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Application Analysis of Multi-beam Bathymetry Technology Based on Genetic Algorithm

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Abstract

Single-beam bathymetry employs a single-point continuous measurement approach, resulting in measurement data only along the navigation route. This poses considerable disadvantages for large expanses of the sea area awaiting measurement. In contrast, multi-beam bathymetry sweeps out depth strips along the navigation line, effectively remedying the deficiencies inherent in single-beam bathymetry. With the direction of the survey line being perpendicular to the slope, in this paper, a mathematical model for coverage width and the overlap rate between adjacent strips is established by combining the geometric plane theorem with parameters such as spacing, slope, depth, and the opening angle of the multi-beam transducer. Subsequently, by substituting the corresponding values, analyses are conducted on the corresponding depth, coverage width, and overlap rate with the previous strip. Based on the sea depth data, the shortest measurement length, the missed measurement rate, and the measurement length with an overlap rate exceeding 20% in the overlapping area for the sea area are derived. In the analysis of the shortest measurement length, a genetic algorithm is adopted. Using the coordinate points (0, 0) to (4, 5) of the protruding section in the middle as an auxiliary line to divide the front and back surfaces, and moving along the direction of the auxiliary line to scan the sea area to be surveyed. The shortest length is determined to be 301.07 nautical miles. Based on the total scanned area, the missed measurement rate is calculated to be 16.55%, and the total length of the overlapping area with an overlap rate exceeding 20% amounts to 51.1 nautical miles.

Keywords

Multi-beam bathymetry; plane geometry; genetic algorithm; shortest measurement

1. Introduction

With the rapid development of the marine economy and scientific research, human beings' demand for understanding the marine environment is increasing day by day. As a blue territory covering 71% of the Earth's surface area, the ocean is not only the core carrier of global climate regulation but also a treasure trove rich in mineral resources, biological resources, and strategic energy sources. In key fields such as marine resource development, environmental protection, disaster early warning, and military security, the acquisition of high-precision seabed terrain data has become a fundamental requirement for supporting decision-making. The traditional single-beam bathymetry technology is limited by the single-point linear detection mode and has inherent defects such as a narrow coverage area (only able to obtain data directly below the ship's hull) and low operation efficiency (requiring repeated cross-navigation), making it difficult to meet the demand for fine-grained detection of the entire area of complex seabed landforms.

The emergence of multi-beam bathymetry technology marks a revolutionary breakthrough in the field of marine surveying and mapping [1]. It synchronously emits more than a hundred beams through an acoustic array to form a fan-shaped detection area perpendicular to the course. A single measurement can cover a seabed strip several kilometers wide (the coverage width is usually 3 to 5 times the water depth. For example, in the 10,000-meter water depth area of the Mariana Trench, the coverage range can reach 30 kilometers [2]. Compared with the single-beam technology, its data density has been increased by two orders of magnitude, and it can distinguish seabed objects at the cubic meter level, meeting the special accuracy standard (error ≤ 0.5% of the water depth) of the International Hydrographic Organization (IHO). This technology has been widely applied in scenarios such as channel dredging projects (such as monitoring the sediment transport in the Yangtze River Estuary channel), submarine pipeline laying (micro-topography adaptability analysis), mineral resource exploration (the correlation between the distribution of cobalt crusts and the flat-topped mountain landforms), and the operation support of deep submersibles (the seabed terrain matching navigation of the Jiaolong submersible).

However, the optimization of the effectiveness of the multi-beam system still faces significant challenges: Firstly, changes in the slope of the seabed terrain will significantly change the spatial distribution pattern of the beam footprints, and detection blind areas or data redundancy are likely to occur in steep slope areas. Secondly, the layout of survey lines requires a dynamic balance between the coverage overlap rate and the detection efficiency [3]. The traditional experience-based design is difficult to meet the demand for efficient detection of complex terrains (such as seamounts and valleys). Studies have shown that when there is an inclination angle α between the direction of the survey line and the intersection line of the seabed slope, the beam overlap rate increases non-linearly as α increases. An overly conservative setting of the survey line interval will lead to more than 30% of invalid data redundancy, severely restricting the economic efficiency of exploration in large-scale sea areas.

