THE MORPHOLOGY OF GEOMAGNETIC STORMS: AN EXTENSION OF THE ANALYSIS OF D_S, THE DISTURBANCE LOCAL-TIME INEQUALITY

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1. INTRODUCTION

This paper describes an extension of the series of analyses of the morphology of geomagnetic storms which I began in 1917. The first results were published ([2a]) in 1918, and were supplemented ([2b]) in 1927 by further results, particularly for weak magnetic disturbance and for the polar regions.

The present extended analysis was nearly completed in its present form in 1918, and its publication has been too long delayed; had the results appeared earlier a misconception (§ 6) would have been prevented, for which some words in my 1918 paper may be counted responsible.

The present extension of the method of analysis should have useful application also in the investigation of ionospheric storms.

2. MATERIAL

The data for the present paper form a part of that used in my 1918 paper ([2a]), and refer to the 40 moderate magnetic storms (1902-11) there discussed. Table 1 gives particulars (not previously published) for these storms, which were selected from those with sudden commencements, contained either in a list ([3]) compiled by E. W. Maunder (1904) from the Greenwich records up to 1903, or (for later years) from the publications of the U. S. Coast and Geodetic Survey for the observatories of Honolulu, Cheltenham (Maryland) and Sitka (Alaska). They were chosen as being all of moderate intensity. Table 1 and Figure 1 show that the storms were fairly uniformly distributed over the Greenwich day (Fig. 1*a*) (except for some excess near Greenwich midnight), and also throughout the calendar year (Fig. 1*b*); Fig. 1*c* shows the influence of the solar cycle on their distribution from year to year, and indicates the annual mean sunspot number for each year. Many of the storms were members of 27-day recurrences, as shown in the columns of N_d in Table 1.

TABLE 1

Data for 40 moderate magnetic storms, 1902-11; serial number *s*; *h* is the hour (G.M.T.) of commencement; *C* is the international daily magnetic character figure, multiplied by 10, for the day of commencement and the two following days; an asterisk * in the first column signifies that the day preceding the storm outbreak was specially quiet (*C* zero or 0.1); *Ns* is the number in the 27-day sequence containing the storm (taking $N = 1000$ for the sequence beginning on 1906 Jan 11); *Nd* is the number of the day of commencement in this sequence, or, when marked with *, the number of the following day.

Serial number s	Date of beginning	Initial hour h	Character figures C	Rotation number Ns	Day number Nd
1	02 May 8	12.0	10,15, 7	951	6
2	03 Apr 5	23.5	11,20, 7	963	15*
3	Aug 25	22.9	7,15, 8	968	22*
4*	Dec 13	12.5	20, 8, 7	972	23
5	Dec 30	3.2	15,17,12	973	13
6*	04 Apr 17	16.3	8,12,13	977	14
7	Aug 3	13.8	15,11, 5	981	14
8	Sep 24	19.5	8,19, 8	983	13*
9	05 Jan 3	23.7	3,10,19	987	6*
10	Jan 16	23.8	2,12,16	987	19*
11	Apr 1	1.1	19,11, 9	990	12
12	Jun 5	1.9	12,10, 4	992	23
13	Jul 5	21.6	7,15,10	994	0*
14	Aug 2	0.5	18,12, 8	995	0
15	Nov 12	8.1	20,15,10	998	21
16*	Dec 12	2.9	11,12, 6	999	24
17	06 Feb 18	22.5	6,17, 4	1002	12*
18	May 13	20.7	7,11.16	1005	15*
19	Jul 29	19.9	12.15, 8	1008	11*
20	07 Jan 11	8.8	8,16,10	1014	13
21	Jan 14	19.6	14,13, 7	1014	17
22	Mar 10	5.0	17.13,17	1016	18
23	Mar 21	13.4	17.13, 4	1017	2
24	May 18	14.0	14,14, 9	1019	6
25	Jul 10	14.4	14,16, 8	1021	5
26*	Sep 10	1.8	17,12,12	1023	13
27	Oct 13	7.7	18,18,15	1024	19
28*	Nov 21	10.7	18,12, 5	1026	4
29	08 Aug 19	0.2	16, 4,16	1036	6
30	Aug 21	8.6	16,10, 3	1036	8
31	Nov 17	1.0	17,10, 5	1039	15
32	09 Mar 18	9.5	13,18, 7	1044	1
33	Mar 26	12.3	11,13,15	1044	9
34	May 18	5.1	18,14, 5	1046	8
35	Sep 21	11.3	15, 9, 3	1050	26
36	Sep 30	4.0	18, 6,12	1051	8
37	Oct 23	0.0	17,16, 9	1052	4
38*	10 Oct 19	7.2	16,13,13	1065	14
39	11 Mar 20	0.8	19.17.12	1071	4
40	Apr 8	11.3	15,17,12	1071	23

The data here used for these storms refer to eight observatories (here numbered 1 to 8) in geomagnetic latitudes not exceeding 50° (See Table 2); their spacing in longitude is illustrated in Fig. 1*d*. In my 1918 paper I considered also four observatories in higher latitudes, Greenwich (9), Potsdam (10), Pavlovsk (11) and Sitka (12).

