September 27, 2013

Hirayama (1934): The first scientific paper on Magnetotellurics

(English translation: H. Toh, Kyoto Univ.)

地電流及び地磁気変化の間の関係に就いて[1]

平　山　　　操

１．緒　　　言

地電流は從來各地にて測定せられ，地磁氣，空中電氣，太陽黑點及び氣象要素等との關係についても其の研究が少くなく，就中地磁氣との關係の密接なことは周知の事で，G. B. Airy[2], W. Ellis[3]等によりて地電流の東西分力及び南北分力の變化は夫々地磁氣の南北分力及び東西分力の變化に酷似してゐることが注意され，S. Chapman, T. T. Whitehead[4]は地磁氣の鉛直分力の變化より地電位差の東西分力及び南北分力を計算し，又先般 S. E. Forbush[5]は地電位差の鉛直分力の急激な變化は概ね同時に，地磁氣の水平分力の變化を伴つていることを指摘して居る．其の他 W. van Bemmelen[6], L. A. Bauer 等の研究がある．

(1) 中央氣象臺彙報
(2) G. B. Airy: Phil. Trans. R. S. vol. 158, (1868) 465. 原文未讀
(3) W. Ellis: Proc. R. S. vol. 52 (1892), p. 191. 原文未讀
(4) S. Chapman and T. T. Whitehead: Transact. Cambridge Phil. Soc. 22, Nr 25, 463, 1922.
(5) S. E. Forbush: Terr. Magn. vol. 38, No. 1, 1933.
(6) W. van Bemmelen: Proc. K. Akad. Amsterdam 1908. 原文未讀

On the Relations between the Variations of Earth Potential Gradient and Terrestrial Magnetism.[1]

By M. HIRAYAMA.

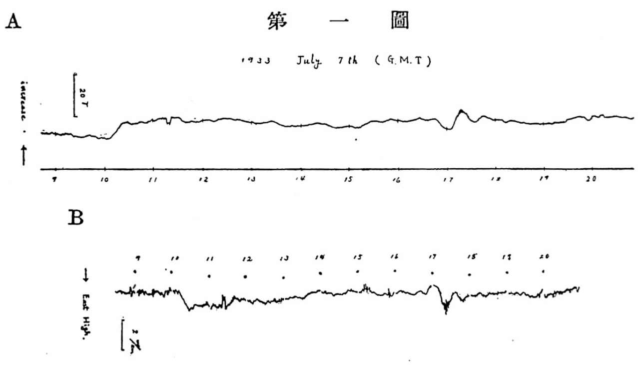
1. Introduction

The telluric currents have been measured at many places on the earth so far. There have been not a few studies on their relation to the geomagnetic field, the atmospheric electricity, the sunspot number or various meteorological factors etc. In particular, the relation to the geomagnetic field is known to be very close. G. B. Airy[2], W. Ellis[3] and so on noted that variations of the east-west and north-south components of the telluric current are very similar to those of the north-south and east-west components of the geomagnetic field, respectively. S. Chapman and T. T. Whitehead[4] calculated the east-west and north-south components of the geoelectric potential difference from variations of the vertical geomagnetic component. Recently, S. E. Forbush[5] also pointed out that rapid variations of the vertical geoelectric component are often associated with the simultaneous variations of the horizontal geomagnetic component. The studies by W. van Bemmelen[6], L. A. Bauer and so on can be listed as the research on the relation as well.

(1) Bulletin of the Central Meteorological Observatory
(2) G. B. Airy: Phil. Trans. R. S. vol. 158, (1868) 465. The text unread.
(3) W. Ellis: Proc. R. S. vol. 52 (1892), p. 191. The text unread.
(4) S. Chapman and T. T. Whitehead: Transact. Cambridge Phil. Soc. 22, Nr 25, 463, 1922.
(5) S. E. Forbush: Terr. Magn. vol. 38, No. 1, 1933.
(6) W. van Bemmelen: Proc. K. Akad. Amsterdam 1908. The text unread.

