A study of multibeam line measurement based on analytic geometry and genetic algorithm

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Abstract. This paper focuses on the multibeam bathymetry technology for seabed terrain detection, and utilizes the geometric model, genetic algorithm to study the multibeam bathymetry line according to the actual situation of multibeam bathymetry coverage width, measurement length and overlap rate. Firstly, this paper uses the geometric analysis of the coverage width in relation to the slope angle α and seawater depth D, establishes the multibeam bathymetry coverage width and overlap rate model, and obtains the results of the coverage width and overlap rate in the specified cases by using python. Secondly, on this basis, a new condition of line direction angle β is introduced to establish a multibeam bathymetry coverage width model based on line direction, and the coverage widths under different line directions are obtained by using pyhon, and the analytical results show that the coverage widths and seawater depths are positively correlated with each other under the main oblique measurement direction. Finally, considering the influence of the minimum coverage area, the range of overlap rate and other constraints, the objective function of the shortest survey line length is established under the oblique measurement direction, and the shortest survey line program is obtained based on the genetic algorithm solution. The model constructed in this paper can provide a new idea in the field of nautical miles surveying and mapping.

Keywords: Multibeam bathymetry, Geometric modeling, Coverage width, Genetic algorithm.

1. Introduction

With the rapid development of science and technology, the hydrographic system has become more diversified[1]. Multibeam bathymetric system is one of the widely used means of national ocean exploration at present[2], capable of obtaining the depth of seawater at multiple measurement points within a strip coverage area, and realizing high-precision and full-coverage sweeping of the seabed topography of the established sea area without any omission[3], for example, obtaining the underwater topography of a certain island's mooring area and the gyre area[4]. On this basis, it is also necessary to consider the influence of survey line placement[5] on the measurement results, which usually includes the coverage width, survey line direction and other aspects. Among them, Chengfang and Hu Naicheng[6] constructed a multibeam survey line placement optimization method based on step-by-step optimization design idea, which not only ensures the full coverage measurement, but also meets the required bathymetry data with predetermined topographic resolution. In response to the researchers' need for on-site survey line design and modification based on the results of multibeam data preprocessing, Wang Fengfan, Ma Yong[7] utilized the system to design an automatic interval judgment in order to provide a suitable survey line laying scheme, which effectively solved the time-consuming drawbacks of manual design. In order to further strengthen the bathymetric accuracy, Zhou Ping[8] performed quality control for the bathymetric data in the strip splicing area, and Wang Junsen et al[9] utilized the overlapping area of adjacent survey lines for the multibeam bathymetric transverse rocking motion residual correction model. Therefore, as the core content of the technical design of the multibeam survey area, the survey line laying plays an extremely important and even decisive role in the quality and efficiency of the survey results of the whole survey area.

Through analysis, it is found that the operation mechanism of the above methods is relatively complex, and there are fewer studies on the coverage width and line direction. For this reason, this paper proposes a new multibeam line optimization scheme based on an in-depth analysis of the impact of coverage width and line direction on the results, and specifically conducts the following studies:

(1) When the seafloor slope is α, this paper establishes a mathematical model of the coverage width and the overlap rate between adjacent strips of multibeam bathymetry. And the model is verified when the transducer opening angle is $90°$, the slope is $1.5°$, and the depth of seawater at the center point is 70m.

(2) Assuming that the angle between the direction of the survey line of the survey vessel and the projection of the normal direction of the seafloor slope on the horizontal plane is β in a scenario of a rectangular sea area, a mathematical model of the width of coverage of the multibeam bathymetry is established. And validate the model in the case when the opening angle of the transducer is $200°$, the slope is $1.5°$, and the depth of seawater at the center point is 120m.

(3) Suppose the scenario is in a rectangular sea area with a length of 2 nautical miles from north to south and a width of 4 nautical miles from east to west, the depth of the sea water at the center point of the sea area is 110 m, the depth is deep in the west and shallow in the east, the slope is $1.5°$, and the opening angle of the multibeam transducer is $120°$. In this paper, a set of survey lines will be designed with the shortest length and can completely cover the whole sea area to be surveyed, and the overlap between neighboring strips is kept in the range of 10%-20%.

