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Geomagnetic Absolute Observation by Applied Vector Proton Method

by

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Abstract

A new method of absolute observation of three geomagnetic field components by a device composed of a geomagnetic total force magnetometer combined with three orthogonal coils to produce a compensating magnetic field was investigated. A vector proton method is an excellent method to measure vector components of geomagnetic fields; however it cannot serve as a magnetic absolute observation because of the inclination of the compensating coil and its fluctuation over time. This study considered a new method based on the vector proton method. Absolute magnetic fields and orientation of compensating coils are calculated from measured values of magnetic total forces for certain patterns of artificial magnetic fields added to each component by the three orthogonal compensating coils.

Assuming that resolution and stability of the geomagnetic total force magnetometer and electric current through the coils are adequate, three components of geomagnetic absolute fields could be measured by the new method with a degree of precision comparable to magnetometers in current use.

1. Introduction

Three absolute geomagnetic components have been observed by using a proton magnetometer to measure total magnetic force and a magnetic theodolite (DI-72) to measure declination (D) and inclination (I) including a test period since 1972. The resolution and sampling rate of the equipment for magnetic variation observation continues to increase and its operation is becoming increasingly automated. On the other hand, absolute observations are still made by manually measuring the angles (or directions perpendicular to the angles) of geomagnetism using the geomagnetic theodolite.

Various studies have been made in order to automate geomagnetic absolute observations: the vector proton method, ASMO (Alldredge and Saldukas, 1964), dIdD (Kokusai Electronics Corporation, 2001; Hegymegi *et al*., 2005), etc. Although these studies were significant from the standpoint of magnetic variation observation, they were not necessarily successful in terms of geomagnetic absolute observation. In the case of the vector proton method, horizontal components (H components) can be measured by canceling out vertical components (Z components) with compensating magnetic fields (Sakuraoka, 1966). At Kakioka, the horizontal magnetic force is about 35,000 nT and the vertical magnetic force is about 30,000 nT. If a compensating magnetic field of 35,000 nT is applied vertically in an upward direction, the vertical components of the geomagnetic field are canceled out and the horizontal components alone remain. The horizontal components can be obtained with a precision of ±0.1 nT under the condition that the vertical magnetic force is within 35,000±80 nT. This method has the advantage that component values can be obtained stably even if the accuracy of the compensating current used to form the compensating magnetic field is not so high. It has the disadvantage, however, that an error of about 0.17 nT occurs with one second inclination angle of the compensating coil. Absolute observations using this method have not been put to practical use yet because the amount of inclination of the compensating coil cannot be understood or controlled.

In the case of ASMO, at first the direction of the total geomagnetic force (the inclination and declination angles at that time defined as I' and D', respectively) is observed, and the amount of variation from I' and D' is measured by applying a compensating magnetic field in two directions perpendicular to the initial total geomagnetic force. Although ASMO has the advantage that the measured value maintains its accuracy with the inclination of compensating coils, its weakness is that I' and D' may fluctuate if the whole observation system inclines due to the installation pillar inclining. dIdD is based on the same principles of measurement and, therefore, has the same problems.

2. System Configuration

Although the total force magnetometer was not originally designed to measure geomagnetic components, the vector proton method enables measurement of components using the geomagnetic total force magnetometer by making perpendicular components extremely small by applying a compensating magnetic field to the horizontal components when measuring vertical components, or to vertical components when measuring horizontal components. With ASMO and dIdD, declination and inclination angles are calculated by using a combination of the value measured by adding the compensating magnetic field to the two axes perpendicular to the direction of the total magnetic force vector, and the value measured without applying a compensating magnetic field (total magnetic force). The vector proton method is easy to understand as measured values are component values. With ASMO, however, some calculations are required.

Based on the understanding of all these methods, we propose a system for measuring total magnetic force values by applying compensating magnetic fields using three orthogonal compensating coils. Figure 1 shows the outline of the system configuration in which there is the centrally-located geomagnetic total force magnetometer sensor and three orthogonal compensating coils. The three orthogonal compensating coils are set on an approximately level surface; the first coil is set perpendicular, the second coil set parallel, and the third coil set vertical to the magnetic north. They are called the x-axis coil (east plus), y-axis coil (north plus), and z-axis coil (upper plus), respectively. The amount of current supplied to each axis coil can be controlled, and a specified compensating magnetic field can be applied in the axial direction of each axis coil. The compensating coil has a mechanism for rotating itself horizontally. Other important conditions include that simultaneously the magnetic component variations are measured with a constant baseline value in short time (in about one minute for one second sampling measurement, as described in the next chapter).

