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10. *The Anomalous Behaviour of Geomagnetic Variations of Short Period in Japan and Its Relation to the Subterranean Structure.**

The 11th report.

(Spectral analysis of geomagnetic disturbances.)

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Summary

Spectral analyses of magnetograms are made in order to investigate frequency dependent behaviour geomagnetic disturbances observed at eight obserbatories in Japan. The distribution of power of the Z component indicates a tendency similar to the ones reported in the previous papers. As for the H component, some new characteristics are brought to light, that is, the ΔH values for a certain period range are large in south-western Japan roughly coinciding with the terrestial heat flow pattern.

1. Introduction

It has been reported by T. Rikitake and his colleagues[1)-6)] that the vertical component of geomagnetic variations of short period, especially geomagnetic bays and similar changes, shows an anomalously large increase in the central part of Japan. In spite of intensive studies over a ten years' period on the possible cause of such a geomagnetic variation anomaly, it is still not clear why we observe the anomaly.

The studies have so far been made mostly on the basis of isolated

* Communicated by T. Rikitake.

1) T. RIKITAKE *et al.*, *Bull. Earthq. Res. Inst.*, **30** (1952), 207; **31** (1953), 19, 89, 101 and 119.

2) T. RIKITAKE *et al.*, *Bull. Earthq. Res. Inst.*, **33** (1955), 297.

3) T. RIKITAKE *et al.*, *Bull. Earthq. Res. Inst.*, **36** (1958), 1.

4) T. RIKITAKE *et al.*, *Bull. Earthq. Res. Inst.*, **37** (1959), 1.

5) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **37** (1959), 545.

6) T. RIKITAKE *et al.*, *Bull. Earthq. Res. Inst.*, **40** (1962), 693.

geomagnetic events, bays, ssc's, sfe's and such like in Japan. K. Whitham[7] and others have recently demonstrated that application of spectral analysis technique to geomagnetic disturbances is useful for inferring conductivity anomalies in the earth's crust and mantle. Their work was conducted for magnetograms obtained at observatories in the north polar cap where wide-band geomagnetic fluctuations are always prevailing.

It is suggested to the writer by Professor Rikitake that spectral analyses of Japanese magnetograms may provide an approach towards a better understanding of the Central Japan Anomaly, although it is hard to evaluate the usefulness of such analyses of magnetograms obtained at a middle latitude like Japan where distributions of geomagnetic disturbance are more regular than those in the polar cap.

It is intended in this paper to report on the results of spectral analyses made for magnetograms from eight magnetic observatories. In Section 2 will be described the magnetic data used. Section 3 will be reserved for outlining the spectral analysis technique, while the results of spectral analyses will be given in Section 4.

2. Data

Standard magnetograms from eight magnetic observatories in Japan at the time of a geomagnetic storm that occurred on Sept. 20, 1959 were analysed. The storm observed at Kakioka (Kk) is illustrated in Fig. 1. A sudden commencement of the storm occurs at about 12: 00 U. T., while the preceding record is also disturbed. In Fig. 2 is illustrated the dis-

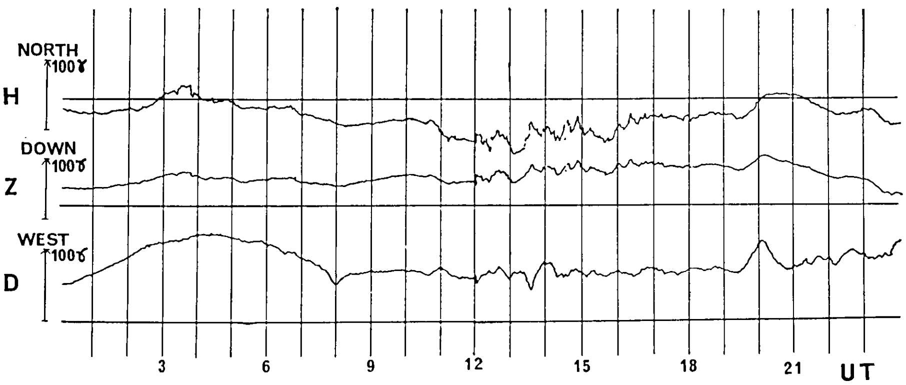

Fig. 1. Storm observed at Kakioka (Kk) on Sep. 20, 1959.

