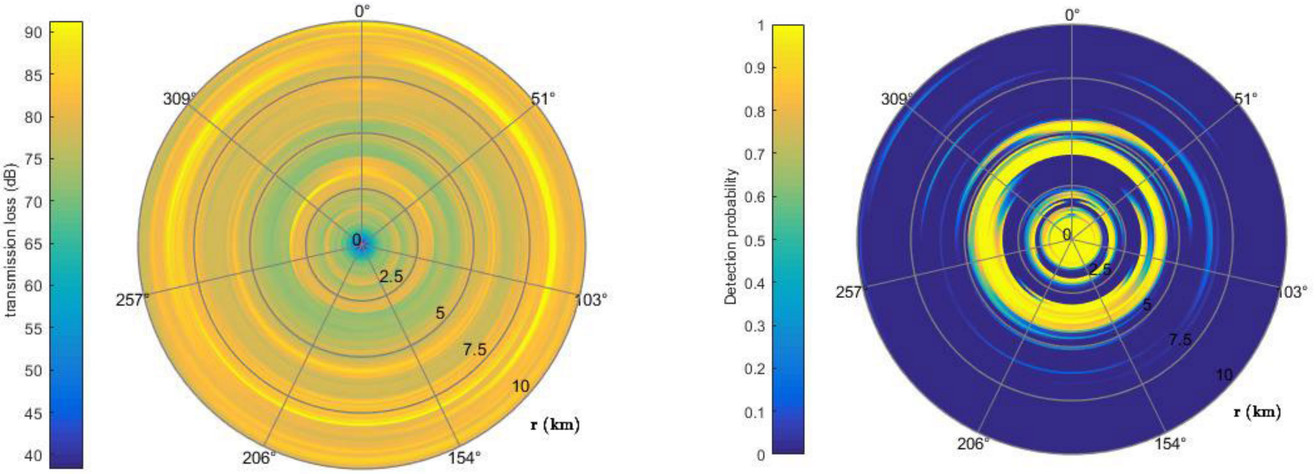
Input: Layout position of the detection platform Output: collaborative detection probability distribution surface
Algorithm: Calculate the sound velocity profile of each detection platform placement position according to formula (4); Obtain the sound energy distribution within the range of each detection platform using the Bellhop calculation model; Calculate the detection probability within the range of each detection platform according to formulas (5), (6), (7), and (8); Add the detection probabilities of each detection platform and calculate the overlapping parts using formula (10); Generate a collaborative detection probability distribution surface, as shown in Figure 9.

TABLE 3. Overall detection performance under different deployment methods.

Layout method	Number of Sonars	Detection range coverage
Center point	1	10.75%
Horizontal uniformity	2	54.95%
Longitudinal uniformity	2	54.95%
Equilateral triangle	3	79.98%
square	4	98.92%

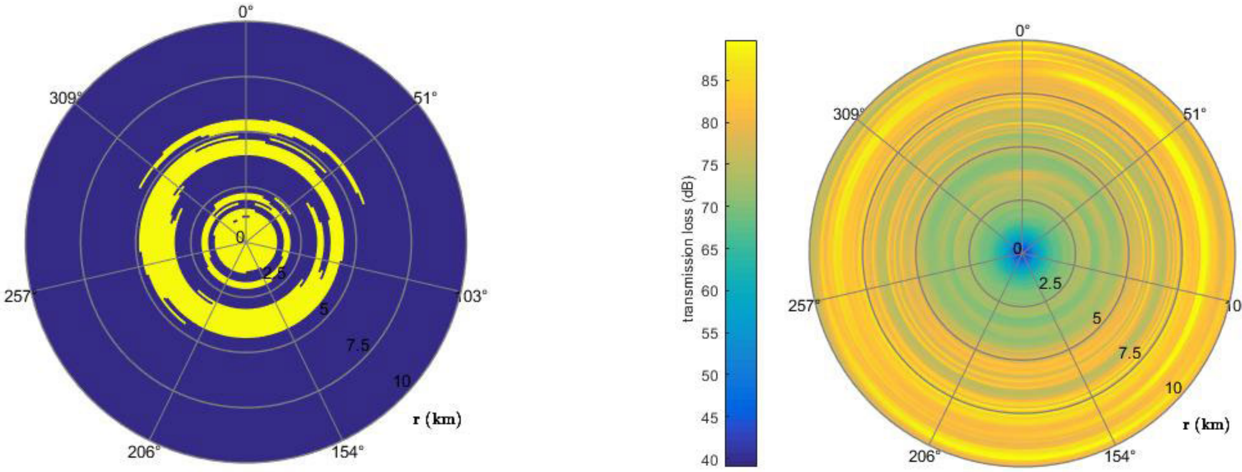
is presented as a probability contour line. The higher the probability obtained, the higher the detection accuracy performs; On the contrary, the lower the probability obtained, the lower the detection accuracy performs. Table 3 lists the overall detection performance of sonar under five different deployment forms.

