III—THE GEOMAGNETIC MEASURES FOR THE TIME-VARIATIONS OF SOLAR CORPUSCULAR RADIATION, DESCRIBED FOR USE IN CORRELATION STUDIES IN OTHER GEOPHYSICAL FIELDS

by

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1 Introduction

Geomagnetic records (magnetograms) provide information on variable electric currents in the ionosphere. These may be analysed into two main groups, usually ascribed to the action of two kinds of solar ionizing radiations,

(1) W-radiation (*wave-radiation*) acting on the sunlit hemisphere only,

(2) P-radiation (*particle-radiation*) affecting mainly the auroral zones, reaching also the night-side of the Earth.

The effects of W-radiation are mainly connected with the following phenomena:

Daily variations on quiet days, solar (Sq) and lunar (L).

Passing increases of these variations caused by excessive radiation emitted from intense solar eruptions, so-called solar-flare effects.

P-radiation causes, while it lasts, disturbances or "geomagnetic activity", the so-called D-field (disturbance-field). The higher intensities of activity are magnetic storms, often with a sudden commencement, and lasting at least several hours. More frequent are magnetic bays, so-called because of their similarity to a coast-line in the magnetogram, and lasting one or two hours.

There is also an after-effect of storms consisting in a depression of the level of the horizontal-field component, most noticeable in equatorial regions, persisting with a gradual recovery through days and sometimes weeks. It is tentatively ascribed to the action of an "equatorial ring-current" (ERC) around the earth.

Pulsations, with periods of a few seconds to a few minutes, occur occasionally quite clearly during disturbed times, as an effect of P-radiation; but there is also a specially regular type occurring during quiet times, without apparent connection with P-radiation.

A great number of measures and characteristics have been proposed to express the intensity of geomagnetic activity. The International Association of Geomagnetism and Aeronomy provides for current information on the time-variations of geomagnetic activity by means of three parameters: for a particular observatory:

(1) the three-hour range index, K,

(2) the daily equivalent amplitude, Ak,

(3) the daily character-figure, C,

and, for the earth as a whole:

(1) the planetary three-hour index Kp,

(2) the daily equivalent planetary amplitude, Ap,

(3) the daily planetary character-figure, Cp.

In addition, for the IGY, a Q-index for quarter-hourly intervals centred at the minutes 00, 15, 30, 45 of each Greenwich hour, will be derived by magnetic observatories in higher geomagnetic latitudes than 58°. The present article will discuss the physical meaning and the statistical properties of these parameters, but not the technical details how they are derived; these have been described in the preceding article.

2 Indices for Individual Stations

2.1 *The K-index*

It is derived from the records of three orthogonal field components, for instance, the components X (north), Y (east), and Z (vertical downward positive). It indicates the intensity of those variations which can be assumed to be related to solar P-radiation; it measures geomagnetic activity, including pulsations, but excluding the after-effect (ERC). An observer scaling K has to eliminate from the observed variations, $Sq+L$, solar-flare effects and the after-effect. The remaining K-variations are visualized as three-dimensional movements of the end-point of the field-vector, plotted from a fixed origin. A rectangular box, with the edges aligned along the directions of the three recorded components, is then imagined, just enclosing the total path of that vector end-point during a three-hour interval. The longest edge of that box is the amplitude a (in γ) on which K is based. In other words, a is the range of the disturbance variation in the most disturbed component.

The relevant information given by the value of a is condensed in a quasi-logarithmic scale for K, according to the following table valid for stations in about 50° geomagnetic latitude:

$K =$ 0 1 2 3 4 5 6 7 8 9

if a is between the limits

0 ... 5 ... 10 ... 20 ... 40 ... 70 ... 120 ... 200 ... 330 ... 500 ... γ

Each station has selected its own table for assigning K from a, from a number of tables which contain simply multiples of these range limits, and which can be indicated by the lower limit for $K = 9$ (in the normal case given, 500 γ). These limits may be 300 γ (for equatorial stations outside the magnetic equator), 350 γ, 500 γ, 600 γ, 750 γ, 1000 γ, 1200 γ, 1500 γ, and 2000 γ (for stations in the auroral zone). The scales have been adopted so that all stations report about the same number of indices 0, 1, 2, ... 9 for a specific year; this "assimilation of frequencies" has, however, been achieved only roughly. It would have been easy to assimilate the frequencies better by computing individual K-scales for each station; but this would be of little use, in view of the quite large systematic daily variation of geomagnetic activity. It has therefore been decided to adhere to the K-scales once selected, and to achieve the standardization by the transition from K to a standardized Ks-index, in which that daily variation is eliminated as far as possible (Section 2.6).

