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Analysis of Orientation Errors in Triaxial Fluxgate Sensors and Research on Their Calibration Methods

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Abstract. Three-axis magnetic flux gate sensors are widely used in Chinese geomagnetic observatories, but due to their directional errors, it is necessary to study error correction methods to improve measurement accuracy. Firstly, the mechanism of directional errors produced by three-axis magnetic flux gate sensors is analyzed, followed by the development of measurement tools for conducting directional error measurement experiments on the high-precision three-axis magnetic flux gate sensors of the Chinese FGM-01 series. Experimental results show that correcting the Z-axis and D-axis directional errors is essential. The observation data after error correction, whether in terms of the standard deviation of its all-day baseline values or the relative difference magnitude with the reference instrument, significantly decrease, demonstrating the clear correction effect and proving the effectiveness of this correction method.

Keywords: Tri-axis Magnetic Flux Gate Sensor, Orientation Error, Calibration

1 Introduction

Three-axis fluxgate sensors have the advantages of high resolution, low power consumption, and low cost, and are widely used in measuring the geomagnetic field signal (Langel et.al.1988; Tohyama et al.1988a,1988b; Ejiri et al.1988;Crassidis & Lai 2005). Currently, nearly 200 sets of three-axis fluxgate magnetometers, mainly GM4 type (Figure 1a), GM4-XL type, and FGM-01 type (Figure 1b), are installed in the Chinese geomagnetic observatories. Most observatories install two or more sets of such instruments for parallel observations, aiming to ensure the continuity and integrity of the observation data and to facilitate timely detection and identification of potential issues in the data. The ideal measurement value of a three-axis fluxgate sensor should be equal to the true value of the measured geomagnetic field variation(Luo et al.2019;Wu 2008). However, due to limitations in manufacturing and installation processes, errors such as non-orthogonality, zero offset, and temperature drift exist in three-axis fluxgate sensors unavoidably(Včelák et al.2006; Foster & Elkaim 2008; Pang 2011). Studies have shown that these errors can lead to deviations of the sensor's measurement values from the true values of the measured geomagnetic field, significantly affecting its measurement accuracy. Therefore, it is of great significance to correct the errors of the sensor(Zhu et al.2005;Li 2008).

Research on the error of three-axis magnetic fluxgate sensors in the past has typically only considered the systematic error of the sensors(Liu et al.2022), with relatively little study on the directional errors introduced during sensor installation. Lassahn & Trenkler (1995) have utilized specialized equipment to measure the angle between the three axes of the sensor, the sensitivity coefficients of each axis output to the magnetic field, but the measurement equipment is expensive and the testing process is cumbersome. Wang Xiaomei et al. (2017) analyzed the variation patterns between the orientation of the instrument, the level of the base, and the observed data of each component of the geomagnetic field based on theoretical calculations and station experiments, providing quantitative relationships. Liu Cheng et al. (2019) established a three-axis calibration model for the magnetic fluxgate magnetometer, determined the attitude angles and scale factor coefficients of the instrument, and then corrected the actual observation data based on the calculation results. The author once developed a measuring device in 2016 to measure and correct the directional errors of the D magnetic axis, eliminating the daily variation distortion recorded by the magnetic fluxgate magnetometer at Hongshan Observatory. However, the aforementioned algorithms or measurements are somewhat difficult (Zhu 2004) and not easy to implement, or only focus on the method of correcting the directional errors of the sensor's D magnetic axis, without yet conducting research on correcting the directional errors of the Z magnetic axis, all of which have shortcomings that need improvement.

This study analyzes the mechanism of directional error generation of the three-axis magnetic flux gate sensor, measures the directional error of the sensor using homemade measurement tools, and corrects the measurement results when reorienting. Finally, by comparing the changes in the actual measurement data before and after correction, the correction effect is analyzed.

