HOURLY VALUES OF EQUATORIAL $D_{st}$ FOR THE IGY

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Using eight magnetic stations in low latitudes, hourly values of $D_{st}$ are determined for the IGY. Three-hourly mean $D_{st}$ values are compared with corresponding values based on Kertz's $D_{st}$ indices. Three-hourly mean $D_{st}$ is also compared with $a_{p}$ indices. It is found that $D_{st}$ correlates well with $a_{p}$ in gross features and that during magnetic storms activity represented by $a_{p}$ recovers more rapidly than $D_{st}$.

1. Introduction

Among transient variations of the Earth's magnetic field the most outstanding in both magnitude and duration are those of magnetic storms. Though their form and severity vary considerably from one event to another, the majority of magnetic storms have certain common characteristics. One of the characteristics is the decrease of the horizontal force, $H$, all over the world in the equatorial and moderate latitudes. This decrease is very nearly axially symmetric and does not depend on longitude or local time. Superimposed on the general decrease in $H$ there are variations in all three components that depend on local time; these variations are of large amplitude in the polar regions.

It is thus convenient to analyze the storm variation $D$ into two parts, $D_{st}$ and $D_{S}$. Given an instant of time $D_{st}$ is the average of $D$ over all longitudes. $D_{S}$ is defined by $D - D_{st}$. The two variations $D_{st}$ and $D_{S}$ may be obtained for a specified latitude, or for a belt of finite width centered at some latitude. These definitions apply to all three magnetic components.

For a well-defined storm $D_{st}$ and $D_{S}$ can be determined as functions of storm time that is measured from the onset of the storm.

Statistical analyses of magnetic storm variations have been made essentially in the manner described above by MOOS$^{(1)}$, CHAPMAN$^{(2,5)}$, VESTINE et al.$^{(6)}$, YOKOUCHI$^{(7,8)}$, SUGIURA and CHAPMAN$^{(9)}$ and others.

However, the determination of $D_{st}$ need not be limited to times of magnetic storms, but can be extended to periods of lesser magnetic activity or even to magnetically quiet times. In fact, $D_{st}$ may be determined continuously as a function of universal time regardless of occurrence of magnetic storms. $D_{st}$ so determined should provide a measure of magnetic activity.

VESTINE et al.$^{(6)}$ have published such continuous $D_{st}$; they gave hourly $D_{st}$ curves for the Second Polar Year, September 1932 to August 1933 (Carnegie Institution of
Washington Publication 580, pp. 230-231). The hourly \( Dst \) values were obtained by averaging hourly departures from the annual mean for San Juan, Ailbag and Honolulu, all in low geomagnetic latitude and spaced approximately evenly in longitude.

More recently Akasofu and Chapman determined \( Dst \) for several magnetic storms (cf. Akasofu and Chapman 1961), and their \( Dst \) curves have been extensively used by other workers. Such \( Dst \) data are now in great demand by those who concern themselves with solar cosmic rays, solar plasma, Earth's radiation belts and other related geophysical phenomena.

Chapman, Akasofu and the present author initiated determination of hourly \( Dst \) values for the IGY with the hope that such data would be published on a routine basis in the future. The work was carried out with assistance from J. C. Cain of NASA and E. J. Chernosky of Air Force Cambridge Research Laboratories.

Kertz has derived three-hourly index for \( Dst \) for the IGY by a method different from the one adopted here. In Section 5, three-hourly \( Dst \) values obtained by our method are compared with the corresponding values based on Kertz's indices.

2. Magnetic Stations Used

The selection of magnetic stations was made with the following considerations: (1) Stations in low latitudes should be used to eliminate as much as possible disturbances originating in the auroral zones; (2) Stations near the magnetic equator should be avoided, because the equatorial electrojet may introduce undesired variations; also magnetic storm variations are irregular and often augmented at the magnetic equator; (3) Stations should be distributed over longitude as uniformly as possible; (4) Reliable hourly \( H \) values are already available.

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<th>Station</th>
<th>Geomagnetic</th>
<th>Geographic</th>
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<td>Latitude</td>
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<td>S 35°3</td>
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The magnetic stations used are listed in Table 1 in the order of geographic longitude. Of the eight stations, five are in the northern and three in the southern hemisphere. The geomagnetic latitudes of the stations range from 9.5 to 33.3.

