2. *The Anomalous Behavior of Geomagnetic Variations of Short Period in Japan and Its Relation to the Subterranean Structure. The 2nd report.*

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1. Introduction.

In the previous paper[1], the writers pointed out the anomalously large amplitude of changes in the vertical component of the earth's magnetic field of short period in the central part of Japan. And according to the results of some simple analyses, the anomalous behavior is preliminarily ascribed to a peculiar distribution of electrical property under Japan. Those analyses, however, were done on the basis of geomagnetic data obtained only from the stations in Japan and her neighborhood.

In order to make a more complete analysis, the writers intended to collect copies of magnetograms of the magnetic storm on June 18, 19 and 20, 1936 from various observatories all over the world. And we have now some 30 copies kindly sent from foreign observatories at the writers' request. The writers are very much obliged to these observatories and it is the writers' duty to report the results of the new analysis as soon as they can. The copies of magnetograms thus collected are so useful that we can analyse them from various viewpoints. But, first of all, the writers would here like to report the study concerning the sudden commencement (SC) observed at $9h$ $41m$ GMT on June 18, 1936.

2. Data used in the analysis.

A magnetic storm occurred with a SC at $9h$ $41m$ GMT on June 18, 1936, an example of the magnetograms obtained at Toyohara Magnetic

1) T. RIKITAKE, I. YOKOYAMA and Y. HISHIYAMA, *Bull. Earthq. Res. Inst.*, **30** (1952), 207.

Observatory being reproduced in Fig. 1.

The writers read off the amplitude of the changes in the three components (ΔH, ΔD and ΔZ) on the magnetograms and then calculated the geomagnetic north (ΔX_m) and east (ΔY_m) components. The results are given in Table I together with the abbreviations and positions of the observatories. The distribution of the observatories is also shown in Fig. 2.

3. Magnetic potential for SC.

In the first place, the writers constructed a chart for showing the distribution of the overhead equivalent current-arrows as shown in Fig. 3 in geomagnetic coordinates. As may be seen in the figure, the arrows seem to be fairly parallel each other in the respective regions such as Europe, Asia and America. And we also find that the arrows are roughly parallel to the latitude circles excepting both sides of the Atlantic Ocean. To bring out the distribution more clearly, we plotted ΔX_m against the geomagnetic latitude as shown in Fig. 4, ΔZ being also plotted in the figure.

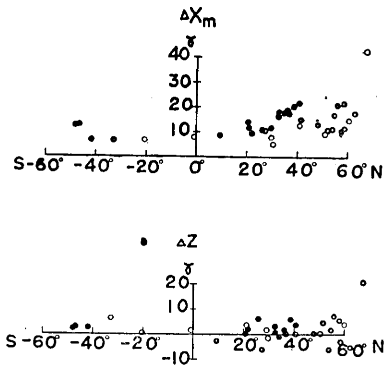

Fig. 4. The distribution of ΔX_m and ΔZ with respect to the geomagnetic latitude.
●: Asia and Australia
○: America
◎: Europe and Africa.

As will be seen in Fig. 4, ΔX_m takes a nearly constant value near the equator and it increases towards the north and south reaching

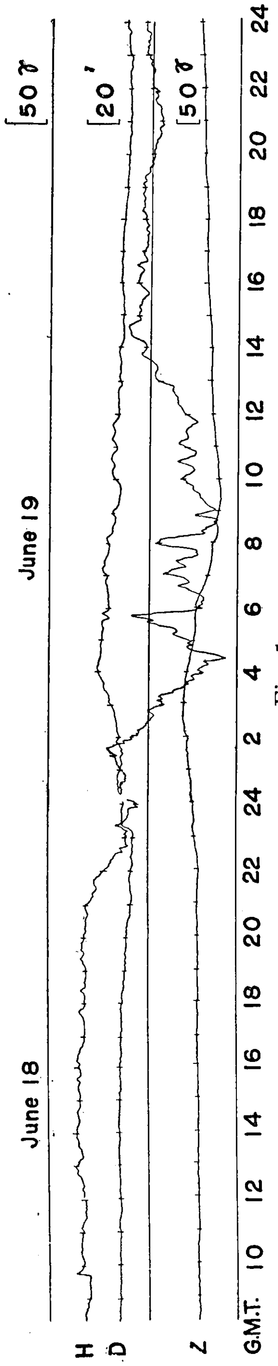

Fig. 1.

