Correction of a Towed Airborne Fluxgate Magnetic Tensor Gradiometer

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***Abstract*—The small impact of the geomagnetic field enables a magnetic tensor gradiometer to be easily installed on the flight platform for airborne geophysical exploration, especially for the detection of shallow buried mines and magnetic moving targets. Using the fluxgates as the core components, the gradiometer has the advantages of wide temperature range, low cost, and high resolution, but has the disadvantage of relatively low accuracy. This is because of the scale factor error, the nonorthogonal error, the misalignment, the zero offset, the dynamic error in a fluxgate, and the inconsistency among the error of fluxgates. In this letter, a correction method for a towed airborne magnetic tensor gradiometer is proposed that is composed of four fluxgates arranged in a cross-shaped structure. The theoretical framework of the proposed method is based on the static error model and the dynamic characteristics of single fluxgate, the feature that the gradient tensor of the geomagnetic field at high altitude is approximately zero, and on the phenomenon that the unchanged tensor rotation as a result of nonuniform magnetic field on the ground can indicate the inconsistency of the scale factors among different tensor components. The actual flight results using a helicopter have demonstrated and validated the performance and effectiveness of the proposed method. The improvement ratios of the field tensor components are from 359.6 to 1765, and the RMS of each component has reached to the level of 1 nT/m.**

***Index Terms*—Airborne, correction, fluxgate, invariant, magnetic tensor gradiometer.**

I. Introduction

MAGNETIC tensor gradiometer is used for measuring the spatial derivatives of three magnetic field components. Compared with the vector magnetometer, the magnetic tensor gradiometer is not extremely sensitive to the geomagnetic field [1]. This property makes the magnetic tensor gradiometer immensely suitable for deployment on a flight platform while conducting an airborne geophysical survey. The magnetic tensor gradiometer has high target resolution [2] and the capability of collecting detailed information, which makes it particularly suitable for purposes such as detection of shallow buried mines and investigation of moving magnetic targets [3], [4].

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The first-order Taylor series expansion method is commonly used in the magnetic full-tensor gradiometer because it is easy to implement and is capable of obtaining the full tensor information. There are two types of tensor gradiometers available to meet the requirements of high-resolution and direction-sensitive sensors.

The first type is the superconducting magnetic tensor gradiometer, such as the airborne magnetic tensor gradiometer in Germany, which has achieved RMS noise levels of less than 10 pT/m with a 4.5-Hz bandwidth [5], the glass earth tensor magnetic airborne gradiometer [6], and its helicopter-borne trial system, which has gradient tensor components with sensitivities down to 50 pT/m at a sampling rate of 10 Hz [7]. The superconducting gradiometer is expensive and difficult to be used at ordinary temperature level despite having high sensitivity.

The second type is the fluxgate magnetic tensor gradiometer including the following instruments: the tetrahedral fluxgate magnetic tensor gradiometer developed by the U.S. Geological Survey [8], the three-sensor gradiometer developed by IBM [9], the multiple magnetic tensor gradiometer system for locating unexploded ordnance [10], the compact fluxgate tensor gradiometer jointly developed by European countries including Britain, Netherlands, and Germany to remove the magnetic interference of the spacecraft for the gravitational wave measurement [11], and the compact fluxgate magnetic full-tensor gradiometer with a spherical feedback coil [12].

The fluxgate magnetic tensor gradiometer has advantages such as low cost and wide temperature range, but it also has a downside of low precision, which brings up the correction requirement of the gradiometer before the production measurement.