In Fig. 1 the stations used in the present investigation are marked with black circles with station names underlined, and the stations used by Kertz are indicated by open circles; for the latter set the mean position of stations for each of the eight groups is shown by a circle with a cross, arrows indicating contributing member stations; station-
Fig. 1. The stations used in this paper (black circles) and those used by Kertz (open circles); for the latter set the mean position for each of eight groups is indicated by a circle with a cross, arrows indicating contributing member stations. Stations used both here and in Kertz's paper are shown by a black circle with an arrow.
used both in this paper and in Kertz’s paper are each marked with a black circle together with an arrow toward the group mean.

3. Method of Derivation of $D_{st}$

For station $i$, the observed magnetic field $H_i^{(0)}$ at universal time $t$ may be considered as the sum of the permanent field $H_{00}^{(0)}$ (including secular variation), solar daily variation $S_{qi}^{(0)}$, lunar daily variation $L^{(0)}$ and disturbance $D^{(0)}$; i.e.

$$ H_i^{(0)}(t) = H_{00}^{(0)}(t) + S_{qi}^{(0)}(t) + L^{(0)}(t) + D^{(0)}(t). $$  \hspace{1cm} (1)

Let the mean of $H_i^{(0)}(t)$ over the 18 months from July 1957 to December 1958 be denoted by $H_{00}^{(0)}$, and let this mean be a zero order approximation for $H_i^{(0)}(t)$. Let the deviation of $H_i^{(0)}(t)$ from $H_{00}^{(0)}$ be $\Delta H_i^{(0)}(t)$; i.e.

$$ H_i^{(0)}(t) = H_{00}^{(0)} + \Delta H_i^{(0)}(t). $$  \hspace{1cm} (2)

We denote the deviation of observed $H_i^{(0)}(t)$ from $H_{00}^{(0)}$ by $\Delta H_i^{(0)}(t)$; i.e.

$$ \Delta H_i^{(0)}(t) = H_i^{(0)}(t) - H_{00}^{(0)} $. $  \hspace{1cm} (3)$

Substituting (1) and (2) in (3), we have

$$ \Delta H_i^{(0)}(t) = \Delta H_{00}^{(0)}(t) + S_{qi}^{(0)}(t) + L^{(0)}(t) + D^{(0)}(t). $$  \hspace{1cm} (4)

For hour $t$ we take the mean of $\Delta H_i^{(0)}(t)$ over the stations:

$$ \overline{\Delta H}(t) = \overline{\Delta H_{00}^{(0)}(t)} + \overline{S_{qi}^{(0)}(t)} + \overline{L^{(0)}(t)} + \overline{D^{(0)}(t)} $$. \hspace{1cm} (5)

where the upper bar in each term signifies the average over the stations.

Since the lunar variation $L$ is small, we assume that the average of $L$ is negligible, and ignore $L$ altogether. Then we have

$$ \Delta H(t) = \Delta H_{00}^{(0)}(t) + \overline{S_{qi}^{(0)}(t)} + \overline{D^{(0)}(t)}. $$  \hspace{1cm} (6)

For station $i$ for month $M$ (where $M = 1, 2, \ldots, 18$ for the 18 months), we take the mean daily variation of the five international quiet days from Greenwich midnight to Greenwich midnight, and subtract from each of the 25 hourly mean values the linear change obtained by linearly connecting the two midnight values. This linear change is assumed to represent the non-cyclic change that should be subtracted from $S_q$. It should be noted that $S_q$ is measured from midnight level instead of its daily mean level.

The $S_q$ variations so obtained were averaged over the stations. One would hope that this mean $S_q$ would be nearly zero, or at least very small, but our results show that $S_q$ was not completely averaged out, and that the mean $S_q$ had ranges of 8–19 gammas, a not quite negligible amount. The form of the residual $S_q$ varied systematically with season.

To represent $S_q$ by a smoothly varying function throughout the whole period the mean $S_q$ was expanded in a double Fourier series with month number $M$ and Greenwich time $T$ as two variables:

$$ \sum_{n=1}^{6} \sum_{m=1}^{6} A_{mn}^{\alpha} \cos(nM + \alpha) \cos(nT + \beta). $$

Coefficients up to $n = m = 6$ were determined.
For each day the mean $S_q$ was synthesized with this series. In the computation a month number with one decimal was assigned to each day. The synthesized mean $S_q$ was assumed to represent $S_q(t)$ in (6), and was removed from $\Delta H(t)$.

We are thus left with $\Delta H_0(t) + D(t)$. When this quantity was plotted for the entire IGY, points remained near a fixed level during quiet periods and did not show any systematic drift all through the IGY. This was taken to mean that the secular variations were very nearly averaged out. Therefore, $\Delta H_0(t)$ was assumed to be a constant. This constant determines the zero level for $Dst$.

