A new reconstruction of the $D_{st}$ index for 1932–2002

A. Karinen and K. Mursula
Department of Physical Sciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland

Received: 15 July 2004 – Revised: 7 October 2004 – Accepted: 18 October 2004 – Published: 28 February 2005

Abstract. We have reconstructed a new, homogeneous geomagnetic $D_{st}$ index for 1932–2002, thus extending the original $D_{st}$ index by 25 years, i.e. by more than one full solar magnetic cycle. The extension was done by using data from the original set of four low-latitude stations for 1941–1956, and by using the nearby CTO station as a predecessor of the HER station for 1932–1940. Despite some open questions related to the composition of the original $D_{st}$ index, the reconstructed index is quite similar to the original one during the overlapping time interval (1957–2002). However, the reconstructed $D_{st}$ index corrects for some known errors in the original $D_{st}$ index, such as the erroneously large daily UT variation in 1971. Also, despite the overall agreement, the reconstructed index deviates from the original index even on the level of annual averages for several years. For instance, all annual averages of the reconstructed index are negative, and for 1962–1966 they are systematically lower (more stormy) than those of the original index. Accordingly, we disagree with the uniquely positive annual average of the original index in 1965, which most likely is erroneous. We also find somewhat higher (less stormy) values than in the original $D_{st}$ index for the three lowest annual averages in 1960, 1989 and 1991, out of which the lowest annual average is found in 1989 rather than in 1991. The annual averages of the geomagnetic $A_p$ index and the reconstructed $D_{st}$ index correlate very well over this time interval, except in the beginning of the series in 1932–1940 and in the declining phase of solar cycles 18, 20 and 21, where high speed solar wind streams cause enhanced geomagnetic activity. Using the superposed epoch method we also find that, on average, the storms in the early extended period (1932–1956) are less intense but tend to have a longer recovery phase, suggesting that there are more HILDCAA-type medium activity intervals during the early period than more recently. We also study the annually averaged storm structure over the 71-year time interval and find that the most stormy years occur during the declining phase of solar cycles 17 and 21 and around the solar maxima of cycles 19 and 22.

Key words. Magnetospheric physics (Magnetospheric configuration and dynamics; Current systems; Storms and substorms)

1 Introduction

The $D_{st}$ index is traditionally calculated from the observations at the four low-latitude magnetic field stations of Hermanus (HER), Honolulu (HON), Kakioka (KAK) and San Juan (SJJ). (For the coordinates and data coverages of the magnetic stations used here, see Table 1). Although the magnetic observations already started earlier at these stations the $D_{st}$ index has been calculated only since the International Geophysical Year in 1957.

At low latitudes the horizontal $H$ component of magnetic perturbation is mostly affected by the intensity of the equatorial ring current. Accordingly, the $D_{st}$ index is calculated from the (normalized) values of this component. Major disturbances in the $D_{st}$ index during geomagnetic storms are negative due to an increasing number of energetic particles carrying the ring current. Large amounts of energy are fed into the inner magnetosphere, for example, in the form of energetic particles, during long periods of southward directed interplanetary magnetic field (IMF). Once the IMF turns northward the ring current begins to decrease and the $D_{st}$ index soon begins a slow rise back to its quiet time level. Positive variations in the $D_{st}$ index are mostly caused by magnetospheric compressions due to interplanetary shocks often occurring in the initial phase of magnetic storms. In this phase, an abrupt increase in solar wind dynamic pressure is often measured on the Earth’s surface as a sudden increase in magnetic intensity called the sudden storm commencement (SSC).

