My acquaintance with the literature of electricity is very limited. Others vocations have for many years diverted my thoughts and my reading from electrical science, and if I have in any case advanced as a novelty what has been done before I hope it will be attributed to ignorance and not to intention. It was only within the last few days, and after the foregoing paper was printed, that I was made aware of the fact that I am not the first to use dust figures in electrical research, but I am still unaware that the experiments I have described have, in their results, any substantial coincidence with the recorded results of other investigations.*

"On the Simultaneity of Magnetic Variations at different places on occasions of Magnetic Disturbance, and on the Relation between Magnetic and Earth Current Phenomena." By WILLIAM ELLIS, F.R.A.S., Superintendent of the Magnetical and Meteorological Department, Royal Observatory, Greenwich. Communicated by W. H. M. CHRISTIE, F.R.S. Received April 7,—Read May 5, 1892.

The observations made in a magnetic observatory usually include absolute measures of magnetic declination, horizontal force, and dip (inclination); with photographic registration of the variations of declination, horizontal force, and vertical force; to which is added, at Greenwich, a photographic registration of earth currents.

As regards magnetic variations, the observations made at the Royal Observatory indicate, for all magnetic elements:—1. A progressive change of value which, when limited periods of time only are considered, is nearly constant from year to year. 2. A solar diurnal variation, the amplitude of which is greater in summer and smaller in winter, and which has also a period sympathetic with the sun spot period, being greater throughout the year when sun spots are numerous, and smaller when sun spots are few. There is also a small lunar diurnal variation. 3. The occurrence of days and periods of irregular magnetic disturbance or magnetic storm, which are more frequent and of greater magnitude when sun spots are numerous than when sun spots are few, being comparatively rare as well as insignificant in character near to the times of minima of sun spots. Disturbances are also in general more numerous in spring and autumn, than at

[* The actual operation of producing dust figures by the discharges of an induction coil was exhibited by the author at the conclusion of the reading of his paper. Two figures were produced, the one agreeing with diagram No. 15, and the other, a new figure, obtained by arching the positive wire and causing it to touch the plate at a succession of points.]

other parts of the year. 4. Earth currents, which, usually feeble, are active and strong at the times of magnetic disturbance, remaining active only so long as disturbance continues. In the absence of magnetic disturbance there exists practically earth current calm.

These are the broad features of magnetic variations as experienced at Greenwich, and which there is reason to believe are generally similar at other places.

Having premised thus much, we will now proceed with the special inquiry to which this paper is directed.

When magnetic disturbance is experienced at Greenwich, the photographic registers show that, after a period of magnetic calm, disturbance commences sometimes very suddenly, and at other times with a premonitory sign or signs. In the latter case the first indication will not unfrequently be a sudden and sharp movement occurring simultaneously in all elements, moderate it may be in amount and of isolated character, followed after a shorter or longer period by general magnetic disturbance; at other times the first sharp movement ushers in at once the disturbance. In other cases disturbance will arise gradually without any special premonitory indication, appearing in one element before showing, in any marked degree, in the others. But when there is sudden initial movement, whether great or small, it is very definite in character, and appears at Greenwich without exception simultaneously in the registers of declination, horizontal force, vertical force, and earth currents. The *instantaneous* movement is the really remarkable point. Much larger motions will occur during the course of a magnetic disturbance, but not usually movements similarly sudden. They are such as will be quite familiar to all those who may be acquainted with photographic registers of magnetic variations, and we shall see that similar characteristics are observed at other places.

Now it is known that any considerable magnetic disturbance or magnetic storm is felt over wide areas of the earth's surface, commencing and terminating at different places at about the same absolute time. But how nearly such commencement is really simultaneous at different places, whether or not in a much closer degree than has before been supposed, does not appear to have hitherto been so carefully studied as seems possible. For the initial movements are so definite and so suddenly manifested that it is evident, from the character of the photographic traces at Greenwich, that at such times a very perceptible, sometimes the whole, movement has occurred in a very few seconds, the fineness and exceeding delicacy of the photographic trace, as compared with that of the ordinary register, showing how rapidly the spot of light has moved across the paper. The accidental comparison of the Greenwich motions with those at other places in one or two instances of the kind seemed to show that the corre-

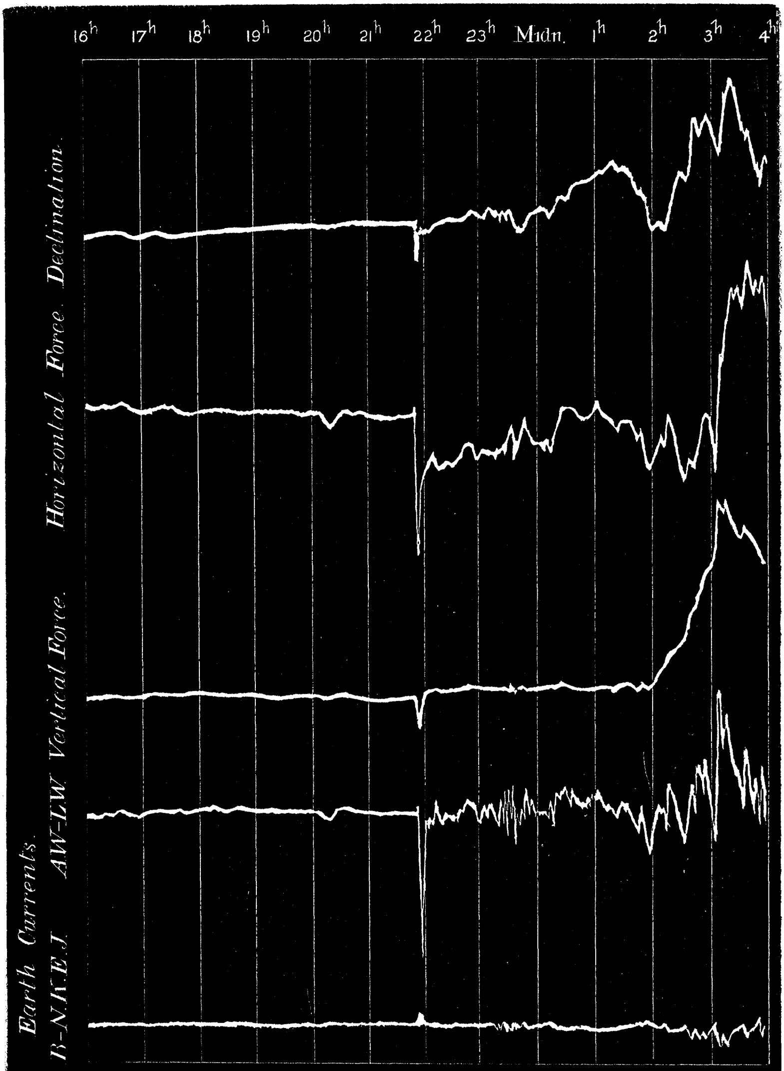
sponding phenomena at other places were in these cases similarly definite. It thus appeared that a systematic comparison of the times of these initial movements at different places might afford the means of determining how nearly the movements at such places are really coincident.