TABLE 2

Geographic (gg) *coordinates and geomagnetic* (gm) *latitude*

	Latitude gg	Latitude gm	Longitude (gg)	
			Angle	Time
1. Batavia	6° S	18° S	107° E	7h.1 E
2. Porto Rico	18 N	30 N	65 W	4 .4 W
3. Honolulu	21 N	21 N	158 W	10 .6 W
4. Zikawei	31 N	20 N	121 E	8 .1 E
5. San Fernando . . .	36 N	41 N	6 W	0 .4 W
6. Baldwin	39 N	49 N	95 W	6 .3 W
7. Cheltenham (Md.) . .	39 N	50 N	77 W	5 .1 W
8. Pola	45 N	45 N	14 E	0 .9 E

My 1918 paper dealt with all three magnetic elements; the present results mainly refer to *H* the horizontal intensity, and *E* the easterly deviation (reckoned in gamma) from the mean compass direction; in addition some results are given for the vertical component (*V*, always reckoned positive, or *Z* if reckoned positive when downwards and negative when upwards).

The data used for each observatory and element were entered on « storm-time » Tables A, each containing 40 rows (one for each storm, $s = 1$ to $s = 40$) and 49 columns, $n = 0$ to $n = 48$ (in some cases there were blank or incomplete rows where the storm data were lacking or incomplete). The column 0 referred to an epoch shortly before the storm began, the later columns referred to epochs at successive later hourly intervals, after the storm had commenced; thus 2 days' data were used for each storm.

The *entries* in the Tables A were derived from the published tables of hourly values of the elements, and consisted of these values *less* the mean value of the element for the month in which the storm began; that is, they were *departures* from the monthly mean. The published hourly values were either instantaneous values, or (e. g. for Potsdam from 1905) means over an hour; they referred to local mean time or to standard zone time. For each observatory the list of Greenwich times of storm commencement (Table 1) was converted into a list of times of commencement given in the time-reckoning used at the observatory. Where instantaneous hourly values were given, the mean epoch for all the entries in column 0 of Table A would be

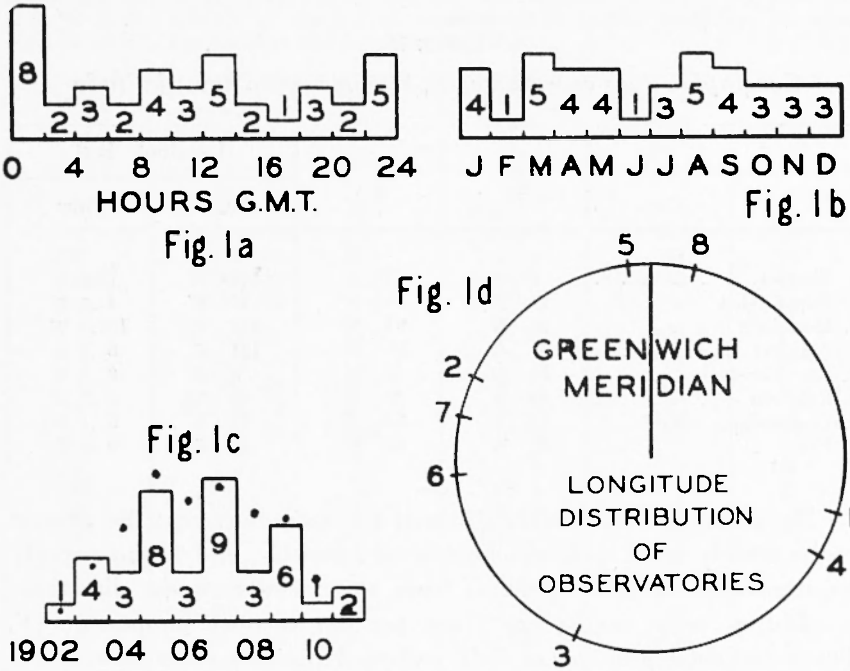

Fig. 1 - The distribution of the commencement times of 40 moderate magnetic storms, over (a) the Greenwich day, (b) the year, and (c) the sunspot cycle; and (d) the longitude distribution of the 8 observatories considered in this paper.

approximately half an hour before the mean time of storm commencement; where the published data were hourly means, the corresponding interval was approximately one hour, because the mean epoch to which the published value referred had to precede the storm commencement by at least half an hour. Over the period 1902-11 most of the observatories considered in this paper gave instantaneous values.

3. THE METHOD OF ANALYSIS

a) The storm-time variation D_{st}. — The method of analysis, already previously applied by N. A. F. Moos [1] to the Bombay data, was very simple. On each Table A, the mean was formed of all the entries in each column n; incomplete rows were omitted (except where they could be completed by interpolation across short gaps) in taking the means of the columns. The sequence of these means gave what I called the mean *storm-time* variation for the element and observatory; later I denoted it by D_{st}. It is the mean variation with respect to *storm-time*, t_{st}, reckoned from the time of storm commencement. The means $n = 0$ to $n = 48$ referred to $t_{st} = -\frac{1}{2}, \frac{1}{2}, \ldots\ldots, 47\frac{1}{2}$, if the published data were instantaneous hourly values.