當観測所に於ては昨年八月以來，地電位差及び地磁氣の變化を連續記録させてゐるが，その記象紙を見るに，地電位差の南北分力は，其の感度が東西分力に比して甚だ小さい爲め，地磁氣との關係も見出し難いが，東西分力の変化は降雨，降雪の際の如き狹範圍の變化を除けば，第一圖に其の一例を示せる如く殆ど悉く相對應し，地磁氣の水平分力が増大すると地電位差は東が高くなつてゐる．

依つて筆者は過去一ヶ年の材料により，兩者の變化の間に介在する關係を求めんと試みた



この圖は昭和八年七月七日の記象紙の一部で，兩者の變化の相對應して居るのが注意され，又十七時と十八時の間に於て三十分位の週期に，三分位の週期が重疊し，その振幅の比が週期により著しく異なる好例を示す．

２．調査の方法及び結果

記象紙に現はれる變化を週期的及び非週期的の二變化に分け，前者にありては一群の週期的變化があるとき，其等の平均の振

Variations of the geoelectric potential difference and the geomagnetic field have been recorded continuously at this observatory since last August. The chart records show that the relation between the geoelectric and geomagnetic fields is difficult to recognize in the north-south geoelectric component, because its sensitivity is very small compared with that of the east-west component. However, variations of the east-west geoelectric component almost always correspond to those of the geomagnetic field as an example shown in Fig. 1, except for very limited periods at the time of rain- or snow-fall. If the horizontal geomagnetic component increases, the east geoelectic potential gets higher.

The author, therefore, tried to reveal the relation between them using the data of the past one year.

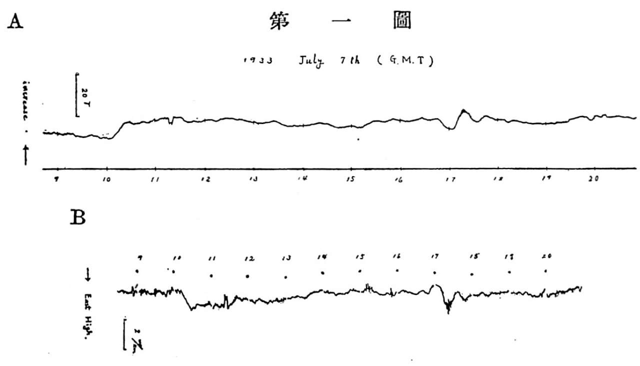
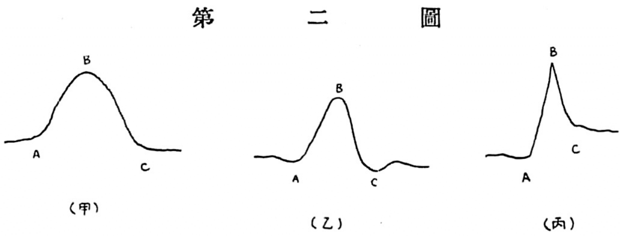


Fig. 1 A part of the chart record on July 7, 1933. It is noteworthy that variations of the geomagnetic field (upper) and the geoelectric field (lower) correspond well with each other. From 17 through 18 GMT, variations of about 3-min period are superimposed on those of about 30-min period. It is a good example of the intense period dependence of the amplitude ratio of the geoelectric field to the geomagnetic field.

2. Method of Investigation and the Results

Variations appeared in the chart records were classified into periodic and aperiodic variations. The amplitude and period

幅及び週期を夫々其の振幅及び週期とし，後者にては，振幅としては AB，BC の平均を，又 time interval AC を週期と考へ，（第二圖參照），これ等を記象紙より讀み取った．然し非週期的變化と雖も，第二圖の如く週期的變化とも看做されるやうなものも少くなく，六十分以上の變化には殊に多かつた．



又通常の日の記象紙では一粍が地磁氣では三分，地電位差では四分になつて居るので，三分以下の短い週期の變化は早廻しにしたものより求めた．（毎月四日間，國際日に早廻しにしたものは一分が）地磁氣及び地電位差共に四粍である．）

又地電位差の東西分力の日變化を見るに，地磁氣の水平分力，鉛直分力の日變化に似て居り，水平分力に對しては若干の位相差があるが，鉛直分力に對しては殆ど位相差が認められず極めて類似せる變化を示して居ること第三圖の通りである．それで記象紙より直接讀み取れない位の長い週期（約二時間以上）の變化は，極めて靜穩な日を選んで調和分析をなし補足した．

of the former were determined as the respective averages of a series of periodic variations. Those of the latter were regarded as the averages of AB and BC for amplitude, and the time interval AC for period (see Fig. 2). The amplitudes and periods thus defined were read from the chart records. However, there were not a few aperiodic variations that were difficult to distinguish them from periodic variations as manifested in Fig. 2. The close resemblance of the two emerged especially in the variations with periods longer than 60 min.