It is practically impossible to catch these first movements by eye observation of the magnets, from the uncertainty as to the time at which they may occur, so that it becomes necessary to rely on the photographic register. Unfortunately, however, the scale of time employed on such registers is necessarily small, one minute of time corresponding usually to about 0·01 inch. This renders difficult any very accurate measurement of time in individual cases. But it appeared to me that by selecting a considerable number of instances of sudden initial movement, and comparing together the times as measured from the photographic registers of magnetic observatories situated in widely different regions of the earth, we might expect in the general average to eliminate any accidental error of measurement due to contracted time scale or other cause, and, supposing no systematic error to exist, so obtain some reliable information as to the degree in which, on the whole, such movements, at different places, are or are not simultaneous.

With this object in view, a selection from the Greenwich registers was made of seventeen cases of sudden distinctive movement, preceding or commencing magnetic disturbance, and occurring during the years 1882 to 1889. The list might have been extended, but the cases selected are typical, and seemed sufficient for the purpose of a preliminary inquiry. Giving the day and approximate hour only of the occurrence of the respective movements at Greenwich, the directors of various magnetic observatories were asked to examine their registers for the corresponding times, and see whether there existed any instance of sudden movement, and, if so, to measure out and supply on each day, and for each magnetic register, the exact local time of commencement of movement to the nearest minute of time, and also the direction and approximate amount of change in each magnetic element. The observatories selected, including Greenwich, nine in number, were, counting from west to east, those of Toronto, Greenwich, Pola, Pawlowsk, Mauritius, Bombay, Batavia, Zi-ka-wei, and Melbourne. This request was complied with in the most obliging manner, and my best thanks are due to the directors of the various establishments for the very kind way in which they endeavoured to supply all necessary information, as well as to the Astronomer Royal for permission to make use of the Greenwich records. In two cases, indeed, Toronto and Zi-ka-wei, copies of the registers were also furnished; the Toronto report, however, included movements of the declination magnet only. Unfortunately at Pola

photographic registration was not commenced until the year 1885, and it thus became necessary to omit Pola in the comparision. It might be supposed that, in giving the Greenwich time of movement to the nearest hour only, it would be possible in some cases to find on the registers at other observatories several movements sufficiently near, any one of which might be taken, and thus not be a corresponding movement in the sense meant. But the movements in question, so abrupt in character, are neither numerous nor easily mistaken. Their character is well illustrated in the annexed reduced copy of the Greenwich registers for 1884, October 1 (one of the selected days), in which it will be perceived how in all elements, declination, horizontal force, vertical force, and earth currents, a definite and rapid movement occurs just before 22h., and simultaneously in all; that in horizontal force corresponding indeed to an increase in the earth's horizontal force of about 1/200th part. It will be thus understood that the really corresponding movements would be readily identified at other places; indeed the returns received show that no difficulty was experienced, the suddenness of movement being a matter of common remark. For instance, at Toronto it is said that "the initial movement was always very sudden," at Mauritius the movements are spoken of as "remarkable jumps," at Bombay as "abrupt and unmistakeable at the beginning," and at Batavia the commencement was "in all cases . . . . . very abrupt." In the Zi-ka-wei curves, so kindly furnished, the same characteristics are to be observed, and the same simultaneous commencement of movement in all elements is shown as in the Greenwich specimen register of 1884, October 1. The certainty with which the selection was made further appears by the circumstance that the stations in addition to Greenwich being seven, and there being seventeen days, 119 identifications had to be made. Not counting six instances in which the corresponding record was not available on account of failure or want of register, it was found that, of the remaining 113 cases, there were only four in which there was discordance, and a re-examination of the registers in two of these cases immediately showed that a wrong movement had been taken. Had there been opportunity for further examination in the two remaining cases, there is little doubt but that the source of the discordance would have been in these also ascertained. All this assures us of the real correspondence of the movements discussed.

It has been mentioned, in regard to Greenwich and Zi-ka-wei, that the three magnets, declination, horizontal force, and vertical force, were on all occasions simultaneously affected. The reports received from other observatories show that, at places for which the times for the different magnets are separately given, the magnets were similarly simultaneously affected. This circumstance is peculiar to



Royal Observatory, Greenwich.—Copies of the Photographic Records of Magnetic Elements and Earth Currents from 1884, Oct. 1, 16^h, to Oct. 2, 4^h, Greenwich Civil Time.

It will be seen how the rapid movement just before 22^h occurs simultaneously in all elements, after a calm state. Downward motion on the paper indicates increase of west declination, and of horizontal and vertical force, and in earth currents corresponds to the passage of a current similar to that from the copper pole of a battery in the direction Angerstein Wharf—Lady Well in the one case, and in the

direction Blackheath—North Kent East Junction in the other. The azimuth of the former line, reckoning from magnetic north to east, is 50°, and of the latter, reckoning from magnetic north to west, is 46°. The direction of strongest earth current at Greenwich is not much different from that of the line joining the A. W.—L. W. earth plates. The current in the A. W.—L. W. circuit is always much stronger than that in the B.—N. K. E. J. circuit, and a current that causes the A. W.—L. W. trace to move in one direction on the paper causes the B.—N. K. E. J. trace to move in the opposite direction.

these sudden movements, which, although abrupt in character, are sometimes of no great magnitude. There is not the same simultaneity of movement in the different elements when disturbance commences, as it were, gradually, or in general during the course of a magnetic storm; the really simultaneous movements are exceptional.

The annexed Table I contains the times of commencement of movement on the seventeen selected days at each of the eight stations. The second column gives the year, day, and hour of disturbance, Greenwich civil time (counting from midnight to midnight), and in following columns are added the times to tenths of a minute for the eight stations, arranged in order of longitude, reckoning from west to east, and reduced to Greenwich time by the application of the differences of longitude given in Table II. From accidental causes, as before mentioned, times were wanting in six cases, and in addition for two in which there were unresolved discordances. These were at Batavia, on 1882, April 16; at Pawlowsk and Mauritius, on April 20; at Melbourne, on August 4; at Toronto, on September 12; at Batavia, on 1883, February 24; at Zi-ka-wei, on September 16; and at Toronto on 1884, July 2. To maintain a proper balance in the table, times in these cases have been adopted by estimation, paying proper regard to the average deviation of the times at each particular station from the general average of all the stations.

The times as received were given usually to the nearest minute; the fractions of a minute that appear in the table are partly due to the time being in most cases the means of those for three magnetic elements, and partly to the fractional value of the longitude used. In a following column is given for each day the mean of the times at the eight stations, and in succeeding columns the deviation of the time at each station from this daily mean.

Every instance of magnetic motion included in the table was accompanied at Greenwich by active earth current. It is known that in some cases earth currents were similarly active at other places, and presumably they were active at all places.

From an inspection of the table it will be seen how nearly these sudden and characteristic magnetic impulses occur at the same absolute time at places geographically widely separated. At some

Table I.—Time of commencement of Magnetic Movement at different Places compared.