My 1918 paper gave graphs (*) of D_{st} for each element for three *groups* of observatories, namely (graph 1) Nos. 1-3 (mean geomagnetic latitude 23°), (graph 2) Nos. 4-7 (40°) and (graph 3) Nos. 8-11 (52°); $D_{st}(E)$, for east declination, was very small; the main D_{st} variation was for H, which increased in the first hour (by 13 gamma, the same for all three graphs), and then decreased (in graph 1) by about 50 gamma from the maximum (and by about 40 gamma in the third graph); the minimum was reached at about $t_{st} = 15^h$. Thereafter there was a slow recovery towards normal; the recovery was far from complete at the end of the two days considered. In V the D_{st} variation was similar but reversed (an initial decrease was followed by an increase); its range was much smaller, about 8 gamma in graph 1.

For the 8 observatories (numerical (**) mean geomagnetic latitude 34°) considered in this paper the mean $D_{st}(H)$ is given in Fig. 2: the values for the hours 9 and later are smoothed by overlapping means of five.

b) *The local-time variation.* — The next step was to form from the Tables A new « local-time » Tables B, two (B_1, B_2) for each element and observatory, each with forty rows (one for each storm, as before,) and with columns headed $m = 1$ to $m = 24$, referring to hours of *local-time* at the observatory. In forming the Tables B the first (pre-storm) values in the Tables A were ignored. In the case of the Tables B for the elements E and V, the entries in row s were the same, except as regards order, as those on row s of Table A; if h_0 is the local hour of the first (pre-storm) entry, $n = 0$, for storm s at the observatory considered, the local hour of the entry on Table A in column n of the row s is $h_0 + n$, less 24 if $h_0 + n > 24$, or less 48 if $h_0 + n > 48$; the 24 entries, $n = 1$ to $n = 24$, of Table A, row s,

(*) These have been reproduced in *Geomagnetism*, p. 276, and in *The Earth's Magnetism*, Chap. 5, and elsewhere.

(**) That is, the mean when N and S latitudes are alike reckoned as positive.

were re-written in row s of Table B_1 in their appropriate local-time columns $h_o + n$ (or $h^o + n - 24$); and the last 24, $n = 25$ to $n = 48$, were similarly re-ordered on row s of Table B_2.

In the case of the Tables B_1, B_2 for H, before the reordering and entry of each hourly value according to its local time, the mean D_{st} value at the foot of column n of Table A was subtracted from all the entries in that column, thus eliminating $D_{st}(H)$ from the

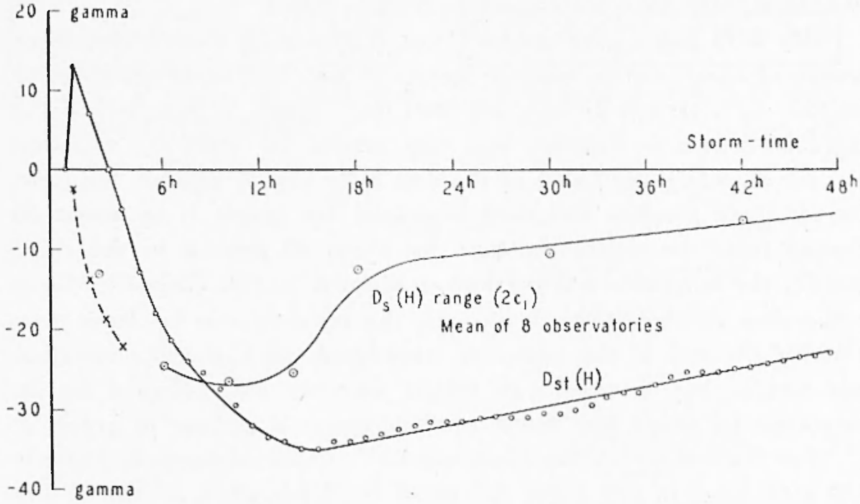

Fig. 2 - Graph of Dst (H), the average storm-time variation of H during the first two days of 40 moderate magnetic storms; mean for 8 observatories in (numerical) mean geomagnetic latitude 34°. Also the corresponding graph of $2\ c_1$, the range of the diurnal component of $D_s(H)$.

Tables B; in the case of E and V, this was not considered necessary, because D_{st} in these elements is small.

The mean of the entries in each column m on the Tables B was calculated; the sequence of means indicated a well-marked variation according to the local time, different for each element H, E, V; for each element the variation showed a regular gradation from one observatory to another, with respect to change of magnetic latitude, but seemed to depend little on the longitude.

The daily variations thus found clearly differed from those characteristic of ordinary or quiet days (now denoted by S_q), which however, seemed still to he present, though overlaid with an additional variation.. In order to isolate the latter, S_q was removed from the variations given by the Tables B. This was done by forming new Tables C, one for each element and observatory, each containing 40 rows ($s = 1$ to $s = 40$) and 24 columns ($m = 1$ to $m = 24$). In each row s was written the series of monthly mean hourly departures from the monthly mean, for the month in which storm s began. In the few cases where a month had two storms, the series was repeated on sheet C. The mean for each column gave the mean solar daily variation to be subtracted from the corresponding sequence of hourly means in the Tables B_1 and B_2 for the same element and observatory (it would have been better to base Tables C on the quiet day monthly mean hourly departures, but the change would not alter the present work very much).

The daily variation found from Tables B_1 or B_2 and C in this way was called the *disturbance daily variation*, and later denoted by S_D. In my 1918 paper graphs (*) of S_D in H, E and V (or Z) were given for the observatories Nos. 1-3 (mean), 4-7 (mean), 8-10 (mean) and for 11, 12 separately. The curves were all substantially diurnal in character, that is, they had one main maximum and one main minimum daily, with the 24-hour harmonic component dominant; they were quite different from S_q. The variations derived from Tables B_1 and B_2 may be denoted by S_{D1} and S_{D2}; the S_{D2} variations were similar to S_{D1} in type, but were of smaller range.