Fig. 1. The magnetic storm observed at Toyohara Magnetic Observatory on June 18 and 19, 1936.

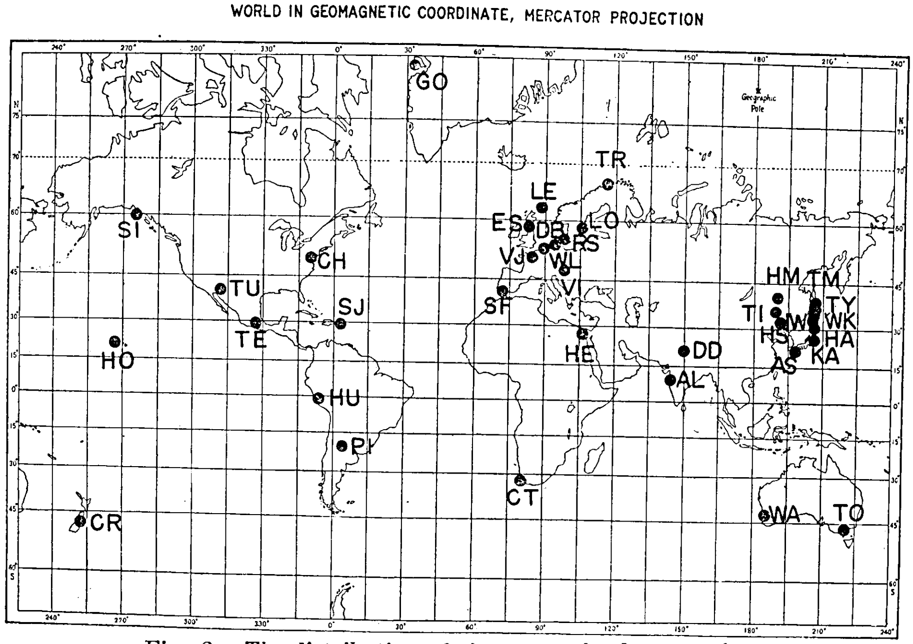

Fig. 2. The distribution of the magnetic observatories.

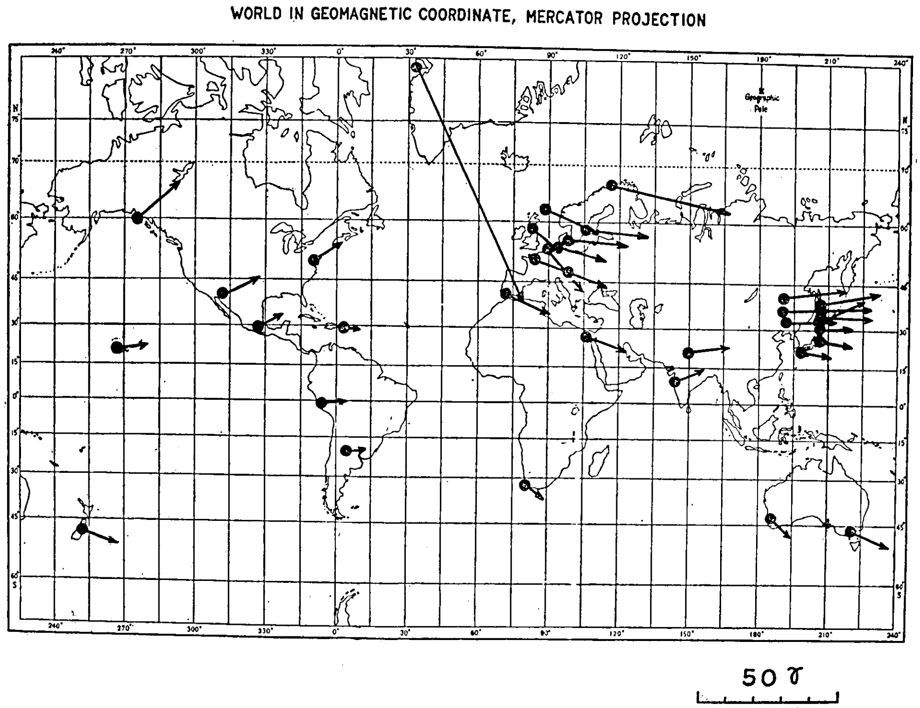

Fig. 3. The distribution of the overhead equivalent current-arrows of the SC at $9h$ $41m$ on June 18, 1936.

