THE PHYSICAL DECOMPOSITION OF THE EARTH'S PERMANENT MAGNETIC FIELD. NO. IV.

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a. INTRODUCTORY NOTE.

This series of papers is a persistent and determined attempt to unravel some of the mysteries of the Earth's magnetism. It is firmly believed that although the necessary data are not as complete as might be desirable, they are, nevertheless, sufficient for the solution of some of the problems by employing strictly legitimate, scientific methods. In some instances unequivocal solutions will not result, and it will be possible only to set forth rival hypotheses and the conclusions based thereon in such a way that, with the aid of future experimental and observational data, a decision can be reached.

It has already become apparent that some of the phenomena of the so-called "permanent" or "quasi-permanent" magnetic field of the Earth are so closely interwoven with those of the fields of force, causing the periodic and a-periodic variations of the Earth's magnetism, that it might be more appropriate to drop the word "permanent" in the title and speak instead of "The Physical Decomposition of the Earth's Magnetic Fields."

For the present, however, in order to exhibit the mode of attack, I shall make no change, even though some of the parts, as in the case of the present number, may deal with phenomena not hitherto associated with those of the "permanent" field.

Thus far these investigations have had to be conducted with inadequate facilities. Accordingly the progress has been somewhat slow. Recently, however, as announced in the two previous issues of the Journal, the facilities for prosecuting investigations of this character and magnitude have been vastly increased by the establishment of the "Department of International Research in Terrestrial Magnetism of the Carnegie Institution."

It has thus not only become possible to conduct the theoretical investigations with greater success, but, what is equally if not more important, the present experimental and observational data can be supplemented where most needed, and where otherwise they would not be obtained in the near future. The attacks can therefore be made in a more complete, methodical and systematic manner than heretofore. To avoid needless duplication of work, the writer will be glad if those engaged in similar or related investigations will put themselves in communication with him.

The proposal is to publish in these papers promptly summaries of the researches as they advance, leaving the fuller publication to the reports of the work of the above-named Department.

b. SECULAR MOTION OF A FREE MAGNETIC NEEDLE.

Status of Investigation.

The law, regarding the clock-wise direction in which the secular motion curve is described, as set forth in the writer's Ph. D. dissertation (University of Berlin) was one carefully built up by an examination of all the *observational* data available. It was a research extending over several years. While, as stated on pp. 50 and 51 of this publication, there were evidences of reversed or indefinite directions near the Pacific Coasts, these were of a minor order in comparison with the direct motion found at all stations where there was a long series of observations. Subsequent investigators, such as Schott and Littlehales again using *observational* data, although they found these minor evidences of reversal and also some contradictory results at some stations, did not deem themselves warranted in drawing any conclusion against the validity of my general law.

My researches on the secular motion of the Earth's magnetic axis from 1780 to 1885 gave a result which indicated the general truth of the law of the secular motion. These researches were taken up subsequently by van Bemmelen with the aid of his extensive collections of early observations, and the path of the secular motion of the magnetic axis, as well as of the magnetic poles, was drawn by him for over two centuries. *The direction in which these paths are described is clock-wise*, and this immediately necessitates that the general law of secular motion be that as announced by me.

The only one who has disputed the validity of this law is Fritsche, he relying wholly on *computed* results derived from potential computations based on incomplete material.

If any one will plot the results given by Fritsche, he will at once see that most of the reversals, or indefinite motions, occur in the region where the observational data are most meager, and where, in consequence, the potential results are most uncertain, *e. g.*, in the Pacific Ocean. It is amusing also to note, in passing, that in the region where by observation for over a century, there apparently has been described a curve in the reversed direction—at Iliuliuk or Dutch Harbor, Alaska—there Fritsche's potential results, for the interval of observation, give a curve described in accordance with my law. We can thus judge of the value of the potential results.

Thoroughly reliable values of all the magnetic elements begin at Iliuliuk about 1880 and extend to the present time, most of the determinations having been made by the Coast and Geodetic Survey. During this period east declination has decreased by nearly 1° and the dip has decreased by about $1/2^\circ$ —*thus implying an anti-clock-wise secular motion.*

However, at Petropawlowsk, situated in nearly the same latitude as Iliuliuk, but about 35° west, the direct motion prevails throughout the same interval of observation as for the latter station.

There has recently occurred in Louisiana a turning point in the secular variation of the magnetic declination, revealing one of the shortest intervals between a maximum and a minimum which has thus far come to light—about seventy years. Thus, at New Orleans, east declination reached a maximum amount of $8\frac{3}{4}^\circ$ near the year 1830; for a period of about one hundred years previous to this, east declination had been increasing steadily. From 1830-1898 east declination diminished, *but it is now increasing again.* In 1898 the declination was $5\frac{1}{2}^\circ$ E. According to the dip observations since 1856, this element has been steadily increasing, *thus prescribing a clock-wise secular motion.* Hence, although we may be dealing in this region with a loop in the general secular motion curve—evidences of such loops were revealed and announced in the publication cited—nevertheless the secular motion has proceeded in a *clock-wise* direction for the comparatively short interval involved.

One can form an idea of the heterogeneity of Fritsche's potential results for epochs prior to 1842 by plotting his paths of the magnetic axis and of the magnetic poles and comparing them with van Bemmelen's based solely on observations. Fritsche's curves will be found to be exceedingly irregular and replete with kinks; one should not wonder then, that he gets secular motion curves consisting similarly of irregular and uncertain motions.