In H, S_D is approximately anti-symmetrical with respect to local noon: its amplitude decreases with increasing latitude up to about 53° magnetic latitude, where $S_D(H)$ changes sign, the change being made rapidly over a narrow belt of latitude. At all the 8 observatories considered in this paper its sign was the same, so that it is suitable to take the average $S_D(H)$ for all 8 as indicating the type of this variation.

In E and Z, S_D is reversed on crossing the equator, but otherwise retains the same phase (not the same for E as for Z) at least up to magnetic latitude 60°. Hence, if the S_D variations for Batavia E and Z are reversed, so as to bring them into phase with those for the northern stations, the mean $S_D(E)$ and $S_D(Z)$ can usefully be taken, for the 8 observatories here considered, to illustrate the type of S_D over their range of latitude. This was the procedure adopted.

4. THE CHANGING AMPLITUDE OF S_D

The decrease in amplitude of S_{D2} as compared with S_{D1} is analogous to the decline in D_{st} in the second as compared with the first

(*) These have been reproduced in *Geomagnetism*, pp. 277, 278 (panels *b*, *c*), and in part in *The Earth's Magnetism* (2nd ed., pp. 45-47, panels *b* only), and elsewhere.

storm day. But whereas the method of analysis enables the change in D_{st} to be followed continuously — or at least from hour to hour — the change in S_D is given only from one day to the next, that is, in the mean, from storm-time $t_{st} = 12^h$ to $t_{st} = 36^h$.

Certainly the part of the storm field other than D_{st}, represented in my 1918 paper only in the form S_{D1} and S_{D2}, must, like D_{st}, vary continuously; by definition it is not present before the storm begins, and it must be expected to die away like the other manifestations of the storm. Thus it cannot be a true daily variation, S_q, particularly in the case of the most intense storms, whose whole active duration may be less than a day.

Nevertheless, in weak disturbance especially, as investigated [2-b] in my 1927 paper, this part of magnetic disturbance manifests itself as an addition to S_q, waxing and waning in intensity in rough parallelism with the degree of magnetic activity; in this form the name *disturbance daily variation* and the symbol S_D are appropriate. This term and symbol will be used in reference to the difference between the solar daily variation (S) as derived from disturbed days (S_d) or all days (S_a), and S_q.

5. THE DISTURBANCE LOCAL-TIME INEQUALITY D_S

When, however, the variation considered is obtained in the way described above, for a day (first or second) of a storm (or group of storms) having a definite beginning and a limited duration, a different name and symbol seem more appropriate, and I adopt the name *disturbance local-time inequality*, and the symbol D_S; here D, as in D_{st}, denotes disturbance, and S refers to position relative to the meridian containing the sun, as measured by the local time. The main reason for the distinction between S_D and D_S is that S_D is (by definition) the difference between two variations both definitely daily, involving 24 hours of time; whereas D_S, as will appear, can be determined from smaller intervals of time, and even from individual hours or instants of storm time. When, as described above, 24 hours of storm-time are used to determine D_S, the entries on each row of the Tables B are not consecutive, except for storms for which the pre-storm local hour h_0 is zero; in other cases the first $24 - h_0$ values come at the end of the row s on Table B_1, and the next h_0 values come at the beginning of the row.

Like D_{st}, D_S is regarded as a function of t_{st}, and in addition D_S, at any instant t_{st}, depends on the local time at that instant at each station; as the local time is here to be considered as a geometrical parameter, giving the longitude of each station relative to the sun, it will be denoted by λ_s. Whereas D_{st} represents the part of the storm field obtained by averaging the field, at each instant t_{st}, all round each circle of latitude, D_S gives the average difference between the instantaneous storm field and this longitudinally averaged field (symmetrical about the earth's axis); to obtain D_S it is of course necessary to consider enough storms to remove the influence of the irregular features peculiar to individual storms.

This was clear to me in 1918, and at that time I particularly wished to know whether D_S was opposite in sign, like D_{st}, during the initial phase of the storm, as compared with the main phase. Consequently I constructed new Tables B, on which were entered, according to their local time, magnetic values for shorter intervals of storm-time than one day. On the original Tables B_1 and B_2, each row contained 24 entries, and each average value at the foot of the columns was based on 40 values (or slightly fewer in some cases, owing to lack of an adequate record of some storms). If an interval of M hours of storm time is taken as the basis of a Table B_M, where M is less than 24, the number of entries in each row will be M (they will come in different columns for different storms), and the hourly means at the foot of the Table will be based on only $40M/24$ or $5M/3$ values. The smaller is this number, the more prominent will be the irregularities of the D_S sequence due to the accidental magnetic variations occurring in each storm. In order to be able to reduce M to 4, I decided to combine the B_M tables (for each element) for the 8 observatories above named; thus if $M = 4$, each hourly value in the resulting D_S sequence, based on 4 hours of storm time, and 8 observatories, is an average of $8 \times 5M/3$ entries, that is, 53. For each of the first four hours of the storm, however, separate B tables ($M = 1$) were made. To reduce the irregularities consequent on the small amount of data involved in the resulting sequences of averages, smoothing was used by overlapping means of five adjacent numbers, in the case of $M = 4$ (but not for $M = 1$).

