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RESEARCH ON THE DESIGN OF SURVEY LINES IN A MARINE MAGNETIC SURVEY

By BIAN Gang, XIA Wei , JIN Shaohua, XIAO Fumin, SUN Xinxuan, CUI Yang
Department of Hydrography and Cartography, Dalian Naval Academy (China)

Abstract

The planning of a marine magnetic survey requires careful consideration in the design of the survey lines to ensure the results of the survey meet expected standards. This paper describes various evaluation methods to determine an optimal survey line layout for a marine magnetic survey that conforms to Chinese marine magnetic survey Standards. Various survey line layouts are tested using simulated data to evaluate the interpolation precision between neighbouring survey lines and the magnetic anomaly map. The test results provide a recommended process to determine the rationality and the optimal layout of the survey line pattern for undertaking marine magnetic surveys.

Résumé

La planification d'un levé magnétique marin requiert un examen minutieux de la conception des profils de sonde pour assurer que les résultats du levé répondent aux normes attendues. Cet article décrit différentes méthodes d'évaluation en vue de déterminer une présentation de profil de sonde optimale pour un levé magnétique marin qui soit conforme aux normes des levés magnétiques marins chinois. Diverses présentations de profils de sonde sont testées à l'aide de données simulées dans le but d'évaluer la précision de l'interpolation entre profils de sonde voisins et la carte des anomalies magnétiques Les résultats des tests permettent de recommander un processus pour déterminer la rationalité et la présentation optimale du schéma de profil de sonde afin d'entreprendre des levés magnétiques marins.

Resumen

La planificación de un levantamiento magnético marino requiere una cuidadosa consideración en el diseño de las trayectorias a seguir para garantizar que los resultados del levantamiento cumplan las normas esperadas. Este artículo describe los diversos métodos de evaluación para determinar una disposición óptima de las trayectorias para un levantamiento magnético marino que sea conforme a las normas chinas de levantamientos magnéticos marinos. Se han efectuado pruebas sobre varias disposiciones de trayectorias, utilizando datos simulados para evaluar la precisión de la interpolación entre trayectorias vecinas y el mapa de anomalías magnéticas. Los resultados de las pruebas proporcionan un proceso recomendado para determinar la racionalidad y la disposición óptima del patrón de trayectorias para llevar cabo levantamientos magnéticos marinos.

1. INTRODUCTION

The planning of a marine magnetic survey line uses a series of crossing main survey lines and reference survey lines to provide an optimal survey network. However blank areas can exist between survey lines. Thus the design of the survey line pattern is a primary requirement for marine magnetic surveys and is important in the assurance of survey precision and efficiency.

There are similarities and differences between marine magnetic surveys and other marine surveys. In a bathymetric survey, the fair chart mostly comprises depth points and derived depth contours assist as a secondary portrayal. In a marine magnetic or a marine gravity survey, the final survey product is mainly represented by contours, which is called a marine magnetic anomaly map or marine gravity anomaly map.

Similarly, compared to a marine gravity survey, the spatial variations of magnetic anomaly values are rapid and complex. Therefore, the design of the survey lines in a marine magnetic survey is even more important than in a marine gravity survey.

The design of the survey lines is discussed in this paper and the requirements in the design of survey lines are described in the Specifications for Marine Magnetic Surveys in China (***refer to Table 1***).

Table 1: *The line spacing in different survey order given by Specifications for Marine Magnetic Survey*

Order	Precision (m_T)	Scale	Line spacing	contour interval
1	2.0nT	1:10,000~1:50,000	0.1~0.5km	10nT
2	5.0nT	1:50,000~1:100,000	0.5~1km	20nT
3	10.0nT	1:100,000~1:250,000	1~2.5km	25nT
4	15.0nT	1:250,000~1:500,000	2.5~5km	50nT

In Table 1, the survey precision requirements are listed in each Order (the precision is calculated by the crossing point of main lines and reference lines). However, the required precision of the magnetic anomaly map (being the survey product) is not prescribed. The line spacing in each survey Order is decided by the corresponding survey scale (corresponding distance of 1cm on survey map), rather than by the characteristics of the magnetic anomaly. Therefore some problems exist when undertaking a practical survey. On the one hand, for certain magnetic anomaly map precisions, the corresponding survey Order is unknown. On the other hand, if the survey Order is given according to Table 1, the precision of the magnetic anomaly map can not be evaluated.

Applying the survey line requirements from Table 1, two kinds of unsatisfactory results will be produced: (1) Survey lines spacing will be too dense. Although the requirement of the survey precision can be satisfied, the work load and the total survey expense will be significantly increased and the survey efficiency will be correspondingly decreased; and (2) the survey lines spacing will be too sparse, so the requirement of the magnetic anomaly map precision will not be met, the extended measurement work will have to be developed and the survey efficiency will also decrease.

After analysis and investigation, the authors consider that the precision of survey points and the magnetic anomaly map must also be prescribed. This can meet the needs of different practical applications such as military, navigation, science research, geological exploration, marine exploitation, underwater detection, marine engineering etc. Given the unambiguous precision of the marine magnetic anomaly map, the appropriate survey line spacing can be determined by the surveying engineer, and the practical magnetic characteristics fully considered.

Two basic problems exist in the survey line layout: (1) What is an optimal survey line layout? (2) How can we design optimized survey lines? Therefore three detailed problems must be analyzed and discussed: (1) the influence of survey line direction; (2) the influence of survey line spacing, and (3) the factors that can be applied to describe these influences. In this paper, the problems above have been resolved and methods have been tested using simulated data.

2. THE EVALUATION METHODS OF THE SURVEY LINE LAYOUT

A magnetic anomaly contour map is the main product from a marine magnetic survey. The spatial distributions of the magnetic anomaly in a survey area can be distinguished and the magnetic anomaly information provided for different applications. To obtain spatial distributions of the magnetic anomaly between survey lines, observed values on a survey line can be used to interpolate the values between two neighbouring lines. The interpolating precision can be applied to reflect the representative capability of the magnetic anomaly in a survey area. Accordingly, the magnetic anomaly map and the interpolating precision can been used to evaluate the rationality of the survey line layout.

2.1 Evaluation with magnetic anomaly map

A marine magnetic anomaly map is the most intuitive and expressive output from a marine magnetic survey. Reviewing the magnetic anomaly map, the general trend and distribution of the magnetic anomaly can be distinguished, and any significant magnetic anomaly can be determined by the magnetic anomaly contours.

Evaluating the magnetic anomaly map means that we can compare a simulated magnetic anomaly map with a true magnetic anomaly map obtained by a given survey line layout. The rationality of the survey line layout can be evaluated by the display of the output map to determine if the survey requirements are met.

After analysis and discussion, evaluating standards can be detailed as follows:

(1) Magnetic anomaly maps are considered to be consistent, whereby the general trend of the magnetic anomaly can be determined and the detailed magnetic anomaly in the given magnitude can be identified.

(2) Magnetic anomaly maps are considered to be basically consistent, whereby the general trend of the magnetic anomaly can be approximately determined and the detailed magnetic anomaly in the given magnitude can usually be identified.

(3) Magnetic anomaly maps are considered to be basically consistent, whereby the general trend of magnetic anomaly can be approximately determined, but the detailed magnetic anomaly in the given magnitude is difficult to identify.

(4) Magnetic anomaly maps are considered to be inconsistent, whereby the general trend of the magnetic anomaly can not be determined and the detailed magnetic anomaly in the given magnitude cannot be identified.

In the Standards above, when the magnetic anomaly map contrast accords with (1) or (2), considering the survey error, the survey line layout is considered rational. When the magnetic anomaly map contrast accords with (3) or (4), the survey line layout is considered irrational.

2.2 Evaluation with interpolation precision between two neighbouring lines

2.2.1 The concept of the interpolation between two neighbouring lines and its precision

The marine magnetic survey line pattern consists of main survey lines and reference lines (a reference line is also called a cut line or tie line in an aeromagnetic survey). To plot a magnetic anomaly map, the magnetic anomaly information of the blank area between survey lines must be interpolated. Therefore the plotting precisions of the magnetic anomaly map are estimated by the precision of observed data and interpolated data.

However, the interpolating precision is mainly determined by variable characteristics of the magnetic anomaly and survey line spacing. So the main aim of the survey line layout is to determine the survey line spacing. By controlling and adjusting the interpolating precision, the given precision of the survey product can be determined. The requirement of the survey line layout is related to the requirement of interpolating precision. To meet different interpolating precisions, the survey line layout can be different. Hence, the interpolating precision is an important value to determine the rationality of the survey line layout.

Actually, the designed reference lines can be adopted to evaluate the interpolating precision. The middle point of two neighboring survey lines can be used to estimate the interpolating precision.

