Magnetic Pulsations Observed by Induction Loops

By Syuiti Imamiti

§ 1. *Introduction.*

Studies of magnetic pulsations were mabe by many investigators. Among them Dr. T. Terada's investigation[1] gives us most interest and many hints on the research of the phenomena. He used high sensitive variometers, namely, bifilars for H and D, and Watson type for Z, and the observed periods of pulsations were most frequent in the interval of 50^s—60^s. Notwithstanding high sensibility of his variometers, it was difficult to record the waves of shorter periods below 30 seconds, owing to the reason that the amplitudes of waves decrease with their periods, and moreover free period of an ordinary variometer is limited by the moment of inertia of the needle and consequently can not be much reduced.

Rapid oscillations of any variable quantity are magnified in its time-derivative, therefore we used induction loops for three components, X, Y and Z, to observe shorter periods below 60 seconds.

The observation was carried out from October 1943 to March 1944 at the ground of the Kakioka Magnetic Observatory.

§ 2. *Equipment of observation.*

Loops for X and Y components are of rectangular form, while that for Z is quadrate. Each loop consists of cap tyre code of 35 turns of copper wire.

Time derivatives of three components of the magnetic field were recorded on the same photographic paper. The drum carrying the photographic paper was 30 cm in diameter, and revolved once an hour, so that 1 mm corresponds to 4.2 sec. To save excessive use of paper, the drum was displaced by the pitch of 5 cm along its axis, and replaced three times a day.

(A) Z—loop.

The cap tyre code forms a quadrate, of which sides being 34 meters each, and it was burried horizontally 30 cm deep under ground, to protect it from disturbance by wind.

A high sensitive galvanometer was connected in series to the circuit of which insulation was frequently tested and proved that it was always kept in good condition.

(B) *X*- and *Y*-loop.

X-loop to observe the time derivative of the north component, dX/dt, was set in due east-west direction. The plane of loop was perpendicular to the north-south line, having 205 meters in length and 5 meters in height and the lower side of the loop burried 1 meter deep in ground. The frame of the loop was supported vertically by solid pilars every 3 meters apart and they were again supported by side pilars to keep the loop fast and not move by wind.

Y-loop to observe the rate of time change of the westward component of magnetic field was similarly settled as *X*-loop, except that its longitudinal side directed to due north.

The two loops, *X* and *Y*, crossed each other perpendicularly at their middles. Electro-magnetic mutual effects of three loops were artificially tested, and no sensitive effect was noticed.

Effective areas of loop circuits, their electric resistances and galvanometer constants used are given in Table 1.

Table 1

Const. / Loop	Effective area of loop	Total resistance of loop	galvanometer		
			Sensibility	C. D. R.	Period of galvanometer
Z	35820m^2	520Ω	2.8×10^{-7}V/mm	500Ω	7 sec
X	35875	522	2.5	1000	10
Y	35875	517	2.1	500	10

From each circuit, we obtain a total induced electromotive force, $E=3.6\times10^{-5}$ volt for dF/dt=1γ/sec, where *F* denotes any component of magnetic field.

In actual, owing to hard westward wind generally prevailing at this season of year, moving of *Y*-loop frequently disturbed the recorded natural variations of the field, especially in day time, and this unfavourable condition resulted in the scarcity of data for sunlit hours.

(C) Correction for galvanometer deflection.

Owing to different and rather large proper periods of three galvanometers, deflections of their mirrors and phases of oscillations need corrections correspond to periods of waves. The corrections of each galvanometer were theoretically calculated and given in Table 2.

Table 2. Galvanometer correction

Const. / Loop / Period	$\alpha_{X,Y,Z}$			$\beta_{X,Y,Z}$		
	X	Y	Z	X	Y	Z
20 sec	0.792	0.805	0.875	0.150	0.146	0.114
30	0.895	0.902	0.940	0.104	0.100	0.078
60	0.972	0.975	0.985	0.054	0.052	0.040
90	0.986	0.988	0.994	0.036	0.035	0.027
120	0.992	0.994	0.996	0.027	0.026	0.020
180	0.997	0.997	0.999	0.018	0.018	0.013

To obtain a real amplitude, observed one is to be divided by the correction corresponds to its period, and a real phase difference is given by adding a difference of phase correction of the two components correspond to their periods to the observed one.

(D) Error of installation of loop.

When loops are not exactly installed, for instance, Z-loop is not strictly horizontal, error will be introduced into observed results. These errors were calculated for three loops and are given in Table 3.

Table 3.

Loop	Amplitude	Phase
X	1 %	1°
Y	5	3
Z	5	3

§ 3. *Results of observation.*

Stray currents by the electric tramway in the Keihin district, about 80 km distant from Kakioka, give effect in day time to the loops(2), especially to the Z-loop, since the amplitudes of dZ/dt of natural magnetic field are ordinary small compared with the other two. In addition to this unfortunate condition, the slight oscillations of loops by wind in day time sometimes disturbed the observations. Accordingly data for day hours are scanty compared with those for other hours.