(a) GM4 Type Fluxgate Magnetomete

(b) FGM-01 Type Fluxgate Magnetometer

Figure 1: Fluxgate Magnetometer

2 Analysis of Directional Errors in Three-Axis Fluxgate Magnetometer Sensors

Three-axis fluxgate magnetometer sensors consist of three identical and mutually orthogonal single-axis magnetic sensors. When installing the orientation, the induction coil axis of the sensor should be aligned with the direction of the measured magnetic field. Currently, Chinese geomagnetic observatories typically orient sensors in the following manner (referred to as the traditional orientation method). The first step is to select a day with calm magnetic fields, adjust the base angle screws of the sensor to center two mutually perpendicular bubbles, thereby determining the orientation of the Z-magnetic axis. The second step is to rotate the sensor horizontally to control the output value of the magnetic declination angle D within the range of -50-50nT, thus determining the orientation of the D-magnetic axis. The orientation of the H-magnetic axis is determined as the D-magnetic axis is determined.

Due to objective reasons such as manufacturing process limitations, it is difficult to make the Z-component coil plane consistent with the outer shape plane of the sensor. Adjusting the bubbles at the bottom of the sensor to be centered cannot ensure the horizontalness of the Z-component coil, causing the Z-magnetic axis to not completely point vertically to the Earth's core. The error that may result from this is referred to in this paper as the Z-magnetic axis directional error. Furthermore, due to residual magnetism in the magnetic core, even if the spatial magnetic field intensity where the sensor is located is 0, there will still be a small offset output, causing the output value of the D-magnetic axis orientation to actually contain an offset value. This error is referred to as the D-magnetic axis directional error.

Assume the offset of the D magnetic axis is S_0, and the projection value of the magnetic field H on the D magnetic axis is S, as shown in Figure 2(a), where A represents the magnetic east direction, B represents the magnetic north direction, and C represents the position of the magnetic axis when the offset S_0 exists and the output value of D is zero. At this point, the output value of the D component is S_0-S; as shown in Figure 2(b), rotate the position of the D magnetic axis horizontally by 180°, and the output value of the D element is S_0+S; the numerical value of the offset S_0 can be obtained through calculation.

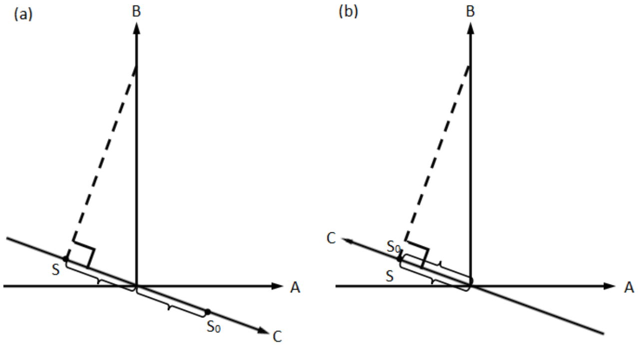
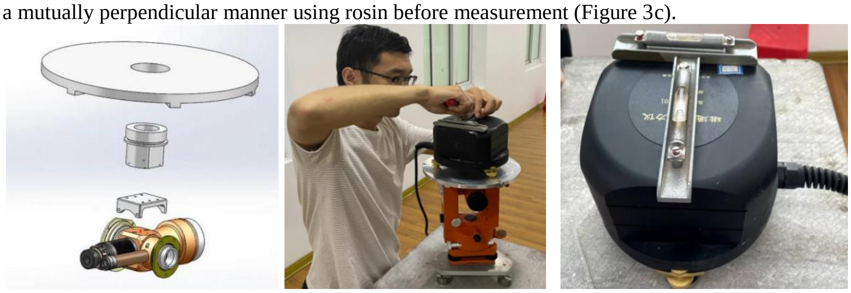


Figure 2: Calculation schematic diagram of offset S_0 at the D magnetic axis orientation position (a) and its position after rotating 180°(b)

Through the above analysis, this paper will measure the offset of sensor D magnetic axis using a homemade measuring tool, inspect the verticality of the Z magnetic axis, and correct the test results during reorientation. The measuring tool, a non-magnetic rotating platform (hereinafter referred to as the platform), is a customized weak magnetic aluminum plate. During measurement, the platform is first mounted on the theodolite telescope (Figure 3a), and then the sensor is placed on the platform. The sensor's rotation is achieved by adjusting the scale of the theodolite (Figure 3b). To check and correct the orientation error of sensor Z magnetic axis, two adjustable levelers are fixed at the top of the sensor in a mutually perpendicular manner using rosin before measurement (Figure 3c).



