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ON THE ACCURACY OF FLUX-GATE MAGNETOMETERS - Calibration Experiment –

by

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Abstract

We examined the efficiency of the flux-gate magnetometers, MB-160 and MB-162, Shimadzu, which we use for variation observation at the Kakioka Magnetic Observatory. We also examined our method and the equipment for the calibration of the installed calibration apparatus in the flux-gate magnetometer.

On the basis of examinations, we obtained the following conclusions:

1. Using our equipment for the calibration at Kakioka, which is composed of mainly one set of 3-axial Helmholtz coil, we can calibrate the installed calibration apparatus within an accuracy of 0.1%.
2. When we use the flux-gate magnetometer with the resolution of 0.1 nT, we can extend the range of the observation from ±500 nT to ±600 nT with a sufficient linearity.
3. The output signal for the calibration which is generated by the installed apparatus in the flux-gate magnetometer is stable. With the use of this installed apparatus, therefore, we are able to calibrate the scale value during the observation.

1. Introduction

The torsion-type magnetic variometer has long been used to measure geomagnetic variations. Measurements taken by this variometer are recorded as analog data. The resolution with which geomagnetic variations are measured is about 0.5 nT, and it will drop below 0.5 depending on the measurement accuracy of the variometer. As data processing technology advances, the torsion-type magnetic variometer is falling into disuse, because the measurement involves the manual work of reading measurements and keeping them on record. The fluxgate magnetometer is now widely used because it has a function of converting analog output into digital output.

Besides the fluxgate magnetometer, other types of instruments with the capability of outputting digital values are used to observe geomagnetic variations: they include the optically pumped magnetometer, Overhauser magnetometer, proton precession magnetometer, etc. For its price, the fluxgate magnetometer excels all other magnetometers. At the Kakioka Magnetic Observatory, the optically pumped magnetometer is used because this observatory is a standard observatory and the performance of the magnetometer is given higher priority than the cost. At Memanbetsu and Kanoya Observatories, the cost efficiency is given higher priority, and therefore the fluxgate magnetometers are used.

The performance of the fluxgate magnetometer has improved markedly in recent years. It is now comparable with that of other magnetometers with a digital output function. A critical difference between the fluxgate magnetometer and other magnetometers with a digital output function is that the fluxgate magnetometer is designed to observe components of geomagnetic variations, not to retain absolute values, while other magnetometers are designed to measure total geomagnetic force and to retain absolute values. If magnetometers other than the fluxgate magnetometer are used to observe components of geomagnetic variations, they have a drawback with respect to the stability of their compensating magnetic field (the total magnetic force is separated vectorially to observe the components, and one set of forces is erased). Therefore, there is no conspicuous difference between the performance of the fluxgate magnetometer and other magnetometers in terms of long-term accuracy. After all, all magnetometers must be calibrated based on observed absolute values.

The fluxgate magnetometer is generally considered to be inferior to other magnetometers in reliability. This is associated with the measurement principle of the fluxgate magnetometer: the fluxgate magnetometer measures voltages proportional to the intensity of their magnetic field, while other magnetometers measure frequencies proportional to the intensity of their magnetic field. Because these voltage or frequency signals are very weak signals, they must be subjected to various types of processing (noise removal, frequency multiplication, voltage amplification, etc.) before they are introduced to final measuring devices (a frequency counter and a voltmeter). The voltage amplification factor of the fluxgate magnetometer has a direct effect on measured values. (The frequencies in other magnetometers are subjected to integer multiplication, and therefore measurement errors do not occur.) This means that when the fluxgate magnetometer is used, measurements can be brought close to the desired values by changing the voltage amplification factor. Although manufacturers do calibration work carefully when making the fluxgate magnetometer to achieve a high level of measurement accuracy, the accuracy of the calibration work itself should be questioned if we are to discuss extremely small measured values.

With the above-mentioned drawback of the fluxgate magnetometer in mind, it should be pointed out that variations in the values given by the fluxgate magnetometer do not always represent real geomagnetic variations. The performance of one measuring instrument when observed in terms of the closeness between the measured value and the real value is called "sensitivity," and a conversion constant used to bring a certain measurement closer to a real value is defined as a "calibrated sensitivity value." The calibrated sensitivity value is expressed with the following equations:

$$S = H_o \div F_o$$

$$H = F_o \times S$$

where S is the calibrated sensitivity value, H_o is the reference magnetic-field variation, F_o is measurement value by magnetometer, and H is the geomagnetic variation.

The next chapter describes the present situation of the sensitivity and fluctuations, the accuracy of calibrated sensitivity values, and other matters regarding the fluxgate magnetometer.