7) K. WHITHAM, *Geophys. Jour.*, 8 (1963), 26.

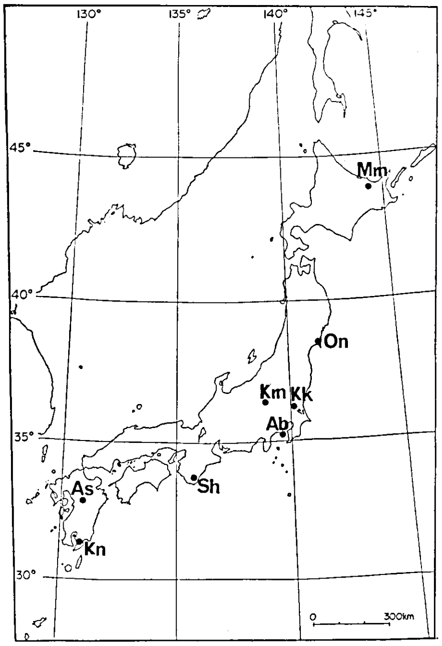

Fig. 2. Distribution of observatories in Japan.

Table 1. Abbreviations and locations of the magnetic observatories.

Abbreviation	Observatory	Geographic latitude (N)	Geographic longitude (E)
Mm	Memambetsu	43.9°	144.2°
On	Onagawa	38.4	141.5
Kk	Kakioka	36.2	140.2
Km	Komoro	36.3	138.4
Ab	Aburatsubo	35.2	139.6
Sh	Shimosato	33.6	135.9
As	Aso	32.9	131.0
Kn	Kanoya	31.4	130.9

tribution of the observatories, and their localities are summarized in Table 1 together with their abbreviations.

3. Outline of Spectral Analysis

Each magnetogram obtained from the eight observatories was hand digitized for each of the three components, H, D and Z (magnetic north-, west- and downward component) from 1:00 to 23:00 U.T. with a sampling interval $\Delta t=3$ m. Power spectra for each component, and coherence and phase difference between H and Z for $M=80$ lags are calculated using the method attributed to Munk, Snodgrass and Tucker.[8)]

Let $x_1, x_2, \cdots, x_i, \cdots, x_n$ and $y_1, y_2, \cdots, y_i, \cdots, y_n$ represent corresponding values of any two components, in this case at the same station. The following eight quantities are then computed.

$$\begin{aligned}
A(l)&=\langle x_i\cdot x_{i-l}\rangle_i\,, & X(k)&=\delta k\left\langle A(l)\left(1+\cos\frac{\pi l}{M}\right)\cos\frac{k\pi l}{M}\right\rangle_l\,,\\
B(l)&=\langle y_i\cdot y_{i-l}\rangle_i\,, & Y(k)&=\delta k\left\langle B(l)\left(1+\cos\frac{\pi l}{M}\right)\cos\frac{k\pi l}{M}\right\rangle_l\,,\\
C(l)&=\langle y_i\cdot x_{i-l}\rangle_i\,, & Z(k)&=\delta k\left\langle \frac{D(l)+C(l)}{2}\left(1+\cos\frac{\pi l}{M}\right)\sin\frac{k\pi l}{M}\right\rangle_l\,,\\
D(l)&=\langle x_i\cdot y_{i-l}\rangle_i\,, & W(k)&=\delta k\left\langle \frac{D(l)-C(l)}{2}\left(1+\cos\frac{\pi l}{M}\right)\sin\frac{k\pi l}{M}\right\rangle_l\,,
\end{aligned}\tag{1}$$

where l is a lag and k a dimensionless integer proportional to frequency. M represents a chosen number of lags, also of final spectral values; thus both l and k have values $0, 1, 2, \cdots, M$. $\delta k=1/2$ for $k=0$ or M and 1 otherwise. The operators $\langle\ \rangle_i$ and $\langle\ \rangle_l$ signify averages taken over all N values of i, and M values of l. A and B are autocorrelations, C and D positive and negative parts of the cross-correlation. X and Y are called the spectra of the respective functions; they are cosine transforms of the autocorrelation. Z is called the co-spectrum, W the quadrature spectrum; they are cosine and sine transforms of the cross-correlations respectively. The term $\left(1+\cos\frac{\pi l}{M}\right)$ is a smoothing function which serves for reducing irregularities in the spectral value arising from certain features of the analytical process.

