Application of an Improved Calibration Flight Scheme in Aeromagnetic Interference Compensation

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Abstract In aeromagnetic measurement, accurate compensation for the interference magnetic field generated by the aircraft platform due to the aircraft maneuvering in the Earth's magnetic field is an important prerequisite for the accurate identification of the magnetic anomaly signal of the detection target. The flaws of the traditional calibration flight scheme in aeromagnetic interference compensation are firstly analyzed, and then an improved scheme is proposed, featuring smaller calibration flight areas, more simplified maneuvers, shorter flight route and less influence from the magnetometer's direction and extreme weather. The improved scheme can enhance the robustness of the aeromagnetic interference compensation matrix and improve the compensation efficiency, and thus both the solved magnetic compensation coefficients and compensation effects are significantly improved. The experimental results of the aeromagnetic interference compensation in an area of Inner Mongolia of China show that the average accuracy of the repeated survey lines, which are compensated by the improved scheme, can be increased by 5 and 3 nT, respectively, compared with the uncompensated results and the results compensated by the traditional scheme. Therefore, the effectiveness and superiority of the improved calibration flight scheme is fully proved.

Plain Language Summary Aeromagnetic measurement technology is the most economical and effective technical means to obtain high-precision and high-resolution geomagnetic information. Because the aircraft used in aeromagnetic measurement is composed of ferromagnetic materials, it will produce an interference magnetic field when maneuvering in the Earth's magnetic field. In order to obtain pure geomagnetic field measurement data, it is necessary to compensate the interference magnetic field. The traditional calibration flight scheme is widely used in the aeromagnetic interference compensation, and has played an important role in the existing aeromagnetic measurement. However, with the continuous improvement of the measurement accuracy of airborne magnetometers, there are higher requirements for calibration, and some defects of the traditional calibration flight scheme are found in practice. Hence, an improved calibration flight scheme is proposed in this paper, which features smaller calibration area, shorter flight route, simplified maneuvers and less influence from the direction of the magnetometer. The experimental results show that the modified scheme can improve the average accuracy of repeated survey lines by 3 nT compared with the traditional one. Therefore, the improved scheme can be directly applied in the aeromagnetic interference compensation of scalar, vector and gradient magnetic measurement of manned and unmanned aerial vehicle (UAV).

1. Introduction

The aeromagnetic measurement technology, which can be implemented in areas difficult for ground magnetic measurement, such as desert, glacier, virgin forest and land-sea junction, is one of the most effective means to quickly and economically obtain high-precision geomagnetic data. It has important applications in the fields of geomagnetic navigation background field construction, mineral resources development, seismogenic sources tracking, hidden tectonic and volcanic structures revealment, etc. (Beamish & White, 2011; De Ritis et al., 2010; Goodge & Finn, 2010; Hood, 2007; Liu et al., 2018, 2021; Minelli et al., 2016).

For aeromagnetic measurement, whether the flight platform is manned or unmanned, the aircraft itself is a complex magnetic interference body due to the ferromagnetic substance and various electronic components contained in the aircraft (Argast et al., 2010; Gopal et al., 2004; Groom et al., 2004; Hardwick, 1984; Naprstek & Lee, 2017; Noriega, 2013, 2015; Wang et al., 2019). During the in-flight measurement, the aircraft attitude is ever-changing because of the turbulence caused by airflow or the influence of aircraft up-and-down and turning,
and the resulting magnetic interference will seriously influence the function and performance of aeromagnetic measurement equipment. Therefore, the aeromagnetic interference compensation is a vital part of aeromagnetic measurement, whose effect directly determines the quality of aeromagnetic data, and the aeromagnetic interference compensation is a bottleneck problem in obtaining high quality aeromagnetic data.

The interference magnetic field caused by aircraft maneuvering can be divided into three types, namely the permanent, the induced, and the eddy-current magnetic field. The permanent magnetic field is generated by the ferromagnetic parts in the aircraft, the induced magnetic field is created by the Earth's magnetic field in soft iron or paramagnetic parts, and the eddy-current magnetic field can be traced to electric currents produced on electrically conducting paths of the airframe, directly proportional to the rate of variation in the magnetic flux (Bickel, 1979a, 1979b; Chen et al., 2018; Nelson, 2003; Noriega & Marszalkowski, 2017; Tolles, 1943; Tolles & Mineola, 1954, 1955). In addition, the current-induced magnetic field caused by electronic components and the remanence effects of internal components of the magnetometer probe can also be included in the above three types.

The current interference magnetic field compensation methods adopted in aeromagnetic measurement mainly include the hard compensation and the soft compensation. The hard compensation, that is, the passive compensation, generally uses fixed magnets or three-axis coils for permanent magnetic field compensation and permalloys for induced magnetic field compensation, but fails to effectively compensate the eddy-current magnetic fields. The soft compensation, that is, the digital magnetic compensation, transforms the physical models of the three interference magnetic fields of the flight platform into the mathematical models based on the aircraft's structure and physical characteristics, solves the corresponding compensation coefficients, and then calculates and removes the magnetic interference. Since there is no need for compensation coil, this method is simple and efficient. It can realize full digitization and automation and adequately compensate the magnetic interference caused by any heading or maneuver. Therefore, this paper mainly studies the application of soft compensation in the aeromagnetic interference compensation.

The article is organized as follows. Section 2 explains the defects of traditional calibration flight scheme in practical use. Section 3 proposes an improved calibration flight scheme and analyzes its merits. Section 4 introduces the aeromagnetic interference compensation model. Section 5 demonstrates the effectiveness of the improved calibration flight scheme. Section 6 discusses the reasons for different compensation effect obtained by traditional and improved calibration flight schemes and proves the applicability of the improved one to other survey lines. Section 7 summarizes the main contributions and draws the conclusion.

2. Statement of the Problem

The general aircraft aeromagnetic interference compensation model proposed by Tolles and Lawson has been gradually developed to the classical Tolles-Lawson equation (Bickel, 1979a, 1979b; Leach, 1980; Tolles & Lawson, 1950). In order to solve it, Leliak (1961) proposed a method to calculate the aeromagnetic interference compensation coefficients based on the aircraft's pitch, roll, and yaw maneuvering flight actions, and it has been in use since then (Du et al., 2019; Feng et al., 2022; Fitzgerald & Perrin, 2015; Hardwick, 1996; Hezel, 2020; Qiao et al., 2021; Rice and Joseph, 1993; Zhou et al., 2014).