No. for reference.	Day and hour.	Observed time of commencement of magnetic movement at the different places reduced to Greenwich civil time. Toronto.	Greenwich.	Pawlowsk.	Mauritius.	Bombay.	Batavia.	Zi-ka-wei.	Melbourne.	Daily mean of times.	Deviation of time at each place from the mean. Toronto.	Greenwich.	Pawlowsk.	Mauritius.	Bombay.	Batavia.	Zi-ka-wei.	Melbourne.
	d. h.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.	m.
1	1882. April 16 23 +	33·6	34·0	33·1	35·8	35·0	37·0	31·3	38·4	34·8	−1·2	−0·8	−1·7	+1·0	+0·2	+2·2	−3·5	+3·6
2	20 3 +	32·6	35·7	35·0	36·0	36·7	39·7	32·3	33·4	35·2	−2·6	+0·5	−0·2	+0·8	+1·5	+4·5	−2·9	−1·8
3	June 15 3 +	1·6	4·7	3·1	3·8	3·7	8·7	0·3	5·1	3·9	−2·3	+0·8	−0·8	−0·1	−0·2	+4·8	−3·6	+1·2
4	Aug. 4 15 +	45·6	48·7	48·2	49·8	49·4	48·7	45·3	50·0	48·2	−2·6	+0·5	0·0	+1·6	+1·2	+0·5	−2·9	+1·8
5	Sept. 12 2 +	50·0	53·5	49·2	54·8	50·7	52·7	46·0	55·1	51·5	−1·5	+2·0	−2·3	+3·3	−0·8	+1·2	−5·5	+3·6
6	Oct. 2 9 +	39·6	39·5	39·2	39·8	39·7	42·7	35·6	45·1	40·2	−0·6	−0·7	−1·0	−0·4	−0·5	+2·5	−4·6	+4·9
7	Nov. 17 10 +	17·6	20·0	20·2	23·1	22·0	20·7	21·3	25·1	21·2	−3·6	−1·2	−1·0	+1·9	+0·8	−0·5	+0·1	+3·9
8	1883. Feb. 24 13 +	40·6	41·7	42·2	41·8	40·7	44·0	38·3	45·1	41·8	−1·2	−0·1	+0·4	0·0	−1·1	+2·2	−3·5	+3·3
9	April 3 9 +	0·6	1·0	1·2	−0·2	1·4	4·7	−1·2	0·1	0·9	−0·3	+0·1	+0·3	−1·1	+0·5	+3·8	−2·1	−0·8
10	July 29 23 +	45·6	46·5	47·2	46·1	44·7	48·7	41·8	55·1	47·0	−1·4	−0·5	+0·2	−0·9	−2·3	+1·7	−5·2	+8·1
11	Sept. 16 2 +	43·6	42·0	44·1	44·8	44·0	46·7	41·0	45·1	43·9	−0·3	−1·9	+0·2	+0·9	+0·1	+2·8	−2·9	+1·2
12	1884. July 2 19 +	14·5	15·3	16·1	16·8	16·4	18·7	15·3	15·1	16·0	−1·5	−0·7	+0·1	+0·8	+0·4	+2·7	−0·7	−0·9
13	Oct. 1 21 +	48·6	50·3	52·1	50·5	51·4	54·7	50·3	50·1	51·0	−2·4	−0·7	+1·1	−0·5	+0·4	+3·7	−0·7	−0·9
14	1885. June 24 22 +	30·6	31·0	31·1	31·8	30·4	32·7	27·3	35·1	31·3	−0·7	−0·3	−0·2	+0·5	−0·9	+1·4	−4·0	+3·8
15	1886. Mar. 30 8 +	21·6	22·7	20·1	22·5	21·7	24·7	20·8	25·1	22·4	−0·8	+0·3	−2·3	+0·1	−0·7	+2·3	−1·6	+2·7
16	1888. Oct. 30 19 +	43·6	44·7	48·1	43·8	45·0	45·7	41·3	45·1	44·7	−1·1	0·0	+3·4	−0·9	+0·3	+1·0	−3·4	+0·4
17	1889. July 17 4 +	47·6	50·0	50·1	49·8	49·0	52·7	47·4	45·1	49·0	−1·4	+1·0	+1·1	+0·8	0·0	+3·7	−1·6	−3·9

stations the times are distinctly greater and at others distinctly less than the average of times for all stations. Either the magnetic impulse is really retarded at some stations and accelerated at others, as referred to the mean, or there exists at individual stations some systematic error, mechanical or otherwise, which affects the times in one particular way. That such error should exist is not unlikely since it is difficult to make accurate, beyond a certain point, a time scale so contracted, and difficult also to measure correctly the photographic trace, besides which the desirability of securing such extreme accuracy has not been before made apparent.

It happens that on five of the selected days, Nos. 6, 7, 8, 9, and 10, corresponding records were found in the magnetic section of the 'Mission Scientifique du Cap Horn,' 1882—1883. Here No. 6 is said to be "une diminution brusque," No. 7 "un mouvement très rapide," and No. 9 is said to commence "brusquement." Engraved copies of the registers on a small scale are given for Nos. 8, 9, and 10, showing the movements to have been of the character described. This affords five comparisons. The times are given only to the nearest five minutes, and the mean of the five resulting deviations, which range from +7·1 m. to −8·6 m., is +1·1 m. There were in addition six other instances of sudden movement contained in the Cape Horn series, not included in our selected list, for which corresponding movements were readily found in the Greenwich records. These movements are spoken of as having at Cape Horn the same abrupt character as those already mentioned. The separate values of deviation referred (by comparison through Greenwich) to the general mean of Table I range from +9·2 m. to −10·8 m., the mean being −2·1 m. Or, combining the two sets, we have from eleven comparisons a mean deviation of −0·7 m.

The mean deviation of time at each station from the general mean for all stations (the means of the columns of differences in Table I) and the difference between the greatest and least values at each station, adding the result for Cape Horn for eleven days just found, are as follows:—

Table II.—Mean Deviation of Time at each Station from the General Mean for all Stations, and Difference between the greatest and least Values of Deviation at each Station.

Station.	Latitude.	Longitude.	Mean deviation.	Difference between the greatest and least values.
	° ′	h. m.	m.	m.
Toronto	43 40 N.	5 17·6 W.	−1·5	3·3
Cape Horn..........	55 31 S.	4 32·3 „	−0·7	20·0
Greenwich	51 29 N.	0 0·0	−0·1	3·9
Pawlowsk...........	59 41 „	2 1·9 E.	−0·2	5·7
Mauritius...........	20 6 S.	3 50·2 „	+0·5	4·4
Bombay	18 54 N.	4 51·3 „	−0·1	3·8
Batavia	6 11 S.	7 7·3 „	+2·4	5·3
Zi-ka-wei	31 12 N.	8 5·7 „	−2·9	5·6
Melbourne	37 50 S.	9 39·9 „	+1·8	12·0

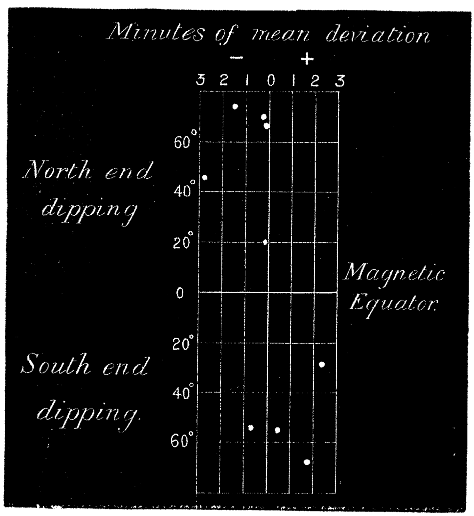
At Cape Horn and Melbourne the times were given only to the nearest 5 minutes; at the other stations they were given to the nearest minute. This may explain the greater differences for Cape Horn and Melbourne in the last column of the table.