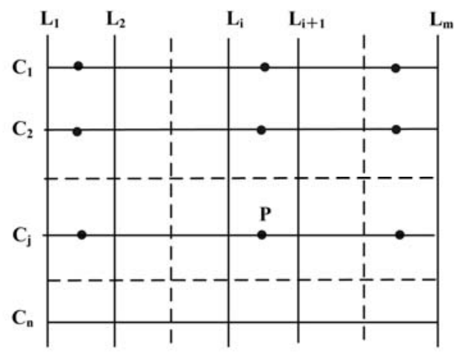


***Figure 1**: The sketch map of evaluating with the middle point*

In ***Figure 1***, the number of main lines (L_n) and reference lines (C_n) is *m* and *n* in a survey area. The main lines are perpendicular to reference lines, and main line spacing is *d*, and there are *m´n* cross points.

On each reference line, middle point P is selected as a reference point to evaluate the interpolating precision. For each reference point, the difference between the interpolated value and the true value t can be obtained.

$$t = T_I - T_R \tag{1}$$

In expression (1), T_I represents the magnetic anomaly value which is interpolated by the corresponding observed value on two neighboring survey lines. T_R is true value of middle point observed on the reference line. As the interpolated magnetic anomaly value T_I and true value T_R on the reference line is irrelevant, we can derive the following formula.

$$m_t^2 = m_I^2 + m_R^2 \tag{2}$$

In expression (2), m_t represents the mean square error (MSE) of the magnetic anomaly difference, m_I is MSE of the interpolated value, m_R is the interpolation precision of the observation value.

The MSE of interpolated value m_I can be analyzed in the following text. Linear interpolating is a common method in survey processing, so the next formula is expressed as follows.

$$T_I = \frac{1}{2}(T_1 + T_2) + \varepsilon \tag{3}$$

In expression (3), T_1 and T_2 represent the observed values on two neighboring main lines which cross a reference line. ε is the corresponding model error, which can be obtained by linear interpolation. With a different interpolating method, the model error can be different. Because the observed values on each main line are independent, the law of propagation of errors is followed.

$$m_I^2 = \frac{1}{4}(m_R^2 + m_R^2) + m_\varepsilon^2 \tag{4}$$

$$m_I^2 = \frac{1}{2}m_R^2 + m_\varepsilon^2 \tag{5}$$

The expression above denotes the relation of the precision and interpolated value. With (5) and (2), then:

$$m_\varepsilon^2 = m_t^2 - \frac{3}{2}m_R^2 \tag{6}$$

This expression reflects the relation of the MSE of the magnetic anomaly difference, the MSE of the observation and the linear interpolation model error.

m_t and m_T can be calculated through observed data of the whole survey area. That is,

$$m_t = \pm\sqrt{\frac{[tt]}{N}} \tag{7}$$

In expression (7), the number of the reference points P is N. The number of main lines and reference lines is m and n, which are crossed, so reference points can be expressed as $N=(m-1)\times n$.

$$m_R = \pm\sqrt{\frac{[\Delta\Delta]}{2mn}} \tag{8}$$

In expression (8), Δ is the difference of the observed value of the reference point, which are respectively obtained by the main and reference lines.

Through expression (6), the precision of the linear interpolation model error of the whole survey area can be obtained.

$$m_\varepsilon^2 = m_t^2 - \frac{3}{2}m_R^2 \tag{9}$$

The linear variation characteristics of the magnetic anomaly can be reflected directly. The smaller the number of m_ε, and hence, the smaller the survey line spacing, the better the linear characteristics of the magnetic anomaly.

From the expressions above, a precise control situation can be analyzed. For example, when the requirement of the magnetic anomaly interpolation precision is less than the observation precision, $m_I \le m_R$, and expression (5) becomes.

$$m_I^2 = \frac{1}{2}m_R^2 + m_\varepsilon^2 \le m_R^2 \tag{10}$$

The requirement of the linear interpolation model error of the whole survey area is.

$$m_\varepsilon^2 \le \frac{1}{2}m_R^2 \tag{11}$$

Combining expression (6), expression（11）now becomes:

$$m_t^2 \le \frac{3}{2}m_R^2 + \frac{1}{2}m_R^2 = 2m_R^2 \tag{12}$$

The requirement of the precision will be: $m_t = \sqrt{2}m_R$

2.2.2 The interpolation model error and its expression

In **Figure 2**, the direction of the reference line is along the axis X, where x_1, x_2 are the coordinates of observed magnetic anomaly values in neighboring survey lines, and x_p is the coordinate of the middle point along the reference line. The coordinate along the main survey lines are the same.

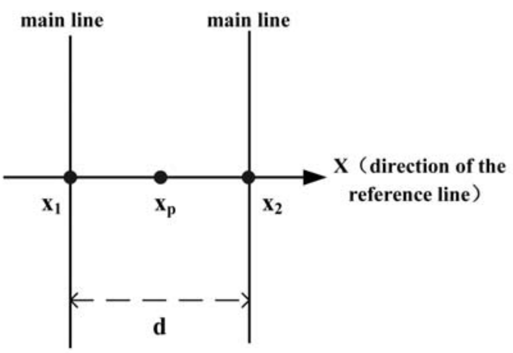


Figure 2*: The sketch map of linear interpolation between lines*

Suppose that the magnetic anomaly function is expressed as *T(x)*, which is deemed as the true value. In interval (x_1, x_2), the differential coefficient is *(n+1)*. On the middle point x_p of the reference line, the function *T(x)* can be expanded as a Taylor series.

$$T(x) = T(x_p) + T'(x_p)(x-x_p) + \frac{T''(x_p)}{2!}(x-x_p)^2 + \ldots + \frac{T^{(n)}(x_p)}{n!}(x-x_p)^n + R_n(x) \tag{13}$$

In expression above, $R_n(x)$ is the interpolation residual part.

$$R_n(x) = \frac{T^{(n+1)}(\xi)}{(n+1)!}(x-x_p)^n \quad \xi \in (x_1, x_2)$$

Neglecting the non-linear part in function *T(x)*, when *n>2*, expression (14) simplifies to:

$$T(x) = T(x_p) + T'(x_p)(x-x_p) + \frac{T''(\xi)}{2!}(x-x_p)^2 \tag{14}$$

$$\frac{T''(\xi)}{2!}(x-x_p)^2$$

The expression, is the non-linear part of function *T(x)* and *T˝(ξ)* is the gradient of *T(x)* along the X axis.

Combined with expression (13) and (14), the observed values $T(x_1)$ and $T(x_2)$ in neighboring main lines of point x_1 and x_2 can be expressed as follows.

$$T(x_1) = T(x_p) + T'(x_p)(x_1-x_p) + \frac{T''(\xi)}{2!}(x_1-x_p)^2 \tag{15}$$

$$T(x_2) = T(x_p) + T'(x_p)(x_2-x_p) + \frac{T''(\xi)}{2!}(x_2-x_p)^2 \tag{16}$$

When the linear interpolation is adopted, the magnetic anomaly value $T(x_p)'$ on the interpolating point can be expressed as:

$$T(x_p)' = \frac{1}{2}\left[T(x_1) + T(x_2)\right] \tag{17}$$

When expression (15) and (16) are adopted in expression (17) and compared to $T(x_p)$, the interpolating model error on point x_p is:

$$\varepsilon = T(x_p)' - T(x_p) = \frac{1}{16}T''(\xi)(x_1-x_2)^2 \tag{18}$$

For $x_2 – x_1 = d$, expression (18) can be finally concluded as:

$$\varepsilon = \frac{1}{16}T''(\xi)\cdot d^2 \tag{19}$$

From expression (18), the conclusion is that the larger the survey line spacing, the smaller the interpolation precision will be. This also leads to an increased complication in the variation of the magnetic anomaly gradient. This is consistent with the analysis described in the Section 3.

Expression (19) is deduced based on the direction of the reference line along the X axis. Actually expression (19) can represent the interpolation error in any direction of the reference line.

Combined with the evaluation methods above, the rationality of the survey line layout can also be evaluated. The error sources of the magnetic anomaly map and the description of its precision are listed in Table 2.

***Table 2**: The error sources of magnetic anomaly map and the description of its precision*

Quality control indices	Data source	Error source (influencing factors)	Precision formula
The precision of the contour map (divided in order 1,2,3 and 4)	Observed data	Magnetometer, the position error, the geomagnetic diurnal variation, the heading error and the environmental factors	$m_R = \pm\sqrt{\frac{[\Delta\Delta]}{2mn}}$
	Interpolated data	1. The observed data for interpolation(influence factors the same as the above)	$m_I^2 = m_t^2 - m_R^2$
		2. The model error (the influence factors include the survey line spacing, the survey line direction and the characteristics of the magnetic anomaly in the survey area)	$m_t = \pm\sqrt{\frac{[v]}{N}}$

3. INFLUENCE OF SURVEY LINE LAYOUT ON SURVEY RESULT

In designing the marine magnetic survey, the survey line layout includes the determination of the survey line direction and spacing. The evaluation method can be used to evaluate the rationality of the survey line layout.