This procedure was applied to the H and E data; for the Z data M was taken as 12, that is, for half days (of storm time).

The D_S sequences thus obtained were completed before the publication of my 1918 paper; owing to war conditions, that paper, which made no mention of those results, was already too long to be acceptable to the Royal Society, and the original draft was reduced by removing a part ([2-d]), later published elsewhere (1919). At the end of the war in 1918, changes of residence, work, and (for a time) interests, delayed the preparation of an account of the extension of the D_S results; gradually their existence became forgotten, and my 1927 paper did not mention them.

6. CRITICISM OF S_D AS NOT TRULY DIURNAL

In 1939 A. G. McNish and H. F. Johnston questioned the diurnal character of S_D, in the course of a study ([4]) of the severe magnetic storm of April 1938, which in its most active phase was much shorter than the 40 moderate storms I discussed. Their doubts were expressed tentatively, as follows.

« Thus one is led to doubt if the anti-symmetrical (S_D) field of great magnetic disturbances progresses according to local time. It may be that the 24-hour period assigned to S_D for moderate storms is purely adventitious. However, judgment on this matter must await the examination of a number of great storms » (p. 349).

Later in their paper they wrote: « Chapman has remarked that D_{st} progresses more rapidly during the greater magnetic disturbances than during the weaker or moderate ones, but presents strong evidence to show that S_D appears to preserve its 24-hour period. The implication that perhaps S_D in also accelerated during this very great storm must be regarded cautiously. The important change in our concepts of magnetic storms, if the conclusion were generalized, emphasizes the need for complete recording of great magnetic storms so that they may be suitably studied ».

Actually, as stated above, I had never myself regarded the matter in this light, though my terminology « residual diurnal variations » (1918) and « disturbance daily variation» (1927) might naturally mislead in this sense. The name is appropriate for the change in the solar daily variation during weak magnetic disturbance (as determined and examined in my 1927 paper), where no storm-time can be assigned because of the lack of a clear epoch of disturbance commencement; but during a storm in which t_{st} can be measured, the variation that I called S_D, and now, in that case, prefer to denote by D_S, represents a geographical distribution of the departure of the storm field from its average value (D_{st}) round each parallel of latitude. Both parts,

D_{st} and D_S, vary with the storm-time t_{st}. This conception was clearly envisaged also by E. H. Vestine and his colleagues [5] in their discussion of magnetic disturbance in Chapters 8 and 10 of their monumental « Description and Analysis » (1947).

Owing to the preoccupations of the second world war it was some years before I re-examined the questions raised [4] by McNish and Johnston; about 1950 I decided to use my original 1918 data to determine S_D or (D_S) at closer intervals; it was a pleasant surprise to find the long-forgotten results already available (and still accessible after over 30 years). The only remaining step was to make a harmonic analysis of the D_S sequences, for the diurnal and semidiurnal components. This was begun by Drs. P. K. Bhattacharya and Wan Cheng Chiu while working with me at the California Institute of Technology, Pasadena, in 1950/1, under a U. S. Signal Corps contract; it was completed in 1952 by D. C. Wilder of the Geophysical Institute of the University of Alaska. The amplitudes were corrected to allow for their reduction by the smoothing process used in the case $M = 4$ (§ 5).

The D_S variations were expressed in terms of local time λ_s, that is, of longitude relative to the sun, measured eastwards from the midnight meridian (opposite to the noon meridian, in the half plane which passes through the sun). In the harmonic analysis they were expressed as

$$a_1 \cos \lambda_S + b_1 \sin \lambda_S + a_2 \cos 2\lambda_S + b_2 \cos 2\lambda_S$$

or

$$c_1 \sin (\lambda_S + \sigma_1) + c_2 \sin (2\lambda_S + \sigma_2);$$

a, b, c are calculated in force units (gammas) for declination (E, east force) as well as for H and Z.

For a storm beginning at Greenwich mean time t_0, reckoned in angle (at the rate 360° per solar day) from Greenwich midnight, the local time λ_s at a station in longitude $\vartheta°$ east of Greenwich, at storm time t_{st} (reckoned in angle like t_0), is given by

$$\lambda_S = t_0 + t_{st} + \vartheta,$$

from which any integral multiple of 360° may be subtracted. Thus, for a given station, λ_s is a function of storm time, as well as of the position of the station (and the commencement time of the individual storm).

The coefficients a, b, and hence also c, σ, are all functions of t_{st}.

7. HARMONIC TERMS IN D_S FOR SUCCESSIVE HALF DAYS

In this part of the work all three elements were considered: the results for each day are as follows.