Note that rather than a homogeneous ring, the ring current is quite asymmetric and often consists of a number of longitudinally limited sections (Lui et al., 1987). Also, it has been known already for quite a long time that other current systems contribute to the magnetic variations even at low latitudes and thereby also to the $D_{st}$ index. This is simply demonstrated by a recent result (Campbell, 2004) that the storm time disturbance at one longitude usually decreases rather than increases with latitude. In particular, the dayside magnetopause current, which depends on solar wind pressure, causes a contribution that is often subtracted from the $D_{st}$ index when estimating the intensity of the ring current (see, e.g. Burton et al., 1975; O’Brian and McPherron, 2000). Also, contributions to the $D_{st}$ index by the tail current and the field-aligned currents (Burton et al., 1975; Alexeev et al., 1996; Campbell, 1996; Turner et al., 2000) and...
Table 1. Geographical and geomagnetic coordinates, according to IGRF 2000 model (IGRF, 2000) and data coverages of the $D_{st}$ magnetic stations.

<table>
<thead>
<tr>
<th>Station, IAGA Code</th>
<th>Geographic Lat.</th>
<th>Long.</th>
<th>Geomagnetic Lat.</th>
<th>Long.</th>
<th>Data Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape Town, CTO</td>
<td>−34.57°</td>
<td>18.28°</td>
<td>−33.89°</td>
<td>82.73°</td>
<td>1932–1940</td>
</tr>
<tr>
<td>Hermanus, HER</td>
<td>−34.42°</td>
<td>19.23°</td>
<td>−33.91°</td>
<td>83.69°</td>
<td>1941–2002</td>
</tr>
<tr>
<td>Honolulu, HON</td>
<td>21.32°</td>
<td>202.00°</td>
<td>21.60°</td>
<td>269.45°</td>
<td>1902–2002</td>
</tr>
<tr>
<td>Kakioka, KAK</td>
<td>36.23°</td>
<td>140.18°</td>
<td>27.17°</td>
<td>208.50°</td>
<td>1913–2002</td>
</tr>
<tr>
<td>San Juan, SJG</td>
<td>18.12°</td>
<td>293.15°</td>
<td>28.53°</td>
<td>5.87°</td>
<td>1926–2002</td>
</tr>
</tbody>
</table>

2 Data quality and availability

As seen in Table 1 all four original $D_{st}$ index stations (HER, HON, KAK, SJG) started operating already long before the international geophysical year (IGY) 1957 when the calculation of the original $D_{st}$ index began (Sugiura and Kamei, 1991; WDC-C2, 2004). Accordingly, we have reconstructed the new $D_{st}$ index using data from these four stations since the start of the HER station in 1941 until the end of 2002. Moreover, since HER was preceded by the nearby Cape Town (CTO) station we have calculated the new $D_{st}$ index from 1932 onwards, using the observations at CTO for 1932–1940 as a substitute for HER. (The exact starting time is 3 August 1932, at 00:00 UT). Taken into account the close proximity of HER and CTO the reconstructed $D_{st}$ series will be quite homogeneous over the whole 71-year time interval. Also, the effects related to the imperfect hemispherical and longitudinal coverage of the $D_{st}$ stations (like the UT variation, see Takalo and Mursula, 2001a,b) will remain closely similar. Unfortunately, no intercalibration between HER and CTO could be made because no simultaneous observations were available.

2.1 Baseline steps

As to data quality, we would like to note that there are some shifts in the baseline level of the $H$ component at HON and SJG. These shifts may be, for example due to an erroneous documentation of the baseline in the original annals of the station. Figure 1 depicts the raw data of the HON station which includes two steps in the baseline, the first on 1 April 1947 at 21:00 UT and the latter on 1 May 1960 at 11:00 UT (see Fig. 1). At SJG, there was one such step on 1 January 1966 at 00:00 UT. Also, a small step was induced and corrected when joining CTO and HER data. We have treated the data around these steps as follows. The data after the step were raised or lowered so as to smoothly join the level before the step. We would like to note that the steps cannot be removed by eliminating the secular variation (see later). However, once the steps are removed and the data are smooth, the absolute level (baseline) of data is not important and will be removed when removing the secular variation.