The general method is to find a uniform magnetic field on the ground and solve linear and/or nonlinear equations under the conditions of equal total fields and/or equal magnetic field components measured by the multiple fluxgates for obtaining the correction coefficients [13]–[16]. In general, the RMS errors of magnetic gradient tensor components after the calibration can reach up to about 10–25 nT/m. This method has three major problems. First, a single tensor component is equal to zero in a uniform magnetic field, which is a necessary but not a sufficient condition for the correction of the tensor gradiometer. It cannot ensure the correctness of the single component under the nonzero magnetic gradient condition and the consistency of the scale factor among different tensor components. Second, it is difficult to reproduce the dynamic characteristics of fluxgates in the flight process, which implies that it is almost impossible to identify the inconsistency in the dynamic characteristics of multiple fluxgates. Since the measurement of airborne magnetic gradient tensor is motion dependent, the inconsistency of the dynamic characteristics leads to moving noise that is one of the reasons for the drop in the magnetic detection signal. Third, the magnetic abnormality on the ground is always severe in or near the actual measurement area, which makes it difficult to find a uniform magnetic field for the correction.

In this letter, the authors have proposed a correction method of the towed airborne magnetic tensor gradiometer that is composed of four fluxgates arranged in a cross-shaped structure. First, the models are established for the scale factor error, the nonorthogonal error, the misalignment, the zero offset, the dynamic error in each single fluxgate, and the inconsistency among the errors of the fluxgates. Then the correction is carried out by utilizing the feature that the gradient tensor of the geomagnetic field at high altitude is approximately zero and the phenomenon that the unchanged tensor rotation in nonuniform magnetic field on the ground can indicate the consistency of the scale factor among different tensor components, which can be used to calculate the uncertain scale factor of each tensor component after the high-altitude correction. Finally, the performance of the proposed method is demonstrated using the actual flight on a helicopter. The characteristics of the proposed method are that the identification of the static and the dynamic errors is adequately covered during the high-altitude correction and the inconsistency of the scale factor among different tensor components is overcome during the ground invariant correction. Therefore, the proposed method does not require finding a uniform magnetic field on the ground and matches easily to the geological conditions of the conventional aeromagnetic survey.

II. Cross-Shaped Fluxgate Magnetic Tensor Gradiometer

Let $\boldsymbol{B}$ be the magnetic induction vector with three components B_x, B_y, and B_z. The magnetic gradient tensor G is composed of the spatial rate of change of the three magnetic field components along the x, y, and z directions, resulting in G having nine components. Since the magnetic tensor gradiometer is primarily used for the quasi-static field measurement in air or free space, where the conduction and the convection currents are absent and the displacement currents are negligible, $\nabla \cdot \boldsymbol{B}$ and $\nabla \times \boldsymbol{B}$ are equal to zero, which indicates that only five components of the gradient tensor are independent. G can be expressed by

$$G = \begin{pmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_y}{\partial x} & \frac{\partial B_z}{\partial x} \\ \frac{\partial B_x}{\partial y} & \frac{\partial B_y}{\partial y} & \frac{\partial B_z}{\partial y} \\ \frac{\partial B_x}{\partial z} & \frac{\partial B_y}{\partial z} & \frac{\partial B_z}{\partial z} \end{pmatrix} = \begin{pmatrix} g_{xx} & g_{yx} & g_{zx} \\ g_{yx} & -(g_{xx}+g_{zz}) & g_{yz} \\ g_{xz} & g_{yz} & g_{zz} \end{pmatrix}. \quad (1)$$

In the cross-shaped fluxgate magnetic tensor gradiometer shown in Fig. 1, the coordinates of the fluxgates are $o_i x_i y_i z_i (i = 0\text{–}3)$. The coordinates of the inertial navigation system are $oxyz$. Fluxgates 0 and 2 placed on the x-axis of the coordinate system $oxyz$ are origin symmetric with the baseline distance of Δx. Fluxgates 1 and 3 similarly placed on the z-axis with the baseline distance of Δz. By representing each magnetic gradient tensor component through the difference approximation, the magnetic gradient tensor G in the inertial navigation coordinate system can be expressed as