2. Present Situation of the Sensitivity of the Fluxgate Magnetometer

As various manufacturers make different fluxgate magnetometers, it is inappropriate to discuss the fluxgate magnetometer without restricting our discussion to specific magnetometer models. In this paper, Models MB-160 and MB-162 made by SHIMADZU CORPORATION are discussed.

Both models have built-in reference magnetic-field signals to allow for easy verification of measured value. The reference magnetic-field signal can be generated in increments of 20 nT over the range from 20 nT to 100 nT. By operating the switch on each model, a reference signal can be generated and superposed on a geomagnetic field being measured. Specifically, a measured value changes by the size of a reference magnetic field the instant the reference magnetic field is applied or removed. (Strictly speaking, the change in a natural magnetic field is also superposed.) The manufacturer maintains that because the reference signal is calibrated correctly, the sensitivity of the magnetometer can be calibrated equally correctly.

The calibrated sensitivity value obtained by operating the switch should always be 1.000 if both the measuring instrument and reference signal are calibrated correctly. In reality, however, this value is not always 1.000. It is not a rare occurrence that a difference of about ±1% occurs with the magnetometers installed at geomagnetic observatories. Furthermore, reports are that annual variations deemed to be associated with sensor temperatures were observed, and the range of variations reached nearly 0.5% (Figure 1). This indicates that either the calibrated reference signal or the measurement system or both should be questioned with respect to specific accuracies, depending on the circumstances. Judging from the state of distribution of repeatedly measured values, the accuracy of a calibrated sensitivity value obtained by operating the switch is estimated to be 0.1% to 0.5% (Figure 2). The obtained accuracy varies depending on the number of times of repetitions (as far as the accuracy alone is concerned, the larger the number of times of repetitions, the higher the accuracy becomes), variations of a natural magnetic field when a reference signal is superposed (it is better to superpose a reference signal when geomagnetic variations are in a calm state), the strength of the reference signal applied (a stronger signal produces better results), and other factors. If the number of times of measurement is increased to 10 to 20 and if the strength of the reference signal applied is increased to 100 nT (the maximum strength to which the built-in reference signal can be set), it will be possible to achieve a level of accuracy of about 0.1%. The sensitivity value is usually calibrated this way when steady-state observations are to be made.

Considering the 1% difference in the previously mentioned calibrated value relative to the 0.1% accuracy, the 1% difference is not negligible at all, because it is too large a measurement error. On the contrary, the 1% difference has a considerable effect on measured values. For example, because the diurnal variation of the "D" component is about 100 nT, a measurement error of about 1 nT will be contained. Other types of errors arising from factors related to the fluxgate magnetometer (the resolution of measured values, the stability of baseline values affected by temperature and level changes, mutual interference when three axes of a sensor do not cross at right angles, errors resulting from the conversion of the amount of the "D" component to an angle, and so forth) have much less impact on the measurement accuracy. For this reason, it is necessary to recalibrate the sensitivity value of the fluxgate magnetometer by using a reference signal other than the built-in reference signal of the fluxgate magnetometer.

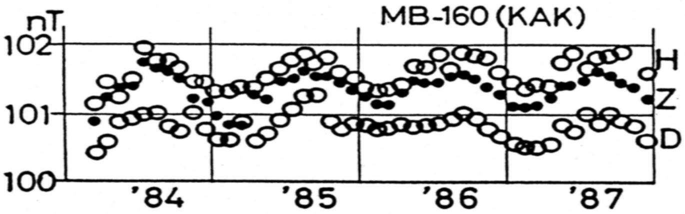


Fig. 1 Change in the sensitivity of the fluxgate magnetometer (change in the output relative to the built-in reference signal of 100 nT)
- Extracted from Gijutsu Hokoku, no. 85 -

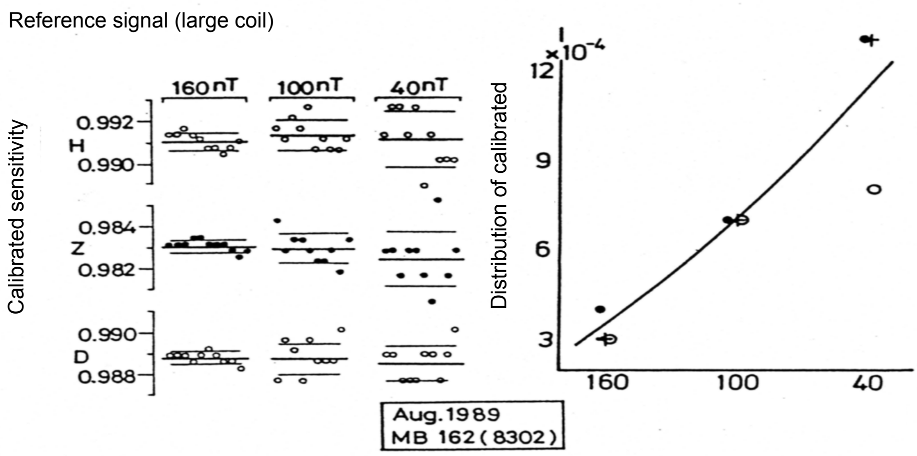


Fig. 2 Reliability of the calibrated sensitivity value (the state of distribution of repeatedly measured values and the strength of a reference signal)

