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Base-Line Value Stability of Geomagnetic Variometer (II)

By

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Abstract: Base-line values of KZ-type Z-variometer are analysed. Of the method described in Part I of this report (Yanagihara, 1975) some modifications are required for some Z-variometers which show complicated characteristics, though there is no need of modification for good Z-variometers under normal condition. Method of analysis is studied for typical cases of abnormal condition. Practical application of the analysis for daily base-line value determination is discussed.

1. Introduction

The base-line values observed by geomagnetic H-variometer at our three observatories, Kakioka, Memambetsu and Kanoya, for horizontal component are expressed well by a function of temperature T and time t for a long period of observation (Yanagihara, 1975). The function $B(T, t)$ consists of three parts: a linear drift $\int D_0 dt$, a temperature-dependent change $\int \xi(T) dT$ and a cross term $W(T, t)$, where D_0 is a constant drift velocity and $\xi(T)$ is a temperature coefficient which is also temperature-dependent.

$$B(T,t)= \int D_0 dt + \int \xi(T) dT + W(T,t) \tag{1}$$

Cross term $W(T, t)$ may mean a temperature-dependent change in drift velocity. In this case it can be omitted by substituting

$$D_0 = h + k(T-T_0) \tag{2}$$

for D_0 in Eq. (1), where T_0 is the mean temperature and h and k are constants. Contribution from $k(T-T_0)$ in $B(T, t)$ forms an out-of-phase part with respect to temperature change, particularly to a nearly sinusoidal annual change which is the largest among temperature changes in routine observation room. Temperature coefficient $\xi(T)$ is usually linear with respect to temperature change.

$$\xi(T) = b + c(T-T_0)/2 \tag{3}$$

Therefore the base-line value is given by

$$B(T,t)=\text{const}+b(T-T_0)+c(T-T_0)^2+\int_0^t\{h+k(T-T_0)\}\mathrm{d}t \qquad (4)$$

which is Eq. (11) of Yanagihara (1975). This formula is applicable also to normal Z-variometers of vertical component.

KZ-type Z-variometer of our observatories is a thread suspension type improved from Watson's model (Watson, 1926; Yanagihara et al., 1973). The suspension system with knife edge in ordinary Z-variometers used in many observatories is not suitable in our country because of numerous earthquakes which may damage the knife edge resulting in abnormal changes in base-line value. Ever since the thread suspension system coming into use, occurrence of abnormal change has been much reduced. But sensible balance between gravity force and vertical geomagnetic force is still disturbed sometimes by some other causes, and unexpected irregular drifts of base-line value result as is the case with many bar-magnet Z-variometers. Minute, invisible dew formed on the magnet of Z-variometer may disturb the balance to cause an abnormal change in base-line value. Kuboki (1964) made many case studies on the effect of humidity on base-line value change for Z-variometers from this point of view.

Even in a period of abnormal drift, temperature-dependence of variometer may be unchanged and the temperature coefficients in Eq. (4) are useful for determining daily base-line values from weekly absolute measurements. However the method of determining the value of coefficients must be modified. For a period including slight abnormal changes, the modified methods will be discussed in the following sections with some examples of Z-variometer; similar analyses must also be applicable to H-variometer of not so good condition. Eq. (4) should be modified for some variometers for which the assumption used in deriving Eq. (4) is not valid. Use of the present analysis in practical determination of daily base-line value will be discussed in the last section.

2. Nonlinear Drift

Fig. 1 shows an analysis of observed base-line values of Kanoya's No. 1 Z-variometer in routine use for a period of three years during which the variometer's condition was average. Two sets of three-component variometers are operated continuously at Kanoya like the other two observatories. No. 1 set is for routine data acquisition and No. 2 set is the backup.

