

Optimisation of multibeam survey lines based on geometric analysis model and Monte Carlo simulation

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Abstract. A multibeam sounding system can continuously measure through a specified survey line and stitch the results to obtain a topographic map of the seabed in the area. In this paper, we propose a method based on geometric mechanism analysis and Monte Carlo simulation to design a survey line for a specific rectangular slope area. Through geometric mechanism analysis and Monte Carlo simulation, it is obtained that the total length of the survey line is shortest when the projection angle of the survey line and the normal vector of the slope surface is 90 degrees in the horizontal plane and the overlap rate of the adjacent strips of the survey line is 10 %; then, according to the constraints on overlap rate and iterative boundaries, 34 unequal spacing survey lines are designed in conjunction with the three-dimensional geometric relationship, and the spacing of the survey lines is gradually denser with the depth of the sea floor decreasing from the west to the east. The design method is of great significance for the depth measurement of seawater in the actual sea area.

Keywords: Multibeam systems, multidimensional geometric modelling, Monte Carlo, line laying, seabed approximation topography.

1. Introduction

Single-beam sounding technology relies on the propagation characteristics of sound waves in water to measure the depth of the water body, and its basic characteristic is the uniform linear propagation of sound waves in a homogeneous medium and reflection at the interface. Through the transducer in the seawater emission of sound waves, and record the acoustic wave reflection back to the multibeam transducer time, when the multibeam detection sonar along the specified measurement line continuous measurement and multiple measurement line measurement results reasonable splicing, its through the scanning of the known obstructions, you can present a more vivid seabed geomorphological three-dimensional image, data results of higher resolution and accuracy [1]. The survey line layout is an important part of the multibeam application in the channel bathymetry, and the scientific and reasonable survey line layout can not only improve the measurement efficiency and save the measurement cost, but also can truly and perfectly reflect the channel topography. In order to get the shortest total survey line length survey line laying method is an important step in marine survey, which covers the whole survey area by laying survey lines from the middle of the channel to both sides. Firstly, a first line is laid at maximum water depth and the swath width of the line is approximated. Then, according to the laid survey line and the width value, neighbouring survey lines are laid to both sides in turn, until the whole survey area is covered [2]. Laying of survey lines in offshore multibeam surveys is usually done with the help of geographic information system (GIS) platforms such as ArcGIS and Global Mapper. However, these platforms lack targeted functionality development, which leads to inefficient operation [3]. And the inter-lines of measurement are not as efficient as they should be. Moreover, there is no measurement information between survey lines, and the relevant information is usually obtained through various interpolation methods using the measurement information of the main survey line and the check line [4]. In order to improve the efficiency of side-scan sonar line deployment, researchers have proposed an optimisation method based on the resolution distribution law of side-scan sonar system [5]. Regarding the spacing of survey lines, the calculations carried out by the International Hydrographic Organisation (IHO), the United States and the United Kingdom, etc. have produced largely consistent results [6]. The technical

scheme of shipborne sonar bathymetric line placement for the joint satellite altimetry technique is difficult to summarise the correlation between the complexity of gravity data and the relationship between optimal shipborne bathymetric line density placement due to the small experimental samples [7]. The GIS system and the consistent line spacing considered by the predecessors in the deployment of survey lines are not applicable in some practical situations, and the methods of first deploying in the deepest and then expanding and optimising the side-scanning sonar system have limitations, this paper proposes a geometric mechanism analysis and Monte Carlo-based survey line design for rectangular sloping sea area, which is able to effectively conform to the requirements of surveying and solve the practical problems, and has better measurement. Solve practical problems and have better economic benefits. Under the premise of meeting the requirement of overlapping rate of adjacent strips of the survey line, firstly, the parameter values of the model are set; then, the direction of the rectangular area is determined and the coordinate system is established; finally, the mathematical model of the coverage width based on the geometric relationship is applied to design the survey line that meets the shortest measurement length and covers the entire rectangular sea area by using the mechanism analysis and Monte Carlo simulation to get the shortest total length of the survey line.

