地磁気観測所要報　第26巻第2号　15−24頁　平成10年3月
Memoirs of the Kakioka Magnetic Observatory Vol.26, No.2, pp.15−24, March 1998

Geomagnetic three components measurement with Overhauser magnetometer

by

A. YAMAZAKI and T. TOKUMOTO

(Received December 26, 1997; Revised February 17, 1998)

Abstract

In the replacement of KASMMER during the period 1989-1992, we developed a technical method to measure geomagnetic three components using Overhauser magnetometers. For applying the Overhauser magnetometers to the components measurement, a modification of the Overhauser magnetometer was necessary, and Fanselau-Braunbek coils were used as compensating coils. Furthermore, a newly designed method was adopted for the D component measurement. In this report, we describe the design of the measuring method in detail and discuss the error estimation and the stability of the base line values.

1. Introduction

Kakioka Automatic Standard Magnetometer (KASMMER) was constructed in 1972 (Yanagihara et al., 1973). Since then, the system has been supplying stable and highly reliable geomagnetic data. The system was composed of the DI-72 (a magnetic theodolite), the MO-PK (a proton magnetometer) for absolute observation, four Optical Pumping Magnetometers (OPM) for variation observation and a computer system for data acquisition. The geomagnetic components observation method using the three OPMs and the Helmholtz coils was described in Yanagihara et al. (1973).

After a while, some parts of the KASMMER system were replaced during the period 1981-1984 (Kuwashima, 1990). In this replacement, a fluxgate magnetometer was added for supporting. Due to deterioration of the OPMs, a large scale replacement of KASMMER was carried out during the period 1989-1992 (Tezuka, 1994; Tsunomura et al., 1994). In this replacement, we have introduced a high sensitivity fluxgate magnetometer and four Overhauser Magnetometers (OHM). The high sensitivity fluxgate magnetometer, resolution of which is 0.01nT, has been installed for getting high resolution one second values. One of the OHM has been installed for getting high resolution F component, and other three OHMs, which are used for three component measurement, for getting stable base lines.

In this replacement, we planned to introduce the new OPMs because the component measurement with the OPMs could obtain highly stable base line value over a long period of time (Sano, 1975; Kuwashima, 1990). However, as described by Tsunomura et al. (1994), it was impossible to get the new OPMs because these OPMs were quite expensive and the cost was estimated to be out of our budget.

The OHMs are, like OPMs, a kind of scalar magnetometer to measure total intensity. However these OHMs cannot be operate in the Helmholtz coils which was used for the OPMs, because these sensors are bigger than those of the OPMs and are not able to make measurement in weak magnetic field as the OPMs. By these reasons, we had to design a new method to measure geomagnetic three components with OHMs.

The principle of the component measurement with the OHMs is an application of the vector proton magnetometer (Hurwitz and Nelson, 1960) using the compensation coils. Though the method is similar to the previous system with the OPMs (Yanagihara et al, 1973; Sano, 1971), there are some differences, especially for D component. In this report, we describe the design of the method to measure geomagnetic three components with the OHMs and report the 3 years observational results.

2. Vector measurements by scalar magnetometers

Scalar magnetometers like the proton magnetometer, OPM and OHM can be used to make vector measurements using compensation coils. The most commonly used coil for vector measurements is the Helmholtz coil. As well known, the proton vector magnetometer is a method to measure nearly absolute values of H and Z components by setting those sensor into the center of the Helmholtz coils. The ASMO method proposed by Alldredge(1960) can measure three components of magnetic field by one scalar sensor. The disadvantage of the method is, however, that it cannot makes the complete successive measurement of the field variations.

The vector measurement method by OPMs, which was an applied method of the vector proton magnetometer and was adopted for the previous KASMMER system, can make the complete successive measurement of the field variations. As the method is described by Yanagihara et al. (1973) and Sano (1971) in detail, here we describe it simply.

By installing an OPM sensor at the center of the Helmholtz coil, the axis of which is vertical for eliminating the vertical (Z) component of magnetic field, it is possible to measure the horizontal (H) component. If the compensating magnetic field is constant, the error due to the variation of Z component will be produced. In order to reduce this error, the compensating field is controlled automatically for the deviation of Z component making use of Z component measurement. By similar way, Z component is measured using the horizontal coil directed to the mean magnetic meridian. The compensating field also consists of the constant part and the auxiliary, time varying part making use of H measurement value.