The question that now arises is, What is the explanation of the small differences between the values of deviation at different places? As already suggested, they must be due either to real difference in the time of the magnetic impulse, depending on geographical position, or to the existence at individual stations of some systematic error.

In regard to the possible variation of the values of deviation with geographical position, there may be variation with latitude or with longitude. It will be observed that in Table II the stations are already arranged in order of longitude, and the run of the numbers would appear to indicate a tendency to negative values at westerly stations, and to positive values, on the whole, at easterly stations, but yet the differences are such (remembering how easily some of these differences might arise, with existing apparatus) as would hardly warrant the assumption that such variation really exists; neither does a change with longitude seem to be one for which there would appear to be any ready physical explanation. The variation in the values of deviation with latitude is better seen by arranging the numbers of Table II in order of latitude, and, considering the divergence of the magnetic equator from the astronomical equator, it seems better to group them according to the values of magnetic dip at the various stations, which has been done as follows, adding also a

graphical representation of the relation between the values of deviation and dip.

Station.	Value of dip.	Mean deviation.
		m.
Toronto	75° N.	−1·5
Pawlowsk	71 ,,	−0·2
Greenwich	67 ,,	−0·1
Zi-ka-wei	46 ,,	−2·9
Bombay	20 ,,	−0·1
Batavia	28 S.	+2·4
Cape Horn	53 ,,	−0·7
Mauritius	55 ,,	+0·5
Melbourne	67 ,,	+1·8



There would seem to be here a tendency to negative values with northerly dip, and to positive values with southerly dip. Remarking how five stations (two with extreme northerly dip, two with extreme southerly dip, and one intermediate) hang together, this apparent tendency may be accidental, and yet there is an undoubted drift to the left in the upper part of the diagram, and to the right in the lower part A variation with latitude certainly appears to be one better admitting of physical explanation than does a variation with longitude. Can anything depend on the distribution of land and water ? Whether the observed deviations represent a real inequality,

or whether the irregularities are wholly accidental, and that the magnetic impulse in these motions is everywhere simultaneous, we cannot say. The data are not sufficient to permit of the formation of any definite conclusion.

But whatever may be the explanation of the irregularities of deviation, it would seem that over a certain portion of the earth's surface the magnetic action in these initial impulses is practically simultaneous. The values of mean deviation for Greenwich, Pawlowsk, Mauritius, and Bombay are −0·1 m., −0·2 m., +0·5 m., and −0·1 m., respectively, an agreement which is certainly striking, and which can hardly be explained on any supposition but that of simultaneous action. For if we divide the series for these places (Table I) into two groups, say of 8 and 9 values each respectively, and take their means, we have as follows:—

	Greenwich.	Pawlowsk.	Mauritius.	Bombay.	Extreme difference.	Mean.
	m.	m.	m.	m.	m.	m.
Mean of first 8 values...	+0·1	−0·8	+1·0	+0·1	1·8	+0·1
Mean of last 9 values...	−0·3	+0·4	0·0	−0·2	0·7	0·0
Difference	0·4	1·2	1·0	0·3	—	—

In the first set the Greenwich and Bombay values agree, so also in the second set (within 0·1 m.). Greenwich and Bombay are thus in close accord, and in a remarkable degree, the agreement amounting almost to a confirmation of the adopted difference of longitude. The extreme difference between the four values at the different stations is seen to be, in the first set 1·8 m., and in the second set 0·7 m. And the differences between the separate values at each station are severally 0·4 m., 1·2 m., 1·0 m., and 0·3 m. Now the latter differences, which may be taken to indicate the amount of accidental irregularity in the values, bear a considerable proportion to the differences between the values at the separate stations (1·8 m. and 0·7 m.), so that these differences are probably wholly accidental. Again, the mean of the first four values is +0·1 m., and of the last four 0·0 m., showing on the whole no real difference. All this indicates that at Greenwich, Pawlowsk, Mauritius, and Bombay the magnetic impulse would appear to be really simultaneous, or at any rate that the variations between the observed deviations at these places afford no trustworthy evidence against such conclusion.

We come thus to an interesting result. The magnetic impulse over that portion of the earth's surface covered by the places last mentioned would evidently appear to be, on the whole, simultaneous; although whether, in like manner, simultaneous over the whole earth

we cannot say. But, considering the inadequacy of our present registering apparatus to ensure in all cases the necessary accuracy of time indication, it becomes a question whether the coincidence may not be generally closer than present means will enable us to measure. To determine this with precision would, however, require some modification of the apparatus now in general use.

The circumstance that the sudden magnetic movements of the character here discussed appear to be so nearly, if not absolutely, simultaneous over the whole earth becomes, if established, a striking physical fact. In numerous cases the disturbance, commencing suddenly, and continuing for many hours, follows on a state of comparative magnetic calm. How is the sudden change to a state of activity brought about, and what is the influence that so instantaneously disturbs the magnetic condition of our globe? The magnetic movements at Greenwich at such times are always accompanied by corresponding earth currents, which, similarly following a state of calm, become at once active, precisely at the commencement of the magnetic disturbance. It is believed that a similar effect is produced at other places, and that this is so is, in some cases, specially mentioned. Some sudden action, apparently from without, sets up, as it seems, both earth current and magnetic activity simultaneously, or nearly so, over the whole earth. It is to be noted that magnetic and earth current disturbance at Greenwich is, on the whole, more frequent in spring and autumn, when, in its diurnal revolution, the whole surface, or nearly the whole surface, of the earth becomes, during each twenty-four hours, exposed to the sun, as though the earth in some way contributed to the production of the phenomena observed, a given external influence appearing to cause at these times a greater activity than at other parts of the year. For magnetic disturbance rises and falls generally with the existence of more or fewer sun spots, in which variation we do not expect to find an annual period. Without, however, discussing further the production of, or relation between, magnetic disturbances and earth currents, on which something will be said in a later part of this paper, we will proceed to offer some particulars more nearly concerning what has gone before.

In asking for corresponding times of magnetic movement at the places mentioned in Table I, request was also in each case made for information on the direction and character of the magnetic movement, and many interesting particulars were thus supplied. It is not proposed on the present occasion to treat these details numerically, but rather to group them in such a way as to show, in a simple and ready manner, the direction of the magnetic movements at each place on the several days. The results are given in Table III, in which the sign + indicates that the north end of the declina-

tion magnet was drawn towards the west, the north end of the horizontal force magnet towards the north, and the north end of the vertical force magnet downwards; the sign − indicating in each case the opposite movement. At Mauritius, Batavia, and Melbourne, at which places the south end of the needle dips, the sign + indicates that the south end of the vertical force magnet was drawn downwards. In the absence of definite information, this is presumed to apply also to Cape Horn, at which the south end also dips. The movement in horizontal force appears to have been in general the most significant. At the stations in tropical regions the movements in declination and vertical force were usually small.