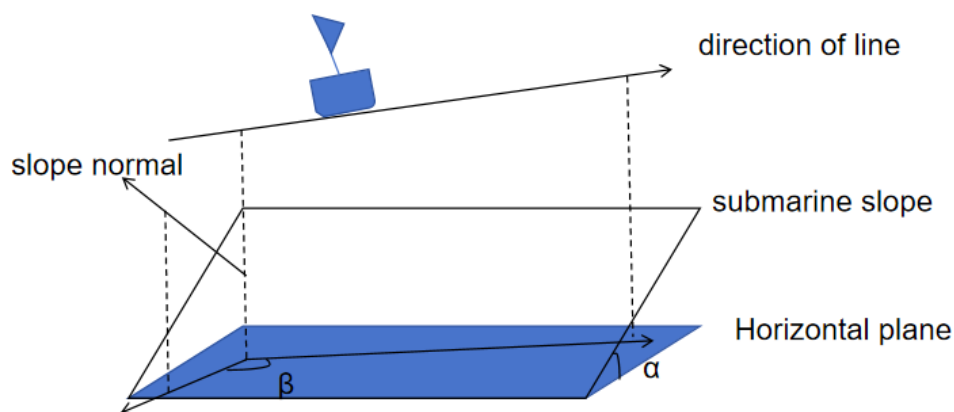
2. Principles of line design

2.1. Overall description of the situation in the surveyed sea area

The sea area is 2 nautical miles long from north to south and 4 nautical miles wide from east to west. The depth of the sea water at the centre of the sea area is D_0 m, the depth is deep in the west and shallow in the east, and the slope is α . Therefore, the seabed topography of the sea area is assumed to be an ideal slope.

The multibeam system and design parameters for the design of the line measurement process are described:

The opening angle of the multibeam transducer is θ and the angle between the direction of the measurement line and the projection of the normal direction of the seabed slope on the horizontal plane is β , and the overlap rate λ between neighbouring strips meets the requirement of 10%~20%. The measurement vessel travels along the direction of the measurement line, and when the measurement vessel is carrying out the measurement, it is fixed and the coverage width varies with the opening angle of the multibeam transducer and the change of the water depth. The overall operation of the vessel and the sea area are shown in Figure 1.



Projection of a slope normal onto a horizontal plane

Figure 1. Schematic representation of the overall situation in the maritime area

2.2. The process of describing the geometric principles of line design

In the process of survey ship measurement, the multibeam transducer is installed on the outboard side of the hull and exceeds the bottom of the ship [8], which receives the seafloor backscatter signal, and after analogue/digital signal processing, forms multiple beams, and simultaneously obtains the bathymetry data of several hundred sampling points on the seafloor strips [9]; so firstly, the coordinate system of the hull is established. In the centre point of the sea as the origin, the x-y-z coordinate system is established, and this paper obtains the following relations by constructing auxiliary lines, sine theorem and other plane geometry relations:

The relationship between the spacing between the survey line and the initial survey line and the water depth:

$$D = D_0 + (\Delta L - x) \tan(\alpha) \quad (1)$$

Description of the formula:

x—Distance between the survey line and the initial line through the centre of the sea area

Relationship between coverage width and overlap of neighbouring strips:

$$\eta = 1 - \frac{\Delta L}{w} = 1 - \frac{\Delta L}{\left(\frac{(D_0 + (\Delta L - x) \tan(\alpha)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} + \alpha)} + \frac{(D_0 + (\Delta L - x) \tan(\alpha)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} - \alpha)} \right) \cos(\alpha)} \quad (2)$$

Description of the formula: w—Coverage width

In a rectangular sea, when the angle β between the direction of the survey line and the normal projection of the seabed slope on the horizontal plane changes, the formulae for calculating the cover width and depth change according to the change in the angle of the slope shown when the survey line is cut in the positive section, so that the real-time slope is λ . After constructing the auxiliary lines and deriving the three-dimensional geometric relationships, the relationship between the cover width and depth with respect to the angle between the direction of the survey line and the angle β between the normal direction of the seabed slope and the projection on the horizontal plane is obtained.

The relationship between the real-time slope and the angle β between the direction of the survey line and the projection of the normal direction of the seabed slope on the horizontal plane, and the initial slope α is as follows:

$$\lambda = \arctan(\cos(\beta - \frac{\pi}{2}) \tan(\alpha)) \quad (3)$$

The relationship between real-time depth and the angle β between the direction of the survey line and the projection of the normal direction of the seabed slope on the horizontal plane, and the initial slope α is as follows:

$$D' = D_0 - kx \sin(\beta - \frac{\pi}{2}) \tan(\alpha) \quad (4)$$

The mathematical relationship between the width of cover and the angle β between the direction of the survey line and the projection of the normal direction of the seabed slope on the horizontal plane, and the initial slope α , is obtained:

$$w_s = \left(\frac{(D' - x \tan(\lambda)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} + \lambda)} + \frac{(D' - x \tan(\lambda)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} - \lambda)} \right) \cos(\lambda) \quad (5)$$

2.3. Design of line layouts

Combining the above mathematical relationships, a set of survey lines that meet the overlap rate requirement, have the shortest measurement length and cover the entire rectangular sea area will be designed with the specific parameters of this paper.