The declination (D) measurement is a little more complex than those of H and Z. In the D measurement, two orthogonal Helmholtz coils are used to eliminate the Z and Hx components (see Fig. 1). The measurement field Hy makes an angle of 60 degree eastward from the mean magnetic meridian. A calculation of the D component is carried out by the following equation.

$$D = D_0 + \Delta D = \cos^{-1}(Hy/H) + D_0 - 60° \quad (1)$$

The adjustment of the compensating field of the Z and Hx is conducted automatically making use of the H, Z, Hy measurement values.

3. Overhauser magnetometer and Fanselau-Braunbek coil

Overhauser proton magnetometer, applying the Overhauser effect, was put into practice by Hrvoic (1984), and is now manufactured by GEM Systems Inc. Canada. The advantage of the magnetometer comparing with proton magnetometer is the capability to make the complete successive measurement of field variations with high resolution (0.01nT). In order to apply the OHMs to the component measurement, these sensors have to be set at the center of the compensating coils.

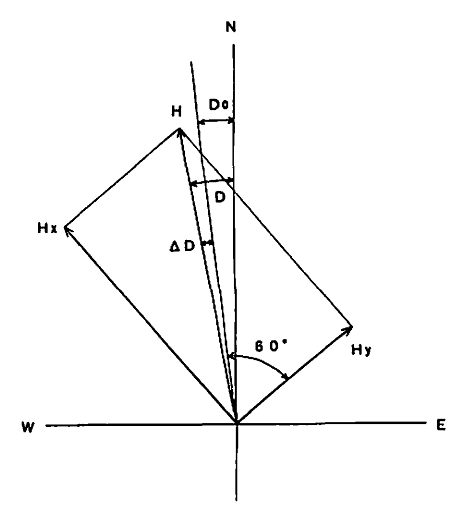

Fig. 1 Principle of the D component measurement using the optical pumping magnetometer.

There were two problems to make it.

1) Problem of sensor size

In the case of the self oscillating type OHMs, there are two bottles filled with liquid of nitro-oxide free radical inside the sensor. As these bottles are globular form of 11cm diameter, the whole body of the sensor is rather large size. It is practically impossible to set this sensor inside the limited uniform zone in the compensating coil. In order to mitigate this confinement, one of the sensor bottles has been converted into a dummy bottle filled with ethyl alcohol. In this case, although the signal decreases slightly, it could measure the geomagnetic field without any hindrance. The dummy bottle is necessary for operation of the magnetometer, but it is unnecessary to set it into the uniform zone. This means only one bottle filled with nitro-oxide free radical needs to be set into the uniform zone.

These developments and experiments were conducted by GEM Systems Inc..

2) Problem of compensation coils

The free radical bottle of 11cm diameter needs to be set into the uniform zone of the compensation coil. If the Helmholtz coils are adopted as the compensation coils to obtain the 11cm uniform zone, we need large coils with the diameter larger than 110cm. It is not so easy to manufacture such large Helmholtz coils and actually impossible to install them on the pillars in the existing sensor houses used for OPMs. Therefore, we decided to adopt the Fanselau-Braunbek coils (Fanselau, 1929; Braunbek, 1934). The coils make larger uniform zone than those of Helmholtz coils. Fig. 2 shows the zone of uniformity less than 10^{-4} in the Fanselau-Braunbek coil. We decided to make three Fanselau-Braunbek coils of 65cm inner coil's diameter. Theoretically, these coils make approximately 20cm diameter's uniform zone with uniformity less than 10^{-4}.

Newly designed OHMs were set into the newly manufactured coils, and we conducted a performance test. As a result, the expected oscillating signal could be obtained, and we confirmed the ability of component measurement with OHMs.