But even if Fritsche's early potential computations had rested on material as good as that of the present day, his computed secular motion curves could by no means have equal value with those based on actual observations. Granted that the early observations are to a certain extent inaccurate, they nevertheless come as close and closer to the actual truth as the results derived from the most refined and accurate potential computations of the present day. [See No. III of these researches, pp. 125-128.]

For the reasons set forth in No. III (c), very little, if any, use can be made of the potential results for secular variation investigations of a refined character even for the epoch 1840-1885. An uncertainty of a degree or so in declination or dip—and a greater accuracy cannot be given them even for the modern potential results—is sufficient at times to either disguise or actually reverse the secular motion. This is especially true in the Pacific Ocean, where, as pointed out on pp. 50, 51, in my paper alluded to, the secular variation in declination for a century or more does not appear to have been great, and where there was some evidence of a conflict of the secular variation waves. The reversals on the Pacific coasts apparently shown for a short period are not on the order of whole degrees in declination and dip, but in fractions thereof!

The limitations to the practical use of the magnetic elements derived from a potential computation cannot be set forth too emphatically. Such results not only cannot compete with observations, even of ordinary accuracy, but not even with such as can be derived by other methods. A potential computation is designed, in general, to bring out merely general facts of theory applying to the magnetic field of the Earth, as a whole.

The complete researches on the secular variation, inclusive of the intensity, accompanied by all available material up to date, will appear in a publication of the above-named Department.

c. VERTICAL EARTH-AIR ELECTRIC CURRENTS.

The conclusions reached in No. III (a and c) with regard to the accuracy of the respective magnetic charts for the epochs 1840-45 and 1885, whereby it became apparent that for the Earth, as a whole, general results derived from the charts for the earlier epoch were probably as correct as the later charts, made it desirable to repeat my investigation respecting vertical electric currents¹ for this earlier period.

¹ See *T. M.*, 1897, Vol. II, p. 11.

My former investigation was based on the rectangular components X , Y , Z (components directed, respectively positive, towards the North, East, and Nadir) computed by Petersen, under Neumayer's direction, from the magnetic elements D (declination), I (inclination), and H (horizontal intensity) scaled from Neumayer's manuscript charts. These components Neumayer furnished to Adolf Schmidt for the latter's mathematical analysis of the permanent magnetic field, and a copy was made at my expense, and courteously furnished to me by Schmidt. These components have since been published by the latter. I had previously scaled the desired data from Neumayer's published charts myself, and as the ΣY 's for certain parallels were appreciable quantities, instead of zero as prescribed by the potential theory, it was deemed very desirable to get a check upon my summations with the aid of data obtained by Neumayer himself from his larger scale charts. Practically, however, the same residuals were again derived. They will be found given in the table, p. 17, of my cited paper for every fifth parallel from 60° N. to 60° S. as dependent upon values of Y for every fifth degree meridian, or upon 72 equidistant values for each parallel.

Schmidt had previously announced as a result of his careful mathematical analysis of the entire magnetic field of the Earth, that a small portion could not be referred to a potential, and hence the existence of vertical earth-air electric currents was indicated, these currents, according to his calculation, amounting on the average, for the entire surface of the Earth, to $1/6$ of an ampere per sq. km.¹

Owing to the difficulties raised by certain investigators as to the existence and possibility of harmonizing currents of this average strength with the known phenomena of atmospheric electricity, Schmidt was led to doubt the validity of his general conclusion and to express the opinion that possibly the results derived by him were to be ascribed to systematic map errors.²

My own investigation, in which the results were shown separately and plotted for each parallel, exhibited such a methodic system of electric currents, as to suggest that there might be some truth in the existence of such currents in spite of the above-named difficulties. Slightly subsequent to the presentation of this paper before the Philosophical Society of Washington, von Bezold laid before the Berlin Academy his paper,³ "Zur Theorie des Erdmagnetismus," which con-

¹ The writer's quantities derived for zones bounded by 5° parallels varied, between 60° N. and 60° S., from 0 to $1/6$ of an ampere per sq. km.

² "Der magnetische Zustand der Erde," 1885, p. 27.

³ Sitz. ber. Berlin Akad. XVIII. April 1, 1897.

tained the summations of Y for the four parallels, 50 N., 45 N., 40 N., and Equator for 1885 as dependent upon Neumayer's charts. The number of parallels were not sufficient, however, to disclose to him the methodic nature of the distribution of the currents, and he refrained from drawing a definite conclusion. Recently, however, he and Schmidt have revived renewed interest in this matter by their proposal of a magnetic survey around the entire Earth, in the vicinity of the parallel 50° N. (Sitz. ber. Berlin Academy 1903.)

VERTICAL ELECTRIC CURRENTS DERIVED FROM THE Y COMPONENTS.

In the present paper I shall give the results, derived from the Y components, as dependent on the best general magnetic charts now available, viz., for the three epochs, 1840-45 (Sabine's charts), 1880 (Creak's charts) and 1885 (Neumayer's charts). The results for 1885 are taken directly from my previous paper with but few slight modifications. Those for the other two epochs depend upon the data scaled from the respective charts and published in de Tillo's tables,¹ combined with similar scalings made independently by various members of the Department of Terrestrial Magnetism working under the supervision of Mr. J. A. Fleming.²

The results for 1885 depended, as stated, upon the data for intervals of 5° in latitude and longitude between 60°N. and 60° S. An investigation showed that, for the general result, it was sufficient to take intervals of 10° longitude, and that the interval, however, should not be much greater than this. Accordingly for the two earlier epochs the Y values utilized pertain to points differing 10° in longitude and 5° in latitude.