The top curve in Fig. 1 shows monthly mean of observed base-line values B_{obs} and the second shows room temperature T. The formula of base-line value with constants calculated by an observer following the method described in

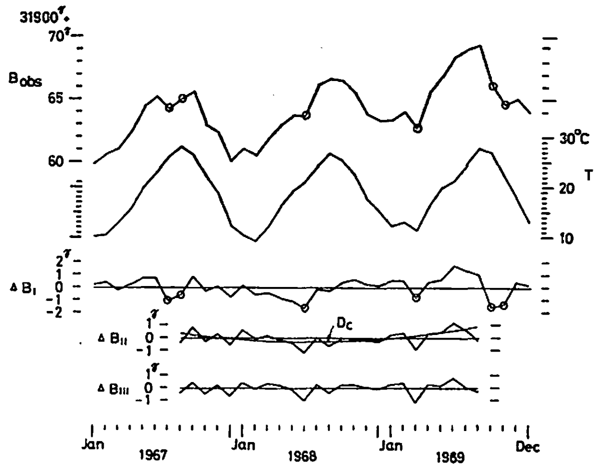

Fig. 1. Analysis of base-line values for Kanoya's No. 1 Z-variometer. For Dc, see Eq. (7).

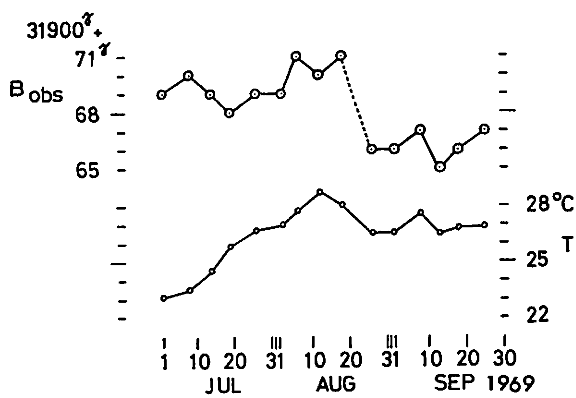

Fig. 2. Weekly observed base-line values and temperatures of Kanoya's No. 1 Z-variometer in July, August and September of 1969.

Yanagihara (1975) is

$$B_{\rm I}=\text{const}+0.117\,t+0.284(T-T_0)+0.0040(T-T_0)^2 + \int_0^t (-0.0520)(T-T_0)\,dt \qquad (5)$$

where $T_0=18.5°\text{C}$ and the unit of t is month. The third curve from the top shows residue $\Delta B_{\rm I}=B_{\rm obs}-B_{\rm I}$ whose standard deviation is $0.79\ \gamma$, a not so small value. The change in $\Delta B_{\rm I}$ is large in the last several months, and slow but systematic variations are found throughout the whole period.

In the third curve, several values each marked by a small circle are rather out of the general trend, and these are marked off similarly on the first curve as well. These abnormal values result in the irregular change of ΔB_{I}. To check the last two of these marked values, weekly observed base-line values are shown in Fig. 2 together with room temperature. There is a sudden drop in the weekly value around August 20, though there is no sign of discontinuous changes in magnetogram trace or in observer's field note.

With the data of after this change ignored and considering the benefit of taking a rounded period for harmonic analysis, an analysis of base-line value is again made for a two-year period of August 1967 to August 1969 in the same way. Though there are marked abnormal values in this period too, no correction is made because no observational malfunctioning has been found. The formula of base-line value for this period is

$$\begin{aligned} B_{\mathrm{II}} &= \mathrm{const} + 0.183\,t + 0.317(T-T_0) + 0.0061(T-T_0)^2 \\ &\quad + \int_0^t (-0.0238)(T-T_0)\,\mathrm{d}t \end{aligned} \qquad (6)$$

Residue $\Delta B_{\mathrm{II}} = B_{\mathrm{obs}} - B_{\mathrm{II}}$ is shown as the fourth curve of Fig. 1. Standard deviation of ΔB_{II} is $0.54\,\gamma$ which is better than that of ΔB_{I}. But a smoothed curve *Dc* obtained by least square method indicates that a small slow change remains in ΔB_{II}.