Based on the mathematical modeling method, this paper constructs an optimized model for multi-beam bathymetry coverage for the special terrain scenario where the vertical plane of the survey line direction forms an inclination angle α with the intersection line of the seabed slope [4]. By analyzing the spatial geometric distribution characteristics of the beams, the optimal survey line interval thresholds under different terrain slopes are quantified. This model aims to achieve two major goals: (1) Ensure that the beam overlap rate between adjacent survey lines is lower than the minimum safety threshold (usually ≤ 20%) specified by the IHO to avoid data redundancy; (2) Maximize the effective detection area of a single voyage and improve the full-coverage exploration efficiency in complex sea areas [5]. The research results can provide theoretical support for major national projects such as resource exploration in the South China Sea island reef area and mapping of the Arctic shipping lanes, and promote the paradigm upgrade of multi-beam technology from "data acquisition" to "intelligent optimization".

2. Model Research on the Problem of Multi-beam Survey Lines in Seabed Slope Terrain

A mathematical model for the coverage width of multi-beam bathymetry and the overlap rate between adjacent strips is established. This model is based on factors such as the seabed slope, the opening angle of the multi-beam transducer, and the water depth. Using this model, one can solve for the seawater depth, coverage width, and overlap rate at different distances.

In this paper, angle conversion, along with the sine and cosine theorems in mathematics, are employed to establish relationships for the coverage width and the overlap rate between adjacent strips [6]. Based on these relationships, the water depth and the measured length of the slope are determined. By applying triangle formulas, the projection of the measured slope length onto the plane is calculated, which gives the measured coverage width. The overlap rate between adjacent strips is then obtained according to its defined formula [7].

2.1 Establishment of the Model for the Problem of Multi-beam Survey Lines in Seabed Slope Terrain

2.1.1 Establishment of the Mathematical Model for Coverage Width

(1) The mathematical model of water depth

In this paper, the initial water depth is set as D , and the water depths on the left and right sides are set as D_i . When the distance of the survey line from the center increases uniformly in the negative direction, the water depth gradually increases uniformly. When the distance of the survey line from the center increases uniformly in the positive direction, the water depth gradually decreases uniformly. The following will discuss the two directions, positive and negative, respectively, and the value of d is a fixed value.

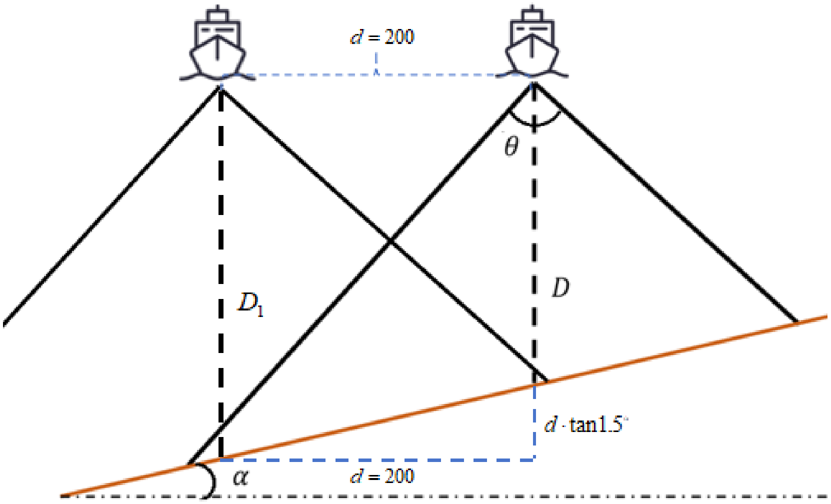

Figure 1. Effect Diagram of the Horizontal Spacing.

It can be concluded from the figure that when the distance from the survey line to the central point is a negative value, the formula is:

$$D_1 = D + d \cdot \tan \alpha \tag{1}$$

$$D_n = D + nd \cdot \tan \alpha \tag{2}$$

d: Fixed spacing value.

When the distance from the survey line to the central point is a positive value, the formula is:

$$D_1 = D - d \cdot \tan \alpha \tag{3}$$

$$D_n = D - nd \cdot \tan \alpha \tag{4}$$

d: Fixed spacing value.

(2) The mathematical model of the coverage width

Using the formulas of plane geometry, the projection of the measured slope on the horizontal plane is calculated according to the water depth D. The width of this projection is the coverage width.