As pulsations of larger amplitude and relatively longer period are more frequent in night than day hours, and beautiful train of nearly simple harmonic waves frequently appear in early morning as well as in sunset hours, it may allow us to deduce general characteristic of pulsation from data at hand.

The pulsations in question generally appear in train of waves with different amplitudes and periods seem to be very irregularly superposed. They appear dominantly in a component, while the corresponding waves are insignificant in other components, and sometimes differ even in periods. Such a case of unparallelism frequently met with Y-component.

Consequently, the photographic records were examined, and conspicuous waves constituting of more or less regular trains, which appear in three components simultaneously, were selected. The mean periods of wave trains were determined by such a way that the time interval of trains was divided by the number of waves contained in the train, while mean amplitudes were obtained arithmetically by scaling the amplitudes of individual waves. The time of occurrence of a wave train was taken the time correspond to the middle point of the train interval.

(A) *Dependence of amplitude on period and time of occurrence.*

(i) Amplitude and period.

The observed amplitudes are given in Table 4. To study any relation between amplitudes and periods, it is convenient that the latter are divided into the following arbitrary groups 30^s–$39^s.9$, 40^s–$49^s.9$, 50^s–$59^s.9$, 60^s–$79^s.9$, 80^s–100^s, and means of each group are obtained. These means are corrected for galvanometer deflections by Table 2, and given in Table 5.

The numerical values of amplitudes in Table 4 and 5 are all given in volt, since each loop has almost equal effective areas and wire turns and the electromotive forces induced in loop circuits are proportional to the amplitudes of magnetic variations when these waves have same period and galvanometers are used in same condition. The results in Table 4 and 5 are again shown in Fig. 1, taking amplitude as ordinates and the periods as abscissa.

The points representing observed amplitudes are dispersed rather irregularly as shown in the diagrams, while crosses denoting means for groups of periods decide reasonable curves.

The curves of X and Z components show similarity in form, except that the latter increases more gradually as periods increase. In fact, it is a very remarkable phenomena that the Z component follows the various fluctuations of the X component with utmost faithfulness, except for a reduced amplitude and a definite retardation.

Table 4. Observed amplitudes

No.	Time of occurrence		Period	Observed amplitude		
				Z-loop	X-loop	Y-loop
	h	m	sec	$\times 10^{-7}$V	$\times 10^{-7}$V	$\times 10^{-7}$V
1	14	40	20.0	4.2	16.3	11.5
2	02	47	18.0	0.6	5.5	6.9
3	06	09	20.0	11.2	40.0	68.8
4	05	05	16.0	2.5	19.5	14.6
5	14	41	18.0	5.9	26.2	33.6
6	04	14	20.0	3.4	27.5	21.0
mean			18.7	4.6	22.5	26.1
7	02	21	30.0	15.4	73.3	—
8	05	27	26.4	3.1	21.5	11.4
9	04	40	22.8	4.2	13.7	7.6
10	19	33	24.8	4.4	22.0	18.5
11	07	47	22.4	2.8	10.5	14.1
12	01	51	24.0	2.8	25.0	22.9
mean			25.1	5.5	27.7	14.9
13	02	29	40.0	6.4	27.0	10.1
14	02	33	36.0	5.3	27.5	—
15	01	04	35.2	2.2	14.5	4.0
16	06	40	36.0	4.8	14.6	28.2
17	22	43	30.4	5.6	22.3	10.7
mean			35.5	4.9	21.2	13.3
18	22	49	44.0	5.9	22.5	9.5
19	21	45	40.6	20.7	94.9	29.4
20	21	26	42.0	24.1	94.8	—
21	21	34	43.2	14.3	52.8	17.8
22	01	24	56.4	2.8	10.2	2.7
23	22	30	57.6	18.2	41.5	8.6
mean			47.3	14.3	52.8	13.6
24	03	03	68.8	7.8	22.5	14.5
25	02	50	76.0	1.6	5.0	2.1
26	20	53	80.0	12.8	47.5	26.2
mean			74.9	7.4	25.0	14.3
27	02	09	82.0	24.6	67.0	25.2
28	02	04	91.2	6.2	18.0	3.4
29	00	21	100.0	9.2	31.3	12.2
mean			91.1	13.4	38.8	13.6

Table 5.