The known (from prior surveys) magnetic anomaly maps have been adopted. When different survey line layouts are applied and simulated magnetic surveys carried out, the interpolation precisions are calculated and the magnetic anomaly contour maps are plotted with simulated data. The change of interpolation precisions and comparisons of the magnetic anomaly maps are analyzed to determine the influence of the survey line layout on the overall survey result.

The background data for simulations have been introduced and analyzed. The simulation and analysis are divided into three types:

1. The influence of the survey line layout on the interpolation precision (without the observation noise).

2. The influence of the survey line layout on the magnetic anomaly map (without the observation noise).

3. The influence of the survey line layout on the interpolation precision and magnetic anomaly map (with the observation noise).

These types of simulation have been confirmed and complement each other.

3.1 Analyzing of background data for simulations

The magnetic anomaly maps of uniform distribution (Simulation background A, in Figure 3) and non-uniform distribution (Simulation background B, in Figure 4) have been adopted as background data to simulate and analyze. The data sources respectively are marine magnetic surveys of a certain area in 2002 and 2006. Corresponding corrections have been completed and the grid data of 50m×50m have been interpolated, which are taken as real data in later simulations.

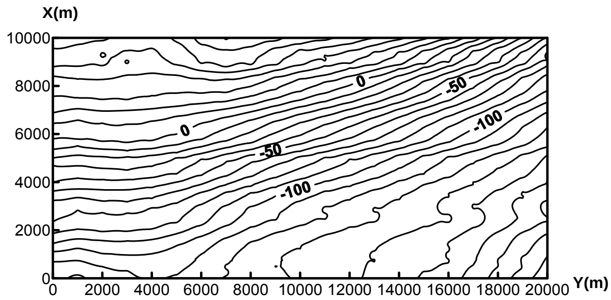
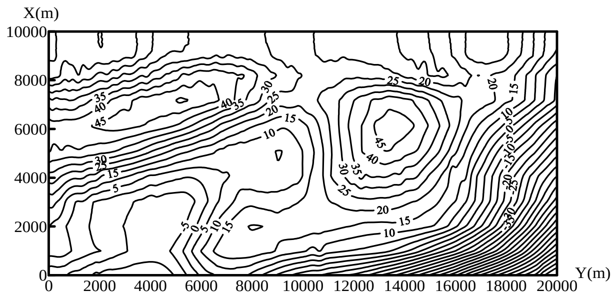
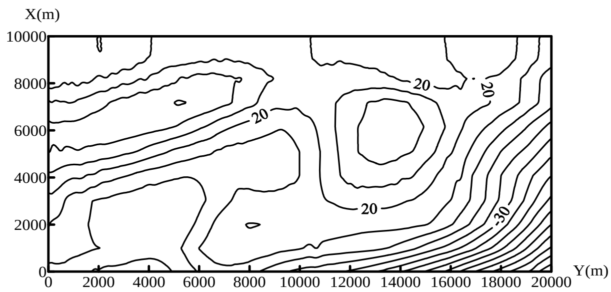


***Figure 3:** Magnetic anomaly map for simulation background A (contour interval 10 nT)*



(a) Contour interval 5 nT



(b) Contour interval 10 nT

***Figure 4(a) and (b):** Magnetic anomaly map for simulation background B*

The contour interval in Figure 4(a) is 5nT and is too dense to compare, so the contour interval of 10nT has been selected (Figure 4(b)) for comparison and analysis. From Figure 4, the distribution of the magnetic anomaly is uniform, the maximum is 50.90nT, the minimum is -128.06nT, and the average is -40.23nT. The direction of the magnetic anomaly gradient is 153.89°.

3.2 Influence of survey line layout on interpolation precision (without observation noise)

The influence of the survey line layout on the survey result can be divided into the impacts of the survey line direction and the survey line spacing. Therefore, different survey line directions and survey line spacing have been simulated and calculated. For analysis and outcomes, the representative simulation schemes are listed in ***Table 3***. The sketch map of survey line direction shown as in ***Figure 5*** (α is the angle of total gradient direction of the magnetic anomaly and the X axis).

Table 3: *Simulation scheme of influence of survey line layout*

Simulation background	A	B
Survey line direction	The axis X	The axis X
	The axis Y	The axis Y
	Total gradient	Total gradient
	Perpendicular of the total gradient	Perpendicular of the total gradient
Survey line spacing	0.1 km -2.2 km；the step 0.1 km	

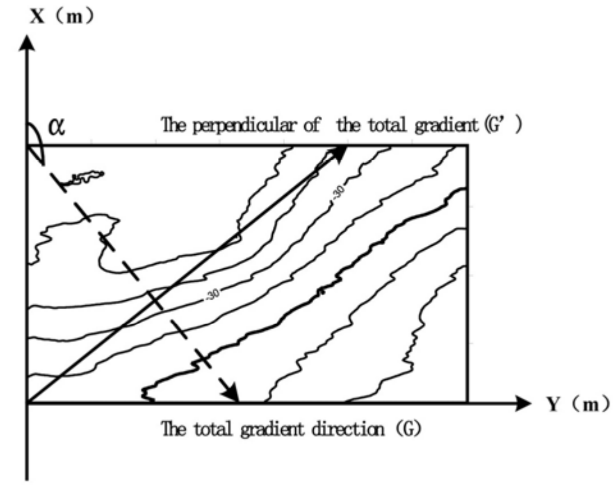


Figure 5: *The sketch map of survey line direction*

The aim of the simulations above are: (1) The impact of the survey line spacing on interpolation precision with the same survey line direction.(2) The impact of different survey line directions on the interpolation precision with the same survey line spacing.

The simulation scheme above has been conducted without observation noise ($m_R=0$), so combined with formulae (2) and (5).

$$m_t = m_I = m_\varepsilon \qquad (20)$$

The magnetic anomaly map of simulation background A (in Figure 3) is the known magnetic map and the influence of the survey line layout has been analyzed. The interval of the simulated survey points is 50m and the reference line spacing is 1000m. The simulation has been completed according to Table 3 with the results listed in ***Table 4*** and charted in ***Figure 6***.

Table 4*: The interpolation precision in different survey line layouts of simulation background A(Unit nT)*

Survey line spacing	Total gradient direction	Axis X	Axis Y	Perpendicular of total gradient	Discrepancy
0.1km	0.02	0.04	0.05	0.07	0.05
0.2km	0.08	0.13	0.21	0.39	0.31
0.3km	0.22	0.31	0.42	0.82	0.60
0.4km	0.31	0.38	0.65	1.23	0.92
0.5km	0.41	0.49	0.93	1.44	1.03
0.6km	0.51	0.69	1.22	1.46	0.95
0.7km	0.55	0.78	1.40	1.60	1.05
0.8km	0.63	0.78	1.70	1.82	1.09
0.9km	0.68	0.82	1.80	2.23	1.55
1.0km	0.69	0.93	1.89	2.56	1.87
1.1km	0.71	0.98	2.11	2.61	1.90
1.2km	0.73	1.01	2.43	2.68	1.95
1.3km	0.75	1.04	2.45	2.70	1.95
1.4km	0.78	1.05	2.53	2.79	2.01
1.5km	0.78	1.06	2.56	2.94	2.16
1.6km	0.80	1.06	2.70	2.94	2.14
1.7km	0.82	1.07	2.79	3.02	2.12
1.8km	0.84	1.07	2.85	3.03	2.19
1.9km	0.85	1.12	2.90	3.05	2.20
2.0km	0.95	1.21	2.93	3.07	2.11
2.1km	0.98	1.28	2.98	3.07	2.09
2.2km	1.02	1.30	3.01	3.10	2.08

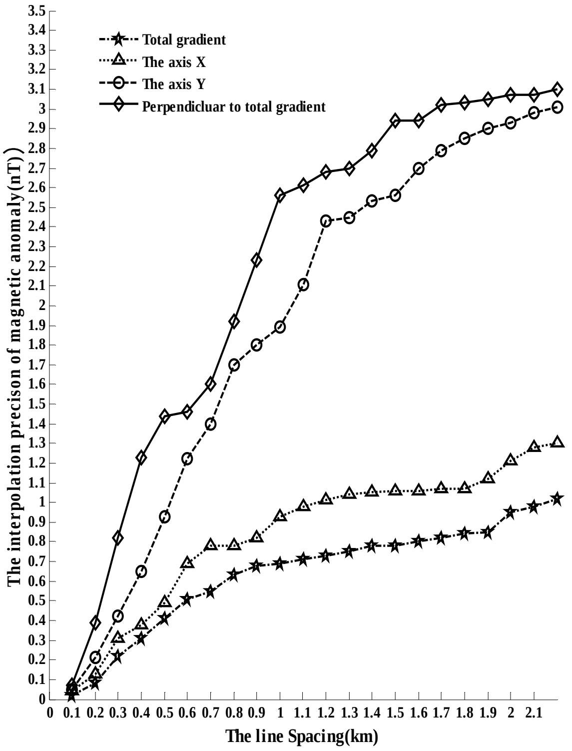


Figure 6: *The interpolation precision in different survey line layouts of simulation background A*

The magnetic anomaly map of simulation background B (in Figure 4) is the known magnetic map and the influence of the survey line layout has also been analyzed. The interval of the simulated survey points is 50m and the reference line spacing is 1000m. The simulation has been completed according to Table 3 with the results listed in ***Table 5*** and charted in ***Figure 7.***

In Figure 6 (corresponding to Table 4 results) and Figure 7 (corresponding to Table 5 results), there are large discrepancies in the interpolation precision in different survey line directions. The maximum discrepancy is 2.19nT in simulation background A (uniform distribution) and 4.21nT in simulation background B (non-uniform distribution). Therefore, the significance of the selection of the survey line direction has been adequately explained.