2. Materials and methods

2.1. Data Acquisition

The research data for this paper was obtained from the open source website Github.

2.2. Research methodology

2.2.1 Overlap rate problem analysis

The relationship between the coverage width of multibeam bathymetry and the overlap rate between neighboring strips is mainly modeled. First of all, we refer to the study on the imputation of the position of the bathymetric point by Ji Gang[10], and construct the profile to determine the relative positional relationship of the points with different distances from the center point., and the geometric relationship between the coverage width W and the depth of seawater D are analyzed in turn, and then the relational equation is established. Considering the solution of overlap rate between adjacent strips, the equation is analyzed, and the overlap rate model is finally constructed after conversion.

2.2.2 Coverage width model analysis

The mathematical model of the coverage width is established mainly based on the direction of the angle β between the traveling survey vessel and the normal projection of the seabed slope. It is analyzed that the direction of the survey line β can determine the actual slope γ constituted by the intersection line between the plane perpendicular to the line direction and the seabed slope, and at the same time, the change of the coverage width of the survey vessel is mainly affected by the depth of seawater and the actual slope of the survey point. Therefore, the center of the sea area is set as the origin, and the relationship equations between the actual slope and the depth of the sea water and β are obtained by the method of establishing a right-angle coordinate system.

2.2.3 Analysis of the line measurement program

The development of this line survey scheme is essentially a parameter optimization model based on the overlap rate model and the coverage width model described above. The purpose is to solve the optimal deployment method. Here, the optimum should be the shortest length of the survey line as the optimization objective, to cover the entire sea area to be surveyed, the overlap rate in the range of 10%-20% as a constraint, to solve the optimal bathymetric design to meet the specified sea area, this paper mainly through the analysis of the nature of the coverage width, the establishment of geometric relationships to get the objective function to solve.

3. Results and analysis

3.1. Construction of an overlap rate model

3.1.1 Graphical analysis

According to the characteristics of the multibeam measurement technology, the measurement ship takes the center point of the sea area as the measurement origin, and observes the two sides with a measurement spacing of 200m in turn. As in Figure. 1, it can be expressed as the profile of the measurement vessel at different distances from the center point, and the measurement vessel at the origin is, Bo then the measurement vessels from the center to the right can be respectively recorded as $Bo_{-1}, Bo_2, \dots, Bo_n$,and similarly to the left can be recorded in turn as $Bo_{-1}, Bo_{-2}, \dots, Bo_{-n}$, and the same rules apply to the rest of the letter numbering.

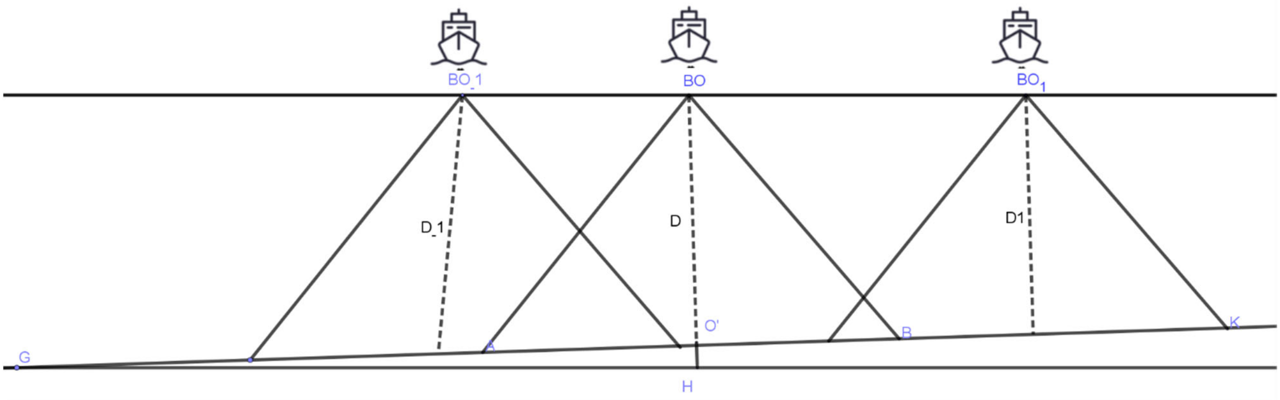

Figure 1. Illustration of a survey vessel

The figure mainly presents the basic relative position relationship of the survey vessel at different distances. It can be seen that through the known information, according to the geometric relationship, the values of the length of each side in the figure can basically be solved, and the following mainly establishes the overlap rate model by analyzing the coverage width as well as the seawater depth.