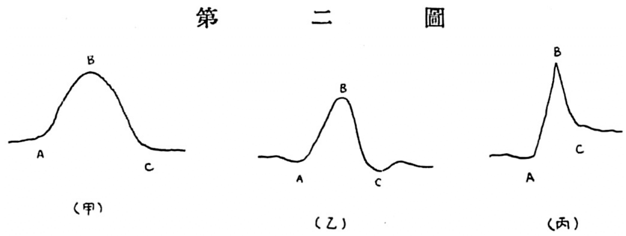


Fig. 2 (No captions were given in the original text.)

Variations of the geoelectric potential difference and the geomagnetic field have been recorded continuously at this observatory since last August. The chart records show that the relation between the geoelectric and geomagnetic fields is difficult to recognize in the north-south geoelectric component, because its sensitivity is very small compared with that of the east-west component. However, variations of the east-west geoelectric component almost always correspond to those of the geomagnetic field as an example shown in Fig. 1, except for very limited periods at the time of rain- or snow-fall. If the horizontal geomagnetic component increases, the east geoelectic potential gets higher.

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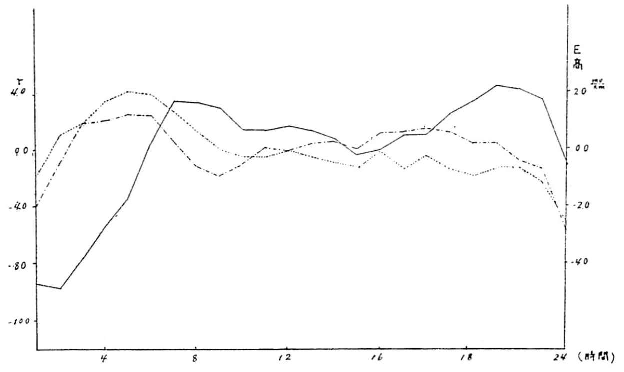
第　三　圖



－－－－　地電位差の東西分力
――――　地磁氣の水平分力
…………　地磁氣の鉛直分力

この圖は一月五日，二月十七日の平均日變化を示す

３．理論的計算

地電位差の記象紙を見るに，東西分力の比較的長い週期の變化殊に日變化に於ては，同時に地磁氣の鉛直分力及び偏角の變化も見られるが，短い週期の變化にては水平分力の變化のみで他の要素の變化は顯著でないことが多い．依つて地電位差の東西分力の變化は地磁氣の南北分力（地理學上の北と磁力の指す北とが一致するものとする．）即ち水平分力の變化のみによって誘起される(7)ものとして計算し，其の結果と比較的短い週期（八十分以下）の場合に適用して見た．

(7) 寺田博士は地磁氣の短週期變化に於ける南北分力と鉛直分力の比及び位相差を説明するに際しこれ等の變化は地中の電流に依るものとして計算されてゐる．

T. Terada: Journ. Coll. Sci. Tokyo Imp. Univ. Vol. XXXVII, Art. 9.

第　三　圖

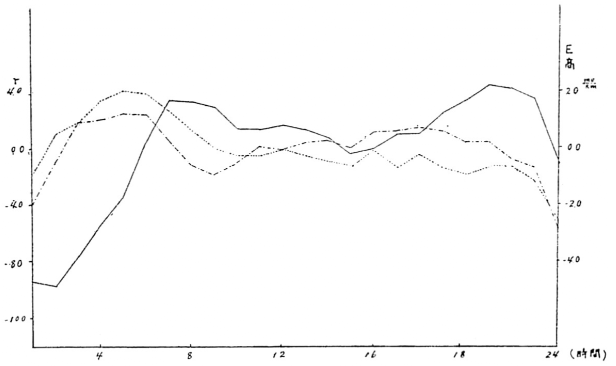


Fig. 3 This figure shows the averaged daily variations of January 5 and February 17.