The conclusions from the simulations are:

The highest interpolation precision is obtained when the survey line direction is the total gradient direction. The lowest interpolation precision appears along the perpendicular of the total gradient. The closer the survey line direction to the total gradient direction, the higher the interpolation precision. Meanwhile, the discrepancy of the interpolation precision in a certain survey line direction will increase as the survey line spacing increases.

Table 5*: The interpolation precision in different survey line layouts of simulation background A(Unit nT)*

Survey line spacing	Total gradient direction	Axis X	Axis Y	Perpendicular of total gradient	Discrepancy
0.1km	0.03	0.05	0.05	0.06	0.03
0.2km	0.08	0.17	0.17	0.21	0.13
0.3km	0.20	0.28	0.30	0.31	0.11
0.4km	0.39	0.42	0.42	0.50	0.11
0.5km	0.44	0.46	0.50	0.70	0.26
0.6km	0.52	0.56	0.61	0.95	0.43
0.7km	0.57	0.64	0.71	1.17	0.60
0.8km	0.60	0.65	0.88	1.41	0.81
0.9km	0.65	0.81	0.92	1.78	1.13
1.0km	0.74	0.91	1.23	2.03	1.29
1.1km	0.85	1.07	1.33	2.30	1.45
1.2km	0.97	1.22	1.57	2.63	1.66
1.3km	1.05	1.39	1.70	2.91	1.86
1.4km	1.26	1.51	2.13	3.23	1.97
1.5km	1.31	1.74	2.30	3.64	2.33
1.6km	1.47	1.93	2.33	3.96	2.49
1.7km	1.65	2.13	2.99	4.41	2.76
1.8km	1.69	2.43	3.07	4.77	3.08
1.9km	1.93	2.55	3.12	5.25	3.32
2.0km	2.16	3.00	3.69	5.62	3.46
2.1km	2.16	3.08	4.10	5.94	3.78
2.2km	2.34	3.45	4.28	6.55	4.21

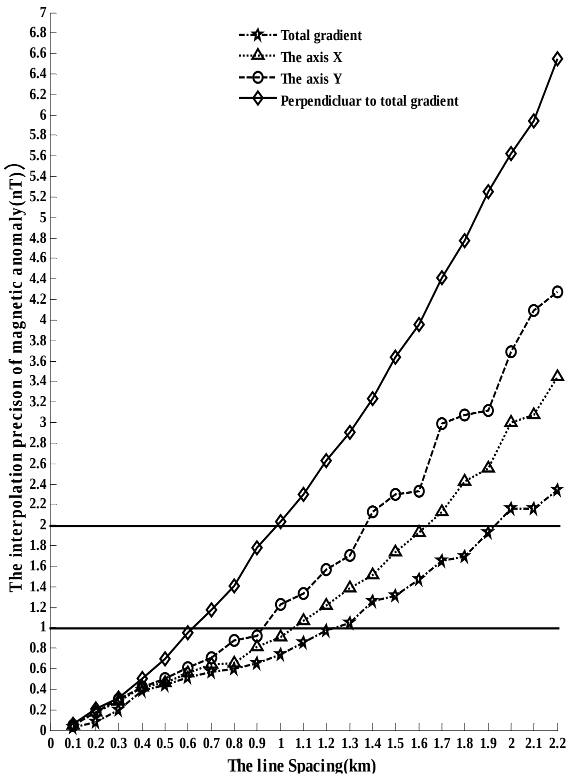


Figure 7: *The interpolation precision in different survey line layouts of simulation background B*

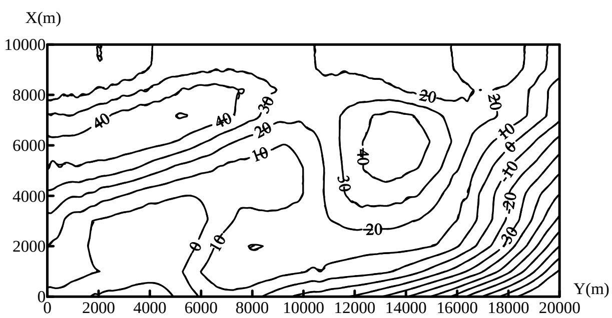
3.3 Influence of survey line layout on magnetic anomaly map (without observation noise)

To analyze the influence of the survey line layout on the magnetic anomaly map and discuss the consistency of interpolation precision, contrastive simulation and analysis have been carried out.

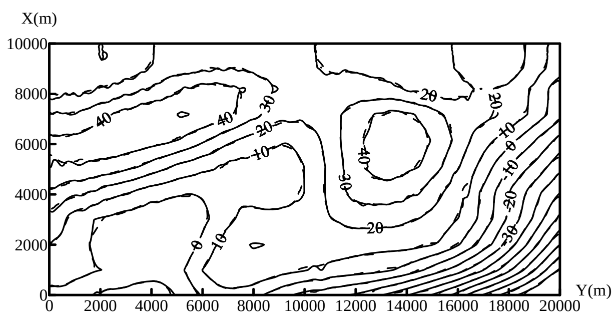
Based on the background B simulation, in which the non-uniform distribution magnetic anomaly has been adopted, the simulation content and the aims are listed in ***Table 6***. The simulated magnetic anomaly maps and the comparative results are shown in ***Figures 8*** to ***12***. For comparison purposes, the known and simulated magnetic anomaly maps have been plotted together in the same map display - the known magnetic anomaly contours are plotted as solid lines and the simulated magnetic anomaly contours are plotted as dashed lines. The contour interval is 10nT.

Table 6*: Simulation scheme of influence on magnetic anomaly map*

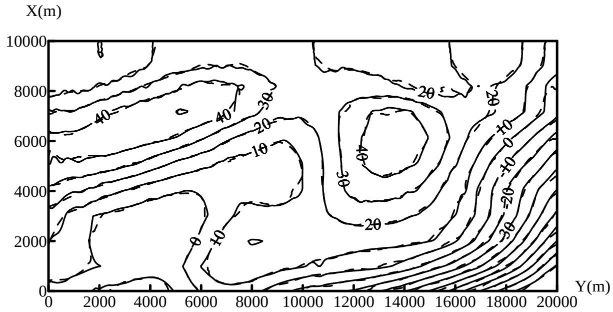
No.	Simulation contents	Simulation parameters		Interpolation precision	Simulation aims
		Survey line spacing	Survey line direction		
1	Magnetic anomaly maps with different survey line spacing are plotted which simulate the same survey line direction (total gradient direction).	0.3 km	Total gradient	0.25 nT	The consistency of interpolation precision and magnetic anomaly map will be checked.
2		0.9 km		0.67 nT	
3		1.2 km		1.00 nT	
4		1.9 km		2.00 nT	
5	Magnetic anomaly maps with different survey line directions are plotted which have been simulated with the same survey line interval.	1.0 km	Total gradient	0.74 nT	
6			Axis X	0.91 nT	
7			Axis Y	1.23 nT	
8			Perpendicular of total gradient	2.03 nT	
9		2.0 km	Total gradient	2.16 nT	
10			Axis X	3.00 nT	
11			Axis Y	3.69 nT	
12			Perpendicular of total gradient	5.62 nT	
13	Magnetic anomaly maps with different survey line directions and survey line spacing are plotted which had the same requirement of the interpolation precision (1.00nT or 2.00nT).	1.2 km	Total gradient	0.97 nT	The matching characteristics of the survey line direction and the survey line spacing will be checked when the survey precision was satisfied.
14		1.0 km	Axis X	0.91 nT	
15		0.9 km	Axis Y	0.92 nT	
16		0.6 km	Perpendicular of total	0.95 nT	
17		1.9 km	Total gradient	1.93 nT	
18		1.6 km	Axis X	1.93 nT	
19		1.3 km	Axis Y	1.78 nT	
20		0.9 km	Perpendicular of total gradient	1.78 nT	