3.1.2 Coverage width W modeling

In this paper, the coverage width model is analyzed firstly, in Fig. 1, a vertical line from O' is made to intersect the horizontal plane at H,which intersects the slope at $\angle 1$. Since the values of θ and α are given, the geometric relationship of W will be plotted directly in the following for calculation.

As shown in Figure. 2, let the top point of the slope be G, and the survey line and the slope intersect at points A and B. $\Delta GHO'$ is a right triangle, $\angle 1$ is known, and since OO', at θ is known, $\Delta AOO'_0$ and θ are known. $\Delta BOO'$are solvable. AO' and BO'can be solved for respectively, i.e., the coverage width W is obtained.

The equation is obtained as follows:

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

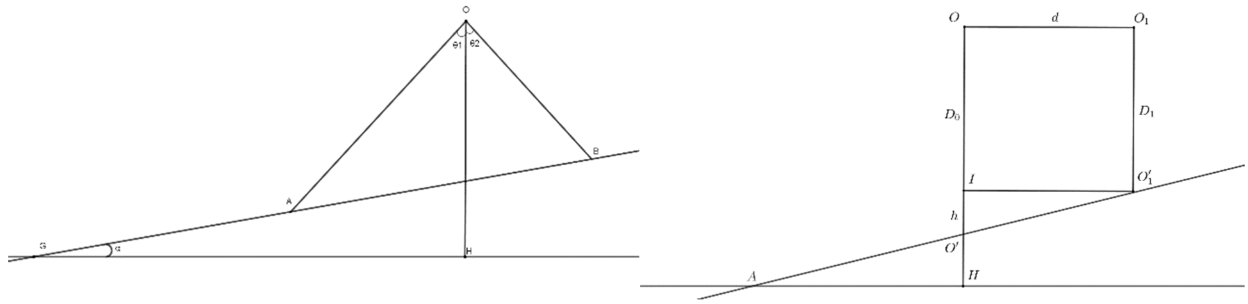

Figure 2. Plot of geometric relationship between coverage width W (left) and seawater depth D (right)

3.1.3 Seawater depth D modeling

In Figure 1, from O_1' as a vertical line to intersect OO' in I, connecting OO', OO_1 that is, the interval of the measurement line d, the following will be directly plotted out the geometric relationship between the W, to be calculated.

As shown in Fig. 2, the geometric relationship of seawater depth D is shown in Fig. 2, D is a known number, and the seawater depth D_1 of the neighboring survey vessel is demanded. Where due to parallel, i.e., $OO_1 = IO_1' = d$, due to $\Delta GHO'$ and $\Delta IO'O_1'$ are similar triangles, i.e., IO' can be found. According to the equation $D_1 = D_0 - IO'$, the seawater depth D_1 of the neighboring survey vessel can be obtained.

The equation is obtained as follows:

$$D = D_0 - dist \cdot \tan\alpha \tag{2}$$

where $dist$ is the distance of the line from the center.

3.1.4 Overlap rate η modeling

Since the formula $\eta = 1 - \frac{d}{W}$ is used as a flat sea application formula, and the sea has a certain slope in the preset scenario of this paper, that is, it is necessary to improve the formula by substituting α.

For example, the formula can be transformed to $\eta = \frac{W-d}{W}$, where W and d are both parallel to the flat sea area, while W in this paper is calculated to be parallel to the slope of the sea floor, and in order to make the data of the same magnitude, it is constructed as $d' = \frac{d}{cos\alpha}$.