Comparing the five figures (a), (b), (c), (d), and (e) in Figure 9, combined with Table 3, it can be seen that when only a single sonar is deployed, only a small portion of the area meets the threshold requirement. As the number of deployed sonar increases, the range of areas that meet the threshold requirement also increases.



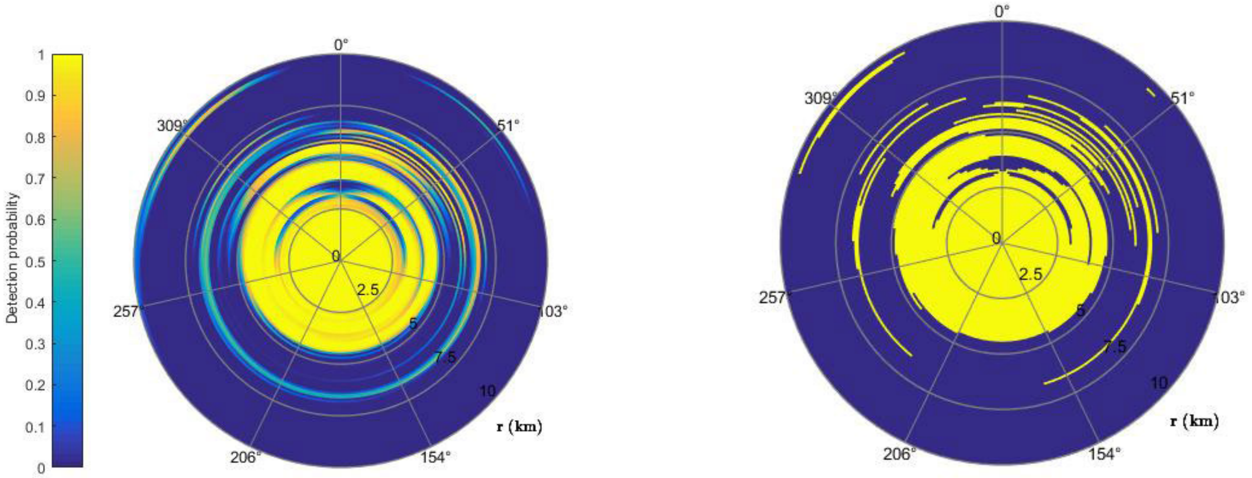
(a) Polar plot of propagation loss at a depth of 500m