Sabine, unfortunately, published his charts in detached portions issued at various intervals of time. Thus the charts extend from the equator to 40° N., on the mercator projection, then from 40 N. to 85 N. the isomagnetic lines are laid down on a polar chart; a similar statement applies to the Southern Hemisphere. At the bounding parallels of the separate charts it is at times rather difficult to scale the data, and, furthermore, those derived from the same parallel from the two separate, adjacent charts are not always quite the same. Sabine had very largely scaled the desired data himself and had published them in his "Contributions" for use in a re-computation of the

¹ de Tillo, *Tables Fondamentales du Magnetisme Terrestre*. 1896.

² The Department has now on file the values D , H , I , X , Y , Z , and F for the two epochs, 1840-45 and 1880, carefully compared and revised. Those requiring the use of these data should communicate with the said Department.

Gaussian coefficients later undertaken by Adams. His own scalings for the same bounding parallel do not always quite agree. It, therefore, happens that for certain parallels, critical for this investigation, viz., 40° N. and S. and likewise for the equator, the derived results have a large inherent error due to impossibility of accurate scalings. To reduce the scaling error somewhat, the 1842 quantities in the table, for parallel 45° depend on those for parallels 50°, 45°, and 40°, for parallel 40°, on those for 45°, 40°, and 35° and for 35°, on those for 40°, 35° and 30°, similar combinations were made to obtain the results for parallels 0°, 5° N. and S.

As was first shown by Gauss, the line-integral of the magnetic force taken around a closed circuit on the Earth's surface, must vanish if all of the magnetic force be due to a potential. If it does not vanish, then the existence of electric currents which pass through the area perpendicularly from one side to the other is shown.

Let W be the total work done in moving a unit magnetic pole around the complete circuit against the Earth's magnetic force, H , the horizontal component of the latter force, ϵ , the angle H makes with the tangent to the path traversed, $d\lambda$, the curve-element, I , the intensity in electro-magnetic units of the supposed vertical electric currents then is:

$$W = \int H \cos \epsilon \, d\lambda = 4 \pi I. \quad (a)$$

If the circuit be traversed in an *anti-clock-wise* direction, a *positive* value of the integral implies *upward* currents, i. e., such passing through the Earth's surface into the air, and a *negative* value, on the other hand, implies a *downward* current.

Choosing parallels of latitude for our circuits and going around the Earth in an eastward direction, $H \cos \epsilon$ becomes the component Y , directed positive to the East; we have then:

$$W = \int_0^{2\pi} Y \, d\lambda = 4 \pi I. \quad (b)$$

For the present purpose, it suffices to take

$$W = d\lambda \sum_0^{2\pi} Y = 4 \pi I. \quad (c)$$

I is the resultant quantity of electricity passing in a second of time perpendicularly through the zone from the North geographical pole to the parallel of latitude around which the complete circuit is

made. If I is to be expressed in *amperes per sq. cm.*, (c) must be multiplied by 10. For I thus expressed we have then:

$$I = \frac{10}{4\pi} \cdot d\lambda \sum_0^{2\pi} Y. \quad (d)$$

In the following table (No. 1) are exhibited separately the results derived from the three epochs, for the region from 60° N. to 60° S. The first three columns give the values of ΣY in units of the 3d decimal. As the 1842 and 1880 quantities refer to a 10° longitude interval, whereas the 1885 quantities as given in my previous paper (1897) to a 5° interval, the 1885 quantities have been divided by two in order to permit comparing them with those for the other epochs. The comparison can also readily be made with the aid of the next three columns, which give for each epoch the average values of Y for the various parallels; *i. e.*, the quantity known as in l_0 in the Gaussian analysis in units of the fifth decimal C. G. S. (γ). A plus sign means a force to the east.

The next four columns contain the quantities I expressed in units of 10,000 amperes, as calculated with the aid of formula (d). Then we have the quantities ΔI —the resultant quantity of electricity passing in a second of time through a zone bounded by two parallels, ϕ_1 and ϕ_2 . If $\phi_2 > \phi_1$, then $\Delta I = I_1 - I_2$; ΔI is likewise expressed in units of 10,000 amperes. Finally are given the values i , the average current intensity, expressed in 0.001 ampere per sq. km. The last column is the mean i giving equal weight to each epoch.

To illustrate: For the surface from the North Pole down to parallel 60° N., the upward currents exceed the downward ones on the average for the three epochs, by 115×10^4 amperes. For the zone between 60° and 55° N. the average excess of downward currents for the three epochs is 23×10^4 amperes; dividing this amount by the total area of the zone, there results an average downward current of 0.019 ampere per square kilometer.

A first comparison of the quantities I , ΔI , and i for the three epochs is apt to prove somewhat disappointing. The quantities for the same zone not only at times differ materially from each other, but are even of opposite sign. Compare, for example, the I figures for 45° N., this parallel having given a maximum positive value for 1885. Even the results from the two charts 1880 and 1885 differ, in general, much more from each other for comparatively well-surveyed

regions than was to have been anticipated. I have satisfied myself that this is not due to the fact that the longitude interval was 10° for 1880, whereas for 1885 it was 5° . The differences appear rather to be caused by systematic errors to be ascribed either to the material used or to the secular variation reductions employed by the respective constructors of the charts.

TABLE I. RESULTS FOR VERTICAL EARTH-AIR ELECTRIC CURRENTS DERIVED FROM Y COMPONENTS.