This observation system consists of the geomagnetic total force magnetometer sensor, the measurement device, three orthogonal compensating coils, the current control unit, equipment for magnetic variation observation, a clock, and the recording unit.

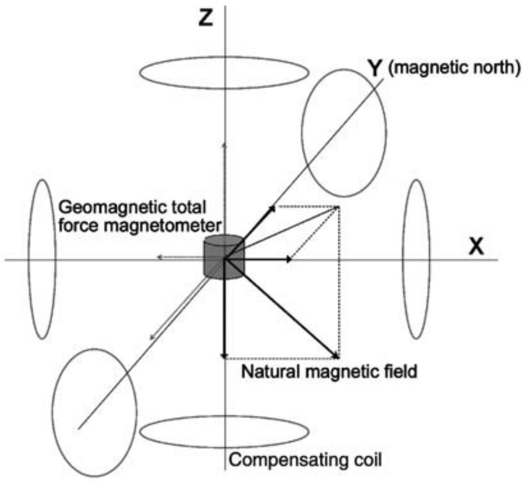

Figure 1 Outline of the observation system
The geomagnetic total force magnetometer is set in the center and three compensating coils are installed on three axes intersecting each other at right angles. The total magnetic force value is measured when each coil forms and applies a magnetic field of an appropriate size.

3. Measurement Procedure and Calculation Method

The coordinate is an orthogonal three-axis coordinate. The y-axis is on a level surface and faces approximately magnetic north, the x-axis is on a level surface and faces east so that its direction is perpendicular to the y-axis, and the z-axis is set vertically to face upward. The y-axis should be set in proper alignment with the horizontal direction of the y-axis coil. The x- and z-axis coils are not necessarily in alignment with the directions of the x- and z-axes; slight displacements due to machining accuracy, installation error, etc., are included in the positions of the x- and z-axis coils. Another method should be used to verify how much the y-axis direction deviates from geographical north (true north). For example, it is conceivably possible to observe the polestar using a compensating coil platform provided with a direction measuring function, a point elaborated on also in Chapter 4. The compensating coils might not “twist” even though they incline due to the effects of temperature change, rainfall, etc., after the angle (defined as D_0) that the y-direction forms with the true north is determined; D_0 should remain constant except when earthquakes or other disturbances occur. In operating the system, however, D_0 should be measured periodically to ensure that the initial angle setting remains unchanged; the frequency with which this periodic measurement is made will differ depending on system and conditions at installation locations.

Although each compensating coil is set approximately parallel to the coordinate axis, slight displacements will remain in actual practice. Since these displacements are considered extremely small, they are expressed as vector components, though it is possible to express them as angles. For example, the vectors of a compensating magnetic field that the x-axis coil forms using a certain amount of current are defined as X_0, X_y, and X_z (Figure 2). Here, the relationship between these vectors is $X_0 \gg X_y, X_z$. Providing that the intensity of a compensating magnetic field, X_0, is 30,000 to 40,000 nT and when the deviation from the x-axis is about 10 minutes, X_y and X_z are about 100 nT. The vectors of compensating magnetic fields that the y- and z-axis coils form are likewise defined as (Y_x, Y_0, Y_z) and (Z_x, Z_y, Z_0). Based on the above-mentioned vector definitions and relations, we have $Y_x = 0$.

If geomagnetic components are defined as (x, y, z), then x is about 0 nT (to be set in this direction when making the initial setting), y is about 30,000 nT, and z is about 35,000 nT in the Kakioka area. Adding compensating magnetic fields makes those components become close to zero, leaving only the other components, which makes calculations simple and easy. Considering the accuracy in calculating the x-component, the intensity of the X_0 should be made approximately equal to that of y and z so that the total magnetic force value can be measured when the y and z components are zero. X_0, Y_0 and Z_0 were defined as 40,000 nT, 30,000 nT, and 35,000 nT respectively, and three patterns of compensating magnetic fields were applied to each axis coil: 0, $\pm X_0$ for the x-axis coil, 0, $-Y_0$, $-2Y_0$ for the y-axis coil, and 0, $+Z_0$, $+2Z_0$ for the z-axis coil, each including the zero compensating magnetic field. By applying these compensating magnetic fields, the total magnetic force value of each was measured. If the vector of a compensating magnetic field of each axis coil is not parallel to the coordinate axis, the amount of influence on X_y and other components increases or decreases relative to the amount of current. In the conventional vector proton method, the multiple