The quasi-logarithmic scale for the K-index as a function of the amplitude a has the advantage that it condenses the information on the geomagnetic activity during a Greenwich day into a succession of 8 digits, mostly written in two groups of four, separated by Greenwich noon, thus:

Cheltenham 1956 June 25: $K = 6652\ 3332$

2.2 *The Equivalent Three-Hour-Range, ak*

The K-scale shares, with other logarithmic scales (for instance, decibels), the property that the arithmetic average of logarithms gives the logarithm of the geometric mean, and not the logarithm of the arithmetic mean. Therefore, the simple sum (or the arithmetic mean) of the K-indices for a day may be quite misleading: Two days at Cheltenham having the K-indices

1111 1111 and 0000 0008 have the same sum, 8,

but the total range in the 24 hours of the first day will be only of the order of 10γ (quiet day), while the total range on the second day will exceed 300γ, a highly disturbed day. Some caution is therefore necessary if days are selected according to their sum of the eight K-indices; low sums do not suffice to select quiet days, but high sums certainly indicate disturbed days. That sum is given in the tables merely as a check.

This property of logarithms induces some workers to prefer to think in *ranges*. It is easy to re-convert each K-index into an equivalent range, ak, which is about the centre of the limiting ranges for a given grade of K. For Cheltenham, the coordination of ak to K is

K	=	0	1	2	3	4	5	6	7	8	9	
ak	=	0	3	7	15	27	48	80	140	240	400	(2γ)

The unit 2 γ for ak has been chosen since the unit γ would give the illusion of an accuracy not justified.

Exactly the same scale as for Cheltenham may be used for other stations, regardless of their K-scale. If it is desired to express ak in the unit γ, that factor is obtained from the lower limit for $K = 9$ valid at that station, by dividing that limit by 250. For instance, at Sodankylä, where the lower limit for $K = 9$ is 1500 γ, the factor is 6 so that, for $K = 3$, the equivalent range is 90 γ; or, in other words, ak for Sodankylä expresses equivalent ranges in the unit 6 γ. The equivalent ranges would be, for instance,

Cheltenham 1956 June 25: ak = 80 80 48 7 15 15 15 7, with the sum 267, and the mean 33.

The Table for the reconversion of K into equivalent range is, of course, conventional since, for Cheltenham, $K = 3$, the amplitude may lie between 20 and 40 γ, and, even in the average for many indices $K = 3$, it may turn out to differ somewhat from the conventionally adopted value of 30 γ. That difference will, however, be only of importance in special studies so that, for all usual purposes, it is advisable to adhere to the conventional reconversion of K into ak as here given. It is clear that, in the exceptional and interesting case of $K = 9$, the actual ranges in the three components should be communicated in addition to K.

2.3 *The Equivalent Daily Amplitude, Ak*

The average of the eight values ak per day is called the equivalent daily amplitude, Ak. It may be expressed in the unit by multiplying it by a factor "Lower Limit for $K = 9$ divided by 250", just as for ak in the preceding section. Thus, for Cheltenham, 1956 June 25, $Ak = 33$, unit 2 γ.

Since both ak and Ak are linear measures, their values may be combined into arithmetic means for any number of intervals. One may, for instance, express the intensity of the magnetic storm at Cheltenham, February 25, 1956, with the K-indices 1576 6653, by saying that, from 03 to 21 UT, the equivalent amplitude (= average of the six equivalent ranges) was 79, in the unit 2 γ, that is, 158 γ. It is also permitted to form averages of Ak for months, years or any groups of selected days. For such purposes, it will save labour to count the frequencies of the K-indices (Section 2.4) and to reconvert into ak in the end.

2.4 *The Frequencies of K-indices*

The last remark in the preceding section refers to frequencies of K-indices. It should be emphasized that geomagnetic activity within a longer time-interval, for instance a month, can hardly be expressed by one figure alone.