Parallel.....	ΣY [Unit 0.001 C. G. S.]			I_0 [Unit 0.00001 C. G. S.]			I [Unit 10000 Amp.]				ΔI [Unit 10000 Amp.]				f [Unit 0.001 Amp. per sq. km.]			
	1842	1880	1885	1842	1880	1885	1842	1880	1885	Mean	1842	1880	1885	Mean	1842	1880	1885	Mean
N 60	+28	+36	+14	+78	+100	+38	+124	+160	+60	+115	-17	-94	+42	-23	-14	-78	+35	-19
50	+21	+13	+20	+58	+36	+56	+107	+66	+102	+92	-61	-66	+142	+5	-45	-49	+104	+3
45	+8	0	+43	+21	0	+119	+46	0	+244	+97	-48	+75	+135	+54	-32	+50	+89	+36
40	0	+12	+60	-1	+33	+169	-2	+75	+379	+151	-3	+47	-21	+8	-2	+29	-12	+5
35	-1	+18	+53	-2	+50	+147	-5	+122	+358	+158	-3	+1	-32	+3	+10	+13	-18	+2
30	+2	+20	+45	+5	+56	+125	+12	+145	+326	+161	+17	+23	-32	+3	+2	+1	-35	+11
25	+2	+19	+34	+6	+53	+94	+15	+146	+260	+149	+3	+1	-66	-21	+2	+1	-54	-40
20	+12	+16	+19	-33	+44	+53	-96	+129	+153	+62	-111	-17	-107	-78	-56	-9	-70	-88
15	-38	-6	+1	-106	-17	+3	-318	-50	+10	-119	-222	-179	-143	-181	-108	-87	-70	-67
10	-48	-25	-18	-133	-70	-51	-413	-215	-156	-261	-95	-165	-166	-142	-45	-78	-79	-43
5	-39	-47	-36	-108	-131	-99	-342	-412	-312	-355	+71	-197	-156	-94	+33	-91	-71	-49
Equator	-43	-58	-56	-120	-161	-157	-380	-513	-498	-464	-38	-101	-186	-108	-17	-46	-84	-49
5	-48	-48	-47	-133	-133	-131	-424	-424	-417	-422	-44	+89	+81	+42	-20	+40	+36	+19
5	-49	-41	-38	-136	-114	-106	-433	-362	-336	-377	-9	+62	+81	+45	-4	+28	+37	+20
10	-29	-31	-28	-81	-86	-76	-254	-272	-239	-255	+179	+90	+97	+122	+81	+41	+44	+55
15	+1	-26	-21	+3	-72	-59	+9	-228	-180	-132	+263	+48	+59	+123	+121	+22	+27	+57
20	+6	-23	-30	+17	-64	-82	+50	-192	-244	-129	+41	+32	-64	+13	+19	+15	+30	+1
25	+22	-48	-52	+61	-133	-146	+177	-386	-420	-210	+127	-194	-176	-81	-62	-95	-85	-39
30	+3	-79	-74	+8	-220	-207	+23	-607	-571	-385	-154	-221	-151	-175	-78	-112	-77	-89
35	+5	-113	-89	-14	-314	-248	-36	-822	-647	-502	-59	-215	-76	-117	-31	-114	-40	-62
40	+4	-113	-101	+11	-314	-281	+27	-768	-686	-476	+63	+54	-39	+26	+36	+31	-22	+15
45	+25	-107	-104	+70	-297	-289	+157	-671	-650	-388	+130	+97	+36	+88	+79	+59	+23	+54
50	+25	-56	-72	+69	-156	-201	+143	-320	-411	-196	-15	+351	+239	+192	-10	+232	+158	+127
55	+24	+16	-21	+67	+44	-59	+122	+81	-107	+32	-21	+401	+304	+228	-15	+295	+223	+168
S 60	+40	+102	+50	+111	+283	+138	+178	+453	+219	+283	+56	+372	+326	+251	+47	+310	+272	+210

Plotting the various quantities, however, the outcome of this investigation appears more satisfactory.

The curves in Figure 1 give a graphical representation of the I quantities for the different epochs as taken from Table I. (The curve marked thus ++++ will be explained later.) It will be noticed that practically the same character of curve is obtained for each of the three respective epochs for the region 45° N. to 20° S. Beyond these limits the curves differ; the 1842 curve is displaced markedly from the two for 1880 and 1885 in the Southern Hemisphere 20° S. to 60° S.; even for this region, however, the three curves unite in showing a depression in the vicinity of 35° S. Except for certain displacements up or down the 1880 and 1885 curves agree

FIG. 1.—Graph of quantities of electricity I .

FIG. 2.—Average distribution of current intensity along a meridian.

very well with each other in spite of the differences noticed in the previous paragraph.

Which curve is more correct for the excepted region 20° S. to 60° S.—the 1842 one or the mean of 1880 and 1885—cannot at present be determined. This is the region of the globe where, as already remarked in No. III, very little advance, if any, had been made between the dates of construction of the 1842 and 1880 and 1885 charts.

The set of curves in Figure 2, showing for the various epochs the distribution of the average current intensity, i , as given by the figures in the table, bear out the remarks in the previous paragraphs. In spite of the apparent inconsistencies in the figures, the three curves show the same general characteristics if we exclude the portions beyond 40° N. and 40° S. In these curves the systematic errors have had an opportunity to cancel themselves to a certain extent. (See my 1897 paper, p. 14.)

