Multi-beam line observation optimization strategy based on random variable unitary iterative model

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Abstract. Multibeam system has many advantages such as large measurement range, fast speed, high accuracy, etc., which can be applied in many fields such as marine topographic survey. In this paper, the relationship between coverage width and other variables is obtained by analyzing the geometric relationship between each parameter, and a multibeam sounding model based on geometric relationship is established. And based on the intelligent optimization algorithm, an iterative optimization model with random variable singularization is designed independently. And the actual terrain data were visualized and simplified into various parameters in line with the model. With the help of the definition of the coverage rate, the relationship between the coverage width and other variables, and the one-to-one correspondence between the translation distance of the slope and the coverage rate, the complex measurement problem can be transformed into a simple linear programming problem, and the relationship model between the coverage rate and other variables is established. In the end, the model can be used to derive the optimal wiring scheme to realize high-precision and full-coverage sweeping of the seabed terrain in the given sea area without omission, provided that the ship speed, beam opening angle and other factors are reasonable.

Keywords: Multi-beam sounding model, Uniformization of random variables, Iterative optimization model, linear programming.

1. Introduction

The birth and development of single beam sounding method has made a great contribution to the progress of underwater surveying technology. However, the single point continuous survey method used in the traditional single beam sounding method can only obtain the survey data along the route, which has a small amount of data, low work efficiency and high survey cost. In order to overcome the defects of single beam sounding method and achieve full coverage of depth measurement, multi-beam sounding system has been developed rapidly.

When the multi-beam sounding system works, the transducer transmits dozens or even hundreds of beams at a time in the plane perpendicular to the track, forming a fan-shaped sound propagation area. Then, the returned sound wave is received by the receiving transducer, and the striped lateral measurement of the seabed is realized according to the wave speed and propagation time. Figure 1 shows the comparison between single-beam sounding and multi-beam sounding systems.