The final model equation is obtained as follows:

$$\eta = 1 - \frac{d'}{W} \tag{3}$$

3.1.5 Model solution

When the conditions are set as follows: the opening angle of the multibeam transducer is 120°, the slope is 1.5°, and the depth of seawater at the center of the sea area is 70 m, the results are calculated by using python as shown in Table 1.

As can be seen from Table 1, under this setup, the depth of the sea water and the width of the coverage varied positively from left to right, while the overlap rate varied inversely. That is, the shallower the sea water is, the smaller the overlap rate is; conversely, the larger the overlap rate is. According to the data in the table, when the distance of the measuring line from the center point reaches 400m, the phenomenon of missed measurements will occur, and the overlap rate at a distance of -400m has already exceeded 20%, which is bound to affect the measurement efficiency.

Table 1. Overlap rate model solution table

Distance of the line from the center point	-800	-600	-400	-200	0	200	400	600	800
depth of sea/meter	90.95	85.71	80.47	75.24	70.00	64.76	59.53	54.29	49.05
Coverage width/ meter	301.49	284.13	266.77	249.41	232.05	214.68	197.32	179.96	162.60
Overlap with previous line/%	0.00	29.59	25.00	19.78	13.78	6.81	-1.39	-11.17	-23.04

3.2. Construction of the coverage width model

3.2.1 Model analysis

Next, the new condition of the angle β of the survey line direction is introduced to investigate the coverage width model.From Fig. 3, it can be seen that when the survey vessel takes the angle of β as the direction of the survey line on the sea surface with a seafloor slope of α, the angle of slope on the crown profile is not α, and so this actual angle of slope is defined as γ. The value of γ needs to be discussed in the calculation process.

The following mainly focuses on the new parameter β. It can be seen that β is the angle between the direction of the survey line and the projection of the normal direction of the seabed slope on the horizontal plane, and since β is on the horizontal plane, it can be used as a proxy for the direction of travel of the survey vessel. According to the schematic diagram in Figure. 3, it can be seen that in this β direction, the seawater gradually becomes shallower as the survey vessel travels forward, i.e., the coverage width of the survey decreases, and it can be preliminarily determined that the model of coverage width of the research object is in the form of a trapezoidal strip with a narrower upper part and a wider lower part.

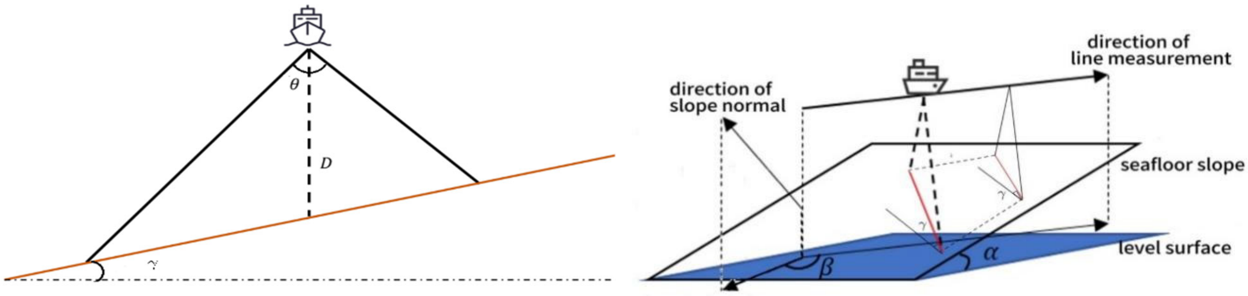

Fig. 3 Coronal profile (left) and schematic diagram (right) under the measured direction of clamping angle

3.2.2 Modeling of multibeam bathymetric coverage width based on line direction

Coverage width modeling is mainly solved by establishing a right-angle coordinate system. The analysis shows that the direction of the survey line of the survey ship can be changed by changing β, considering the difference of the actual situation in different directions, the case of $90° < \beta < 180°$ is firstly studied.