(a) **(b)** **（c）**

Figure 3: Schematic assembly and actual operation of non-magnetic rotation platform
(a) Non-magnetic rotation platform connection schematic diagram (b) Sensor top with external level (c) Actual operation of non-magnetic rotation platform

3 Laboratory Determination and Calibration of Directional Deviation

The measurement part of this experiment was conducted in the absolute measurement room of Hongshan observatory. The FGM-01 magnetic fluxgate magnetometer was used as the instrument under test (see Fig. 3c).

First, we examined the perpendicularity of the Z magnetic axis using the platform. After leveling the non-magnetic theodolite, we began adjusting the sensor's base angle screws to center two mutually perpendicular bubbles. By rotating the platform, we recorded the output values of the Z element at four positions 90° apart, as shown in Table 1. From the first set of data, it can be observed that the output values of the Z element at the four positions are not equal. The maximum difference between the two values at positions 180° apart reaches 749nT, indicating that the sensor's leveling with the bubbles does not accurately represent the perpendicularity of the Z magnetic axis, suggesting the presence of directional error. We continued adjusting the three base screws to make the Z element's output values as close as possible at different positions. Data from the 2nd to the 6th sets represent the stepwise adjustment of the Z component output values by the base screws. The 6th set of data reflects the measurement result when the base angle screws were adjusted to their extreme positions, with a difference of only 1nT between the two values at positions 180° apart, revealing that the bubbles on the sensor were no longer centered. Additionally, we adjusted a pair of external bubbles previously fixed at the top of the sensor for leveling.

Subsequently, we measured the offset of the D magnetic axis according to the method shown in Figure 2. By rotating the platform, we read the output values of the D element in two directions 180° apart, and calculated the D magnetic axis offset to be 109nT.

Finally, the instrument under test was moved to the relative recording room of the Hongshan observatory. We first checked and leveled the external bubbles fixed at the top of the sensor to correct the Z magnetic axis directional error. Then, we adjusted the sensor to ensure the output value of the D element to be (109±50) nT, completing the correction of the D magnetic axis directional error, and initiating the instrument to begin recording observations.

Table 1 Adjustment Results of the FGM-01 Instrument for the Verticality of the Z Magnetic Axis

Level Angle	Z-Element Output Value（nT）					
	1	2	3	4	5	6
290°	215	198	85	155	-150	-158
200°	-59	-131	-177	-115	-134	-135
110°	-534	-518	-403	-161	-160	-157
20°	-215	-146	-94	-127	-142	-136

It should be noted that we know the daily variation of the geomagnetic field is very small. When conducting experiments, it is advisable to choose a period when the magnetic field is calm and the temperature is stable. It can be considered that at this time, the geomagnetic field is stable and uniform.

4 Analysis of Results

To verify the correction effects mentioned above, the data from the instrument before and after calibration was compared in the following two ways.

