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Research on relevant issues of multi-beam detection technology used for probing water depth

Zimeng Li, Yang Li, Jintao Nie, Guangchao Zhu, Yongqian Feng, Xufei Zhuang*

School of Information Engineering, Inner Mongolia University of Technology, Hohhot, 010050, China
**Corresponding author: zxf@imut.edu.cn*

Abstract: *This article provides a detailed overview of research conducted to address issues in multibeam bathymetric surveying technology. It begins by analyzing the limitations of single-beam bathymetry, particularly its deficiencies in data density and coverage. The article then introduces multibeam bathymetric systems and discusses the new challenges they pose while addressing issues with single-beam technology, such as strip overlap rates and potential measurement failures.Next, the article describes the research team's approach and methods for tackling these challenges. This includes establishing mathematical models to calculate sea depth, coverage width, and overlap rates, followed by simulation calculations and analysis using real-world data. The specific results cover three main areas, including calculations of sea depth, coverage width, and overlap rates under different distance and angle conditions. Finally, the article summarizes the research's contributions to multibeam bathymetric technology and provides an outlook on future developments. It emphasizes the importance of technological improvements and addressing application challenges.*

Keywords: *Multiple beam sounding technology, Data density and coverage, Research methods and simulation calculation*

1. Introduction

Single-beam depth measurement technology uses the propagation characteristics of sound waves in water to measure water depth. However, single-beam depth measurement technology also has its drawbacks. Due to its nature as a single-point continuous measurement technology, the measurement results are dense along the ship's trajectory but lack data in other areas. To address this, multi-beam depth measurement systems were developed[1]. These systems can simultaneously emit hundreds of beams during a single measurement, overcoming the limitations of single-beam depth measurement technology. However, this introduces new issues such as strip coverage rates, where gaps may occur if the intervals are too large, leading to undetected areas.

The emergence of multi-beam depth measurement systems overcomes the drawbacks of single-beam depth measurement but also introduces new problems, such as strip coverage rates. If strip coverage occurs, the covered portion can be halved. However, gaps may appear in areas without coverage, leading to measurement errors and potential failures. To address these issues, the following tasks were undertaken[2-3]:

Based on the given graph and initial slope value of 1.5 degrees, with the sea depth at the center point being 70 meters, a mathematical model was established to calculate the sea depth, coverage width, and overlap rate at distances of -800, -600, -400, -200, 0, 200, 400, 600, and 800 meters from the center point along the measuring side.

Analyzing the given graph in a three-dimensional context with angles β and opening angle of 120 degrees, slope of 1.5 degrees, and sea depth of 120 meters at the center point, a mathematical model was developed to calculate coverage width for distances of 0, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, and 2.1 meters from the measuring ship to the center point, at side angles of 0, 45, 90, 135, 180, 225, 270, and 315 degrees.

Designing a model for a rectangular sea area with a length of two nautical miles north-south and a width of four nautical miles east-west. The sea depth at the center point is 110 meters, with a slope of 1.5 degrees from west deep to east shallow. The transducer used in measurements has an opening angle of 120 degrees. The task is to design the shortest measuring side that covers the entire area and ensures an overlap rate between adjacent strips of 10% to 20%.

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Using a series of single-beam measurement data from several years ago for a five nautical mile north-south by four nautical mile east-west area, design a multi-beam measurement ship. The design requirements include full coverage of the area, minimizing overlap between adjacent strips to below 20%, and minimizing the length of measuring lines. After designing, calculate the total length of the sides, the percentage of missed area relative to the total area, and the total length of the overlap region not exceeding 20%.

2. Research ideas

For the first part, knowing the opening angle of the multibeam transducer, the angle between the plane perpendicular to the direction of the line and the slope of the seabed, and the depth of the sea water at the centre of the sea area, we calculate the depth of the sea water, the depth of the coverage, and the overlap with the previous line at distances from the centre of the line of -800, -600, -400, -200, 0, 200, 400, 600, and 800 metres, respectively. By developing a mathematical model in planar space, the team hoped to analyse the multibeam physics problem while investigating the geometrical relationships between slope, seabed depth, and distance from the centre of the sea and calculating the depth of seawater, breadth of coverage, and overlap with the previous line of measurement. We firstly studied the case when the distance from the centre point of the survey line is 0. According to the known condition that the depth of the sea water is 70 m, we constructed the auxiliary line, selected the most suitable auxiliary triangle for the problem, and calculated the depth of the sea water and the difference of the elevation and the breadth of coverage through the geometrical and trigonometric relationships, and then through the equation of the relationship between the distance of the survey line from the centre point, the breadth of coverage, and the overlap rate with the previous survey line, we can calculate the depth of sea water, the breadth of coverage, and the overlap rate with the previous line. The overlap rate of the previous line can be calculated. Through the above steps, the seawater depth, coverage width and overlap rate with the previous line can be obtained for each line.