Period \ Loop	Z	X	Y
sec	$\times 10^{-7}$V	$\times 10^{-7}$V	$\times 10^{-7}$V
18.7	5.3	29.2	33.5
25.1	6.0	32.6	17.1
35.5	5.2	23.1	14.3
47.3	14.7	55.6	14.2
74.9	7.5	25.4	14.4
91.1	13.4	39.2	13.7

On the other hand, variation of amplitude of Y-component with period seems insignicant, but it is worthy to notice that it increases rapidly in the region of period 20 sec. The cause of this rapid increase may be sought in the fact that the regular trains of waves with shorter periods and rather larger amplitudes in Y-compoent were frequently observed near sunrise hours and at times of disturbances, as already stated. Commencement of pulsations is sometimes gradual and sometimes abrupt, and waves overlaped on the initial part of bay variations in night hours frequently begin abruptly. The initial motions of waves which distinctly begin with larger amplitudes are frequently appeared with increasing of Z component and decreasing of X and Y.

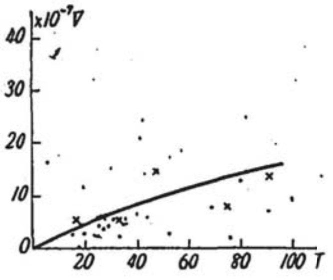


Fig. 1a Z

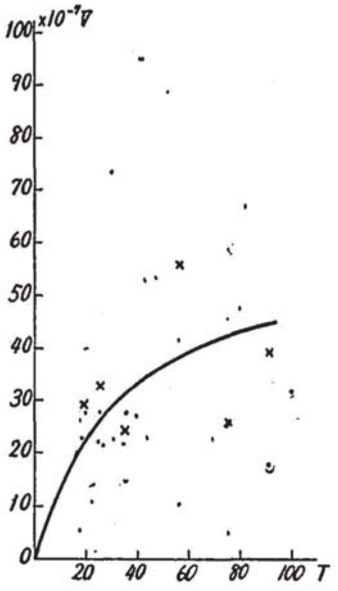


Fig. 1b X

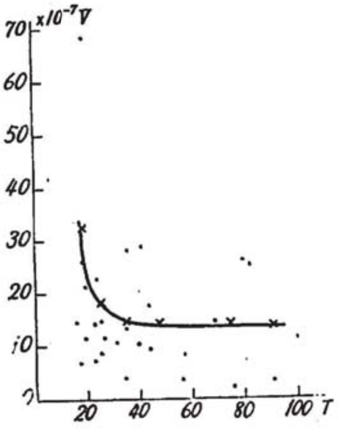


Fig. 1c Y

Table 6.

period \ Amplitude ratio	Z/X	Z/Y	Y/X
18.7 sec	0.18	0.16	1.15
25.1	0.18	0.35	0.52
35.5	0.22	0.36	0.62
47.3	0.26	1.03	0.26
74.9	0.30	0.52	0.57
91.1	0.34	0.98	0.35

(ii) Amplitude ratio and period.

(a) Z/X. From Table 5, amplitude ratios of Z to X were calculated for each group of periods, and the results are shown in Table 6 and also plotted in Fig. 2a, where the mean periods are taken as abscissa.

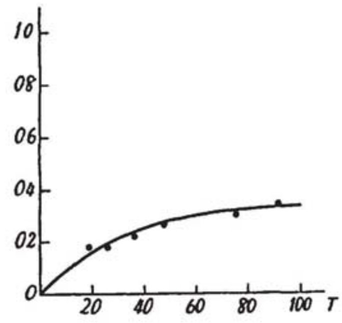


Fig. 2a Z/X

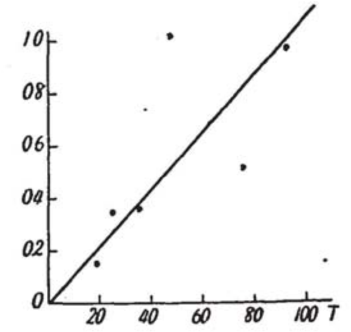


Fig. 2b Z/Y

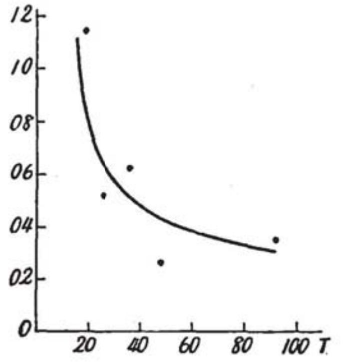


Fig. 2c Y/X

As will be seen, the ratio increases at first rapidly with the period, then gradually tends to an asymptotic value. Similar relations are seen in Fig. 1a and 1b, where points representing means of amplitude of each group are rather dispersed, while the points representing amplitude ratio Z/X well decide a curve as seen in Fig. 2a. This evidence seems to be resulted from the fact that the waves appearing in Z-loop are generally a rèduced facsimiles of those in the X-loop, except their phases, as already mentioned.

(b) Z/Y and Y/X. Z/Y and Y/X obtained from Table 5 may be seen in Table 6 and also are plotted in Fig. 2b and 2c.

As the amplitude of Y component varies not sensibly with periods, as will be seen in Fig. 1c, the plotting curves of amplitude ratios Z/Y and Y/X are largely affected by Z and X respectively, except for the part of period below 20 seconds.