4.1 Comparative analysis of calibration results for daily variation records accuracy

The purpose of the calibration for daily variation records accuracy is to examine the accuracy of the fluxgate magnetometer in recording diurnal variation data. The specific method is as follows: On a selected day, an absolute measurement is carried out every hour, and two sets of valid data are obtained for each measurement. The precision and stability are measured by calculating the change in the baseline value and the standard deviation (Gao et al. 1991; Zhang & Yang 2011). The tested instrument underwent diurnal variation calibration both before and after correction, with 10 absolute measurements each time, as shown in Figure 4. As can be seen from Figure 4, there is a clear diurnal variation pattern on the baseline value curves of the tested instrument before correction, with the maximum baseline value change D_B being 0.26′, H_B being 1.7nT, and Z_B being 1.0nT, and the standard deviation for D_B being 0.07′, H_B being 0.5nT, and Z_B being 0.3nT. After correction, the maximum baseline value changes for each element were D_B being 0.07′, H_B being 1.0nT, and Z_B being 0.6nT, with standard deviations of D_B being 0.02′, H_B being 0.3nT, and Z_B being 0.2nT. Compared to the pre-correction data, there was a reduction in both the maximum baseline value changes and standard deviations for each element, with the D element showing the most significant decrease in maximum baseline value change, by 0.19′. The results indicate that the observational data accuracy of the tested instrument post-correction is significantly superior to that of the pre-correction, and it more truly reflects the diurnal variation of the geomagnetic field.

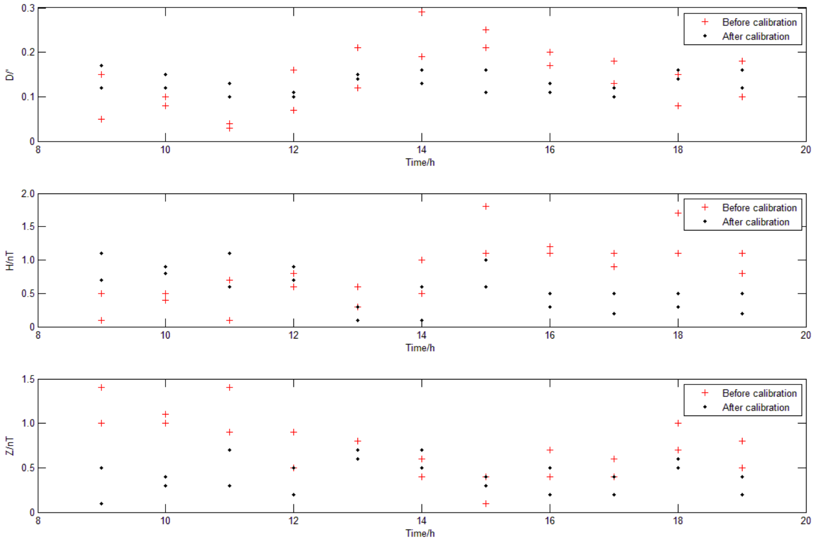
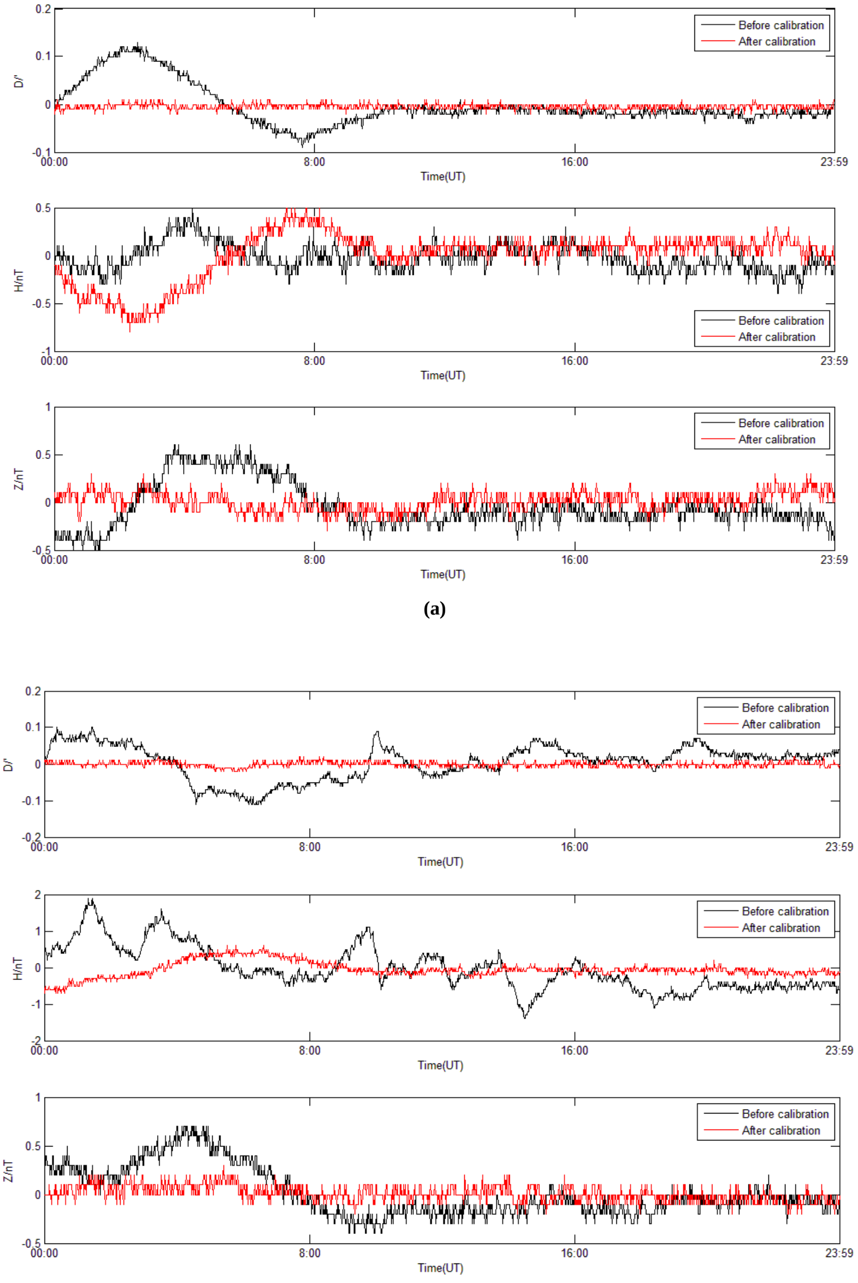