In determining the value of this constant it is important to exclude, as much as possible, days that are in the recovery phase of magnetic storms; inclusion of such days will lower the zero level of $Dst$.

All the quiet periods in which two or more successive days had $ap$ not exceeding 7 were selected, and the quantity $\Delta H(t) - S_q(t) (\Delta H_0 + D(t))$ was averaged over all these selected quiet days. This average, which was 31 gamma, was taken to be the constant $\Delta H_0$.

Removing this constant from all the hourly values, we obtain $\overline{D(t)}$. This average disturbance variation is the sum of $Dst(t)$ and the average $DS(t)$. Since the selected eight stations are all in low latitudes and are distributed approximately uniformly over longitudes, $DS(t)$ is assumed to be negligible, and we take $\overline{D(t)}$ to represent $Dst(t)$.

Summarizing, $Dst$ is determined by

$$Dst(t) = \overline{H(t)} - \overline{H_0} - S_q(t) - \Delta H_0.$$  \hspace{1cm} (7)

Here, the first term is the average over the stations of the hourly $H$ value measured from the mean $H$ for the IGY, the second term represents the mean $S_q$, and the third term is the mean $Dst$ for the quiet periods.

Since $Dst$ varies with latitude, it is desirable to normalize to the variation appropriate to the equator. Assuming that the $Dst$ field is uniform and parallel to the geomagnetic axis, we multiply the hourly $Dst$ values obtained in the manner described above by sec $\theta_m$, where $\theta_m$ is the mean geomagnetic latitude of the eight stations. In our case $\theta_m$ is 22° and the normalization factor is 1.08.

We will call the values normalized to the magnetic equator the equatorial $Dst$ values.

4. Tabulations and Graphs of $Dst$

Hourly equatorial $Dst$ values determined by the method described in the preceding section are tabulated in Table 2. In the tabulations, hourly values are given in units of gamma.

The same equatorial hourly $Dst$ values are graphically shown in Fig. 2. Like Dr. Bartels' $Kp$ diagram each line represents one solar rotation of 27 days.

To compare our $Dst$ with the three-hourly index $ap$, the hourly equatorial $Dst$ values were averaged over each of the same three-hourly intervals as for $ap$, and the three-hourly $Dst$ values so obtained are plotted together with $ap$ in Fig. 3. Since $Dst$ is negative during disturbed periods, the $ap$ indices are plotted with negative sign.

Comparison of $Dst$ with $ap$ is made in Section 7.
## Table 2

### Hourly equatorial $D$st values.

#### JULY 1957

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*ANNALS OF THE INTERNATIONAL GEOPHYSICAL YEAR*
Fig. 2. Hourly $Dst$ plots.
5. Comparison with Kertz’s Dst Indices

Kertz has determined Dst indices by a different method (see part II, p. 49, of this volume).

To compare his results with ours, Kertz’s indices were converted to three-hourly values in gammas. This conversion was made by multiplying his indices by \(-3\).

In Fig. 4, our three-hourly Dst (marked A) and Kertz’s Dst (marked B) are plotted parallel to each other.

Since Kertz took weighted overlapping means of three-hourly intervals, the curves representing his Dst values are on the whole smoother than ours.

There appears to be a diurnal component not averaged out in Kertz’s Dst. Examples are: 10 to 20, 24 to 28 September 1957; 22 to 24 May 1958; 14 to 17, 19 to 21 October 1958; 15 to 22 November 1958. These diurnal components are probably due to DS not being averaged out.

The method we used does not involve any smoothing process. Hence our hourly Dst plots in Fig. 2 show variations in greater detail than the plots in Fig. 4 based on Kertz’s results. For instance in Fig. 2 an increase in \(H\) in the initial phase can be seen in many of the storms.

6. Discussions

It is generally thought that the magnetic field decrease in the main phase of a magnetic storm is due to a ring current. According to Chapman (11), such a ring current was first suggested by Störmer in 1911, though Störmer’s current ring was not a complete ring, but a stream of electrons deflected round the Earth on the afternoon side. Chapman further refers to Schmidt’s study made in 1924 on an electrically neutral ring current.

Chapman and Ferraro (12, 13) investigated a mechanism of formation of a ring current, its equilibrium, stability and decay.

Singer (14) proposed for the main phase decrease of the magnetic field during a magnetic storm a mechanism in which charged particles trapped in the Earth’s magnetic field drift longitudinally, thereby constituting net westward current.