(iii) Hourly distribution of waves with different amplitude.

The observed amplitude in Table 4 were grouped every two hours according to the time of occurrence, and mean values of each group were calculated.

The results may be seen in Table 7 and were plotted in Fig. 3. In the table, the values are all corrected fòr galvanometer.

As will be seen in the figures, the values at day times are missed owing to the effect of electric tramway and wind, as already stated.

From these figures, it follows that amplitude distribution in different hours of X and that of Z are nearly parallel each other except for a reduced ordinate of the latter, and these two components have peaks at 20h—22h zone.

On the contrary, the distribution of Y component, as will be seen in Fig. 3c, shows quite different form compared with the other two. From afternoon hours to

Table 7.

Time \ Loop	Z	X	Y
h h 0— 2	4.3	21.1	10.8
2— 4	8.7	31.8	10.7
4— 6	3.7	25.5	16.7
6— 8	6.8	25.2	42.2
14—16	5.8	27.6	28.8
18—20	4.8	25.9	21.2
20—22	18.3	75.5	25.2
22—24	10.2	30.8	10.0

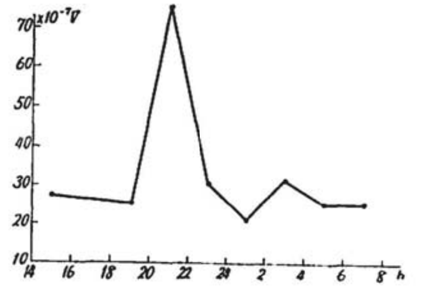


Fig. 3b X

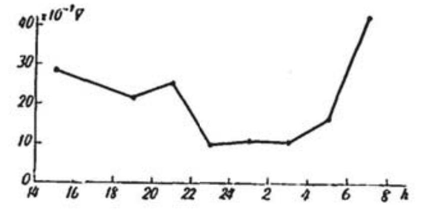


Fig. 3c Y

Fig. 3a Z

night hours, amplitude distribution varies not sensibly with time of occurrence, while it increases rapidly in morning hours. It will be noteworthy that the Y curve in Fig. 3c has small maximum at 20h—22h corresponding to that of X and Z component. The morning hour increase of Y component may be caused by the trains of regular waves of rather larger amplitude.

(iv) Amplitude ratio and time of occurrence.

The results are given in Table 8 and plotted in Fig. 4.

(a) Z/X. Plotting the mean ratio of Z/X in Table 8 as ordinate with hour of day as abscissa in a diagram, it seems that occurrence of Z/X has no special dependence on hours of day.

(b) Z/Y and Y/X. The points representing mean amplitudes ratio Z/Y are dispersed rather irregularly as shown in Fig. 4b. It seems that Z/Y has its maximum at midnight hours, while Y/X curve in Fig. 4c may be seen that its minimum meets with the same hours and increase towards sunrise hours as well as afternoon, showing almost symmetry to midnight, although the data are not sufficient to make sure of the above characteristics.

(B) *Frequency distribution of period and hourly distribution of waves of different period.*

Owing to scanty of data for day hours, the studying of distribution for whole hours

Table 8.

Loop / Time	Z/X	Z/Y	Y/X
h h 0—2	0.20	0.32	0.51
2—4	0.27	0.81	0.34
4—6	0.15	0.22	0.65
6—8	0.27	0.16	1.67
14—16	0.21	0.20	1.04
18—20	0.19	0.23	0.82
20—22	0.24	0.73	0.33
22—24	0.33	1.02	0.32

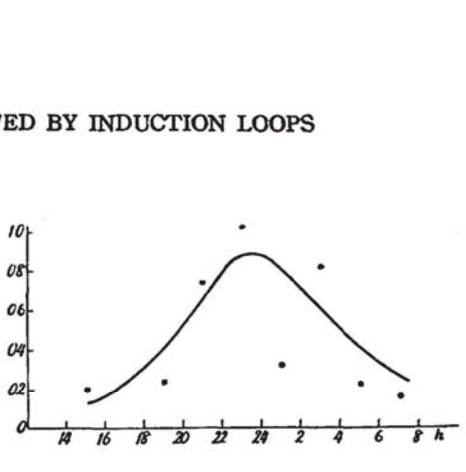


Fig. 4b Z/Y

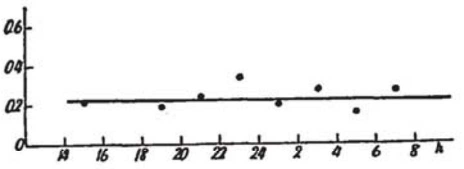


Fig. 4a Z/X

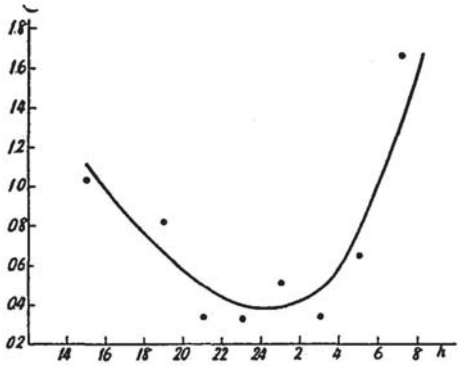


Fig. 4c X/Y

of day and frequency distribution of periods also are imperfect, though some principal points of them will be given in the following sections.