3. Theoretical Calculation

The chart records of the geoelectric potential difference showed that its east-west component was mostly accompanied by simultaneous short-period variations of the horizontal geomagnetic component with negligible variations in other geomagnetic components, while the declination and the downward geomagnetic component also varied simultaneously at longer periods especially for daily variations. I, therefore, proceeded to my calculation by assuming the east-west geoelectric component being induced solely by those of the northward geomagnetic component(7) (here I also assumed that the geographical north and the geomagnetic north were identical.). I applied the results of my calculation to relatively short periods (shorter than 80 minutes).

(7) Dr. Terada calculated the amplitude ratios and phase differences between the northward and downward components of the short-period geomagnetic variations assuming them being induced in the Earth.

T. Terada: Journ. Coll. Sci. Tokyo Imp. Univ. Vol. XXXVII, Art. 9.

先づ地表面を無限に廣い平面と考へ，x 軸を北に，y 軸を西に，z 軸を鉛直下方にとり z の負側は眞空で，正側は一様な傳導率に，誘磁率μをもつ導體であると假定し，更に電氣力 E は x 軸に無關係，磁力 H は y，z 軸に無關係であるとする．すると $E_x = 0$, $H_y = H_z = 0$ と考へたから，maxwell の基本方程式は次のやうになる. 但し E 及び H の x, y, z 成分を夫々E_x, E_y, E_z 及び H_x, H_y, H_z とする．

$$\mu\frac{\partial H_x}{\partial t}=\frac{\partial E_y}{\partial z}-\frac{\partial E_z}{\partial y} \quad \cdots\cdots (1)$$

$$4\pi\kappa E_y=\frac{\partial H_x}{\partial z}, \qquad 4\pi\kappa E_z=-\frac{\partial H_x}{\partial y} \quad \cdots\cdots (2)$$

$$\frac{\partial E_y}{\partial y}+\frac{\partial E_z}{\partial z}=0 \quad \cdots\cdots (3)$$

(1), (2)より

$$4\pi\kappa\mu\frac{\partial H_x}{\partial t}=\frac{\partial^2 H_x}{\partial y^2}+\frac{\partial^2 H_x}{\partial z^2} \quad \cdots\cdots (4)$$

今 $H_x \propto e^{-pt+i(my+qt)+\alpha z}$ とすると

$$\alpha^2=m^2-4\pi\kappa\mu(p-iq) \quad \cdots\cdots (5)$$

$\alpha=-(\alpha'+i\beta')$ とおくと $\alpha'. \beta'$ は夫々

$$\alpha'=\sqrt{\frac{1}{2}\left\{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}+(m^2-4\pi\kappa\mu p)\right\}}$$
$$\beta'=\sqrt{\frac{1}{2}\left\{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}-(m^2-4\pi\kappa\mu p)\right\}} \quad \cdots\cdots (6)$$

となる．依つて(2)より

$$E_y=-\frac{\alpha'+i\beta'}{4\pi\kappa}e^{-(pt+\alpha' z)+i(my-\beta' z+qt)}$$

$$E_z=-\frac{im}{4\pi\kappa}e^{-(pt+\alpha' z)+i(my-\beta' z+qt)}$$

或は實數部分をとり

$$\begin{cases} H_x=e^{-(pt+\alpha' z)}\cos(my-\beta' z+qt) \\ E_y=-\dfrac{C}{4\pi\kappa}e^{-(pt+\alpha' z)}\cos(my-\beta' z+qt+\sigma) \quad \cdots\cdots (7) \\ E_z=\dfrac{m}{4\pi\kappa}e^{-(pt+\alpha' z)}\sin(my-\beta' z+qt) \end{cases}$$