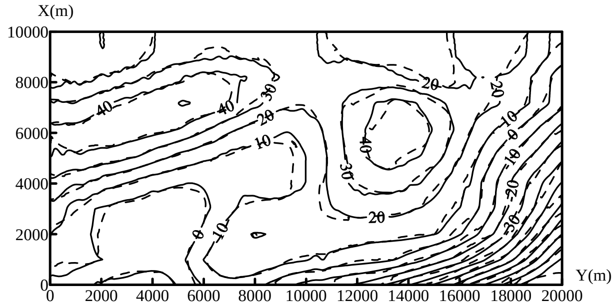
Simulation N°1 (Line spacing is 0.3km)



Simulation N°2 (Line spacing is 0.9km)

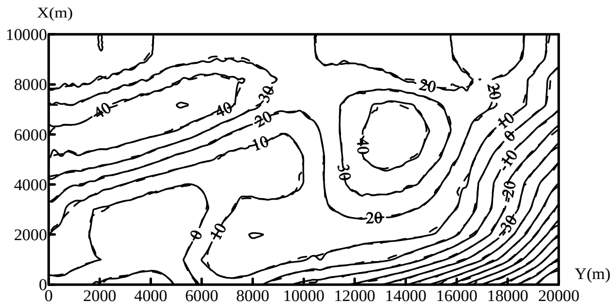


Simulation No.3 (Line spacing is 1.2km)

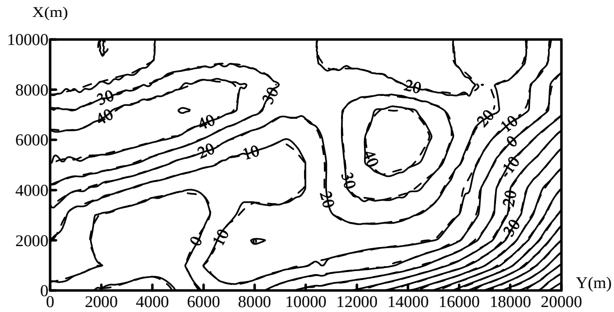


Simulation No.4 (Line spacing is 1.93km)

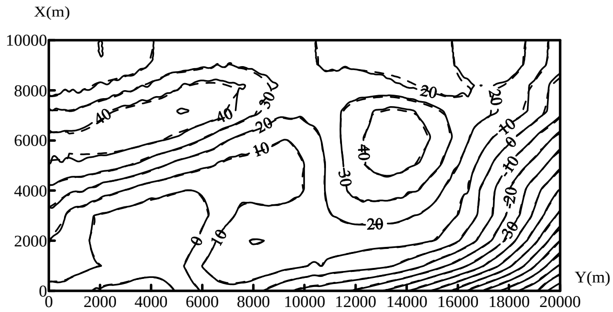
Figure 8: *The comparison of simulated map and known map for simulations No.1 to No.4 (survey line direction is the total gradient)*



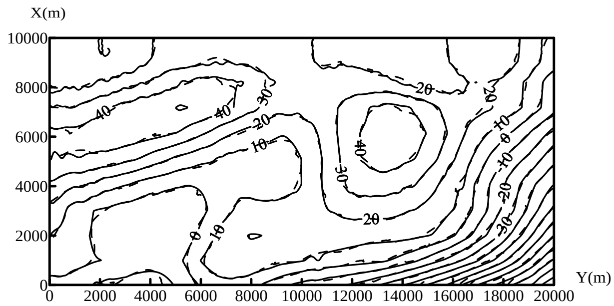
Simulation No.5 (Line direction is the total gradient)



Simulation No.6 (Line direction is the Axis X)

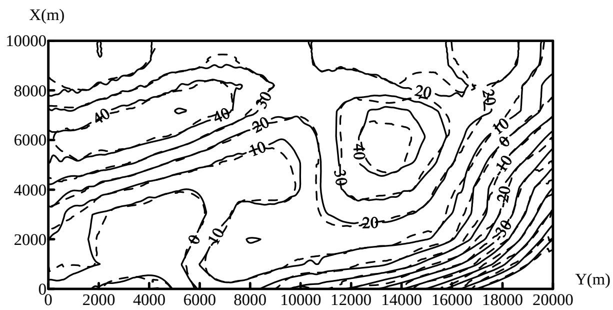


Simulation No.7 (Line direction is the Axis Y)

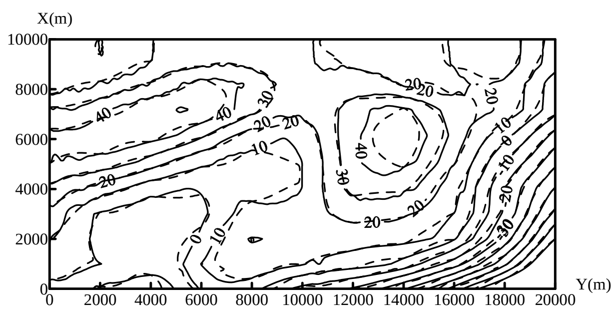


Simulation No.8
(Line direction is Perpendicular to total gradient)

Figure 9: *The comparison of simulated map and known map for simulations No.5 to No.8 (survey line spacing is 1km)*



Simulation No.9 (Line direction is the total gradient)



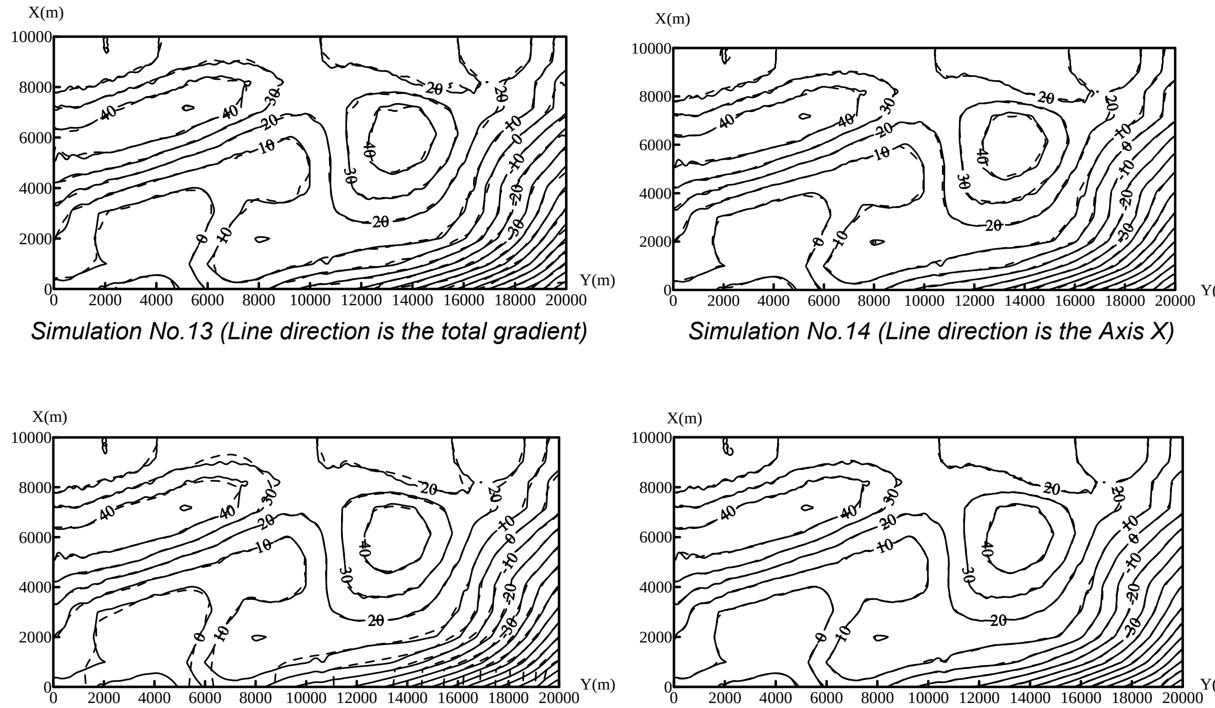
Simulation No.10 (Line direction is the Axis X)

Figure 10: *The comparison of simulated map and known map for simulations No.9 to No.12 (survey line spacing is 1km)*

As shown in ***Figure 8*** (corresponding to simulations No.1 - No.4), if the survey line direction is fixed (the total gradient direction has been adopted), the discrepancy between the simulated magnetic anomaly map with different survey line spacing and the known magnetic anomaly map can be detected. There is better agreement between the simulated map and the known map (only few magnetic anomalies have been lost), if the survey line spacing is less than 1.2km (M_I=1nT). The worst difference will be found in simulation No.4, when the survey line spacing is more than 1.9km. Although the general trend of the magnetic anomaly can be approximately determined, distortion exists in the magnetic anomaly map. This distortion is relative and can be detected if the discrepancy is more than 2nT for a contour interval of 10nT, which is 1/5 of the contour interval in this paper.