(i) Frequency distribution of period.

The results are plotted in Fig. 5a and it shows that the maximum frequency meets with the interval 20—30 sec., while after Terada the most frequent periods were found at the interval 50—60 sec. Though this disagreement may be sought in the facts that our data include many regular pulsations and selection of waves was limited to those of simultaneously appeared in the three components, the different system of observation used will be taken into account at first, that is, he used ordinary variometers, while our observation was obtained by induction loops.

(*ii*) *Hourly* distribution of periods.

As it will be seen in Fig. 5b, it has maximum near midnight hours and somewhat rapidly decrease towards sunrise as well as sunset hours.

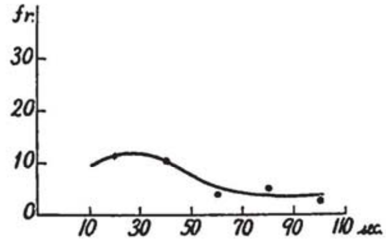


Fig 5a

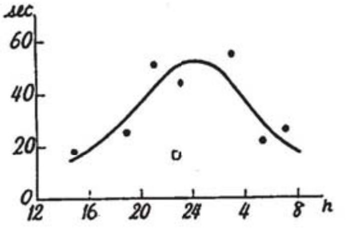


Fig 5b

(C) *Relation of the phase differences with the periods and the times of occurrence.*

(i) The phase difference and the periods of waves.

(a) Phase relation of X and Z components. As already mentioned, pulsations appearing simultaneously in X-and Z-loop run remarkably parallel to each other, but this correspondences are not always hold in their phases. In the great majority of cases, the phase differences of waves of these two components are zero, i. e. the two components are nearly parallel each other, while small part of them are differ by π radian, i, e, these are nearly inverted.

In these cases, when they are measured from the position of zero or π phase difference taken as basis points, Z component always lags bihind X.

The phase differences between the two components are obtained taking·the phase of X as basis, and classified them into two groups according to basis position of zero and π phase difference, and the former is indicated by ($X<0$, $Z>0$), which means X and Z increase together, and the latter group by ($X<0$, $Z<0$). The ratio of these two cases to total are given in Table 9.

Table 9.

$X<0,\ Z>0$	$X<0,\ Z<0$
24/29	5/29

The phase difference of Z and X are given by the notation δ_{XZ} with positive sign when Z waves retard after X and denoted by fractions of corresponding periods.
The values of δ_{XZ} are shown in Table 10 and 11 and plotted in Fig. 6a. Corrected values for galvanometer deflection are also given in tables at right side of observed ones.

As will be seen, Z waves show remarkable retardation after X and the phase differences of the two increase rapidly with decreasing of period, sometimes amounting to more than a quarter period in the case of 20^s waves and gradually decrease for longer waves over than 1 minute.

Table 10. $\delta_{XZ}(X<0,\ Z>0)$

No.	Period	XZ		No.	Period	XZ	
		Obs.	Corr.			Obs.	Corr.
	sec				sec		
2	18.0	0.133	0.172	18	44.0	0.091	0.111
3	20.0	0.120	0.156	19	40.6	0.100	0.122
4	16.0	0.220	0.261	20	42.0	0.076	0.097
5	18.0	0.200	0.239	21	43.2	0.074	0.095
6	20.0	0.120	0.156	22	56.4	0.071	0.086
mean	18.4	0.159	0.197	23	57.6	0.084	0.099
7	30.0	0.093	0.116	mean	47.3	0.083	0.102
8	26.4	0.166	0.195	24	68.8	0.047	0.057
10	24.8	0.161	0.192	25	76.0	0.011	0.019
11	22.4	0.000	0.033	26	80.0	0.095	0.103
12	24.0	0.166	0.198	mean	74.9	0.051	0.060
mean	25.5	0.117	0.147	27	82.0	0.068	0.076
13	40.0	0.100	0.122	28	91.2	0.078	0.085
14	36.0	0.089	0.113	mean	86.6	0.073	0.081
17	30.4	0.106	0.132				
mean	35.5	0.098	0.122				

Table 11.
$\delta_{XZ}(X<0,\ Z<0)$

No.	Period	XZ	
		Obs.	Corr.
	sec		
1	20.0	0.120	0.156
9	22.8	0.140	0.107
15	35.2	0.091	0.115
16	36.0	0.056	0.080
29	100.0	0.030	0.085

(b) Phase relation of X and Y components.

