Research Article

Simulation Analysis of Magnetic Gradient Full-Tensor Measurement System

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1. Introduction

The ferromagnetic object magnetized by the geomagnetic field will produce a magnetic field, which will affect the constant distribution of the geomagnetic field. This phenomenon that causes the abnormality of the geomagnetic field is called magnetic anomaly [1]. Magnetic anomaly detection refers to the technology of obtaining several characteristics of the magnetic target with the process of acquiring and processing the magnetic anomaly information of a magnetic target. Magnetic anomaly detection technology has many advantages such as strong anti-interference ability, rich information, and good concealment performance [2–4]. It is widely used in underwater or underground target detection, aerial magnetic survey, navigation and positioning, mineral exploration, and other fields [5–9]. At present, it can be roughly divided into four phases: total magnetic field detection, total magnetic field gradient detection, the magnetic component field detection, and the magnetic gradient full-tensor field detection phase [10]. The phase of magnetic gradient full-tensor detection is the latest development stage of magnetic anomaly detection. It has unique advantages such as being less affected by system attitude changes and less environmental interference. It can get much richer target information and be not affected by the total magnetic background field basically. This technology has gradually developed into a research hotspot in the fields of Earth resource exploration, aerial exploration, and military reconnaissance, and its application prospects are very broad [11–14].

It is impossible to directly measure the magnetic gradient full tensor. In actual measurement, the magnetic gradient full-tensor measurement system is generally used to measure the components of the magnetic field vector field; and the difference method is used to obtain the full-tensor field of the magnetic gradient approximately. Presently, the magnetic gradient full-tensor measurement system mainly includes two types: superconducting magnetometer and fluxgate magnetometer [15, 16]. The former has high sensitivity, good stability, and strong reliability, but the preparation process is complicated and costly. The latter uses several fluxgates to measure the magnetic vector component to obtain the spatial change rate, which is portable, economical, and practical.
At present, the magnetic gradient full-tensor measurement systems constructed by the fluxgate magnetometer can be divided into two types. One is the two-dimensional plane shape including cross, equilateral triangle, right triangle, and square; the other is three-dimensional, which includes regular tetrahedron, right-angle tetrahedron, and regular tetrahedron. Various systems can achieve the measurement purpose under specific environmental conditions. However, under the same measurement environment, the selection of the measurement system is still unclear, and there is very little analysis in the structure of different systems. But the configuration of the fluxgate magnetometer will have a great impact on the measurement of the magnetic gradient full tensor. It even directly affects the feasibility of measurement. Therefore, it is necessary to analyze and compare the impact on the measurement of the magnetic gradient full tensor. Therefore, it is necessary to analyze and compare the impact on the measurement of the magnetic gradient full tensor. According to Maxwell’s equations, in a passive ambient static magnetic field, the divergence and curl of the magnetic field are both zero.

\[
\text{div} \, \vec{B} = \nabla \cdot \vec{B} = 0, \tag{2}
\]

\[
\text{rot} \, \vec{B} = \nabla \times \vec{B},
\]

In equation (1), \( U \) is the magnetic scalar potential; \( B_x, B_y, \) and \( B_z \) are the three components of the magnetic field at any point in space \((x, y, z)\); \( B_{ij}(i, j = x, y, z) \) is the component of the magnetic gradient full tensor. According to Maxwell’s equations, in a passive ambient static magnetic field, the divergence and curl of the magnetic field are both zero.

\[
\begin{bmatrix}
\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0, \\
\frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} \\
\frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial x} \\
\frac{\partial B_y}{\partial z} = \frac{\partial B_z}{\partial y}
\end{bmatrix}
\tag{4}
\]

According to equations (2) and (3),

\[
G = \begin{bmatrix}
\frac{\partial^2 U}{\partial x^2} & \frac{\partial^2 U}{\partial x \partial y} & \frac{\partial^2 U}{\partial x \partial z} \\
\frac{\partial^2 U}{\partial y \partial x} & \frac{\partial^2 U}{\partial y^2} & \frac{\partial^2 U}{\partial y \partial z} \\
\frac{\partial^2 U}{\partial z \partial x} & \frac{\partial^2 U}{\partial z \partial y} & \frac{\partial^2 U}{\partial z^2}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{\partial B_x}{\partial x} \\
\frac{\partial B_y}{\partial x} \\
\frac{\partial B_z}{\partial x}
\end{bmatrix}
\begin{bmatrix}
\frac{\partial B_x}{\partial y} \\
\frac{\partial B_y}{\partial y} \\
\frac{\partial B_z}{\partial y}
\end{bmatrix}
\begin{bmatrix}
\frac{\partial B_x}{\partial z} \\
\frac{\partial B_y}{\partial z} \\
\frac{\partial B_z}{\partial z}
\end{bmatrix}
\]