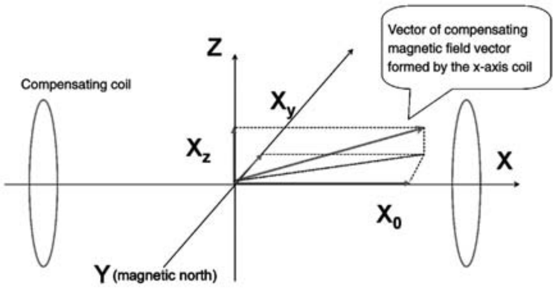

Figure 2 Compensating magnetic field vectors
Components of the compensating magnetic field formed by the x-axis coil when the direction of the x-axis coil is displaced at a very small angle from the x coordinate axis are expressed as (X_0, X_y, X_z). Components of the compensating magnetic field formed by other axis coils are also expressed in the same way.

compensating magnetic fields were not applied at one time. This restriction was removed, and the patterns of compensating magnetic fields shown in Table 1 were applied. Approximate total magnetic force values were estimated by applying appropriate values, and these estimated values are shown in Table 1. C_x, C_y and C_z are the coefficients associated with the intensity of compensating magnetic fields of each axis. On line No. 0 in this table, the total geomagnetic force value is shown when $C_x = C_y = C_z = 0$, which means there is no compensating magnetic field. On line No. 1, the total magnetic force value 30,191.5 nT (the nearly horizontal component) measured by applying $C_z \times Z_0$ ($1 \times 35{,}000$ nT) in the upward direction relative to the z component is shown. On line No. 1, the z-axis coil inclines. Therefore, in addition to the z component, -100 nT ($= C_z \times Z_x$) is added to the x component, and $+90$ nT ($= C_z \times Z_y$) to the y component.

Table 1 Additional patterns of compensating magnetic fields and total magnetic force values

No.	C_x	C_y	C_z	Total magnetic force value [nT]
0	0	0	0	46314.8
1	0	0	1	30191.5
2	0	0	2	46130.5
3	0	-1	0	35280.3
4	0	-1	2	34722.6
5	0	-2	0	46307.2
6	0	-2	1	29813.0
7	0	-2	2	45643.3
8	1	0	0	61208.1
9	1	0	1	50000.1
10	1	0	2	60857.4
11	1	-1	0	53292.4
12	1	-1	1	39782.6
13	1	-1	2	52680.8
14	1	-2	0	61104.3
15	1	-2	1	49652.0
16	1	-2	2	60389.8
17	-1	0	0	61186.0
18	-1	0	1	50230.2
19	-1	0	2	61257.3
20	-1	-1	0	53379.4
21	-1	-1	1	40220.6
22	-1	-1	2	53254.8
23	-1	-2	0	61278.0
24	-1	-2	1	50123.3
25	-1	-2	2	60989.5

The components of geomagnetic fields and vectors of each compensating magnetic field are defined as follows:
$(x, y, z) = (-120, 30100, -35200)$
$(X_0, X_y, X_z) = (40000, 100, -70)$
$(Y_x, Y_0, Y_z) = (90, 30000, 80)$
$(Z_x, Z_y, Z_0) = (-100, 90, 35000)$
The unit of figures above is nT. Total magnetic force values shown above are obtained by multiplying C_x, C_y, C_z and adding the results of this multiplication to each component of the geomagnetic fields.

Since there are three patterns of compensating magnetic fields for each axis coil, the total number of patterns is $3^3 = 27$. Depending on the combination of patterns the total magnetic force value may become too small to be measured. As the case of $(C_x, C_y, C_z) = (0, -1, +1)$ is not included, the total number of patterns to be used is 26. In Table 1, minimum total magnetic force values are up to about 30,000 nT (1st and 6th) when x and z components are extremely small and only the y components remain. Maximum total magnetic force values are up to about 61,000 nT (8th, 10th, 14th, 16th, 17th, 19th, 23rd and 25th) when x, y and z components are large. It should be noted that these values are in the range of values that can be measured by the Overhauser magnetometer or other instruments. Unlike ASMO, the maximum total magnetic force value is nearly twice as large as the minimum value. This indicates that tuning may be necessary before beginning each measurement operation.