4. Geomagnetic three components measurement with Overhauser magnetometers

1) H measurement

As shown in Fig. 3, the measured field Hmes is given by

$$H_{mes}^2 = H^2 + (Z - Zc)^2 \quad (2)$$

and H component can be derived as follows

$$H = \{H_{mes}^2 - (Z - Zc)^2\}^{1/2}$$

where Zc is the compensation field in Z component. Here if $|Z| \fallingdotseq |Zc|$ then H is given approximately by

$$H \fallingdotseq H_{mes} - \frac{(Z - Zc)^2}{2H_{mes}}. \quad (3)$$

Although the compensating field Zc had been adjusted automatically using the feed-back of Z measurement to the hardware, we have adopted the measurement method to correct by calculations in the software. This is one of the dif-

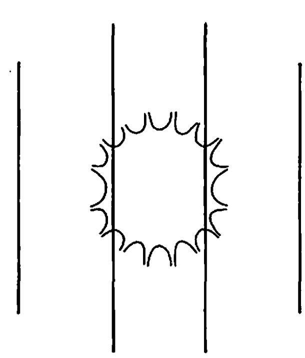

Fig. 2 Zone of the uniformity less than 10^{-4} in the Fanselau-Braunbek coil. The calculated magnetic field is in the direction of the coil axis.

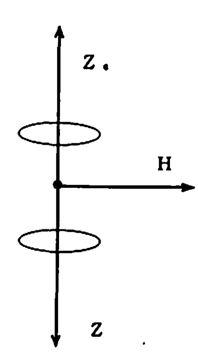

Fig. 3 Principle of the H component measurement

ference from the previous KASMMER system. One of the advantages of this correction method is to be able to make the system simple because of unnecessity of the automatic adjusting instruments and another is to be easy to check or to deal with the abnormal OHM measurements.

2) Z measurement

As shown in Fig. 4, the measuring field Zmes is given by

$$Z_{mes}^2 = Z^2 + (H - Hc)^2 + \Delta d^2 \quad (4)$$

and Z component can be derived as follows

$$Z = \{Z_{mes}^2 - (H - Hc)^2 - \Delta d^2\}^{1/2}$$

where Hc is the compensation field in H component. Here if $|H| \fallingdotseq |Hc|$ and Zmes$\gg \Delta d$ then Z is given approximately by

$$Z \fallingdotseq Z_{mes} - \frac{(H - Hc)^2 + \Delta d^2}{2 Z_{mes}} \quad (5)$$

where the Δd is equal to $H\sin\Delta D$ as shown in Fig. 5.

It is an improvement of the measurement system to correct the error due to Δd which had not been corrected in the previous KASMMER system.

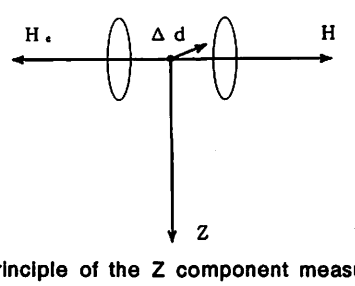

Fig. 4 Principle of the Z component measurement.

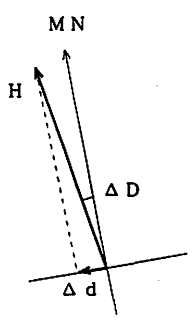

Fig. 5 Relation between ΔD and Δd. MN means magnetic north (mean magnetic meridian).

3) D measurement

To the D component measurement, the previous OPMs method as described in section 2 could not be applied. One reason is OHMs can not be operated normally in the weak field less than 28, 000nT and another is that it is not easy to manufacture the two axes Fanselau-Braunbek coils. Consequently we had to design a new method to measure the D component.

As shown in Fig. 6, the horizontal axis coil is oriented to θ_0 degree eastward from the mean magnetic meridian. The total intensity F is given by

$$F^2 = Hx^2 + Hy^2 + Z^2 \quad (6)$$

where Hx is the magnetic field component oriented θ_0 degree eastward from the mean magnetic meridian in the horizontal plane and Hy is the perpendicular components to the Hx.

As shown in Fig. 7, the measured field Hyz_{mes} is given by

$$Hyz_{mes}^2 = (Hx - Hx_c)^2 + Hy^2 + Z^2 \quad (7)$$

where Hx_c is the compensating field of the Hx component.