Consider, for instance, two months of 30 days each (240 three-hour intervals) with the following frequencies of K:

$K =$	0	1	2	3	4	5	6	7	8	9	Sum
Month I	15	30	45	50	50	40	10	–	–	–	240
Month II	35	50	44	41	31	27	6	2	2	2	240

The average of the K-indices is 3·0 for month I, 2·5 for month II, which makes month I appear more disturbed than II. The average daily amplitude Ak is 22 for both months, which would mean "both months equally disturbed". Actually, month II is quite different from month I: it has more quiet intervals ($K = 0$ or 1), but it contains also a quite heavy magnetic storm, while activity in month I never surpassed $K = 6$. These two examples are not artificial; similar actual cases will be discussed later (Section 3.7).

In order to describe a month, it may be sufficient to combine a few classes of K, thus:

$K =$	0+1	2+3	4+5	6+7	8	9	Sum
Month I	45	95	90	10	–	–	240
Month II	85	85	58	8	2	2	240

It will be convenient to reduce the number of the intervals per month to 240 even for the months with 31, 28 or 29 days. That reduction will, in general, leave the frequencies of the (rarer) interesting higher K-indices unchanged.

2.5 *The Classical Magnetic Daily Character-Figure C*

Since 1905, most observatories have taken part in a simple scheme of characterization. They ascribe, to each full day between successive Greenwich midnights, a character $C = 0$, if it was quiet, $C = 1$, if it was moderately disturbed and $C = 2$, if it was heavily disturbed. The method of assigning these characters was left entirely to the discretion of the directors of each observatory.

Assigning characters is equivalent to "ranking" the daily magnetograms in the order of their activity and to choosing two limits of activity, an upper one for $C = 0$, and a lower one for $C = 2$. In assigning those limits, the observatories heartily disagree in the percentages of $C = 0$ or 2. For instance, in the year 1949, the number of days with

	$C =$ 0	1	2
was for Lovö	30	139	196 days, average $C = 1{\cdot}45$
for Abinger	36	299	30 days, average $C = 0{\cdot}98$
for Honolulu	337	24	4 days, average $C = 0{\cdot}09$

These individual characters C are not often used in correlation studies; their combination to world-wide-figures will be described below.

2.6 *The Standardized Index, Ks*

At a given station the frequencies of K-indices, counted separately for the eight three-hour intervals, have a pronounced daily variation. At stations outside the auroral zone, for instance, the intervals before or around local midnight are more often disturbed than those before or around local noon. Take the station Lerwick (Shetland Islands, geomagnetic latitude 62·5°). On 424 days in winter (months November to February), the frequencies of K-indices for two three-hour intervals of the Greenwich days were as follows:

$K =$	0	1	2	3	4	5	6	7	8	9	Sum
12 ... 15UT	32	150	140	66	22	6	3	6	–	–	424
21 ... 24	53	74	83	120	52	22	12	6	1	1	424

The average equivalent range ak (taking into account that the lower limit for $K = 9$ at Lerwick is 750γ) for the two intervals is 31γ and 53γ. At stations within the auroral zone that daily variation is still bigger; at Tromsö, for instance, the evening interval 18 ... 21 UT has an equivalent range more than four times as big as the morning interval 06 ... 09 UT (in winter).

By a standardization process which will not be described here in detail, a conversion table has been derived for a number of observatories to change every K-index into a standardized index Ks. While K is one of the integers 0 to 9, Ks is given in thirds, as follows: If, at the outset, Ks is conceived as a continuous variable between 0·0 and 9·0, the interval (say) 1·5 to 2·5 is divided equally into thirds, designated by 2 –, 2o, and 2+. The limiting symbols 0o and 9o comprise only 1/6 of a full interval, namely, from 0·0 to 1/6, and from (9 – 1/6) to 9·0. As example, the conversion table for Lerwick, months November to February (winter) is given here:

	Three-hour interval, Universal Time							
	00 ... 03	... 06	... 09	... 12	... 15	... 18	... 21	... 24
$K = 0$, $Ks =$	0	0	0	0	0	0	0	0
$K = 1$, $Ks =$	1+	2 –	2 –	1+	1o	1o	1o	1o
$K = 2$, $Ks =$	2+	3 –	3o	3o	3 –	2+	2o	2o
$K = 3$, $Ks =$	3+	4o	4+	4+	4o	3+	3o	3o
$K = 4$, $Ks =$	4+	5o	6 –	6 –	5o	4+	4 –	4o
$K = 5$, $Ks =$	5+	6o	7 –	7 –	6 –	5o	5 –	5o
$K = 6$, $Ks =$	6o	7o	7+	7+	7 –	6 –	6 –	6 –
$K = 7$, $Ks =$	7o	8 –	8o	8o	7+	7o	7 –	7 –
$K = 8$, $Ks =$	8o	8+	9 –	9 –	8+	8o	7+	7+
$K = 9$, $Ws =$	9o	9o	9o	9o	9o	9o	9o	9o

The object of the standardization is to provide, in *Ks*, an index of geomagnetic activity which, for an individual three-hour interval, should have about the same standard for all stations, independent of daytime. Of course, that aim has not been achieved completely; but it can be claimed that, for a given three-hour interval, the *Ks*-indices scatter much less than the *K*-indices.

It is not generally recommended to use the *Ks*-indices instead of the *K*-indices; the main purpose of *Ks* is to provide a basis for *Kp* (Section 3.1).

3 Indices for the Whole World

3.1 *The Planetary Three-Hour Index Kp*

In a scale of thirds, in the order

0o 0+ 1− 1o 1+ 2− 2o 2+ ... 7+ 8− 8o 8+ 9− 9o,

which may be condensed to a scale of integers

0 1 2 ... 8 9,

Kp indicates the intensity of geomagnetic activity, as expression of solar corpuscular radiation, for every three-hour interval of the Greenwich day. A full day is therefore expressed by an array of eight such symbols, with the first valid for 00 to 03 UT, etc., for instance,

1956 June 25 *Kp* = 6+ 7− 6+ 4− 3+ 5− 4o 2+.

Kp is the average of the standardized *Ks*-indices for 12 selected observatories.

3.2 *The Three-Hourly Equivalent Planetary Amplitude, ap*

It is co-ordinated to the *Kp*-index by the following table:

Kp =	0o	0+	1−	1o	1+	2−	2o	2+	3−	3o	3+	4−	4o	4+
ap =	0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp =	5−	5o	5+	6−	6o	6+	7−	7o	7+	8−	8o	8+	9−	9o
ap =	39	48	56	67	80	94	111	132	154	179	207	236	300	400

At a standard station, with 500γ as lower limit for $K = 9$, the average range of the most disturbed of the three force components, in a three-hour interval with *Kp*, can be taken as 2 . *ap* (for instance, for *Kp* = 3+, as 36 γ). In other words, *ap* is an equivalent amplitude in the unit 2 γ. *ap* is the planetary counterpart to *ak*, described in Section 2.2; it can be used if a linear scale is preferred to the quasi-logarithmic scale of *Kp*.

3.3 *The Daily Equivalent Planetary Amplitude Ap*

The average of the eight values of *ap* for a day is the daily equivalent planetary amplitude *Ap*. Like *ap*, *Ap* may be conceived as expressed in the unit 2 γ for a standard station. Averages of *ap* may also be formed for other combinations of three-hour intervals, such as months, etc. *Ap* is the planetary counterpart to *Ak* (Section 2.3).

3.4 *The Daily International Character-Figure, Ci, and the Daily Planetary Character-Figure, Cp*

The oldest world-wide measure of magnetic activity is the average of the characters *C* (see Section 2.5) for all collaborating observatories, varying between 0·0 and

2·0. *Ci* is available for all days since 1884. The system has worked tolerably well, especially for the purpose of distinguishing between days in the same month.