2.2 Outliers

There are also some clearly erroneous data points at some stations which are seen as outliers and which have been removed from data. The outliers were found as follows. We have first constructed a new data set by filtering the original data by a three-point median filter which replaces each point by the median of the point itself and the two surrounding data points, thus removing all single outliers. Then the filtered data set was subtracted from the original data set. The standard deviation of this difference data set is on the order of magnitude of the average absolute difference between two successive (normal) data points. Finally, we have examined as possible outliers all those data points where the difference
is more than 20–40 times the standard deviation (about to 100–200 nT). Based on this analysis we found seven outlying data points in SJG data (27 October 1932 at 15:00, 12 March 1933 at 16:00, 3 April 1933 at 08:00, 7 April 1933 at 14:00, 20 January 1947 at 11:00, 4 June 1952 at 18:00, and 21 March 1979 at 11:00), and only one outlier in HON data (18 October 1971 at 17:00; see Fig. 1). The CTO, HER and KAK stations had no outliers in their data.

2.3 Data gaps

There are some data gaps at all five stations. The overall data coverages at the five stations during the respective observation times during 1932–2002 were the following: CTO 99.743%, HER 99.988%, HON 97.497%, KAK 99.755%, and SJG 97.850%. Fortunately, most data gaps are relatively short, only a few hours long. In fact, the number of data gaps rapidly decreases with length, and only relatively few data gaps were longer than three days. We have listed the dates of these “long” data gaps in Table 4.

Table 2. Data gaps longer than 3 days for HON, SJG and KAK.

<table>
<thead>
<tr>
<th>Station</th>
<th>Date</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAK</td>
<td>01 Jan 1985 00:00–13 Jan 1985 03:00</td>
<td>133 days</td>
</tr>
<tr>
<td>CTO</td>
<td>20 Aug 1985 14:00–21 Aug 1985 03:00</td>
<td>7 days</td>
</tr>
<tr>
<td>SJG</td>
<td>27 Jul 1987 00:00–29 Jul 1987 15:00</td>
<td>29 days</td>
</tr>
</tbody>
</table>

Fig. 1. The $H$ component at HON before (blue) and after (red) removing the two steps at 1 April 1947 and 1 May 1960. One outlying data point during 1971 was removed from the data. The gap during 1978 was filled.

Naturally, our different data gap policy leads to a larger data gap policy leads to a larger difference between the original $D_{st}$ index and the reconstructed $D_{st}$ index during the long data gaps than on average. Also, the smaller set of stations leads, for example to a slightly different UT variation in the $D_{st}$ index during Sect. 3. Accordingly, the longer data gap can be filled only after the diurnal variation has been removed and the $D(t)$ series has been calculated for the station in question. Three days is an appropriate length to interpolate since the $D(t)$ index depicts strong autocorrelation up to a lag of about a week, corresponding to the typical development of a storm. The net effect of these short data gaps (at most 3 days) is that some 1.367% out of the hourly $D_{st}$ indices in the early period (1932–1956) and 1.789% in the later period (1957–2002) were reconstructed based on such partly missing, linearly interpolated data.

For the long data gaps (Table 2) we have not used interpolation nor filled the gaps with data from other stations. Rather, during the long gaps we have calculated the $D_{st}$ index using only data from those original $D_{st}$ stations which were in operation. Note that this differs from the policy of the original $D_{st}$ index where data from stations other than the original $D_{st}$ stations have been used. As mentioned by Mayaud (1980), gaps did exist in the data that were used to construct the original $D_{st}$ index. Thus, the original $D_{st}$ index includes data from one or more stations beyond the four original $D_{st}$ stations. However, there is no explicit mention of data gaps in the original $D_{st}$ formula, nor how such data gaps were filled, nor which stations were used. Therefore, the original $D_{st}$ index is not fully reproducible and, in this sense, not a truly scientific quantity.

Naturally, our different data gap policy leads to a larger difference between the original $D_{st}$ index and the reconstructed $D_{st}$ index during the long data gaps than on average.
the long gaps. However, similar changes also occur in the original $D_{st}$ index where the data gaps have been filled with other stations. Our data gap procedure is only more straightforward and fully reproducible. Moreover, if needed for a detailed analysis of some gap interval, a more detailed $D_{st}$ index can be reconstructed using data from a larger number of stations, yielding a more reliable longitudinal and hemispheric coverage. (For example, Hakkinen et al. (2003) have suggested using 6 stations to calculate a more symmetric $D_{st}$ index called $D_{st16}$).