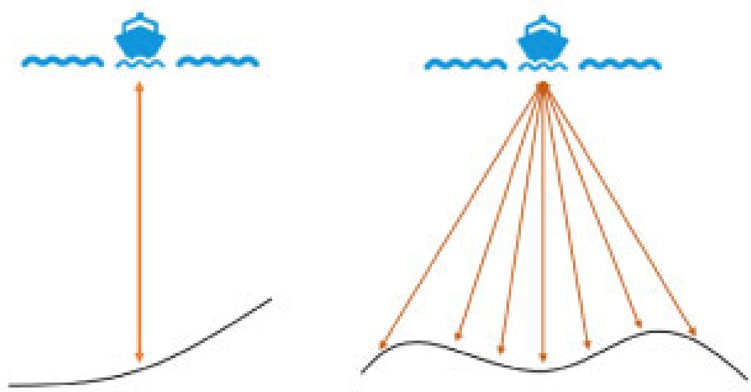

Figure 1. Comparison of single-beam and multi-beam measurements

For the beam detection method, Shi et al. proposed a new data-driven coverage path planning method (CPP), which can cost-effectively obtain high-quality mapping results and meet the requirements of coverage and uncertainty [1]. However, the paths obtained by this method are complex and irregular, which are difficult to be detected during the actual ship sea level movement and prone to repeated measurements. Li Yonghang et al. equipped with multibeam detection, side-scan sonar and shallow profile acoustic system to achieve simultaneous data acquisition, aiming to improve the survey efficiency, optimize the survey method and save the survey cost [2]. However, the method is only applicable to shallow sea area surveys and no path scheme is given. Fang Yi-han et al. proposed an acoustic real-time positioning method based on robust estimation, which obtains the spatial position of the seafloor transponder through iterative computation, and effectively eliminates the sudden noise and error [3]. Wang et al. proposed a robust optimization method based on switchable constraints for underwater images to eliminate the closed-loop in the AUV localization and surveying, and carried out simulation and underwater experiments [4]. However, the tested cameras in shallow sea areas are easily affected by light refraction and water ripples, while the cameras in deep sea areas will affect the image quality due to insufficient light, and a lot of optimization work needs to be done in image processing.Liu et al. proposed a method to detect the seafloor extension in the arc region of the Mariana Trench by combining data clustering, slope and gradient using compression and excitation networks, and a geomorphic seafloor classification strategy was implemented to realize a robust automatic delineation method [5]. Jiang et al. analyzed the change pattern and size of the resolution displayed by the multibeam detection system along the vertical track direction and different water depth track direction, which provided a basis for accurately evaluating the target detection capability of the multibeam detection system [6]. Based on the sonar equation, Hu Jun et al. proposed the Snippet data processing flow of Kongsberg EM multibeam system, and applied the method to the measured data of EM2040 multibeam in shallow water to verify the feasibility of the method [7]. Based on the shallow water multibeam sounding data in Macao waters, Wang Qi et al. improved the data processing results significantly after tidal correction and sound velocity correction, which can provide an important guidance for shallow water multibeam sounding data processing [8]. Sha Hongliang et al. elaborated that multibeam water detection, especially deep water detection such as lakes and oceans, has the advantages of high measurement accuracy and fast measurement speed, and proposed the method of acoustic integrated single-beam detection [9]. The development trend of deep-water multibeam detection is to improve the detection resolution, improve the detection accuracy, expand the detection coverage and strengthen the water detection [10].

In this paper, an optimal multi-beam sounding method is studied, which tries to overcome the shortcomings of single beam sounding and the limitations of particle swarm optimization and dynamic programming algorithms in multi-beam measurement. An iterative optimization model based on random variable uniformization is designed to solve the problem of line spacing arrangement in Marine survey, and the shortest path required for survey and the total number of lines under the shortest path condition are obtained. According to the model, the problems in real ocean survey are solved.

2. Materials and methods

2.1. Data acquisition and preprocessing

The sea water depth data used in this paper are obtained from the China offshore topographic data set written by Luan Zhendong and Zhang Jianxing from the global ocean bathymetric data and the Earth Big Data Science engineering Data Sharing service system. Since the sea water depth data is obtained, this paper inverts the sea water data to reflect the seabed topography data. For the obtained submarine terrain data, this paper uses MATLAB to pre-process these terrain data, that is, visual processing, so as to more intuitively reflect the submarine terrain situation (Figure 2).