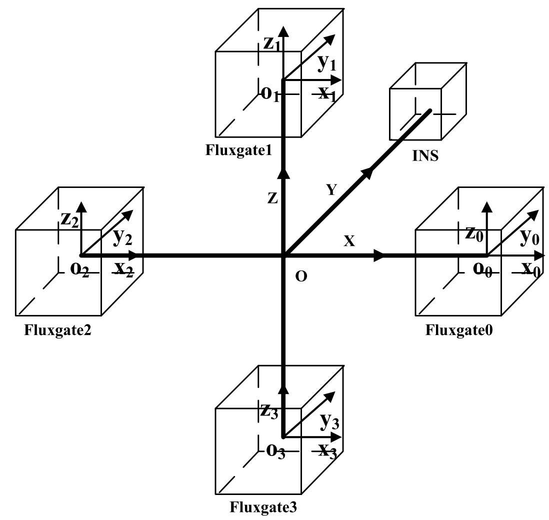

Fig. 1. Structure scheme of the cross-shaped fluxgate magnetic tensor gradiometer.

$$G = \begin{bmatrix} \frac{B_{0x}-B_{2x}}{\Delta x} & \frac{B_{0y}-B_{2y}}{\Delta x} & \frac{B_{0z}-B_{2z}}{\Delta x} \\ \frac{B_{0y}-B_{2y}}{\Delta x} & -\left(\frac{B_{0x}-B_{2x}}{\Delta x}+\frac{B_{1z}-B_{3z}}{\Delta z}\right) & \frac{B_{1y}-B_{3y}}{\Delta z} \\ \frac{B_{1x}-B_{3x}}{\Delta z} & \frac{B_{1y}-B_{3y}}{\Delta z} & \frac{B_{1z}-B_{3z}}{\Delta z} \end{bmatrix}. \quad (2)$$

III. Error Model of Fluxgate Magnetic Tensor Gradiometer

A. Error Model of a Single Fluxgate

The static error of a single fluxgate includes the scale factor error, the nonorthogonal error, the misalignment, and the zero offset, which also exist in SQUID vector magnetometers [17]. In addition, the fluxgate itself has a certain dynamic characteristic. These accumulated errors and the inconsistency of these errors are the causes of the error of the fluxgate magnetic tensor gradiometer. Therefore, the error model of a single fluxgate is modeled at first.

After the rigid connection between the inertial navigation system and the fluxgate magnetic tensor gradiometer, the coordinate axis of each fluxgate coordinate system is aligned to the coordinate axis of the inertial navigation coordinate system. The error model of a single fluxgate is as follows [18]:

$$\boldsymbol{D}_j \frac{d^j \boldsymbol{T}}{dt^j} + \boldsymbol{D}_{j-1} \frac{d^{j-1} \boldsymbol{T}}{dt^{j-1}} + \cdots + \boldsymbol{D}_1 \frac{d\boldsymbol{T}}{dt} + \boldsymbol{D}_0 \boldsymbol{T} = \boldsymbol{F}\boldsymbol{E}\boldsymbol{M}^{-1}\boldsymbol{B} + \boldsymbol{R} + \boldsymbol{\Phi} \quad (3)$$

$$g_{uv} = \frac{\Delta B_u}{\Delta s_v} = \frac{b_{nu} - b_{mu}}{\Delta s_v} = \frac{\left(\boldsymbol{P}_{nu0}\boldsymbol{T}_n + \sum_{j=1}^{h}\frac{d^j\boldsymbol{Q}_{nuj}\boldsymbol{T}_n}{dt^j} + O_{nu}\right) - \left(\boldsymbol{P}_{mu0}\boldsymbol{T}_m + \sum_{j=1}^{h}\frac{d^j\boldsymbol{Q}_{muj}\boldsymbol{T}_m}{dt^j} + O_{mu}\right)}{\Delta s_v} \tag{6}$$

where $\boldsymbol{F}$ is the scale factor error matrix; $\boldsymbol{E}$ is the nonorthogonal error matrix; $\boldsymbol{R}$ is the zero offset vector; $\boldsymbol{M}$ is the misalignment matrix between the fluxgate coordinate system and the inertial navigation coordinate system; $\boldsymbol{D}_j$ is in front of the jth-order derivative of the fluxgate measured value versus the time, i.e., the description matrix of dynamic characteristics; $\boldsymbol{T}$ is the measured value of the fluxgate in its measurement coordinates; $\boldsymbol{B}$ is the true magnetic field in the fluxgate position in the inertial navigation coordinate system; and Φ is the measurement noise of the fluxgate.