Fortunately, there were very few simultaneous long data gaps. In fact, there were only two data gaps that occurred simultaneously in HON and SJG and were 3–4 days (13 October 1984 00:00–16 October 1984 03:00) and 7–8 days (8 January 1985 19:00–16 January 1985 13:00) long. At these times the $D_{st}$ index was reconstructed based only on HER and KAK data. Otherwise, for a very large fraction of long data gaps, data from three stations were available.

3 $D_{st}$ derivation

In the derivation of the $D_{st}$ index we have followed, as far as possible, the original formula (Sugiura, 1964; Sugiura and Hendrics, 1967; Sugiura, 1969; Sugiura and Kamei, 1991) (see also the $D_{st}$ index homepage of WDC-C2, 2004). Hourly values of the $H$ component of the magnetic stations were obtained from WDC-C1 (2004) at Copenhagen, WDC-C2 (2004) at Kyoto and SPIDR (2004) at Boulder. The formula can be divided into three parts as follows.

3.1 Removing the secular variation

For each observatory, annual mean values of $H$ were calculated for the five internationally selected quietest days of each month (for a list of these days, see, e.g. WDC-C1 (2004) web page). For the first five years, 1932–1936, a second order polynomial was fitted to these annual averages in order to find a baseline or the secular variation for these years. This polynomial was then extended until the end of 1936 in order to find the baseline at the end of that year. When calculating the baseline for 1937, the point at the end of 1936 was used as an additional data point in the polynomial fitting, together with the annual averages in 1933–1937. This procedure for calculating the polynomial baseline was then repeated analogously for all later years using the corresponding six data points (the annual averages of the year in question and the four previous years, and the additional data point at the end of the previous year from the previous fit).

Finally, in order to remove the secular variation, the baseline value calculated for each hour using the polynomial of the respective year was subtracted from all hourly $H$ values. These differences then form the deviations $\Delta H$. We would like to note that the formula to calculate the $D_{st}$ index (see, e.g. the $D_{st}$ web page of WDC-C2 (2004)) is unambiguous on this point of removing the secular variation.

3.2 Treatment of the $S_q$ variation

The daily solar quiet ($S_q$) variation was treated in the following way. First, the average 24-hour local time (LT) variation (superposed daily variation) was calculated from the $\Delta H$ values of the five quietest days of each month. A linear change from one superposed day (or rather night) to another was calculated using the nightside activity levels, and then subtracted from the 24 hourly values. Accordingly, 24 rescaled hourly values were obtained for each month. These 288 ($12 \times 24$) values for each year form a 2-dimensional matrix which is called here $S_q^o$. The midnight activity levels were calculated here using the last and first hourly values around the local midnights, in order to have a symmetric treatment for the two nights. This choice also yielded a slightly better correlation with the original $D_{st}$ index, although the original formula, as we understand it, uses only one hour from each midnight (one hour before the first midnight, and one hour after the second midnight). This is one point where the formula is slightly ambiguous.

Second, the $S_q^o$ matrix for each year was replaced by the following 2-dimensional inverse Fourier series approximation:

$$S_q^L(s, t) = \sum_{m=0}^{N_1-6} \sum_{n=0}^{N_2-18} A(m, n) e^{i2\pi \frac{sm}{N_1}} e^{i2\pi \frac{tn}{N_2}},$$

where $s$ (actually $s+1$) and $t$ describe the month and hour, respectively, and $N_1=12$ and $N_2=24$. Only the DC component and the first six Fourier components were included in Eq. (1), in agreement with the original formula. The Fourier amplitudes $A(m, n)$ were calculated from the $S_q^o$ values as follows:

$$A(m, n) = \sum_{s=0}^{N_1-1} \sum_{t=0}^{N_2-1} S_q^o(s, t) e^{-i2\pi \frac{sm}{N_1}} e^{-i2\pi \frac{tn}{N_2}}.$$

This expression involves the same number (48) of Fourier coefficients as the original formula, although a slightly different form of the inverse Fourier transformation is given there. We calculate the Fourier transform and its inverse using the FFT code adopted within the MATLAB program package (MATLAB, 2001). We are not aware of how this numerical exercise was conducted for the original $D_{st}$ index.