In Figure 3 the mean i curve for the three epochs, giving each equal weight (see figures in last column of Table I) has been drawn, without any smoothing process, for the region 45° N. to 45° S.—the heavy black line. With it is compared (the light black line) another i curve derived totally independently, viz., from declination charts alone, as explained in the next section.

FIG. 3.—Average distribution of current intensity; heavy line is the mean current from the Y components, whereas the light line is the mean current from the declination charts.

VERTICAL EARTH-AIR ELECTRIC CURRENTS FROM DECLINATION CHARTS ALONE.

A downward electric current, *i. e.*, one passing from the air through the Earth's surface, in accordance with Ampere's rule, will deflect the north end of the magnetic needle to the West. An upward current, on the other hand, will deflect the north end to the East.

Turning back to the I values in Table I we shall find, for example,

that over the zone from 60° N. to the equator, that $[-464-(+115)]$
 $10^4 = -579 \times 10^4$ amperes of electric current passes through this
 portion of the earth's surface every second from the air. In other
 words, we have for this portion in general downward currents, so
 that along the equator, for instance, the north end of the magnetic
 needle should suffer a practically constant deflection to the West, if
 such currents exist. Similarly for other parallels there will be indi-
 cations of vertical currents from declinations alone.

To investigate this matter, we proceed thus:

The mean declination for various parallels, using a longitude
 interval of 10° , is obtained for the four best isogonic charts at present
 on hand, viz., 1840-45 (Sabine), 1858 (British Admiralty), 1880
 (Creak), and 1885 (Neumayer). All of these charts were con-
 structed on the basis of actually *observed* results, not on *computed*
 ones.

Next, for the same parallels and for practically the same longitude
 interval, the mean declination is again obtained from the *computed*
 declinations for 1829 (Erman and Petersen), 1830 (Gauss), 1842
 and 1885 (Fritsche).¹ These computed quantities were derived by
 the respective analysts, on the assumption that the entire magnetic
 force was due to a potential—in other words excluding an effect from
 possible earth-air electric currents. If now such currents do exist,
 then the mean observed or chart declinations should differ system-
 atically from the mean computed declinations.

Table II presents the results thus derived. The computations
 have been made under the supervision of Mr. J. A. Fleming. The
 mean declinations for the various epochs, whether observed or com-
 puted, were found to differ too much from each other above 45° N.
 and 40° S., to warrant extending the table beyond these latitudes.

In above table *east* declination is *plus*, and a *minus* sign of ΔD
 means a deflection of north end towards the *west*.

We first have the mean observed or chart declinations for 1842,
 dependent upon the scalings of Sabine's charts by Sabine, de Tillo,
 and the Department. Next those for 1858 from the chart scalings by
 de Tillo and the Department. Then those for 1880 from the scalings
 by de Tillo and the Department, and finally those for 1885 from

¹ Unfortunately, the computed declinations resulting from the analyses by Adams
 and Neumayer-Petersen were not available, as they have not been published. In the
 case of Schmidt's analysis, the computed declinations, even if he had published
 them, were, of course, not to be used for this investigation, since his computations
 included the possibility of the existence of vertical electric currents.

the scalings by de Tillo and Leyst. The means of the four charts are next tabulated, giving each chart equal weight. The following five columns contain the mean computed declinations and the means from the four computations, again giving each equal weight. The column ΔD , formed by subtracting algebraically the "computed" means from the "observed" means, gives the quantities which are to

TABLE II. RESULTS FOR VERTICAL EARTH-AIR ELECTRIC CURRENTS DERIVED FROM DECLINATIONS ALONE.

Parallel.....	Mean Declination Observed.					Mean Declination Computed.					ΔD (O.-C.).....	Prob. Error of ΔD	1 in 10 ⁴ A.....	ΔI in 10 ⁴ A.....	1 in 10 ³ A per sq. km.....
	1842	1858	1880	1885	Mean	1829	1830	1842	1885	Mean					
	Sabine	Brit. Ad.	Creak.	New-mayer.	of all (Ob'd)	Erman-Petersen.	Gauss.	Fritzsche.	Fritzsche.	of all (Comp'd)					
°	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N 50	-1.88	-2.04	-1.50	-1.40	-1.70	-1.26	-1.53	-1.86	-1.44	-1.52	-0.18	±0.13	-129	+237	+75
40	-1.07	-0.93	-0.76	-0.67	-0.86	-0.95	-1.02	-1.03	-0.83	-0.96	+0.10	±0.07	+108	+144	+45
30	-0.53	-0.49	-0.44	-0.42	-0.47	-0.69	-0.66	-0.53	-0.48	-0.59	+0.12	±0.04	+163	+179	+44
20	-0.55	-0.30	-0.46	-0.46	-0.44	-0.52	-0.48	-0.34	-0.38	-0.43	-0.01	±0.04	-16	-195	+46
10	-0.52	-0.38	-0.66	-0.67	-0.58	-0.49	-0.46	-0.38	-0.45	-0.44	-0.12	±0.05	-211	-137	+31
Equator	-0.83	-0.68	-0.86	-0.93	-0.82	-0.60	-0.67	-0.60	-0.65	-0.63	-0.19	±0.04	-348	-144	+10
10	-1.27	-1.10	-1.23	-1.22	-1.20	-0.91	-1.10	-0.97	-0.99	-0.99	-0.21	±0.04	-370	+44	+10
20	-1.56	-1.59	-1.86	-1.82	-1.71	-1.40	-1.70	-1.45	-1.49	-1.51	-0.20	±0.07	-326	-123	+31
30	-1.94	-2.35	-2.83	-2.66	-2.44	-2.00	-2.25	-2.01	-2.19	-2.11	-0.33	±0.14	-449	-143	+31
S 40	-2.31	-2.64	-3.60	-3.48	-3.01	-2.49	-2.41	-2.42	-2.88	-2.55	-0.46	±0.23	-499	-50	-14