The total magnetic force value is calculated with the equation (1); it is expressed as a scalar value obtained by adding the vector of a natural magnetic field and that of a compensating magnetic field. Here, F is a total magnetic force value, i in the parentheses corresponds to the number in Table 1, and is in the range of $0 \leq i \leq 25$. x, y and z are defined as the geomagnetic component value on line No. 0 in Table 1. δ_x, δ_y, and δ_z are the amounts of change of geomagnetic component values, and are known values. If a compensating magnetic field as specified in Table 1 is applied, 26 total magnetic force values can be measured. x, y and z geomagnetic component values and nine (3×3) by three vectors of compensating magnetic fields are unknown. Since

$Y_x = 0$, the total unknown number is $3 + (3 \times 3) - 1 = 11$. Unknown values are calculated by making numerical calculations and selecting the values most commensurate with measured total magnetic force values. In this study, we performed calculations using the modified Levenberg-Marquardt method (Nakagawa and Koyanagi, 1982).

$$\begin{aligned} F(i) &= \sqrt{X_C^{\,2}(i) + Y_C^{\,2}(i) + Z_C^{\,2}(i)} \\ X_C(i) &= x + \delta_x(i) + C_x(i)X_0 + C_y(i)Y_x + C_z(i)Z_x \\ Y_C(i) &= y + \delta_y(i) + C_x(i)X_y + C_y(i)Y_0 + C_z(i)Z_y \\ Z_C(i) &= z + \delta_z(i) + C_x(i)X_z + C_y(i)Y_z + C_z(i)Z_0 \end{aligned} \tag{1}$$

It is considered that in making calculations, the amount of current or the intensity of a compensating magnetic field is accurate. If errors are not contained in the total magnetic force value measured, an unknown value can be calculated with a high degree of accuracy. If random errors of less than 1 nT are contained in a total magnetic force value, accurate values cannot be calculated. One example of calculations is shown in Table 2. In this table, the values are the differences between calculated values and correct solutions, and those shown on each line are the values calculated based on different initial values. Although the residuals of each line in Table 2 become sufficiently small, they settle to different values depending on initial values, leading to a situation where solutions are indeterminate. After reviewing these results, we note the following characteristics:

(1) The intensities X_0, Y_0 and Z_0 of compensating magnetic fields are on the whole calculated accurately.
(2) X_y is also close to correct values.
(3) $x+Z_x$, $y+Z_y$, and $z-Y_z$ become almost constant.

The level of accuracy as mentioned above means an accuracy of 1 nT or less. Values indicated in (3) above are shown in the last three columns to the right in Table 2. Geomagnetic components and the effect of the inclination of compensating coils could not be separated, and the degree of freedom commensurate with these effects alone remains. The relative angle between the x- and y-axis coils on the level surface can be verified from (2) and $Y_x = 0$.

If the inclination of the z-axis coil (Z_x, Z_y) is known, x and y become known from (3) and z also becomes known from the total magnetic force value F. To eliminate the degree of freedom

Table 2 Examples of calculations made using patterns of compensating magnetic fields (Table 1)