It is theoretically possible to measure the intensity of a geomagnetic field as is, if the measurement range of the fluxgate magnetometer can be extended. In this case, because the number of effective measurement digits of the fluxgate magnetometer is limited, the resolution required to measure geomagnetic variations becomes insufficient. In general, direct-current components are erased by adding a compensating magnetic field (the stability of this compensating magnetic field, which directly affects the stability of the fluxgate magnetometer, has recently improved greatly, and good results can now be obtained) so that only variations are measured. The measurement range is determined by operating the dial indicator on the panel of the fluxgate magnetometer. It is usually set to ±500 nT. In this measurement range, geomagnetic variations can be measured with the resolution of 0.1 nT, so that ordinary geomagnetic variations, such as the ones that occur during geomagnetic storms, can be measured with sufficient margins.

One single calibrated sensitivity value is usually used on the assumption that the sensitivity is uniform in the range of ±500 nT. Regarding the uniformity of the sensitivity inside a smaller range of ±100 nT, some experiments were conducted using the built-in reference signal and the results were reported. We conducted experiments by extending the range beyond ±100 nT to check the uniformity of the sensitivity. In conducting experiments, we used the following two methods:

(1) Overall connection method: We used a set value as a mid-point and measured the sensitivity within a range of ±100 nT with a built-in reference signal. While applying the compensating magnetic field previously mentioned, we measured the sensitivity values by successively moving the set point gradually.

(2) Sensitivity measurement method: The magnetometer was set to produce an output near zero under normal operating conditions. In this setup, we measured the sensitivity in the measurement range by using an external reference signal (generated by a large Helmholtz coil and other devices to be explained later).

As shown in Figure 3, the sensitivity values obtained are linearly distributed. Figure 3 shows only the results of an experiment conducted using one specific magnetometer (MB-162 No. 8901) and the method (2) mentioned above. The same linear tendency, however, was noted with the results of an experiment conducted using another magnetometer (MB-162 No. 8302) and the method (1) mentioned above. It was verified that sensitivity values are uniform in a wide range and that the same calibrated sensitivity value can be used as a typical, uniform value if we want to improve the accuracy of the calibrated sensitivity value to 0.1%.

Figure 3 shows the calibrated sensitivity values represented as digital output values. The same tendency as observed with digital output values is noted with analog output values.

Sensitivity values are dispersed at the central portion (where the strength of the applied reference signal is less than 100 nT) more than at other portions, as shown in Figure 3. This shows that the accuracy of the calibrated sensitivity values is poor. This dispersion is attributed to the fact that the applied reference signals were weak, and as a result, the required level of relative resolution for the measured values could not be obtained. This means that if we are to obtain high-accuracy sensitivity values by using weak reference signals, it is important to make measurements repeatedly (reports are that measurement must be made repeatedly 10 to 20 times).

Calibrated sensitivity values are also shown in the region beyond the range of ±500 nT, and they can be considered to be a continuation of sensitivity values in the range of ±500 nT. This means that even if the measurement range is set to ±500 nT, it is possible to make measurements in the range up to ±600 nT.

The fluxgate magnetometer consists of three parts: a sensor, a measurement system, and a cable. Although these parts are usually used as one set, any of these three parts can be replaced with one part of another compatible measuring instrument. If a fluxgate magnetometer with a part of another compatible measuring instrument assembled is used to make measurements, the output values may vary by several percent of error or up to 10% of error. As explained earlier, the fluxgate magnetometer can output correct measurements after being calibrated.

The manufacturer calibrates it by adjusting the coil constant of a sensor, the supply current for sensitivity calibration of a measurement system, the amplification