In the integral form, the auto-correlation function $A(\tau)$ can be represented by power spectrum as follows:

$$A(\tau)=\frac{1}{T_0}\int_{-T_0/2}^{T_0/2}x(t)x(t+\tau)dt=\int X(\omega)e^{-i\omega\tau}d\omega\,, \tag{2}$$

If $\tau=0$

$$\overline{x(t)^2}=\frac{1}{T_0}\int_{-T_0/2}^{T_0/2}x(t)^2dt=\int X(\omega)d\omega\,. \tag{3}$$

8) W. MUNK, F. E. SNODGRASS and M. J. TUCKER, *Bull. S. I. O.*, 7 (1959), 283.

Thus power spectrum is an estimate of $E(k)$, the power per unit interval of F and centered on $F=k$, where $F=2Mf\Delta t$ is a dimensionless number proportional to the frequency f. Δt is the time interval between successive readings of x. $X(0)$ refers to half of this energy density centered at $F=1/4$. Thus $\sum_0^M X(k)$ is the total power of the record. $[X(k)]^{1/2}$ is a measure of the mean amplitude over the particular frequency interval concerned.

From the co- and quadrature spectra, the coherence $R(k)$ and the phase lead of the y- record relative to the x- record $\theta(k)$ are calculated as follows:

$$R(k)=(Z^2+W^2)/[XY]^{1/2}\,, \qquad \tan\theta(k)=W/Z\,. \tag{4}$$

If the forms of two waves are identical and simultaneous, $R(k)=1$ and $\theta(k)=0$. If they are identical but displaced in time, $R(k)=1$ and θ takes a value different from 0. If the records are unrelated, $R(k)$ tends to zero for long records but otherwise has a random value. When $R(k)=1$, $[Y(k)/X(k)]^{1/2}$ gives the ratio of the amplitudes of the x- and y- records over an appropriate frequency interval.

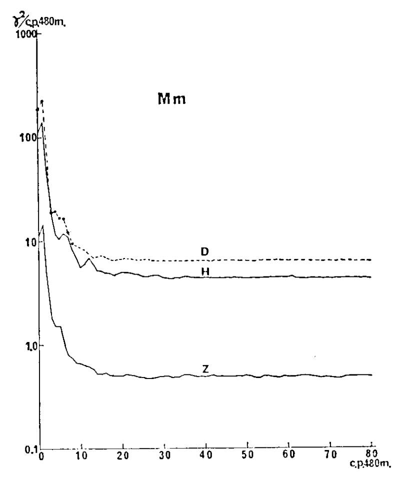

Fig. 3-1. Power spectra of the three geomagnetic components (H, D, Z) for Memambetsu (Mm) in units of γ^2/cycles per 480 min,

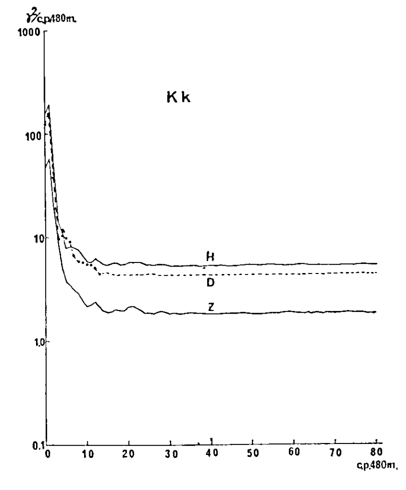

Fig. 3-2. Power spectra of the three geomagnetic components (H, D, Z) for Kakioka (Kk) in units of γ^2/cycles per 480 min,