As shown in Figure 1, in the traditional calibration flight, a complete flight cycle consists of a square calibration flight line in 4 cardinal directions and a corresponding arc-shaped turning flight line (Noriega, 2011; Tuck, 2019; Tuck et al., 2019; Vijay Gopal et al., 2004; Wołoszyn, 2012). In the calibrated flight line of each direction, maneuvering flights with three sinusoidal trajectories, including pitch, roll, and yaw, are performed. The motion range angle for roll and pitch is 15°, and 10° for yaw. The flight time of each maneuver is about 30 s, and the calibration flight time of each direction is 90 s. According to the average flight speed of 200 km/hr, the range of
the calibration area is about 5 × 5 km. After the last heading, the aircraft must fly back to the initial heading to end the calibration flight.

The above-mentioned traditional calibration flight scheme is widely used in the aeromagnetic interference compensation of manned aircraft or UAV aeromagnetic measurement, and has played an important role in the existing aeromagnetic measurement. However, with the continuous improvement of the measurement accuracy there are higher requirements for calibration, and some defects of the traditional calibration flight scheme are found in practice, which are summarized as follows:

1. Due to the limitation of geographical latitude or the airborne magnetometer direction, it may not be possible to keep the airborne magnetometer in its active area or cause the measurement signal loss during the calibration flight, especially in the turning flight section. Or the airborne magnetometer has just recovered from the dead zone after turning with unstable performance, and the direct implementation of the maneuvers will reduce the quality of measurement signal. Therefore, the compensation result is not ideal, and the calibration flight needs to be re-arranged.

2. A complete calibration flight cycle consists of four directions of a square, and each direction contains three maneuvers (i.e., pitch, roll and yaw). When the calibration flight is implemented, the three maneuvers must be completed consecutively. The cumbersome operation and such a large range of maneuvers further increase the difficulty of flying.

3. Each set of maneuvers in each direction should be consistent, which requires the range of motion and maneuver time of the aircraft are basically the same when performing each maneuver. However, in actual flight, due to the influence of many factors such as climate and personnel operation, the maneuvers of different sets and in different directions varies greatly. Therefore, it is impossible to find a set of fairly standard coefficients for every maneuver through actual flight, which makes compensation matrix ill-conditioned and seriously affects the quality of compensation coefficients.

4. In order to implement the calibration, the aircraft should fly in an area with small magnetic field gradient changes (generally the range is within 25–36 km²), the flight altitude should be as high as possible (generally greater than 2,500 m), the total magnetic intensity on the flight path should be gentle, and the total change should be less than 200 nT (ideally less than 100 nT). However, it is difficult to find a place where the geomagnetic field changes uniformly in such a large area.

For the ill-conditioned problems of the aeromagnetic interference model caused by the traditional calibration flight scheme, the least squares solution is not enough to accurately solve the compensation coefficients. For this reason, neural networks method (Williams, 1993), ridge estimation method (Praga-Alejo et al., 2008), truncated singular value decomposition method (Gu et al., 2013), Huber loss method (Ge et al., 2019b), linear regression method (Dou et al., 2021), and other methods are used to solve the aeromagnetic interference compensation equation in order to improve the calculation accuracy of compensation coefficients. Although the biased estimation techniques used above can suppress the ill-conditioned problems of the aeromagnetic interference model to a certain extent, these methods are equivalent to the optimization problem of solving the multivariate linear equations. Actually, no perfect solution has been found so far for tackling the root of ill-conditioned problem, that is, the defects of the traditional square calibration flight scheme. Based on the above considerations, we propose an improved calibration flight scheme.

3. Improved Calibration Flight Scheme

In order to solve problems existing in traditional calibration flight routes and maneuvers, we propose a new calibration flight scheme. The specific realization of the improved calibration flight routes and maneuvers is shown in Figure 2.
Firstly, in the selected calibration area, we take a reference point with small variation gradient of the surrounding geomagnetic field as the central point. Then, around the center point, we set up eight survey lines as a group of calibration flights. According to the flight sequence, the azimuth angles of the survey lines are set to 270°, 135°, 0°, 225°, 90°, 315°, 180°, and 45°, respectively. Finally, we carry out calibration flight along each survey line, and execute maneuver when the aircraft is about 500 m away from the center point. It should be noted that, the spatial position deviation of each calibration line intersecting at the center point should not be greater than 50 m, and each group of calibration flight only performs one maneuver (pitch or roll), then another maneuver is performed in the next group of calibration flight. The above flight sequence is based on the specific conditions of our test area. If readers use it in other test areas, they can flexibly determine the azimuth of the survey line.

The above two groups are a complete calibration flight, with a total of sixteen survey lines. In order to avoid the interference of ground magnetic field, it is required that the altitude of the calibration flight relative to the ground is not less than 2,500 m. During the calibration flight, the speed of the aircraft is required to be stable, and there is no violent flight actions or redundant electrical equipment to switch on and off.

Compared with the traditional calibration flight scheme, the improved one has the following merits:

1. After the aircraft turns, there is still a certain flight distance for executing the next maneuver. Therefore, there is enough time for the magnetometer to recover performance, which is helpful in improving the quality of the measurement signal when maneuvering.

2. The yaw maneuver is reduced during the calibration flight, because in the improved calibration scheme, there are two groups of maneuvers, each group of eight survey lines contains eight azimuth information. When the aircraft flies in the survey line corresponding to each azimuth, it is equivalent to collecting the yaw angle information of the survey line. One group of maneuvers collects the yaw angle information of eight survey lines, while the two groups can collect 16, so there is enough data to calculate the magnetic compensation coefficients. This operation further reduces the difficulty of aircraft maneuvering and improves the compensation efficiency.

3. Only one maneuver is performed for each calibration flight route, and thus three maneuvers are reduced to one, which simplifies the operation process, increases the possibility that the maneuvers of each group are basically the same, and improves the robustness of the compensation matrix.

4. The calibration flight is carried out around a point in the air, which shortens the flight route, reduces the calibration flight area, and lowers the difficulty of location selection for the calibration area.