reveal the fact whether vertical electric currents exist. Adjacent to this column are tabulated the probable errors of ΔD , viz.:

$$\epsilon = 0.6745 \sqrt{\frac{[v v]}{n(n-1)}} ,$$

as derived from a consideration of the differences of the tabulated mean D 's from their respective means. By looking over the quantities thus far referred to, it will be seen that for the portions 30° N. to about 20° S. the mean declinations derived from the various charts agree well with each other, as do also those derived by computation. From the ΔD quantities the I 's have been computed as follows: From equation (d), substituting for ΣY , 36 I_0 , we get:

$$I = \frac{10 \times 36}{4 \pi} \cdot d \lambda \cdot I_0 .$$

I_0 , may be regarded as the average change in Y to be ascribed to vertical electric currents along any given parallel, since the average Y on the potential hypothesis would be zero; call it, therefore, ΔY . As

$Y = X \tan D$, and since the average direction of the magnetic meridian agrees very closely with the geographic meridian, we can assume with sufficient approximation that the effect of the vertical currents on the X component is on the average zero, so that $\Delta Y = \frac{H}{\cos D} \cdot \Delta D$. Expressing ΔD in decimals of a degree and substituting for l_0 , the value of ΔY in terms of ΔD , we get:

$$I = \frac{10 \times 36}{4 \pi} \cdot d\lambda \cdot \frac{H}{\cos D} \cdot \frac{\Delta D}{57.3}.$$

With the aid of this equation, the values of I in Table II have been computed from the ΔD . For our case H and D are the mean values for the parallel concerned; as D is in general less than 2° , $\cos D$ may be set equal to unity with sufficient approximation.

The ΔI 's are next formed as before, and from them the average current intensities i are computed.

The I curve derived from the ΔD quantities is shown in Figure 1 by + + + + +. It will be seen that, in general, it agrees well with the other I curves. Finally the i curve will be found in Figure 3—the light black line—and it will be seen that it agrees well, in its general characteristics, with the mean i curve obtained from the Y components, as in fact it should; from later statements it will be seen that the effect of the electric currents is measured practically entirely by the declination observations.

The average current intensity for the region 45 N. to 45 S. is from the Y components 0.04 ampere per sq. km., and as obtained from the declinations alone 0.03 ampere, or from the combined results about 1/30 ampere per sq. km. This is about 1/5 of the quantity given by Schmidt for the whole earth as derived alone from the Y components for 1885.

TABLE III. VERTICAL EARTH-AIR ELECTRIC CURRENTS AS DERIVED FROM BOTH INVESTIGATIONS (TABLES I AND II).

[Double weight is given to the results in Table I.]

ZONE.	I in 10^4 A.	ZONE.	I in 10^4 A.	i in A per sq. km.
50 N to Equator, . . .	-419	50 N to 40 N,	+120	+038
40 N to Equator, . . .	-539	40 N to 30 N,	+5	+001
30 N to Equator, . . .	-544	30 N to 20 N,	-231	-057
20 N to Equator, . . .	-313	20 N to 10 N,	-223	-052
10 N to Equator, . . .	-90	10 N to Equator, . . .	-90	-020
Equator to 10 S, . . .	+105	Equator to 10 S, . . .	+105	+024
Equator to 20 S, . . .	+203	10 S to 20 S,	+98	+023
Equator to 30 S, . . .	-9	20 S to 30 S,	-212	-053
Equator to 40 S, . . .	-86	30 S to 40 S,	-77	-021

The figures in the last column give a maximum downward current in the zones 20 N. to 30 N. and 20 S. to 30 S. and upward currents in the equatorial belt, and again beyond parallel 30°.

The general conclusion to be drawn appears to be:

All of the modern magnetic charts—i. e., since those of Sabine for 1840-45—unite in indicating the probable existence of vertical earth-air electric currents of the average intensity over the region 45° N. to 45° S. of 1/30 of an ampere per square kilometer of surface. These currents proceed upward (from the earth into the air) near the equatorial regions where there are ascending air currents, and downward near the parallels 25 to 30°; i. e., in the regions of descending air currents. Near the parallels 40° the electric currents are again upward, thus corresponding once more with the general atmospheric circulation. Beyond the parallels 45° the results appear too uncertain to warrant drawing a definite conclusion.

If it be true that the vertical electric currents are to be associated with air currents, and are hence convection currents, the importance of choosing circuits for testing the validity of the potential hypothesis in localities of steady air currents is made manifest. The present investigation clearly indicates—whether we take the Y components or simply the declinations—that the results are most certain in the zones of comparatively simple atmospheric circulation, where on the average the direction of the air currents is fairly constant as in the tropical belts. (See figures in Tables I and II.)

It is thus clear that meteorological conditions may play an important part—as already pointed out in my 1897 paper—in investigations as to the existence of vertical electric currents from magnetic surveys over limited areas. This is a point to be examined. We may also find an explanation in this statement as to the cause of the uncertainty of the results from the different charts in the zones of more complex atmospheric circulation—where along the same parallel we may in consequence encounter both upward and downward electric currents, thus wholly or nearly annulling each other in the average result.