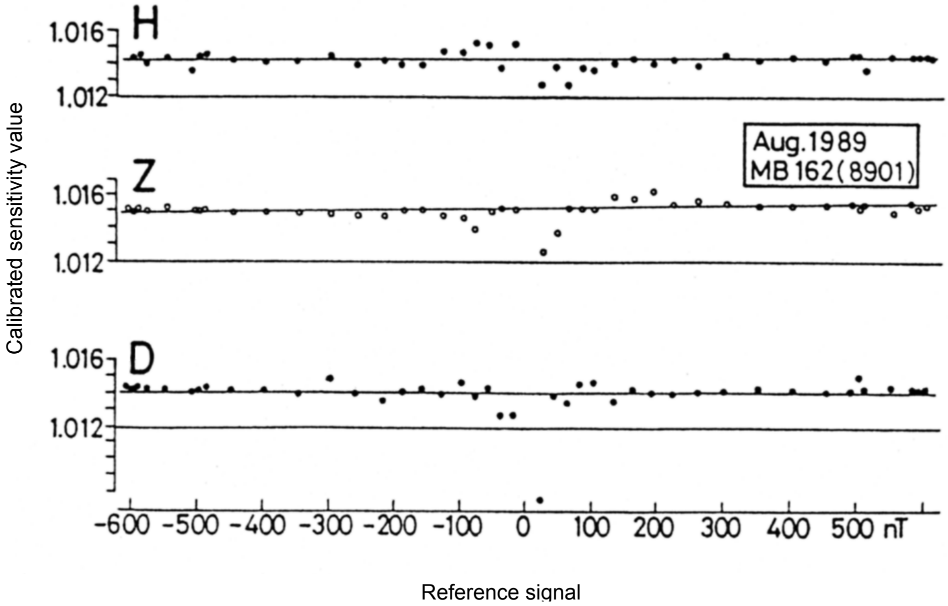


Fig. 3 Linearity of sensitivity values of the fluxgate magnetometer

factor of voltages to be output by a sensor, etc., all as one set. Therefore, if parts of another measuring instrument and those of the fluxgate magnetometer are combined as one set, this set must be considered to be a new set and it must be newly calibrated. If it is not calibrated, the measured values are unreliable, except for a case in which only a cable is replaced. We conducted an experiment by replacing a 100-meter cable with a 300-meter cable and found that there was no significant difference between the sensitivity values measured using the 100-meter cable and those measured using the 300-meter cable. This is thought to be due to the fact that the resistance of the cables is so small as to be negligible compared with the resistance in the measuring instrument itself. (See Figure 4.)

In making measurement for the long term, it is important to take into consideration the change in the sensitivity of the fluxgate magnetometer over time. An example of this change in the sensitivity over time is shown in Figure 5. As shown in Figure 5, as the temperature of a detector or the measuring instrument itself changes by 10 degrees, the sensitivity changes by a maximum of 0.1% (Z component). This is a significant change that exceeds the measurement accuracy (about 0.05%) obtained by increasing the number of times that the measurement is repeatedly made.

With regard to the D component, however, no noticeable change in the sensitivity is observed.

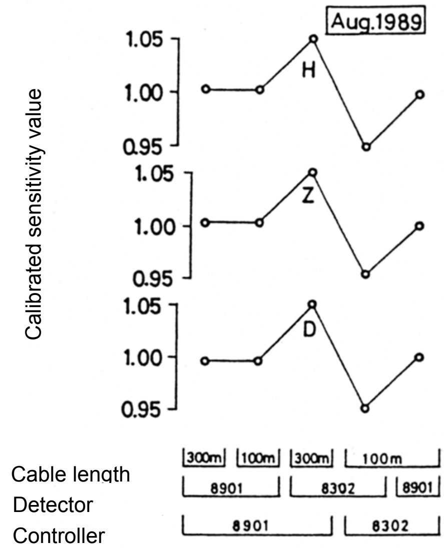


Fig. 4 Calibrated sensitivity values relative to compatible magnetometers

Considering the case of MB-160 shown in Figure 1, it would be more sensible to make the measurement by assuming that the calibrated sensitivity values do change over time. The sensitivity changes as sensor temperatures change, as shown in Figure 1, and the sensitivity values remain unaffected by the types of reference signals, as shown in Figure 5. (The subscript "i" attached to a straight line means that the built-in reference signal was used, while the subscript "o" means that an external reference signal was used.) Therefore, it is presumed that the built-in reference signal remains unchanged.

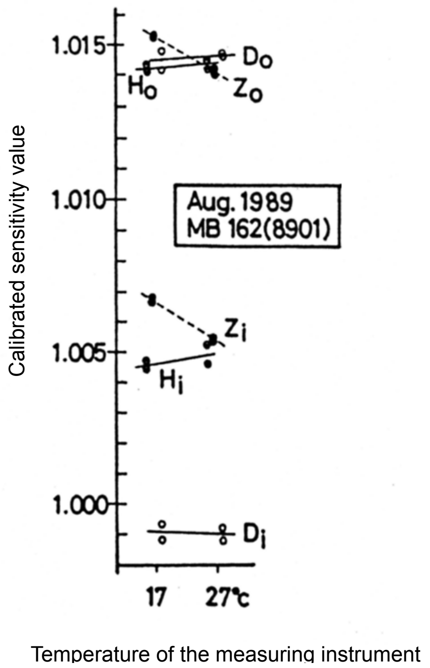


Fig. 5 Dependence of the calibrated sensitivity value on temperatures

This assumption indicates that a built-in reference signal calibrated using a certain method at a certain time can be used throughout the service life of the magnetometer.