For the second part, if the opening angle of the multibeam transducer is 120°, the slope is 1.5°, and the depth of the sea water at the centre point of the sea area is 120 m, a mathematical model of the coverage width of the multibeam bathymetry is established and the coverage width of the multibeam bathymetry is calculated for the positions of each column.

On the basis of the planar graph, it is expanded into a three-dimensional space, and the sea level and the direction of the survey line become a three-dimensional graph, and the method of calculating the coverage in the case of the existence of the angle between the direction of the survey line and the normal direction of the seafloor slope in the projection on the horizontal plane is taken into consideration. Based on this situation, the width of the sea surface corresponding to the angle and distance is different. In other words, if the ship's point of measurement is changed along the lateral direction and the projection on the horizontal plane is changed, the angle β between the direction of the corresponding line of measurement and the projection on the horizontal plane normal to the slope of the seabed changes all the time, and the angle θ of the slope changes accordingly. Therefore, this topic requires a certain ability of spatial three-dimensional conception and spatial imagination.

$$W(x) = (D - x\tan\alpha) \times \left(\frac{\sin\frac{\theta}{2}}{\sin\left(90 + \alpha - \frac{\theta}{2}\right)} + \frac{\sin\frac{\theta}{2}}{\sin\left(90 - \alpha - \frac{\theta}{2}\right)} \right) \times \cos\alpha \tag{1}$$

θ: multibeam transducer opening angle in radians;

α: slope in radians;

D: seawater depth in metres;

d: distance between two adjacent survey lines, in metres;

w: width of coverage of the strip, in metres;

η: overlap rate of the two neighbouring laterals.

For the third part, for problem three, we united on the first by determining the basic steps of the survey line design, according to the requirements of the topic, the design of a north-south length of 2 nautical miles, east-west width of 4 nautical miles of the rectangular sea area, the depth of seawater at the centre of the sea area of 110 m, the depth of the west and east of the shallow, with a gradient of 1.5 ∘, design a set of the shortest length of the measurement, the survey line can be completely covered by the entire sea area to be measured, and the adjacent strips of the strip between the overlap rate meets 10% ~ 20%. The overlap rate between adjacent strips meets 10%~20%, so according to the requirements, the team selected the overlap rate of 15% to carry out the next practical theoretical derivation, and determined the calculation method of the coverage width and the spacing of the survey lines, after which we carried out the actual calculations through python code for the preliminary modelling. In order to design the set of measurement lines with the shortest measurement length, completely cover the sea area to be measured, and meet the requirement of 10% to 20% overlap rate between adjacent frequency bands, the following factors must be considered:

1) Selection of a suitable transducer aperture angle: it is well known that the aperture angle of a multibeam transducer is 120°. However, the aperture angle of the transducer must be properly adjusted to cover the entire sea area to be measured. Too large an aperture angle may cover a larger area, but this will increase the length of the measurement line. With too small an aperture angle, the length of the measuring line may be reduced, but some areas of the sea may be neglected, so we must find the right balance.

2) Choose the right number and distribution of measurement lines: To determine whether the overlap between adjacent bands is 10% and 20%, we must choose the right number and distribution of measurement lines. Too many lines will increase the length of the lines. If the number of survey lines is too low, some marine areas will not be covered, even if the overlap rate is too high or too low. Ensure that rock survey lines are evenly distributed.

3) Consider the influence of slope and depth: When designing the measurement vessel, we must consider the depth of the sea water in the centre of the sea area of 110 m depth, slope of 1.5 ° east and west flat depth, which will affect the length and distribution of the measurement vessel.