(b)Polar plot with detection capability at a depth of 500



(c) Polar coordinate map of detection distance at a depth of 500m

(d)Polar plot of propagation loss at a depth of 1500m

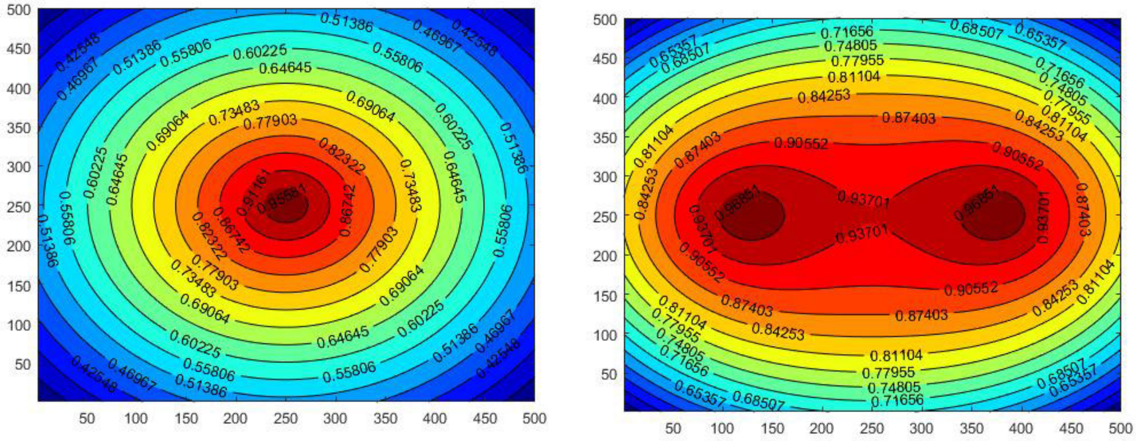


(e)Polar plot with detection capability at a depth of 1500m

(f) Polar coordinate map of detection distance at a depth of 1500m

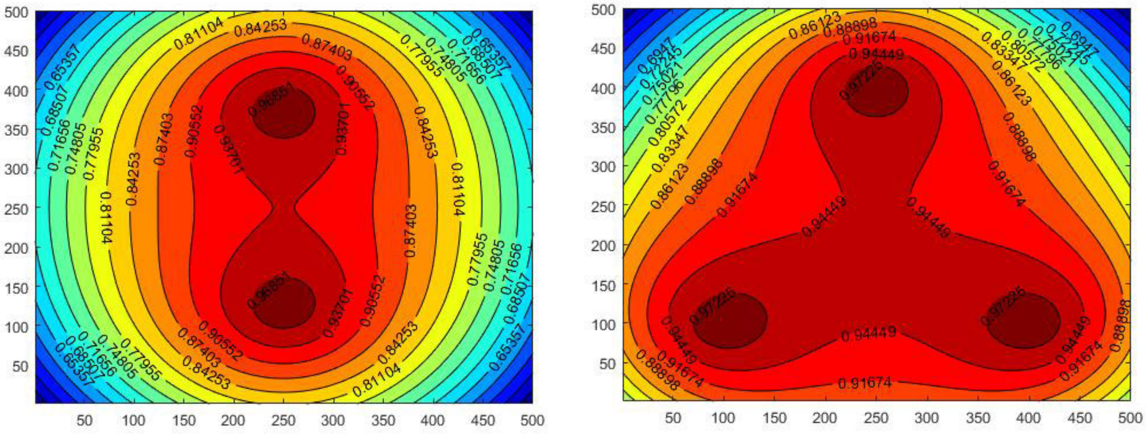
FIGURE 8. **Sonar detection performance map at depths of 500m and 1500m.**

From the above research, it can be found that when the task area is fixed, as the number of deployed sonar increases, the detection range coverage also increases. However, considering the limitations of operational costs,



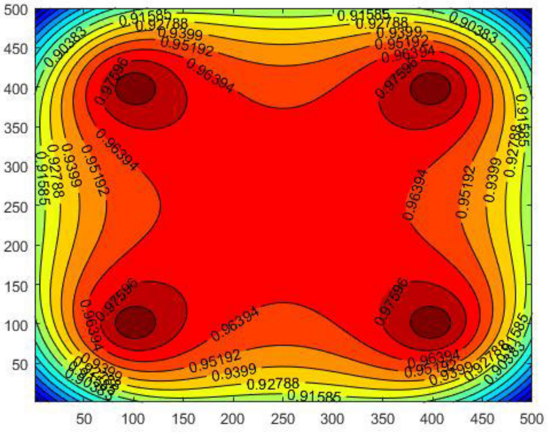
(a) Probability map of center point deployment detection

(b) Horizontal uniform distribution detection probability map



(c) Longitudinal uniform distribution detection probability map

(d) Probabilistic map of regular triangle deployment detection



(e) Square layout detection probability map

FIGURE 9. **Collaborative detection probability distribution surface map.**

when placing four sonar units in a square layout, the detection coverage rate is 98.92%, which means that the task area basically meets the threshold requirements, so there will be no additional number of deployed sonar units.

Comparing the above experimental results, it reflects the advantages of multi platform collaborative detection and the better detection performance of the square layout.

IV. CONCLUSION

This article takes the marine environment as the background and delves into the issue of underwater detection performance in anti-submarine warfare. The main conclusions obtained from the study are as follows:

(1)Starting from the sonar equation and combining with the sonar quality factor, a sonar detection performance analysis system was constructed to verify the significant impact of the ocean environment on sound propagation. At the same time, a polar coordinate system was constructed to analyze the underwater detection capability of sonar, realizing the visualization of sonar detection performance and providing a more intuitive and in-depth understanding and analysis of sonar detection performance.