\[
\begin{bmatrix}
B_{xx} & B_{xy} & B_{xz} \\
B_{yx} & B_{yy} & B_{yz} \\
B_{zx} & B_{zy} & B_{zz}
\end{bmatrix}
\]
3. Magnetic Gradient Full-Tensor Measurement System

3.1. Cross Measurement System. The model of the cross-shaped magnetic gradient full-tensor measurement system is shown in Figure 1. The system is composed of four fluxgate magnetometers. The center point is taken as the axis center (O) of the system coordinate axis. The fluxgates are marked as 1, 2, 3, and 4, respectively. The centers of No. 1 and No. 3 fluxgates are parallel to the x-axis, and their baseline distance is b. No. 2 and No. 4 fluxgates are parallel to the y-axis, and their baseline distance is also b [18].

The three-component magnetic fields measured by the four fluxgates are as follows:

\[
\begin{align*}
B_1 &= \begin{bmatrix} B_{1x} \\ B_{1y} \\ B_{1z} \end{bmatrix}, \\
B_2 &= \begin{bmatrix} B_{2x} \\ B_{2y} \\ B_{2z} \end{bmatrix}, \\
B_3 &= \begin{bmatrix} B_{3x} \\ B_{3y} \\ B_{3z} \end{bmatrix}, \\
B_4 &= \begin{bmatrix} B_{4x} \\ B_{4y} \\ B_{4z} \end{bmatrix}.
\end{align*}
\]

(7)

In equation (7), \(B_i (i = 1, 2, 3, 4)\) is the magnetic field vector of the fluxgate No. \(i\), and \(B_{ij} (i = 1, 2, 3, 4; j = x, y, z)\) is the component of the fluxgate No. \(i\) in the \(j\) direction. The expression of the magnetic gradient full tensor at the axis O of the system is as follows:

\[
G = \frac{1}{d} \begin{bmatrix}
B_{1x} - B_{3x} & B_{1y} - B_{3y} & B_{1z} - B_{3z} \\
B_{2x} - B_{4x} & B_{2y} - B_{4y} & B_{2z} - B_{4z} \\
B_{1z} - B_{3z} & B_{2z} - B_{4z} & B_{3x} + B_{4x} - (B_{1x} + B_{2x})
\end{bmatrix}.
\]

(8)

\[
G = \frac{1}{\sqrt{3}d} \begin{bmatrix}
\sqrt{3} (B_{1x} - B_{3x}) & \sqrt{3} (B_{1y} - B_{3y}) & \sqrt{3} (B_{1z} - B_{3z}) \\
2B_{2x} - (B_{1x} + B_{3x}) & 2B_{2y} - (B_{1y} + B_{3y}) & 2B_{2z} - (B_{1z} + B_{3z}) \\
\sqrt{3} (B_{1z} - B_{3z}) & 2B_{2z} - (B_{1z} + B_{3z}) & (B_{1y} + B_{3y}) - 2B_{2y} - \sqrt{3} (B_{1x} - B_{3x})
\end{bmatrix}.
\]

(9)

3.2. Equilateral Triangle Measurement System. The triangular magnetic gradient full-tensor measurement system is composed of three fluxgate magnetometers. No. 1, No. 2, and No. 3 fluxgates are, respectively, located at the apex of the triangle. The side length of the equilateral triangle is the baseline distance (\(d\)) of the system. The geometric center of the triangle is taken as the axis center (O) of the system coordinate axis. The system model is shown in Figure 2.