The phase differences between X and Y component, δ_{XY}, were classified into two cases, as above, namely ($X<0$, $Y<0$) and ($X<0$, $Y>0$). The former means no phase difference between the two components, and the latter means π phase retardation of Y component waves with respect to X. The results are given in Table 12 and 13 and plotted in Fig. 6 b.

It will be seen that phase of Y component waves sometimes progress to and sometimes retarded after X waves.

(ii) Hourly distribution of phase differences.

Hourly distribution of δ_{XZ} and δ_{XY} based on Table 4 and Table 10~13 are plotted in Fig. 7 a and 7 b respectively.

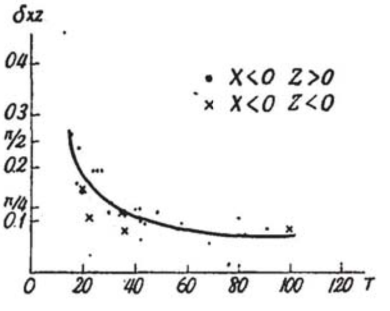


Fig. 6a

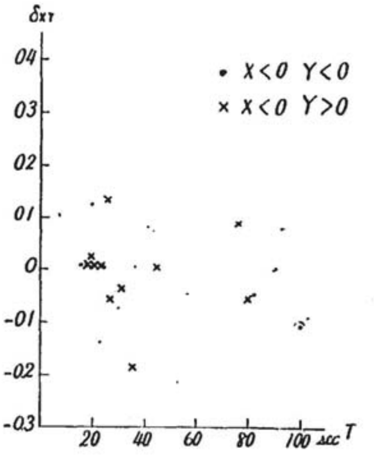


Fig. 6b

Table 12. δ_{XY} $(X<0,\ Y<0)$

No.	Period	XY		No.	Period	XY	
		Obs.	Corr.			Obs.	Corr.
	sec				sec		
4	16.0	0.000	0.006	19	40.6	0.080	0.083
5	18.0	0.000	0.005	20	42.0	—	—
6	20.0	0.120	0.126	21	43.2	0.074	0.077
mean	18.0	0.040	0.046	22	56.4	-0.049	-0.047
7	30.0	-0.080	-0.076	mean	45.6	0.036	0.038
11	22.4	-0.141	-0.137	27	82.0	-0.048	-0.047
12	24.0	0.000	0.004	28	91.2	0.000	0.001
mean	25.5	-0.074	-0.069	29	100.0	-0.108	-0.107
13	40.0	-0.020	-0.017	mean	91.1	-0.052	-0.051
14	36.0	0.333	0.337				
16	36.0	0.000	0.004				
mean	37.3	0.104	0.108				

Table 13. $\delta_{XY}(X<0,\ Y>0)$

No.	Period	XY		No.	Period	XY	
		Obs.	Corr.			Obs.	Corr.
	sec				sec		
1	20.0	0.020	0.024	15	35.2	-0.192	-0.188
2	18.0	0.000	0.005	17	30.4	-0.039	-0.035
3	20.0	0.000	0.004	mean	32.8	-0.116	-0.112
mean	19.3	0.007	0.011	18	44.0	-0.001	0.002
8	26.4	-0.061	-0.057	25	76.0	0.089	0.090
9	22.8	0.000	0.004	26	80.0	-0.055	-0.054
10	24.8	0.130	0.134	mean	66.7	0.011	0.013
mean	24.7	0.023	0.027				

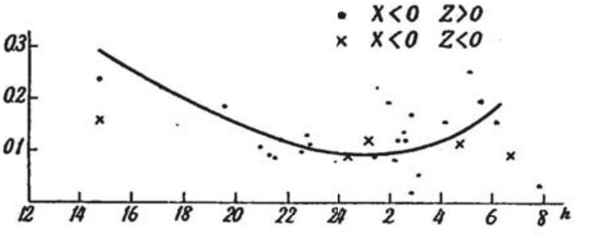


Fig. 7a

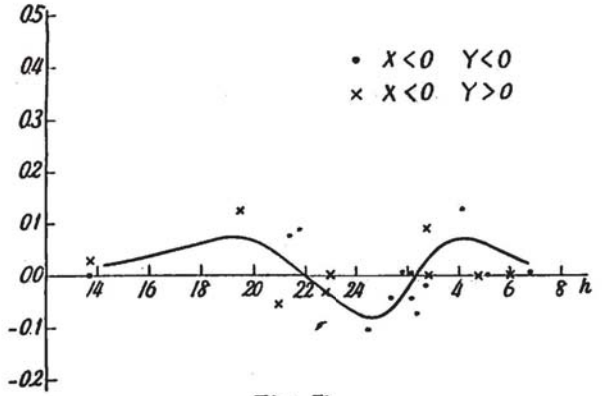


Fig. 7b

In Fig. 7 a, the points representing phase difference between X and Z waves are not so much dispersed, and they seem to show a minimum near night hours.