A substitute *Cp*, based on *Kp* exclusively, has been proposed, and is now available for 1932/33 and currently since 1937. It is derived from the daily sum of the eight amplitudes *ap* for each day (see Section 3.2), as follows:

Upper limit of the sum of the eight values of *ap* per day:

	22	34	44	55	66	78	90	104	120	139	164	190	228
Cp =	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0	1·1	1·2

(continued) sum *ap* up to

	273	320	379	453	561	729	1119	1399	1699	1999	2399	3199	3200
Cp =	1·3	1·4	1·5	1·6	1·7	1·8	1·9	2·0	2·1	2·2	2·3	2·4	2·5

Example:

March 1 1940

Kp =	1o	3o	3−	2o	2o	1+	1o	0+
ap =	4	15	12	7	7	5	4	2

Sum *ap* = 56 *Cp* = 0·4 *Ap* = 7

(*Ci* = 0·3)

Cp is so defined that the frequency distributions of *Ci* snd *Cp* in the ten years 1940 to 1949 are practically the same. Even now, the daily values of *Ci* and *Cp* are nearly identical, differing rarely by more than 0·2. It is a statistical miracle that two entirely different definitions like those of *Ci* and *Cp* lead to such a good agreement. Nevertheless, *Cp* is more reliable and should be used in preference to *Ci*, unless *Ap* is preferred.

An approximate relation between *Cp* (or *Ci*) and *Ap* is given by the following table:

Ci or *Cp* =	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0
Ap =	2	4	5	6	8	9	11	12	14	16	19
Ci or *Cp* =	1·1	1·2	1·3	1·4	1·5	1·6	1·7	1·8	1·9	2·0	
Ap =	22	26	31	37	44	52	63	80	110	160	

3.5 *A Contracted Scale for Ci and Cp*

For certain purposes it is desirable to express the geomagnetic activity on days by a single digit. This may be done by *C*9, which contracts the scales of *Ci* and *Cp* as follows:

*C*9 =	0	1	2	3	4	5	6	7	8	9
Ci or *Cp* =	0·0	0·2	0·4	0·6	0·8	1·0	1·2	1·5	1·9	2·0
	0·1	0·3	0·5	0·7	0·9	1·1	to	to		to
							1·4	1·8		2.5

3.6 *Local Substitutes for Cp*

If it should be necessary to make a preliminary estimate of *Cp* for a recent day before the final value of *Cp* is available, this can be done on the basis of the local *K*-indices. These are converted into equivalent three-hour ranges *ak* (Section 2.2), and from the sum of the eight values *ak* per day, by means of the table in Section 3.4, a character figure may be deduced which may be called *Ck*.

If, for any observatory, conversion tables *K* into *Ks* (Section 2.6) are available, the *Ks* may be used instead of *Kp* as described in Section 3.4, and lead to a better estimate (called *Cs*) for *Cp*.

3.7 *Characterization of Months*

It has already been said in Section 2.4 that longer time-intervals, such as months and years, cannot be adequately described by a single figure with respect to geomagnetic activity. This holds also for the monthly means of *Ci* or *Cp*, which in the past have often been used. A blatant case is March 1940, with an average $Cp = 0{\cdot}80$: the first 23 days had an average 0·40, but the last 8 days had an average 1·74, due to three days of intense storm with $Cp = 2{\cdot}1$ each. April 1950 had the same monthly mean, but the most disturbed day had $Cp = 1{\cdot}6$ only; no *Kp* was higher than 7 −.

For ranking months according to magnetic activity, frequency tables of *Kp* similar to those discussed in Section 2.4 are recommended. A few examples, including the average *Ap*, follow; the number per month is reduced to 240.

$Kp =$		0 1	2 3	4 5	6 7	8	9	*Ap*
March	1940	93	76	36	15	16	4	36
July	1944	140	99	1	—	—	—	6
Nov.	1944	158	68	14	—	—	—	6
June	1954	152	83	5	—	—	—	6
April	1956	26	138	53	17	4	2	27

For use in correlation studies with other phenomena, the response curve of the phenomenon to geomagnetic activity is important for the question by which parameter a month is best characterized. For instance, for the equatorial ring current, and for the decrease of cosmic ray intensity, only the highest degrees of *Kp* (7 to 9) are really effective; while, for stations in 60° geomagnetic latitude, appearance of aurora may perhaps already be connected with $Kp = 4$. Within the auroral zone, absence of aurora and of the *SD*-current system may be bound to the rare cases $Kp =$ 0o or 0+.