As shown in ***Figure 9*** (corresponding to simulation No.5 - No.8) and ***Figure 10*** (corresponding to simulation No.9 - No.12), if the survey line spacing is fixed, the discrepancy between the simulated magnetic anomaly map in different survey line directions and the known magnetic anomaly map can be detected. For results of simulations No. 6 – No. 12, when the survey line spacing is less than 1km, the variation of the interpolation precision in the different survey line direction is 0.74~2.03. When the simulated magnetic anomaly map and the known magnetic anomaly map is coincident, little discrepancy between the contours can be detected in a few areas. However, the variation of interpolation precision in different survey line directions range from 0.74 to 2.03. When the survey line spacing is more than 2km, the larger discrepancy will be found between the simulated map and the known map, and the distortion is distinct.

Comparing the magnetic anomaly maps of the simulations No.1 to No. 12, the interpolation precision creates consistent magnetic anomaly maps. The higher the interpolation precision, the smaller the distortion is detected and the agreement improves.



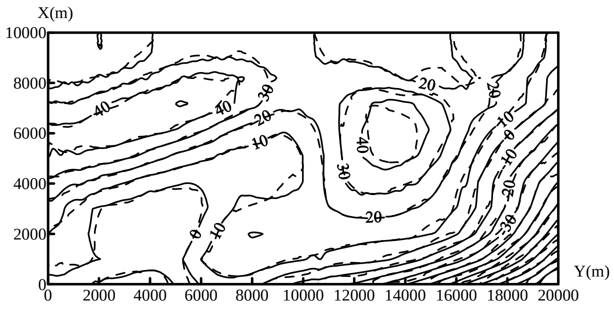
Simulation No.13 (Line direction is the total gradient)

Simulation No.14 (Line direction is the Axis X)

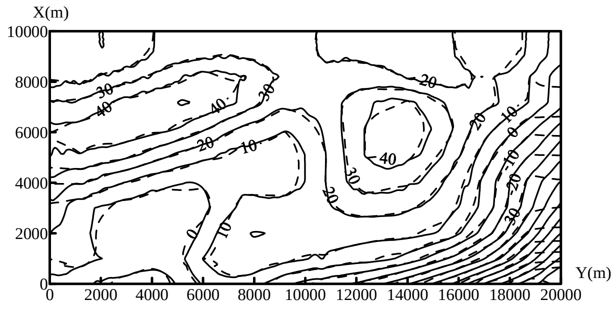
Simulation No.15 (Line direction is the total gradient)

Simulation No.16 (Line direction is the Axis X)

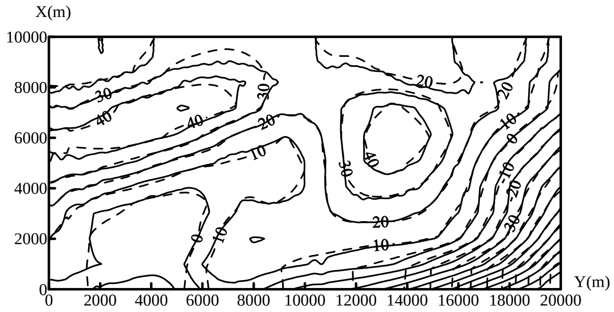
Figure 11: *The comparison of simulated map and known map for simulation No.13 to No.16 (interpolation precision is less than 1nT)*



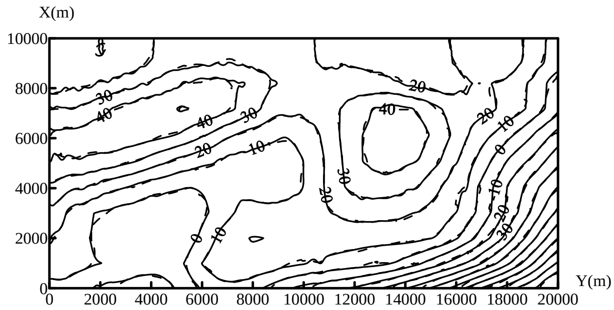
Simulation No.17 (Line direction is the total gradient)



Simulation No.18 (Line direction is the Axis X)



Simulation No.19 (Line direction is the total gradient)



Simulation No.20 (Line direction is the Axis X)

Figure 12: *The comparison of simulated map and known map for simulation No.17 to No.20 (interpolation precision is less than 2nT)*

Results of the simulations No.13 to No. 20 are analyzed, and the matching characteristics of the survey line direction and the survey line spacing discussed. As Shown in ***Figure 11*** (corresponding to simulations No.13 to No.16) and despite the survey line spacing and survey line directions being different, the interpolation precisions are almost the same, and the simulated and known maps are coincident. For example, the interpolation precision where the survey line spacing is 1.2km in total gradient direction and 0.6km perpendicular of the total gradient direction are equal (1nT). Line numbers along the latter will be twice the former. The same result is in simulation No.17 to No.20 (as shown in ***Figure 14***). To obtain the interpolation precision of 2nT, the survey line spacing is 1.9km in total gradient and 0.8km perpendicular of the total gradient. The line numbers will be doubled.

So the maximum line spacing along a certain survey line direction will meet the requirement of interpolation precision. Line numbers are minimized when survey lines are designed along the total gradient.

3.4 Influence of survey line layout on interpolation precision and magnetic anomaly map (with observation noise)

In survey practice, observation errors inevitably exist. To simulate closer to the real survey practice, the observation error of normal distribution have been added in the representative simulations above and simulation scheme are listed in ***Table*** *7*.

Table 7*: Simulation scheme with observation noise*

No	Simulation contents	Simulation parameters	
		line spacing	line direction
21	1.0 nT of observation noise was added in the related simulation	0.5 km	Survey line direction is in the total gradient, the axis X, the axis Y and the perpendicular of the total gradient
22		1.0 km	
23		1.5 km	
24		2.0 km	
25	1.4 nT of observation noise was added in the related simulation	0.5 km	
26		1.0 km	
27		1.5 km	
28		2.0 km	

The simulation aims of ***Table 7*** are described below. With the observation noise added: (1) The consistency of interpolation precision and magnetic anomaly map is verified; and (2) the law of propagation of errors have been validated for the interpolation precision. The detailed simulation results have been listed in ***Table 8*** and ***Figure 13*** and ***14***.

Table 8*: The interpolation precisions in different survey line layouts of simulation background B (With the observation noise)*

No.	Noise magnitude	Survey line spacing	Survey line direction											
			Total gradient			Axis X			Axis Y			Perpendicular of total gradient		
			m_t	m_R	m_I	m_t	m_R	m_I	m_t	m_R	m_I	m_t	m_R	m_I
21	1.0nT	0.5km	1.24	0.98	0.76	1.37	0.98	0.96	1.40	1.01	0.97	1.47	1.02	1.06
22		1.0km	1.27	1.00	0.78	1.40	1.00	0.98	1.53	1.00	1.16	2.35	0.99	2.13
23		1.5km	1.70	1.02	1.36	2.01	0.99	1.74	2.51	0.99	2.31	3.72	1.00	3.58
24		2.0km	2.41	1.00	2.20	3.19	1.02	3.02	5.19	0.99	5.10	5.89	1.00	5.80
25	1.4nT	0.5km	1.74	1.40	1.03	1.75	1.41	1.04	1.76	1.41	1.05	1.83	1.41	1.18
26		1.0km	1.76	1.39	1.07	1.79	1.38	1.15	2.02	1.41	1.45	2.53	1.40	2.11
27		1.5km	1.97	1.39	1.40	2.22	1.42	1.70	2.85	1.40	2.48	4.91	1.41	4.70
28		2.0km	2.78	1.42	2.39	3.49	1.42	3.18	4.59	1.42	4.36	5.96	1.41	5.79