Firstly, the distribution of survey lines is analysed; in order to get the shortest survey line path that meets the overlap rate requirement and covers the rectangular sea area. According to the IHO Hydrographic Code, depending on the seabed characteristics, the line spacing may need to be reduced, or increased if the environment permits. Check bathymetry lines should be laid at discrete intervals. The lines are usually laid parallel to each other, so it is assumed in this paper that the lines are parallel to each other, that the lines are not equally spaced and that the vessel is always travelling in a straight line.

From the formula above, it can be deduced that the decrease in the depth of the sea water will lead to a reduction in the width of the coverage, taking into account the characteristics of the depth of the sea water in the rectangular sea area in the title - from east to west gradually become deeper. Accordingly, it can be inferred that the closer to the east, the smaller the coverage width detected by the survey vessel, so more survey lines need to be laid. Therefore, the design of this paper can be considered to be more dense in the east than in the west when laying survey lines.

2.4. Angle β selection

First of all, for the selection of angle β selection mechanism analysis, because of the symmetry of the left and right, it is only consider β in the range of 0 to 90 degrees, when the time β greater than or equal to 90 degrees, with the increase of β , the extension of the measuring line to the intersection with the long side of the rectangular sea, found that the intersection point from the top side of the shortest distance from the apex, but also because of the upper measuring line should be more compact, need to have a certain amount of distance to be able to ensure that overlap rate of the case of the measuring line to ensure that the maximum degree of distance measurement Layout, to prevent the possibility of leakage between the survey line or the overlap between the two ship detection is too large. Similarly can be obtained, when the time β less than or equal to 90 degrees, with the reduction of β the extension of the measurement line to the intersection with the long side of the rectangular sea, found that the intersection point from the lower side of the shortest distance from the apex, but also because of the upper measurement line should be more compact, need to adjust the distance to a certain extent to be able to ensure the overlap rate of the case of the line of measurement to maximise the degree of the measurement of the distance laid to prevent leakage of measurement between the line of measurement or the overlap between the two ship detection of the possibility of an increase in the rate of detection. Therefore, the length of the survey line is the longest. Therefore, we take β equals 90 degrees, when the length of the line is the shortest, and the possibility of the above problems is minimised. Thus, the initial choice β equals 90 degrees is to maximise the adjustable distance of the survey line, minimise the length of the survey, and increase the coverage of the sea area.

In order to check β equals 90 degrees whether the requirement of the shortest measuring length is fulfilled, Monte Carlo simulation is used to optimise the selection of the angles;

Based on the above mathematical formulas and the requirements of survey line deployment, an optimisation equation is constructed with the objective function as the total length of the survey line, the decision variable as the angle β between the direction of the survey line and the projection of the normal direction of the seabed slope on the horizontal plane, and the constraints as the geometrical relationship between the measurement area covering the whole sea area to be surveyed and the relevant angles.

$$\text{objective function: } \min \sum_{i=1}^n l_i \quad (6)$$

$$\text{Decision variables: } \beta \quad (7)$$

$$\text{restrictive condition} \left\{ \begin{array}{l} 2\pi \geq \beta \geq \frac{\pi}{2} \\ d > 0 \\ n > 0 \\ \sum_{i=1}^n w_i L_i (1 - \eta_i) > S \\ 20\% \geq \eta_i \geq 10\% \\ i \leq n \end{array} \right. \quad (8)$$

$$D_s = D' - k l_i \sin(\beta - \frac{\pi}{2}) \tan(\alpha) \quad (9)$$

$$w_i = \left(\frac{(D_s + k d_i \tan(\lambda)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} + \lambda)} + \frac{(D_s + k d_i \tan(\lambda)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} - \lambda)} \right) \cos(\lambda) \quad (10)$$

$$\eta_i = 1 - \frac{k d_i}{w_i} \quad (11)$$

$$n = \frac{(\frac{2}{\tan \beta} + 4) \sin \beta}{d} \quad (12)$$

$$S = 8k^2 \quad (13)$$

$$l_i = (i - \frac{1}{2}) d_i \quad (14)$$

$$\text{if } : l_i \leq \frac{1}{2} (4k - \frac{2k}{\tan \beta}) \sin \beta, L_i = \frac{2k}{\sin \beta} \quad (15)$$

$$\text{if } : l_i > \frac{1}{2} (4k - \frac{2k}{\tan \beta}) \sin \beta, L_i = \frac{2 \cos \beta - [l_i - \frac{1}{2} (4 - \frac{2}{\tan \beta}) \sin \beta]}{2 \cos \beta} k \quad (16)$$