3.8 *Recurrence Intervals of* 27 *Days* (*Solar Rotations*)

For astrophysical purposes, the solar rotations are counted according to Carrington's numbering. For geophysical purposes, it is more convenient to use an internationally adopted period of exactly 27 days according to universal time. The numbers and first days of these "rotations" for 1957/58 are given here (the intervals start at 00 UT of the first day):

No.	First day		No.	First day	
1691	1957 January	13	1695	1957 May	1
1692	1957 February	9	1696	1957 May	28
1693	1957 March	8	1697	1957 June	24
1694	1957 April	4	1698	1957 July	21

No.	First day		No.	First day	
1699	1957 August	17	1709	1958 May	14
1700	1957 September	13	1710	1958 June	10
1701	1957 October	10	1711	1958 July	7
1702	1957 November	6	1712	1958 August	3
1703	1957 December	3	1713	1958 August	30
1704	1957 December	30	1714	1958 September	26
1705	1958 January	26	1715	1958 October	23
1706	1958 February	22	1716	1958 November	19
1707	1958 March	21	1717	1958 December	16
1708	1958 April	17			

3.9 *International Quiet and Disturbed Days*

The $C+K$-centre, for each calendar month, issues lists containing the dates of 5 quiet days, 10 quiet days, and 5 disturbed days. When these days are considered, it should always be remembered that their average degree of activity may change very much from month to month. The average value of Ap was, for instance, for the 5 quiet and 5 disturbed days,

March	1940, quiet Ap =	2, disturbed Ap =	159
July	1944	3,	9
June	1956	8,	34

There are months in which really quiet days (with $Cp = 0{\cdot}0$, or $Ap = 2$) do not occur; in these cases, even those 5 days selected as least disturbed represent a level of disturbance which, in actually quiet months, would already be regarded as relatively disturbed.

3.10 *Activity in Polar Regions*

While Kp represents the level of geomagnetic activity over the greater part of the Earth's surface—apart from typical daily variations according to local time—polar stations, especially those inside the auroral zone, often exhibit special and peculiar disturbances. The physics of those phenomena will be furthered by the records to be obtained in the IGY; for the statistics, the Q-index will be available.

3.11 *Kp-Index and Aurora*

The higher values of the Kp-index can be used to judge the possibility of low-latitude aurora. This aspect is discussed in a paper:

J. BARTELS and S. CHAPMAN, Eine zwanzigjährige Reihe erdmagnetischer Störungsdaten, dargestellt im Hinblick auf das mögliche Auftreten von Polarlicht ausserhalb der Polarlichtzone. (A twenty-years' series of geomagnetic activity data, represented with respect to the possible appearance of aurora outside the auroral zones). To appear in *Nachrichten Akad. Wiss. Göttingen, Math.-Phys. Klasse* 1957.

Copies, including English translations of the text, will be made available to all those interested.

4 Sources of Data

Monthly tables of K-indices are distributed by many individual observatories. Please enquire particulars from the nearest geomagnetic observatory or service.

Such tables appear also in print for some stations: Cheltenham (near Washington) K-indices are given quarterly in the *Journal of Geophysical Research*; K for the British observatories Abinger, (Hartland), Eskdalemuir, Lerwick appear in the *Journal of Atmospheric and Terrestrial Physics.*

Monthly tables of Kp, Ap and Cp are distributed, about 3 weeks after the end of each month, by the Geophysikalisches Institut, Herzberger Landstr. 180, (20b) Göttingen (Germany), together with 27-day recurrence diagrams of Kp, brought up to date by Ks from German stations.

Quarterly tables of geomagnetic indices, including reports on special events, are distributed by the $C+K$-Centre, Meteorologisch Instituut, De Bilt (Holland). They appear also in the *Journal of Geophysical Research*, where also additional data on magnetic storms from individual stations are given.

For past material, the *Bulletins of the International Association of Geomagnetism and Aeronomy*, No. 12, 12a, ... 12j (for 1955) should be consulted. They are available from the Secretary of the Association, Dr. V. LAURSEN, Meteorologisk Institut, Charlottenlund (Denmark).

A collection of daily characters $C9$ and Kp up to 1950 has been given by J. BARTELS, *Akad. d. Wiss. Gottingen, Math.-Phys. Klasse, Sonderheft* 1951; a second issue (up to June 1957) is in the Press.

For more detailed information, compare also the bibliography given at the end of the article on the K-index.