5. The following experimental results also show that the proposed calibration flight scheme can obtain better magnetic compensation coefficients and improve the accuracy of aeromagnetic measurement data.

Here, we use Table 1 to make an intuitive comparison between the traditional and improved calibration flight scheme.

Next, let's briefly introduce the classical Tolles-Lawson aeromagnetic interference compensation model, and then analyze the experimental results.

| Comparison items                  | Traditional calibration flight scheme | Improved calibration flight scheme |
|-----------------------------------|--------------------------------------|-----------------------------------|
| Size of calibration area          | 5 × 5 km                             | 1 × 1 km                          |
| Number of flight directions       | 4                                    | 8                                 |
| Maneuvers                         | Pitch, roll and yaw                  | Pitch, roll                       |
| Duration of each maneuver         | 30 s                                 | 16 s                              |
| Operation process                 | Relatively complex                    | Relatively simple                  |
| Affected by weather               | Great impact                          | Less impact                       |
| Robustness of compensation matrix | Strong                                | Weak                              |
4. Aeromagnetic Interference Compensation Model

The general formula for the soft compensation is (Leliak, 1961; Tolles & Lawson, 1950)

\[
T' = T + \Delta T = T + H + AT' + B \frac{dT}{dt}
\]  

(1)

Where \( T' \) and \( T \) are the geomagnetic field vectors (including interference magnetic field) measured by the magnetometer, and the vectors of the real geomagnetic field in the aircraft coordinate system, respectively; \( \Delta T \) is the interference magnetic field; \( \frac{dT}{dt} \) is the rate of change of geomagnetic field over time caused by aircraft maneuver; \( H, A, \) and \( B \) denote the permanent interference magnetic field vector, the induced interference magnetic field coefficient matrix, and the eddy-current interference magnetic field coefficient matrix, respectively.

The aircraft coordinate system is defined as follows. The origin of the coordinate system is the center point of the magnetometer probe; the \( x \)-axis is parallel to the horizontal axis of the aircraft, and the positive direction is the direction of left wing; the \( y \)-axis is parallel to the longitudinal axis of the aircraft, and the positive direction is the nose direction; the \( z \)-axis, the \( x \) and \( y \) axes form a right-handed coordinate system, which is perpendicular to the positive direction of the fuselage in downwards direction.

In the vector measurement mode, the interference magnetic field compensation model can be expressed as

\[
T'_x = T_x + H_x + a_{11} T_x + a_{12} T_y + a_{13} T_z + b_{11} \frac{d(T_x)}{dt} + b_{12} \frac{d(T_y)}{dt} + b_{13} \frac{d(T_z)}{dt}
\]

\[
T'_y = T_y + H_y + a_{21} T_x + a_{22} T_y + a_{23} T_z + b_{21} \frac{d(T_x)}{dt} + b_{22} \frac{d(T_y)}{dt} + b_{23} \frac{d(T_z)}{dt}
\]

\[
T'_z = T_z + H_z + a_{31} T_x + a_{32} T_y + a_{33} T_z + b_{31} \frac{d(T_x)}{dt} + b_{32} \frac{d(T_y)}{dt} + b_{33} \frac{d(T_z)}{dt}
\]

(2)

where \( T'_x, T'_y, \) and \( T'_z \) represent the three components of the geomagnetic field (including interference magnetic field) measured by the magnetometer in the aircraft coordinate system, respectively; \( T_x, T_y, \) and \( T_z \) represent the three components of the real geomagnetic field in the aircraft coordinate system, respectively; \( \frac{d(T_x)}{dt}, \frac{d(T_y)}{dt}, \) and \( \frac{d(T_z)}{dt} \) represent the time rate of change of the real geomagnetic field in the three-axis direction of the aircraft coordinate system, respectively; twenty-one coefficients, including \( H_x, H_y, H_z, a_{11}, a_{12}, a_{13}, a_{21}, a_{22}, a_{23}, a_{31}, a_{32}, a_{33}, b_{11}, b_{12}, b_{13}, b_{21}, b_{22}, b_{23}, b_{31}, b_{32}, b_{33} \) and \( b_{33} \), are called magnetic compensation coefficients, mainly related to the structure and material characteristics of the aircraft and the installation of the magnetometer probe. Therefore, when the installation positions of the aircraft and the magnetometer probe are determined, they do not change with the movement of the aircraft and can be regarded as constants.

Comparing Equation 2 with Equation 1, we can obtain

\[
T' = \begin{bmatrix} T'_x \\ T'_y \\ T'_z \end{bmatrix}
\]

(3)

\[
T = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}
\]

(4)

\[
H = \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix}
\]

(5)

\[
A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}
\]

(6)

\[
B = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}
\]

(7)
Define $X$, $Y$, and $Z$ as the angle between the geomagnetic field vector and the $x$, $y$, and $z$ axes of the aircraft coordinate system. The projection of the geomagnetic vector on the aircraft coordinate axis can be expressed as

$$T_x = T \cos X, \quad T_y = T \cos Y, \quad T_z = T \cos Z$$  \hspace{1cm} (8)

Then the total magnetic intensity can be expressed as

$$T = T_x \cos X + T_y \cos Y + T_z \cos Z$$  \hspace{1cm} (9)

Therefore, in the measurement mode of total magnetic intensity, the interference magnetic field compensation model can be obtained

$$T' - T = H_x \cos X + H_y \cos Y + H_z \cos Z + a_{11} T \cos^2 X + a_{12} T \cos X \cos Y +$$
$$a_{13} T \cos X \cos Z + b_{11} T \frac{d(\cos X)}{dt} + b_{12} T \frac{d(\cos Y)}{dt} +$$
$$b_{13} T \frac{d(\cos Z)}{dt} + a_{21} T \cos X \cos Y + a_{22} T \cos^2 Y + a_{23} T \cos Y \cos Z +$$
$$b_{21} T \frac{d(\cos X)}{dt} + b_{22} T \frac{d(\cos Y)}{dt} + b_{23} T \frac{d(\cos Z)}{dt} +$$
$$a_{31} T \cos X \cos Z + a_{32} T \cos Y \cos Z + a_{33} T \cos^2 Z +$$
$$b_{31} T \frac{d(\cos X)}{dt} + b_{32} T \frac{d(\cos Y)}{dt} + b_{33} T \frac{d(\cos Z)}{dt}$$  \hspace{1cm} (10)