但し

First, suppose the ground surface to be an infinitely large plane, and take x-, y- and z-axis to the northward, westward and downward directions, respectively. Also assume that the upper half-space ($z < 0$) is occupied by vacuum, while the lower ($z > 0$) is a uniform conductor with a permeability of μ. I further assume that the electric field, E, is independent of x, whereas the magnetic field, H, is independent of both y and z. It follows that $E_x = 0$, $H_y = H_z = 0$, which gives the following Maxwell equations;

$$\mu\frac{\partial H_x}{\partial t}=\frac{\partial E_y}{\partial z}-\frac{\partial E_z}{\partial y} \quad \cdots\cdots (1)$$

$$4\pi\kappa E_y=\frac{\partial H_x}{\partial z}, \qquad 4\pi\kappa E_z=-\frac{\partial H_x}{\partial y} \quad \cdots\cdots (2)$$

$$\frac{\partial E_y}{\partial y}+\frac{\partial E_z}{\partial z}=0 \quad \cdots\cdots (3)$$

where E_x, E_y, E_z and H_x, H_y, H_z are the x-, y- and z-component of E and H, respectively. Eqs. (1) and (2) are combined to give:

$$4\pi\kappa\mu\frac{\partial H_x}{\partial t}=\frac{\partial^2 H_x}{\partial y^2}+\frac{\partial^2 H_x}{\partial z^2} \quad \cdots\cdots (4)$$

Suppose $H_x \propto e^{-pt+i(my+qt)+\alpha z}$, then it is readily shown:

$$\alpha^2=m^2-4\pi\kappa\mu(p-iq) \quad \cdots\cdots (5)$$

If we write $\alpha = -(\alpha' + i\beta')$, α' and β' are respectively given by:

$$\alpha'=\sqrt{\frac{1}{2}\left\{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}+(m^2-4\pi\kappa\mu p)\right\}}$$
$$\beta'=\sqrt{\frac{1}{2}\left\{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}-(m^2-4\pi\kappa\mu p)\right\}} \quad \cdots\cdots (6)$$

It follows from Eq. (2) that;

$$E_y=-\frac{\alpha'+i\beta'}{4\pi\kappa}e^{-(pt+\alpha' z)+i(my-\beta' z+qt)}$$

$$E_z=-\frac{im}{4\pi\kappa}e^{-(pt+\alpha' z)+i(my-\beta' z+qt)}$$

or by taking the real parts of E and H;

$$\begin{cases} H_x=e^{-(pt+\alpha' z)}\cos(my-\beta' z+qt) \\ E_y=-\dfrac{C}{4\pi\kappa}e^{-(pt+\alpha' z)}\cos(my-\beta' z+qt+\sigma) \quad \cdots\cdots (7) \\ E_z=\dfrac{m}{4\pi\kappa}e^{-(pt+\alpha' z)}\sin(my-\beta' z+qt) \end{cases}$$

with

$$C^2=\alpha'^2+\beta'^2=\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}$$
$$\tan\sigma=\beta'/\alpha'=\sqrt{\frac{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}-(m^2-4\pi\kappa\mu p)}{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}+(m^2-4\pi\kappa\mu p)}} \quad \cdots\cdots\cdots\cdots(8)$$

故に振幅の比は

$$\frac{E_y}{H_x}=\frac{C}{4\pi\kappa}=\frac{1}{4\pi\kappa}\sqrt[4]{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}$$
$$\frac{E_z}{H_x}=\frac{m}{4\pi\kappa} \quad \cdots\cdots\cdots\cdots(9)$$

簡單に減衰しない場合（$p=0$）を考へれば

$$\frac{E_y}{H_x}=\frac{1}{4\pi\kappa}\sqrt[4]{m^4+16\pi^2\kappa^2\mu^2q^2} \quad \cdots\cdots\cdots\cdots(10)$$

今誘磁率 $\mu=1$ とし，κ の値としては地表近くでは $10^{-13}-10^{-14}$(emn)の間にて變化すると云ふ W. J. Rooney 及び O. H. Gish[8]の測定の結果を採用し 5×10^{-14}emn と考へる．