The error model of the three-axis fluxgate is rewritten as the correction model

$$\boldsymbol{B} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} = \boldsymbol{C}_0\boldsymbol{T} + \sum_{j=1}^{h}\frac{d^j\boldsymbol{C}_j\boldsymbol{T}}{dt^j} + \boldsymbol{O} \tag{4}$$

where $\boldsymbol{C}_j$ is the correction matrix for the jth-order derivative of $\boldsymbol{T}$; h is the highest order of derivative of $\boldsymbol{T}$ and varies from one fluxgate to the next; $\boldsymbol{O}$ is the correction vector for the zero offset; and b_x, b_y, and b_z are the three true components of the magnetic field in the inertial navigation coordinate system. The correction model for the single magnetic field component can be expressed as

$$b_u = \boldsymbol{P}_{u0}\boldsymbol{T} + \sum_{j=1}^{h}\frac{d^j\boldsymbol{Q}_{uj}\boldsymbol{T}}{dt^j} + O_u \tag{5}$$

where u is one of the x-, y-, and z-axes; $\boldsymbol{P}_{u0}$ is the row vector corresponding to b_u in the correction matrix $\boldsymbol{C}_0$; $\boldsymbol{Q}_{uj}$ is the row vector corresponding to b_u in the correction matrix $\boldsymbol{C}_j$; and O_u is the coefficient corresponding to b_u in the correction vector $\boldsymbol{O}$.

B. Error Model of the Fluxgate Magnetic Tensor Gradiometer

In terms of the cross-shaped fluxgate magnetic tensor gradiometer, one of the true gradient tensor components in the inertial navigation coordinate system can be expressed as (6), shown at the top of the page, where m and n are the fluxgate labels, taking 0–3; u and v are the coordinate axes, taking x, y, and z; g_{uv} is a tensor component; ΔB_u is the variation of the magnetic field along the u-axis; and Δs_v is the baseline distance between the fluxgate n and m.

Suppose that O_{uv} is the zero offset of the tensor component g_{uv}, the described correction model of the tensor component can be further rewritten as

$$g_{uv} = \boldsymbol{P}_{nu0}\frac{\boldsymbol{T}_n}{\Delta s_v} - \boldsymbol{P}_{mu0}\frac{\boldsymbol{T}_m}{\Delta s_v} + \sum_{j=1}^{h}\left(\frac{d^j\boldsymbol{Q}_{nuj}\frac{\boldsymbol{T}_n}{\Delta s_v}}{dt^j} - \frac{d^j\boldsymbol{Q}_{muj}\frac{\boldsymbol{T}_m}{\Delta s_v}}{dt^j}\right) + O_{uv}. \tag{7}$$

IV. Correction Method of Fluxgate Magnetic Tensor Gradiometer

A. Correction of the Magnetic Gradient Tensor Components at High Altitude

The magnetic gradient tensor of the geomagnetic field is approximately zero at high altitude (order of magnitude of pT/m). Let p_{uv} be the correction coefficient of the measured values along the u-axis of the fluxgate n. The mentioned correction model of the gradient tensor component can be rewritten as

$$\frac{g_{uv}}{p_{uv}} = \frac{\boldsymbol{P}_{nu0}}{p_{uv}}\frac{\boldsymbol{T}_n}{\Delta s_v} - \frac{\boldsymbol{P}_{mu0}}{p_{uv}}\frac{\boldsymbol{T}_m}{\Delta s_v} + \sum_{j=1}^{h}\left(\frac{d^j\frac{\boldsymbol{Q}_{nuj}}{p_{uv}}\frac{\boldsymbol{T}_n}{\Delta s_v}}{dt^j} - \frac{d^j\frac{\boldsymbol{Q}_{muj}}{p_{uv}}\frac{\boldsymbol{T}_m}{\Delta s_v}}{dt^j}\right) + \frac{O_{uv}}{p_{uv}} = 0. \tag{8}$$

Thus, there must be a certain correction coefficient that equals to one after dividing (12) by p_{uv} and the corresponding measured value becomes the known value of the linear equation in (8). All the coefficients in (8), namely, $((\boldsymbol{P}_{nu}0)/(p_{uv}))$, $((\boldsymbol{P}_{mu}0)/(p_{uv}))$, $((\boldsymbol{Q}_{nuj})/(p_{uv}))$, $((\boldsymbol{Q}_{muj})/(p_{uv}))$, and $((O_{uv})/(p_{uv}))$, can be obtained using the least squares method to solve the equations.