In actual operations, in order to calculate the magnetic compensation coefficients, it is usually necessary to find an area where the Earth’s magnetic field changes uniformly, and the aircraft conducts calibration flights by sequentially performing prescribed maneuvers along the selected route. Assuming that the geomagnetic field is uniform in the selected calibration area, then $T = T_0$ in the Equation 10. Since the three coordinate axes of $x$, $y$, and $z$ are orthogonal, there are

$$\cos^2 X + \cos^2 Y + \cos^2 Z = 1$$  \hspace{1cm} (11)

$$\cos X \frac{d(\cos X)}{dt} + \cos Y \frac{d(\cos Y)}{dt} + \cos Z \frac{d(\cos Z)}{dt} = 0$$  \hspace{1cm} (12)

Substituting $T = T_0$ and Equations 11 and 12 into Equation 10, we can obtain

$$T' - T_0 = H_x \cos X + H_y \cos Y + H_z \cos Z + T_0 [(a_{11} - a_{33}) \cos^2 X +$$
$$(a_{22} - a_{33}) \cos^2 Y + a_{33} + (a_{12} + a_{21}) \cos X \cos Y + (a_{13} + a_{31}) \cos X \cos Z +$$
$$(a_{23} + a_{32}) \cos Y \cos Z] + T_0 [(b_{11} - b_{33}) \frac{d(\cos X)}{dt} + b_{12} \frac{d(\cos Y)}{dt} +$$
$$b_{13} \frac{d(\cos Z)}{dt} + (a_{21} - b_{32}) \frac{d(\cos X)}{dt} + b_{22} \frac{d(\cos Y)}{dt} +$$
$$b_{23} \frac{d(\cos Z)}{dt} + b_{31} \frac{d(\cos X)}{dt} + (a_{31} - b_{23}) \frac{d(\cos Y)}{dt} +$$
$$b_{32} \frac{d(\cos Z)}{dt} + b_{33} \frac{d(\cos Y)}{dt})$$  \hspace{1cm} (13)

We can see that the compiled compensation model contains a total of seventeen interference components, of which $a_{11}$ is a constant that does not change with the attitude of the aircraft, and linearly related to the total magnetic intensity $T_0$.

Equation 13 is further modified into the matrix multiplication form and we can obtain

$$L = CX$$  \hspace{1cm} (14)

where $L$ represents the difference matrix between the geomagnetic field (including interference magnetic field) measured by the magnetometer and the real geomagnetic field; $C$ represents the coefficient matrix; $X$ represents the magnetic compensation coefficients matrix to be solved.

Solving the normal Equation 14, the magnetic compensation coefficients can be obtained. Substituting the calculated magnetic compensation coefficients into Equation 13, the interference magnetic field can be obtained.
Subtracting the interference magnetic field from the magnetometer measurement data, we can get the true geomagnetic field, as shown below

\[ T = T' - \Delta T \]  

(15)

where \(\Delta T\) represents the interference magnetic field.

In the numerical experiment, for the fairness of comparison, no matter adopting the traditional or improved calibration flight scheme, the least squares spectral decomposition method (Wang et al., 2004) is used to calculate the magnetic compensation coefficients when solving the normal Equation 14, instead of the biased estimation methods such as ridge estimation.

Traditionally the magnetic compensation effect is evaluated according to the figure of merit (FOM) or improvement ratio (IR). However, the ultimate goal of the magnetic compensation is to improve the accuracy of aeromagnetic measurement, and the accuracy standard of aeromagnetic measurement is generally based on the accuracy of discrepancies of repeated survey lines or intersections. Therefore, the accuracy of repeated survey lines discrepancies (different repeated survey lines are made pairwise and the accuracy of differences are calculated) is used to compare the effects before and after the interference magnetic field compensation in this paper.

5. Numerical Experiments

5.1. Introduction of Experiment Background

The experiment was implemented in the Inner Mongolia, China. A Cessna 208B aircraft is used for flight test, and the magnetometers were installed in the 4.5 m length tail boom. As shown in Figure 3, the scalar magnetometer and the vector magnetometer were equipped at the pole and the middle of the tail boom, respectively. The cabinet, consisting of the data acquisition system, the power distributor, the navigator, and other auxiliary facilities, is installed in the middle of the plane. The scalar magnetometer was a CS-3 cesium optical pump magnetometer, and the vector magnetometer was a three-axis fluxgate magnetometer. The flying speed of the whole flight test is about 200 km/hr, and the data sampling rate is set to 1 Hz.

5.2. Calibration Flight

According to the traditional calibration flight scheme, three calibration flights were implemented, and the flight routes are shown in Figure 4. Due to the high wind speed in the sky, the flight trajectory was irregular. One calibration flight was implemented adopting the improved calibration flight scheme, and the flight route is shown...
in Figure 5. The flight altitude of these two calibration schemes is about 3,000 m above the ground.

Taking the SN01 repeated survey lines in the North–South direction as an example. It includes six survey lines flying from South to North and from North to South, numbered L1-L6 in sequence, and three of them are in the same direction. The flight altitude of SN01 is about 140 m from the ground, the length of each survey line is about 20 km. The comparison of the original SN01 repeated survey lines is shown in Figure 6, and the statistical results of the discrepancy accuracy are shown in Table 2. $L_{\text{NS}}$ denotes the survey lines flying from North to South, and $L_{\text{SN}}$ denotes the survey lines flying from South to North.

From Table 2 we can see that the conformity of the same-direction survey lines is better, the maximum difference of the discrepancy is less than 10 nT, and the average accuracy is better than 2 nT. By contrast, the conformity of opposite-direction survey lines is poor, and there exists an obvious system error, which is caused by the interference magnetic field generated after the aircraft turns. The maximum difference of the discrepancy is 21.5 nT, and the average accuracy is about 11 nT. The average accuracy of the entire SN01 repeated survey lines is about 7 nT.
It can be seen that before the interference magnetic field is compensated, there is an obvious system error between the repeated survey lines in opposite-directions, so the interference magnetic field compensation technologies should be used to eliminate or reduce its influence.