From the equation (6) and (7), Hx is given by

$$Hx = \frac{F^2 - Hyz_{mes}^2 + Hx_c^2}{2 Hx_c} \quad (8)$$

As shown in Fig. 8, the D component is calculated by the following equation.

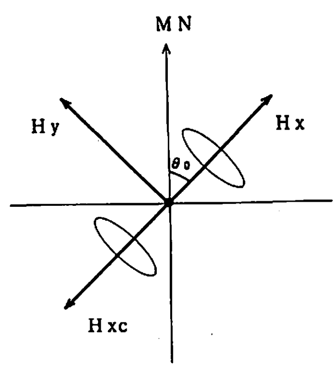

Fig. 6 Direction of the horizontal coil axis for the D component measurement and Hx, Hy component.

$$D = D_0 + \Delta D = \cos^{-1}(Hx/H) + D_0 - \theta_0 \quad (9)$$

where θ_0 has been oriented 45 degree at the routine observation.

On the other hand, we also examined the method which is similar to the ASMO method for the D component measurement. Although the experimental results were good, this method was not adopted because the method could not obtain the successive one second value of the geomagnetic variations.

The component measurement with OHMs are made by above mentioned method. Layout of the four sensor houses of the OHMs are shown in Fig. 9. For more precise calculation, the differences of the intensities of the geomagnetic field between sensor houses should be corrected. These differences used for the calculation are shown in Table 1. The intensities of the compensating fields are also shown in Table 2.

An actual calculating procedure with the computer for the components measurement with OHMs is shown in Fig.10. At the first step, Hx is determined by measuring value of the F and Hyz_{mes}. In the following step, the initial values for H, Z and D are given. In the final step, H, Z and D values are determined by the convergence of successive calculations. To converge the calculation,

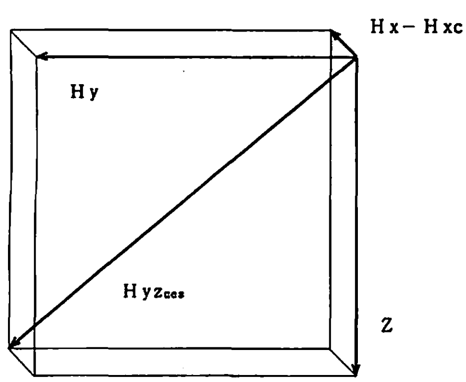

Fig. 7 Relation between the measured field Hyz_{mes}, Z and $Hx-Hx_c$.

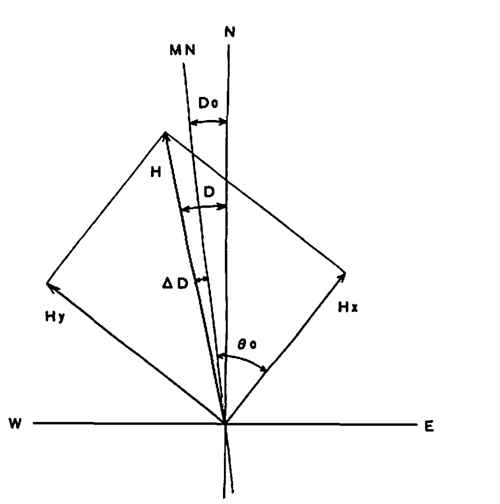

Fig. 8 Relation between the Hx, H and D component.

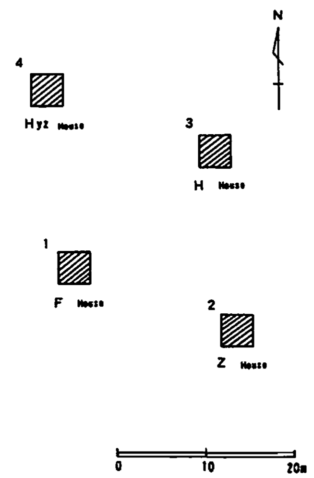

Fig. 9 Sensor houses for the OHMs.

Table 1 Differences of the intensities of the geomagnetic field between each OHM sensor houses.