In order to make some tests as to the manner of distribution of the upward and downward electric currents, the currents over quadrilaterals bounded by two parallels 10° apart and two meridians, likewise 10° apart, have been derived for the entire region from 60° N. to 60° S., for the three epochs 1842, 1880, and 1885. As a general

result it did not appear as though the directions of the electric currents—whether up or down—were to be associated with the distribution of land and water. *There was, however, a decided indication, for each epoch, that over the areas of low pressure, where the air-currents are upward, there the electric currents were likewise, in general, upward, and that over the areas of high pressure where there are descending air-currents, there the electric currents were likewise downward.*

Thus, as the average result, from the three epochs we have:

Region	{ For Areas of Low Pressure: " " " High	Quantity of Electricity. +829 x 10 ⁴ Amperes. -638 x 10 ⁴ " "
60° N. to 60° S.		

(+ means upward electric currents; — downward electric currents.)

A re-investigation of the existence of vertical electric currents and their cause will be made as soon as we have at our disposal strictly homogeneous data of which the value is precisely known. With the formation of the Department of Terrestrial Magnetism of the Carnegie Institution, the prospects are bright that at no very distant date the construction of new magnetic charts depending on more complete and homogeneous material than was at the command of the previous constructors can be undertaken. Plans are now under consideration for the magnetic surveys of oceanic areas, and it is hoped before long that a beginning can be made in the North Pacific Ocean. It is also gratifying to note the renewed interest that will be taken in magnetic observations at sea, because of the formation of a Committee, on the motion of von Bezold, at the recent meeting of the International Association of Academies, for considering methods of increasing the accuracy of sea work.

The average effect of electric currents for the region 45 N. to 45 S. is on the east-west component of the Earth's magnetic force, (Y), 0.001 C. G. S. unit, or about 1/50 of the average value of Y . The average effect on the horizontal intensity is about 1/1000 part; *i. e.*, on the order of the error of a field determination. However, the average effect on the declination is about 0.2°—about six times the error of a reduced field determination of the declination on land, and about 1-2 times the error of a determination at sea by the most approved methods. It would, therefore, seem perfectly feasible to detect the vertical electric currents in zones where their effect on the declination is fairly steady; *i. e.*, in general of the same sign, for the

error of a single observation would have to be many times that of the errors of land and sea determination even with the present appliances, to fail to disclose a constant average effect along an entire zone of 0.2° in declination.

d. REMARKS UPON THE RESIDUAL FIELD AND THE DIURNAL VARIATION FIELD.

THE RESIDUAL FIELD.

In No. I a decomposition of the Earth's permanent magnetic field was made into a primary and a secondary field.¹ The first field was defined as representing the portion which could be referred to a uniform magnetization about a diameter of the Earth, and the secondary field, called the "residual field," was the remaining portion of the total magnetization. The primary field is mathematically expressed by the first harmonic in the Gaussian expansion, whereas the residual field includes the remaining harmonic terms.

The diameter of the primary or "normal" magnetization for 1885 made an angle of $11^\circ 25.7'$ with the rotation axis and pierced the Northern Hemisphere in longitude $68^\circ 30.6'$ W. of Greenwich. The magnetic moment of this field was taken as $0.32298 R^3$, C. G. S. units, R being the Earth's mean radius. These figures were dependent on Schmidt's analysis of the Earth, and a slight revision would be required in accordance with his latest published Gaussian coefficients. According to the deductions in Nos. II and III, however, these slight revisions are on the order of error of determination; it will, therefore, not be worth while to make any change.

In No. II was shown how the determination of the magnetic axis and of the magnetic moment were dependent upon the portion of the Earth considered in the calculations, so that strictly the quantities adopted apply only to the area embraced. Fortunately, however, the effect of the neglected portions of the Earth—the polar regions—diminishes rapidly with advancing latitude, so that the values as adopted for the primary field, depending as they did upon data from 60° N. to 60° S., will not differ sufficiently from those obtained, had there been data over the entire globe, to vitiate the general deductions regarding the characteristics of the secondary field.

Further contemplation of the method of decomposition of the total field employed in these papers has strengthened my belief that the

¹ See *T. M.*, March, 1899.

process is fundamentally correct. In the selection of a primary or normal field, the first natural thought, of course, is to take one symmetrical about the rotation axis, as several eminent investigators have done. Doing this and constructing the resulting residual field, there will be revealed at once a magnetic system consisting chiefly of an east-west magnetization. To further resolve this residual field, in order to get at the underlying physical causes, the next step would be to eliminate the system of forces arising from a simple or uniform magnetization about an equatorial diameter. The magnetic moment of the resulting uniform equatorial field is found to be about $1/5$ of that symmetrical about the rotation axis. The combination of the two is the initial uniform magnetic system started with in these researches.

Umow's recent investigations, as to the fundamental type of magnetization of the Earth, resulted in deducing a uniform magnetization about a diameter inclined to the rotation axis.

The residual field derived after deducting the total uniform magnetization was shown graphically for 1885 in No. I. It has now been constructed by the Department of Terrestrial Magnetism for two other epochs; viz., 1842 and 1880, the former depending on Sabine's charts and the latter upon Creak's charts. The residual fields for these two epochs agree so well in all the principal features with the one for 1885, that it is not worth while to reproduce them here.