In short, we need to choose the appropriate parameters according to the actual situation of the sensor hole angle, the number and distribution of measurement lines, etc. In the specific design, we must fully consider the size, shape, depth and slope of the sea area to be measured, and finally determine a series of measurements of the shortest length of the measurement line. This can completely cover the entire sea area to be measured and meet the requirement of a 10% to 20% overlap rate of adjacent frequency bands.

For the fourth part, or several consecutive survey lines, so that these can cover as much as possible the entire sea area to be surveyed. This needs to take into account factors such as the size and shape of the sea area and the topography of the seabed.

In response to requirement (2), "The overlap rate between adjacent strips should be kept below 20 per cent as far as possible", we need to take into account the distance and angle between adjacent survey lines, as well as the size and shape of the sea area, when laying out survey lines. The overlap rate needs to be as small as possible, and at the same time, the layout of the survey lines should ensure that the entire sea area is covered.

For requirement (3) "The total length of the survey line should be as short as possible", we need to shorten the total length of the survey line as much as possible on the premise of meeting the first two requirements, in order to reduce the measurement time and workload.

For calculating the indicators:

1) the total length of the survey line: directly derived from the actual measurement results of the survey line.

2) Percentage of missed sea area in the total sea area to be measured: firstly, it is necessary to calculate the area of missed sea area, i.e. the area of sea area not covered by the survey line, and then calculate its percentage in the total sea area to be measured.

3) Total length of the part of the overlapping area with an overlap rate of more than 20 per cent: it is necessary to calculate the total length of the overlapping area first, and then calculate the length of the part with an overlap rate of more than 20 per cent.

3. Model assumption

Trigonometric model diagrams in the plane of the base(figure 1):

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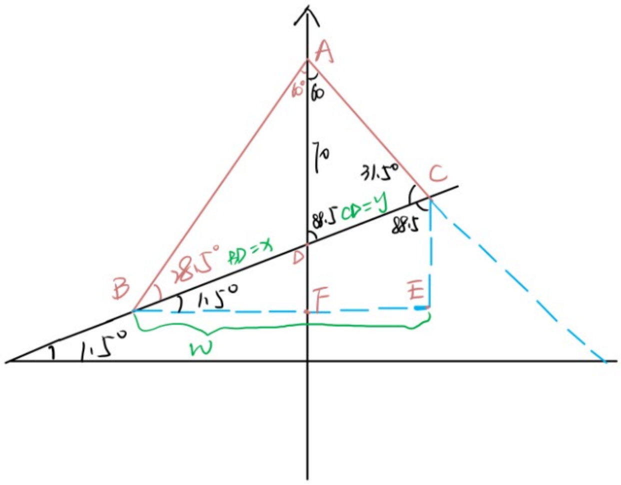

Figure 1: Trigonometric model diagrams

The figure models the line at a distance of 0 m from the centre, w is the coverage width, AD is the seafloor depth and η is the overlap rate.

The model plot when the distance of the survey line from the centre point is different(figure 2):

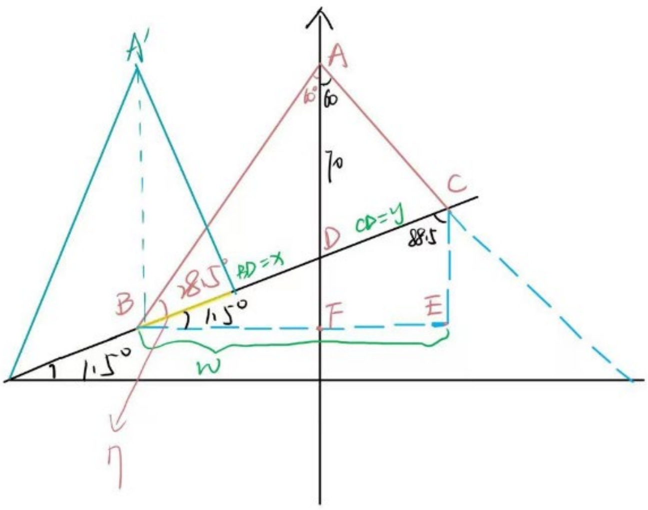

Figure 2: Trigonometric model diagrams

In this figure, AA' is the distance of the survey line from the centre point, η is the overlap of two adjacent survey lines, according to which the overlap rate is calculated, and the other calculations are analogous to the calculation of the trigonometric model diagram in the base plane.