Table I. Japan and her vicinity.

Station	Abbreviation	Geomagnetic latitude	Geomagnetic longitude	Geographic latitude	Geographic longitude	ΔX_m	ΔY_m	ΔZ
Huma	HM	40°.6	192°.7	51°.7	126°.7	21γ.7	−3γ.4	3γ.7
Tomarigishi	TM	38.6	203.5	49.0	142.9	20.2	−4.4	5.8
Toyohara	TY	36.9	203.5	47.0	142.8	17.4	−1.2	0.0
Tsitsihar	TI	36.1	191.9	47.3	123.9	18.5	−1.9	1.4
Wakkanai	WK	34.4	203.4	45.4	141.7	17.6	−0.1	−1.0
Hsinking	HS	32.7	193.3	43.9	125.3	17.8	−1.7	0.9
Iwamizawa	IW	32.5	207.8	43.2	141.8	16.3	−8.0	3.1
Hirosaki	HA	29.5	206.2	40.6	140.5	11.7	−1.1	—
Kakioka	KA	26.0	206.0	36.2	140.2	10.8	2.3	6.0
Aso	AS	22.0	198.0	32.9	131.0	9.7	1.7	1.8

Table I. (Continued) Asia and Australia.

Station	Abbreviation	Geomagnetic latitude	Geomagnetic longitude	Geographic latitude	Geographic longitude	ΔX_m	ΔY_m	ΔZ
Dehra Dun	DD	20°.5	149°.9	30°.3	78°.0	13γ.9	−1γ.9	0γ.0
Alibag	AL	9.5	143.6	18.6	72.9	8.9	−3.3	−2.7
Watheroo	WA	−41.8	185.6	−30.3	115.9	6.6	6.3	2.7
Toolangi	TO	−46.7	220.8	−37.5	145.5	12.8	5.2	3.1
Christchurch	CR	−47.7	252.5	−43.5	172.7	12.4	4.4	2.2

Table I. (Continued) America.

Station	Abbreviation	Geomagnetic latitude	Geomagnetic longitude	Geographic latitude	Geographic longitude	ΔX_m	ΔY_m	ΔZ
Sitka	SI	60°.0	275°.4	57°.0	224°.7	15γ.0	−12γ.7	3γ.8
Cheltenham	CH	50.1	350.5	38.7	283.2	9.5	− 5.5	0.3
Tucson	TU	40.4	312.2	32.2	249.2	12.6	− 6.3	0.0
San Juan	SJ	29.9	3.2	18.4	293.9	5.0	0.4	−1.6
Teoloyucan	TE	29.6	327.1	19.7	260.8	7.8	− 4.7	1.8
Honolulu	HO	21.1	266.5	21.3	201.9	11.6	− 1.3	3.3
Huancayo	HU	− 0.6	353.8	−12.0	284.7	8.2	− 0.9	1.5
Pilar	PI	−20.2	4.6	−31.7	296.1	6.1	− 0.8	0.0

Table I. (Continued) Europe and Africa.

Station	Abbreviation	Geomagnetic latitude	Geomagnetic longitude	Geographic latitude	Geographic longitude	ΔX_m	ΔY_m	ΔZ
Godhavn	GO	79°.8	32°.5	69°.2	306°.5	36γ.8	80γ.8	98γ.0
Tromsö	TR	67.1	116.7	69.7	18.9	42.2	9.2	20.4
Lerwick	LE	62.5	88.6	60.1	358.8	17.9	8.0	−5.5
Eskdalemuir	ES	58.5	82.9	55.3	356.8	11.8	7.3	−3.5
Lovö	LO	58.1	105.8	59.4	17.8	21.9	2.0	5.5
Rude Skov	RS	55.8	98.5	55.8	12.4	21.4	1.5	7.0
Wilhelmshaven	WL	54.5	92.9	53.5	8.2	17.4	4.1	1.4
De Bilt	DB	53.8	89.6	52.1	5.2	11.5	14.4	−6.2
Val Joyeux	VJ	51.3	84.5	48.8	2.0	10.5	4.1	4.4
Wien	VI	47.9	98.1	48.2	16.2	13.4	5.0	0.0
San Fernando	SF	41.0	71.3	36.5	353.8	15.0	6.9	—
Helwan	HE	27.2	106.4	29.9	31.3	10.2	10.5	−6.3
Cape Town	CT	−32.7	79.9	−33.9	18.5	6.2	4.8	6.4

a very large value at the auroral zones though there may be seen some systematic discrepancies between the distribution in Asia and that in America and Europe. The increase of the amplitude of SC has already been pointed out by one of the writers[2] (T. R.) and T. Nagata[3].