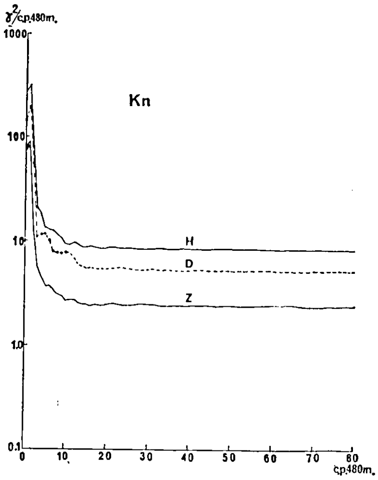

Fig. 3-3. Power spectra of the three geomagnetic components (H, D, Z) for Kanoya (Kn) in units of γ^2/cycles per 480 min.

3. Results of Spectral Analysis

Fig 3-1, 3-2 and 3-3 show power spectra, or energy densities, of the three componets for observatories Mm, Kk and Kn respectively in units of γ^2/cycles per 480 min. Errors in the original hand digitizing procedure are about 0.4 mm. If these are assumed to be uncorrelated with the level of disturbance, for a scale value $K\gamma$/mm, the noise energy density is

$$1/2(0.4K)^2/(M/2M\Delta t)=(0.4K)^2\Delta t$$
$$=1.0\times10^{-3}K^2\gamma^2/\text{c.p. } 480\text{ m}.$$

Since K varies $1.0\sim6.4\gamma$/mm, the noise energy density varies $0.001\sim0.041\gamma^2$/c.p. 480 m. So all spectral values are far greater than the noise level.

The attenuation curves of powers with increasing frequency are similar for each observatory, but the levels of them, especially for Z component, differ much from observatory to observatory.

In the statistical investigations of the bay-type disturbances or ssc's in Japan, the ratio of the maximum ΔZ to the maximum ΔH has been adopted as a measure of ΔZ activity. In order to compare the results of the present analyses with the results obtained before, the ratios of mean amplitude of Z component to H component are calculated for each observatory and illustrated in Fig. 4. It is remarkable that $\Delta Z/\Delta H$ exceeds 1.0 at Ab and Sh around a frequency $F=3$ ($T=160$ m). As the total power ratios of ΔZ to ΔH at Ab and Sh are 0.63 and 0.51 respectively, the $F=3$ wave of Z variation is anomalously predominant in this area. It has been noticed at times of bays that the maximum amplitude of ΔZ is about 60% of that of ΔH in the central part of Japan.[1] But on some occasions (for example, at the time of a bay that occurred on April 18, 1958)[3], ΔZ is slightly larger than ΔH at Ab and Sh so that the results shown in Fig. 4 are not unreasonable. Fig. 4 also shows that there are two types of frequency dependent behaviour of $\Delta Z/\Delta H$ variation, (1) $\Delta Z/\Delta H$ takes a maximum value at $F=3$ (Ab, Sh, Kk) and (2) $\Delta Z/\Delta H$ takes a minimum (As, Km, Kn) or a small maximum value