5.3. Aeromagnetic Interference Compensation

Based on the test data of three traditional calibration flight routes, the interference magnetic field compensation coefficients are calculated respectively, and then the interference magnetic field of the SN01 repeated survey lines is calculated. According to Equation 13, the interference magnetic field compensation coefficients calculated based on the second traditional calibration flight route data denoted as M1 are shown in Table 3. The influence of the interference magnetic field is removed from the original measurement data, and the calculation results are shown in Figure 7. Due to the large maneuvering of the aircraft during the flight turning phase, the quality of the data collected by the magnetometer is not good, so the effect of the aeromagnetic interference compensation is very poor. Therefore, the measurement data at the flight turning phase needs to be discarded.

After removing the data of the flight turning phase in the traditional calibration flight scheme, the interference magnetic field is compensated again. The interference magnetic field compensation coefficients calculated based on the third traditional calibration flight route data denoted as M2 are shown in Table 3, and those of the second one denoted as M3 are also shown in Table 3. The calculation results based the first and third calibration flight routes are shown in Figure 8, and those of the second one in Figure 9.

We can see that the compensation coefficients calculated from the test data of the first and third calibration flight routes are still not ideal. The compensation coefficients calculated from the test data of the second calibration flight route, to a certain extent, weaken the influence of the system error.

| Comparison items | Maximum | Minimum | Average value | Standard deviation | Root mean square error |
|------------------|---------|---------|---------------|--------------------|-----------------------|
| L1NS–L2SN        | −3.31   | −20.92  | −10.98        | 2.20               | 11.19                 |
| L1NS–L3NS        | 4.49    | −8.08   | −0.04         | 1.08               | 1.08                  |
| L1NS–L4SN        | −3.93   | −19.68  | −10.20        | 1.74               | 10.35                 |
| L1NS–L5NS        | 6.72    | −3.04   | −0.02         | 1.10               | 1.10                  |
| L1NS–L6SN        | −5.16   | −21.06  | −10.83        | 2.08               | 11.02                 |
| L2SN–L3NS        | 20.75   | 3.78    | 10.93         | 2.16               | 11.14                 |
| L2SN–L4SN        | 9.73    | −6.79   | 0.78          | 1.75               | 1.92                  |
| L2SN–L5NS        | 21.46   | 3.60    | 10.96         | 2.43               | 11.23                 |
| L2SN–L6SN        | 6.67    | −3.87   | 0.15          | 1.46               | 1.47                  |
| L3NS–L4SN        | −7.05   | −14.30  | −10.16        | 1.41               | 10.25                 |
| L3NS–L5NS        | 6.04    | −2.88   | 0.03          | 0.88               | 0.88                  |
| L3NS–L6NS        | −7.02   | −17.07  | −10.78        | 1.75               | 10.92                 |
| L4SN–L5NS        | 17.82   | 6.64    | 10.18         | 1.46               | 10.29                 |
| L4SN–L6SN        | 3.03    | −4.79   | 0.63          | 0.94               | 1.13                  |
| L5NS–L6NS        | −6.49   | −19.61  | −10.81        | 1.75               | 10.95                 |
| Average accuracy |         |         | 1.61          | 6.99               |                       |

Figure 6. Comparison of original SN01 repeated survey lines.
between the opposite-direction survey lines and improve the average accuracy (better than 4.9 nT) of the repeated survey lines, whose accuracy statistics are shown in Table 4. However, the magnetic compensation effect of the traditional scheme is limited. There is still an interval between the opposite-direction survey lines in Figure 9, while the system error between the opposite-direction survey lines in the statistical results in Table 4 is still large.

| Compensation coefficients | M1          | M2          | M3          | M4          |
|----------------------------|-------------|-------------|-------------|-------------|
| $H_x$                      | -842.11035931 | -57.70843356 | -21.74324839 | -4.30946577 |
| $H_y$                      | 541.87343015  | -49.22098826 | -50.44067261 | -5.02828149 |
| $H_z$                      | -59.25209771  | 22.96642680  | 14.58443071  | -1.52232002 |
| $a_{11}-a_{33}$            | 0.01220756   | 0.00136729   | 0.00056774   | 0.00008449  |
| $a_{22}-a_{33}$            | 0.00784072   | -0.00105328  | -0.00053954  | 0.00018834  |
| $a_{12}+a_{21}$            | -0.00557831  | 0.00046531   | 0.00076545   | -0.00001741 |
| $a_{13}+a_{31}$            | 0.01027226   | -0.00071398  | -0.00058039  | 0.00001936  |
| $a_{23}+a_{32}$            | -0.001016823 | 0.00023041   | 0.00040697   | -0.00011551 |
| $b_{11}-b_{33}$            | 0.00934317   | -0.00086712  | -0.00033596  | -0.00007109 |
| $b_{12}$                   | 0.00536908   | 0.00422655   | 0.00136494   | 0.0007617  |
| $b_{13}$                   | 0.01818797   | -0.00128789  | -0.00020330  | -0.00003605 |
| $b_{21}$                   | 0.01151746   | -0.00219993  | -0.00074785  | -0.0005785 |
| $b_{22}-b_{33}$            | 0.01083909   | 0.00230213   | 0.00135574   | -0.00005219 |
| $b_{23}$                   | 0.02136583   | -0.00288349  | -0.00196578  | -0.00017383 |
| $b_{31}$                   | 0.01002070   | 0.00010126   | 0.00000222   | 0.00001038  |
| $b_{32}$                   | -0.000201403 | -0.00014626  | -0.00014048  | 0.00000215  |

Table 3
The Interference Magnetic Field Compensation Coefficients Calculated Based on the Traditional and Improved Calibration Flight Scheme

Figure 7. Comparison of SN01 repeated survey lines after the first aeromagnetic interference compensation based on the traditional calibration flight scheme.
(the average value of the difference between the repeated survey lines represents the system error). Compared with the original SN01 repeated survey lines, the average accuracy is improved by 2.1 nT. However, it should be noted that the interference magnetic field compensation has reduced the average accuracy of the same-direction survey lines by 1 nT.

Figure 8. Comparison of SN01 repeated survey lines after the second aeromagnetic interference compensation based on the traditional calibration flight scheme (The first and third calibration flight routes).