The residual magnetization can thus be broadly characterized: it consists chiefly of two main magnetizations transverse to the axis of rotation, one system lying in the Northern Hemisphere, the north end attracting pole (N_1) being east of the south end attracting poles (S'_1 , S''_1), and the other in the Southern Hemisphere, the direction of magnetization being the reverse of the former, the north pole (N_2) lying now west of the south pole (S_2). The poles of the two systems are situated, approximately, near the 40° parallels—this is even true of the tertiary system N_3 , S_3 . (See plate II, No. I.)

The secondary magnetic equators (the lines along which the residual vertical force is zero) occupy practically the same positions for the three epochs. It is as yet too early to decide as to any probable secular shifting of the positions of the secondary poles. The interval is too short, in view of the meagerness of the data on which the charts depend, as revealed in No. III, to make certain any deductions.

What has thus far been gained by the decomposition?

In the first place, the residual field clearly exhibits the fact that it is not a heterogeneous one, but, in general, remarkably systematic

in its structure. There is, therefore, a very strong indication that it is produced by some distinct physical cause operating in the same general manner over the entire Earth. The hope is thus clearly held out, that we may still further resolve the residual field, starting with fundamental, physical causes.

My present belief is, that the chief physical cause of the residual field is to be referred to the distribution of temperature within the stratum of the Earth's crust here concerned.

In No. I, I showed the very remarkable correspondence between the principal features of the residual magnetic field and those exhibited by the chart of isabnormal temperature lines. It was found that the Earth as a magnet acted like any other magnet as regards application of heat. Thus wherever the Earth's surface was shown to be relatively warm, on the average for the year, there the magnetization of the Earth showed a decrease, and where, on the other hand, it was relatively cold, there it suffered an increase. The comparison held so far, that, as stated in No. I, p. 51, it was possible to reproduce the residual magnetic field, in its general characteristics, with the aid of temperature charts.

The criticism has been made that this relation between residual magnetism and temperature distribution might only be an apparent one, since the latter referred to surface conditions, whereas the former pertained to strata, at considerable depths below the surface.

However, the isabnormal temperatures plotted were based on annual means; hence the effects due to annual variation and diurnal variation were eliminated. I am not aware that any one has given a physical explanation of the situations of the maxima and minima shown on an annual isanomalous temperature chart. Their annual positions are probably largely dependent on the radiation of the internal heat of the Earth. We can not say, as yet, at what depth the principal features shown at the surface are eliminated; it is known that the isothermal surfaces in the interior conform with those of the surface to a considerable depth. In any case, there is no question that as land areas are pierced a steady increase of temperature is encountered. Over oceanic areas, on the other hand, there is at first a decrease until nearly a zero temperature is reached at the ocean beds, and then, presumably, an increase as the penetration continues. So that we shall have temperature gradients along parallels of latitude down to a considerable depth.

I shall not discuss this matter further now, as it is being made the subject of a special examination, the results of which will be

communicated later. Many have surmised that the distortion of the Earth's magnetic field is to be attributed to the distribution of land and water; but the problem is to show in what manner the distribution causes the observed effects. The first attempt, as stated, will be to ascertain whether the cause is to be sought in the distribution of temperature in the upper stratum of the Earth's crust, as produced largely by the distribution of land and water. The results of our decomposition have thus revealed one promising mode of attack of the problem as to the causes of the asymmetrical distribution of the Earth's magnetism.

Another result of the decomposition is treated in the next section.

THE DIURNAL VARIATION FIELD.

It was pointed out in No. I that there was a very close similarity between the chart of the residual permanent magnetic field and that of the system of forces causing the diurnal variation of the Earth's magnetism. The two magnetic systems were identical except in one respect; viz., the first was to be referred to a system of magnetic forces in the Earth's interior, whereas the other to a system outside, the relative positions of the poles being governed accordingly. Thus in the summer at Greenwich mean noon, for example, the north end attracting pole of the first system would be about vertically below the south end attracting pole of the second system, and the south end attracting pole of the first would be about directly below the north end attracting pole of the second system—this statement held for the main transverse magnetization in each hemisphere.

There appears to be more than a chance connection in this relation as was shown by my comparison of the horizontal vector diagrams for various parallels as resulting from the two respective fields. (See p. 47, No. I.) This matter since has been developed further, as will be shown in a future communication. .

I have had the impression for some time that the Earth's permanent magnetic field plays a very important part in the production of the diurnal variation field as observed on the Earth's surface. No satisfactory explanation has as yet been given of the manner in which the peculiar magnetic system of forces causing the diurnal variation is actually produced.

Schuster's first attempt at the construction of the equipotential lines of the diurnal variation field, based as it was on exceedingly meager data, was, nevertheless, remarkably correct in its general

features as shown by the recent more elaborate work of Fritsche. We therefore have now a fairly accurate map of this field.

The existence of some form of radiation from the Sun which does not penetrate to the lowest strata of our atmosphere, and which is yet capable of deflecting magnetic needles on the Earth's surface, appears to have been definitely proven by the recent magnetic observations during solar eclipses. It was furthermore shown that the eclipse magnetic variation was a phenomenon similar to the diurnal variation, and that it differed from the latter only in degree; the ranges in the declination variations, *e. g.*, were proportional to the amounts of radiation cut off by the respective bodies: the Moon and the Earth.

It is known how a moving electrified particle will be deflected by a magnetic field, and how, in general, it will be made to travel in a spiral path whose axis is the line of magnetic force.

Is it possible that, as a result of the combined action of the permanent magnetic field of the rotating Earth and the electrified particles radiated by the Sun, there is formed in the regions above us a secondary magnetic system precisely similar to that of the Earth? (See Paragraph 3, No. III, September, 1903, issue, p. 111.)