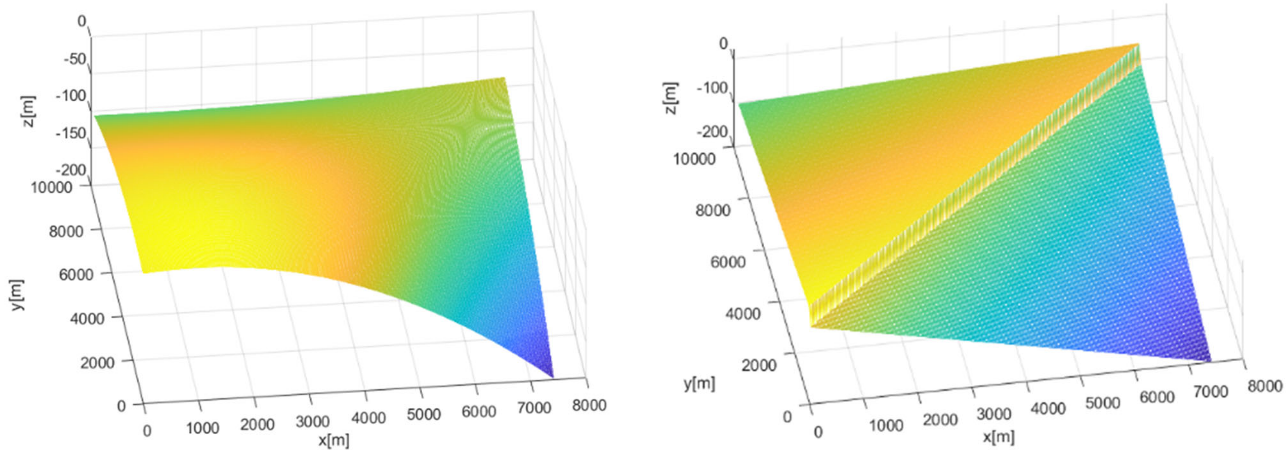

Figure 2. Seafloor topographic map (left) Simplified seafloor topographic map (right)

According to the analysis of the features on the left of the figure, the terrain is relatively flat in the northeast corner, while it has a certain slope in the southwest area. With the help of the four vertices rich in features in the figure, the terrain can be simplified into a horizontal plane and a slope plane with a certain slope, as shown on the right.

2.2. Research method

2.2.1 Establishment of multi-beam sounding model

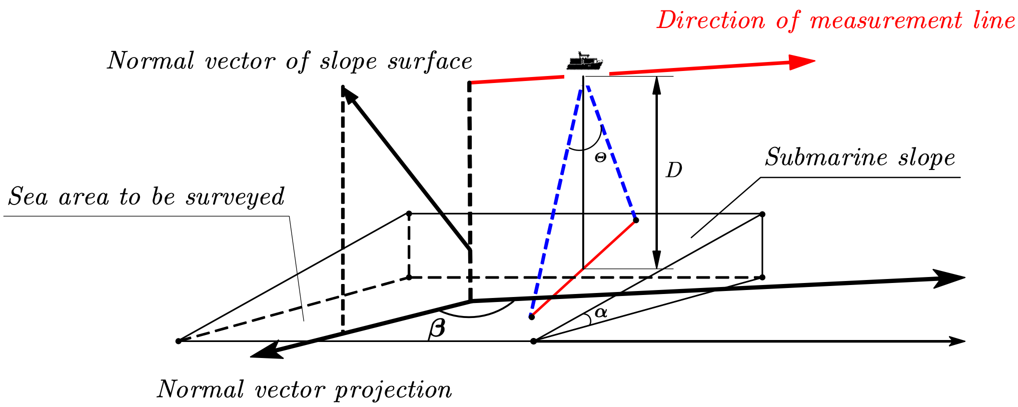

Figure 3. Schematic diagram of multi-beam principle

The construction of this model is essentially a geometric problem. According to the geometric relationship between different angles and the sine theorem, the coverage width W can be represented by the depth of seawater D, slope Angle α, the opening Angle of the transducer θ, and the direction of the measurement line (as shown in Figure 3), so as to establish the mathematical model of the coverage width of multi-beam detection. By defining the overlap rate between adjacent strips as $\eta = 1 - d/W$, a mathematical model of the overlap rate between adjacent strips can be established. A multi-beam sounding model can be obtained by integrating the two models

2.2.2 Summary of aggregation degree and rule of line spacing variation with length of western boundary of distance sea area