B. Correction of Tensor Rotation Invariant on the Ground

The relative value of each tensor component is gained after the high-altitude correction and can be expressed as

$$g_{uv_{\text{mid}}} = \frac{g_{uv}}{p_{uv}}. \tag{9}$$

Since each gradient tensor component corresponds to different correction coefficients p_{uv}, the inconsistency of scale factor exists in the tensor components. One of the tensor rotation invariants C_T can be obtained by tensor contraction. Its characteristic is that the value remains constant during the coordinate rotation. When inconsistency of scale factor exists in the tensor components, the C_T demonstrates a distinct variation and can be used to correct it.

The correction model of the magnetic tensor component is re-expressed as

$$g_{uv} = p_{uv}g_{uv_{\text{mid}}}. \tag{10}$$

Then, the correction model of the tensor invariant can be expressed as

$$C_T^2 = \sum_{u,v=(x,y,z}g_{uv}^2 = \sum_{u,v=(x,y,z)}p_{uv}^2g_{uv_{\text{mid}}}^2. \tag{11}$$

The steps in the correction method are as follows.

1) Rotate the magnetic tensor gradiometer around its origin of coordinates in the nonuniform magnetic field on the ground and record the measurements.

2) Correct the measurements in accordance to the correction coefficients obtained at high altitude and obtain the corresponding $g_{uv_{\text{mid}}}$.
3) Set the correction coefficient p_{uv} in (11) as one, then calculate the C_Ts, and average them.
4) Consider the average of C_T and the $g_{uv_{\text{mid}}}$ as the known value in (11) and estimate p_{uv} using the generalized least squares fitting.
5) According to the correction coefficients obtained at high altitude and the estimated p_{uv}, all correction coefficients of each tensor component can be obtained, namely, $\boldsymbol{P}_{nu0}$, $\boldsymbol{P}_{mu0}$, $\boldsymbol{Q}_{nuj}$, $\boldsymbol{Q}_{muj}$, and O_{uv}.

The correction method based on the rotation invariant is similar to the ellipsoid fitting correction method of magnetometers [19], because the key to both methods is utilizing the invariant to form the constraint. The difference between the two methods is that the total field is the invariant in the magnetometer's correction and the tensor contraction is the invariant in the correction of the magnetic tensor gradiometer. In addition, there are two points to be noted.

1) The rotation invariant-based correction can be implemented only in a situation when the magnetic gradient tensor is not equal to zero. In most of the actual geological conditions of the conventional aeromagnetic survey, the magnetic field on the ground is nonuniform, which means that the magnetic gradient tensor exists and the condition of this method can be easily met.
2) The condition of taking the p_{uv} as one is that the magnetic tensor gradiometer is not affected by the magnetic interference of the aircraft. For example, the towed magnetic tensor gradiometer adopted in this letter can maintain safe distance from the aircraft. In this case, according to the different error matrices in (3), the achieved matrix in the correction model resembles the identity matrix and the p_{uv}s are elements on the primary diagonal. Therefore, the p_{uv} is approximately equal to one. Obviously, this method is limited by the manufacturing and installation levels of sensors. With modern technology, the nonorthogonal and the misalignment angles are generally within 1°, which can ensure the validation of the condition.