The table gives an interesting synopsis of the direction of magnetic movement in the several cases, and the general similarity of movement at each station on different days. Thus the movements in the three magnetic elements on different days at Cape Horn, Bombay, Batavia, and Zi-ka-wei were, so far as information is available, in each case similar throughout, and, with one or two exceptions, also at Greenwich, Pawlowsk, and Mauritius; at Melbourne there were variations, and at Toronto, for which place information in regard to the declination change only was received, there were also variations. At Greenwich the increase in all elements was always accompanied by earth current of one character as respects direction of current, the instances of decrease in the magnetic elements being accompanied by earth current of opposite character.

The general, indeed remarkable, similarity in the character of the initial magnetic impulse on different days at the several places, considered in connexion with the coincidence in time, indicates the advent in these cases of some powerful disturbance or sudden shock influencing the magnetism of the whole earth nearly always in the same way, an influence in which the earth becomes, as it were, at once involved, a state of general magnetic calm being at all places immediately converted into a state of magnetic activity. Whether these magnetic movements occur more frequently when any particular region of the earth is turned towards the sun is a question that the selected cases of Table I, with the additional instances to be found in Table IV, are too few to determine; but this point may receive elucidation from a more extended inquiry which the many years of Greenwich records will readily afford, and with which object some tabulation thereof has been already made.

Our inquiry has been confined to a consideration of the initial magnetic movements preceding disturbance. As pointed out, these movements occur simultaneously, both for the different magnetic elements and for all places. The character of the magnetic change is mostly similar at any one place on different days, but is not necessarily the same for all places; that is to say, the initial phenomena become, on

the different occasions, repeated at each station in a generally similar manner, but with the individual difference peculiar to the station. Disturbance having, however, once set in, it is found that, although the magnetic irregularity will be practically similar for places not geographically distant, as Greenwich and Kew, there is not the same complete similarity in the movements at places widely separated. The magnetic impulse at any moment during disturbance may, of course, be simultaneously propagated through the earth, as in the case of the initial movements; but it is not usually possible to fix on any phase of movement, and say to what phase it corresponds at another distant station, unless the movement is sudden, when the initial type again recurs, and such recurrence, occurring during disturbance at Greenwich, has been found to correspond with recurrence at other places. Generally it is only these cases of sudden, not necessarily large, movement, occurring at the beginning or during a magnetic disturbance, that we can readily identify as being really simultaneous and corresponding movements.

Reference has been made to the earth currents always so active during magnetic disturbance. Mr. C. V. Walker, formerly telegraph superintendent of the South Eastern Railway, in a paper read before the Royal Society in the year 1861, came to the conclusion, from observations made on the telegraph lines under his control, that earth currents, at least at times of great magnetic disturbance, exercised a direct action upon magnetomoters, just as artificial currents confined to a wire exercise a direct action upon a magnet. Two insulated lines of wire were afterwards established in connexion with the Royal Observatory, one passing from the Observatory to Dartford, the other from the Observatory to Croydon, expressly for the study of earth currents. The distance between the earth plates in the Dartford circuit was 10 miles, and in the Croydon circuit 8 miles. Sir George Airy, discussing the earth currents observed in these lines during the years 1865 to 1867 ('Phil. Trans.,' vol. 158, p. 471), confirmed generally Mr. Walker's result, considering that "it is impossible to avoid the conclusion that the magnetic disturbances are produced by terrestrial galvanic currents below the magnets;" but there were some anomalies, the earth current appearing, in some cases, distinctly to follow the magnetic motion, instead of being coincident with, or preceding, it, as, on the supposition mentioned, should always happen, and in other cases preceding it by a longer interval of time than the conditions seemed to require.

In the year 1868 the earth current lines to Dartford and Croydon were replaced by two others running, one from near Morden College, Blackheath, to the North Kent East Junction of the South Eastern Railway (distance between earth plates $2\frac{1}{2}$ miles), and the other from Angerstein Wharf (on the bank of the River Thames, near Charlton)

Table III.—Observed Direction of First Movement for the Magnetic Elements of Declination, Horizontal Force, and Vertical Force for the 17 days given in Table I, and for the 5 days on which there are corresponding records for Cape Horn. (It was remarked on all occasions at Toronto, and on various occasions at Greenwich and Pawlowsk, that there was a preceding movement, usually small, in the direction opposite to the direction given in the table as that of first movement.)

No. for reference.	Civil day.	Magnetic element.	Name of place, and direction of magnetic movement.								
			Toronto.	Cape Horn.	Greenwich.	Pawlowsk.	Mauritius.	Bombay.	Batavia.	Zi-ka-wei.	Melbourne.
1	1882. April 16....	dec.	—	..	+	+	—	+	..	—	+
		h.f.	..	..	+	+	+	+	..	+	—
		v.f.	..	..	+	+	..	—	..	..	+
2	April 20....	dec.	—	..	+	..	..	+	+	—	+
		h.f.	..	..	+	..	..	+	+	+	—
		v.f.	..	..	+	..	..	—	—	..	+
3	June 15....	dec.	—	..	+	+	+	+	+	—	+
		h.f.	..	..	+	+	+	+	+	..	+
		v.f.	..	..	+	+	..	—	—	..	—
4	Aug. 4....	dec.	—	..	+	..	—	+	+	..	..
		h.f.	..	..	+	..	+	+	+	+	..
		v.f.	..	..	+	..	+	—	—	..	..
5	Sept. 12....	dec.	..	..	+	+	—	+	+	—	+
		h.f.	..	..	+	+	+	+	+	+	+
		v.f.	..	..	..	+	+	—	—	—	—
6	Oct. 2....	dec.	+	+	+	+	—	+	+	—	+
		h.f.	..	+	+	±	+	+	+	+	+
		v.f.	..	—	..	..	+	—	—	—	—
7	Nov. 17....	dec.	+	..	—	±	—	+	+	—	—
		h.f.	..	..	—	+	..	+	+	+	+
		v.f.	..	..	—	±	..	—	—	—	—
8	1883. Feb. 24....	dec.	—	+	+	+	..	+	..	—	..
		h.f.	..	..	+	+	+	+	..	+	+
		v.f.	..	—	+	+	+	—	..	..	—
9	April 3....	dec.	+	+	—	—	+	+	+	..	—
		h.f.	..	+	—	+	+	+	+	+	+
		v.f.	..	..	—	—	+	—	—	—	—
10	July 29....	dec.	—	+	+	+	—	+	+	—	+
		h.f.	..	+	+	+	+	+	+	+	—
		v.f.	..	—	..	..	+	—	—	..	—

Table III—*continued.*

No. for reference.	Civil day.	Magnetic element.	Name of place and direction of magnetic movement.								
			Toronto.	Cape Horn.	Greenwich.	Pawlowsk.	Mauritius.	Bombay.	Batavia.	Zi-ka-wei.	Melbourne.
11	1883. Sept. 16....	dec.	—	..	+	+	—	+	+	..	—
		h.f.	..	..	+	+	+	+	+	..	+
		v.f.	..	..	+	—	+	—	—	..	..
12	1884. July 2....	dec.	..	..	+	+	±	+	+	..	—
		h.f.	..	..	+	+	+	+	+	+	+
		v.f.	..	..	+	+	+	—	—	—	..
13	Oct. 1....	dec.	+	..	+	+	—	+	+	..	—
		h.f.	..	..	+	+	+	+	+	+	+
		v.f.	..	..	+	+	+	—	—	..	..
14	1885. June 24....	dec.	—	..	+	+	—	+	+	—	..
		h.f.	..	..	+	+	+	+	+	+	+
		v.f.	..	..	+	..	+	—	—	..	..
15	1886. Mar. 30	dec.	+	..	±	..	±	+	+	..	+
		h.f.	..	..	±	..	+	+	+	..	+
		v.f.	..	..	±	..	+	—	—	..	—
16	1888. Oct. 30....	dec.	—	..	+	+	..	+	+	..	..
		h.f.	..	..	+	+	..	+	+	+	+
		v.f.	..	..	+	..	+	—	—	..	..
17	1889. July 17....	dec.	—	..	+	+	+	+	+	—	+
		h.f.	..	..	+	..	+	+	+	+	+
		v.f.	..	..	+	..	+	—	—	—	..