	x	y	z	X_0	X_y	X_z	Y_x	Y_0	Y_z	Z_x	Z_y	Z_0	$x+Z_x$	$y+Z_y$	$z-Y_z$
	-164.2	52.1	45.9	-0.6	1.1	-186.4	0.0	-0.3	44.6	163.0	-51.9	0.1	-1.2	0.1	1.3
	-43.1	104.1	89.8	0.0	0.7	-48.9	0.0	-0.5	89.1	42.9	-103.8	0.1	-0.3	0.3	0.8
	-37.0	-42.7	-36.0	0.0	0.2	-42.4	0.0	0.0	-36.2	36.8	42.3	-0.1	-0.2	-0.4	0.2
	45.8	150.6	129.6	0.2	0.2	52.0	0.0	-0.7	128.8	-45.3	-150.2	-0.2	0.4	0.5	0.8
	-146.8	33.6	29.9	-0.5	0.9	-166.6	0.0	-0.2	28.9	145.7	-33.6	0.1	-1.1	0.1	1.1
	-196.1	-96.6	-80.8	-0.9	0.0	-222.9	0.0	0.0	-82.0	194.6	95.8	-0.4	-1.5	-0.8	1.2
	-167.6	-20.7	-16.4	-0.6	0.6	-190.4	0.0	-0.1	-17.5	166.4	20.5	0.0	-1.2	-0.2	1.1
	-117.3	-81.3	-68.4	-0.3	0.1	-133.5	0.0	0.0	-69.0	116.4	80.6	-0.2	-0.9	-0.7	0.6
	-165.2	14.1	13.4	-0.6	0.9	-187.6	0.0	-0.2	12.2	164.0	-14.2	0.1	-1.2	0.0	1.1
	-59.3	91.1	78.7	0.0	0.8	-67.2	0.0	-0.4	77.9	58.9	-90.8	0.2	-0.4	0.3	0.8
	126.3	-35.2	-29.9	0.1	-0.1	142.8	0.0	-0.1	-29.8	-125.2	34.9	-0.7	1.1	-0.3	-0.1
Ave.	-84.0	15.4	14.2	-0.3	0.5	-95.6	0.0	-0.2	13.4	83.5	-15.5	-0.1	-0.6	-0.1	0.8
s.d.	101.6	79.2	67.6	0.4	0.4	115.2	0.0	0.2	67.5	100.8	78.8	0.3	0.8	0.4	0.4

In this table, a difference between the calculated value and the actual value is shown in nT units. Average values (Ave.) and standard deviations (s.d.) are shown on the two lines at the bottom.

mentioned in (3), it is necessary to add additional limiting conditions or different measurement results.

(a) The z-axis coil does not incline at all ($Z_x = Z_y = 0$).

(b) Measurement is made using the same patterns of compensating magnetic fields after the z-axis coil rotates on the z-axis 180 degrees.

In the above two cases, calculations were made and correct values were obtained for both cases. In practice, however, it is difficult to set the z-axis in such a way that it does not incline at all, as mentioned in (a) above. Even if it is set on a completely level surface, we do not have the means for verifying the levelness of the level surface. Concerning (b), assuming that the inclination is minimal, it was thought that the vectors (Z_x, Z_y, Z_0) of compensating magnetic fields that the z-axis coil forms would become ($-Z_x$, $-Z_y$, Z_0) by turning 180 degrees along the vertical axis (hereafter called reversal). However, it is important to note that this supposition stands up only if the rotation axis is in proper alignment with the z-axis direction. For example, if the pillar on which the z-axis coil rests inclines, the amount of inclination is the total of $Z_x \rightarrow Z_{xp} + Z_x$, etc., ($Z_{xp}$ is defined as the quantity of influence of the inclination of the pillar on the x component. Z_{xp} is also an unknown value), the inclination of the pillar, and the inclination of the coil itself. It should be concluded that reversal causes ($Z_{xp} + Z_x$, $Z_{yp} + Z_y$, Z_0) to become ($Z_{xp} - Z_x$, $Z_{yp} - Z_y$, Z_0). If this is taken into consideration, Z_{xp} and Z_{yp}, whose positive or negative signs do not change even after reversal, and, as in the case of the first result, cannot be separated from x and y, therefore accurate values cannot be calculated. To ensure perpendicularity of the rotation axis, it is possible to suspend the z-axis coil. Or, if $Z_{xp} = Z_{yp} = 0$ can be established by using a method of floating a compensating coil on the surface of liquid (level surface), it will be possible to calculate correct geomagnetic component values. Table 3 shows an example of calculation results made based on (b). In this case, it was verified that the calculation results settle to the same value regardless of the set initial value. On each line in Table 3, random errors to be added to measured total magnetic force values are changed. In this table, values are calculated with an accuracy of 0.3 nT or less. A change in the accuracy of calculated values is