Eq. (4), or Eq. (11) of Yanagihara (1975), is based on the assumption of linear drift except temperature-dependence of drift velocity. If an actual drift is nonlinear, residues ΔB's must include the portion corresponding to the deviation from linear drift. As the average drift of variometer shows an exponential decay (Kuboki, 1963), the drift is essentially nonlinear. The assumption of linear drift is valid in practical application only for very stable variometers. When the deviation from a linear drift is small, the terms in Eq. (4) other than the linear drift term are not affected so much by it. If necessary for making the formula more reliable, similar calculation should be made to obtain corrected value which is the difference between the observed base-line value and the amount of remaining slow change in ΔB's. This process may be repeated as required. This iterative method improves reliability of the formula, especially of temperature-dependent terms.

For the present particular variometer, it is doubtful that the small slow change in ΔB_{II} represents the difference between the said exponential drift and linear drift. It is rather considered that there was some other factor which increased the drift in the period of August 1967 to August 1969, and the increased drift went back rapidly to the original level expected from an exponential or linear drift on about 20 August 1969 when the said sudden change occurred. The unknown factor might be high humidity, but is not clear at present. In any case the said iterative method is valid as far as the remaining variation in ΔB_{II} is slow and smooth. A smooth curve expressed by

$$Dc = \text{const} - 0.141\,t + 0.0066\,t^2 \tag{7}$$

shown in Fig. 1 is assumed here to represent the excess slow drift. Next, calculation of coefficients b, c, h and k in Eq. (4) is made for residue $B_{obs}-Dc$ in the same way. The formula thus improved is

$$B_{III} = \text{const} + 0.034\,t + 0.0066\,t^2 + 0.316(T-T_0) + 0.0085(T-T_0)^2 + \int_0^t (-0.0233)(T-T_0)\,\mathrm{d}t \tag{8}$$

This formula includes the effect of nonlinear drift Dc. Residue $\Delta B_{III} = B_{obs} - B_{III}$ is shown as the bottom curve of Fig. 1. Standard deviation of ΔB_{III} is $0.45\,\gamma$.

It is emphasized here that the aim of correcting nonlinear drift is not in obtaining the best empirical formula but in determining temperature-dependent parts more accurately. Calculated temperature coefficients of the present variometer are shown in Fig. 3 where I, II and III are those for B_I, B_{II} and B_{III}, respectively. Though the three are not so different, fortunately, from each other, III is the best.

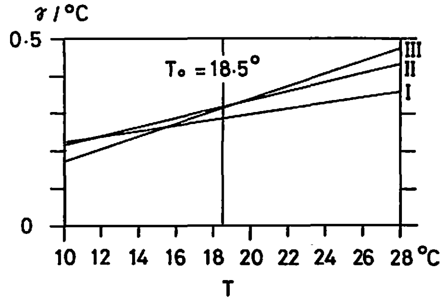

Fig. 3. Temperature coefficients of Kanoya's No. 1 Z-variometer.

3. Peculiar Drift in Wet Season and Nonlinear Temperature-Dependence of Temperature Coefficient

The iterative method described in the preceding section gives a reliable expression of temperature-dependence for most variometers in normal condition. But indiscriminate application may result in getting inaccurate temperature coefficients because the validity of the basic assumption of this method depends on the environmental and internal conditions of individual variometers. Two

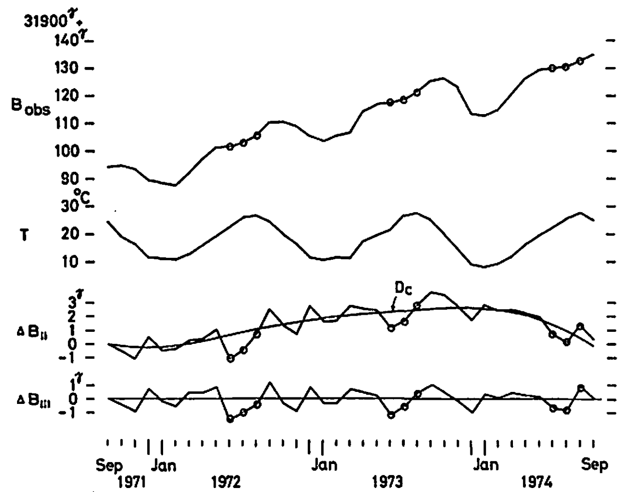

Fig. 4. Analysis of base-line values for Kanoya's No. 2 Z-variometer (I).