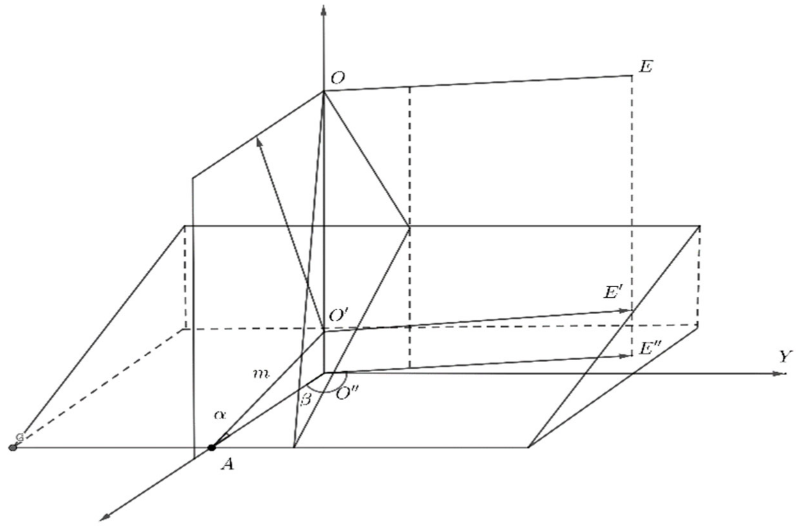

Figure 4. Diagram of the establishment of the Cartesian Coordinate System

The way to build the system is mainly shown in Figure. 4:Let the location of the survey ship be the point O, O' and O'' are the projection points of the point O on the seafloor slope and the horizontal plane, respectively, and set up the right-angled coordinate system with the point O'' as the origin, and the z-axis of OO'' as the figure. Where the x-axis and the intersection line of the dihedral angle α intersect at point A, point E represents the measuring vessel during traveling, set $O'A = m, O'E = n$.

(1) Actual slope angle γ modeling

From the geometric analysis of Fig. 3, it can be seen that the actual slope angle γ needs to be solved first. γ is the angle between the intersection line between the sweep plane of the survey vessel and the seabed slope and the horizontal plane, so the direction vector of this intersection line is obtained, and according to the dihedral angle theorem this intersection line can be solved for by solving for the normal vectors of the two planes.

Known:

Slope normal vector: $(\tan\alpha, 0,1)$

Sweeping crown surface normal vector: $(\cos\beta, \sin\beta, 0)$

Solvable:

$$\text{half} - \text{way line} = (\sin\beta, -\cos\beta, -\sin\beta\tan\alpha) = (1, -\frac{1}{\tan\beta}, -\tan\alpha) \tag{4}$$

Finally, the relation on γ is obtained as follows:

$$\cos\gamma' = \frac{-\tan\alpha}{\sqrt{1 + \frac{1}{\tan^2\beta} + \tan^2\alpha}} \tag{5}$$

$$\gamma = | 90 - \gamma' | \tag{6}$$

(2) Seawater depth D modeling

It can be analyzed that the coverage width W varies with the seawater depth D, in order to calculate the coverage width when the measuring vessel travels different distances, this paper needs to find the value of the corresponding D. Specifically can be solved according to the geometric model in Figure 2.

Known seabed slope Eq:

$$z = -x \cdot \tan\alpha + m\sin\alpha \tag{7}$$

Solvable:

$$E' = (\cos\beta, \sin\beta, m\sin\alpha - n\tan\alpha\cos\beta) \tag{8}$$

$$\overrightarrow{O'E'} = (\cos\beta, \sin\beta, -\tan\alpha\cos\beta) \tag{9}$$

Finally the relation on D is obtained as:

$$D = D_0 - dist\,|\tan\alpha \cdot \cos\beta| \tag{10}$$

Since the above formula assumes the premise of $90° < \beta < 180°$, i.e. the measurement direction is from low to high. Since it is found through calculation that when $\beta < 90°$, the actual slope angle γ will not change, while the depth of seawater will change the sign in Eq. (6) because the measurement direction is from high to low, the final relation about D is obtained as:

$$D = D_0 + dist \cdot \tan\alpha \cdot \cos\beta \tag{11}$$

The multibeam bathymetric coverage width model based on survey line direction is finally obtained:

$$W = \frac{2D\tan(\frac{\theta}{2})}{\sin\gamma\tan(\frac{\theta}{2}) + \cos\gamma} \tag{12}$$

$$\begin{cases} \gamma = |90 - \gamma'| \\ \cos\gamma' = \dfrac{-\tan\alpha}{\sqrt{1 + \dfrac{1}{\tan^2\beta} + \tan^2\alpha}} \\ D = D_0 + dist \cdot \tan\alpha \cdot \cos\beta \end{cases} \tag{13}$$