TABLE 3

Harmonic coefficients of D_S *for the first 4 half days of 40 moderate magnetic storms (mean of 8 observatories); diurnal and semidiurnal components. (Unit 0.1 gamma).*

Half day		a_1	b_1	c_1	σ_1	a_2	b_2	c_2	σ_2
Ds(H)	1	—12	101	101	— 7°	— 9	1	9	— 82°
	2	11	85	85	7	— 7	— 2	7	—106
	3	19	51	54	20	—15	— 1	15	— 94
	4	17	29	34	30	— 5	— 2	5	—113
Ds(E)	1	75	8	75	87	23	—10	24	104
	2	63	—33	71	117	11	5	12	65
	3	23	—26	35	138	19	9	9	7
	4	13	—16	21	143	4	4	6	45
Ds(V)	1	22	—33	40	146	— 2	— 3	4	214
	2	— 4	—33	33	187	— 3	5	6	211
	3	— 5	—17	18	196	5	1	5	79
	4	— 7	—11	13	212	0	2	2	0

As was to be expected from the form of the D_S curves in panels *b*, *c*, of Figures 3-5 of my 1918 paper, the amplitudes of the second harmonic in Table 3 are small compared with those of the first harmonic; for example, the sums of c_1 and c_2, respectively, in Table 3 are (in the units there used) 274, 36 for *H*, 202, 51 for *E*, and 104, 17 for *V*. Without a further investigation, based on more extensive data, one can hardly be certain whether the systematic changes shown by c_2 and σ_2 are real; hence I confine the present discussion of the results to c_1 and σ_1.

The diurnal harmonic components of D_S (*H*) given in Table 3 are illustrated in Figure 3, which is a *harmonic dial* (cf. pp. 563-6 of *Geomagnetism*). The four points marked 1, 2, 3, 4 along the full line, which relates to D_S (*H*), refer to the successive half days 1, 2, 3, 4. For each half day, the point represents the *end* of a vector drawn from *O*, with length representing c_1 (on the scale indicated), and with the direction making the angle σ_1 with the horizontal axis Ob_1. The vertical coordinate of the point is a_1, the horizontal one is b_1.

Clearly c_1 is greatest for the first half day, and steadily diminishes from each half day to the next, while the phase σ_1 steadily increases; this is clearly illustrated by the change in the vector from the origin to the points 1, 2, 3, 4 of the $D_S(H)$ line on Figure 3.

The elements E and V show a similar change, but the phase

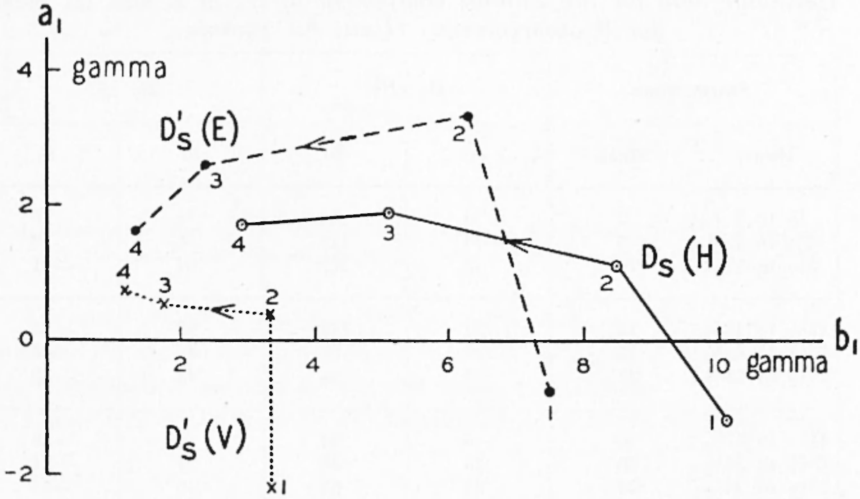

Fig. 3 - Harmonic dial for the diurnal component of *Ds* in *H*, *E* and *V*, in successive half days of the 40 storms.

for E is about 90°, and for V is about 180°, greater than for H, on corresponding half days. The similarity is illustrated in Figure 3 by plotting c_1, $\sigma_1 - 90°$ for D_S (E), and c_1, $\sigma_1 - 180°$ for D_S (V); the lines joining the points for the four half days, in order, are drawn broken for E, and dotted for V; and these lines are marked D'_S (E), D'_S (V), the accents referring to the changes of phase made for these elements; the true harmonic dial diagram for D_S (E) may be got by giving the D'_S (E) line an anticlockwise rotation through 90° about O; for D (V), a rotation through 180° is needed.

The diagram shows that, for the mean of the 8 observatories, D_{st} on these 4 half days is greatest for H and least for V. On account of the small values of c_1 for V, this element was not considered in greater detail.

8. THE DIURNAL COMPONENT OF D_S AT 4-HOURLY INTERVALS

For the elements H and E, the values of a_1, b_1, were determined for each successive group of 4 hourly values from the commencement of the storm (§ 5). The results are given in Table 4.

TABLE 4

Harmonic data for the 24-hour component of D_S *in* E *and* H; *mean for 8 observatories. (Unit. 0.1 gamma).*

Storm time		D_s (H)		D_s (E)	
Hours	Mean	a_1	b_1	a_1	b_1
½ to 3 ½	2	—14	66	45	16
4½ to 7 ½	6	—34	125	88	9
8½ to 11½	10	13	112	91	— 1
12½ to 15½	14	31	132	98	—35
16½ to 19½	18	2	80	44	—33
20½ to 23½	22	1	44	48	—30
24½ to 27½	26	4	54	30	—29
28½ to 31½	30	23	49	21	—24
32½ to 35½	34	31	51	19	—24
36½ to 39½	38	13	42	28	— 7
40½ to 43½	42	19	13	—8	—12
44½ to 47½	46	18	31	18	—30

These results for D_S (H) are plotted in Figure 4, another harmonic dial, like Figure 3. The results for D_S (E) are not plotted as they stand, but only after modification in *two* respects:

1) the phase is decreased by 90°, as in Fig. 3 (this amounts to plotting each dial with $-b_1$, a_1 as the a, b coordinates), and

2) magnification in the ratio $\Sigma c_1(H)/\Sigma c_1(E)$, where Σ signifies the sum of the four values of c_1 (for H or for E) in Table 3.