Figure 9. Comparison of SN01 repeated survey lines after the aeromagnetic interference compensation based on the traditional calibration flight scheme (The second calibration flight route).
The magnetic compensation coefficients calculated based on improved calibration flight scheme data denoted as M4 are shown in Table 3, and the interference magnetic field compensation is performed on the SN01 repeated survey lines. The compensation results are shown in Figure 10. It can be seen that the interval between the opposite-direction survey lines has basically disappeared. Compared with Figure 6, the systematic error between the opposite-direction survey lines has been greatly weakened. From the statistical results in Table 5, we can see that the system error between opposite-direction survey lines is also relatively small, the maximum difference of the discrepancy between the opposite-direction survey lines has been reduced to about 12 nT, and the average accuracy is better than 3 nT. The average accuracy of the same-direction survey lines has also been improved to a certain extent. The average accuracy of the entire SN01 repeated survey lines reaches 1.9 nT. Compared with the uncompensated SN01 repeated survey lines (see Table 2), the average accuracy is improved by 5.1 nT. Compared with the SN01 repeated survey lines after compensation based on the traditional calibration flight scheme (see Table 4), the average accuracy is improved by 3 nT.

6. Discussion

As can be seen from Figure 4, the actual traditional calibration flight path is not a regular square, because the flight test time of aeromagnetic survey is in October. Windy weather takes over in this time in Inner Mongolia in China, with the ground wind speed of about 8 m/s, and the wind speed at 3,000 m altitude reaches 15 m/s. Such extreme weather conditions bring many difficulties for pilots to carry out calibration flight maneuvers. Based on the calculation that the flight time of each maneuver is about 30 s, the calibration flight time of each side is 90 s, the average flight speed is 200 km/hr, and the originally planned area for calibration flight is about 5 × 5 km.

| Comparison items | Maximum | Minimum | Average value | Standard deviation | Root mean square error |
|------------------|---------|---------|---------------|--------------------|-----------------------|
| L1NS–L2SN        | 13.83   | −6.76   | 5.80          | 3.23               | 6.64                  |
| L1NS–L3NS        | 4.62    | −11.24  | −0.33         | 2.24               | 2.26                  |
| L1NS–L4SN        | 13.07   | −3.57   | 6.22          | 2.52               | 6.71                  |
| L1NS–L5NS        | 10.05   | −7.47   | 0.22          | 2.45               | 2.46                  |
| L1NS–L6SN        | 14.36   | −5.28   | 5.89          | 2.77               | 6.51                  |
| L2SN–L3NS        | 9.26    | −14.25  | −6.13         | 2.87               | 6.77                  |
| L2SN–L4SN        | 12.57   | −6.10   | 0.42          | 2.49               | 2.52                  |
| L2SN–L5NS        | 11.23   | −13.52  | −5.58         | 3.36               | 6.51                  |
| L2SN–L6SN        | 8.97    | −6.43   | 0.09          | 2.17               | 2.17                  |
| L3NS–L4SN        | 12.36   | 0.81    | 6.55          | 2.06               | 6.86                  |
| L3NS–L5NS        | 10.16   | −5.45   | 0.55          | 2.23               | 2.29                  |
| L3NS–L6SN        | 13.30   | −1.22   | 6.22          | 2.19               | 6.59                  |
| L4SN–L5NS        | 3.54    | −12.00  | −6.00         | 2.26               | 6.41                  |
| L4SN–L6SN        | 4.94    | −7.26   | −0.33         | 2.01               | 2.04                  |
| L5NS–L6SN        | 13.48   | −5.98   | 5.67          | 2.60               | 6.24                  |
| Average accuracy  |         |         | 2.50          | 4.87               |                       |

Figure 10. Comparison of SN01 repeated survey lines after the aeromagnetic interference compensation based on the improved calibration flight scheme.
Table 5

| Comparison items | Maximum | Minimum | Average value | Standard deviation | Root mean square error |
|------------------|---------|---------|---------------|--------------------|-----------------------|
| L1NS–L2SN       | 4.49    | −11.79  | −1.87         | 2.18               | 2.87                  |
| L1NS–L3NS       | 4.55    | −8.22   | −0.03         | 1.09               | 1.09                  |
| L1NS–L4SN       | 5.33    | −10.36  | −1.15         | 1.69               | 2.04                  |
| L1NS–L5NS       | 6.74    | −3.13   | −0.01         | 1.10               | 1.10                  |
| L1NS–L6SN       | 3.82    | −11.98  | −1.64         | 2.03               | 2.61                  |
| L2SN–L3NS       | 11.40   | −4.24   | 1.84          | 2.11               | 2.80                  |
| L2SN–L4SN       | 9.04    | −5.38   | 0.72          | 1.63               | 1.78                  |
| L2SN–L5NS       | 12.20   | −4.36   | 1.86          | 2.35               | 2.99                  |
| L2SN–L6SN       | 5.80    | −2.94   | 0.24          | 1.19               | 1.22                  |
| L3NS–L4SN       | 2.32    | −5.19   | −1.12         | 1.36               | 1.76                  |
| L3NS–L5NS       | 6.26    | −3.05   | 0.02          | 0.89               | 0.89                  |
| L3NS–L6SN       | 2.56    | −8.04   | −1.60         | 1.74               | 2.37                  |
| L4SN–L5SN       | 8.60    | −1.82   | 1.14          | 1.38               | 1.79                  |
| L4SN–L6SN       | 3.00    | −4.45   | −0.49         | 0.89               | 1.01                  |
| L5NS–L6SN       | 3.09    | −10.63  | −1.62         | 1.76               | 2.39                  |
| Average accuracy |         |         | 1.56          | 1.91               |                       |

However, due to the influence of downwind and upwind flight, the actual calibration area is about 13 × 9 km, exceeding the area selected in the plan. The resulting problems include the following: (a) The maneuvers cannot be strictly aligned with each other as shown in Figure 1, that is to say, the flight distance of one side is longer when flying downwind, and shorter when flying upwind; after flying the last heading, the aircraft must fly back to the initial heading to end the calibration flight. Therefore, the upwind flights always produce some long-distance flight data without any maneuver which will have an adverse impact on the calculation of the interference magnetic field compensation coefficients. (b) The selected 5 × 5 km calibration flight area in the original plan is determined by the survey line flight in the early stage. The change of the total geomagnetic intensity in this area is less than 100 nT, but the actual calibration area is 13 × 9 km, which has exceeded the survey scope, and the change of the total geomagnetic intensity in this area cannot be accurately mastered. Therefore, the reliability of using the calibration flight data of this area to calculate the interference magnetic field compensation coefficients cannot be guaranteed. According to the above analysis, the traditional calibration flight scheme is greatly affected by the weather. When adopting this scheme, the calibration flight should be carried out on magnetostatic days with good weather, low wind speed (≤5 m/s) and good visibility.