V. Flight Experiment

A. Experimental Design

The site for the flight experiment is chosen in Wudalianchi, Heilongjiang Province, China. Since the site is close to a volcano, the magnetic field on the ground is nonuniform. The fluxgate magnetic tensor gradiometer consists of four three-component fluxgates (Mag629 made by the British Bartington Company) installed in a cross-shaped structure. The frequency response of the sensor is flat from dc to 100 Hz. The baseline distance between two opposite fluxgates of each pair is 10 cm. The NI CompactRIO architecture is used as the data acquisition system. In addition, a GPS-enhanced attitude and heading reference system is used as the aided measuring devices that measure six degrees of freedom of the magnetic tensor gradiometer as 40 samples/s. The sampling rate of the gradiometer is also 40 samples/s after averaging the actual samples to match the aided measuring devices.

The fluxgate magnetic tensor gradiometer is installed in a cylindrical towed bird made from glass-fiber reinforced plastic. The towed bird is hung up far from the helicopter (Eurocopter AS350b3) with a lightweight high-strength 35-m-long rope. Once the helicopter reaches the altitude of 1000 m, the helicopter follows a preset rectangular shaped flight path maintaining the specified altitude to accomplish the high-altitude correction. After the helicopter is landed, the fluxgate magnetic tensor gradiometer is taken out of the towed bird and is rotated around its center at the height of 1 m above the ground to accomplish the invariant correction. Fig. 2 shows the photograph taken by an aerial photography

Fig. 2. Photograph of the fluxgate magnetic tensor gradiometer towed by the helicopter in the flight experiment.

TABLE I
RMSs of Six Tensor Components and C_T Before and After Correction

	Before correction (nT/m)	After correction (nT/m)	Improvement ratio
g_{xx}	1543	0.874	1765
g_{yx}	359.3	0.686	523.7
g_{zx}	517.5	1.000	517.5
g_{xz}	600.6	0.808	743.3
g_{yz}	481.3	1.302	369.6
g_{zz}	277.6	0.772	359.6
C_T	24553.7	2.400	10230.7

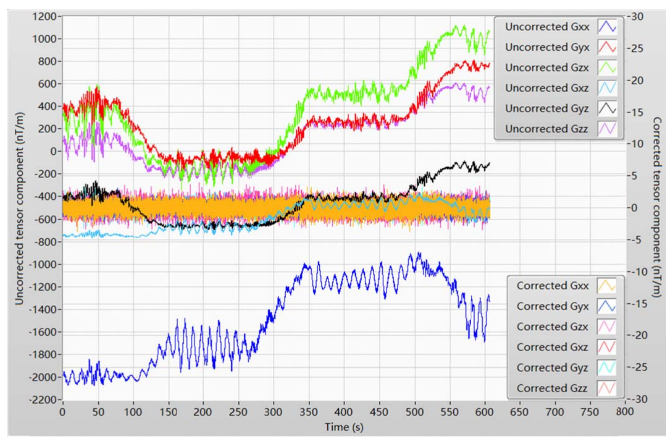

Fig. 3. Comparison of the tensor components before and after the correction on the high-altitude flight path (two separate scales are shown for the vertical axis to improve the information on the figure).

apparatus installed on the landing gear of the helicopter during the flight experiment.

B. Experimental Results

The comparison of the tensor components before and after the correction on the high-altitude flight path is shown in Table I and Fig. 3. The RMS of each tensor component reaches about 1 nT/m, and the improvement ratios range from 359.6 to 1765. The performance of the tensor rotation invariance is also shown in Table I.

VI. CONCLUSION

The fluxgate magnetic tensor gradiometer has the advantages of low price, lightweight, and wide temperature range, but has low accuracy because there are many factors that can cause the error. Therefore, substantial correction is essential, especially in the airborne survey application where the quick motion transforms error into noise that completely submerges the useful signal. The proposed correction method makes full use of the characteristics that the magnetic gradient tensor at high altitude is approximately zero and the invariants are constant by rotating around its center in nonzero magnetic gradient area on the ground. These characteristics ensure the integrity and the correctness of the proposed correction method and are also in good agreement with the geological conditions of the conventional aeromagnetic survey. In view of the fact that other fluxgate tensor gradiometers with different structures as well as the airborne magnetic full-tensor SQUID gradiometers have similar error factors, the proposed method can be applied to these systems after slight modifications.

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