3.2.3 Solving a multibeam bathymetric coverage width model based on line orientation

The set conditions are as follows: the opening angle of the multibeam transducer is $120°$, the slope is $1.5°$, the depth of seawater at the center point of the sea area is 120m, and the results are obtained using python calculation as in Table 2.

Table 2. Coverage width model solution table

Coverage width/meter		Distance of the line from the center point/nautical miles							
		0	0.3	0.6	0.9	1.2	1.5	1.8	2.1
Measuring line direction angle/°	0	415.69	466.09	516.49	566.89	617.29	667.69	718.09	768.48
	45	402.85	437.38	471.92	506.46	540.99	575.53	610.06	644.60
	90	415.36	415.36	415.36	415.36	415.36	415.36	415.36	415.36
	135	402.85	368.31	333.77	299.24	264.70	230.17	195.63	161.09
	180	415.69	365.29	314.89	264.50	214.10	163.70	113.30	62.90
	225	402.85	368.31	333.77	299.24	264.70	230.17	195.63	161.09
	270	415.36	415.36	415.36	415.36	415.36	415.36	415.36	415.36
	315	402.85	437.38	471.92	506.46	540.99	575.53	610.06	644.60

By analyzing the data in the table, it can be seen that three categories can be roughly analyzed according to the distribution law of the coverage width. The first category is the north-south longitudinal category, which mainly includes the groups with the angle of the survey line direction of $0°$ and $180°$, all of which are parallel to the seabed slope for the bathymetry, and therefore $\gamma = \alpha$; the second category is the oblique category, which mainly includes the groups with the angle of the survey line direction of $45°$, $135°$, $225°$ and $315°$ groups, which are oblique to the seafloor slope for bathymetry, so $\gamma < \alpha$; the third category is east-west parallel category, mainly including the line direction angle of $90°$ and $270°$ groups, are parallel to the seafloor slope intersecting the line bathymetry, so γ no solution, that is, bathymetry process of the ocean in the sea The sea depth is unchanged in the process of bathymetry.

3.3. Modeling of Line Survey Programs

3.3.1 Analysis of survey line deployment

In order to design the shortest survey line, this paper can consider the use of the appropriate direction of the survey line, which can minimize the length of the survey line and at the same time ensure the complete coverage of the entire sea area to be surveyed. According to the analysis of study (2), two types of directions, north-south and east-west, can be excluded, so this paper mainly focuses on the second type of oblique measurement direction.