Notwithstanding the fairly regular distribution of horizontal component, ΔZ is distributed very irregularly as is to be seen in Fig. 4, so that it will be almost impossible to draw equal variation lines for Z-component. Even in a comparatively narrow area such as the Western Europe, the sign of ΔZ changes from one observatory to another. For example, ΔZ in British observatories takes minus signs, while those observed in Sweden, Denmark or France are positive. The distribution in Japan is also complicated. ΔZ at Kakioka is positive and large, while that at Wakkanai is negative and small. As has been pointed out by a number of geomagneticians, a part of the cause of the heterogeneity in ΔZ may be due to the influence of the form of land and sea. However, no detailed study on the said influence has been conducted yet. The writers hope that the present study will contribute to the clarification of this problem.

In order to discuss quantitatively, the writers intended to obtain the distribution of magnetic potential from the data given in Table I. For that purpose, a method of graphical integration devised by M. Hasegawa and M. Ôta[4] seems to be adequate. The writers constructed charts for equal variation lines of ΔX_m and ΔY_m. Since we have a few observatories in the polar regions, the distribution of ΔX_m and ΔY_m determined here must be rather ambiguous. As concerns the neighborhood of Japan which is situated in the middle latitude, however, the analysis based on the charts should approximately give right results. Using the values of ΔX_m on the meridians of every 30° in latitude and those of ΔY_m along the parallel circles of every 15°, the pseudo-potentials at the intersection point of the i-th meridian and the j-th parallel circle are obtained by means of numerical integration, where the pseudo-potentials are respectively defined by

$$\left.\begin{aligned} W_{x,ij} &= a\int_0^\theta \Delta X_m d\theta\ , \\ W_{y,ij} &= -a\sin\theta\int_0^\phi \Delta Y_m d\phi\ . \end{aligned}\right\} \qquad (1)$$

2) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **28** (1950), 219.

3) T. NAGATA, *Rep. Ionos. Res. Japan*, **5** (1951), 134.

4) M. HASEGAWA and M. ÔTA, *Trans. Oslo Meeting, I.A.T.M.E.I.U.G.G.*, (1950), 431.

In (1), θ and ϕ denote respectively the co-latitude and longitude, while a is the radius of the earth. Since the integration constants are not known, the true value of magnetic potential should be obtained by the following means. If we denote the true value of potential at the point (i, j) by W_{ij}, we have the relations

$$\left.\begin{aligned} W_{x,ij} &= W_{ij} + C_{x,i} , \\ W_{y,ij} &= W_{ij} + C_{y,j} , \end{aligned}\right\} \qquad (2)$$

where $C_{x,i}$ is the constant on the i-th meridian, while $C_{y,i}$ is that along the j-th parallel circle. Hence, we have the next relations on the i-th and $i+1$-th meridians.

$$\left.\begin{aligned} W_{x,ij} - W_{y,ij} &= C_{x,i} - C_{y,j} , \\ W_{x,i+1j} - W_{y,i+1j} &= C_{x,i+1} - C_{y,j} . \end{aligned}\right\} \qquad (3)$$

And making the difference of the above two expressions, it follows that

$$(W_{x,ij} - W_{y,ij}) - (W_{x,i+1j} - W_{y,i+1j}) = C_{x,i} - C_{x,i+1}. \qquad (4)$$

After the same calculation along the j-th parallel circle, we can estimate $C_{x,0} - C_{x,1}$, $C_{x,0} - C_{x,2}$, ..., $C_{x,0} - C_{x,11}$. Thus all constants except $C_{x,0}$ are determined. The same calculation should be made along the other parallel circles. After all, the mean value $\overline{C}_{x,i}$ of all can be taken as the most probable value if all errors are considered to be accidental.