3.3 Hourly $D_{st}$ index

The above derived $S_q^L$ values give the final quiet-time $S_q$ variation for each hour, which is then subtracted from the hourly $\Delta H$ values to yield the disturbance variations $D(t)$ for each observatory. Finally, the disturbance variations in universal time (UT) from the four stations were normalized by their respective cosines of geomagnetic (dipole) latitudes and then averaged. Note that the dipole latitude is not a constant but rather changes in time. Therefore, we have calculated the dipole latitudes for each hour using the IGRF models (IGRF, 2000) determined for every fifth year. For the intermediate time, the Gaussian coefficients (for more details, see IGRF,
2000) were interpolated (after 2000 extrapolated) and the dipole latitude was calculated for each station. Note also that, according to the original formula (e.g. Suguri and Kamei, 1991), the disturbance variations should first be averaged and then normalized by the average cosine of the dipole latitudes. However, similarly to some other authors reconstructing the \( D_{st} \) index (e.g. H"akkinen et al., 2003) we find little motivation for the original formula on this point. Moreover, we also obtain a slightly better correlation with the original \( D_{st} \) using the chosen method rather than the formula, suggesting that there may be a lapse in the formula on this point. However, as already noted by H"akkinen et al. (2003), the difference between the two methods is rather small.

4 Original and reconstructed \( D_{st} \) indices in 1957–2002

Figure 2 depicts the original \( D_{st} \) index for 1957–2002 and the reconstructed index for 1932–2002, with the early part (1932–1956) and the later part (1957–2002) denoted in different colors. The mean and the standard deviation of the original \( D_{st} \) are \( \mu = -16.48 \) nT and \( \sigma = 25.06 \) nT while those for the full reconstructed \( D_{st} \) index in 1957–2002 are closely similar: \( \mu = -16.79 \) nT and \( \sigma = 24.81 \) nT. The correlation between the original and the reconstructed \( D_{st} \) indices over the whole time interval of 1957–2002 is 98.68%. Moreover, the average absolute difference between the two series during this time is only 3.09 nT. Comparing this with the average absolute value of the original \( D_{st} \) index of 19.99 nT, one can say that we have reconstructed the hourly \( D_{st} \) index with an overall accuracy of about 15.48%. The agreement is so good that the original \( D_{st} \) index is only seldom distinguishable in Fig. 2 from the reconstructed \( D_{st} \) index. The largest difference comes most likely from the subtraction of the secular variation from the data of the individual \( D_{st} \) stations (H"akkinen et al., 2003).

In fact, the reconstruction is even better than suggested by the above numbers. Since, as described above, the treatment of data gaps in the original formula is unknown, the original and reconstructed \( D_{st} \) indices will be different for these times. Accordingly, if we neglect all hours with no data in any of the stations (including short and long data gaps), the correlation between the two \( D_{st} \) indices increases to 98.75% and the average absolute difference between the two series decreases to 3.03 nT. This set of common measurements covers 94.326% of the time interval 1957–2002. The corresponding \( D_{st} \) indices are called here the gapless \( D_{st} \) values. However, we would like to note that the data gap policy even affects these values since there are gaps also during the five quietest days of some months, and the \( S_q \) variation and, thus, the disturbances \( D(t) \) depend on how the data gaps are treated. Therefore, without knowing the data gap policy, one cannot completely reconstruct the \( D_{st} \) index. This problem is one of the main features contributing to the
remaining difference between the original and reconstructed $D_{st}$ indices, especially during the “gapless” time intervals.