Figure 4: Baseline values obtained through daily calibration before and after calibration of the test instrument

4.2 The comparison of the difference curve of daily variation before and after instrument calibration

The comparison of the difference curve of daily variation can generally describe the consistency of data from different instruments at a station. Using the standard instrument GM4 located in the relative recording room of Hongshan observatory as the reference instrument, the minute values of the instrument under test are compared with those of the reference instrument. The difference curves before and after correction are shown in Figure 5.geomagnetic quiet day and geomagnetic disturbance day are shown in Figure 5(a) and 5(b). It can be observed that the difference between the instrument under test and the reference instrument is significant before calibration, especially for the D component. Even when the magnetic field is relatively stable, the maximum variation in the difference of the D component still reaches 0.22′. After calibration, the differences in magnetic field components between the instrument under test and the reference instrument are significantly reduced, particularly for the D and Z components, with the difference curves coming much closer to a straight line compared to the reference instrument. Selecting data from five geomagnetically quiet days and five disturbed days before and after the calibration of the instrument under test, we computed the range of difference with the reference instrument and calculated the average amplitude (Table 2). As can be seen from Table 2, before calibration, the range of relative differences for the D and Z components were “-0.11 ~ 0.14′, -0.4 ~ 0.6nT” respectively, with the amplitude being roughly the same during quiet and disturbed days. For the H component, the amplitude of the difference was nearly double during disturbed days compared to quiet days. After calibration, the amplitude of the difference for the H component decreased slightly, while the improvement for the D and Z components was quite significant, with amplitudes during quiet days being “-0.02 ~ 0.03′ and -0.2 ~ 0.3nT” and during disturbed days being “-0.05 ~ 0.04′ and -0.3 ~ 0.2nT”, showing a marked decrease compared to before calibration. This indicates that the aforementioned calibration method is effective in correcting the magnetic field components.