± indicates that the direction of first motion was doubtful.

.. indicates that no information was received, or that there was no record, or (in a few cases) that the change was small.

to Lady Well, Lewisham (distance between earth plates 3 miles): these positions being selected in order that the recording apparatus at the Royal Observatory, through which the wires passed, should be nearly in the middle of the straight lines joining the respective earth plates. Now it has been mentioned that the instances of sharply-defined magnetic impulses contained in Table I were all accompanied (in the just-described newer earth current lines) by active earth currents, in themselves just as sharply defined. The distinctive character and generally isolated position of these magnetic and earth current movements thus afford a peculiarly favourable opportunity for investigating any relation that may exist between them, much more so than

would any attempt to discuss movements of a mixed or involved nature, and it is found that motions of the declination and horizontal force magnets for the instances contained in Table I are, without exception, in direction such as would be produced by the action of a current passing through a wire under the magnet, similar to that of the actual accompanying earth current.

But then comes a further question:—Do earth current and magnetic times really agree? For in the discussion of the Dartford and Croydon earth current records, the earth current on some occasions, according to the instrumental time scales, seemed undoubtedly to follow the magnetic movement, instead of being coincident with, or preceding, it. But the system on which the time scales were in those days laid down was not arranged with a view to the accurate measurement of small intervals of time, and in this respect did not permit of an accuracy equal to that to be obtained from later registers, on which a time indication is made at every individual hour. Thus we are now able to effect a much more certain comparison of the times of magnetic and earth current movement than was before possible. This has been done for a considerable number of instances of sudden initial movement, including all those of Table I (excepting 1882, April 16, on which day the earth current register was defective), and also a number of others, the whole particulars being given in Table IV.

When it is considered that each separate difference in this table includes the sum of the errors of two time measures from photographs having a time scale in which one minute corresponds to about 0·01 inch, the agreement of results, it will be seen, is very good. Every case selected for measurement is given; nothing has been rejected. The variation between individual differences does not exceed in amount that which may well be expected, with a time scale so contracted, and would appear to be simply due to unavoidable errors of measurement. The mean of the 31 differences is −0·14 m., equivalent to 8 sec., or, dividing the 31 differences into three groups of 11, 10, and 10 values respectively, the means of these groups are found to be −0·19 m., −0·12 m., and −0·10 m., equivalent to 11 sec., 7 sec., and 6 sec. respectively, thus persistently showing the earth current to precede by a few seconds the magnetic movement. Not that these results should be taken too strictly, but simply as showing, when definite comparison can be made, that the coincidence of time is really very close, possibly more so than present existing means will permit us to determine. This so far removes the before-mentioned time anomaly, the observed facts being now seen to be altogether consistent with the supposition that earth currents may produce the magnetic movements, whether or not, as regards cause and effect, this be the true relation. For it has to be remembered that in

Table IV.—Comparison of the time of commencement of Magnetic Movement with the appearance of Active Earth Current, preceding Magnetic Disturbance, at Greenwich.

Greenwich civil time of commencement of magnetic movement.					Minutes of corresponding earth current.	Excess of the latter.	Greenwich civil time of commencement of magnetic movement.					Minutes of corresponding earth current.	Excess of the latter.
		d.	h.	m.	m.	m.			d.	h.	m.	m.	m.
1880.	Aug.	11	10	18·4	20·0	+1·6	1882.	Nov.	25	16	28·0	28·0	0·0
		12	11	37·7	35·0	−2·7	1883.	Feb.	24	13	41·7	41·0	−0·7
1881.	Jan.	30	19	41·5	40·0	−1·5		April	3	9	1·0	1·0	0·0
		31	8	37·4	38·0	+0·6		June	30	5	14·7	13·0	−1·7
1882.	April	20	3	35·7	37·0	+1·3		July	29	23	46·5	47·0	+0·5
	June	15	3	4·7	4·0	−0·7		Aug.	15	9	50·0	49·0	−1·0
	Aug.	4	5	50·0	50·0	0·0		Sept.	16	2	42·0	43·0	+1·0
		4	15	48·7	48·0	−0·7	1884.	July	2	19	15·3	16·0	+0·7
	Sept.	11	22	41·0	40·0	−1·0		Oct.	1	21	50·3	51·0	+0·7
		12	2	53·5	54·0	+0·5	1885.	June	24	22	31·0	31·0	0·0
	Oct.	2	9	39·5	40·0	+0·5			25	3	41·7	42·0	+0·3
	Nov.	11	23	17·3	17·0	−0·3	1886.	Mar.	30	8	22·7	22·0	−0·7
		15	8	14·7	13·0	−1·7	1888.	Oct.	30	19	44·7	44·0	−0·7
		16	8	17·3	17·0	−0·3	1889.	July	17	4	50·0	49·0	−1·0
		17	10	20·0	23·0	+3·0	1891.	Mar.	2	1	49·3	49·0	−0·3
		19	12	43·0	43·0	0·0							

magnetic disturbances the variations of vertical force, which are sometimes very great, have also to be considered, as well as those of declination and horizontal force. But even admitting the supposition to be correct, there remains for consideration the question as to how the diurnal magnetic variations are produced.

Magnetic disturbances and irregular magnetic motions of every kind are always accompanied at Greenwich by earth currents more or less powerful, the correspondence being most complete, as may be seen in the engraved copies of magnetic and earth current movements given since the year 1882 in the annual Greenwich volume. The diurnal magnetic variation of declination or horizontal force, on the other hand, which (when there is no accidental magnetic irregularity) consists principally of one bold daily sweep, has no corresponding earth current, being accompanied principally by alternating currents, weak in character, and generally of short period. That is to say, a sudden magnetic movement of an amplitude no greater than that of the undisturbed diurnal curve (comparing one part of the day with another) will be accompanied by active earth current, whilst the bold sweep of the undisturbed diurnal curve has no marked earth current counterpart, but only fluctuations of feeble character. The amplitude of the diurnal magnetic variation may be greater than the motion in many of the cases of movement included in Table I, but the earth current in the former case would be insignificant, whilst in the latter it is most marked. Irregularity in magnetic action and activity of earth current are correlative phenomena, rising and falling together in intensity, earth current activity indicating irregularity of magnetic movement or magnetic storm, superposed on, and, indeed, frequently masking, the ordinary diurnal curve.