typical situations which preclude application of the formula are the wet season, in which peculiar drift may occur, and nonlinear temperature-dependence of temperature coefficient. One example is found in Kanoya's No. 2 Z-variometer in which the two situations arose at the same time. Fig. 4 shows, like Fig. 1, an analysis of its base-line values for a period of three years from September 1971 to September 1974. The top curve shows monthly means of observed base-line value B_{obs} and the second is room temperature T. An observer has made a similar analysis for a five-year period 1965–1969 and obtained a first approximate formula B_{I} of base-line value. But his result is not shown here because a large abnormal drift is found in the first two years. Formula B_{II} of base-line value is determined for the three-year period, and residue $\Delta B_{II}=B_{obs}-B_{II}$ is shown as the third curve in Fig. 4. The assumed nonlinear drift for ΔB_{II} is shown by a smooth curve Dc. Using $B_{obs}-Dc$ for B_{obs}, each coefficient of Eq. (4) is calculated. The formula thus improved is

$$B_{III}=\text{const}+Dc+1.133\,t+0.670(T-T_0)-0.0741(T-T_0)^2 + \int_0^t 0.1086(T-T_0)\,dt \qquad (9)$$

where $T_0=17.9$°C. Residue $\Delta B_{III}=B_{obs}-B_{III}$ is shown as the bottom curve in Fig. 4. Standard deviation of ΔB_{III} is $0.68\,\gamma$, a not so bad value. However it should be noted that a cyclic change is found in the variation of ΔB_{III}. This is more clearly seen in Fig. 5 which shows mean annual variation of ΔB_{III}. Table 1 shows annual and semi-annual terms of B_{obs}, calculated value B_{III} and their

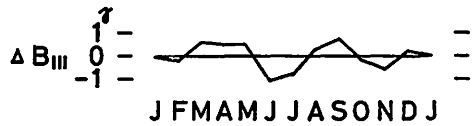

Fig. 5. Mean annual variation of the residue ΔB_{III} of Kanoya's No. 2 Z-variometer.

Table 1. Harmonic analysis of base-line value (B_{obs}, B_{III} and ΔB_{III}) and temperature T for Kanoya's No. 1 and No. 2 Z-variometers.

	In-phase term				Out-of-phase term		
	B_{obs}	B_{III}	ΔB_{III}	T	B_{obs}	B_{III}	ΔB_{III}
No. 1	γ	γ	γ	°C	γ	γ	γ
Annual	2.48	2.48	0.00	7.85	0.30	0.30	0.00
Semi-annual	0.27	0.28	−0.01	0.74	0.32	0.32	0.00
No. 2							
Annual	5.40	5.47	−0.07	8.49	−1.15	−1.23	0.08
Semi-annual	−0.22	−0.66	0.44	0.91	−2.98	−2.63	−0.35

difference ΔB_{III} for Kanoya's No. 1 and No. 2 Z-variometers. Large differences are found in the semi-annual terms for No. 2 Z-variometer.

If the assumption in Eq. (4) is right for this variometer the semi-annual term of ΔB_{III} should disappear. The large difference implies that the assumption is not valid in this case. Coefficient k of the out-of-phase part is determined mainly by large annual temperature change term. So if there is any extra annual variation of base-line value independent of temperature change, the k value may be incorrect though the annual term of base-line value is numerically approximated by the calculated value. The incorrect k value causes the discrepancy between the observed and calculated values for semi-annual term. Calculated temperature-dependent part must also be incorrect because of the in-phase part of the extra annual variation. Kanoya's No. 2 Z-variometer seems to be an example of this case. What is the cause of the extra annual variation?

From ΔB_{III} of Fig. 4 or its mean annual variation shown in Fig. 5, it is seen that the values of June, July and August are abnormal. This tendency can be traced back to B_{obs}. At Kanoya, both air temperature and humidity of outdoors rise rapidly in June and remain high throughout these three months. The outdoor air inevitably finds its way into the observation house. In summer, the temperature of indoor air and variometer magnet are somewhat lower than that of outdoors because of heat-insulation of the observation house. This causes minute dew to form on the cool surfaces of variometer magnet. The dew changes the moment of inertia of the magnet and disturbs the normal balance between gravity force and geomagnetic vertical force. This may be the cause of the abnormal change in base-line value in summer season, namely, the extra and apparent annual variation.