The essence of this problem is an optimization problem. The change of the direction of the survey line will lead to the change of the Angle β between the direction of the survey line and the projection of the normal direction of the submarine slope on the horizontal plane, and the analysis shows that the minimum sum of the survey line length is a special case of the multi-beam survey model, that is, the $\gamma = 90°$, which can simplify the model and reduce the variables. This point studies the situation when the lines are parallel to each other and the distance d between the lines is not all equal, that is, the variables are only the distance d between the lines and the total number of lines n. The coin problem using particle swarm optimization algorithm or dynamic programming algorithm is considered, but after analysis and trial, the quantity to be solved by particle swarm optimization algorithm is random and uncorrelated when the population is generated. The dynamic programming algorithm has the requirement of knowing the quantity to be solved, that is, "the coin denomination needs to be given in advance". By deducing the relationship between overlap rate η and line spacing d, it can be found that the first line spacing is related to the previous line spacing, so an iterative optimization algorithm based on random variable unitization is designed in this paper. The spacing of each survey line is converted into an overlap rate with a restricted range, that is, the iteration starts from the west boundary line of the sea area. The spacing between the current survey line and the previous survey line generated randomly in each iteration and conforming to the constraint conditions can be obtained according to its expression, and the sum of the current survey line spacing can be obtained to get the total length, which is different from the length of the sea area by 4 nautical miles, if and only if the first time is greater than the length of the sea area. At the end of the iteration cycle, the number of iterations at this time can be obtained, and the total length of an equal width line L can be calculated, which is the total length of the optimized shortest line, and the spacing sequence of the line can be obtained in the order of iteration. The scatterplot obtained by the self-designed optimization model can be used to analyze the aggregation degree and law of line spacing with the change of the length of the western boundary of the distance sea area.

2.2.3 Exploration of optimal wiring path in actual environment

For the exploration of the optimal routing path in the actual environment, the most important thing is to simplify the practical problem into the multi-beam exploration model that has been explored above. The second is to process the actual water depth data, extract the parameters needed in the mathematical model by visualization and surface linear programming from the actual water depth data, and bring them into it.

In order to facilitate measurement, the optimal routing strategy can be adjusted appropriately, and the overlap rate η of each strip on the slope can be set to be equal without affecting the optimal solution. Under this condition, the value of the overlap rate η can be associated with the slope translation distance, and then the complex measurement problem can be transformed into a simple linear programming problem. Then the points of the accessories are judged by linear programming to find the points that meet the measurement conditions, so as to find the optimal wiring path in the actual environment.

3. Result and analysis

3.1. Multi-beam exploration model based on three-dimensional geometric relationship

When the direction of the survey line is fixed, the mathematical model of the coverage width of multi-beam exploration can be obtained according to the two-dimensional geometric relationship as follows:

$$W = l\cos\alpha = \frac{2(D - x\tan\alpha)\cos^2\alpha\sin\theta}{\cos\theta + \cos 2\alpha} \tag{1}$$

However, in the actual situation, due to the uncertain direction of the ship's survey line, the gradient of the vertical plane and the intersection line of the slope is constantly changing. Therefore, a model is first established to solve the Angle between the plane perpendicular to the direction of the survey line and the intersection line of the submarine slope and the horizontal plane, which is set as γ (see the left of Figure 4). After calculating the relationship between γ and α, θ, the sea water depth D_2 when the ship is at any position is shown in the figure.

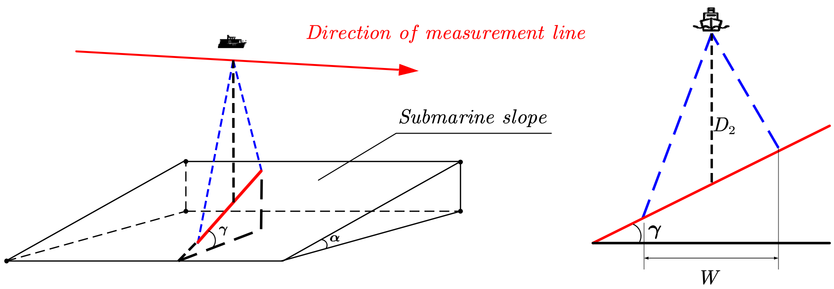

Figure 4. Sailing diagram (left) and vertical section diagram along the survey line (right)

For the analysis of this problem, this paper first adopts the method of establishing Cartesian coordinate system to get the vector and then solving the Angle.