From Figure 2 we can see that the improved calibration flight scheme has 8 directions, one maneuver in each direction, and the duration of each maneuver is about 16 s. Sixteen calibration flight compensation survey lines pass through the fixed intersection and complete all maneuvers in turn, and the spatial position deviation of each compensation survey line at the fixed intersection is less than 50 m. Since the flight route is shorter and the maneuvers are more simplified, it is almost unaffected by the gale weather, which can be seen from the true flight route shown in Figure 5. Therefore, compared with the traditional calibration flight scheme, the improved one is more convenient and flexible in practical application with more stable calibration compensation matrix and better solved compensation parameters.

In terms of magnetic compensation effect, for the three calibration flights implemented according to the traditional calibration flight scheme, only the compensation coefficients calculated from the test data of the second calibration flight route weaken the influence of the system error between the opposite-direction survey lines. This is because in the traditional calibration flight, the magnetometer signal loses its lock and enters the dead zone at one turn. After the turn, the magnetometer just recovers from the dead zone and its performance is not very stable. The direct implementation of the calibration maneuver leads to the low quality of the measurement signal, and the variation range of geomagnetic field on the whole flight path is up to 4,800 nT. After the turning data are removed, the interference magnetic field is compensated again. The compensation coefficients calculated from the test data of the first and third calibration flight routes are still not ideal. At this time, the variation amplitude of geomagnetic field on the whole flight route is about 110 nT. The compensation coefficients calculated based on the test data of the second calibration flight route improves the accuracy of aeromagnetic measurement to a certain extent (see Figure 9 and Table 4), and the variation amplitude of geomagnetic field on the whole flight route is about 55 nT. For the calibration flight implemented based on the improved calibration flight scheme, the compensation coefficients calculated from the test data greatly improve the accuracy of aeromagnetic measurement (see Figure 10 and Table 5), and the variation amplitude of geomagnetic field on the flight route within 500 m around the intersection is about 15 nT.

In order to further prove the applicability of the improved calibration flight scheme to other survey lines, the calculated compensation coefficients are used to compensate the interference magnetic field of the SN02 repeated survey lines in the north-south direction. The original SN02 repeated survey lines whose flight status is similar to SN01 repeated survey lines are shown in Figure 11, and the statistical results of the discrepancy are shown in Table 6. The SN02 repeated survey lines after compensation based on the traditional and improved calibration
flight scheme are shown in Figures 12 and 13, respectively, and the statistical results of the discrepancy are shown in Tables 7 and 8, respectively.

It can be seen from Figure 11 and Table 6 that before the interference magnetic field compensation, similar to the SN01 repeated survey lines, the SN02 repeated survey lines have good conformity with the same-direction survey lines, the maximum difference of the discrepancy is about 11.4 nT, and the average accuracy is better than 1.6 nT. However, the conformity of the opposite-direction survey lines is poor, the maximum difference of the discrepancy is 19 nT, and the average accuracy is about 11 nT. The average accuracy of the entire SN02 repeated survey lines before compensation is about 6.7 nT.

It can be seen from Figure 12 and Table 7 that after the interference magnetic field compensation based on traditional calibration flight scheme, the system error between opposite-direction survey lines is weakened and the average accuracy of opposite-direction repeated survey lines is improved by 3.4 nT. However, the average accuracy of the same-direction repeated survey lines is better than 2.1 nT, which is about 0.5 nT lower than that before the compensation. The average accuracy of the entire SN02 repeated survey lines is about 5.4 nT. Compared with the results before the interference magnetic field compensation (see Table 6), the average accuracy is improved by 1.3 nT.

It can be seen from Figure 13 and Table 8 that after the interference magnetic field compensation based on the improved calibration flight scheme, the overall conformity of the SN02 repeated survey lines is better. The maximum difference of the discrepancy between the opposite-direction survey lines has been reduced to about 11 nT, and the average accuracy is about 2 nT. The average accuracy of the same-direction survey lines has also been improved to a certain extent. The average accuracy of the entire survey lines is 1.17 nT, which is about 5.4 nT lower than that before the compensation. The average accuracy of the entire SN02 repeated survey lines is about 1.17 nT.

![Figure 11. Comparison of original SN02 repeated survey lines.](image)

| Comparison items | Maximum | Minimum | Average value | Standard deviation | Root mean square error |
|------------------|---------|---------|---------------|--------------------|-----------------------|
| L1_{NS}−L2_{SN} | −3.57   | −14.63  | −10.41        | 1.28               | 10.49                 |
| L1_{NS}−L3_{NS} | 7.81    | −2.56   | 0.09          | 1.09               | 1.09                  |
| L1_{NS}−L4_{SN} | −3.33   | −13.78  | −10.38        | 1.16               | 10.44                 |
| L1_{NS}−L5_{NS} | 1.48    | −4.81   | −0.11         | 0.64               | 0.65                  |
| L1_{NS}−L6_{SN} | −6.46   | −14.64  | −10.68        | 1.21               | 10.75                 |
| L2_{SN}−L3_{NS} | 15.77   | 6.80    | 10.50         | 1.15               | 10.56                 |
| L2_{SN}−L4_{SN} | 2.17    | −1.60   | 0.03          | 0.68               | 0.68                  |
| L2_{SN}−L5_{NS} | 15.66   | −0.83   | 10.30         | 1.56               | 10.42                 |
| L2_{SN}−L6_{SN} | 1.78    | −4.79   | −0.27         | 0.93               | 0.97                  |
| L3_{NS}−L4_{SN} | −7.60   | −15.67  | −10.46        | 1.07               | 10.52                 |
| L3_{NS}−L5_{NS} | 3.73    | −11.44  | −0.20         | 1.54               | 1.56                  |
| L3_{NS}−L6_{SN} | −7.81   | −19.00  | −10.77        | 1.54               | 10.88                 |
| L4_{SN}−L5_{NS} | 15.05   | −0.93   | 10.26         | 1.50               | 10.37                 |
| L4_{SN}−L6_{SN} | 1.67    | −4.82   | −0.31         | 0.84               | 0.89                  |
| L5_{NS}−L6_{SN} | −3.20   | −15.81  | −10.57        | 1.31               | 10.65                 |
| Average accuracy | 1.17    | 6.73    | 1.17          | 6.73               | 6.73                  |
SN02 repeated survey lines is about 1.5 nT. Compared with the results before the interference magnetic field compensation (see Table 6), the average accuracy is improved by 5.3 nT. Compared with the results after compensation based on the traditional calibration flight scheme (see Table 7), the average accuracy is improved by 4 nT.