S. E. Forbush の record より地電位差の鉛直分力の振幅（E_z）と地磁氣の水平分力の振幅（H_x）との比を求めると，大略 8×10 mu/km/γ程度[9]である．依つて(9)式より波長λ（$=2\pi/m$）は $1\cdot3\times10^4$ 粁となる．m がこの程度であるとすると，週期の餘り大きくない範圍では m^4 は $16\pi^2\kappa^2\mu^2q^2$ に比して省略することが出來る．又他方に於て $m=0$ とすると(10)式より $\frac{E_y}{H_x}\propto T^{-\frac{1}{2}}$ となり，實際の曲線を表はす $\frac{E_y}{H_x}\propto T^{-0.4}$ に近いものとなる．この點より考へても $16\pi^2\kappa^2\mu^2q^2$ が主項で m^4 が補正項であると想像される．依つて(10)式を用ひ $\frac{E_y}{H_x}\propto\sqrt{\frac{\mu q}{4\pi\kappa}}$ より振幅の比を計算すると次の通りである．

$$C^2=\alpha'^2+\beta'^2=\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}$$
$$\tan\sigma=\beta'/\alpha'=\sqrt{\frac{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}-(m^2-4\pi\kappa\mu p)}{\sqrt{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}+(m^2-4\pi\kappa\mu p)}} \quad \cdots\cdots\cdots\cdots(8)$$

Hence, the amplitude ratios are given by:

$$\frac{E_y}{H_x}=\frac{C}{4\pi\kappa}=\frac{1}{4\pi\kappa}\sqrt[4]{(m^2-4\pi\kappa\mu p)^2+16\pi^2\kappa^2\mu^2q^2}$$
$$\frac{E_z}{H_x}=\frac{m}{4\pi\kappa} \quad \cdots\cdots\cdots\cdots(9)$$

If we consider the case of very weak decay (p = 0), the former ratio becomes:

$$\frac{E_y}{H_x}=\frac{1}{4\pi\kappa}\sqrt[4]{m^4+16\pi^2\kappa^2\mu^2q^2} \quad \cdots\cdots\cdots\cdots(10)$$

Now I assume μ = 1, and consider κ = 5 x 10^{-14}emu adopting the results of measurements by W. J. Rooney and O. H. Gish[8] who claimed that κ varied between 10^{-13} and 10^{-14}(emu) in the vicinity of the Earth's surface.

According to the record by S. E. Forbush, the ratio of the downward geoelectric component (E_z) to the northward geomagnetic component (H_x) is approximately 8 x 10^2 mV/km/γ[9]. It follows from Eq. (9) that the wavelength λ (= $2\pi/m$) becomes 1.3 x 10^4km. If m is thus small, m^4 is negligible compared with $16\pi^2\kappa^2\mu^2q^2$ so far as the period in concern is not very long. On the other hand, if m = 0, Eq. (10) is reduced to $\frac{E_y}{H_x}\propto T^{-\frac{1}{2}}$, which is close to the observed curve of $\frac{E_y}{H_x}\propto T^{-0.4}$. This also supports that $16\pi^2\kappa^2\mu^2q^2$ is the leading term while m^4 is the correcting term. Hence, using $\frac{E_y}{H_x}\propto\sqrt{\frac{\mu q}{4\pi\kappa}}$ derived from Eq. (10), the amplitude ratio is calculated as follows:

(8) W. J. Rooney and O. H. Gish: Earth-resistivity survey at Huancayo. Revu. Terr. Mag. 35, 61-72 (1930).

(9) この値は僅かの data と而も rough を讀みとりから出したもので，非常に不確實ではあるが，大體の order を知るには差支へないと思ふ．

(8) W. J. Rooney and O. H. Gish: Earth-resistivity survey at Huancayo. Revu. Terr. Mag. 35, 61-72 (1930).

(9) This value is based on not only few data but also rough reading, and thus very uncertain. However, it is considered to be enough for rough order estimation.