Nevertheless, the agreement between the original and reconstructed $D_{st}$ indices is better during the gapless intervals than during gaps. The correlation between the two indices during the short data gaps is 98.22% and 97.89% during the long data gaps. The average absolute differences for the two cases are about 4.52 nT and 4.07 nT. (The fact that the latter is slightly smaller may result from the fact that there are relatively more simultaneous short data gaps in two or more $D_{st}$ stations than simultaneous “long” data gaps mentioned above.) Taking into account the total amounts of the short and long data gaps in 1957–2002, their contributions to the average absolute difference between the original and reconstructed $D_{st}$ indices are about 2.62% and 4.71%, respectively.

We have further compared the original and the reconstructed $D_{st}$ indices during the gapless intervals. The mean and the standard deviation of the original $D_{st}$ for these times are $\mu = -16.30$ nT and $\sigma = 24.81$ nT while those for the reconstructed $D_{st}$ are closely similar: $\mu = -16.70$ nT and $\sigma = 24.58$ nT. Figure 3 depicts the histogram distributions of these indices separately for two ranges: the bulk of the values for $D_{st} > -150$ nT and the long tail of $D_{st} < -100$ nT. The close similarity of these figures further verifies that the agreement between the original and reconstructed $D_{st}$ indices is very good during gapless time intervals.

### 4.1 Problems in the original $D_{st}$ index

The $D_{st}$ index is known to depict a small but persistent diurnal UT variation (Mayaud, 1978; Saroso et al., 1993; Siscoe and Crooker, 1996; Cliver et al., 2000) which mainly results from the asymmetric distribution of the $D_{st}$ stations (Takalo and Mursula, 2001a). Figure 4 shows the annual averages of the diurnal UT variation in the original and reconstructed indices using all hourly values. Note first how similar the overall level and the temporal fluctuations in the two indices are for most years. However, the original $D_{st}$ index exhibits an exceptionally large UT variation in 1971 (Takalo and Mursula, 2001a,b). It was noted earlier (Karinen et al., 2001) that an UT variation closely similar to that in 1971 can be reproduced if the $S_q$ variation was erroneously treated in SJJG when deriving the original $D_{st}$ index. Since the reconstructed $D_{st}$ index depicts a roughly similar average in 1971 as in all other years, it is highly probable that the derivation of the original $D_{st}$ index for 1971 was indeed erroneous. This is also reflected in the fact that the correlation between the original and reconstructed indices is only 97.97% in 1971, i.e. weaker than on average. Note also that the data gaps in 1971 were not abnormally large and that the annual average of the UT variation in the original index remains the same, exceptionally high level, even if one uses only gapless days. Thus, the problem is not related to the treatment of data gaps.

Concluding, the original $D_{st}$ index in 1971 is erroneous and can be corrected by the newly reconstructed $D_{st}$ index.

Figure 5 shows the annual averages of the original and the reconstructed $D_{st}$ indices using all hourly values. Also, the absolute difference between the original and reconstructed $D_{st}$ in 1957–2002 is depicted. For most years, this difference is typically about 2–3 nT, i.e. on the same order of magnitude as the average absolute difference between hourly values that was discussed earlier. However, there are a few years where the difference is enhanced. In particular, in 1963–1966, this difference is nearly three times larger than the average difference, with the original $D_{st}$ index being larger (less negative) than the reconstructed index. Among these years the year 1965 is very special since it is the only year for which the annual average of the original $D_{st}$ index is positive, far above the annual average of any other year. Not questioning this result, the traditional view has been to accept the year 1965 as having been exceptionally quiet in the $D_{st}$ index. According to the reconstructed $D_{st}$ index, the annual average in 1965, although still attaining the highest value, is negative as in
all other years and reaches roughly the same level as some other quiet years. Thus, the extremely small nature of the year 1965 in the original \( D_{st} \) index is most likely an artefact. Note also that the two years (1960, 1991) with the lowest annual values in the original \( D_{st} \) index tend to be raised slightly higher, thus, to a more regular level in the reconstructed index.