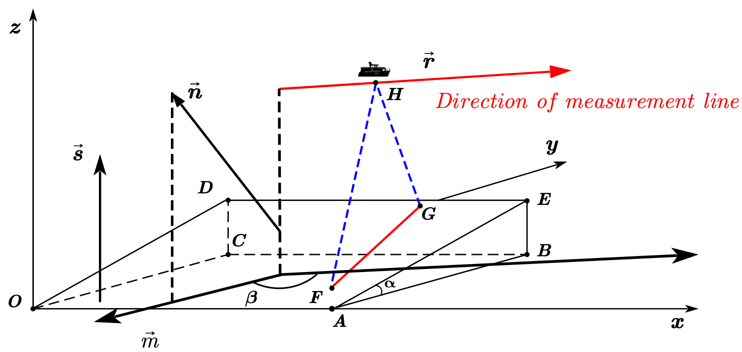

Figure 5. Vector solution based on Cartesian coordinate system

As shown in Figure 5, the coordinate system is established with the origin of the coordinates O and the line OA where it is located as the x axis. Suppose the normal vector of the slope is $\vec{n}$, the normal vector of the horizontal plane is $\vec{s}$, the direction vector of the slope normal vector projected on the horizontal plane is $\vec{m}$, and the direction vector of the measurement line direction is $\vec{r}$ (which is also the normal vector of the plane FGH). It can be assumed that all of the vectors $\vec{n}$, $\vec{r}$, $\vec{m}$, $\vec{r}$ and above are unit vectors. The eight points of the target O, A, B, C, D, E, F and G are shown in the figure. The points H are the position of the ship at this time.

Therefore, from the geometric relationship shown in Figure 5, it can be obtained:

$$\begin{cases} \vec{n} = (0, -\sin\alpha, \cos\alpha) \\ \vec{r} = (\sin\beta, -\cos\beta, 0) \\ \vec{s} = (0, 0, 1) \end{cases} \tag{2}$$

From the relationship between vectors in Figure 5, we can obtain:

$$\overrightarrow{FG} = \vec{n} \times \vec{r} \tag{3}$$

Therefore, the resulting Angle expression should be:

$$\gamma = \frac{\pi}{2} - \arccos\left|\frac{\vec{s} \cdot \overrightarrow{FG}}{|\vec{s}| \cdot \left|\overrightarrow{FG}\right|}\right| \tag{4}$$

Substitution simplifies to:

$$\gamma=\frac{\pi}{2}-\arccos\left(\frac{\sin\alpha\sin\beta}{\sqrt{\cos^2\alpha+\sin^2\beta\sin^2\alpha}}\right) \tag{5}$$

A mathematical model of the coverage width can be obtained by replacing equation 5 with equation 1:

$$W=\frac{2(D-x\tan\gamma)\cos^2\gamma\sin\theta}{\cos\theta+\cos2\gamma} \tag{6}$$

3.2. Iterative optimization model of random variable simplification

3.2.1 Line path planning Optimum line direction Angle β design

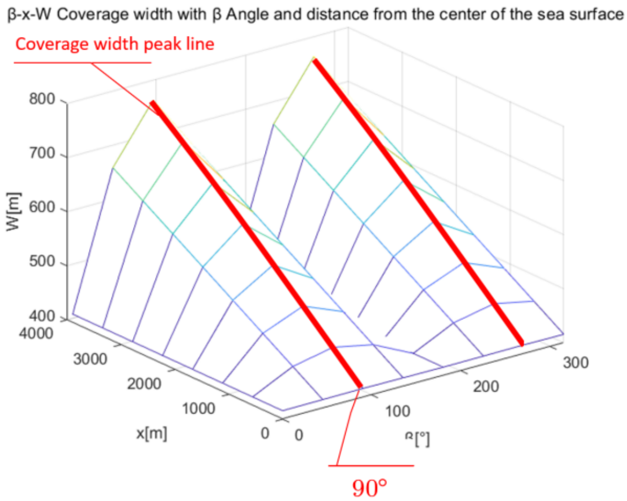

Figure 6. Surface diagram of coverage width variation

To minimize survey line length, paths should not be overly dense; that is, coverage width W must not be too small. W should be maximized to shorten survey line length. For a slope of known angle α, coverage width W is related to survey line direction angle β. When distance from sea area center point x is fixed, curve of W vs. β is parabolic, with maximum value at β (Figure 6).