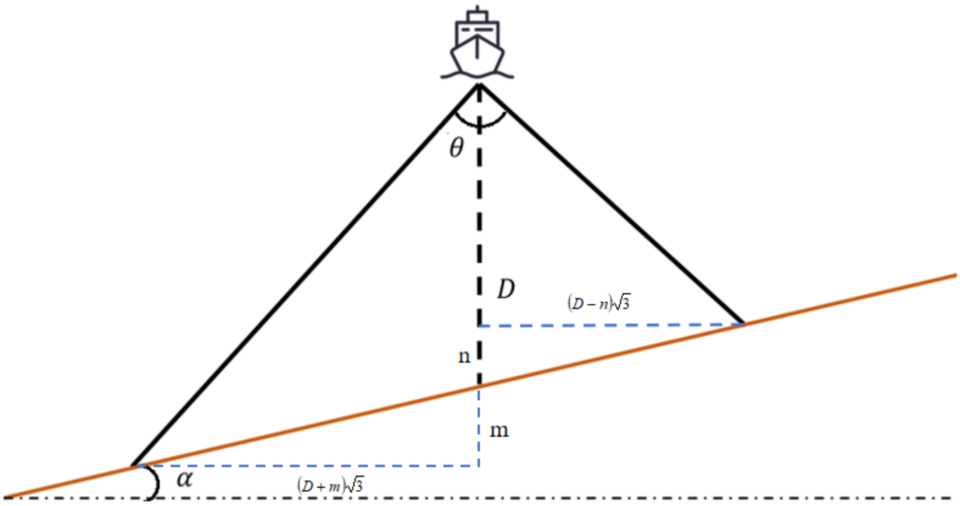

Figure 2. Geometric Construction.

The relational expression can be listed according to the figure.

$$\begin{cases} \tan\alpha = \dfrac{m}{(D+m)\tan\dfrac{\theta}{2}} \\ \tan\alpha = \dfrac{n}{(D-m)\tan\dfrac{\theta}{2}} \\ W = (2D+m-n)\tan\dfrac{\theta}{2} \end{cases} \tag{5}$$

The mathematical model of the coverage width is obtained as follows:

$$W = \tan\frac{\theta}{2}\cdot(2D+\frac{D\cdot\tan\frac{\theta}{2}\tan\alpha}{1-\tan\frac{\theta}{2}\tan\alpha}-\frac{D\cdot\tan\frac{\theta}{2}\tan\alpha}{1+\tan\frac{\theta}{2}\tan\alpha}) \tag{6}$$

2.1.2 Establishment of the Mathematical Model for the Overlap Rate Between Adjacent Strips

Given the coverage width of the strip, the overlap rate between the current survey line and the previous survey line can be calculated according to the definition of the overlap rate between adjacent strips.

$$\eta = 1-\frac{d}{W} \tag{7}$$

$$W = \tan\frac{\theta}{2}\cdot(2D+\frac{D\cdot\tan\frac{\theta}{2}\tan\alpha}{1-\tan\frac{\theta}{2}\tan\alpha}-\frac{D\cdot\tan\frac{\theta}{2}\tan\alpha}{1+\tan\frac{\theta}{2}\tan\alpha}) \tag{8}$$

By combining equations (7) and (8), we obtain that

The mathematical model of the overlap rate between adjacent strips is:

$$\eta = 1-\frac{d}{\tan\frac{\theta}{2}\cdot(2D+\frac{D\cdot\tan\frac{\theta}{2}\tan\alpha}{1-\tan\frac{\theta}{2}\tan\alpha}-\frac{D\cdot\tan\frac{\theta}{2}\tan\alpha}{1+\tan\frac{\theta}{2}\tan\alpha})} \tag{9}$$

2.2 Model Conclusions and Analysis

The opening angle of the multi-beam transducer is 120°, and the slope is 1.5°. With the seawater depth at the central point of the sea area being 70m, this value is substituted into the mathematical models of the coverage width and the overlap rate between adjacent strips. The results calculated by the software are shown in Table 1 below.

Table 1. Calculation Results.

The distance from the measuring line to the central point / m	-800	-600	-400	-200	0	200	400
The depth of the seawater / m	90.95	85.71	80.47	75.24	70	64.76	59.53
Coverage width / m	315.71	297.52	279.33	261.18	242.99	224.8	206.64
The overlapping rate with the previous measuring line / %	/	36.65	32.78	28.4	23.42	17.69	11.03

It can be seen from Table 1 that when the distances on the left and right from the central point of the survey line change uniformly and the slope is fixed, the coverage width increases as the seawater depth continuously increases.

As the seawater depth decreases continuously, the overlap rate between adjacent strips gradually decreases. Among them, there is a missed measurement of the overlap rate between adjacent strips in the range from 600 meters to 800 meters away from the central point.

3. The Application of Multi-beam Survey Lines in Seabed Topography

Scan the sea area to be measured according to the seawater depth data. It is necessary to ensure that the strips formed by the scanning cover the entire sea area as much as possible [8]. The overlap rate between adjacent strips should be controlled below 20% as much as possible, and the total measurement length should be as short as possible. Record the total measurement length, the missed measurement rate, and the total length of the part where the overlap rate exceeds 20%.