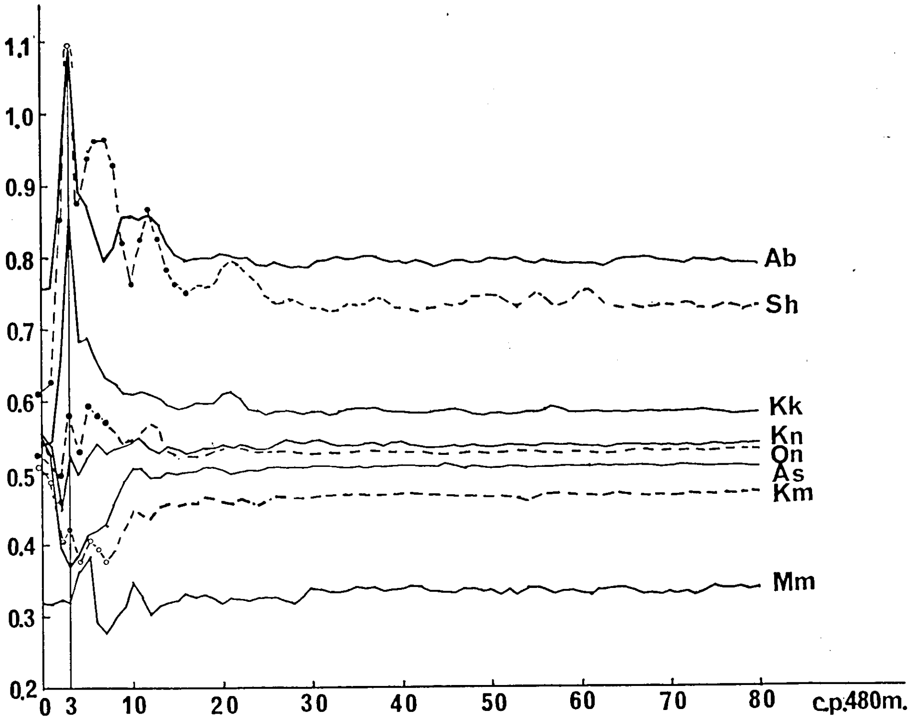

Fig. 4. Ratios of mean amplitude of Z to H component for each observatory.

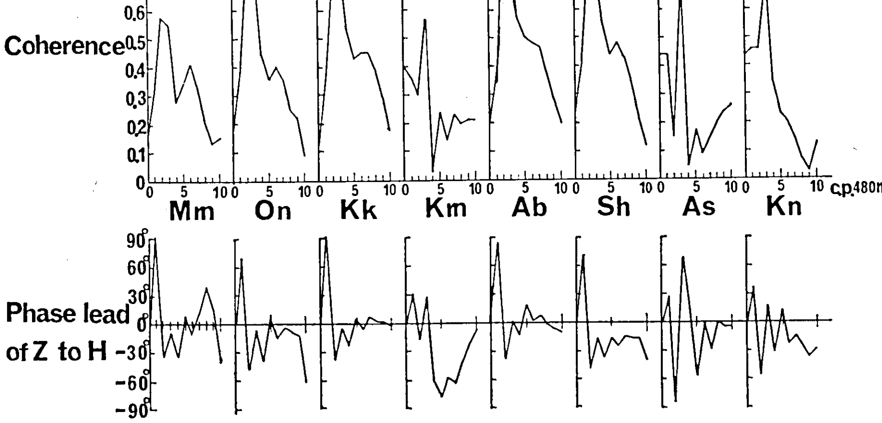

Fig. 5. Coherence between Z and H for each observatory (upper graph) and phase lead of Z-record to H-record (lower graph) for $F=0\sim10$.

(On, Mm) at the same frequency. The observatories belonging to type (1) are apparently located near the center of the Central Japan Anomaly, while the type (2) observatories around the above-mentioned area. For shorter periods, $\Delta Z/\Delta H$ takes on a constant value for each observatory, but the values of $\Delta Z/\Delta H$ are large for the observatories belonging to the type (1) and small for the type (2) ones. To be more specific, the distributions of $\Delta Z/\Delta H$ and power for $F=3$ and shorter periods should be illustrated on charts. But before illustrating them, it is interesting to investigate the characteristics of the $F=3$ wave from another point of view. Fig. 5 shows coherence between Z and H, and phase lead of Z- record to H- record for $F=0\sim10$. For shorter periods coherence $R(k)$ indicates small random values and $\theta(k)$ is nearly zero. At $F=3$, coherence is good for all the observatories and phase difference has the smallest absolute value at almost all the observatories and can be regarded as negligibly small. Although bay-type disturbance is an aperiodic variation having a duration of a few hours, a bay observed in Japan is a very coherent wave especially in the central part of Japan; so that the present $F=3$ wave can be regarded as a variation equivalent to a geomagnetic bay so far as the Z and H components are concerned.

In Fig. 6–Fig. 9 are illustrated the distributions of $\Delta Z/\Delta H$ and power

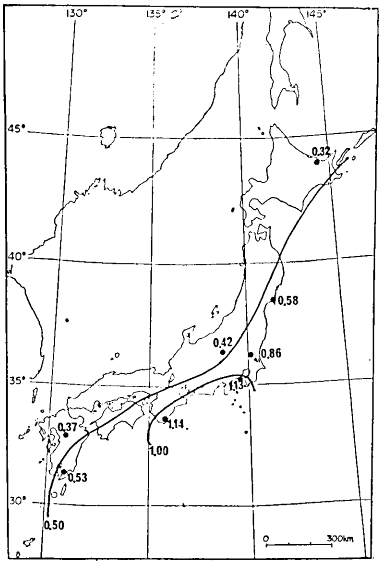

Fig. 6–1. Distribution of mean amplitude ratio $\Delta Z/\Delta H$ for $T=160$ min.