Judging from the results of two experiments (Figures 1 and 5), it is thought that the sensitivity changes as sensor temperatures change and that the sensitivity changes at the rate of less than 0.05%/°C. To keep the sensitivity measurement error to about 0.1%, therefore, the change in the sensor temperature must be kept below 2°C. If the change in the sensor temperature exceeds 2°C, another different sensitivity value must be applied.

3. Sensitivity Calibration Methods and Resultant Accuracy

In the previous chapter, we discussed the present situation of the sensitivity of the fluxgate magnetometer, and indicated that the sensitivity must be calibrated using appropriate calibration methods in order to measure geomagnetic variations with a high level of accuracy by using the fluxgate magnetometer. This chapter describes the sensitivity calibration methods and resulting accuracy.

A method of calibrating the sensitivity using the built-in reference signal of the fluxgate magnetometer is generally used. This is the simplest method: applying the reference signal by pressing a sensitivity-calibration push button and reading the change in the measured value shown on the magnetometer. Because the fluxgate magnetometer usually has a built-in reference signal of about 100 nT and is capable of resolution up to 0.1 nT, the sensitivity can be calibrated with a degree of accuracy as high as 0.1%. The reference signal and natural variations in the magnetic field are superposed, causing interference to the process in which the magnetometer produces a sensitivity value. If this interfering effect is strong, the degree of calibration accuracy will drop. By making measurements when the geomagnetic variations are in a calm state and using mean values obtained through repeated measurements, it is possible to achieve 0.1% accuracy. One problem of this method is the reliability of the built-in reference signal. That is, although it is stated in the specifications that the reference signal accuracy is 100 nT, 100.0 nT is not necessarily a guaranteed figure. As mentioned in the previous chapter, it would be safer to assume that ±1% of a margin of error is contained in the stated signal accuracy.

With the second method, geomagnetic variations are measured using the fluxgate magnetometer, while at the same time they are measured using a standard measuring instrument specially designed for observation of geomagnetic variations. Using this method, the reference signal used to calibrate sensitivity is the value of geomagnetic variation designated by the standard measuring instrument. Although this method has the advantage that sensitivity variations can be checked and calibrated by continuing to make measurements over a long period of time, it has a drawback with respect to the calibration accuracy. If we are to achieve a satisfactory level of calibration accuracy by using this method, the following requirements must be met:

- Geomagnetic variations at a point where there is a standard measuring instrument must be exactly the same as geomagnetic variations at a point where there is a calibrating meter.
- If rapid geomagnetic variations are to be measured, measurement must be made with exactly the same timing.
- If slow geomagnetic variations are to be measured, long-time stability is required.

Furthermore, the intensity of geomagnetic variations to be measured is generally very small, and the geomagnetic variation of 100 nT required to achieve the 0.1% accuracy seldom happens. To compensate for the insufficiency in the relative resolution due to the small amount of variation, it is possible to increase the apparent resolution to more than 0.1 nT by superposing similar phenomena (for example, the amplitude of diurnal variations on the order of some 10 nT). However, this technique does not always produce good results.

The crucial drawback of this method is that the reference value must be provided by a standard measuring instrument in parallel, and measurement must be made for the long term to calibrate the correct sensitivity values.

With the third method, a device for making an artificial magnetic field is used together with the built-in reference signal for calibration. To make artificial magnetic fields, large Helmholtz coils and power supplies are installed at the Kakioka Magnetic observatory. The accuracy of an artificial magnetic field required to calibrate the sensitivity value correctly is determined by the coil constant and the current accuracy. Although the coil constant and current accuracy values are known values, we examined and evaluated them and described the results in this paper.

If the sensitivity of the magnetometer is calibrated using the large Helmholtz coils, the direction of magnetic-field measurement (sensor direction) using the magnetometer must match the orientation of a magnetic field formed by the Helmholtz coils. Although the match accuracy should be as high as possible, it is a waste of time to attempt to increase the match accuracy above a certain required level. If the orientation of a magnetic field "A" formed by the Helmholtz coils deviates from the direction of a geomagnetic field to be measured (sensor direction of the magnetometer) by θ°, the relationship between the orientation of the magnetic field "A" and the size of the magnetic field "B" formed in the sensor direction is expressed as follows:

$$B = A \times \cos\theta$$

B/A directly affects the accuracy of sensitivity calibration. Because the accuracy of calibrating the sensitivity by monitoring the state of distribution of sensitivity values is 0.1% at best, 2° should be satisfactory as the value of θ . Factors that lead to the occurrence of errors must be reduced to a minimum, and therefore it is recommended that θ should be adjusted to about 0.2°. To confirm that the direction of magnetic-field measurement matches the orientation of the magnetic field formed by the Helmholtz coils, the amount of magnetic variations in the orthogonal direction (Z or D when H is calibrated) must be checked by turning the current to the Helmholtz coils on and off. If a deviation of θ° is noted, the relationship between the size "A" of the magnetic field formed by the Helmholtz coils and the size "C" of the magnetic field in the orthogonal direction can be expressed as follows:

$$C = A \times \cos\theta$$

To bring θ within 0.2°, C should be less than 1.5 nT if A is 500 nT. 0.2° is a figure determined with a sufficient margin, and there should be no problem even if C is set to 15 nT, 10 times as large as 1.5 nT. This technique of checking the sizes or intensities of magnetic fields assumes that the orthogonality of the magnetometer sensor is correct. Results of experiments conducted in the past show that the orthogonality was on the order of a few minutes (0.1°), which was quite satisfactory (refer to the report of Kamii for further details). In the setup described above, turn the current to the Helmholtz coils on and off and read the values given by the magnetometer. As mentioned earlier, the relative resolution can be increased if a larger current is supplied to the Helmholtz coils. Because the measurement range of the magnetometer is usually set to ±500 nT, the artificial magnetic field should be increased gradually from about ±50 nT to ±500 nT, and sensitivity values should be examined to check the uniformity while monitoring the values given by the magnetometer. If the intensity of the artificial magnetic field is low, the relative resolution is also low, and therefore the calibration accuracy must be increased by making measurements repeatedly.

We will here discuss the reference-current accuracy and the coil-constant accuracy of a device for generating a reference magnetic field at each geomagnetic observatory.

A stabilized power supply (TYPE2852) made by Yokogawa Electric Corporation was used to generate the reference current. Because an indication of current instabilities was noted, another different model (TYPE2561) made by the same company is now used. Although both power supplies can maintain an accuracy of ±0.03%, they must be tested and calibrated periodically to maintain this accuracy level. The effective calibration period, however, has already expired for reasons of operating conditions and costs.

It is desirable to ask the manufacturer to test and calibrate the reference current and to obtain an official calibration certificate. In conducting the present experiment, however, we tried to calibrate it by ourselves within the scope considered appropriate by using measuring equipment that we owned. We used three digital multimeters (Model TR6851 made by Advantest). A maximum deviation of measured values given by these three multimeters was 0.02%, and the mean value of all measurements made was ±0.01%, which was considered to be correct. We found that the output of the stabilized power supply (TYPE2561) was larger than the set value by 0.02%. Considering that the measurement accuracy of the value of a dummy resistor used to convert current into voltage was ±0.03%, it was thought that an appropriate margin of error could still be maintained. More specifically, the current value set using the dial indicator on the power supply unit was thought to be constant within the range of ±0.03%. It remained constant in the measurement range of 1 mA to 100 mA that we used for this experiment, and no deviation from the range of ±0.03% was noted even if the measurement range was changed (Figure 6). In discussing the 0.1% accuracy with which the sensitivity value must be calibrated, the set current value should be considered to be sufficiently reliable.

The stabilized power supply (TYPE2852) was used for about 10 years after it was calibrated, and its output value could not be trusted. Considerable dispersion was noted in the range from 1 mA to 100 mA (maximum deviation: ±1%), and a considerable difference was also noted between different set ranges.

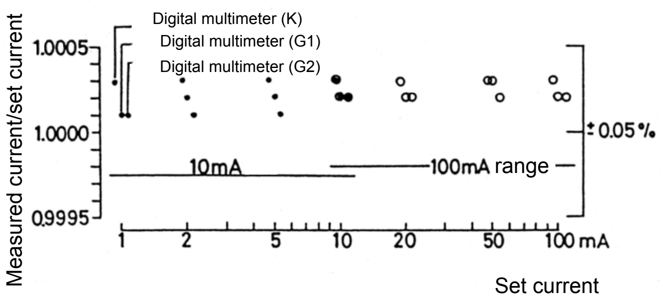


Fig. 6 Accuracy of the current used to form a reference magnetic field (type 2561)

Differences in the measured values given by previously mentioned multimeters were also large, indicating that the output current was unstable. It is very regrettable that, by continuing to calibrate the sensitivity, we have continued using this power supply with confidence until just recently.

The coil constants of the Helmholtz coils now being used are shown in Table 1 (values adopted in the past). They were calculated using the equations shown in Figure 7, based on the sizes of coil frames and the number of coil turns.

As is apparent from the equations, the coil-constant accuracy calculated is dependent on the accuracy of measuring the coil lengths and intervals. Judging from how the coil lengths and intervals entered in the test report were different, the limit of the coil-constant accuracy was considered to be 0.1%. It would be safer to define it as about 0.2%.