(a)

(b)

Figure 5: The difference curve between the tested instrument before and after calibration and the reference instrument
(a)geomagnetic quiet day (b)geomagnetic disturbance day

Table 2 The change amplitude of the daily variation difference between the tested instrument and the reference instrument on a daily basis

	before calibration				after calibration			
	Date	D（′）	H（nT）	Z（nT）	Date	D	H	Z
Magnetic Quiet Day	5.1	-0.11 ~ 0.12	-0.7 ~ 1.0	-0.4 ~ 0.6	5.5	-0.02 ~ 0.03	-0.7 ~ 0.6	-0.3 ~ 0.2
	5.19	-0.12 ~ 0.13	-0.4 ~ 0.8	-0.3 ~ 0.8	5.8	-0.02 ~ 0.02	-0.5 ~ 0.4	-0.2 ~ 0.2
	5.20	-0.11 ~ 0.16	-0.5 ~ 0.4	-0.4 ~ 0.4	5.19	-0.03 ~ 0.03	-0.5 ~ 0.4	-0.2 ~ 0.3
	5.21	-0.11 ~ 0.12	-0.5 ~ 0.3	-0.5 ~ 0.6	5.21	-0.01 ~ 0.03	-0.4 ~ 0.4	-0.3 ~ 0.3
	5.25	-0.09 ~ 0.14	-0.7 ~ 0.6	-0.4 ~ 0.7	5.25	-0.02 ~ 0.02	-0.6 ~ 0.6	-0.2 ~ 0.3
	Mean	-0.11 ~ 0.13	-0.6 ~ 0.6	-0.4 ~ 0.6	Mean	-0.02 ~ 0.03	-0.5 ~ 0.5	-0.2 ~ 0.3
Magnetic Disturbed Day	5.5	-0.11 ~ 0.13	-1.4 ~ 0.4	-0.3 ~ 0.9	5.1	-0.02 ~ 0.04	-0.8 ~ 0.9	-0.3 ~ 0.3
	5.6	-0.12 ~ 0.09	-1.5 ~ 1.6	-0.5 ~ 0.5	5.11	-0.07 ~ 0.03	-1.3 ~ 1.0	-0.3 ~ 0.2
	5.8	-0.11 ~ 0.13	-0.8 ~ 1.2	-0.4 ~ 0.7	5.14	-0.07 ~ 0.05	-0.9 ~ 1.4	-0.2 ~ 0.3
	5.17	-0.13 ~ 0.16	-1.7 ~ 1.2	-0.6 ~ 0.6	5.15	-0.05 ~ 0.02	-1.0 ~ 0.8	-0.2 ~ 0.3
	5.31	-0.11 ~ 0.17	-1.3 ~ 1.0	-0.4 ~ 0.5	5.27	-0.03 ~ 0.05	-1.0 ~ 0.9	-0.3 ~ 0.1
	Mean	-0.12 ~ 0.14	-1.3 ~ 1.1	-0.4 ~ 0.6	Mean	-0.05 ~ 0.04	-1.0 ~ 1.0	-0.3 ~ 0.2

5 Discussion and Conclusion

This paper has analyzed the generation mechanism of orientation errors in triaxial fluxgate magnetometers and conducted a station experiment on an FGM-01 instrument using a self-made measurement device. The experimental and research results show that orientation errors occur in both the Z and D magnetic axes of the sensor, and it is necessary to correct these errors. The observational data, after correction for orientation errors, demonstrated a significant reduction in both the standard deviation of baseline values and the amplitude of differences when compared to a reference instrument, proving the effectiveness of the correction method. The measurement device used in the experiment is low-cost, simple to operate, and easy to disseminate, boasting a high performance-to-price ratio. In this study, the author found that the improvement effects on the D and Z components are more pronounced, whether on magnetically quiet or disturbed days, but not as significant for the H component. This indicates that the accuracy of geomagnetic daily variation records is influenced by factors other than orientation errors, including orthogonality, among others. We will continue to examine the impact of instrument orthogonality and correction methods in future work. The research presented in this paper provides a reference for the standardized installation and regular adjustment of orientation in fluxgate magnetometers at geomagnetic stations.

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Competing Interests

The authors have no competing interests to declare.

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