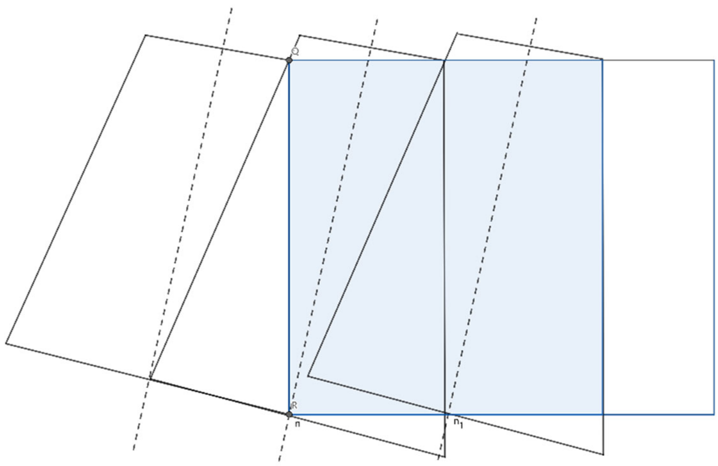

Figure 5. Schematic distribution of trapezoidal strips

In order to ensure that the length of the survey line is the shortest and covers the entire sea area to be surveyed, the trapezoidal strips on the boundary of the sea area should be laid so that the edges of the strips and the vertices intersect with each other, as shown in Figure. 5. The overall rectangle in the figure can be regarded as the horizontal projection of the sea area to be measured, in which the trapezoidal shape represents the measurement strip at an angle of β. To ensure that the entire sea area to be measured is covered and the overlap is within 10%-20%, the distribution of measurements shown in the figure can be carried out.

3.3.2 Establishment of univariate optimization model for line measurement scheme based on genetic algorithm

(1) Establishment of the objective function

Firstly, the objective function relation equation needs to be calculated, which is mainly solved by the method of constructing the system. According to schematic figure 6, for the convenience of calculation in this paper, the trapezoidal hypotenuse in figure 5 is extended into a triangle for analysis, while the triangle representing the first measurement strip is displaced to the center of the rectangle, so that the right measurement hypotenuse of the triangle passes through the projection point O of the center point of the sea area.

Take the upper left corner of the rectangle as the origin of the coordinates, where MN is denoted as the parallel line of BC passing through the point X and. Make XD parallel to AC and OD perpendicular to XD.

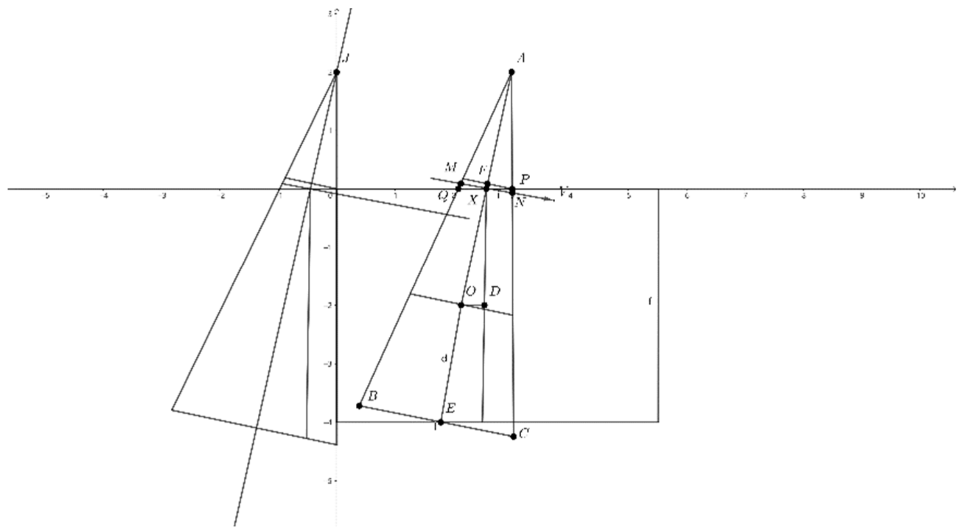

Figure 6. Plot of strip analysis in coordinate system

(1) Solve the equation of the line AM

First determine the coordinates of X as $(1+2\tan\angle 1,\ 0)$. The length of MN on the slope can be obtained from the coverage width model input β, $x=OX$, assuming that the output is l, then $MN=\cos 1.5°\cdot l=L$ (converted to plane)

Similarly, the coordinates of point M can be obtained as$(1+2\tan\angle 1-\frac{1}{2}L\cos\angle 1,\ \frac{1}{2}L\sin\angle 1)$

Due to the similarity triangle theorem it is known that $\angle PXN=\angle 1$, which gives the coordinates of point P as$(1+\frac{1}{2}L\cos\angle 1, 0)$

To solve the equation $y_{AM}=kx+m$, where

$$k=\tan(180^{\circ}-2\angle 1) \tag{14}$$

$$m=\frac{1}{2}L\sin\angle 1-\tan(180^{\circ}-2\angle 1)\cdot(1+2\tan\angle 1-\frac{1}{2}L\cos\angle 1) \tag{15}$$