Table 3 An example of calculations including z-axis coil reversal

	x	y	z	X_0	X_y	X_z	Y_x	Y_0	Y_z	Z_x	Z_y	Z_0
	-0.03	0.05	-0.06	-0.08	-0.03	-0.01	0.00	-0.06	0.08	0.01	0.01	0.06
	0.15	0.13	0.10	0.00	0.11	0.18	0.00	0.06	0.02	0.02	-0.03	-0.06
	-0.02	0.00	0.06	0.05	0.02	0.14	0.00	0.00	0.09	-0.09	-0.03	0.04
	0.07	-0.03	-0.12	-0.08	-0.13	0.11	0.00	0.01	-0.13	0.00	-0.04	0.03
	0.02	-0.19	0.14	0.13	-0.14	0.02	0.00	-0.20	0.19	-0.06	0.00	0.07
	0.05	-0.07	-0.07	-0.03	-0.01	-0.04	0.00	0.03	-0.09	-0.04	-0.02	0.05
	0.00	0.04	-0.02	-0.13	-0.03	-0.01	0.00	0.09	-0.11	0.04	0.02	-0.06
	-0.09	0.04	-0.15	-0.06	-0.10	0.04	0.00	0.05	-0.21	0.00	-0.05	-0.05
	0.00	0.22	0.20	0.01	0.18	0.07	0.00	0.14	0.26	0.08	-0.07	0.03
	-0.08	-0.22	-0.04	0.14	-0.01	-0.08	0.00	-0.19	-0.07	-0.08	-0.02	0.02
	-0.04	-0.28	-0.13	0.11	0.12	0.23	0.00	-0.21	-0.12	0.01	-0.04	-0.04
Ave.	0.00	-0.03	-0.01	0.01	0.00	0.06	0.00	-0.03	-0.01	-0.01	-0.02	0.01
s.d.	0.07	0.15	0.12	0.09	0.10	0.10	0.00	0.12	0.15	0.05	0.03	0.05

In this table, a difference between the calculated value and the actual value is shown in nT units. Average values (Ave.) and standard deviations (s.d.) are shown on the two lines at the bottom.

commensurate with a change in the severity of random errors to be added to measured values. This means that the accuracy of calculated values is influenced by the accuracy of observation of total magnetic force values.

As a point of further note concerning the measurement sampling conducted to acquire geomagnetic absolute values, in the case of ASMO, measurement is made three times, by feeding a zero compensating current, positive compensating current and negative compensating current, or by again feeding positive and negative compensating currents after turning the compensating coil 180 degrees and measuring total magnetic force values about 10 times with respect to the declination and inclination angle. Geomagnetic absolute values measured in this way are handled as one set of geomagnetic absolute value data. Since measurement is made in the same way before and after the reversal of the z-axis coil in the case of the method used in this study, the number of times measurement is made becomes 52 (=26×2). 26 is the number of times that was calculated by defining the number of compensating coil patterns for each axis coil as 3. This number of times does not necessarily mean that measurement must be made exactly 26 times. It must be admitted, however, that this number of times is larger than that of ASMO. In the case of ASMO, declination and inclination angles are measured separately. In the case of the method used in this study, however, absolute values of three geomagnetic field components are measured and calculated as one set. If measurement is continuously made by generating the compensating magnetic field patterns in Table 1 over and over again, calculations can begin on completion of the 52nd measurement, so that geomagnetic absolute values can be acquired for each round of measurement (repeated 52 times). Making measurements in this uninterrupted manner does not mean that the time to sample geomagnetic absolute values becomes longer, even if measurement must be made many times to collect one set of data.

4. Measuring the Declination Angle

It was noted in Chapter 3 that the direction of the horizontal components of the y-axis coil was defined as the y-axis and the degree of its deviation from geographic north be specified separately. Generally, a device combining compensating coils and the theodolite will be used to observe the polestar or marks on the ground whose directions are known. Although this method is straightforward and easy to understand, some drawbacks that may cause errors in measurements should be noted: problems with the theodolite, deformation and error of the scale plate, machining accuracy associated with the parallelism between the telescope and compensating coil, read errors, etc. In addition, the compensating coils and theodolite must be operated manually at present. Here we propose a different method, and describe the results of the study we conducted into this method.