The assumption that the magnetic movements in a magnetic storm are due to action of the accompanying earth currents thus appears not to be one that will explain the ordinary diurnal magnetic variation, as, indeed, Sir George Airy had previously found ('Phil. Trans.,' vol. 160, p. 226) from discussion of the earth currents observed in the old Dartford and Croydon earth current lines. The phenomena have, indeed, different characteristics. The period of the diurnal magnetic variation is the solar day, and the principal sweep in the curve occurs whilst the sun is above the horizon. Magnetic irregularities, on the other hand, and their accompanying earth currents, appear at any moment. Although both probably solar in origin, they are not produced in the same way. The diurnal variation progresses gradually, the principal phase occurring successively at different places, as they become turned towards the sun, but magnetic irregularities arise suddenly and simultaneously at all places. The special characteristics of the two classes of phenomena may be stated as follows :—

	Diurnal magnetic variation.	Superposed magnetic disturbance.
Characteristic.	One bold sweep progressing uniformly.	Irregular motions.
Occurs at different places.	Successively.	Simultaneously.
Earth current condition.	No corresponding earth current; only weak intermittent currents.	Active earth currents.

However bold the diurnal variation may be, so long as it progresses uniformly, the earth currents remain fluctuating and feeble, and apparently cannot produce the long sweep of the diurnal curve. But if any magnetic irregularity arises, a corresponding earth current at once appears. It was pointed out with respect to the magnetic movements on the selected days (Tables I and III), that the earth currents observed at Greenwich in connexion therewith always had a definite relation with the motions in declination and horizontal force. This, taken in connexion with the coincidence in time (Table IV), certainly suggests mutual relation. But, in view of the circumstance that the diurnal magnetic variation does not appear to depend on earth current, can we suppose that it may be otherwise with the irregular magnetic motions, and that they are produced by earth currents? When a magnetic storm arises the earth would appear to become as a whole instantaneously affected, necessarily, it would seem, from without. Is it that both classes of phenomena, irregular magnetic variations and earth currents, are produced by independent action, and that any mutual relation, if existing, is of secondary character. In the Greenwich registers the variations of horizontal force, during periods of magnetic disturbance, follow with surprising closeness the accompanying earth current variations, the turning points being in a very remarkable degree simultaneous. But, after the initial movement, there is not a similar resemblance as regards declination changes. And how are the variations of vertical force produced? Can there be here any relation with earth currents?

The general direction of strongest earth current at Greenwich at the present time is one not very different from that of the line joining the Angerstein Wharf—Lady Well earth plates. Does this direction of strongest earth current depend on geological formation, or is it slowly variable, as are the magnetic elements? If not variable, the earth current influence on the declination and horizontal force magnets, if such influence exists, would be different when the direction of the magnetic meridian has greatly changed. This is a point the study of which might in the course of time throw considerable light on the relation between magnetic and earth current irregulari-

ties, in regard to which there is yet much to learn. It would tend to help this, as well as other inquiries concerning earth current phenomena, if at some of the magnetic observatories in different parts of the world, the magnetic registers were supplemented by a registration of earth currents, as a regular part of the daily work.

The comparison of the times of magnetic impulses with those of the corresponding earth currents, Table IV, gave, as a mean result, that, at Greenwich, the magnetic impulse, on the whole, followed the earth current by some few seconds. To determine more exactly and with greater certainty, and especially in individual cases, what may really be the interval, if appreciable, between the phenomena would require apparatus designed to indicate simultaneously and measure accurately much smaller intervals of time than is at present possible. This leads us to mention a difficulty that affects the registration of magnetical and meteorological phenomena of all kinds, and one not readily overcome. To obtain continuous registration of any element a contracted time scale is necessary, otherwise the accumulated registers would become overwhelming, neither is an extended time scale, under ordinary circumstances, required. But on occasions of disturbance or storm, whether magnetic or atmospheric, it becomes desirable to possess the power of greatly increasing the extent of the time scale, in order to obtain, not only a more accurate time indication, but also a better record of the details of phenomena. The difficulty becomes increased because of the uncertainty of the advent of any special phenomenon of which fuller particulars would be desirable. Still, if it were possible to provide means of easily changing the speed of movement of a register, much valuable information might be gained.

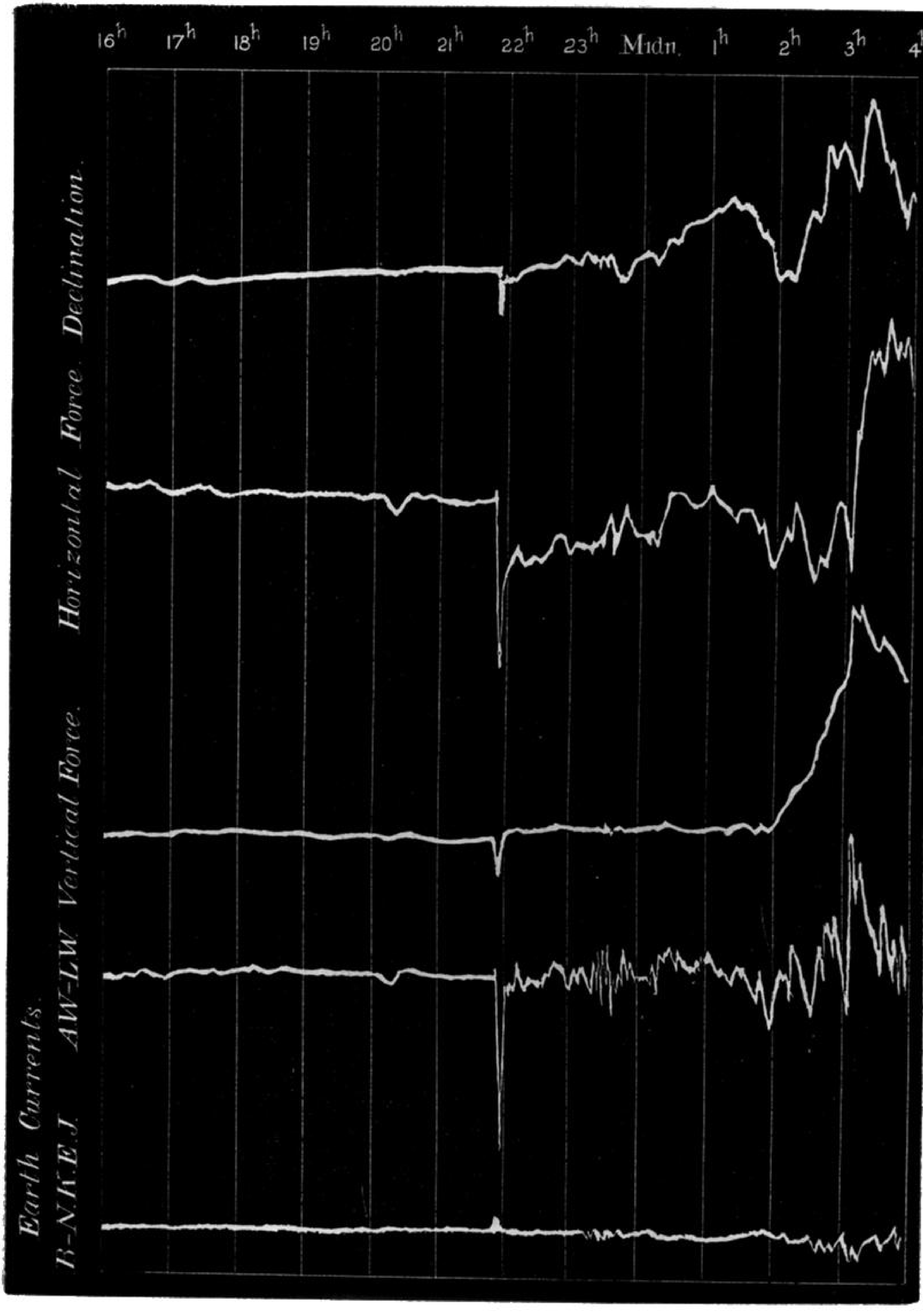
In recapitulation of the results which may be considered to have been arrived at in this paper, we may remark that, though it was known that magnetic storms were felt generally at the same time over wide areas of the earth's surface, it had not been ascertained that any magnetic movements were so entirely coincident at different places as now appears, at any rate so far as concerns the initial magnetic impulses that precede disturbance, and which, it would seem, really occur at the same instant of time, or nearly so, over the whole earth. It appears also, in addition, that the change that takes place at such times in the earth's magnetic condition is, on all occasions, in great measure of like character. A definite magnetic effect is produced suddenly and simultaneously, in which the variations of the magnetic elements, whilst different at different places, are, on different occasions, locally similar, forming thus a type of the magnetic phenomena that, repeating itself usually in the same way, generally presages or introduces a magnetic disturbance or storm.