Similar to the cross-shaped measurement system, according to the three components of the magnetic field vector measured by the No. 1, No. 2, and No. 3 fluxgates, the full tensor of the magnetic gradient of the axis can be obtained:

3.3. Right Triangle Measurement System. The model of the right triangle magnetic gradient full-tensor measurement system is shown in Figure 3. The difference from the equilateral triangle measurement system is that the connection between the centers of the three fluxgate magnetometers is isosceles right triangle. The position where the No. 3 fluxgate is located is the axis center (O) of the system coordinate axis, and the right-angle side length \(d\) is the
baseline distance. The full tensor of the magnetic gradient of the axis \( O \) is shown as follows:

\[
G = \frac{1}{d} \begin{bmatrix}
B_{1x} - B_{3x} & B_{1y} - B_{3y} & B_{1z} - B_{3z} \\
B_{2x} - B_{3x} & B_{2y} - B_{3y} & B_{2z} - B_{3z} \\
B_{1z} - B_{3z} & B_{2z} - B_{3z} & B_{3x} + B_{3y} - (B_{1x} + B_{2y})
\end{bmatrix}.
\]

(10)

3.4. Square Measurement System. Figure 4 is a square magnetic gradient full-tensor measurement system. The center points of the No. 1, No. 2, No. 3, and No. 4 fluxgates are connected to form a square. The center point of the square is taken as the axis center \((O)\) of the coordinate axis of the system. The side length \( d \) of the square is the baseline distance, and the magnetic gradient full tensor of the axis \( O \) is calculated as

\[
G = \frac{1}{2d} \begin{bmatrix}
(B_{1x} + B_{4x}) - (B_{2x} + B_{3x}) & (B_{1y} + B_{4y}) - (B_{2y} + B_{3y}) & (B_{1z} + B_{4z}) - (B_{2z} + B_{3z}) \\
(B_{1x} + B_{2x}) - (B_{3x} + B_{4x}) & (B_{1y} + B_{2y}) - (B_{3y} + B_{4y}) & (B_{1z} + B_{2z}) - (B_{3z} + B_{4z}) \\
(B_{1z} + B_{4z}) - (B_{2z} + B_{3z}) & (B_{1z} + B_{2z}) - (B_{3z} + B_{4z}) & (B_{2x} + B_{3x} + B_{3y} + B_{4y}) - (B_{1x} + B_{1y} + B_{2y} + B_{4x})
\end{bmatrix}.
\]

(11)

3.5. Regular Tetrahedron Shape Measurement System. The regular tetrahedral magnetic gradient full-tensor measurement system is built by 4 fluxgate magnetometers. The connection at the center of the fluxgate forms a regular tetrahedral structure. The structure model is shown in Figure 5. The centers of the No. 1, No. 2, and No. 3 fluxgates form the bottom surface of a regular tetrahedron, and the center of the bottom triangle is taken as the axis center \((O)\) of the coordinate axis of the system. The side length of the regular tetrahedron is the baseline distance \((d)\) of the system. The magnetic field of the center \( O \) is shown as

\[
G = \frac{1}{d} \begin{bmatrix}
\frac{2B_{1x} - (B_{2x} + B_{3x})}{\sqrt{3}} & \frac{2B_{1y} - (B_{2y} + B_{3y})}{\sqrt{3}} & \frac{2B_{1z} - (B_{2z} + B_{3z})}{\sqrt{3}} \\
\frac{B_{1x} + B_{2x} - 2B_{3x}}{\sqrt{3}} & \frac{B_{1y} + B_{2y} - 2B_{3y}}{\sqrt{3}} & \frac{B_{1z} + B_{2z} - 2B_{3z}}{\sqrt{3}} \\
\frac{3B_{4x} - (B_{1x} + B_{2x} + B_{3x})}{\sqrt{6}} & \frac{3B_{4y} - (B_{1y} + B_{2y} + B_{3y})}{\sqrt{6}} & \frac{3B_{4z} - (B_{1z} + B_{2z} + B_{3z})}{\sqrt{6}}
\end{bmatrix}.
\]

(12)
3.6. Right-Angle Tetrahedron Shape Measurement System. The model of the right-angled tetrahedral magnetic gradient full-tensor measurement system is shown in Figure 6. The line connecting the centers of the fluxgate magnetometers No. 1, No. 2, and No. 3 forms the base of an isosceles right triangle, and the length of the right-angle side is the baseline distance \(d\). The distance between No. 4 and No. 1 fluxgates is also \(d\), and the center of No. 1 fluxgate is the axis center \(O\) of the coordinate axis of the system. The full tensor of the magnetic gradient system is

\[
G = \frac{1}{2d} \begin{bmatrix} B_{2x} - B_{1x} & B_{2y} - B_{1y} & B_{2z} - B_{1z} \\ B_{3x} - B_{1x} & B_{3y} - B_{1y} & B_{3z} - B_{1z} \\ B_{4x} - B_{1x} & B_{4y} - B_{1y} & B_{4z} - B_{1z} \end{bmatrix}.
\]

(13)

The structure comparison of seven kinds of full-tensor measurement systems is shown in Table 1.