This abnormal change is shown in a different manner in Fig. 6. Crosses in the figure show monthly mean values of $B_{obs}-(1.133\,t+Dc)$, where the bracketed term is the calculated approximation of drift in B_{III}. Circles are the three-month mean. With June, July and August excluded, a smooth curve is obtained by the least square method for each of temperature-descending and -ascending periods.

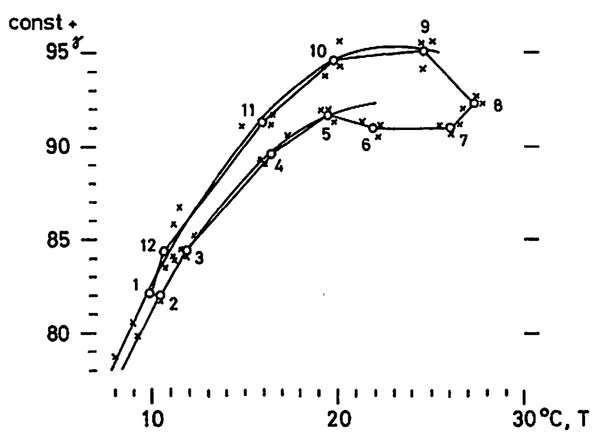

Fig. 6. Temperature-dependence of base-line values of Kanoya's No. 2 Z-variometer with the drift, $1.133\,t + Dc$, subtracted.

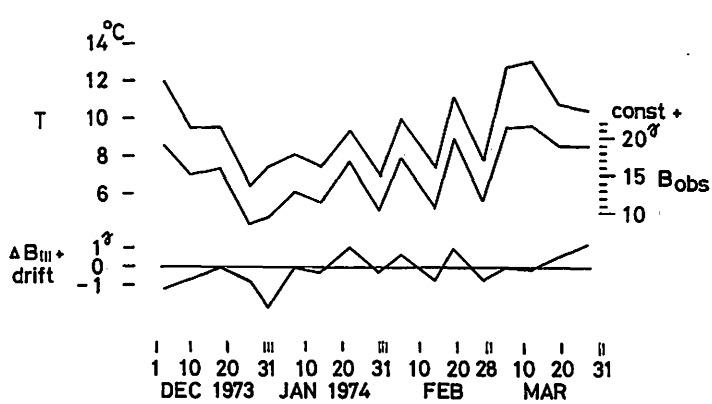

Fig. 7. Unsuitableness of B_{III} for Kanoya's No. 2 Z-variometer in very low temperatures.

Deviation from the smooth curve commences in June. The mean of the two smooth curves may represent the true temperature-dependence as is described in Section 2 of Yanagihara (1975), excluding the three summer months. An example of discrepancy in very low temperatures (Fig. 7) suggests that extraporation into the high temperature range may also be risky.

Weekly observed base-line value B_{obs}, temperature T and $B_{obs}-\{0.670(T-T_0)-0.0741(T-T_0)^2\}$ for a winter season are shown in Fig. 7. The terms in the large brackets are the temperature-dependent part of B_{III}. If the terms are appropriate the bottom curve should be smooth, but this curve is approximately in phase with the temperature curve. Therefore the temperature-dependent part is not appropriate at least for very low temperatures. This may partly be due to the fact that with the extra annual variation superposed on the temperature-dependent variation, the b and c terms are incorrect.

The primary cause seems to be the nonlinear temperature-dependence of temperature coefficient of the variometer as is discussed in the following.

When drift velocity is nearly constant for a short period, weekly observed base-line values are expressed by a linear function of temperature T and time t, as Eq. (6) of Yanagihara (1975):

$$B_{IV}=\text{const}+\xi_{IV}T+\eta_{IV}t \tag{10}$$

If the temperature change is large compared with the drift during the period, temperature coefficient ξ_{IV} is calculated with sufficient accuracy by the least square method. Squares in Fig. 8 show the calculated temperature coefficients of Kanoya's No. 2 Z-variometer for two months, January and February, of designated years.