$Tdf = [F_4] - [F_1] = 1.6$nT
F_4 : F component in Hyz house
F_1 : F component in F house

$Tdh = [H_4] - [H_3] = 14.4$nT
H_4 : H component in Hyz house
H_3 : H component in H house

$Thz = [Z_3] - [Z_2] = -18.4$nT
Z_3 : Z component in H house
Z_2 : Z component in Z house

$Tzh = [H_2] - [H_3] = -0.2$nT
H_2 : H component in Z house
H_3 : H component in H house

Table 2 Parameters of the compensating field.

	coil constant (nT/mA)	coil current (mA)	compensating field (nT)
Zc	975.704	36.1315	35253.6
Hc	975.366	30.8225	30063.2
Hxc	975.769	21.8118	21283.3

the calculation is carried out three times. These calculations are made for one second values.

5. Error estimation

In the components measurement with OHMs, some errors will be caused by the mechanical inaccuracy of compensating coils, tilting variation of the pillars or geomagnetic variations. The error estimations for the vector proton magnetometer are carried out by Hurwitz and Nelson (1960) and Sakuraoka (1966), and for the OPMs method by Sano (1971). We discuss about the error in the component measurement for the adopted method for OHMs.

1) H component errors

As shown in Fig.11, the unknown angles η and τ caused by the mechanical inaccuracy are the angles of the compensating fields to the perpendicular direction. The small angles u and v are the tilting angles of the coil to the horizontal plane. As these angles are very small, the higher terms can be omitted and the following expansion equation is obtained as an approximation.

$$H \fallingdotseq H_{mes} + Z_c u - Z_c \eta \cos\tau - \frac{(Z - Z_c)^2}{2H} - \frac{\Delta d\, Z_c(\eta \sin\tau + v)}{H} - \frac{Z_c^2\{(\eta\sin\tau + v)^2 + (\eta\cos\tau - u)^2\}}{2H} \qquad (10)$$

The fourth term in the right side of equation (10) is due to the time variations of the Z component. This term is corrected in the calculation as mentioned in section 4. The second term, $Z_c u$, is due to the tilting of the coil level. Other terms are mainly due to the mechanical errors. If the exact absolute value is not necessary, these terms are not so serious for the variation observation.

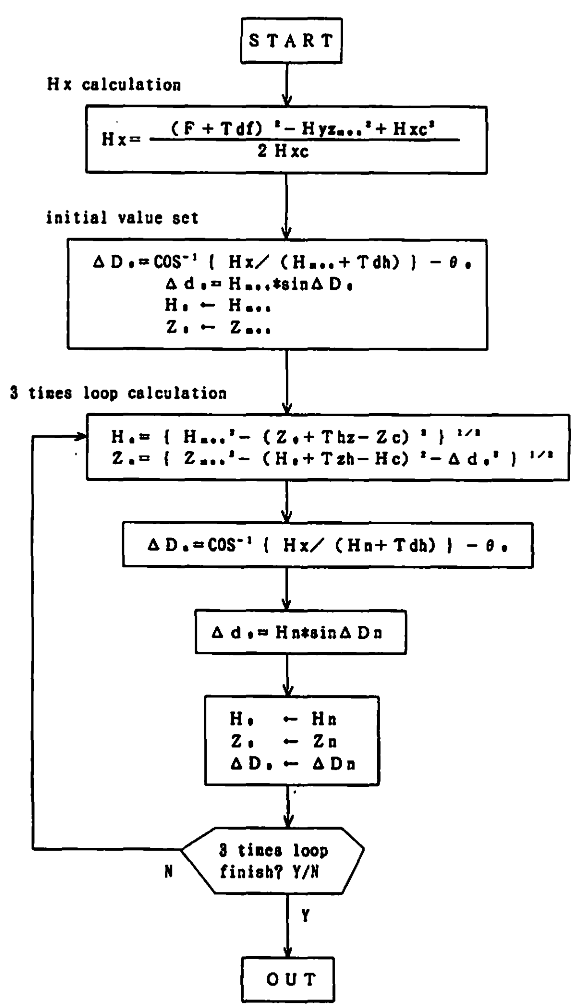

Fig.10 Calculating procedure for the components measurement with OHMs.