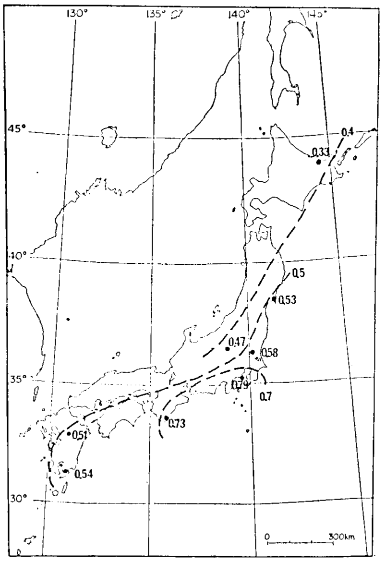

Fig. 6–2. Distribution of mean amplitude ratio $\Delta Z/\Delta H$ for sporter periods ($T\leqq30$ min.).

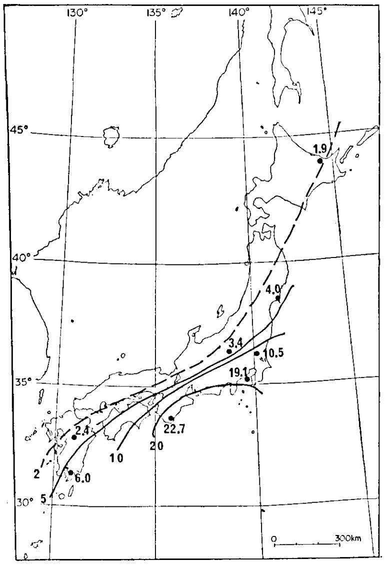

Fig. 7-1. Distribution of power of the Z components for $T=160$ min. in units of γ^2/cycles per 480 min.

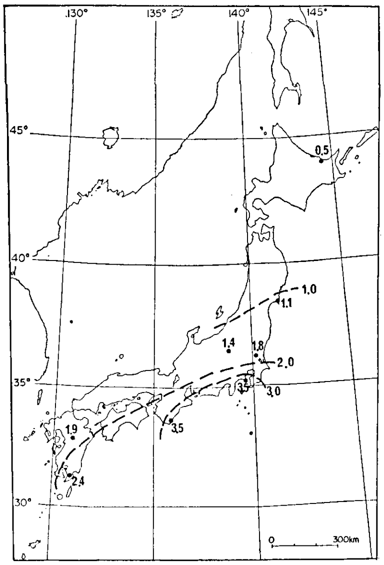

Fig. 7-2. Distribution of power of the Z component for shorter periods in units of γ^2/cycles per 480 min.

of Z, H and D components for $F=3$ ($T=160$ m.) and shorter periods ($T\leqq 30$ m.). Fig. 6-1 and Fig. 6-2 show the distribution of mean amplitude ratio $\Delta Z/\Delta H$ for $T=160$ m. and $T\leqq 30$ m. respectively. Comparing Fig. 6-1 with the chart showing the statistical distribution of $\Delta Z/\Delta H$ for short-period variations (mainly bay-type disturbances),[2] it is observed that the $\Delta Z/\Delta H$ ratios for $T=160$ m. are larger than those for short-period variations as a whole. Because of the lack of stations, it cannot be helped that the equal $\Delta Z/\Delta H$ lines are somewhat ambiguous. But the 1.0 and 0.5 equal $\Delta Z/\Delta H$ lines seem to roughly agree respectively with the 0.6 and 0.2 ones which have been statistically obtained for bays. Apart from the absolute value of $\Delta Z/\Delta H$, this pattern seems to be fairly coincident with the statistically obtained one, and so the anomalously large $\Delta Z/\Delta H$ value as observed in the central part of Japan is well confirmed even in the present analyses. In Fig. 6-2 is shown the $\Delta Z/\Delta H$ distribution for shorter periods. A pattern of equal $\Delta Z/\Delta H$ lines similar to that for $T=160$ m. can also be seen. Fig. 7-1 shows the distribution of power of the Z component. Enormous powers are observed in the central part of Japan. It would be meaningless to compare quantitatively these powers with the maximum amplitudes at the time of a bay because the source fields on the overhead current systems differ from one another.