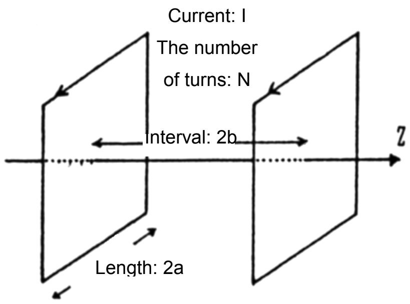
In this experiment, we determined the coil constants using a method that was not influenced by the accuracy of measuring the coil lengths and intervals. Specifically, we used a magnetometer set in the center of the coil to check the variations of a reference magnetic field formed by the Helmholtz coils and the power supply system.

To check the change of the magnetic field, we used an optically pumped magnetometer (MQM-100) made by Mitsubishi Electric Corp. The value given by this magnetometer does not contain sensitivity-related errors that accompany the measurement of variations, as previously described. Furthermore, the correctness of the values given by this magnetometer was verified through a comparison with the values given by an optically pumped magnetometer that we owned (made by NEC Corp; it is part of the KASMMER system).

The optically pumped magnetometer measures only the intensity of a geomagnetic field (total magnetic force), and cannot measure only variations of a geomagnetic field formed by the Helmholtz coils in a specific direction. The intensity of a magnetic field formed by the Helmholtz coils in a horizontal or vertical direction was converted to total magnetic force, and the total magnetic force value was compared with actual measurements (inclination values used were the values that we collected during observations). In this case, although the orientation of the Helmholtz coils is a factor responsible for causing conversion errors,

Table 1 Coil constants of the large Helmholtz coils

	North-south coil (nT/mA)	East-west coil (nT/mA)	Vertical coil (nT/mA)
Values adopted in the past	11.232	11.633	10.866
Accuracy of above values	0.010	0.010	0.010
Measured values	11.222	11.628	10.869
Accuracy of above measured values	0.001	0.004	0.002
Difference (values adopted in the past - measured values)	+ 0.010	+ 0.005	- 0.003



$$C=(1.6\times a^2\times N)/((a^2+b^2)\times\sqrt{(2a^2+b^2)})$$

C: Coil constant (nT/mA)
2a: Length of one side of a rectangular coil (m)
2b: Interval between a pair of rectangular coils (m)
N: The number of turns of the coil

$$B_z=I\times C$$

Bz: Intensity (nT) of a magnetic field formed in the Z direction
I: Current supplied to the coil (mA)
C: Coil constant (nT/mA)

Fig. 7 How to calculate the coil constant

errors, there should be no problem if both horizontal and vertical coils are tilted by less than 2°. According to the results of experiments that Kamii et al. conducted at a later date, the tilt was less than 10', and this should cause no problem at all. Coil constants calculated are shown in Table 1 (values measured in this experiment).

The coil constant of the coil for forming a horizontal magnetic field in the east-west direction could not be calculated by using this method because a large error might occur when the intensity of the magnetic field formed in the east-west direction was converted to total magnetic force and the required coil-constant accuracy could not be obtained. As a solution, variations of the magnetic field formed by the Helmholtz coils were measured using the fluxgate magnetometer. The sensitivity of this fluxgate magnetometer was calibrated using the coil for forming a horizontal magnetic field in the north-south direction. Coil constants calculated this way are shown in Table 1 (values measured in this experiment).

The difference between the values adopted in the past and those measured in this experiment ranged from 0.01 (0.1%) to - 0.003 (0.03%). It is not necessarily a significant difference if we consider the accuracy of values adopted in the past. However, because the measurement accuracy is 0.05% in this experiment, it was thought that the values adopted in the past should be changed. Although concern remains as to the calibrated reference current value (the stabilized power supply, TYPE2561, was later calibrated by the manufacturer and 0.01 % was achieved), we propose that the coil constants determined in this experiment be used from now on.

If we are to calibrate the sensitivity of the fluxgate magnetometer with the accuracy of 0.1% (sensitivity values are generally calibrated with the accuracy of 0.1%), this level of accuracy can be achieved by applying the artificial magnetic field formed by the Helmholtz coils and the reference current.

There are three methods for obtaining sensitivity values, as previously described. The good and bad points of these three methods are summarized in Table 2.

Table 2 Good and bad points of the three sensitivity calibration methods

Reference value	Good point	Bad point
Large Helmholtz coil	The reliability of the reference value is high.	The state of variations that occur cannot be monitored (measurement is impossible after setting).
Internal calibration signal	Variations can be monitored easily.	The reliability of the reference value is low. Variations of the reference signal cannot be monitored (the reliability is low).
Geomagnetic variations	Variations can be monitored.	Geomagnetic variations must be measured using the fluxgate magnetometer, while at the same time they must be measured using a standard measuring instrument. (High-reliability equipment is required.) It takes time and labor to process data. (A large quantity of data is required.)