2) Z component errors

The small angles due to the mechanical inaccuracy and due to the tilting of coils are shown in Fig.12. If the higher terms are omitted, the following expansion equation is obtained as an approximation.

$$Z \fallingdotseq Z_{mes} - H_c u - H_c \alpha - H_c \beta v - \frac{(H - H_c)^2 + \Delta d^2}{2Z} - \frac{H_c^2 \beta^2 + 2\Delta d\, H_c \beta}{2Z} \qquad (11)$$

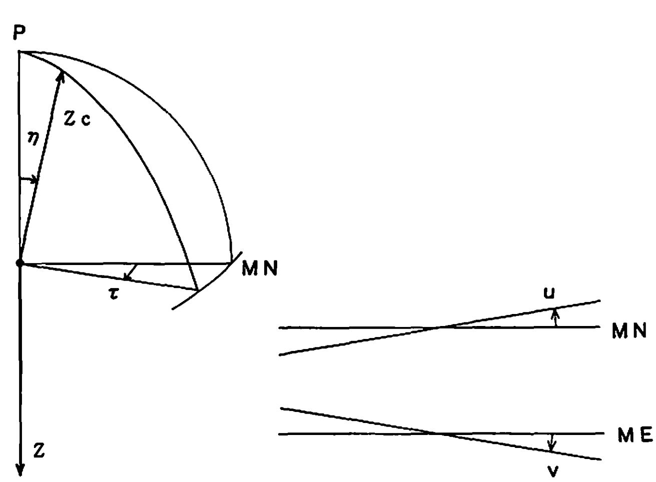

Fig.11 Mechanical errors (η, τ) of the compensating coil and coil level (u, v) for the H component measurement.

The fifth term in the right side of equation (11) is due to the time variations of the H and D. This term is corrected in the calculation. The second term, $-H_c u$, is due to the tilting of the coil level. Other terms are not so serious for the variation observation.

3) D component errors

The D component is calculated using the Hx and H components as shown in equation (9). As the errors of H component are already mentioned above, here we discuss about the errors of the Hx component. Now the calculated Hx component from equation (8) using measured F and Hyz_{mes} value is represented by Hxp. If we use the small angles as shown in Fig.13 and omit the higher terms, the following expansion equation is obtained as an approximation.

$$Hx \fallingdotseq Hxp + Zu + Hy\beta + Z\alpha \qquad (12)$$

The second term, Zu, is due to the tilting of the coil level. Other terms are not so serious for the variation observation.

Besides these errors, the random noises of the D component are generally larger than those of H and Z. Because the random noises included in the F, Hyz_{mes} and H measurement values are amplified through calculating the D component. Table 3 shows the noise amplification factors of the F, Hyz_{mes} and H components into the D component. These amplification factors are derived from the intensities of magnetic fields at Kakioka (H=30,100nT; Z=35,000nT). Actually, the resolution of the D component is not better than those of the H or Z components. However, as these noises are random, these noises are diminished in the one minute values by averaging.

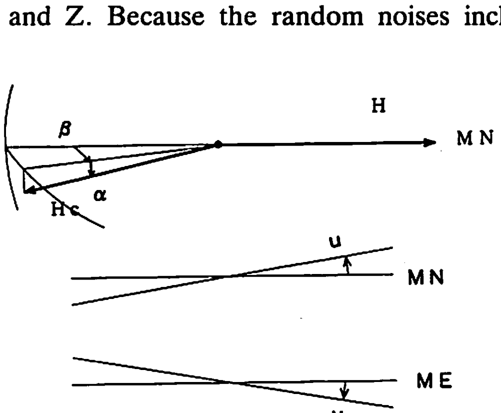

Fig.12 Mechanical errors (α, β) of the compensating coil and coil level (u, v) for the Z component measurement.

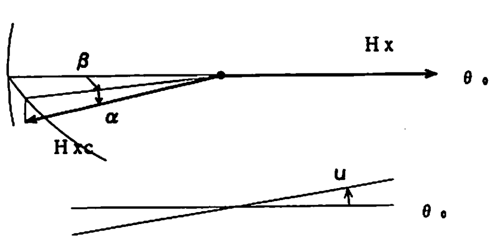

Fig.13 Mechanical errors (α, β) of the compensating coil and coil level (u) for the D component measurement.