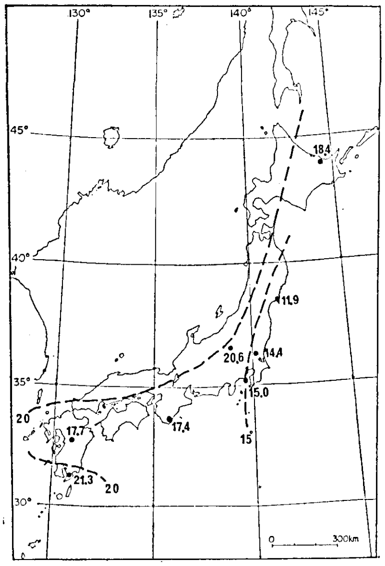

Fig. 8-1. Distribution of power of the H component for $T=160$ min. in units of γ^2/cycles per 480 min.

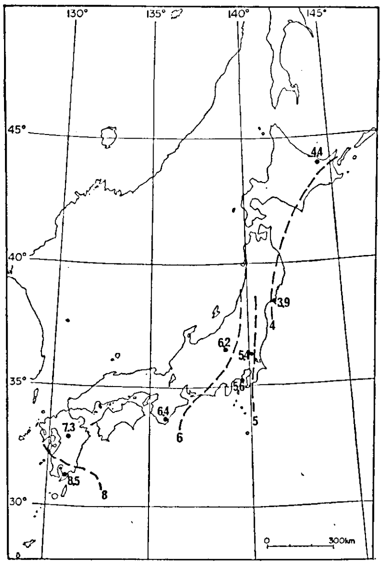

Fig. 8-2. Distribution of power of the H component for shorter periods in units of γ^2/cyles per 480 min.

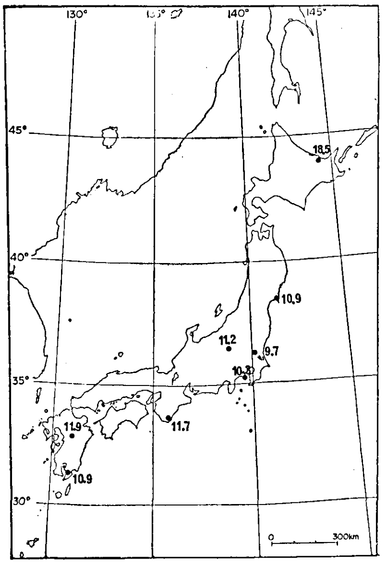

Fig. 9-1. Distribution of power of the D component for $T=160$ min. in units of γ^2/cycles per 480 min.

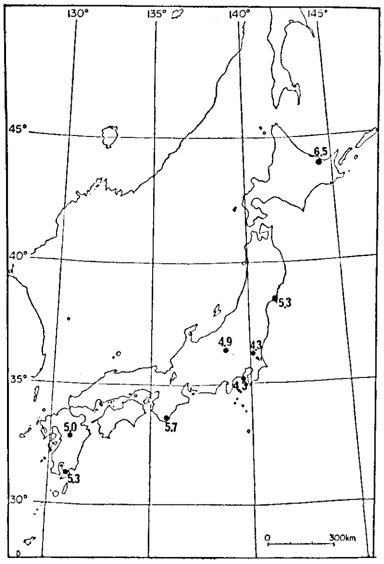

Fig. 9-2. Distribution of power of the D component for shorter periods in units of γ^2/cycles per 480 min.