The absolute observation system described above is defined as A, and another similar system is prepared and defined as B. On the coordinates established on the level surface, east is defined as the x direction and north is defined as the y direction. It is assumed that accurate geographical coordinates of A and B are known. The x- and

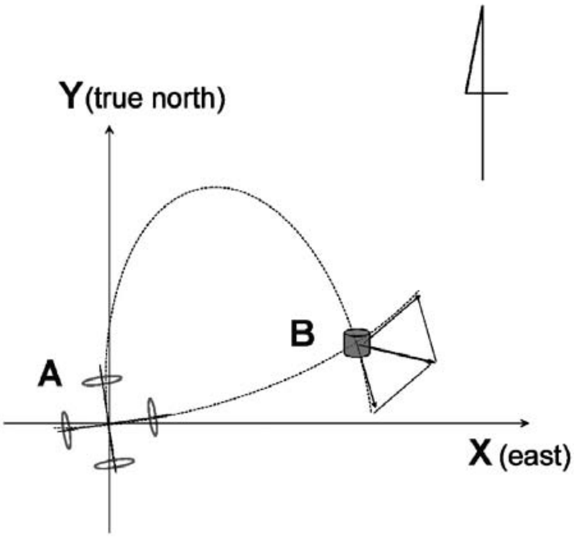

Figure 3 Schematic diagram of declination angle measurement
As the x- and y-axis coils at A form compensating magnetic fields on B, the total magnetic force value at B changes. The directions of the x- and y-axis coils on the level surface are determined based on the A and B coordinates and the total magnetic force value at B.

y-axis coils of A are driven to generate compensating magnetic fields, and B is used to measure total magnetic force values. This is a method that allows the direction of the y-axis of A in the geographic coordinate can become known based on these measured total magnetic force values and the relative positions of A and B. If the geographical direction of the y-axis coil is known, the geomagnetic declination angle can be determined by rotating the three geomagnetic component values acquired in Chapter 3 on the coordinate. The same symbols, such as X_y, are used. Note that these symbols represent the values on the geographic coordinate previously mentioned. In general, therefore, $Y_x \neq 0$. In this study, the x- and y-axis coils were regarded as magnetic dipoles, and magnetic fields measured at B were calculated. If the distance between A and B is short and if their x- and y-axis coils cannot approximate to magnetic dipoles, the quantity of influence on B must be directly calculated based on the size and frame shape of coils. B is set on the same level surface as A is, and compensating magnetic fields are formed to reduce the z components to almost zero. This allows the magnetic fields of the z components formed at B to decrease so that the influence of the z components is removed from the total magnetic force values of B, thus increasing the accuracy of the direction of the x- and y-axis coils on the level surface. The relative angle between the x- and y-axis coils on the level surface is known, as described in (1) and (2) in Chapter 3. Therefore calculations were made by including the relative angle between the x- and y-axis coils as a restricting condition.

Table 4 shows one example of calculation results. Because the z component was intentionally decreased, variations in X_z, Y_z and the z component values at B are large. However, X_0, X_y, Y_x and Y_0 become stabilized at 2 to 3 nT. Depending on the initial values, there are many cases in which the results of these calculations do not settle to normal values. By making many calculations and averaging only calculation results with smaller residuals, it is expected that accuracy can be increased to 1 nT or less (2nd line from the bottom in Table 4). This value is equivalent to a few seconds in terms of the angle of a compensating coil on a level surface.

Once the installation pillar, compensating coils, etc., are fixed in position oriented to specific directions, it is thought that they will rotate only minimally along the vertical axis even if their inclination changes, and that therefore measurements can be made with a low degree of frequency. Note that an extremely large current is required to apply a magnetic field having an intensity of some tens of thousands of nT to point B, and the effect of such a large magnetic field will spread correspondingly far and wide, therefore due consideration should be given to such points before making such magnetic fields practical or introducing them to magnetic variation measurement.

5. Conclusion

As described above, geomagnetic absolute values can be measured using the combination of geomagnetic total force magnetometer and three orthogonal compensating coils. The x- and y-axis coils can be coupled to each other. There is the possibility that the direction of the y-axis from true north can be known using the method described in Chapter 4. It is advisable that the device have a rotating mechanism to align the y-axis coil approximately to the direction of magnetic north in making the initial setting, although the x- and y-axis coils do not need to rotate along the vertical axis during normal observations. In addition, the coil inclination should be adjustable so that X_z and Y_z can be prevented from growing extremely large. The z-axis coil should have a mechanism that allows it to rotate independently of the x- and y-axis coils. It is important to further improve the suspension system and other structures so that the inclination of the coils becomes symmetrical to the level surface before and after the reversal of the z-axis coil. If the angle of the reversal is not precisely 180 degrees, an error of 2% or less per degree is expected to occur, although this depends on the intensity of Z_x and Z_y. If the displacement is less than 3 minutes, the difference between Z_x and Z_y before and after reversal will be 0.1 nT or less.