It has been further shown that at Greenwich the sudden magnetic impulses immediately preceding or commencing disturbance are concurrent in time with the sudden appearance in each case of an earth current, in advance by a few seconds of the magnetic impulse, and having always the same relation with the magnetic movements, increase of magnetic declination, horizontal force, and vertical force, being accompanied by a current in one and the same direction, and decrease of these elements by a current in the opposite direction. A like concurrence in time between such magnetic movements and earth currents is presumably true also for other places.

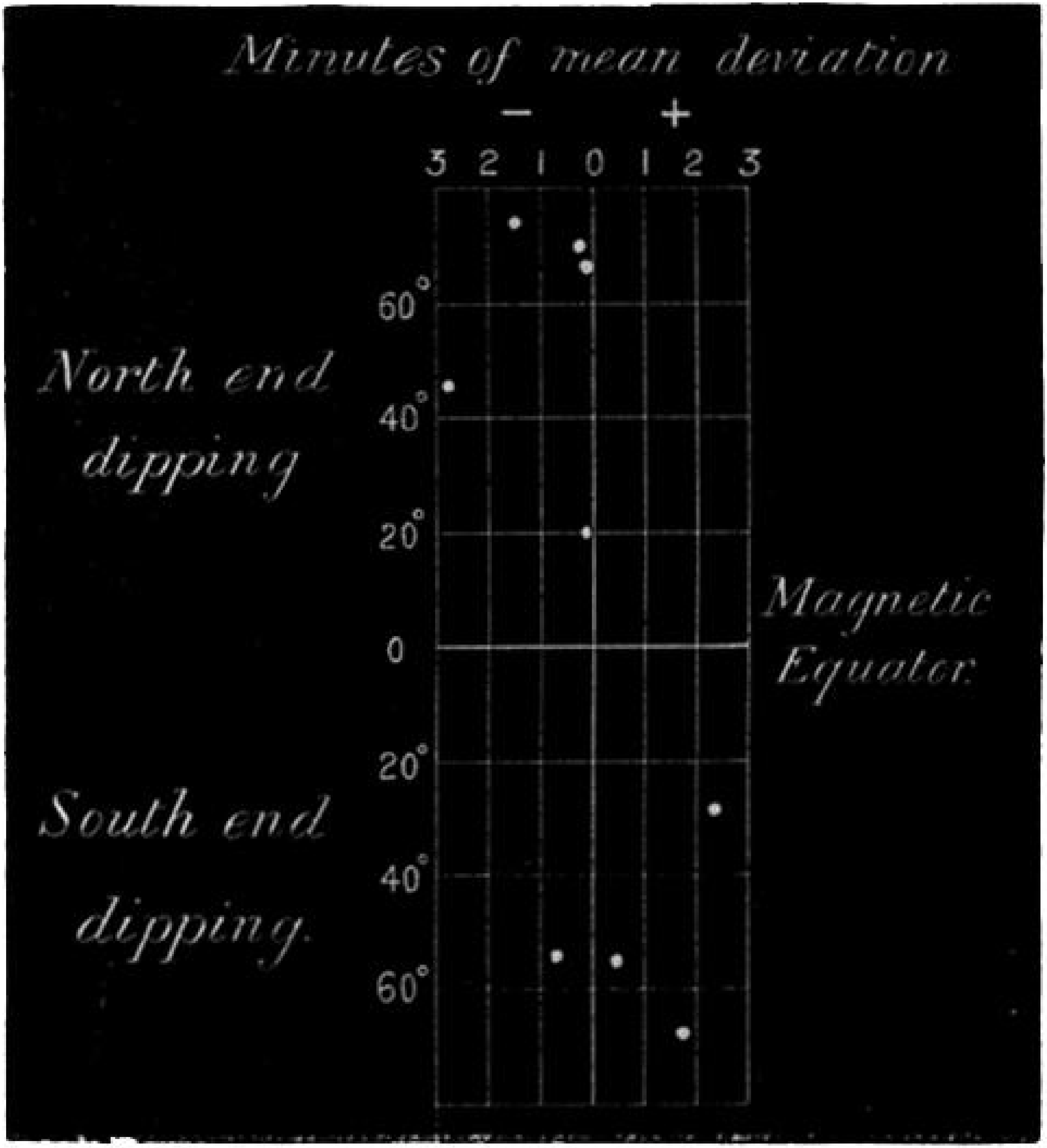
If the near time relation thus established between initial magnetic and earth current movements at Greenwich applies generally during the course of a magnetic storm, any difficulty as respects the assumption that the irregular changes of magnetic declination and horizontal force may be produced by the accompanying earth currents seems removed. But though the changes of horizontal force during a magnetic disturbance closely follow the earth current changes, those of declination do not show the same correspondence, and the variations of vertical force have also to be explained, in addition to which it would conclusively seem that the diurnal magnetic variation does not depend on earth current, since the bold sweep of this curve (when undisturbed) is accompanied by comparative earth current calm.

With reference to the comparison of times of magnetic impulses at different places, it does not seem probable that with existing apparatus any better result would be obtained by making comparison for an increased number of *days*. But it would be interesting, even with the present apparatus, to obtain corresponding times, if possible, for a greater number of *places*, in order more conclusively to determine whether the constant difference of time that appears to exist between some stations (Table II) is really a physical fact, or whether it may not be due to small systematic error in the individual registering apparatus. Registers on an extended scale, on the system mentioned in a preceding paragraph, would, however, be much more likely to give definite information on this point.

If this paper has added anything to the knowledge of a difficult subject, it will be felt that some labour has not been expended in vain.



Royal Observatory, Greenwich.—Copies of the Photographic Records of Magnetic Elements and Earth Currents from 1884, Oct. 1, 16h, to Oct. 2, 4h, Greenwich Civil Time.


Minutes of mean deviation
−
+
3 2 1 0 1 2 3
60°
40°
20°
0
20°
40°
60°
North end dipping
South end dipping.
Magnetic Equator.