Thus we can obtain the true potential W_{ij} from (2) apart from a constant $C_{x,0}$ which is determined so as to make the sum of all values of $W_{x,ij}$, corrected by $C_{x,i}$, vanish. That is to say, the constant should be determined so as to satisfy the relation

$$\int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} W \sin\theta d\theta d\phi = 0 ,$$

where the integral must cover the whole surface of the earth. Since the potential satisfies

$$\nabla^2 W = 0 ,$$

the integral becomes equal to $4\pi C$ where C denotes the constant part of potential. The constant part of the potential for geomagnetic variation has no meaning. Hence, C may be taken to be zero. But in actual analysis, the accuracy of the procedure for obtaining $C_{x,0}$ may not be satisfactory. We are going to discuss this error later.

The distribution of potential determined after the graphical method mentioned above is shown in Fig. 5 in which we see that the contours are fairly parallel to the direction of the equivalent current arrows shown in Fig. 3. It seems remarkable that the distribution of the potential is nearly zonal.

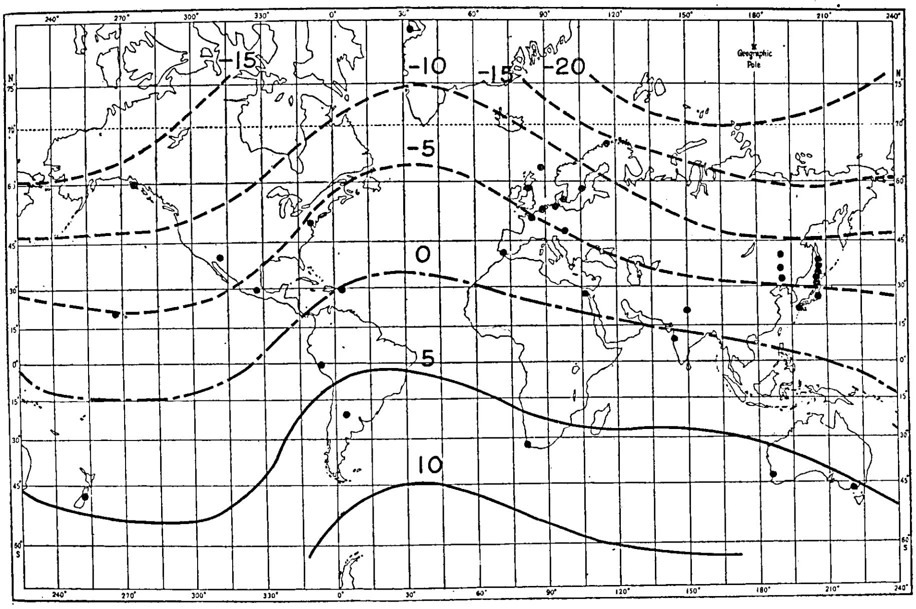

Fig. 5. The distribution of magnetic potential as obtained by means of the graphical method. The figures should be read in *gamma* multiplied by the earth's radius.

4. Separation of the potential into external and internal origin parts.

Combining the distribution of the potential with that of Z-component the writers wish to separate the parts originated out- and inside the earth. For that purpose, a method of surface integral due to E. H. Vestine[5] can be used. In case of a complicated distribution of magnetic field, the surface integral method seems to be easier than the usual spherical surface harmonic method as stated by Vestine himself. And one of the writers (T. R.)[6] applied the method to the field of geomagnetic daily variation with success.

According to Vestine, the difference of the potential of external origin W_e and internal one W_i satisfies the relation

$$W_e - W_i = (1/2\pi)\int_0^{2\pi}\int_0^{\pi/2}(W+2aZ)\cos\psi d\psi d\phi \ , \tag{5}$$

which is derived from the theory of potential, where the pole of polar coordinates (a, θ, ϕ) is taken at the point at which $W_e - W_i$ is required.

5) E. H. Vestine, *Terr. Mag.*, **46** (1941), 27.

6) T. Rikitake, *Coll. Paper Ionos. Res. Comm. N.R.C. Japan*, **4** (1948), 61.

a is the earth's radius and $\psi=\theta/2$. By averaging the values with respect to azimuth, (5) can be written as

$$W_e-W_i=\int_0^{\pi/2}(\overline{W}+2a\overline{Z})\cos\psi d\psi\ , \tag{6}$$

where $\overline{W}$ and $\overline{Z}$ mean the averaged data.