It can be seen from Table 1 that the measurement system can be divided into two types: two-dimensional plane and three-dimensional stereo according to the number of dimensions, which also determines the type of observation point. Among all measurement systems, the number of magnetometers used in triangle is the smallest, which is 3; the number of magnetometers used in the regular hexahedron is the largest, which is 8. The three-dimensional shape measurement system can measure 9 independent components individually, while the two-dimensional plane can measure 6 independent components.

3.7. Hexahedron Shape Measurement System. As shown in Figure 7, the regular hexahedron shape measurement system model is composed of 8 fluxgate magnetometers centered at the apex of the regular hexahedron. The side length of the regular hexahedron is the baseline distance \(d\), and the center of the regular hexahedron is the coordinate axis center \(O\) of the system. The full-tensor expression of the magnetic gradient at the axis is

\[
G = \frac{1}{2d} \begin{bmatrix} B_{6x} + B_{5x} + B_{4x} + B_{3x} - (B_{1x} + B_{2x} + B_{3x} + B_{4x}) & B_{1y} + B_{2y} + B_{3y} + B_{4y} - (B_{5y} + B_{6y} + B_{7y} + B_{8y}) \\ B_{1z} + B_{2z} + B_{3z} + B_{4z} - (B_{5z} + B_{6z} + B_{7z} + B_{8z}) & B_{1y} + B_{2y} + B_{3y} + B_{4y} - (B_{5y} + B_{6y} + B_{7y} + B_{8y}) \\ B_{1z} + B_{2z} + B_{3z} + B_{4z} - (B_{5z} + B_{6z} + B_{7z} + B_{8z}) & B_{1y} + B_{2y} + B_{3y} + B_{4y} - (B_{5y} + B_{6y} + B_{7y} + B_{8y}) \\ B_{1z} + B_{2z} + B_{3z} + B_{4z} - (B_{5z} + B_{6z} + B_{7z} + B_{8z}) & B_{1y} + B_{2y} + B_{3y} + B_{4y} - (B_{5y} + B_{6y} + B_{7y} + B_{8y}) \\ B_{1z} + B_{2z} + B_{3z} + B_{4z} - (B_{5z} + B_{6z} + B_{7z} + B_{8z}) & B_{1y} + B_{2y} + B_{3y} + B_{4y} - (B_{5y} + B_{6y} + B_{7y} + B_{8y}) \\ B_{1z} + B_{2z} + B_{3z} + B_{4z} - (B_{5z} + B_{6z} + B_{7z} + B_{8z}) & B_{1y} + B_{2y} + B_{3y} + B_{4y} - (B_{5y} + B_{6y} + B_{7y} + B_{8y}) \end{bmatrix}.
\]

(14)
4. Simulation Experiment of Magnetic Gradient Full-Tensor Measurement System

4.1. Magnetic Dipole Model. When the distance between the magnetic target point and the observation point is more than 2.5 times the diameter or length of the magnetic target point, the magnetic field generated by the magnetic target point can be equivalent to a magnetic dipole [19–21]. In the process of measuring the magnetic gradient full tensor, the magnetic gradient full-tensor measurement system is often far away from the magnetic target. According to actual experience, a magnetic dipole model can be used to replace the magnetic target for modeling.

As shown in Figure 8, the magnetic dipole model is established. In the Cartesian coordinate system, the position of the magnetic target is \((x_0, y_0, z_0)\), and the position of the observation point \((x, y, z)\) is the axis of the magnetic gradient full-tensor measurement system. The projection components at the observation point of the magnetic anomaly field generated are represented by \(B_x\), \(B_y\), and \(B_z\), which are the three-component magnetic anomaly.