This ratio is 274/202 or 1.36. This magnification is made with the aim of rendering the modified E dial points in Fig. 4 comparable with the H dial points, in order to see whether (apart from a constant difference of phase and scale) D_S (E) and D_S (H) as represented by their main (diurnal) harmonic component, vary in unison, with respect to storm time.

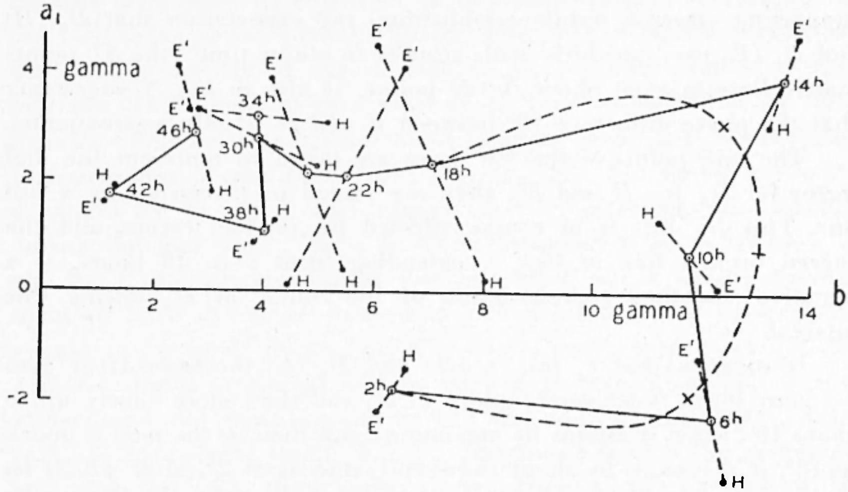

Fig. 4 - Harmonic dial for the diurnal component of $Ds(H)$ and $D's$ (E), at successive four-hour intervals of storm-time, centred at the epochs 2^h, 6^h,...

For each 4-hourly epoch of storm time, 2, 6, . . . , the H and E' (modified E) dial points are marked H and E' and joined by a broken line; the epoch is marked at the mid point of this line.

These HE' lines seem to be distributed in a fairly random way,

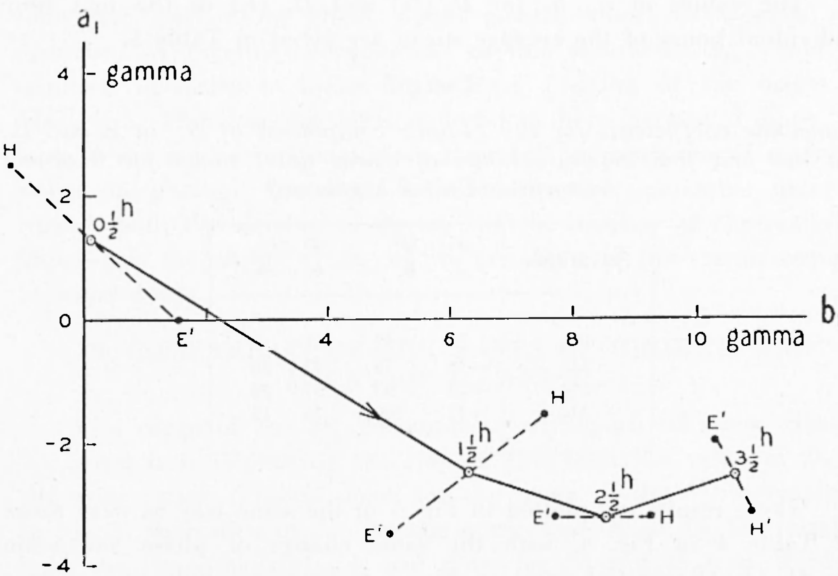

Fig. 5 - Harmonic dial for the diurnal component of $D_s(H)$ and $D'_s(E)$, for the storm-time hours $0\frac{1}{2}$ to $3\frac{1}{2}$.

supporting (though hardly establishing) the expectation that D_S (H) and D_S (E) vary similarly with respect to storm time (the E' points mostly lie somewhat above the H points, as also in Fig. 3, suggesting that the phase difference 90° between E and H is only approximate).

The mid points of the HE' lines are taken to represent the dial vector for D_S for H and E'; they are joined in succession by a full line. This D_S line is of course affected by random errors, and the curved broken line in Fig. 4, extending from 2 to 18 hours, is a tentative smoothed representation of the course of D_S during this interval.

It suggests that c_1 for D_S (H) and D_S (E) increases from zero (at zero storm time) very rapidly to 2^h, and then more slowly up to about 10^h, when it attains its maximum; and then in the next 8 hours, to 18^h, it decreases to about the same value as at 2^h, after which its rate of decrease quickly declines. During the period from about 6^h to 14^h the phase angle σ_1 increases by about 30°. The maximum value of c_1, at about 10^h, is about 13 gamma; this applies to D_S (H), and is reduced in the ratio 202/274 to about 10 gamma for D_S (E).