The value for 1974 is accurate and reliable because the standard deviation of the difference between observed and calculated values is only 0.20 γ for large changes in temperature, but it is rather off from straight line III, the temperature

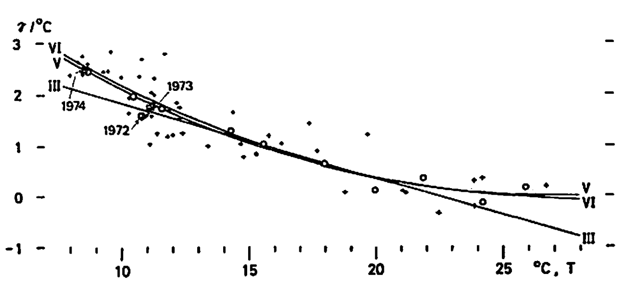

Fig. 8. Temperature-dependence of temperature coefficient of Kanoya's No. 2 Z-variometer. For III, V and VI, see Eqs. (9), (12) and (13).

coefficient of B_{III}. On the other hand the values for 1972 and 1973 are not so reliable because the standard deviation values are $0.73\,\gamma$ and $1.00\,\gamma$, respectively. Therefore the apparent fit of the values with the straight line III is incidental. The large values of standard deviation must come from unstable drift even in such a short period.

The best way of obtaining temperature coefficient is to use the difference between a pair of observed values separated by a shortest possible interval which is a week or so in normal routine operation. Let ΔB_{obs} be the difference of observed base-line values and ΔT be that of temperature, and $\Delta B_{obs}/\Delta T$ gives temperature coefficient provided that drift is negligible in the said interval. The least square method is applied to

$$\Delta B_{obs}=\xi_V \Delta T \tag{11}$$

to obtain reliable values of temperature coefficient ξ_V for all the cases in which temperature changed and crossed any of the levels 8°, 10°, 12°, ..., 26°C. Errors coming from small changes in drift may be ignored if they appear at random. Calculated ξ_V is shown by circle in Fig. 8, where individual plots of ξ_V are not exactly at the said temperature levels because the mean value of all cases is used. Temperature-dependence of ξ_V is clearly non-linear. A smooth curve denoted by V is given by

$$\xi_V=0.617-0.1344(T-T_0)+0.00703(T-T_0)^2 \tag{12}$$

Another calculation of the temperature-dependence of temperature coefficient is made by direct application of the least square method to every value of $\Delta B_{obs}/\Delta T$ whose ΔT is larger than 2°C.

$$\xi_{VI}=0.643-0.1422(T-T_0)+0.00688(T-T_0)^2 \tag{13}$$

This formula gives a curve designated by VI in Fig. 8, very similar to curve V. Crosses of the figure show individual values of $\Delta B_{obs}/\Delta T$.

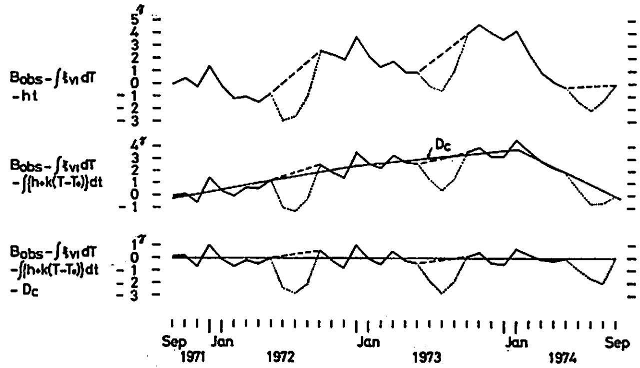

Fig. 9. Analysis of base-line values for Kanoya's No. 2 Z-variometer (II).

The two curves of temperature coefficient nearly coincide and seem to express reliable temperature-dependence. They deviate from the straight line III of B_{III} in low and high temperatures. This is the cause of the unsuitableness of ΔB_{III} plus drift shown in Fig. 7.