With stimulus from the discovery of the trapped radiation belts the problem drew renewed interest in the recent years. Thus Dessler and Parker (15) gave a hydromagnetic interpretation of the effect of a ring current consisting of trapped particles. The magnetic field of a model ring current has been computed by Akasofu and Chapman (16) and Akasofu, Cain and Chapman (17).

As to direct magnetic observation of a ring current by satellite or space probe there has been no definitive determination of the position of a ring current. However, Vanguard 3 magnetic measurements definitely indicate that the ring current must be above a few thousand kilometers from the Earth’s surface (Cain et al (18)).

We believe that Dst is mainly due to the ring current, but that Dst also includes the magnetic field due to the currents on the interface between the magnetosphere and solar plasma and some residue of the polar disturbances. The second of these three parts is much less than the first, and may be negligible except in the initial phase of magnetic storms. The residue of the polar disturbances may be removed at least approximately by a more refined analysis, but such refinement is not attempted here.
DAYS IN SOLAR ROTATION INTERVAL

A: $D_{st}$
B: $a_p$

1957 JUL

1697

1698 JUL AUG

1699

1700 SEP OCT

Fig. 3. Comparison of $D_{st}$ (A) with $a_p$ (B).
The hourly $D_{st}$ plots as shown in Fig. 2 demonstrate the development and decay of a magnetic storm ring current very clearly. Even when there is no well-defined magnetic storm there often appears to be weak ring current activity lasting continuously for a considerable length of time. Some of these variations may be due to polar disturbances not completely eliminated.

The magnetic field observed on the Earth's surface is modulated by the strength of the solar wind. and such an effect may be included in the $D_{st}$ variations.

7. Comparison of $D_{st}$ with $ap$ Indices

Figure 3 gives a graphical comparison of three-hourly mean $D_{st}$ with three-hourly magnetic indices $ap$. The latter indices are averages of three-hourly ranges for twelve stations lying between 48 and 63° geomagnetic latitude. The three-hourly $D_{st}$ values presented here are based on hourly values of $H$ for eight stations between 9 and 34° geomagnetic latitude.

The $D_{st}$ field is due to the electric currents flowing at great distances from the Earth, whereas the currents responsible for the magnetic disturbance represented by $ap$ flow in the ionosphere.

Though the two indices differ widely in their derivations and represent magnetic fields produced by currents flowing in so different altitudes, the curves in Fig. 3 for these indices are remarkably parallel. Major changes of $D_{st}$ are accompanied by large variations of $ap$ variations of nearly equal magnitude. There is often a noticeable correlation between secondary peaks in $D_{st}$ and those in $ap$.

It is uncertain how far the details of our $D_{st}$ are due to $DS$ that is not completely eliminated. However, it is very unlikely that all the minor changes and irregularities in our $D_{st}$ are due to $DS$ not being averaged out.
Fig. 4: Comparison of $D_s$ determined by author (A) with $D_s$ based on Kertz's indices (B).
There is a tendency for $ap$ to recover more rapidly than $Dst$ after a magnetic storm. This means that in a magnetic storm, polar disturbance dies away more quickly than does the ring current.

8. A Remark on the Induction in the Earth and in the Ionosphere

If a magnetic field varying with time is applied to the Earth, the magnetic induction within the conducting Earth will modify the applied field. The effect is to increase the variation in $H$, and the magnitude of the effect depends on the time scale of the applied field. Since $Dst$ involves variations with periods of wide range, the effect of the magnetic induction in the Earth cannot be accurately estimated by a simple method.

The Earth, to some degree, is shielded by the ionosphere from varying magnetic fields produced by sources external to the ionosphere. This shielding effect depends on the rate of change of the applied magnetic field.

To deduce the magnetic field of a ring current from our $Dst$ values appropriate corrections must be made for the induced magnetic fields.
Acknowledgements

Professor S. Chapman initiated the publication of the hourly Dst data in the Annals of the IGY. I wish to express my thanks to him for his discussions and advice regarding the presentation; to Dr. J. C. Cain for his advice on machine computation and for discussions; to Dr. S-I. Akasofu for his participation in the original planning and discussions; and to Mr. E. J. Chernosky and Miss M. P. Hagan for their contribution in the preparation of the observatory data in a form suitable for the machine processing.

I am greatly indebted to Mrs. Shirley Hendricks who performed the computation with an IBM 7090, and supervised plotting with an automatic plotter.

Our sincere thanks are extended to the directors of the magnetic observatories who made the necessary data available to us. Assistance received from the World Data Center A for Geomagnetism is gratefully acknowledged.

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References