3.2.2 Design of line and path planning model

Coordinate system established on the basis of the optimal survey line direction (right of Figure 7) :

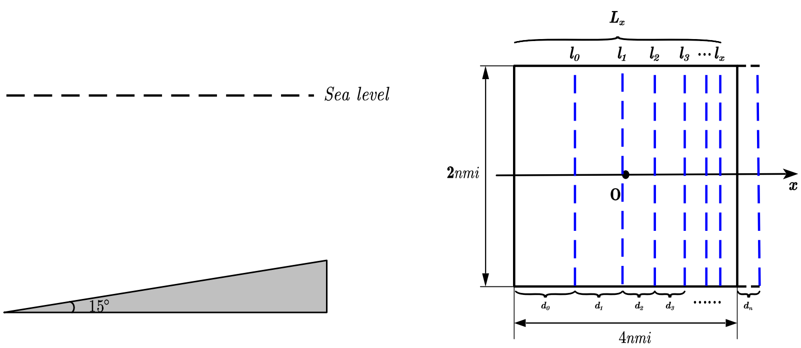

Figure 7. Schematic diagram of optimization model

When covering along $\beta=90^\circ$, each measurement line remains unchanged. Therefore, a one-dimensional coordinate system can be established with the center point of the rectangular sea area as the coordinate origin and the east as the positive direction (d_0, equation 7). dx is the distance between l_x and l_{x-1} (L_x, equation 8). The overlap rate corresponding to each measurement line is related to η_x, dx, and W_x (d_x, equation 9). It can be seen that η_x is only related to the current coordinates $(L_x - 2\times1852)$ and d_x is affected by d_{x-1}. To obtain the shortest path and satisfy η_x [0.1, 0.2], it is necessary to use an optimization algorithm to obtain the shortest route and design the spacing distribution of the survey lines d_x.

$$\frac{2\cos^2\alpha\sin\theta}{\cos\theta+\cos2\alpha}\left[-\tan\alpha\cdot(d_0-2\times1852)+110\right]=\alpha_0 \tag{7}$$

$$\eta_x=1-\frac{d_x}{\frac{2\cos^2\alpha\sin\theta}{\cos\theta+\cos2\alpha}\left(d_0+\sum_{i=1}^{x}d_i\right)+232.19} \tag{8}$$

$$d_x=\frac{(1-\eta_x)\left[232.19-0.03\left(d_0+\sum_{i=1}^{x-1}d_i\right)\right]}{1+0.03(1-\eta_x)} \tag{9}$$

3.2.3 Comparison and design of optimization algorithms

The particle swarm optimization algorithm can use the random iteration of bird population to produce the optimal solution. However, there is no correlation between the line spacing of each population $[d_1, d_2, \cdots, d_{dim}]$ randomly generated by the particle swarm optimization algorithm, so it does not meet the conditions of this problem.

The coin selection problem of dynamic programming is similar to the problem, but the coin denominations of dynamic programming (corresponding to the problem $[d_1, d_2, \cdots, d_{dim}]$) need to be set, and the denominations are not related to each other, and do not meet the conditions of the problem.

Therefore, it is necessary to design an algorithm that can reflect the correlation between the elements of $[d_1, d_2, \cdots, d_{dim}]$, meet all the conditions of the overlap of lines and have the shortest route.