If we only know the potential apart from a constant U, (6) becomes

$$W_e-W_i=\int_0^{\pi/2}(\overline{W}-U+2a\overline{Z})\cos\psi d\psi+U. \tag{7}$$

In the present case, the writers prepared a sheet of transparent paper on which the lines of equal distance from a point at which W_e-W_i is required are drawn at an interval of 1,000 km and the 12 lines showing the azimuths of every 30° are also indicated. The lines are shown in Fig. 6. The paper is placed on the charts for the potential and for the Z-component so as to let the pole agree with the respective points at which W_e-W_i is required. And then the values at the intersection points of equal distances and equal azimuths are read off. By averaging the 12 reading on one equal distance line, we have $\overline{W}$ and $\overline{Z}$ with regard to every distance. Then W_e-W_i is calculated according to (6) or (7) by means of the numerical integration method. The transparent paper is prepared for 35° in latitude. In order to

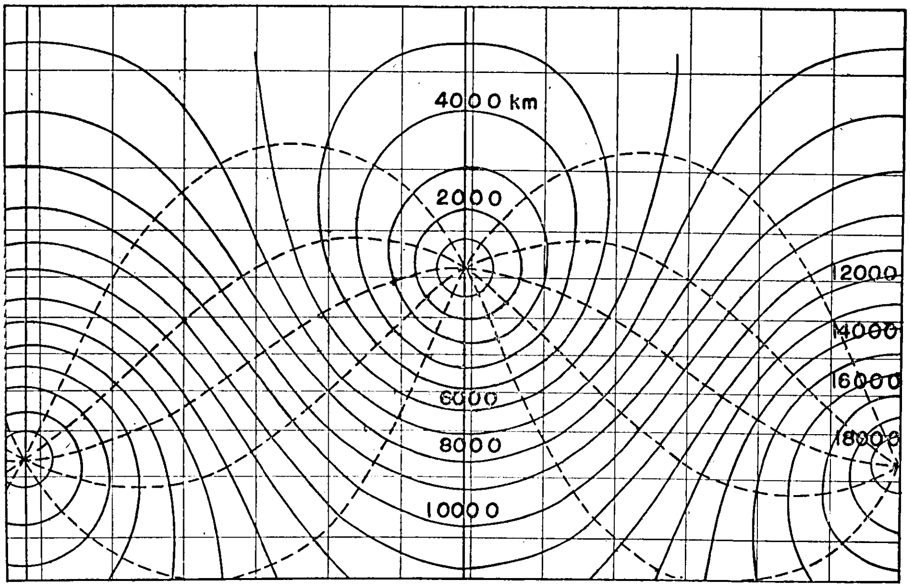

Fig. 6. The lines of equal distance written at an interval of 1,000 km and of showing the azimuths of every 30° from a point whose latitude is 35°.

make separation of both parts of potential only in Japan and her neighborhood, we may approximately use the same paper for all the observatories. In actual treatment, however, the region from the pole to 1,000 *km* which is most effective for $W_e - W_i$ are divided at an interval of 100 *km* and the numerical integrations are carried out. As for the Z-component, it is almost impossible to make the distribution chart of world-wide scale because of its irregular distribution as was pointed out by the writers. However, we have a comparatively dense distribution of observatories in Japan and her vicinity at the present occasion, so that we might tentatively draw equal variation lines near Japan. Meanwhile, we have to get ΔZ on the basis of ambiguous interploations for points such as in the oceans, Siberia or Africa. Roughly speaking, however, since the distribution nearer to the pole is the most effective, we may have approximately correct results in Japan and her vicinity where we have many observations.

We can thus determine $W_e - W_i$ for respective observatories. Then we may write after (7) the relation as follows:

$$W_e - W_i = W' + U \,, \tag{8}$$

where U is the same constant for the potential. Combining (8) with the relation

$$W_e + W_i = W + U \,, \tag{9}$$

we get

$$\left.\begin{aligned} W_e &= \tfrac{1}{2}(W + W') + U \,, \\ W_i &= \tfrac{1}{2}(W - W') \,. \end{aligned}\right\} \tag{10}$$

As was stated at the end of the last section, the constant part of

Table II.

The external and internal parts for SC. (The values are divided by the radius of the earth.)