(2)Aiming at the information fusion problem of heterogeneous detection platforms, a joint detection probability distribution surface is proposed, which integrates the detection capabilities of multiple sonar systems and displays the overall detection probability of the region in the form of contour lines. At the same time, simulation experiments were conducted to compare the detection performance of different deployment strategies of sonar, demonstrating the advantages of multi platform joint detection and the better detection performance of the square deployment form.

It can be seen that the research results of this article have important reference value for the implementation of underwater exploration tasks, and provide a scientific basis for the deployment of exploration platforms.

ACKNOWLEDGMENT

(Chaofeng Lan and Zelong Yu contributed equally to this work.)

REFERENCES

[1] T. Z. Wang, D. J. Zhang, and L. Jiang, "Development analysis and reflection on the concept of underwater warfare in the U.S. Navy," *Ship Sci. Technol.*, vol. 43, no. 11, pp. 186–189, 2021.

[2] M. Erol, L. F. M. Vieira, and M. Gerla, "AUV-aided localization for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl. (WASA)*, Aug. 2007, pp. 44–54.

[3] T. Hardy and G. Barlow, "Unmanned underwater vehicle (UUV) deployment and retrieval considerations for submarines," presented at the INEC, UUV Deployment Retrieval Options Submarines, Hamburg, Germany.

[4] H. Guo and M. Yu, "Data fusion in distributed multi-sensor system," *Geo-Spatial Inf. Sci., Quart.*, vol. 19, no. 3, pp. 15–18, 2004.

[5] W. D. Zhang, "Research progress and challenges faced by unmanned water systems," *J. Automat.*, vol. 46, no. 5, pp. 847–857, 2020.

[6] L. F. Ji, J. J. Chen, and S. P. Wu, "Research on collaborative detection and integrated target identification technology in naval battlefield," *Radar Countermeasures*, no. 4, pp. 5–9, 2007.

[7] X. Y. Wu, "Research on optimization methods for search capability of anti submarine systems," Univ. Defense Sci. Technol., Hunan, China, Tech. Rep., 2012, pp. 74–77.

[8] J. Y. Zou, "Performance analysis and parameter optimization of multi sonar collaborative detection," Harbin Eng. Univ., Harbin, China, Tech. Rep., 2019, pp. 29–42.

[9] Z. L. Zhou, X. Z. Yin, and Z. H. Huang, "Research on the detection performance of multibase sonar systems," in *Proc. Chin. Soc. Acoust. Underwater Acoust. Branch, Shandong Soc. Acoust., China Shipbuilding Eng. Soc. Ship Instrum. Academic Committee, Acad. Conf. Chin. Soc. Acoust. Underwater Acoust. Branch*, 2022, pp. 115–117.

[10] X. H. Du, "Performance analysis of airborne sonar buoy multi base detection formation," *Ship Electron. Eng.*, vol. 42, no. 12, pp. 140–146, 2022.

[11] Y. T. Gu, Q. Li, and X. F. Shi, "Research on the submarine search efficiency of suspended sonar based on discovery probability models," *Ship Electron. Eng.*, vol. 43, no. 1, pp. 138–143, 2023.

[12] Z. Bai, B. C. Zhang, and W. Y. Zhu, "Analysis of victory mechanism and research on countermeasures in anti submarine operations," *Mod. Defense Technol.*, pp. 1–13, Aug. 2023.

[13] P. Q. Fan, "Research on the optimal working depth selection of sonar systems in shallow water," in *Proc. Nat. Conf. Underwater Acoust., Chin. Soc. Acoust., Underwater Acoust. Branch Editorial Office Tech. Acoust.*, 2011, pp. 52–54.

[14] S. Q. Wang, "Design and implementation of underwater sound field simulation system based on bellhop model," Huazhong Univ. Sci. Technol., Hubei, China, Tech. Rep., 2020, doi: 10.27157/d.cnki.ghzku.2020.006685.

[15] W. H. Guo, "The impact of environmental uncertainty on sonar range prediction," *Equip. Environ. Eng.*, vol. 5, no. 2, pp. 25–27 and 65, 2008.

[16] Z. H. Zhang, "Research on the main influencing factors of passive sonar range," *Sci. Technol. Inf.*, no. 23, pp. 23–24, 2010.