If we are to obtain highly accurate measured values by making measurements for a long time using the fluxgate magnetometer, the following method should be used to calibrate the sensitivity values:

(1) Calibrate the built-in reference signal of the magnetometer using the large Helmholtz coils.

$$\alpha = S_o / S_I$$

α : Calibration coefficient of the built-in reference signal

S_o : Sensitivity value of the magnetometer measured using the large coils

S_I : Sensitivity value of the magnetometer measured using the built-in reference signal

(2) While the fluxgate magnetometer is used, the sensitivity values must be checked periodically using the built-in reference signal, and the sensitivity values to be adopted must be determined and used.

$$S = \alpha \times S_I$$

S: Sensitivity value to be adopted

4. Accuracy of the Fluxgate Magnetometer

The measurement accuracy of the fluxgate magnetometer is affected most by sensitivity-related factors, as described earlier. If the sensitivity is calibrated using the methods described in the previous chapter and if measured values are corrected properly, the accuracy of values given by the fluxgate magnetometer will be improved. Because the sensitivity can be calibrated with the accuracy of 0.1%, measured values can also be obtained with the same level of accuracy. That is, if a variation of about 100 nT occurs (this is equivalent to diurnal variation), the resolution of 0.1 nT, which is 0.1% of 100 nT, can be maintained, and this resolution level compares with that of the optically pumped magnetometer, a magnetometer of the highest-level accuracy available today. If a variation of more than 100 nT occurs (this is equivalent to "Dst" of a geomagnetic storm, when variation close to 1000 nT is experienced), there is the possibility that errors on the order of about 1 nT are contained in the measured values, and therefore the optically pumped magnetometer still excels the fluxgate magnetometer in this regard.

Another concern is the stability of calibrated sensitivity values. The sensitivity value can be calibrated with an accuracy higher than 0.1% under the given conditions in which the fluxgate magnetometer is placed (under conditions in which the sensitivity is calibrated). However, after a lapse of a certain time length, it is unknown whether the calibrated value is still maintained or not. Sensitivity values calibrated using the built-in reference signal change over the years, as previously mentioned. If this change is the change in the sensitivity (output values of geomagnetic variations), not in the built-in reference signal, there is a remedy that we can use to correct this change. Specifically, we would like to propose that the built-in reference signal be calibrated using the large Helmholtz coils (the true value that allows 100 nT to be maintained constantly) and that sensitivity values be obtained using the built-in reference signal during measurements. It was reasoned from past data on the secular change in calibrated values that what changes over the years is the sensitivity, not the reference signal. The grounds for this reasoning are as follows:

(1) The change in the sensitivity calibrated with the built-in reference signal is associated with the change in sensor temperatures. It is thought

improbable that the change in the sensitivity is associated with the measurement system (the power supply section that generates the built-in reference signal is located inside this measurement system).

(2) If what changes over the years is the reference current, the change in the reference current should be proportional to the change in the baseline value because the V/I conversion circuit is used to erase the background magnetic field. This proportional relationship, however, cannot be observed.

(3) The sensitivity of the fluxgate magnetometer calibrated through a comparison with values given by the optically pumped magnetometer also changes (details are unknown due to a lack of accuracy). This indicates that what changes over the years is not the built-in reference signal.

(4) The change in the sensitivity cannot be explained even if we examine the change in the coil constant of a sensor coil. In the fluxgate magnetometer, one single coil is used to calibrate sensitivity to erase background magnetic fields. However, how the sensitivity changes is quite different from how the baseline value changes. The cause of the change in the sensitivity is not known as of this moment. Nakajima, one of the authors of this paper, is conducting research to verify whether the hypothesis that the built-in reference signal remains stable is correct by comparing the values given by the fluxgate magnetometer with those given by the optically pumped magnetometer.

5. Summary

Although the performance of the fluxgate magnetometer has been improved considerably in recent years, some sensitivity-related matters are not yet resolved completely, and the fluxgate magnetometer is still behind the optically pumped magnetometer in performance. In this paper, we described the sensitivity of the fluxgate magnetometer (MB-160 and MB-162 made by SHIMADZU CORPORATION), as well as the calibration methods.

The main points presented in this paper are summarized as follows:

(1) The measurement accuracy based on the calibrated sensitivity value is 0.1% at best under the circumstances.

(2) The values given by the magnetometer are uniform over a wide range. In the ±500-nT range, it is possible to measure the intensity up to ±600 nT.

(3) Complete confidence should not be put in the built-in reference signal.

(4) The sensitivity could be calibrated with the absolute accuracy of 0.1% when we used the device for forming a reference magnetic field (a large Helmholtz coil and a power supply combined) at the Kakioka Magnetic Observatory.

(5) Research is being conducted on the calibrated sensitivity values. We see a good possibility of being able to calibrate the sensitivity by using the internal reference signal calibrated by the large Helmholtz coils.

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