Station	W_e	W_i
HM	-3.6^{γ}	-4.3^{γ}
TM	-2.7	-4.8
TY	-2.5	-4.5
TI	-2.5	-3.9
WK	-2.0	-4.4
HS	-1.7	-3.8
IW	-1.7	-4.2
KA	-0.5	-4.0
AS	$+0.2$	-3.5

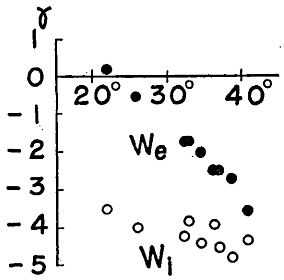

Fig. 7. The external and internal parts of the potential are arranged according to the geomagnetic latitude of the stations which are situated in Japan and her vicinity.

potential was considered to be zero. In determining actually, however, the writers are afraid that the constant part may not vanish wholly on account of errors. In that case, the comparison of the magnitude of the external part with the internal one may be somewhat dangerous.

W_e and W_i thus determined are given in Table II for respective stations.

The distributions of W_e and W_i are graphically shown in Fig. 7 in which we see that the values of W_i are large compared with those of W_e. Although W_e seems to be distributed fairly zonally, the distribution of W_i is somewhat complicated. The equi-potential lines for the external and internal origin parts are tentatively shown in Figs. 8 and 9.

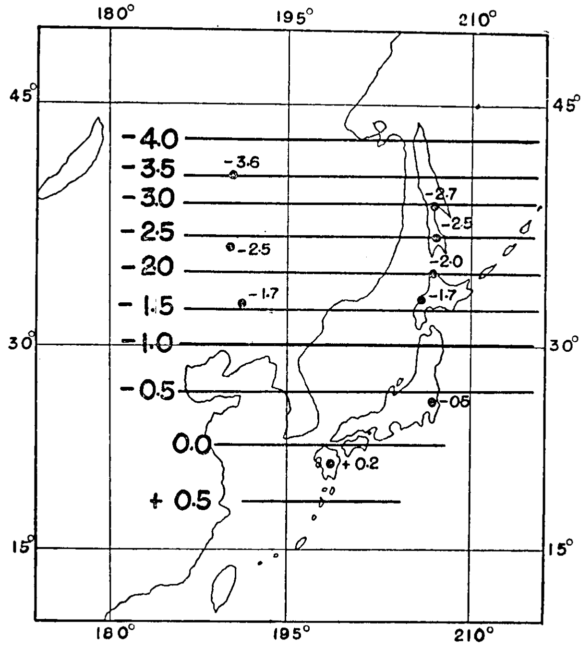

Fig. 8.

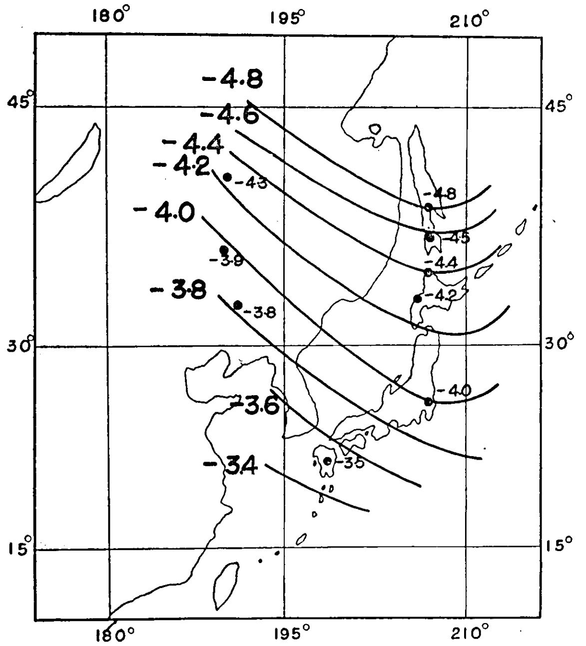

Fig. 9.

Fig. 8. The equi-potential lines for the external origin part of the magnetic potential. The unit is *gamma* multiplied by the earth's radius.

Fig. 9. The equi-potential lines for the internal origin part of the magnetic potential. The unit is *gamma* multiplied by the earth's radius.

5. Discussions.

In the last section, it has been proved that the peculiar distribution of W_i occurs at the time of SC, while W_e is distributed almost zonally. As is well known, the relation between the external and internal origin parts of various geomagnetic variations can be explained by the electromagnetic induction theory within the conducting earth so far as the averaged state such as deduced from a spherical harmonic analysis is concerned. From the standpoint of that theory, it is impossible to explain the anomalous distribution of the internal part which is obtained here. And, as the writers have briefly dealt with in their preliminary study, we naturally suppose that some heterogeneous distribution of electrical conductivity might exist beneath the area.