9. VARIATIONS OF D_S DURING THE FIRST 4 HOURS

The values of a_1, b_1 for D_S (H) and D_S (E) in the first four individual hours of the average storm are given in Table 5.

TABLE 5

Harmonic coefficients for the 24-hour component of D_S *in* E *and* H, *for the first four separate hours of storm time; mean for 8 observatories. (Unit 0.1 gamma)*

Storm time	D_s (H) a_1	b_1	D_s (E) a_1	b_1
0½	25	—12	11	0
1½	—16	75	37	26
2½	—33	93	57	24
3½	—32	109	76	15

These results are plotted in Fig. 5 in the same way as were those of Table 4 in Fig. 4, with the same change of phase and scale for D_S (E). Each dial point in Fig. 5 is based on only one quarter the amount of data underlying each point in Figure 4, and greater random error may be expected; it is surprising that the lengths of the *HE′* lines, which perhaps partly indicate the random error, are not notably greater in Fig. 5 than in Fig. 4. The point for $0\frac{1}{2}^h$, however, which has the least value of c_1, may be unreliable by more than its whole small magnitude, and its phase angle is very uncertain. The positions of the points for $1\frac{1}{2}$, $2\frac{1}{2}$ and $3\frac{1}{2}$ hours are much as might be expected, and suggest that c_1 increases most rapidly during the first hour. There is no valid evidence as to whether or not D_S (H) is reversed during this first hour, but it would certainly seem to have the same sign from 1^h onwards. As D_S in any case semms to be small during the first hour, much more material and a more careful treatment will be needed to determine how it then varies; and the same applies to the end of the second day, when again c_1 has become small (Fig. 4). The uncertainty of the magnitude and phase of D_S at these early and late times is due not only to the relatively greater ratio of the probable error to c_1, when c_1 is small; the uncertainty depends also on the question whether the position of the *origin* of the dials in Figs. 4, 5 is correct.

As explained in Section 3 *b* of this paper, in my determination of D_S the mean solar daily variation *S* for all the storm-months was subtracted from the mean sequence derived on each Table B; this *S* certainly involves some S_D in addition to S_q, and the S_D will be somewhat greater for these storm months than for months less disturbed. A careful determination of this subtracted S_D would be required in order to locate the correct position of the origin in Figs. 4, 5. This has not been undertaken here because I hope ere long to organize a new and more thorough investigation of magnetic storm morphology, based on considerably more extensive data, as regards both the number of storms and the number of observatories. Meanwhile the nature of D_S in the first hour of the storms remains in some doubt.

10. COMPARISON OF THE RATES OF GROWTH AND DECAY OF D_{st} AND D_S

The *range* of the D_S variation at any epoch of storm time is $2\,c_1$, and it is interesting to compare this with the value of D_{st} at the same epoch. This is done, for the mean of the 8 observatories, in Fig. 2; the values of $2\,c_1$ for the storm hours 6, 10, 14, 18 are taken from the (smoothed) Fig. 4, and those for 30 and 42 from Table 3 for D_S (H). The values for the first four hours, and their mean, are from Tables 5, 4; the point nearest the beginning of the storm is rather uncertain.

Despite the accidental error inevitable in the diagram, Fig. 2 shows that D_S (H) follows a course very different from that of $D_{st}(H)$; it attains its maximum earlier, and then decreases much more rapidly; and if it suffers any reversal near the storm commencement, this is over very quickly, well before $D_{st}(H)$ reverses.

11. CONCLUSION AND ACKNOWLEDGMENTS

The methods of the present paper should be further applied, to determine the progression of D_S in higher latitudes, at different seasons, and for groups of storms graded in intensity: and also to ionospheric storms.

I hope soon to publish (in the forthcoming Supplementary Volume, dedicated to Professor F. J. M. Stratton, F.R.S., of the Journal of Atmospheric and Terrestrial Physics) a general review of the morphology of magnetic storms: some of the results of the present paper will there be considered in connection with the development of the great storm of April 1938 ([4]).

In conclusion, it is a pleasure to acknowledge the assistance received in some of the calculations of this paper from Drs. P. K. Bhattachariya and Wan Cheng Chiu, and from D. C. Wilder of the Geophysical Institute of the University of Alaska, who also prepared the diagrams.

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SUMMARY

The « D » field of magnetic disturbance has in the past been analysed into a part D_{st} *depending on time reckoned from the storm commencement — storm-time — and a part whose distribution has a simple form relative to the meridian containing the sun. This part reveals itself at times of weak or moderate magnetic activity as an addition to the field of the solar daily magnetic variation* (S), *present in its pure forme* S_q *on quiet days; the addition is called the disturbance daily variation, denoted by* S_D. *But during storms with definite commencement, the average course of this part of the* D *field, which is*

non-uniform round the earth, and is oriented in a definite way relative to the noon meridian, can be followed not only from one day to the next, as has been done in the past, but over shorter periods, even from hour to hour; as then studied, it is not a daily variation at all, but a distributed field changing in form and intensity with storm time. This part of the field is here called the D_S *field, or disturbance (solar) local-time inequality. It varies with storm time in a manner materially different from* D_{st}, *developing more rapidly than the main phase of* D_{st} *and decaying much faster.*

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