It was found through the error estimations that the mechanical errors ($\alpha\ \beta\ \eta\ \tau$) are not so serious for the variation observations if the exact absolute values are not necessary. It is estimated that if the accuracy of these values are better than about 2', the accuracy of the variation observation must be kept within 0.1nT during a middle size magnetic storm (ΔH=200nT, ΔZ= 100nT, ΔD=15'). Since the accuracy of the manufactured Fanselau-Braunbek coils is better than 1', it is concluded that they are enough for the variation observations.

As to the effect of tilting of the coil level, the variation observations are not affected very much if the tilting angles are fixed. However, from the investigations of the long term variation observation with OPMs, it is known that the pillars have time variations of tilting (Kuwashima, 1990). It is inferred, therefore, that the largest error factor for the long term observation is due to tilting variations. The tilting coefficients of the measuring methods are shown in Table 4. It is found that the D component measurement with OHMs is more sensitive with the tilting variations than that of OPMs.

6. Stability of the base line value

After the testing period for a few months the routine observation with OHMs has been car-

Table 3 Noise amplification factors of the F, Hyz_{mes} and H component effective for the D component.

$\Delta D/\Delta F$	=	-0.349	'/nT
$\Delta D/\Delta Hyz_{mes}$	=	+0.311	'/nT
$\Delta D/\Delta H$	=	+0.114	'/nT

ried out since August, 1993. Figure 14 shows the observed base line values for 3 years. Here the base line values of F component are given by the standard proton magnetometer (MO-PK), those of H, Z and D components are given by absolute observations using standard magnetic theodolite (DI-72) and the proton magnetometer.

An annual variations of about 1.0nT amplitude is recognized in the base line values of F component. Since this variation is well correlated with the sensor room temperature, it is found that the OHM used for F measurement has a temperature dependence. As it has been basically thought that OHMs are independent of temperature same as the proton magnetometers, this matter should be investigated in more detail.

As the ranges of the base line values of H and Z components were within 3 nT for 3 years, the purpose to obtain the long term stable base line values have been almost accomplished. These variations of the base line values have a good correlation with tilting variations. On the other hand, those variations of the D component were about 0.6'. The stability of the D component has not been so good as that of the previous system by using the OPMs or that of the high sensitivity flux-gate magnetometer. It is inferred, as mentioned in the section 5, the variations of the D component have been caused by the errors due to the tilting variations of the H and Hyz_{mes} measurement and by the annual variation of the F component base line value.

For getting more stable base line values, the corrections for tilting should be done using the digital tiltmeters.

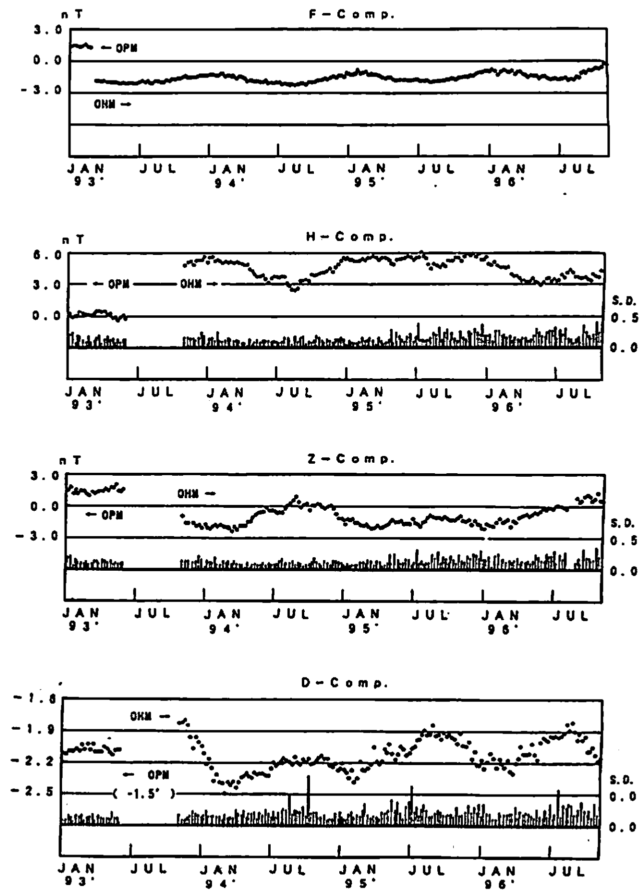

Fig.14 Observed base line values of F, H, Z and D components by OHMs (OCT. 1993 - OCT. 1996). S.D. means the standard deviation of each absolute observation.

