Study on the calibration method for tri-axis fluxgate gradiometer

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Abstract. Aiming at the measurement errors caused by non-orthogonality, inconsistent sensitivity, zero-offset of the tri-axis fluxgate sensor and the position misalignment of two fluxgate sensors composed of the gradiometer, this paper establishes the correction model of measurement error of magnetometer and gradiometer, puts forward the comprehensive coefficient method, and uses the non-magnetic turntable to calibrate the Mag648 three-axis magnetometer and gradiometer in the uniform magnetic environment. The experimental results show that the method can reduce the maximum total magnetic field deviation of the two magnetometers from 552.4 nT to 15.0 nT, and reduce the maximum output deviation of the three-component gradiometer from 3891.5 nT to 37.2 nT, which effectively improves the reliability of the three-axis magnetic sensor in measurement.

1. Introduction
The three-axis magnetometer can detect the strength and direction of the magnetic field. It is a magnetic field measuring instrument based on the nonlinear characteristics of the soft magnetic material. Because of its small size, light weight and low power consumption, it is often used as the attitude sensitive device of micro satellite [1]. The gradiometer is mainly composed of two fluxgate tri-axis magnetometers with similar performance. The measured value is the difference between two magnetometers. Compared with a single fluxgate magnetometer, the gradiometer can suppress background magnetic interference to a certain extent [2]. It has a wide range of applications in scientific research, national defense construction, daily life and other fields. In general, due to the limitation of processing technology, the magnetometer will have some problems, such as zero deviation error, inconsistent sensitivity of tri-axis, and the three axes are difficult to be completely orthogonal. In addition, the gradiometer will also cause errors due to the inconsistent placement of two fluxgate magnetometers [3], which will seriously affect their measurement performance. Therefore, it is necessary to be calibrated before using.

At present, the main correction methods for the measurement error of the three-axis magnetometer are as follows: fitting the three-axis magnetic field strength data with ellipsoid surface, and determining the calibration parameters by recurrence method [4]. Analyzing and modeling the measurement results and error sources of the three-axis magnetometer, establishing the calibration model of the three-axis magnetometer [5]. Estimating and modifying the parameters of the model by the least square algorithm [6]. Estimating calibration parameter of three-axis magnetometer based on the genetic algorithm and particle swarm optimization algorithm [7]. The gradiometer is composed of two magnetometers, its calibration method is mainly to calibrate a single magnetometer, or to correct the errors caused by the inconsistency of the two magnetometers by coordinate transformation.
In this paper, the error characteristics and properties of the three-axis magnetometer and its gradiometer are analyzed, the measurement error correction model is established, and the comprehensive coefficient method is proposed. In the uniform magnetic environment, the fluxgate magnetometer is put into a stable and evenly distributed physical field by using the non-magnetic turntable, and some groups of data are measured at the same point in different directions, and the corresponding error compensation coefficients are calculated respectively, so the corrected magnetic field results are obtained. Finally, this method was used to calibrate Mag648 three-axis magnetometer and its gradiometer, and the error calibration of magnetometer and gradiometer was completed quickly and accurately.

2. Error analysis
The error of fluxgate magnetometer is caused by many factors. According to the characteristics and properties of the error, the error of three-axis magnetometer can be divided into three kinds: system error, random error and coarse error, in which the system error can be compensated.

2.1 Zero position error
Due to the influence of the processing technology of the magnetometer, the output value of the magnetometer is not zero under the condition of zero magnetism. When only the zero position error caused by core remanence and circuit drift is considered, the relationship between the output of the three-axis magnetometer and the ideal output is as follows:

$$\begin{bmatrix}
    B_{x1} \\
    B_{y1} \\
    B_{z1}
\end{bmatrix} = \begin{bmatrix}
    B_x \\
    B_y \\
    B_z
\end{bmatrix} + \begin{bmatrix}
    B_{x0} \\
    B_{y0} \\
    B_{z0}
\end{bmatrix}$$

$$\begin{bmatrix}
    B_{x1} \\
    B_{y1} \\
    B_{z1}
\end{bmatrix} = \begin{bmatrix}
    K_x & 0 & 0 \\
    0 & K_y & 0 \\
    0 & 0 & K_z
\end{bmatrix}\begin{bmatrix}
    B_x \\
    B_y \\
    B_z
\end{bmatrix}$$

$$\begin{bmatrix}
    B_{x1} \\
    B_{y1} \\
    B_{z1}
\end{bmatrix} = \begin{bmatrix}
    0 & 0 & K_x \\
    0 & K_y & 0 \\
    K_z & 0 & 0
\end{bmatrix}\begin{bmatrix}
    B_x \\
    B_y \\
    B_z
\end{bmatrix}$$

2.2 Sensitivity error
In an ideal state, the sensitivity of the three magnetic sensing elements and their excitation circuits of the three-axis magnetometer should be the same. However, due to the difference in manufacturing process, the sensitivity of the three coordinate axes is different. If the sensitivity of the three axes is $K_x$, $K_y$ and $K_z$ respectively, when there is a difference in sensitivity, the actual measurement results of the three coordinate axes of the three-axis magnetometer are:

2.3 Orthogonal error
Due to the limitation of processing technology, the three coordinate axes of the ideal three-axis magnetometer do not coincide with the actual one. Moreover, the three coordinate axes of the three-axis magnetometer are usually difficult to be completely orthogonal.