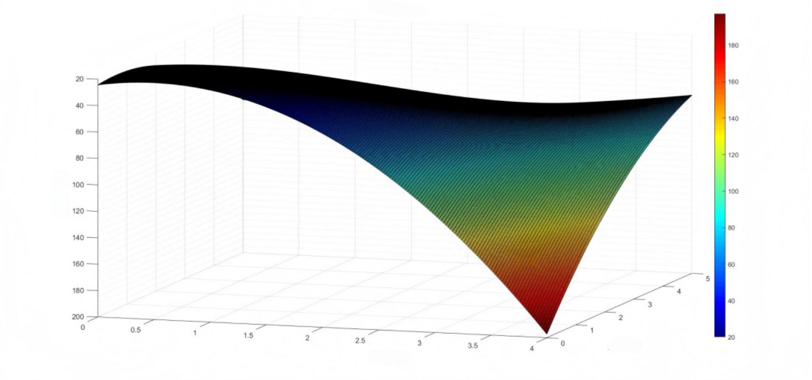

Figure 3. Three-dimensional Seabed Topography Map.

In this paper, based on the seabed depth data, a three-dimensional seabed topography map is established. The coordinate points of the protruding part in the middle range from (0, 0) to (4, 5). A straight line is drawn along the protruding part in the middle to divide the rectangle into the front and rear sides, and calculations are carried out respectively to determine the scanning length, the missed measurement rate, and the length of the part exceeding the overlap rate. The genetic algorithm is employed to analyze this area in the front and rear sections.

3.1 Establishment of the Three-dimensional Seabed Topography Scanning Model

(1) The total length of the survey line

In this paper, by drawing an auxiliary line, the rectangular sea area to be measured is divided into two parts, the front part and the rear part. The direction of the survey line is parallel to the direction of the auxiliary line [9]. The direction parallel to the auxiliary line can be approximately regarded as having the same seawater depth. By using the genetic algorithm model, the points are continuously iterated step by step to find the optimal landing points, and then the total length of the survey line is obtained.

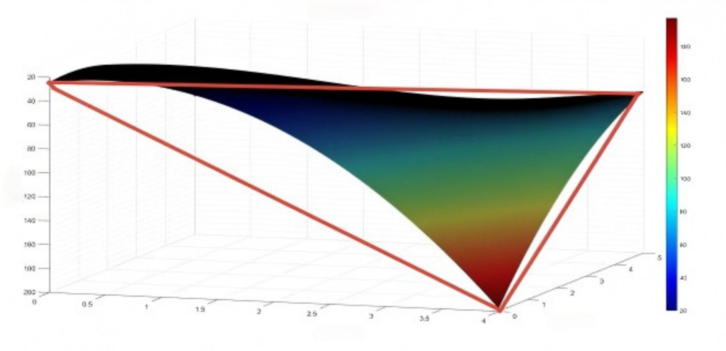

Figure 4. Auxiliary Division Diagram a of the Rectangular Sea Area to be Measured.

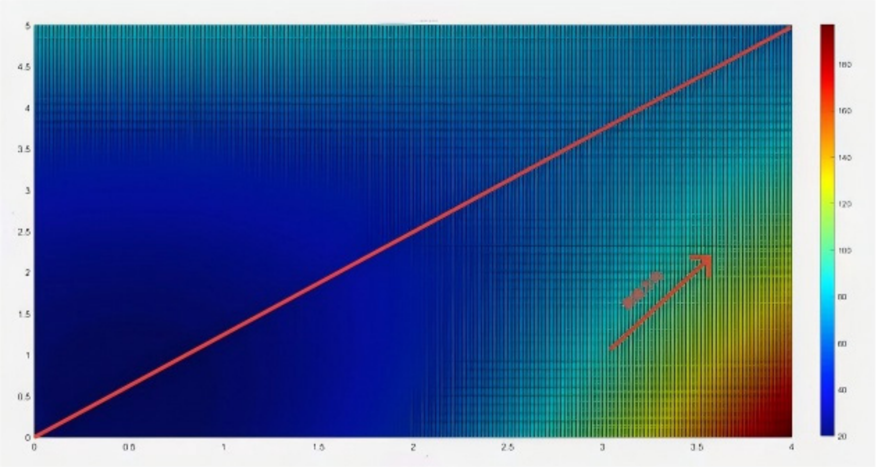

Figure 5. Auxiliary Division Diagram b of the Rectangular Sea Area to be Measured.

(2) The missed measurement rate of the sea area to be measured
Subtract the ratio of the total scanning area to the total area of the sea area to be measured from 1. That is, the formula for the missed measurement rate of this sea area is as follows:

$$\alpha = \frac{S_z - S_s}{S_z} \tag{10}$$

Among them, S_z is the total area of the sea area to be measured, and S_s is the scanning area of the multi-beam bathymetry. α is the missed measurement rate of the sea area to be measured.