(2) Solve for PQ length

Since when $y=0$,the $x_Q=1+2\tan\angle 1-\frac{1}{2}L\cos\angle 1-\frac{\frac{1}{2}L\sin\angle 1}{\tan(180^{\circ}-2\angle 1)}$, Finally the following formula is obtained for the length of PQ:

$$PQ=L\cos\angle 1-2\tan\angle 1+\frac{\frac{1}{2}L\sin\angle 1}{\tan(180^{\circ}-2\angle 1)} \tag{16}$$

(3) Overlap rate η

Since the seafloor topography has a slope at this point, it needs to be derived from the ratio of the overlap area to the area of a single strip, i.e.:

$$\eta=\frac{S_{\text{overlap}}}{S_{\text{all}}} \tag{17}$$

Among them,

$$S_{all}=\frac{1}{2}(L\cos^2\angle 1+8\sin\angle 1+\frac{2PQ\sin\angle 1}{\sin 2\angle 1})\cdot(\frac{1}{4}L\tan\angle 1+\frac{4}{\cos\angle 1}) \tag{18}$$

$$S_{\text{overlap}}=8\sin 2\angle 1 \tag{19}$$

(4) The total length L_{total}

Finally, the single measurement length EF is obtained based on the calculation of XE and ηXF lengths, and finally the formula about the total length L_{total} is obtained as follows:

$$L_{\text{all}} = n(\frac{1}{4}L \cdot \tan\angle 1 + \frac{4}{\cos\angle 1}) \tag{20}$$

(2) Model Summary

In summary, the optimization model to establish the multibeam line measurement scheme is synthesized as follows:

$$minL_{\text{all}} = n(\frac{1}{4}L \cdot \tan\angle 1 + \frac{4}{\cos\angle 1}) \tag{21}$$

$$s.t.\begin{cases} nPQ \geq 2 \\ 10\% \leq \eta \leq 20\% \\ W_{\text{all}} \geq 8 \end{cases} \tag{22}$$

3.3.3 Solving a univariate optimization model for a line survey scheme

Based on the summary of the above model, this paper applies genetic algorithm to solve the line measurement scheme, and the genetic algorithm solution process is shown in Table 3.

Table 3. Genetic Algorithm Process Table

Genetic Algorithm Solution Process
Step1 Set initial state, parameters, and coding, etc., import data
Step2 Initialize and start iterative evolution
Step3 Select, reorganize, mutate, and merge feasible solutions
Step4 Assign fitness values based on the magnitude of the objective function value
Step5 Calculate the ordinal number of the contemporary optimal individual
Step6 Repeat steps 3, 4, and 5 until evolution meets the optimal number of genetic generations
Step7 Result decoding output

The optimization model is simulated and solved iteratively by the python program until the change of the survey line length reaches the termination condition, then the result will be output as the optimal survey line solution. The final result is: when $\beta = 50.94°$ the line length is the shortest, and the length is 44.2 nautical miles, the overlap rate is 10.87%.

4. Conclusions

In conclusion, for the multibeam bathymetry technology, this paper takes into account the quality of the measurement results and the measurement efficiency on the basis of the survey line deployment program research, using the geometric model, genetic algorithms and other methods, combined with the discussion of the coverage width, the direction of the survey line to carry out the modeling of the survey line program. Firstly, for the overlap rate modeling of multibeam bathymetry, this paper utilizes geometric analysis of the coverage width in relation to the slope angle α and the depth of seawater D, and obtains the model validation results using pyhon. Secondly, on this basis, a new condition of line direction angle β is introduced to establish a multibeam bathymetry coverage width model based on line direction, and the coverage widths under different line directions are obtained by using pyhon, and the analytical results show that the coverage widths and seawater depths are positively correlated in most cases. Finally, considering the influence of the minimum coverage area, the range of overlap rate and other constraints, we choose the shortest survey line length as the objective function under the oblique survey direction, and construct the univariate optimization model of the survey line scheme based on the genetic algorithm, and finally obtain the optimal results of the survey line scheme through repeated iterative optimization.

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