The magnetic anomaly vector field generated by the magnetic target at the observation point is
The magnetic field value of each point can be determined by using the magnetic dipole equation several times. Take Figure 1 as an example to calculate the coordinates of No. 1 to No. 4 fluxgates, as shown in the following equation:

\[
\mathbf{r}_1 = \left(x + \frac{d}{2}, y, z\right), \quad \mathbf{r}_2 = \left(x, y + \frac{d}{2}, z\right),
\]

\[
\mathbf{r}_3 = \left(x - \frac{d}{2}, y, z\right), \quad \mathbf{r}_4 = \left(x, y - \frac{d}{2}, z\right).
\]

In equation (17), \(r_1, r_2, r_3, r_4\) are the position coordinates of No. 1 to No. 4, with point O as the reference point. The magnetic field value of each magnetometer can be obtained, and then the full tensor of the magnetic gradient can be gotten.

4.2. Simulation Experiment. Assuming that the magnetic dipole is located in a vacuum, the position of the magnetic source is \((3, 4, 5)\). The magnetic declination angle \(D = 15^\circ\), the magnetic inclination angle \(I = 30^\circ\), the magnetic moment modulus \(m = 200 A\cdot m^2\), \(m_x = m \cos I \cos d\), \(m_y = m \cos I \sin d\), \(m_z = \sin I\), and the grid area is 20m × 60m. During the sampling process, the attitude of the tensor measurement system is unchanged, and it moves unidirectionally along the x-axis. The sampling interval is set to 1 m; the baseline distance is set to 0.3 m. Taking the cross-shaped magnetic gradient full-tensor measurement system as an example, the comparison between distribution value and theoretical value of tensor is shown in Figure 9. The full-tensor distribution value of the seven structures is shown in Figure 10. In order to highlight the impact of the structural error in measurement system on the tensor measurement, the output values of the three-axis fluxgate are ideal during the simulation.

4.3. Simulation Results and Analysis. It can be seen from Figure 10 that each measurement system can measure the full tensor within the allowable error range, but the error between the tensor value and theoretical value obtained from different structures is different. Among them, the errors of cross, equilateral triangle, right triangle, and square are relatively small. In order to describe the measurement error of tensor more clearly, equation (18) is used to calculate the relative error (RE) of each point in the simulation. In Figure 11, the measurement errors of each point of the measurement system are compared and shown.

\[
RE(i) = f(i) - y(i) (i = 1, 2, 3, \ldots).
\]

In equation (18), \(f(i)\) is the measured value of each point, and \(y(i)\) is the theoretical value of each point. It can be seen from Figure 11(a) that the Bxx measured by the square magnetic gradient full-tensor measurement system has the highest accuracy. Within the range of ±30 nT/m, the maximum measurement error does not exceed 0.02 nT/m. The accuracy of right-angle tetrahedron is the worst, exceeding 2 nT/m. As can be seen from Figure 11(b), the Bxy measured by the cross-shaped magnetic gradient full-tensor measurement system has the highest accuracy. Within the range of ±30 nT/m, the maximum measurement error is not about 0.03 nT/m. The measurement accuracy of the right-angled tetrahedron is the worst, reaching 1.7 nT/m.
It can be seen in Figure 11(c) that the Bxz measured by the cross-shaped magnetic gradient full-tensor measurement system has the highest accuracy. In the range of ±30 nT/m, the maximum measurement error does not exceed 0.02 nT/m. The measurement accuracy of the right-angled tetrahedron is the worst, exceeding 2 nT/m. It can be seen in Figure 11(d) that Byy measured by the cross-shaped magnetic gradient full-tensor measurement system has the highest accuracy. Within the range of ±30 nT/m, the maximum measurement error does not exceed 0.01 nT/m, and the measurement accuracy of the regular hexahedron is the worst, reaching 15 nT/m. From Figure 11, it is basically possible to analyze the pros and cons of the seven measurement systems for each component, and the order from the best to the worst is shown in Table 2.

In order to further test the overall measurement accuracy of each system, equation (19) is used to calculate the root mean square error (RMSE) [22] to quantitatively analyze the overall deviation of the measurement system. The calculated values are shown in Table 3.
Figure 10: Comparison of the measured values of the magnetic gradient full-tensor system with seven structures and theoretical values.
Figure 11: Continued.
Figure 11: Comparison of measured RE of seven magnetic gradient full-tensor systems.