3.2.4 Iterative optimization model design based on random variable unitization

1. Realization of single random variables

According to the expression η_x (formula 8), when given a definite overlap rate η_x in order from west to east, the distance d_x between the current line and the previous line can be directly determined according to the memory length L_x. Therefore, in the sequence iteration process starting from the westernmost part of the sea area, if η_x is within the required range $[0.1, 0.2]$ of the random number, (d_x, L_x) has real-time alternations, thus reducing the complexity of the algorithm and improving the computational efficiency. However, according to the formula, it can be seen that is only relevant to d_x, and based on the real-time alternations, L_x is only relevant to η_x, so as to meet the overlap rate range, and realize multidimensional variable $[d_1, d_2, \cdots, d_{dim}, dim, L_x]$ uniformization to η_x, simplifying the model.

2. Objective function design

The number of measured lines can be used as the direct objective function, and the path length is the indirect objective function. However, in order to cover the entire sea area to be measured, it is necessary to make the total coverage of the path slightly larger than the sea area, that is $L_x \geqslant 4$ the sea mile, while the number of measured lines is minimum, so the end mark of the most iterative judgment condition can be used.

3.2.5 The optimization model is solved

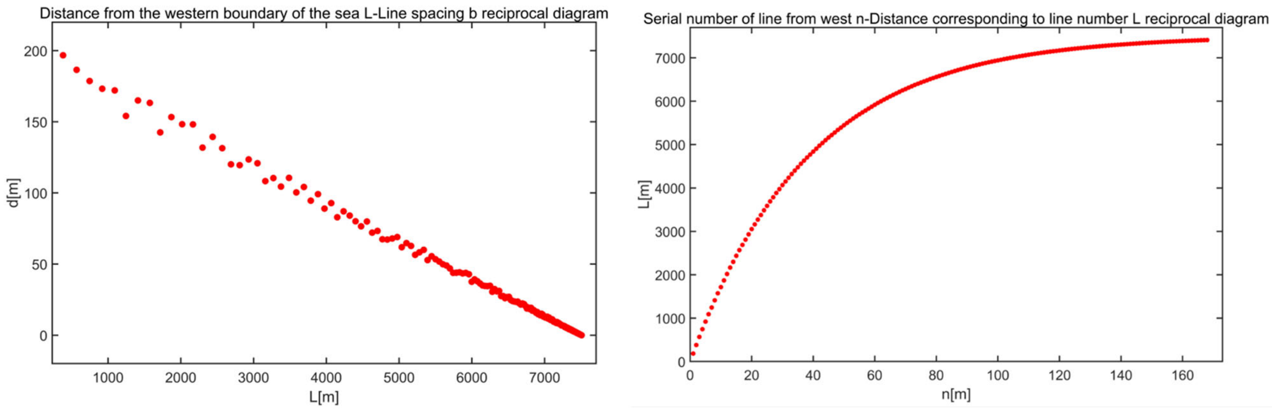

Figure 8. Mapping between L-b (left) and n-L (right)

The left of Figure 8 shows that as L increases, the measuring line points become denser. This is because the depth decreases with increasing L, and the overlap degree D affects the measuring line spacing. The total number of lines is 168±1, and the corresponding minimum measurement length is 334 to 338 nautical miles. The recommended survey line spacing scheme is (from west to east, unit is m).

3.3. Application of iterative optimization model with random variable unitization

3.3.1 Calculation of minimum number of lines n

The shortest survey line route depends on the number of survey lines, n, when determining topographic data, and only the shortest survey line route can be as small as possible. The simplified slope slope is approximately 1.5°, consistent with the earlier model. Therefore, the optimal value of n can be obtained by directly applying the iterative optimization model based on random variable unitization. To ensure that the strip covers the entire sea area and the overlap rate of adjacent strips is minimized to 20%, we modify the range of η_x to $[0,0,2]$ and incorporate it into the model. The resulting value of n reflects the optimal survey line route of the slope.

For designing the shortest line route, it is necessary to minimize overlap and ensure maximum coverage for each wire harness on the other half of the horizontal plane. When overlap is zero, the line route is shortest and maximum coverage width is achieved, allowing us to derive the specific routing scheme. At the intersection of two planes, measuring the depth of the slope may interact with measuring the depth of the horizontal plane, impacting the optimal survey line scheme. Minimizing the value of 'n' further determines its optimal value when both depths are measured simultaneously. Refer to Table 1 for details.