In making actual observations, a judgment of abnormal values should be made and other means for performing checkouts should be used concurrently. By recording and comparing the current values of compensating coils, as well as the readings on inclinometers, the reliability of calculated values can be increased. This method can be put into practice since there are no technical problems in controlling a current to be passed through coils and automatically measuring total magnetic force values. Manual operation is required only for reversing the z-axis coil. The use of this method is expected to eliminate individual errors in absolute observation, cut down on observation time, lighten the effort of observation, and automate calculation of measurement results. Furthermore, if the z-axis coil can be automatically reversed using a motor or similar rather than reversing it manually, it will become possible to continuously measure geomagnetic absolute values.

6. References

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Table 4 An example of declination angle calculation

	X_0	X_y	X_z	Y_x	Y_0	Y_z	x	y	z	D_x	D_y
	-1.3	0.6	-30.0	0.0	-2.8	20.0	0.0	5.6	-120.0	4.0	2.4
	-0.6	0.4	45.0	-0.3	0.6	17.5	4.1	-2.5	-118.0	2.3	1.6
	-1.0	-2.2	170.0	1.6	0.1	-180.0	-1.1	1.9	-120.0	-10.8	-11.0
	-1.5	-0.6	170.0	0.6	-0.9	-61.7	-3.5	3.4	69.1	-2.3	-3.0
	0.0	0.4	-30.0	-0.3	0.7	16.0	2.7	-1.6	-90.8	2.0	1.2
	-0.4	0.6	14.7	-0.3	0.1	20.0	2.8	-0.6	-120.0	3.2	2.0
	-0.1	0.3	-29.9	-0.2	0.5	17.6	2.4	-0.7	-111.0	1.8	1.2
	-0.7	-2.1	170.0	1.5	0.9	-180.0	2.1	-2.2	-120.0	-10.3	-10.8
	-0.8	1.0	17.3	-0.2	-2.1	20.0	4.6	-0.3	-120.0	5.6	2.9
	0.1	-0.6	-30.0	0.5	0.1	-60.2	-2.6	1.0	80.0	-3.3	-3.5
	0.0	0.0	-30.0	0.1	-0.4	-4.4	-3.6	2.5	79.9	0.2	-0.3
	-0.4	0.7	12.0	-0.3	-0.1	20.0	3.3	-0.9	-120.0	3.6	2.2
	-2.0	0.3	130.2	0.0	-2.5	20.0	1.2	3.5	-120.0	2.9	2.1
	1.2	-1.0	-30.0	0.4	3.8	-118.6	0.7	-6.0	80.0	-6.0	-6.1
Ave.	-0.5	-0.2	39.2	0.2	-0.1	-32.4	0.9	0.2	-60.8	-0.5	-1.4
s.d.	0.8	1.0	80.3	0.6	1.6	72.9	2.6	2.9	87.6	5.1	4.7

In this table, the difference between the calculated value and the actual value is shown. x, y and z are the magnetic fields at B. Average values (Ave.) and standard deviations (s.d.) are shown on the two lines at the bottom.

D_x and D_y are the displacements from the geographical north, are calculated based on the direction of the x- and the y-axis coil respectively. Since they are calculated assuming that the relative angle between the x- and y-axis coils is constant, both values approximate to each other.

D_x and D_y are expressed in seconds, and all others in nT. 13 patterns of compensating magnetic fields that should allow total magnetic force values to be in the range of 30,000 to 80,000 nT were selected from 15 patterns (= 3×5), i.e., 0, ±1 for the x-axis coil and 0, ±1, ±2 for the y-axis coil. These 13 patterns of compensating magnetic fields were applied by feeding an appropriate amount of current to the compensating coils; a different amount of current each time is fed to these compensating coils, so 13 patterns of compensating magnetic fields were applied. These declination angle calculations were performed under the conditions that the distance between A and B is 5 to 6 meters, the difference in height is several centimeters (5cm), and so forth. Values shown on each line were calculated by randomly changing the initial values in the range of ±100 nT.

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