Top figure of Fig. 9 shows the residual values of B_{obs} with non-cyclic change and the correct temperature-dependent part $\int \xi_{\mathrm{VI}} dT$ subtracted. Mean annual variation of the residual value, except June, July and August, forms the out-of-phase part with respect to temperature change as is shown in Fig. 10. A smooth curve superposed upon the mean annual variation of the residual value at the top of Fig. 10 shows the most suitable out-of-phase variation calculated from the annual term of temperature variation shown at the bottom of the figure. Coefficient k of the out-of-phase part calculated from them is 0.0819 γ/month/°C.

The out-of-phase part $\int k(T-T_0)\, dt$ is subtracted from the top curve of Fig. 9 and the residual values are shown in the middle of the same figure. Non-linear drift is approximated by Dc which consists of three straight lines. Subtracting Dc from the middle curve, final residues of base-line value are shown at the bottom of Fig. 9. The final residues are all small and no cyclic or systematic variation is found except those in June, July and August. Standard deviation is 0.47 γ for 28 values, with these three months excluded.

Analysis of base-line value has been made rather in detail for a variometer to know typical abnormal characteristics and how to treat them. But those variometers which show such complicated changes should better be replaced by good variometers for routine use.

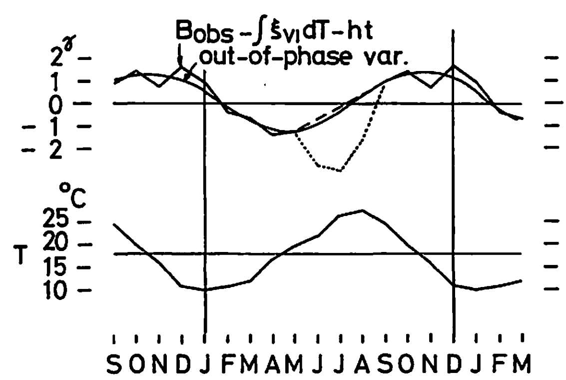

Fig. 10. Mean annual variation of the residual of base-line values shown at the top of Fig. 9 (upper) and temperatures (lower). A smooth curve in the upper part is the out-of-phase variation with respect to the annual term of temperature change when k=0.0819 γ/month/°C.

4. Time Change of Temperature Coefficient

Temperature coefficient of a variometer at a given temperature is considered to be virtually constant for a long time on physical point of view unless there is some cause for change. Nevertheless faced with abnormal changes in base-line value, observers tend to ascribe them to a change in temperature coefficient. While some cases might truly be due to the change in temperature coefficient, most of them must have been caused by abnormal drifts due to disturbed balance of variometer magnet reflecting slight changes in some unidentified factors such as torque of the suspension fibre, moment of inertia of the magnet and magnetic moment.

Time change of temperature coefficient is examined here for Kanoya's No. 2 Z-variometer. The change is expected of this variometer because its temperature coefficient is large and complicated as is shown in the preceding section.

At its installation in December 1957, the said variometer's temperature coefficient was $2.0\,\gamma/^{\circ}\mathrm{C}$ at 10°C (Kuboki, 1963), which is very close to the present value shown in Fig. 8. For a period from September 1961 to September 1963, temperature coefficient ξ_{VI} is calculated in the same way as is described in the preceding section. Fig. 11 shows the curves of ξ_{VI} for 1961–1963 and 1971–1974. Circles of the figure represent individual values of $\Delta B_{\mathrm{obs}}/\Delta T$ for 1961–1963. The change between the two periods amounts to only about 10 per cent for temperature coefficients larger than $1\,\gamma/^{\circ}\mathrm{C}$, or about one per cent per year which is negligible for a few years considering the accuracy of determination of temperature coefficient.