Table 1. Calculation results of n in different cases

At the border, different routing conditions	The route area on the slope covers the plane	The plane-running area covers the slope
n on the slope	53	59
The value of n in the plane	47	48
Total n value	100	117

3.3.2 Optimal routing and parameter measurement scheme design

It is not appropriate to use the minimum value of n to reflect the optimal routing scheme, as it may not cover the whole sea area to be measured. Additionally, a simple design should have equal coverage for each strip on the slope and an equal number of strips, resulting in $n=100$, the total number of strips. To simulate the total number of ideal lines and obtain the overlap rate value η, the iterative optimization model above is carried out for traversal. This results in a relationship curve between the total number n of lines and overlap rate η.

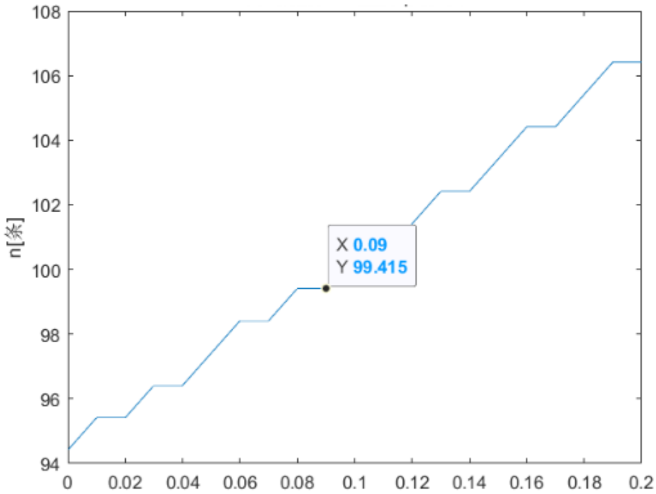

Figure 9. Relationship between the number of measured lines n and overlap degree η

The overlap rate $\eta=0.08$ and $n=100$ are employed as the ideal test parameters. As shown in Figure 9, the optimal routing scheme features equal coverage for all strips on the slope (0.09), with 43 strips on the slope and 57 strips on the horizontal plane. The shortest track length is 320 nautical miles. To obtain the area proportion of missing test areas and the total length of tracks with excess 20\% strip coverage, linear programming is used to traverse sample values, obtaining the ratio of samples meeting measurement conditions to total samples. Easy calculation using total track length. Flexible use of η expressions and variable relationships is necessary to transform the problem.

4. Conclusion

In this paper, based on two-dimensional and three-dimensional slope model, overcoming the limitations of particle swarm algorithm and dynamic programming algorithm, an iterative optimization model of random variable singularization is designed independently based on intelligent optimization algorithm, which overcomes the difficulty of particle swarm algorithm that the variables are random and unrelated, and makes up for the known number of denomination of the dynamic programming algorithm, the "Coin Problem", and solves the problem of small amount of data acquired by single-beam surveying, and low working efficiency. It overcomes the difficulty of random correlation of variables in particle swarm algorithm, makes up for the known denomination of the "coin problem" in dynamic programming algorithm, and solves the problems of low data volume, low working efficiency and large survey cost acquired by single-beam measurement. Multiple complex independent variables are transformed into a single bounded and random variable with real-time iterative effect, which is capable of solving multiple variable optimization problems with unknown numbers. A relationship model between a single variable η and a real-time variable d is established and based on this model, the distribution of survey line spacing of the survey vessel in the actual environment is solved, and the shortest path and the total number of survey lines under the shortest path in a specific sea area are obtained, as well as the percentage of the omitted sea area to the total area to be surveyed is measured by the optimization model, so as to validate the reliability of the model.

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