If W_i is supposed to be caused by electric currents flowing near the earth's surface, the stream lines are almost the same as shown in Fig. 9 and currents of 2,000 *amperes* flow between the consecutive lines from east to west. The loops of the stream lines in the neighborhood of Japan seems to be the most remarkable, the fact corresponding to the anomalously large amplitude of ΔZ in that locality.[7]

A noticeable result obtained in the present study is that the values of internal parts are large compared with those of external parts. One of the writers (T.R.)[2] found out in his previous analysis of SC in the middle and low latitude that the ratio of the coefficients of internal part to external one for the first harmonic amounts to about 0.25 on the whole. As already mentioned in the last section, the elimination of the constant part of potential might not have been perfectly done,

7) According to Vestine's method, we can obtain the external and internal origin parts of Z from the following relations;

$$Z_e + Z_i = Z\ ,$$

$$Z_e - Z_i = W_i - \frac{1}{2a}\int_0^{\pi/2} (\overline{W} - \overline{U})\,\mathrm{cosec}^2\psi\,\cos\psi\,d\psi\ .$$

The writers calculated ΔZ_e and ΔZ_i with these relations as shown in the following table.

However, the accuracy of the numerical integration of the above expression is not good because the integrand becomes enormously large for small value of ψ owing to the factor $\mathrm{cosec}^2\psi$. Notwithstanding the bad accuracy of integration, we can clearly see the large amplitude of ΔZ_i at Kakioka in the table.

Station	ΔZ_e	ΔZ_i
HM	-2γ	5γ
TM	-2	7
TY	-4	4
TI	-2	4
WK	-5	4
HS	-4	4
IW	-3	5
KA	-2	8
AS	-2	4

so that it will be meaningless to compare the magnitude of W_i with that of W_e. However, we obtain $\Delta X_{m,e}=12\gamma$ from the distribution of W_e which is shown in Fig. 8 and $\Delta X_{m,i}=3.5\gamma$ from that of W_i in Fig. 9 for Japan. Hence the internal part of the horizontal force amounts to about 30 percent of the external part, the result being roughly compatible with the aforementioned study.

6. Conclusion and Acknowledgement.

On the basis of world-wide geomagnetic data, the SC at $9h$ $41m$ GMT on June 18, 1936 is analysed especially with regard to the peculiar distribution of changes in geomagnetic field in Japan and her neighborhood where we have many temporary stations. The internal origin parts of the potential of SC is separated from the external ones with the aid of the surface integral method. It is made clear that the distribution of the internal part near Japan is anomalous. If it is supposed that the distribution is caused by the electric currents beneath the earth's surface, we find circular flows around Japan. That seems why we notice an anomalously great amplitude in Z-component there.

The writers are now carrying on the same analysis with respect to the other marked changes during the same storm. The results will be published in this Bulletin as soon as possible.

In conclusion, the writers are very much obliged to many geomagneticians who kindly cooperate with them by sending them geomagnetic data. The writers wish to express their hearty thanks to the following persons:

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Note added in the proof: After the preparation of the manuscript, the observation at Apia (geomagnetic latitude: $-16°.0$, geomagnetic longitude: $260°.2$, geographic latitude: $-13°.8$, geographic longitude: $188°.2$) became available. The writers would here like to note that $\Delta X_m = 5.8\gamma$, $\Delta Y_m = 0.1\gamma$, and $\Delta Z = -1.6\gamma$ at Apia.

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2. 日本に於ける地磁気短周期変化の異常と地下構造 (第2報)

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横　山　泉
菱　山　よ　ね　子

序報に於て日本に於ける地磁気短周期変化の異常を指摘したが，本報文に於ては世界各地の観測結果をもとゝして検討を加えた．

1936年6月18日9時41分 GMT の磁気嵐急始を解析して，ポテンシヤルと鉛直分力より，日本附近の変化磁場を地球外および地球内に原因を有する2部分に分離した．その結果地球内に起因する部分は第9図のような分布を示し，これが地表近くを流れる電流によって起ると考える時は，日本附近に渦状の電流系があることゝなり，通常の電磁感応の理論によっては，その分布を説明できず，地下に特殊の電気伝導度分布を考えねばならない．