An observer reported (Kuboki, 1963) that the temperature coefficient of the said variometer changed suddenly from $0.8\,\gamma/^{\circ}\mathrm{C}$ to $2.4\,\gamma/^{\circ}\mathrm{C}$ at 17.9°C on November 12, 1962. While the former value is very close to the value shown in Fig. 11, the latter is not acceptable because it is far beyond the scatter of individual

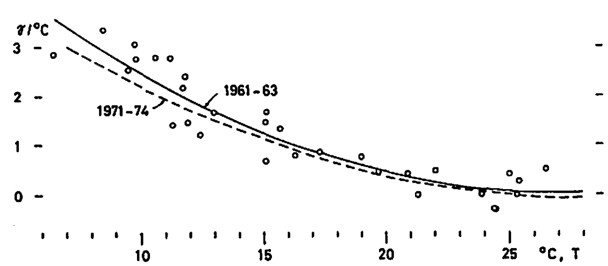

Fig. 11. Temperature coefficients of Kanoya's No. 2 Z-variometer for 1961–63 (full line) and 1971–74 (broken line).

values shown by circles. Detailed examination of the change in base-line value around this date indicates that he mistook a small abnormal drift for a change in temperature coefficient.

5. Practical Application of the Present Analysis to Base-Line Value Determination

Daily base-line values of a variometer are usually determined from weekly absolute measurements. For the days between two consecutive absolute measurements, interporation is made with temperature change and drift taken into consideration. When the variometer is in normal condition, the method of Yanagihara (1975) gives a good estimation in the following manner. Calculated temperature-dependent part is subtracted from observed values at first. Time change of the residual should show a smooth curve. The curve represents drift including the out-of-phase part with respect to temperature change. Daily base-line values are easily calculated as the sum of the drift and the temperature-dependent part for each day.

Before applying this method, magnetogram trace should carefully be examined for any jumps, i. e., discontinuous changes in base-line values, and corrections should be made by use of the diffenence between the absolute measurements before and after the jump and the amount of the jump as well as a comparison with the other magnetograms of the same day. It is insufficient to do it only for the cases of clear jump in magnetogram trace. One example that occurred in August 1969 is shown in Figs. 1 and 2. An improvement from B_{I} to B_{II} has been described.

Effect of nonlinear drift may be found in residue ΔB_{II}. It is approximated by Dc and the iterative method gives more appropriate temperature coefficient. The residue is improved from ΔB_{II} to ΔB_{III}. The temperature coefficient of B_{III} should be used for daily base-line value determination in the same way as is described in the first paragraph of this section.

A step-like rapid change in base-line value in the middle of a period selected for calculation can be eliminated similarly by assuming a suitable Dc. Incorrect estimation of non-cyclic change may affect ΔB_{II} and give incorrect value of temperature coefficient. Incorrect estimation is caused by deviations of observed values at both ends of the selected period from the normal value, particularly by accidental abnormal drifts and temperature difference between the beginning and the end of the period. It is not wise to select a period of which end temperatures are much different. If necessary, an analysis of base-line value is made first for uncorrected non-cyclic changes to obtain a first approximation of temperature coefficient. Next, an analysis should be made by using corrected values at both ends of the relevant data period. The correct values are those at the same temperature calculated by the approximate temperature coefficient. This process is to be repeated. Correcting non-cyclic changes of temperature at first is not advisable because Eq. (4) is not linear with respect to temperature.

Annual or semi-annual variation should not be included in Dc. If ΔB_{II} contains any of these, there is a possibility of having undesirable abnormal drift such as those described in Section 3, and the calculated temperature coefficient may be incorrect.

It is hoped that B_{I}, B_{II} and B_{III} be sufficient for determining temperature coefficient for variometers in routine use. When a variometer unfortunately shows abnormal drifts or complicated characteristics such as those shown in Section 3, the various methods of analysis described in Section 3 should be tried. Even in this case it is important to know temperature coefficient first. With calculated temperature-dependent part from observed base-line values subtracted, residual values represent the drift, including abnormal one. They make daily base-line value determination possible.

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地磁気変化計の安定性 (II)

柳 原 一 夫

（名古屋地方気象台）

第一報に引き続いて KZ 型垂直分力用変化計の基線値を解析した．垂直分力変化計でも正常の状態にあれば第一報における水平分力変化計と同様の解析が可能であるが，垂直分力変化計の場合はドリフト異常を起こしやすく，これに対しては解析法の修正が必要となる．また温度係数の温度に対する非直線性など変化計特性の複雑なものもある．これらの典型的な場合について解析法を示した．第一報に述べた標準的解析法と併せて実際の基線値決定に応用しうるものである．

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