Table 2: Arrangement of magnetic gradient full-tensor measurement system.

| Tensors | Pros and cons |
|---------|---------------|
| $B_{xx}$ (nT/m) | Cross shape | Hexahedron shape | Regular tetrahedron shape | Equilateral triangle shape | Right triangle shape | Right-angle tetrahedron shape |
| $B_{xy}$ (nT/m) | Cross shape | Square shape | Hexahedron shape | Regular tetrahedron shape | Equilateral triangle shape | Right triangle shape | Right-angle tetrahedron shape |
| $B_{xz}$ (nT/m) | Cross shape | Square shape | Hexahedron shape | Regular tetrahedron shape | Equilateral triangle shape | Right triangle shape | Right-angle tetrahedron shape |
| $B_{yz}$ (nT/m) | Cross shape | Square shape | Right triangle shape | Equilateral triangle shape | Right triangle shape | Right-angle tetrahedron shape | Regular tetrahedron shape |
| $B_{xy}$ (nT/m) | Cross shape | Right triangle shape | Square shape | Equilateral triangle shape | Right triangle shape | Right-angle tetrahedron shape | Regular tetrahedron shape |
the highest in the analyzed measurement accuracy. If we select them, the overall measurement accuracy of the cross shape is relatively great errors. Among the right-angled triangle and right-angled tetrahedral measurement systems have relatively high accuracy, while the measurement conditions, the cross-shaped and square measurement systems have smaller structural errors and higher measurement accuracy. In addition, the cross-shaped measurement system has the best overall performance. Of course, in engineering practice, the planar magnetic gradient full-tensor measurement system is easy to install, and the center point of the structure is easier to find. The three-dimensional magnetic gradient full-tensor measurement system can obtain many independent components and can directly obtain the vertical component. The magnetic gradient full-tensor measurement system should be selected to use according to actual needs. The research results in this paper provide a theoretical reference for the construction and application development of the magnetic gradient full-tensor system.

### Data Availability

The data that support the findings of this study are included within the article.

#### Table 3: RMSE comparison of measured values of seven kinds of magnetic gradient full-tensor system.

| Tensor | Cross shape | Equilateral triangle shape | Right triangle shape | Square shape | Regular tetrahedron shape | Right-angle tetrahedron shape | Right triangle shape |
|--------|-------------|----------------------------|----------------------|-------------|---------------------------|------------------------------|---------------------|
| Bxx (nT/m) | 0.0093 | 0.2468 | 0.5652 | 0.0011 | 0.0565 | 0.5652 | 0.0187 |
| Bxy (nT/m) | 0.0066 | 0.1220 | 0.4182 | 0.0101 | 0.1036 | 0.4136 | 0.0133 |
| Bxz (nT/m) | 0.0080 | 0.2923 | 0.4977 | 0.0086 | 0.1366 | 0.4977 | 0.0161 |
| Byx (nT/m) | 0.0090 | 0.1217 | 0.3929 | 0.0164 | 2.9141 | 0.3929 | 7.8728 |
| Byy (nT/m) | 0.0019 | 0.2961 | 0.4736 | 0.0207 | 3.5112 | 0.4736 | 0.0039 |

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (f_i - y_i)^2} \quad (i = 1, 2, 3, ..., n). \quad (19)
\]

In equation (19), \( f_i \) is the measured value of each point, and \( y_i \) is the theoretical value of each point. It can be seen from Tables 2 and 3 that, under the same measurement conditions, the cross-shaped and square measurement systems have relatively high accuracy, while the right-angled triangle and right-angled tetrahedral measurement systems have relatively great errors. Among them, the overall measurement accuracy of the cross shape is the highest in the analyzed measurement accuracy.

#### 5. Conclusion

In this paper, seven magnetic gradient full-tensor measurement system models are studied in detail, and the full-tensor measurement theory of the tensor measurement array is analyzed. The magnetic dipole model is used to simulate the measurement system. Different measurement systems are quantitatively compared and analyzed. The analysis shows that, under the same measurement conditions, the cross-shaped and square measurement systems have smaller structural errors and higher measurement accuracy. In addition, the cross-shaped measurement system has the best overall performance. Of course, in engineering practice, the planar magnetic gradient full-tensor measurement system is easy to install, and the center point of the structure is easier to find. The three-dimensional magnetic gradient full-tensor measurement system can obtain many independent components and can directly obtain the vertical component. The magnetic gradient full-tensor measurement system should be selected to use according to actual needs. The research results in this paper provide a theoretical reference for the construction and application development of the magnetic gradient full-tensor system.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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