(3) The total length of the part where the overlap rate exceeds 20%
Add up the lengths of the survey lines for which the overlap rate between adjacent strips exceeds 20%, and the sum is the total length for which the overlap rate exceeds 20%. The formula is as follows:

$$L = \sum_{1}^{N} l_i \tag{11}$$

Among them, L is the total length for which the overlap rate exceeds 20%, and l_i is the length of the ith survey line for which the overlap rate exceeds 20%.

3.2 Analysis of the Model Results

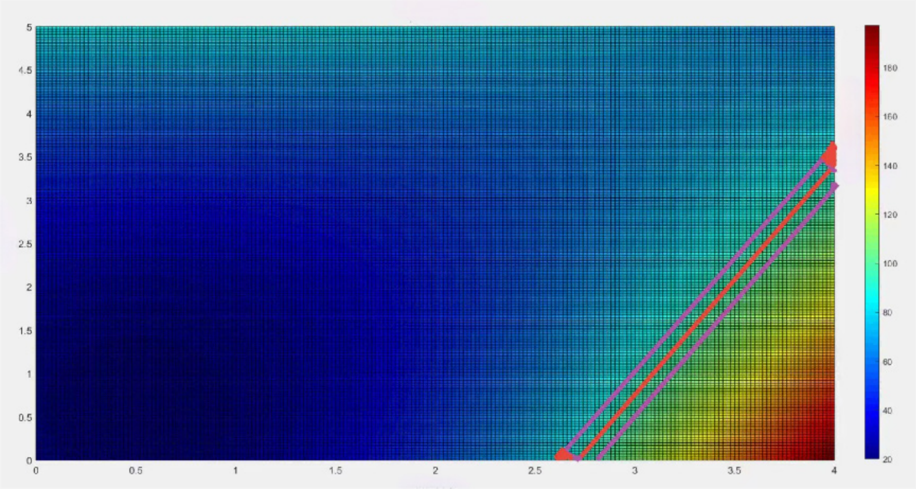

Figure 6. Map of the Missed Measurement Area.

In this paper, based on the genetic algorithm, iterative calculations are carried out step by step from the deeper part to the shallower part. The measurement direction is parallel to the auxiliary line, and the corresponding distances are calculated successively to cover the area as much as possible through the iteration of the genetic algorithm [10]. The shortest measurement length is 301.07 nautical miles. Each time the bathymetry is carried out along the measurement direction, there will be missed measurements in the red areas at the boundaries, as shown in Figure 6. According to the measurement length, the measurement area is calculated, and then the missed measurement area is obtained by subtracting the measurement area from the total area [11]. According to the formula, the missed measurement rate is 16.55%. The overlap rate between adjacent strips can be obtained from the measurement route. By adding up the measurement lengths of the overlap rates greater than 20%, the final total length of the part exceeding 20% is 51.1 nautical miles [12].

4. Conclusion

This paper focuses on the problem of survey line optimization that the multi-beam bathymetry technology faces in practical applications. Through mathematical modeling and algorithm design, it systematically solves the difficult problem of survey line interval planning in complex seabed topography scenarios. The coverage width and overlap rate model constructed based on the geometric plane theorem (combined with parameters such as slope, depth, and transducer opening angle) quantifies the boundaries of detection efficiency under different topographic conditions. In the application of multi-beam bathymetry, when the direction of the survey line is perpendicular to the intersection line of the seabed slope surface, the shortest measurement length of the sea area can be optimized to 301.07 nautical miles, the missed measurement rate is controlled at 16.55%, and the redundant area with an overlap rate exceeding 20% only accounts for 51.1 nautical miles, which is significantly better than the traditional empirical survey line planning method.

The research verifies that the multi-beam bathymetry technology can break through the limitations of topographic slope on coverage efficiency through model-driven optimization. In addition, the application of the genetic algorithm in path planning reflects the paradigm upgrade of marine surveying and mapping from "data collection" to "intelligent decision-making", which is highly consistent with the concept of intelligent integrated land-water measurement proposed by the Key Laboratory of Marine Surveying and Mapping of the Ministry of Natural Resources. Future research can combine the unmanned aerial vehicle (UAV) lidar bathymetry technology to construct a multi-modal fusion detection system, further improve the full coverage capability in shallow water areas and complex terrains, and promote the leapfrog development of marine surveying and mapping from "two-dimensional strips" to "three-dimensional real scenes".

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