Figure 1. Schematic diagram of measurement coordinate system and reference orthogonal coordinate system.
As shown in Figure 1, the three axes of the magnetometer are \(X_1, Y_1,\) and \(Z_1\) respectively, and the corresponding output signals are \(B_{x1}, B_{y1}\) and \(B_{z1}\) respectively. Let the orthogonal coordinate system be \(X, Y, Z.\) Because the three axes of the magnetometer are not orthogonal, assume that the angles between the axes \(X_1\) and \(X, Y, Z\) are \(\alpha_x, \alpha_y, \alpha_z;\) the angles between the axes \(Y_1\) and \(X, Y, Z\) are \(\beta_x, \beta_y, \beta_z;\) the angles between the axes \(Z_1\) and \(X, Y, Z\) are \(\gamma_x, \gamma_y, \gamma_z.\) When only the orthogonal errors of the magnetometer are considered, the output signals of the magnetometer are:

\[
\begin{bmatrix}
B_{x1} \\
B_{y1} \\
B_{z1}
\end{bmatrix} =
\begin{bmatrix}
\cos \alpha_x & \cos \alpha_y & \cos \alpha_z \\
\cos \beta_x & \cos \beta_y & \cos \beta_z \\
\cos \gamma_x & \cos \gamma_y & \cos \gamma_z
\end{bmatrix}
\begin{bmatrix}
B_x \\
B_y \\
B_z
\end{bmatrix}
\]

Ideally, \(\alpha_x = \beta_y = \gamma_z = 0, \ \alpha_y = \alpha_x = \beta_z = \gamma_x = \gamma_y = 90^\circ.\)

2.4 Position error

The error is mainly for gradiometer. Because the gradiometer is composed of two three-axis magnetometers with similar performance, assuming that each magnetometer is calibrated and belongs to the ideal type, the error of gradiometer is mainly caused by the placement of two magnetometers. Taking one magnetometer as the measurement reference, the output signal of the second magnetometer is consistent with the orthogonal error output form.

3. Calibration method

In order to facilitate error compensation, the commonness of various factors affecting the error is analyzed, and the expression of the commonness is obtained. According to the above error analysis, these influences can be summarized into two situations mathematically:

- In the calibration calculation, it is equivalent to multiplying matrix \(B,\) which composed of \(B_x, B_y\) and \(B_z\) by a matrix of three times three. The elements on the diagonal of the matrix are close to 1, and the values of elements on the non-diagonal are near 0, such as the orthogonal error, sensitivity error and position error of gradiometer.
- In calibration calculation, it is equivalent to adding a constant to \(B_x, B_y\) and \(B_z\) respectively, such as zero position error.

Considering the orthogonal error, sensitivity error, zero position error and position error, the relationship between the output of magnetometer and the ideal output can be expressed as follows:

\[
B_1 = A \cdot B + B_0 \tag{4}
\]

Where \(B_1 = \begin{bmatrix} B_{x1} \\ B_{y1} \\ B_{z1} \end{bmatrix}, \ A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}, \ B = \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}, \ B_0 = \begin{bmatrix} B_{x0} \\ B_{y0} \\ B_{z0} \end{bmatrix}, \ B_1\) is the output result, \(B\) is the ideal measurement result, \(A\) and \(B_0\) are the coefficients to be measured, and \(B_{x0} = 0\) for the gradiometer. The advantage of this method is that it can calibrate the errors of triaxial magnetometer and gradiometer quickly and accurately, without considering the single factors, which reduces the calibration time and improves the efficiency.

In this case, matrix \(A\) and \(B_0\) are obtained from multiple sets of measurement data, and matrix \(B\) is obtained from the values of matrix \(A\) and \(B_0\) from another set of measurement data. When the coefficient matrix is determined, we can get:

\[
B = A^{−1}B_0A^{−1} \tag{5}
\]

In order to eliminate the system error, the key is to solve the element values of matrix \(A\) and \(B_0.\) In order to improve the accuracy of measurement and reduce the influence of random error, the matrix \(A\) and \(B_0\) are solved by the principle of least square method.
4. Experimental verification

Place the calibration system in the stable and evenly distributed laboratory, fix the gradiometer composed of three-axis magnetometer on the non-magnetic turntable, use the potassium optical pump magnetometer to monitor the background field, record 24 groups of data measured in different directions through the rotating turntable at the same point, and calculate the corresponding error compensation coefficient respectively. According to the formula (4) and (5), calculate the corresponding error compensation coefficient respectively. The whole process of error compensation coefficient is shown in Figure 2.