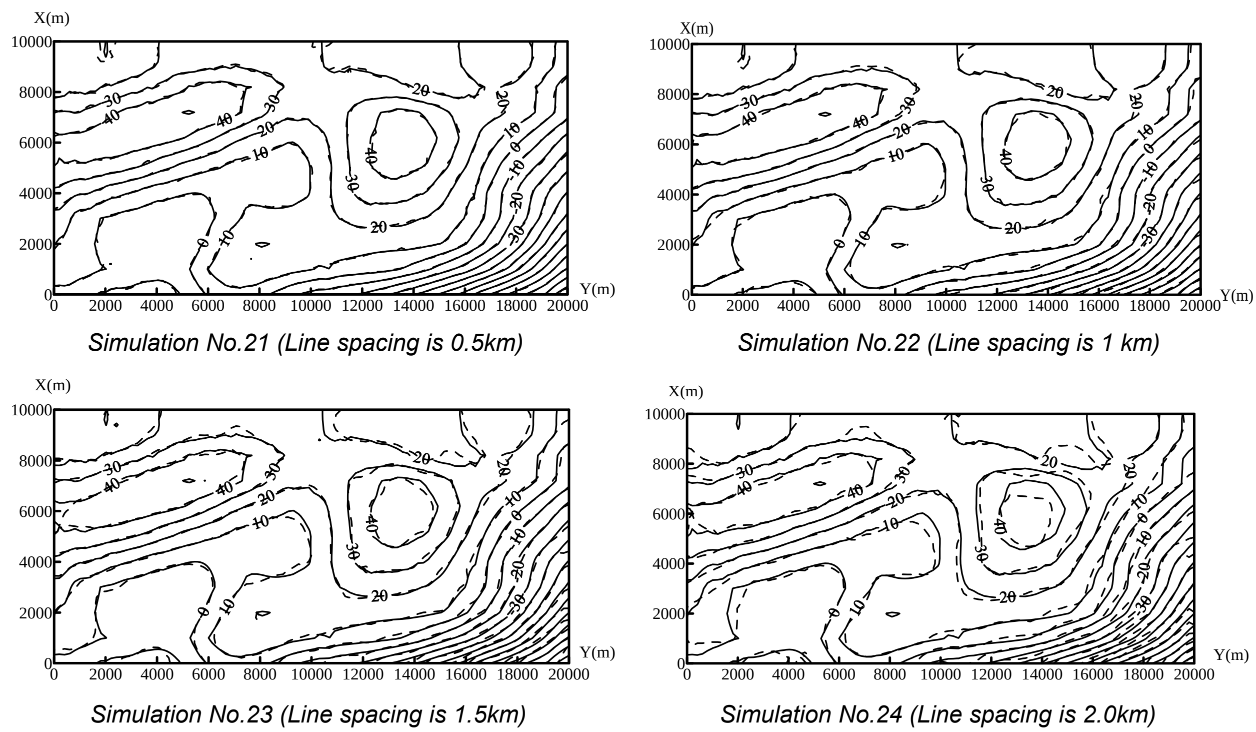
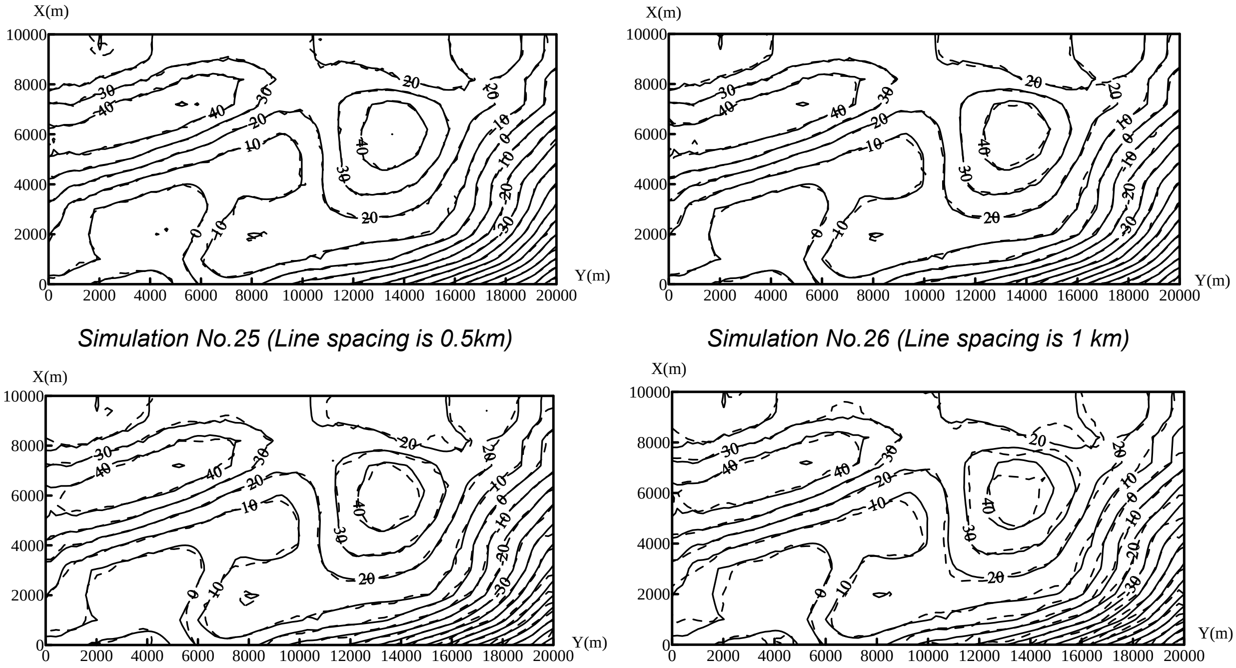


Figure 13: *The comparison of simulated map and known map for simulation No.21 to No.24 (the observation noise is 1nT, line direction is total gradient)*



Simulation No.25 (Line spacing is 0.5km)

Simulation No.26 (Line spacing is 1 km)

Simulation No.27 (Line spacing is 1.5km)

Simulation No.28 (Line spacing is 2.0km)

***Figure 14**: The comparison of simulated map and known map for simulation No.21 to No.24 (the observation noise is 1.44nT, line direction is total gradient)*

In ***Table 8***, m_t , can be calculated by the difference of the reference points between the interpolated value and the observed value with observation noise. m_R can be calculated by cross points of the main lines and the reference lines with observation noise. m_I can be calculated by the difference of the reference points between the interpolated value by the main lines with the observation noise and the observed value in the reference lines without the observation noise.

The law of propagation of errors (See formulae (2)) has been verified by the numerical values in ***Table 9***.

A comparison of the interpolation precision, with and without observation noise added, is shown in ***Figure 15***.

As shown in Figure 15 and Table 8, the obvious differences can be detected in the interpolation precision of different survey line layouts between the survey line spacing and observation noise. Meanwhile the agreement between the magnetic anomaly maps can be perfectly reflected by the corresponding interpolation precision. By increasing the observation noise to obtain the same interpolation precision, the corresponding survey line spacing must be decreased. For example, if survey lines are designed along the total gradient, to obtain the interpolation precision of 1nT, the survey line spacing must be less than 1km with observation noise of 1nT and 1.4nT.

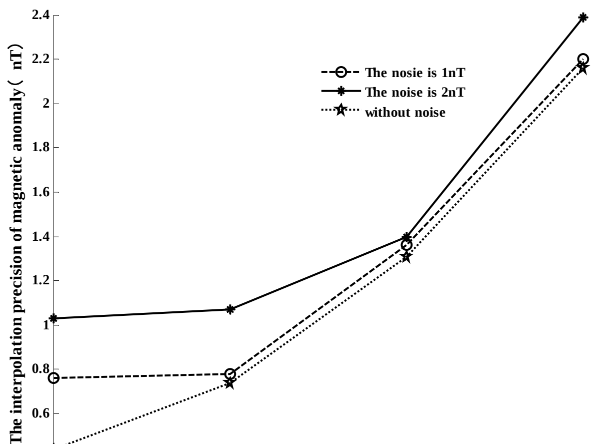


***Figure 15**: The comparison map of the interpolation precision with and without observation noise*

4. THE SURVEY LINE DESIGN METHOD

Based on the analysis above, we can conclude that the interpolation precision can be applied in the evaluation of the rationality of the survey line layout. Further, it can be used to optimize the survey line layout for marine magnetic surveys.

The rule of survey line layout is to control blank areas between the survey lines and then adjust the interpolation precision and survey precision to meet the total requirements of the magnetic anomaly map precision. Therefore, the rational survey line direction must be selected first based on the priori-magnetic information of survey area, then control and adjust the survey line spacing to match the interpolation precision between survey lines and survey precision.

4.1 Determination of survey line direction

The main requirement in the determination of survey line direction is to accurately ascertain the total gradient of the magnetic anomaly of the survey area. So the priori-magnetic anomaly map must be digitized for gridding data. For the non-observed area, the known magnetic anomaly map can be obtained by using a regional magnetic field model. The gradient of each point can be calculated using gridded data, and the total gradient of the whole survey area can be calculated.

If the obtained total gradient direction is close to the axis X (north to south) or the axis Y (east to west), the axis can be selected as the survey line direction to simplify the survey practice.