Table 4 Tilting coefficients of the measuring methods. These coefficients are made by the values of the geomagnetic intensity at Kakioka
(H: 30,100nT; Z: 35,000nT).
Unit: Tilting angle --- second
H,Z -------- nT
D ---------- minute
U_h: Tilting angle of the vertical coil in the direction of mean magnetic meridian.
U_z,U_{hy},U_{hx}: Tilting angle of the horizontal coil in the direction of coil axis.
U_{N-S}: Tilting angle in the direction of the magnetic north-south(mean magnetic meridian)
U_{E-W}: Tilting angle in the direction of the magnetic east-west.

	H	Z	D
OPM method	$-0.170U_h$	$0.146U_z$	$0.0112U_h-0.0224U_{hy}$
OHM method	$-0.170U_h$	$0.146U_z$	$0.0193U_h-0.0273U_{hx}$
ASMO method(only D)			$-0.0194U_{hy}$
FLUX-GATE	$-0.170U_{N-S}$	$0.146U_{N-S}$	$0.0194U_{E-W}$

Acknowlegement

We would like to express our appreciation to Mr. S. Tsunomura for his helpful advice and encouragements for this work.

References

Alldredge, L. R., A proposed automatic standard magnetic observatory, J. Geophys. Res., 65, 3777-3786, 1960.

Braunbek, W., Die erzeugung weitgehend homogener magnetfelder durch Kreisstrome, Z. F. Physik, 88, 399-402, 1934.

Fanselau, G., Die erzeugung weitgehend homogener magnetfelder durch Kreisstrome, Z. F. Physik, 54, 260-269, 1929.

Hrvoic, I., Proton magnetometers for measurement of the Earth's magnetic field, GEM Systems Inc., 16, 1984.

Hurwitz, L. and J. H. Nelson, Proton vector magnetometer, J. Geophys. Res., 65, 1759-1765, 1960.

Kuwashima, M., Kakioka automatic standard magnetometer (KASMMER), Phys. Earth Planet. Inter., 59, 97-103, 1990.

Sakuraoka, T., Observation on H- and Z- component and compensating magnetic field of vector proton magnetometer, MO-P, for routine use, Mem. Kakioka Mag. Obs., 12, 85-97, 1966. (in Japanese)

Sano, Y., A measuring method of magnetic field component with optical pumping magnetometer and its error and stability related to the compensating field, Mem. Kakioka Mag. Obs., 14, 19-38, 1971. (in Japanese)

Sano, Y., Stability and accuracy of standard magnetic observation by KASMMER system, Mem. Kakioka Mag. Obs., 16, 121-141, 1975. (in Japanese)

Tezuka, M., The replacement of Kakioka automatic standard magnetometer, Mem. Kakioka Mag. Obs. 25, 1-2, 1994.

Tsunomura, S., A. Yamazaki, T. Tokumoto and Y. Yamada, The new system of Kakioka automatic standard magnetometer, Mem. Kakioka Mag. Obs. 25, 3-32, 1994.

Yanagihara, K., M. Kawamura, Y. Sano and T. Kuboki, New standard magnetic observation system of Kakioka (KASMMER), Geophys. Mag., 36, 217-281, 1973.

オーバーハウザー磁力計を用いた地磁気三成分測定

山崎　明・徳本哲男

(1997年12月26日受付，1998年2月17日改訂)

概　　要

1989年から1992年にかけてのKASMMERの更新に際し，筆者らはオーバーハウザー磁力計を用いて地磁気3成分を測定する技術開発を行った．オーバーハウザー磁力計を成分観測に適用するためにはセンサーの改造が必要であり，また補償コイルにファンスロー・ブラウンベックコイルを用いた．また，D成分では新たに考案した測定方式を採用した．本文では測定方法の詳細と誤差解析，および基線値の安定性について述べる．