![Figure 2. Verification experiment](image)

4.1 Calibration of tri-axis magnetometer

Firstly, two magnetometers, No. 1 and No. 2, which make up the gradiometer, are calibrated. The coefficients $A$ and $B_0$ of the two are calculated by the comprehensive coefficient method. The coefficients of No. 1 magnetometer are as follows:

$$
A = \begin{bmatrix}
0.975499 & -0.143540 & -0.146500 \\
0.145060 & 0.986456 & 0.025568 \\
0.147589 & -0.045840 & 0.987140 \\
\end{bmatrix},
B_0 = \begin{bmatrix}
32.62039 \\
21.38123 \\
35.51766 \\
\end{bmatrix}.
$$

The coefficients of No. 2 magnetometer are as follows:

$$
A = \begin{bmatrix}
0.993664 & -0.063040 & 0.043400 \\
0.071869 & 0.996171 & -0.019500 \\
0.038840 & 0.005231 & 0.996819 \\
\end{bmatrix},
B_0 = \begin{bmatrix}
-116.6620 \\
-102.8250 \\
75.71142 \\
\end{bmatrix}.
$$

The calibration results of the two magnetometers are shown in Figure 3. Where (a) is the total magnetic field calibration result of No. 1 magnetometer and (b) is the total magnetic field calibration result of No. 2 magnetometer.

![Figure 3. Comparison of calibration results of total magnetic field.](image)

As can be seen from the above figure, the measured value of the uncalibrated magnetometer fluctuates greatly, reaching a maximum of 552.4 nT. After calibration by the comprehensive
coefficient method, the measurement deviation is reduced by two orders of magnitude, and the
maximum fluctuation is within 15 nT, which is almost consistent with the real value.

4.2 Gradiometer calibration
Fluxgate gradiometer is mainly composed of two fluxgate sensors with similar performance. The
measured value is the difference between the two magnetic sensors. In Section 3.1, the No.1 and No.2
magnetometers are calibrated. At the same time, the position error of gradiometer is calibrated, and the
coefficient $A$ to be measured is calculated:

$$
A = \begin{bmatrix}
0.980339 & -0.029510 & -0.196840 \\
0.040454 & 0.997740 & 0.052478 \\
0.194338 & -0.059370 & 0.979027 \\
\end{bmatrix}
$$

The calibration results of gradiometer are shown in Figure 4. Where (a), (b) and (c) are the
calibration results of gradiometer in x, y and z directions respectively.

Figure 4. Comparison of calibration results of gradient component.

It can be seen from the above figure that before the gradiometer is calibrated, the measurement
deviation in all directions is very large, and the maximum fluctuation reaches 3891.5 nT/m. after
calibration, the measurement accuracy of the gradient component of the magnetic field is improved by three orders of magnitude, and the maximum deviation is not more than 37.2 nT/m, which proves the effectiveness of the algorithm, and the result fails to achieve the calibration effect of absolute 0. The main reason may be that the fluxgate probe is rotating. The induced magnetic field is produced, and there is a certain gradient difference of magnetic field in the actual measurement site.

5. Conclusion
In this paper, the measurement errors of three-axis magnetometer and its gradiometer are analyzed. According to the characteristics and properties of the errors, the error correction model and correction algorithm are established. In the uniform magnetic environment, the gradiometer is calibrated by a non-magnetic turntable. The experimental results show that the method is effective. In addition, the method can also be used to calibrate multiple magnetometer arrays. The whole process does not need to consider too many error interference factors, so it has high accuracy and practicability.

References
[1] Zhang, R., Zhu, Z.C., Zhang, J., et al. (2006) Microsatellite attitude determination based on magnetometer. Journal of Astronautics, 27(4):578-581.
[2] Ripka, P. (2006) Advances in fluxgate sensors. Sensors & Actuators A Physical, 129(1-2): 86-93.
[3] Ren, Y., Wang, Y., Wang M., et al. (2014) A Measuring system for well logging attitude and a method of sensor calibration. Sensor, 14(5):9256-9270.
[4] Sheng, W., Jiang, Y. (2015) A non-line calibration method of three-axis magnetic sensor system. Journal of Projectiles, Rockets, Missiles and Guidance, 35(3):179-182.
[5] Hao, D., Sheng, T., Chen, X.Q. (2011) The error correction of three-axis magnetometer measurement. Spacecraft Environment Engineering, 28(5):463-466.
[6] Alonso, R., Shuster, M.D. (2002) Complete linear attitude-independent magnetometer calibration. Journal of the Astronautical Sciences, 50(4):477-490.
[7] Eugnhyun, K. (2011) Attitude-independent magnetometer calibration considering magnetic torquer coupling effect. Journal of Spacecraft and Rockets, 48(4):691-694.