The initial variables are as follows: D'=110;θ=120°;α=1.5°;k=1852;

Description of the formula:

L_i—Line length

S—total sea area

D_i—line spacing

n—number of lines

η_i—coverage between neighbouring strips

D—real-time sea depth

k—nautical mile unit conversion factor

After 40,000 Monte Carlo simulations, the optimal value is finally converged to 90 degrees, which verifies the reasonableness of the above mechanism analysis. The convergence diagram of Monte Carlo simulation is shown in Figure 2.:

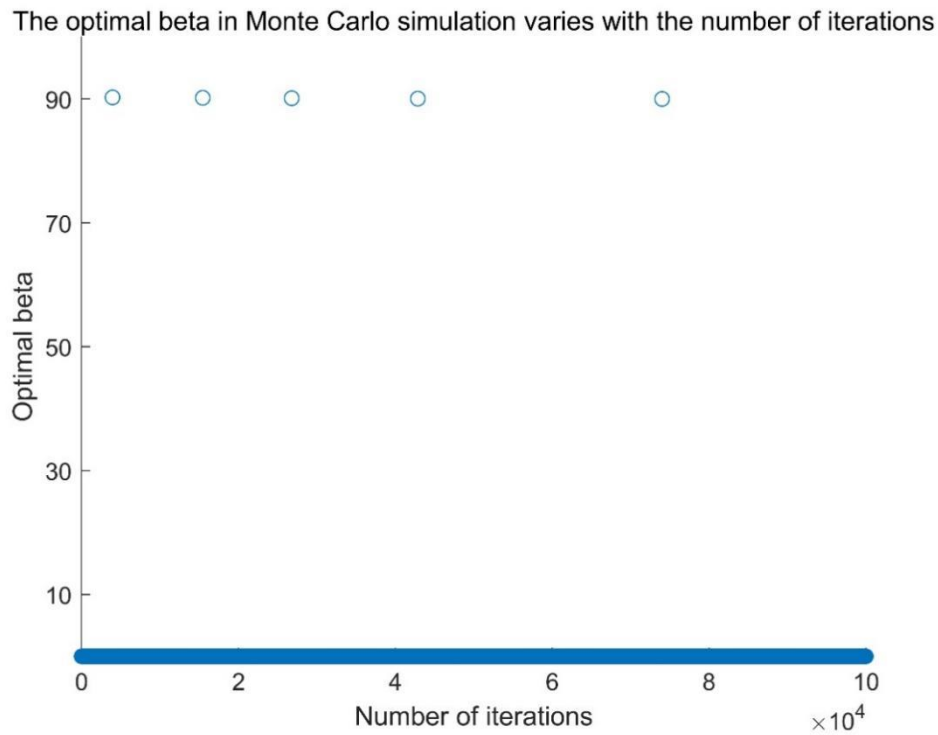


Figure 2. Monte Carlo iterative diagram

2.5. Selection of values η

From Eq. (2), a decrease in the overlap ratio leads to an increase in the spacing between lines d and a decrease in the width of the coverage w . At the same time, the number of lines required is reduced, thus realising a reduction in the measurement length.

Therefore, the overlap rate is taken η equals 10% to minimise the measurement length.

2.6. Coordinate system establishment

In the rectangular sea area, assume that the east direction is the top and the west direction is the bottom, and use the right side of the rectangular area as the x-axis in order to

The coordinate system is established as shown in Figure 3.:

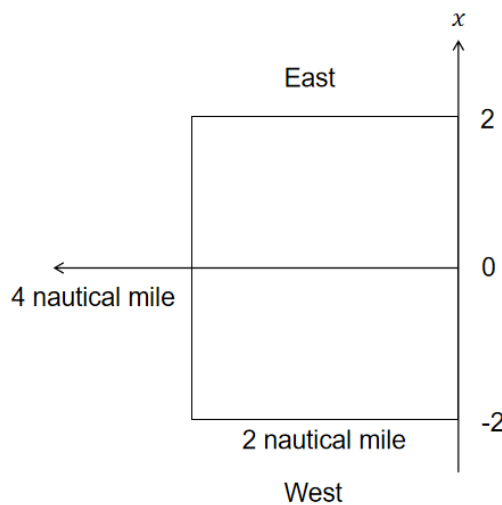


Figure 3. Coordinate System Establishment Chart

2.7. Specific process for line design

Step1: Calculation of the coverage width for multibeam detection

$$w_i = \left(\frac{(D_0 - x_i \tan(\alpha)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} + \alpha)} + \frac{(D_0 - x_i \tan(\alpha)) \sin(\frac{\theta}{2})}{\sin(\frac{\pi}{2} - \frac{\theta}{2} - \alpha)} \right) \cos(\alpha) \tag{17}$$