T(分) $\frac{E_y}{H_x}\left(\frac{\text{mu}}{\text{km}}/\gamma\right)$	10	20	30	40	50	60	80
	1·29	0·91	0·75	0·66	0·59	0·54	0·47

この値を實際の値と比較し(10)式の展開式

$$\frac{E_y}{H_x}=\sqrt{\frac{\mu q}{4\pi\kappa}}\left(1+\frac{1}{4}\,\frac{m^4}{16\,\pi^2\kappa^2\mu^2q^2}\right)$$

より左邊 $\frac{E_y}{H_x}$ は實測値を，$\sqrt{\frac{\mu q}{4\pi\kappa}}$ は上の計算値を用ひて λ の値を求めると次の如くである．

T(分) λ(粁)	10	20	30	40	50	60	80
	1·3	1·4	1·4	1·7	1·7	1·7	1·9

この値は寺田博士が地磁氣の短週期變化に於ける南北分力と鉛直分力との比より求められた 1200 粁に甚だ近いものである．

今波長を 1600 粁と假定し，(10)式より E_y/H_x を計算して實測の結果と比較して見るに次に示せる如く甚だよく一致して居る．

T(分) $\frac{E_y}{H_x}\left(\frac{\text{mu}}{\text{km}}/\gamma\right)$	5	10	20	30	40	50	60	80
計　算	1·82	1·31	0·96	0·83	0·76	0·72	0·70	0·67
實　測	1·80	1·34	0·98	0·86	0·77	0·72	0·69	0·64

この様に比較的短い週期の變化にありては兩者の關係は略〻(10)式にて滿足されるであらうと考へられるが，日變化の如き長い週期の變化にありては，基本方程式に更に H_y, H_z の項を加へ，且つ地球を球と看做さねばならぬと思はれる．

T(分) $\frac{E_y}{H_x}\left(\frac{\text{mu}}{\text{km}}/\gamma\right)$	10	20	30	40	50	60	80
	1·29	0·91	0·75	0·66	0·59	0·54	0·47

*This tabulates periods in minute (the upper row) and the ratios E_y/H_x in mV/km/nT. No captions were given in the original text.

To compare the tabulated values with the observation, I derived the following values for λ using the expanded form of Eq. (10);

$$\frac{E_y}{H_x}=\sqrt{\frac{\mu q}{4\pi\kappa}}\left(1+\frac{1}{4}\,\frac{m^4}{16\,\pi^2\kappa^2\mu^2q^2}\right)$$

by substituting the observed values for $\frac{E_y}{H_x}$ on L.H.S. and the calculated values above for $\sqrt{\frac{\mu q}{4\pi\kappa}}$.

T(分) λ(粁)	10	20	30	40	50	60	80
	1·3	1·4	1·4	1·7	1·7	1·7	1·9

*This table shows periods in minute (the upper row) and the wavelengths in 10^3 km. No captions were given in the original text.

These values are very close to the value of 1200km which Dr. Terada calculated from the ratio of the northward to downward components of the short-period geomagnetic variations.

Now assuming the wavelength to be 1600km, comparison of the observation with E_y/H_x calculated from Eq. (10) gives very good agreement as follows:

T(分) $\frac{E_y}{H_x}\left(\frac{\text{mu}}{\text{km}}/\gamma\right)$	5	10	20	30	40	50	60	80
計　算	1·82	1·31	0·96	0·83	0·76	0·72	0·70	0·67
實　測	1·80	1·34	0·98	0·86	0·77	0·72	0·69	0·64

*This compares the calculated (the middle row) and observed (the bottom row) ratios E_y/H_x in mV/km/nT. The upper row shows periods in minute. No captions were given in the original text.

The relation between the two, therefore, can be approximated by Eq. (10) in the case of relatively short-period variations. However, as for long-period variations such as daily variations, H_y and H_z terms should be further added to the fundamental equation, whereas the Earth should be treated as a sphere at the same time.

４．結論

以上を要約すれば次の通りである．

地電位差の東西分力の變化は地磁氣の水平分力の變化と密接な關係があり，前者の後者に對する變化の大きさの割合は，變化の緩急によって異なり，大體に於て $T^{-0.4}$ 比例するものである．而してこれ等兩者の變化が maxwell の基本方程式に依って結び付けられて居るものとして計算した結果はよく實際と一致して居る．

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（昭和八年八月　於臨時豊原地磁氣觀測所）

4. Conclusions

Everything described above can be summarized as follows:

Variations of the east-west geoelectric component are closely related with those of the horizontal geomagnetic component, and the ratio of the former variation magnitude to the latter is dependent on their periods, i.e., approximately proportional to $T^{-0.4}$. The calculated ratios assuming that those variations of the two components are tied with each other by the Maxwell equations coincide well with the actual observations.

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