[17] G. Fei, P. Changming, and Z. Ren, "A study on the influence of thermocline and its changes on the probability of passive sonar detection," *Appl. Acoust.*, vol. 33, no. 2, pp. 138–144, 2014.

[18] T. Hongwei, "Research on the impact of marine environment on sonar systems," *Technol. Innov. Appl.*, no. 30, pp. 56–57, 2018.

[19] D. Liu, "Sound propagation in shallow sea periodic undulating seabed environments," *Acta Physica Sinica*, vol. 70, no. 3, pp. 165–175, 2021.

[20] D. Liu, "Sound propagation in shallow undulating seabed environments," *Acoustic Technol.*, vol. 41, no. 3, pp. 388–396, 2022.

[21] Q. Y. Wei, "Simulation study on detection and direction finding performance of two types of linear arrays in sound field environment," Harbin Eng. Univ., Harbin, China, 2020, doi: 10.27060/d.cnki.ghbcu.2020.000390.

[22] W. Y. Zhu, "Research on sonar detection range prediction based on knowledge base matching," Harbin Eng. Univ., Harbin, China, Tech. Rep., 2018.

[23] M. J. Yao and L. C. Lu, "The influence of bubble layers on sound propagation in shallow undulating sea surfaces," *Acta Physica Sinica*, vol. 69, no. 2, pp. 162–171, 2020.

[24] T. Tian, *Sonar Technology*, vol. 12. Harbin, China: Harbin Engineering Univ. Press, 2009, pp. 16–20.

[25] H. Medwin, C. S. Clay, and F. Latte, "Fundamentals of acoustical oceanography," *Phys. Today*, vol. 52, no. 7, pp. 54–56, 1999.

[26] R. Locarnini, A. Mishonov, and O. Baranova, "World ocean atlas 2018: Temperature," Silver Spring, NOAA Atlas NESDIS, Tech. Rep., 2019, vol. 1.

[27] M. M. Zweng, J. Reagan, and D. Seidov, "World ocean atlas 2018 volume 2: Salinity," NOAA Atlas NESDIS, Tech. Rep., 2019.

[28] W. H. F. Smith and D. T. Sandwell, "Global sea floor topography from satellite altimetry and ship depth soundings," *Science*, vol. 277, no. 5334, pp. 1956–1962, Sep. 1997.

[29] Y. Liu, "Research on sound propagation of horizontally varying sound velocity profile under rough sea ice cover," Harbin Eng. Univ., Harbin, China, Tech. Rep., 2021, doi: 10.27060/d.cnki.ghbcu.2021.001582.

CHAOFENG LAN received the Ph.D. degree in underwater acoustic engineering from Harbin Engineering University, in 2012. She was a Postdoctoral Researcher of power engineering and the engineering of thermal physical flow stations with the Harbin Institute of Technology, and was released in 2018. She hosted one National Natural Science Foundation of China, two Natural Science Foundation of Heilongjiang Province, and one Foundation of the Education Department. She is currently an Associate Professor and the Ph.D. Supervisor. She has published more than 50 SCI/EI search articles and authorized more than ten invention patents. Her main research interests include artificial intelligence AI algorithms, underwater acoustic signal analysis and processing, speech signal analysis and processing, medical signal modeling and prediction, and machine vision recognition and detection.

ZELONG YU is currently pursuing the master's degree in communication engineering with the University of the Harbin Science and Technology. His main research interest includes underwater detection technology.

HUAN CHEN received the Ph.D. degree from the University of Harbin Engineering, Harbin, China, in 2011.

He is currently with the China Ship Development and Design Center, Wuhan, China. His current research interests include target location and recognition and noise control technology.

LEI ZHANG is currently a Professor. His main research interests include artificial intelligence AI algorithms, medical signal modeling, and prediction.

MENG ZHANG received the Ph.D. degree from the Harbin Institute of Technology, in 2019.

From 2016 to 2018, she was a Researcher with Harvard University. From 2020 to 2021, she was a Postdoctoral Fellow with Sun Yat-sen University. In 2021, she joined Guangzhou University as a Lecturer. She has published more than 30 research articles. She is responsible for multiple research projects, including the National Natural Science Foundation Youth Project, the Guangzhou Science and Technology Project, and the General Postdoctoral Fund Project. Her current research interests include micro/nano sensing, microfluidics, and soft electronics.

• • •