Step2: Calculation of line spacing between different lines

$$d_i = w_i(1 - \eta) \tag{18}$$

Step3: Solve for the bearing of the ship's line of sight

The band can be obtained by measuring the total number of line spacing iterations less than the boundary constraints on the long edge of the rectangular sea domain:

$$x_{i+1} = x_i + d_i \tag{19}$$

$$\sum_{i=1}^n d_i \leq 4 \tag{20}$$

Description of the formula:

x_i ——Orientation of the (i)th line of measurement

x_{i+1} ——Orientation of the (i+1)th line of measurement

Step4: Solving for the number of lines

The logic of the solution is to firstly substitute the initial value $x_1 = -2$ into Eq. (18) find out w_1 and then through Eq. (19) to find out d_1 , through the decision boundary conditions to decide whether to pass Eq. (20) if not reached all the d_i 's add up to 4, then repeat the above process until the iteration boundaries are met, and finally the output n . The specific flowchart is shown in Figure 4.

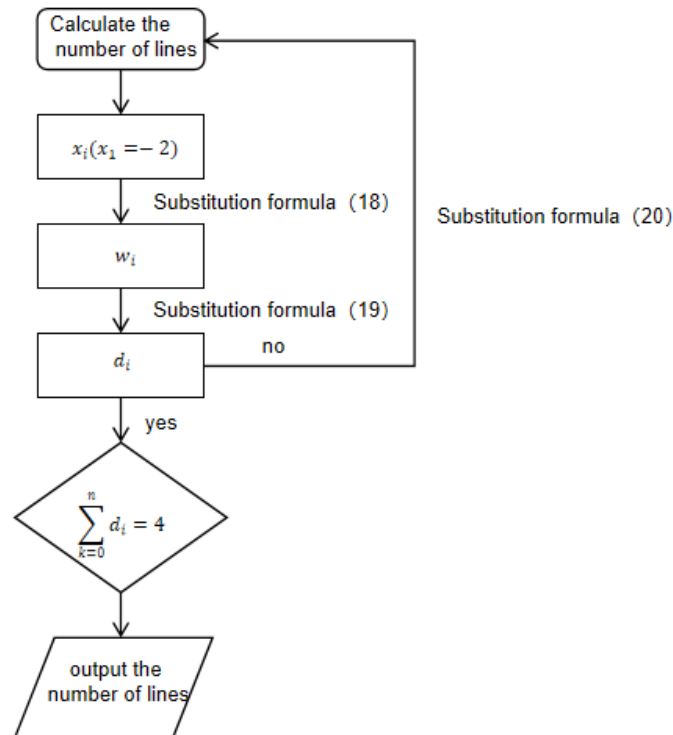


Figure 4. Iterative Process Flowchart

Step5: Calculate the total length of the line

$$L = 2n \tag{21}$$

3. Results

3.1. Visualisation of the distribution of survey lines

The results of the survey line placement distribution visualisation are shown in Figure 5. and Figure 6.