Table 7

| Comparison items | Maximum | Minimum | Average value | Standard deviation | Root mean square error |
|------------------|---------|---------|---------------|--------------------|-----------------------|
| L1_{NS}, L2_{SN} | 15.16   | −0.21   | 7.21          | 2.36               | 7.59                  |
| L1_{NS}, L3_{NS} | 7.92    | −6.16   | −0.32         | 1.98               | 2.01                  |
| L1_{NS}, L4_{SN} | 15.75   | 1.97    | 7.30          | 1.96               | 7.56                  |
| L1_{NS}, L5_{NS} | 5.89    | −7.79   | 0.02          | 2.11               | 2.11                  |
| L1_{NS}, L6_{SN} | 13.85   | −0.40   | 6.99          | 1.92               | 7.25                  |
| L2_{SN}, L3_{NS} | 1.97    | −14.39  | −7.53         | 2.30               | 7.87                  |
| L2_{SN}, L4_{SN} | 7.97    | −6.05   | 0.09          | 1.95               | 1.95                  |
| L2_{SN}, L5_{NS} | 0.44    | −22.01  | −7.19         | 2.72               | 7.69                  |
| L2_{SN}, L6_{SN} | 6.43    | −8.65   | −0.23         | 2.11               | 2.12                  |
| L3_{NS}, L4_{SN} | 14.26   | −1.31   | 7.62          | 2.11               | 7.91                  |
| L3_{NS}, L5_{NS} | 8.26    | −14.69  | 0.34          | 2.70               | 2.72                  |
| L3_{NS}, L6_{SN} | 14.58   | −3.35   | 7.30          | 2.32               | 7.66                  |
| L4_{SN}, L5_{NS} | 0.21    | −20.55  | −7.28         | 2.51               | 7.70                  |
| L4_{SN}, L6_{SN} | 5.19    | −6.38   | −0.32         | 1.71               | 1.74                  |
| L5_{NS}, L6_{SN} | 16.88   | 0.66    | 6.97          | 2.20               | 7.31                  |
| Average accuracy |         |         | 2.20          | 5.41               |                       |

Figure 12. Comparison of SN02 repeated survey lines after the aeromagnetic interference compensation based on the traditional calibration flight scheme.
**Table 8**  
*Precision Statistics of the Discrepancy of SN02 Repeated Survey Lines After the Aeromagnetic Interference Compensation Based on the Improved Calibration Flight Scheme (Unit: nT)*

| Comparison items | Maximum | Minimum | Average value | Standard deviation | Root mean square error |
|------------------|---------|---------|---------------|--------------------|------------------------|
| L1NS-L2SN        | 5.31    | −5.44   | −1.30         | 1.28               | 1.83                   |
| L1NS-L3NS        | 7.81    | −2.58   | 0.10          | 1.10               | 1.10                   |
| L1NS-L4SN        | 6.06    | −4.85   | −1.16         | 1.22               | 1.68                   |
| L1NS-L5NS        | 1.62    | −5.12   | −0.11         | 0.66               | 0.67                   |
| L1NS-L6SN        | 3.35    | −5.28   | −1.46         | 1.16               | 1.86                   |
| L2SN-L3NS        | 6.89    | −1.88   | 1.40          | 1.16               | 1.82                   |
| L2SN-L4SN        | 2.64    | −1.59   | 0.14          | 0.56               | 0.57                   |
| L2SN-L5NS        | 6.67    | −9.69   | 1.19          | 1.57               | 1.97                   |
| L2SN-L6SN        | 2.68    | −3.90   | −0.16         | 0.70               | 0.72                   |
| L3NS-L4SN        | 2.27    | −6.71   | −1.26         | 1.06               | 1.64                   |
| L3NS-L5NS        | 3.50    | −11.81  | −0.21         | 1.55               | 1.57                   |
| L3NS-L6SN        | 1.19    | −9.91   | −1.55         | 1.44               | 2.12                   |
| L4SN-L5NS        | 6.34    | −10.85  | 1.05          | 1.57               | 1.88                   |
| L4SN-L6SN        | 1.96    | −4.60   | −0.30         | 0.68               | 0.75                   |
| L5NS-L6SN        | 6.52    | −6.39   | −1.35         | 1.33               | 1.89                   |
| Average accuracy  |         |         |               | 1.14               | 1.47                   |

**Figure 13.** Comparison of SN02 repeated survey lines after the aeromagnetic interference compensation based on the improved calibration flight scheme.
Therefore, the above experimental results fully prove the effectiveness and superiority of the improved calibration flight scheme proposed in this paper.

7. Conclusion

The interference magnetic field of the aircraft itself is one of the restrictive factors that affect the further improvement of the aeromagnetic measurement accuracy. Therefore, in the aeromagnetic measurement, the interference magnetic field compensation is an indispensable step in data processing. An improved calibration flight scheme is proposed in this paper. Compared with the traditional scheme, the improved one features smaller calibration area, shorter flight route, simplified maneuvers and less influence from the direction of the magnetometer and extreme weather, and thus it can calculate better magnetic compensation coefficients and greatly improve the quality of magnetic compensation of aeromagnetic measurement. The improved scheme can be directly applied in the interference magnetic field compensation of scalar, vector and gradient magnetic measurement of manned aircraft and UAV.

Data Availability Statement

The software designed in this paper is performed with the programming language C/C++. All figures are drawn using the MATLAB. The software and the experimental data presented in this paper can be downloaded from the Supplement related to the online version of this article. The Supplement related to this article is available online at https://datadryad.org/stash/share/nLcetPWrFa4EDZHOiWLtNT5V52W9StO34bdGY.

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