In triangle Q'P'S, sin∠Q'SP = Q'T'/SQ' to find SQ'.

In triangle Q"SQ', tan∠Q"SQ'=Q"Q'/SQ' can be found for ∠Q"SQ, which is the slope angle α corresponding to the change in direction of the survey line.

Analogous to the first question, the code can be used to find the coverage width at the centre of different sea areas with different line direction angles.

(The code has implemented the conversion of nautical miles and metres, 1 nautical mile = 1852 metres)

4. Solution results

The results of the first part are presented in the table 1:

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Table 1: Results of Part I

Distance of the line from the centre/m	-800	-600	-400	-200	0	200	400	600	800
Depth of sea water/m	90.94	85.71	80.47	75.24	70	64.76	59.53	54.29	49.60
Coverage width/m	315.6885	297.5131	279.33	261.1623	242.9870	224.8116	206.6362	188.4608	170.2854
Overlap rate with previous line/%	36.65%	32.78%	28.4%	23.42%	17.69%	11.04%	3.21%	-6.12%	-17.45%

The results of the second part are presented in the table 2:

Table 2: Part II results

Coverage width/m	Distance/nautical mile from the centre of the sea by the survey vessel							
	0	0.3	0.6	0.9	1.2	1.5	1.8	2.1
0	416	466	516	567	617	668	718	768
45	416	452	487	523	559	594	630	666
90	417	417	417	417	417	417	417	417
135	416	380	345	309	273	238	202	166
180	416	365	315	264	214	164	113	63
225	416	380	345	309	273	238	202	166
270	417	417	417	417	417	417	417	417

5. Conclusions

This study is dedicated to an in-depth exploration of the application of multi-wave sounding technology in detecting the depth of water bodies, covering the whole process from the background and objectives of the study to the methodology and results. Through detailed analyses and empirical studies, we have gained a series of insights into the performance and application potential of multi-wave detection technology.

In the process of applying the multi-wave sounding technique to detect the depth of water bodies, we found that there are several problems that seriously affect the accuracy and reliability of the measurement results. Firstly, there is the problem of signal interference, which mainly comes from the complex underwater terrain structure, the traffic of other vessels and the variable meteorological conditions. These factors lead to attenuation and deformation of the measurement signals, thus affecting the accuracy of the depth data. Secondly, there is the problem of instrument accuracy. The accuracy and stability of existing multi-wave detection equipment still need to be improved, especially under extreme environmental conditions. In addition, environmental factors such as water temperature, salinity, turbidity, etc. also have a non-negligible impact on the measurement results.

Aiming at these problems, we put forward a series of improvement measures and strategies. Firstly, we should increase the technical research and development, improve the signal processing technology, and enhance the anti-interference ability of the signal. Secondly, the precision and stability of instrumentation should be improved, especially the adaptability in extreme environments. In addition, errors in the measurement process can be detected and corrected in time through the establishment of a better monitoring and early warning system.

For different types of water bodies, such as freshwater and seawater, the specific challenges and solutions for multi-wave detection technologies differ. In freshwater environments, the focus is on improving the accuracy and stability of the instrumentation as there are fewer impurities and relatively less signal attenuation. In seawater environments, on the other hand, more advanced signal processing techniques and more stable instrumentation are required to ensure the accuracy of the measurement results due to the greater influence of factors such as salinity and turbidity.

Compared with other related technologies, such as acoustic wave detection and radar detection, multi-wave detection technology has advantages in some aspects, such as higher accuracy and stronger environmental adaptability. However, there are also some shortcomings, such as higher equipment costs and greater operational complexity. Therefore, in practical application, the appropriate technical method should be selected according to specific needs and conditions.

Looking ahead, multi-wave detection technology still has a lot of space and potential for development

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in detecting the depth of water bodies. With the continuous progress of science and technology and the reduction of cost, the technology is expected to be more widely used in the future. However, at the same time, we should also recognise the challenges and opportunities facing this field, such as how to improve the stability of instrumentation, how to further reduce costs, and how to better adapt to the complex and changing water environment. These issues need to be further studied and explored in order to promote the continuous progress and development of multi-wave detection technology.

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