4.2 Determination of survey line spacing

When the survey line direction has been determined, we can design the survey line spacing according to the flow chart shown as in ***Figure 16***. In the technical design of a marine magnetic survey, the priori-magnetic information of survey area must be fully known and the rational preliminary survey can be brought forward. Further optimization of the survey line layout can be given based on the new magnetic information obtained by the preliminary survey. The magnetic anomaly map which satisfied the prearranged survey precision can be obtained with the optimized survey line layout and the highest survey efficiency can be assured.

Compared to the new survey line layout, the practical magnetic field has not been considered in the traditional survey layout (shown in Table 1). The optimization of the survey line layout in a step by step process has been embodied by the method discussed in this paper.

The complexity and the difficulty of the survey line layout will be certainly increased. Using modern computing and specialist software, the design of survey lines for marine magnetic surveys can be programmed. This can be applied in practical survey conduct and marine magnetic survey outcomes can be improved.

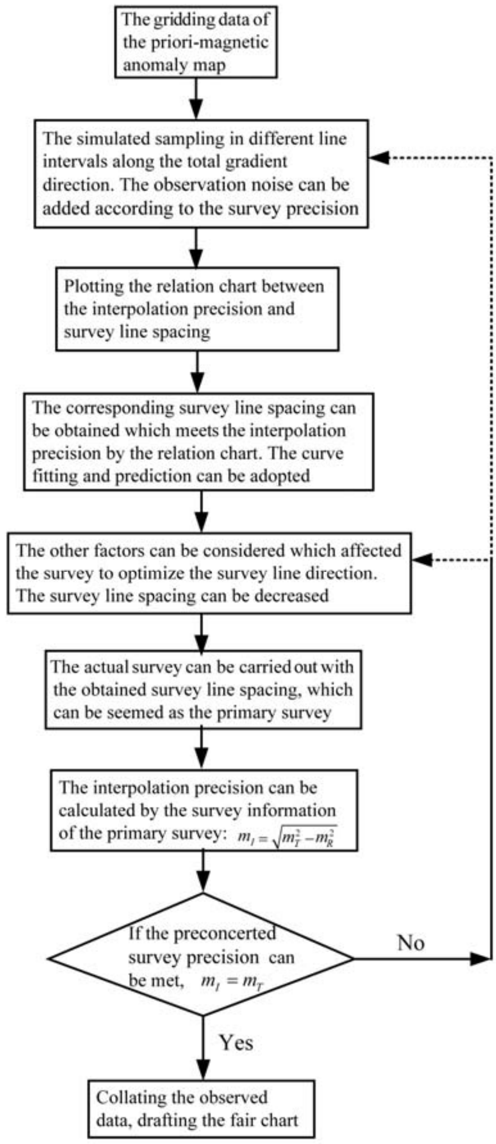


Figure 16*: The flow chart of the survey line layout*

5. CONCLUSIONS

The design of the survey line layout has been thoroughly and systematically studied. The evaluation methods of survey line layout have been described and the influence of survey line layout have been simulated and discussed. Finally, a new design method for survey line layout has been described. Based on the study of this paper, we can conclude that:

(1) The evaluation method of magnetic anomaly map and interpolation precision between the survey lines can be effectively applied in evaluation of the rationality of survey line layout.

(2) The highest interpolation precision can be obtained if survey lines are designed along the total gradient. By increasing the survey line spacing, the difference of the interpolation precision between different survey line directions will also be increased. However, regard to certain survey line direction, the interpolation precision will be different, which will decrease with increasing the survey line spacing.

(3) The value of the interpolation precision and magnetic anomaly map is consistent in evaluation of the rationality of survey line layout. The higher the interpolation precision, the less distortion in the magnetic anomaly map and the more the agreement will be. Meanwhile the simulation with observation noise shows that the interpolation precision is in accord with the law of propagation of errors and the theoretical analysis of the interpolation precision is inosculated.

(4) The integral research of the survey line layout shows that the new method of the survey line layout described is rational and feasible. An optimization of survey line layout in a step by step has been described, which is in accord with survey practice.

6. REFERENCES

- BIAN Gang, LIU Yanchun,YU Bo (2008). "The Evaluation of Interpolation Residual Precision with Midpoint of Reference Lines in Marine Magnetic Survey", *Journal of Geodesy and Geodynamics*, 28(3), pp. 96~99.

- E.C. Boumweester adg A.W. Heemink (1993). "Optimal Line Spacing in Hydrographic Survey", *International Hydrographic Review*, LXX(1), pp. 37~48.

- HUANG Motao, ZHAI Guojun, OUYANG Yongzong (2006). "Research On Error Compensation in Marine Magnetic Survey", *Journal of Geomatics and Information Science of Wuhan University*, 31(7), pp. 603~606.

- LIANG Kailong and LIU Yanchun (1996). Marine Gravity and Magnetic Survey, *Publishing House of Surveying and Mapping, China.*

- LIU Yanchun (2004). The Spatial Constructer of the Marine Sounding and Data Processing, *Publishing House of Surveying and Mapping, China.*

- LIU Yanchun and XIAO Fumin (2006).The conspectus of the Hydrography, *Publishing House of Surveying and Mapping*, China.

- LIU Yanchun, LI Mingsan, HUANG Motao (2001). "The Rank-Defect Adjustment Model for Survey-line Systematic Errors in Marine Survey Net", *Journal of Geomatics and Information Science of Wuhan University*, 26(3), pp. 533~538.

- National Supervisor Bureau for Quality Technique (1998). The Criteria of Hydrographic Survey. *Chinese criteria press*, China.

7. BIOGRAPHIES OF THE AUTHORS

Dr BIAN Gang has been a lecturer in the Department of Hydrography & Cartography of the Dalian Naval Academy since 2011. He received his Doctor's degree in Geodesy and Surveying Engineering Subject in 2008. He worked on the naval training ship fleet from 2009 to 2011 and was appointed as the navigation officer of training ship SHI Chang. He is engaged in hydrographic surveying theory and data processing and has extensive experience in marine magnetic survey practice and data processing.
Email: trighosts@163.com.
Cell phone: +8613387859531

Professor Dr XIA Wei is the Associate Professor in the Department of Hydrography & Cartography of Dalian Naval Academy. He worked in the Naval Survey Troop from 2001 to 2002 which? where? he was appointed as the substitute captain of the survey unit. He has worked as a lecturer in the Department of Hydrography & Cartography of the Dalian Naval Academy since 2003 and researched hydrographic surveying theory and data processing. He received his Doctor's degree in Geodesy and Surveying Engineering in 2009. He has extensive experience in multibeam sounding survey practice and data processing.
Email: xiawei_1976@hotmail.com.
Cell phone: +8613998545423

Dr JIN Shaohua has been a lecturer in the Department of Hydrography & Cartography of the Dalian Naval Academy since 2006. He worked in the Naval Survey Troop from 2004 to 2005 and was appointed as the substitute captain of the survey unit. He is engaged in hydrographic surveying theory and data processing. He received his Doctor's degree in Geodesy and Surveying Engineering in 2011. He has extensive experience in marine magnetic survey practice and data processing.
Email: jsh197835@163.com.
Cell phone: +8613840933021

Professor Dr XIAO Fumin is the Associate Professor in the Department of Hydrography & Cartography of the Dalian Naval Academy. He worked in the Naval Survey Troop from 1989 to1994 which? where he was appointed as the substitute captain of the survey unit. He has been a lecturer in the Department of Hydrography & Cartography of the Dalian Naval Academy since 1995 and researched hydrographic surveying theory and data processing. He received his Doctor's degree in Geodesy and Surveying Engineering Subject in 2007. He is currently the Associate Professor of the department and has extensive experience in hydrographic surveying practice and data processing.
Email: Xiaofum@163.com.
Cell phone: +8613842695886

Dr SUN Xinxuan has been a lecturer in the Department of Hydrography & Cartography of the Dalian Naval Academy since 2005. He worked in the Naval Survey Troop from 1999 to 2002 where which? he was appointed as the captain of survey unit. He is engaged in hydrographic surveying theory and data processing. He obtained his Doctor's degree in Geodesy and Surveying Engineering Subject in 2009. He has extensive experience in chart datum transfer theory and algorithms.
Email: xinxuan_sun@163.com.
Cell phone: +8618640862069

Dr CUI Yang has been a lecturer in the Department of Hydrography & Cartography of the Dalian Naval Academy since 2006. She worked in the Naval Survey Troop from 2004 to 2005 and was appointed as the substitute captain of the survey unit. She is engaged in marine geodesy survey theory and data processing. She obtained her Doctor's degree in Geodesy and Surveying Engineering in 2013. She has extensive experience in marine geodesy survey practice and data processing.
Email: 13998435151@163.com.
Cell phone: +8613998435151

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