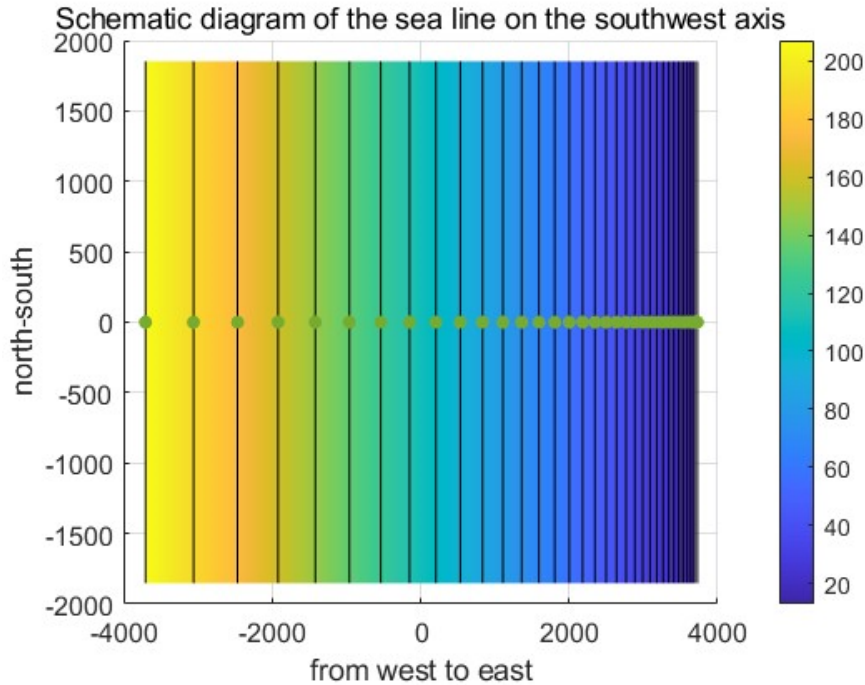


Figure 5. Schematic of the line survey of the sea area in two-dimensional top view

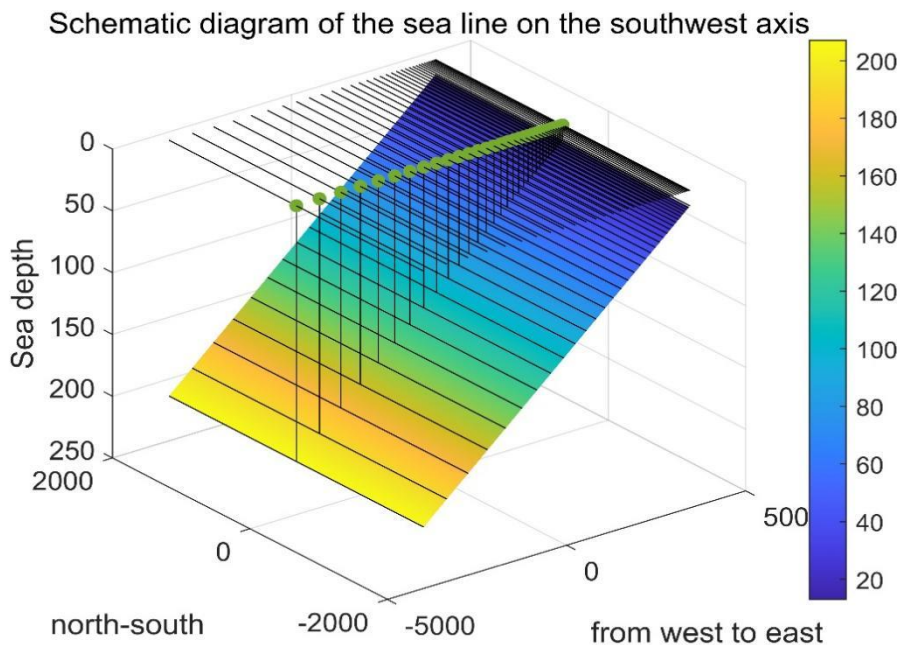


Figure 6. Schematic of the 3D south-west axial seaward hydrographic lines

3.2. Description of the results of the distribution of survey lines

The distribution of survey lines shows that there are 34 unequally spaced lines, and the length of each line is equal to the width of the rectangular sea area on the north and south sides, so the total distance of the lines is 68 nautical miles according to Equation (21). As the depth of the sea water

decreases, the spacing of the survey lines is gradually denser from west to east, and the overall trend is sparse in the west and dense in the east.

4. Conclusions

Multi-beam detection system is the evolution of single-beam detection technology, the work relies on the principle of acoustic wave propagation, through the acoustic wave propagation speed and duration in seawater to measure the depth of seawater. In this paper, from solving the problem of multibeam detection system, we comprehensively establish a multidimensional spatial geometric relationship model, multi-directional auxiliary lines, surfaces and the use of geometric relationships for the mechanism of analysis and Monte Carlo simulation to find the optimal value of the projection angle of the survey line and the normal vector of the slope surface in the horizontal plane, and then use the constraints and the different seawater depths based on the iterative boundaries designed a set of 34 unequal spacing of the survey line, with a total survey line length of 68 nautical miles. The overall trend of the survey lines is sparse in the west and dense in the east. The proposed method based on geometric analysis model and Monte Carlo simulation is reasonable and feasible, and is less restricted by the complex seabed environment and multipath effect [10], which is more in line with the measurement requirements.

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