Distribution of δ_{XY} for hours of day is greatly different from that of δ_{XZ} as will be seen Fig. 7b, showing two maxima near 4h and 20h and minimum near midnight hours.

Summary

Pulsations of which period varing 20 sec. to nearly 60 sec. were observed by induction loops of three components, X, Y and Z.

(I) General characteristics of pulsations

(a) Characteristics of observed pulsations 20-60 sec. of periods show almost same tendency as that of longer periods 40—70 sec.

(b) Z component waves are generally the reduced facsimiles of those in X waves, except that the former always lags behind the latter in definite amounts depending on the period, while Y waves frequently differ from X and Z component waves in their period and amplitude.

(c) Regular pulsations of nearly 20 sec. of period with longer duration, accompanying beat, frequently appear near sunrise hour as well as at the time of disturbance. In these cases, predominant amplitudes of Y component are frequently observed.

(d) Initial motions of pulsations are sometimes abrupt and sometimes gradual. Waves overlaped on bay variations in night hours have abrupt commencements. Distinct initial

motions frequently begin with increase of Z component and decrease of X.

(II) Frequency of periods.

During the observation, waves 20-30 sec. of periods are most frequently appeared, whereas in the night hours longer periods predominate.

(III) Amplitude.

(a) In average, X component waves are more conspicuous than Z waves.

(b) Z and X components increase at first rapidly with the periods, then gradually tends to an asymptotic value.

(c) Y component waves do not change regularly with period, and sometimes rapidly increase with period near 20 second.

(d) Amplitude ratios of each two loops are seen in Table 6, and the range of their values are as follows.

$$Z/X : 0.18-0.34, \quad Z/Y : 0.16-1.03, \quad Y/X : 0.26-1.15.$$

(e) Hourly distributions of amplitude of Z and X component are similar forms, showing their minima at 20h—22h, while Y component near midnight, and conspicuous amplitude of regular waves frequently observed at sunrise hours.

(1V) Phase difference

(a) Z component always retard after X component, and δ_{XZ} rapidly increase with shorter periods amounting to more than $\pi/2$.

(b) Variation of δ_{XY} with period shows, by no means single sign, sometimes Y waves progress to and sometimes retard after X waves.

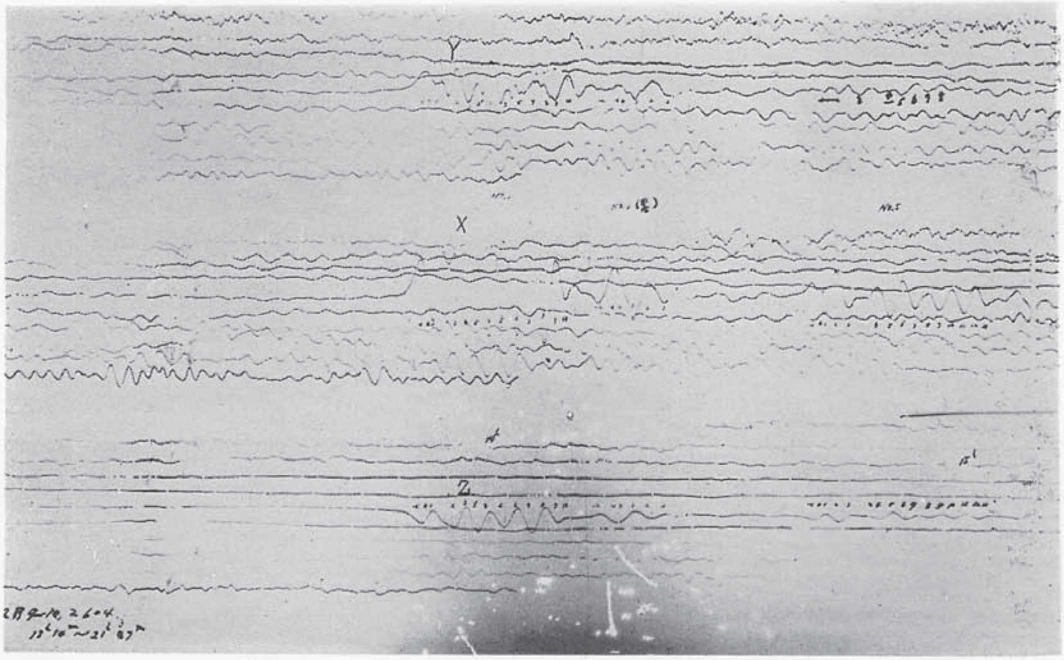
(c) Hourly distribution of δ_{XZ} seems to have a minimum near midnight hour, while that of δ_{XY} two maxima near sunrise hours as well as sunset and minimum at midnight.