But the tendency shown in Fig. 7–1 seems fairly consistent with the maximum ΔZ amplitude pattern obtained at the time of a bay. For shorter periods, a similar pattern is obtained as can be seen in Fig. 7–2. Although it is observed that the $\Delta Z/\Delta H$ values at Ab and Sh are about the same, power of Z component at Sh is larger than that at Ab. A similar tendency that the Z amplitude at Sh is larger than that at Ab is always seen at the time of a bay. This difference between the distribution of Z-power and $\Delta Z/\Delta H$ is caused by the differences of H-power at respective observatories.

In Fig. 8–1, a remarkable feature is seen in the distribution of power of H component. The power is the smallest at On situated in the north-eastern part of Japan and increases towards south-western Japan. A large H-power region seems to exist along the Japan Sea, judging from the values at Mm, Km, As, Kn, although there is no observatory along the coast of Japan Sea. $20\gamma^2$/c.p. 480 m. and $15\gamma^2$/c.p. 480 m. contours do not always coincide with the Central Japan Anomaly (Z-contour), but seem to be roughly coincident with the distribution pattern of terrestrial heat flow obtained by S. Uyeda and K. Horai.[9] According to their survey, the terrestrial heat flow is two or three times larger than the world's value on the Japan Sea side of Japan Islands, while in the eastern part of Tohoku district (near around the station On) a half of the average value. In the high heat flow regions, the power of H component for $T=160$ m. seems to be large, and in the low regions small. It is of interest that such a pattern is likely to be observed only for a particular period range. For $T=480$ m. equal H-power lines are NW to SE direction. For a range from 240 to 60 m, patterns similar to that for $T=160$ m. are obtained. For shorter periods, as shown in Fig. 8–2, equal H-power lines are nearly NS direction in the eastern part of Japan. For all periods, the power at On is distinctively small, while the powers at Kn, As are large.

As for the D component, it is difficult to find such a distinct tendency as mentioned above, but it is noticed that at On, Kk the powers are small.

4. Discussion

The present analysis of Z component brings out results comparable with those which have been already obtained by Rikitake and others.

9) S. UYEDA and K. HORAI, *J. Geophys. Res.*, **69** (1964), 2121.

As for the anomalies of ΔH, Rikitake reported on more or less similar results in his study of bay-type disturbances in Japan.[10] He investigated some 100 bay-like events during 1959 and showed that the ΔH amplitude was about 30 per cent larger towards the south-western part of Japan, provided the general increase of geomagnetic bay towards the auroral zone is taken into account. Because of the lack of the stations, it would be premature to discuss the physical significance of the apparent coincidence of ΔH activity with the heat flow pattern. But any theory that accounts for the ΔZ pattern of the Central Japan Anomaly should also account for such an anomaly in ΔH.

It would appear necessary to conduct further investigations of the present kind in order to reach a full understanding of tne geomagnetic variation anomaly in Japan. Especially, it is important to have a much denser network of observatories.

5. Acknowledgements

The writer would like to express his sincere gratitude to Prof. T. Rikitake, who has given him constant support and advice in the course of the study. He thanks Dr. T. Yukutake and Mr. M. Sawada for their valuable discussions in various problems. His thanks are also due to Mr. Y. Hagiwara who has kindly guided and advised the writer in making use of electronic computers.

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10. 日本における地磁気短周期変化の異常と地下構造 (第11報)

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地球物理学専門課程 笹井洋一

周期数時間以下の地磁気短周期変化の各周期毎の特性を調べるために磁気嵐の主相に重なつてあらわれる短周期擾乱のスペクトル解析を行なつた．解析は日本各地の 8 カ所の地磁気観測記録について行ない，周期6分から8時間までの波の振幅，異なる成分の間の位相差等を求めた．地磁気鉛直成分の変化に対しては，周期2時間程度の波について，既に報告された日本列島中央部での地磁気湾形変化に伴なう異常とほぼ同様な著しい異常が認められる．周期の短かい波についても同様な結果を得た．更に地磁気水平分力の変化について，東北地方東部で振幅が小さく，西南日本で振幅が大きいという結果を得たがその分布は日本における地殻熱流量分布とかなり似ているように思われる．

10) T. Rikitake, *J. Geomag. Geoelec.*, **17** (1965), 95.