Research on Multi-beam Lateral Line Deep-sea Exploration

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Abstract: This article mainly studies the issues of beam coverage and measurement efficiency of multi-beam detection in seafloor slopes, and conducts modeling and optimization work based on the sine theorem, trust region solution method, multiplicative factor, genetic algorithm and other methods. It is necessary to consider that the coverage width of multi-beam measurements in a given rectangular area changes with the angle between the direction of the survey line and the projection of the normal direction of the seafloor slope on the seafloor horizontal plane, and the overlap rate is considered by applying a multiplicative factor Impact. However, it is necessary to consider and compare the advantages and disadvantages of parallel and crossing paths, and finally use the parallel path method to obtain the measurement line combination method with the shortest measurement length that can completely cover the entire seabed area to be measured. Finally, we obtained the total survey line distance is 43.8665 nautical miles. A total of 10 survey line strips can completely cover the seabed area, and the distance between adjacent survey lines is 324.67.

1. Introduction

Deep-sea exploration is a strategic approach and an important means for mankind to achieve sustainable development[1,2]. An important means to realize deep-sea exploration is the multi-beam bathymetry system, which is mainly used for the measurement of seabed topography, sea sweeping and offshore construction area measurement.[3,4,5] The method of using the characteristics of sound waves in water to determine water depth is called single-beam bathymetry.[6,7] Sound waves propagate in a straight line at a constant speed in a homogeneous medium and are reflected at various interfaces. Based on this phenomenon, the transducer of the measuring ship emits sound waves vertically to the seafloor, and calculates the time from when the sound wave is emitted to when the signal is received. According to the propagation speed and time of sound waves in sea water, the depth of sea water can be calculated. Multi-beam sounding technology is improved on the basis of single-beam sounding. This technology can simultaneously emit dozens or hundreds of beams on a plane perpendicular to the shipping route, and obtain the sound waves reflected from the seafloor through receiving transducers[8]. This technology overcomes the limitations of single-beam bathymetry and can measure a complete water depth zone with a certain width centered on the surveying ship's survey line in a flat area on the seabed.[9,10,11]

Hypothesis1: The speed of ship is given and the opening angle of the transducer remains unchanged.

Hypothesis2: In the experiment, the water density distribution is uniform and the sound speed remains constant, which will not affect the accuracy of multi beam detection.[12,13]

Hypothesis3: The depth of the sea area to be measured changes continuously, the slope of the sea area remains unchanged, and there is no area of high mutation.

Hypothesis4: The signal propagation speed is much greater than the ship's traveling speed, and the time for the wave to be reflected back to the ship's receiver is negligible. That is, the impact of the beam propagation speed itself on the detection results is not considered, and each detection is completed in a very short time.

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Hypothesis5: The impact of water flow velocity on multi-beam detection is negligible and will not affect the accuracy of multi-beam detection.

2. Deep-sea exploration

2.1 Analysis of question

Question: In a rectangular sea area 2 nautical miles long from north to south and 4 nautical miles wide from east to west, the sea water depth gradually becomes shallower from west to east, the slope is 1.5 degrees, and the opening angle of the multi-beam transducer is 120 degrees, this is a case where Ocean bathymetric survey layout optimization problem.[14,15]

2.2 Model building

It is necessary to consider the situation when the ship travels in different survey line directions. The three-dimensional diagram is shown in Figure 1. Use the center line and arbitrary survey line directions to describe the multi-beam detection geometric structure and process and establish a geometric model. Note that the height of the seafloor slope is h, the angle between the central survey line and the horizontal plane is α, the length of the hypotenuse is L', the angle between any survey line and the horizontal plane is γ, and the length of the hypotenuse is L, as shown in Figure 1.

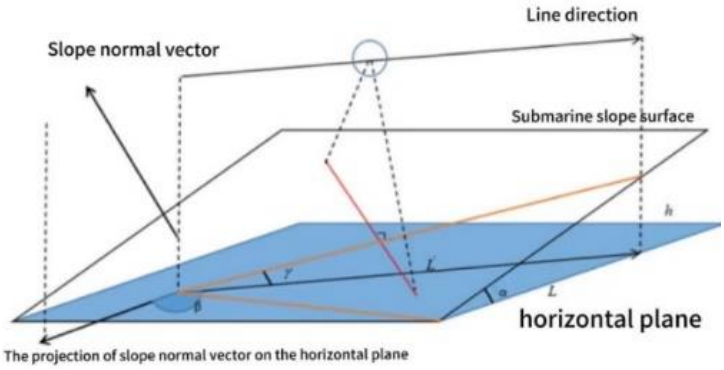


Figure 1. Scene detection data label diagram

The obtained γ is a function related to β, which we record as $\gamma(\beta)$ .Using the depth of seawater at the center point is $D_0 = 120m$, the slope of the seafloor slope is $\alpha = 1.5^\circ$, and the opening angle $\theta = 120^\circ$ of the transducer that have been explained in the question information, we might as well set:

$$\begin{cases} k_0 = \tan\frac{\theta}{2} \\ k_1 = \sin(\frac{\pi}{2}+\frac{\theta}{2}) \\ k_2 = \sin(\frac{\pi}{2}-\frac{\theta}{2}) \\ k_3 = \sin(\frac{\pi}{2}-\frac{\theta}{2}-\gamma(\beta)) \\ k_4 = \sin(\frac{\pi}{2}+\frac{\theta}{2}-\gamma(\beta)) \end{cases} \tag{1}$$

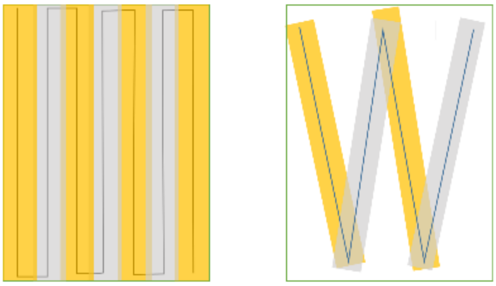
After derivation can be obtained:

$$W = D\cdot k_0(\frac{k_1}{k_3}+\frac{k_2}{k_4}) \tag{2}$$

Coverage width W should also meet the following constraints:

$$\begin{cases} 10\% \le \eta = 1-\frac{\mathrm{d}}{\mathrm{W}} \le 20\% \\ 2 \le N(1-\eta)w+(N-1)\eta w \end{cases} \tag{3}$$

Where N is the number of strips. Equation (2) and condition (3) describe the quantitative and functional relationships that should be satisfied between each parameter. Next, we need to explore the path of the survey line so that it can completely cover the entire sea area to be measured, while ensuring the shortest length.



Option 1 Option 2

Figure 2. Schematic diagram of boat route planning in a rectangular area

To further enhance the analysis and discussion, let's delve into the practical implications and potential challenges associated with the proposed path planning scheme.First, we can obtain the coverage rate on a single seafloor slope. Based on this, we discuss the path planning problem. In order to achieve the highest coverage, we try to let the detection ship sweep a larger area as much as possible, and ensure that the design requirements are met when adjacent strip lines are close. In Figure 2, we considered two boat path planning options in the rectangular area.[16,17,18] The left and right pictures are option one and option two respectively. We observed this rectangular sea area from a bird's-eye view. In Scheme 2, when the boat strip lines are not parallel to the rectangular boundary, an overlapping area appears at the turning point, and there are a large number of gaps between adjacent strip lines. Even if the overlap area can be reduced by reducing the angle with the rectangular boundary, it will still greatly reduce the efficiency of multi-beam detection, increase the measurement length and fail to meet the overlap rate requirements.

One critical aspect is the navigational complexity introduced by maintaining parallel strip lines in varying sea conditions. Sea currents, wind patterns, and other environmental factors can significantly influence the vessel's ability to maintain a precise course, potentially leading to deviations from the planned path. These deviations can impact the coverage accuracy and efficiency of the survey.[19]

In order to solve the above problems, we adopt the path planning scheme in scheme 1 in Figure 1

And Each strip line is parallel to the rectangular area, minimizing the use of the multi-beam detection range, and controlling the overlap. There are obvious advantages in terms of efficiency.[20,21,22] We can adjust the spacing between the two strip lines to control the overlap between 10% and 20%.

It should be noted that since the seafloor topography is generally deeper in the west and shallower in the east, it can be seen that as the depth decreases, the coverage width of multi-beam measurement will decrease[23,24], so the question can be simplified to within a rectangular area, the coverage width of the multi-beam measurement changes and the solution is to solve the problem of filling this rectangular area under such a coverage width. Considering the overlap rate factor, in actual operation, we apply a multiplicative factor $\lambda \in (0.8, 0.9)$ to the coverage width W. The specific value depends on the current overlap rate setting.[25]

After the direction of the survey line is determined, the optimal value of the spacing between adjacent survey lines is solved using the exhaustive method, and the value is determined between the interval coverage rates. After MATLAB calculation equations (2) and (3) are solved simultaneously, and the relationship with the total measurement line length is obtained as shown in Figure 3:

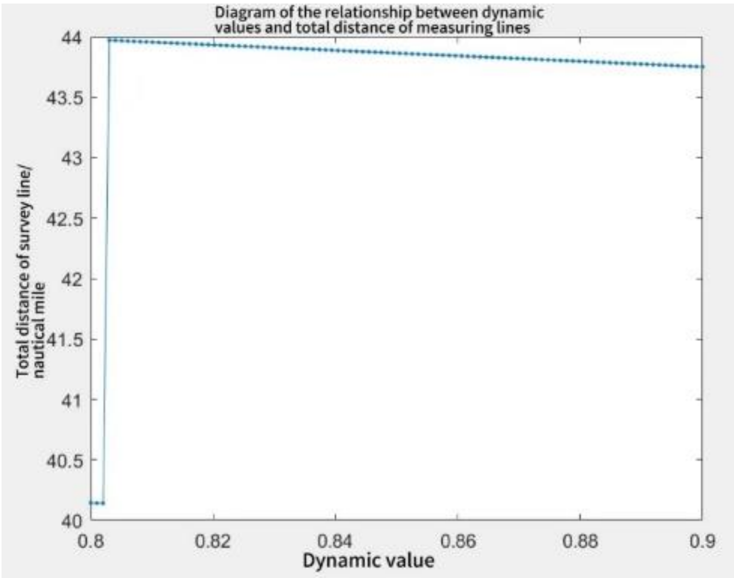


Figure 3. Relationship diagram of the distance of the side line in the coverage value range

After MATLAB calculations, equations (2) and (3) are solved simultaneously, and finally the total survey line distance is 43.8665 nautical miles. A total of 10 survey strips can completely cover the rectangular area in Figure 3, and the distance between adjacent survey lines is 324.67 meter.

3. Model evaluation

3.1 Disadvantages and advantages of the model

The model design is based on the needs of the actual sea area and takes into account the characteristics of the sea area and the measurement objectives, so the results are more practical.

1) Taking into account the overlap ratio: The overlap rate requirement between adjacent survey lines is considered in the model, which is crucial for subsequent data processing and analysis, because the overlapping area can improve the accuracy and reliability of the data.

2) Taking into account the seabed topography: The model takes into account changes in seafloor terrain during design, which is a good reflection of the actual situation. In this way, the model can better adapt to the characteristics of different sea areas.

3) Solved the path planning problem: During the solution process, by designing different boat route plans, the model effectively solved the problem of path planning, maximizing coverage and minimizing the length of the measurement line.

4) Numerical calculation methods were used: The model uses numerical calculation methods to solve, which has high efficiency and accuracy in practical applications and can quickly obtain results.

But there are some disadvantages:

1) The computational complexity is high: The solution process in the model involves complex mathematical calculations, especially exhaustive calculations for multiple different parameters, which will increase the complexity and time-consuming of the calculations.

2) Limited to sea area characteristics: The applicable scope of the model is limited by the characteristics of the sea area considered,[26,27] and it may be necessary to re-adjust parameters or re-establish the model for sea areas in other areas.

3) There is an oversimplification: When building the model, factors such as seafloor topography may have been simplified to a certain extent, which affect the accuracy, applicability of the model.

4) Depends on the set overlap ratio requirements: The overlap rate requirements in the model are based on preset conditions, which may limit the flexibility and applicability of the model.

5) There is a local optimal solution: During the exhaustive calculation process, a local optimal solution occur instead of a global solution, which requires additional optimization and verification.[28]

3.2 Model promotion

These models can be generalized in a variety of ways. First of all, it can be applied to the fields of ocean exploration, seabed topography survey, seabed geophysical prospecting, seabed pipeline inspection and other fields to improve measurement efficiency and accuracy and provide strong support for related industries. Secondly, it can be applied in marine scientific research to help scientists better understand the marine environment and ecosystems, and provide scientific basis for protecting the marine ecological environment. In addition, these models can also be used in marine engineering design and construction to help designers and construction personnel better understand the seabed topography and marine environment, and improve the safety and reliability of projects. Finally, these models can also be used in marine education and science popularization to help students and the public better understand marine science and technology, and improve marine awareness and protection awareness. In summary, these models have a wide range of potential applications and can be promoted and applied in a variety of ways.

4. Conclusions

Although it possesses practical advantages in adapting to different sea conditions and considers real-world constraints, it also exhibits limitations such as high computational complexity, restricted scope, oversimplification, reliance on preset conditions, and the potential for local optimal solutions. However, despite acknowledging its limitations, the model's versatility and potential benefits make it a valuable tool for advancing deep-sea exploration and related endeavors, offering opportunities for further improvement and application in various fields[29].

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