In conclusion, the author wishes to express his sincerest thanks to Dr. T. Yoshimatsu for his kind helps throughout the course of the investigation and treatment of the data.

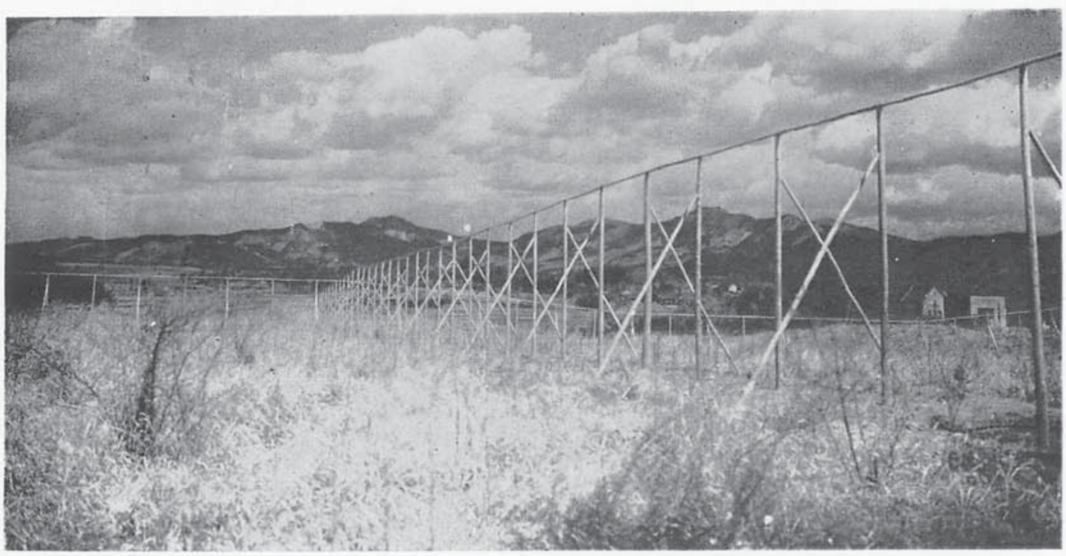
References

(1) Journal of College of Science, Imperial University of Tokyo, Vol XXXVII. Art 9 1917

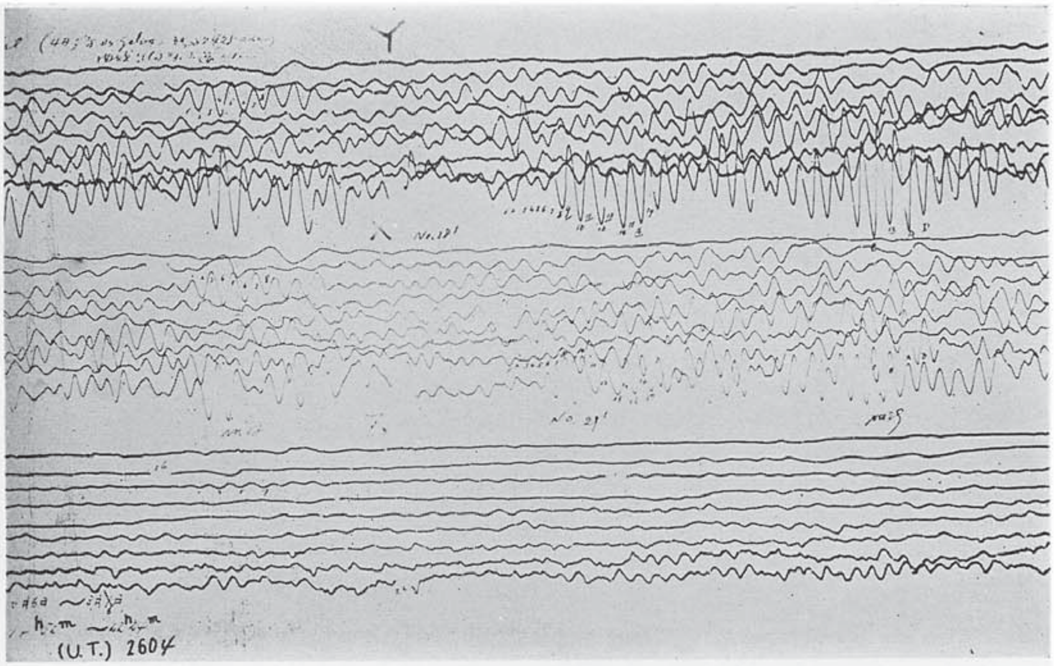
(2) Memoirs of the Kakioka Magnetic Observatory, Vol 1. No. 2, 3. p. 12—26, 1938



Waves of X and Z components appeared in parallel but not that of Y.



General View of the loops of X and Y components.



Conspicuous pulsations of *Y* component in sunrise hour.