We have also calculated the annual averages for both the original and the reconstructed \( D_{st} \) index using only gapless data. For most years the values are roughly the same as in Fig. 5 and the difference remains enhanced for the same years. Thus the problem in the original \( D_{st} \) index with the year 1965 is not related to data gaps.

5 The early \( D_{st} \) index in 1932–1956

5.1 Statistical properties and comparison with later period

The full reconstruction of the \( D_{st} \) index for the early period 1932–1956 is depicted in Fig. 2. The mean and the standard deviation of the reconstructed \( D_{st} \) index for this period are \( \mu = -17.03 \) nT and \( \sigma = 24.14 \) nT, using all data. These are quite similar to the corresponding values \( (\mu = -16.79 \) nT and \( \sigma = 24.81 \) nT) for the later time interval 1957–2002. Using only gapless data in 1932–1956 (which form about 96\% of time) the values are \( \mu = -16.94 \) nT and \( \sigma = 24.13 \) nT, i.e. almost exactly the same as those for the reconstructed \( D_{st} \) index in 1957–2002 \( (\mu = -16.70 \) nT and \( \sigma = 25.58 \) nT; see Fig. 3). On the other hand, if only the values during the gaps are taken into account, we find \( \mu = -19.48 \) nT and \( \sigma = 30.84 \) nT for the early period and \( \mu = -18.36 \) nT and \( \sigma = 28.41 \) nT for the later period.

Figure 3 depicts the histogram distribution also for the reconstructed \( D_{st} \) in 1932–1956, using gapless data. The histograms for the early \( D_{st} \) index and the two other \( D_{st} \) indices are very similar, although the former depicts a slightly less regular pattern, especially around -150 nT, probably due to smaller statistics. The close similarity of these figures further verifies that the agreement between the original and reconstructed \( D_{st} \) indices is very good, especially during gapless time intervals.

The annually averaged range of the diurnal UT variation (see Fig. 4) remains roughly at the same level in the early period as later. This is true although Fig. 4 includes all hourly values, and despite the fact that a new station (CTO) with a slightly different longitude was used in 1932–1940. Note also that no year in the early period depicts a similar, exceptionally large UT variation as in 1971. This further underlines the above discussed erroneous nature of the \( D_{st} \) index in 1971.

5.2 Long-term evolution of the \( D_{st} \) index

The long-term evolution of the \( D_{st} \) index depicted in Fig. 5 includes interesting details that greatly motivate the extension of the series to earlier times. Note first that the original \( D_{st} \) index depicts dramatic fluctuations during its first years from very low values in late 1950s and early 1960s to exceptionally high values in mid-1960s. Also, because of the particular construction method of the \( D_{st} \) index (viz., the way in which secular variation is removed) the low values of the \( D_{st} \) index during the first 4–5 years of the time series, in particular the minimum of the original \( D_{st} \) index in 1960 (the fourth year of the original \( D_{st} \) index) and the implied extremely disturbed time period, may be doubted.

However, our continuation of the \( D_{st} \) index to earlier years removes this doubt and, as depicted in Fig. 5, verifies that 1960 was among the most disturbed years in the \( D_{st} \) index during the whole 71-year period. Note also that according to the newly reconstructed \( D_{st} \) index the most disturbed year during the last 20 years was not 1991, as in the original \( D_{st} \) index, but rather 1989. Furthermore, although the high annual averages in the original \( D_{st} \) index in the mid-1960s are, as discussed above, erroneous and overestimated, they still remain above the long-term \( D_{st} \) average.

When moving further back in time with the new \( D_{st} \) index, we find (see Fig. 5) that the annually averaged \( D_{st} \) indices in the early period 1932–1956 are roughly in the same level as in the later period. For instance, there are no years in the early period where the annual \( D_{st} \) index is positive or even very close to zero. (This also suggests that the positive value in 1965 in the original \( D_{st} \) index was erroneous.) Curiously, the highest values in the early part and the later part are roughly equal (about \(-6 \) nT) in the reconstructed index.

The following long-term evolution in the \( D_{st} \) index can be noted over the 71-year time interval (Fig. 5; see also Fig. 7). First, the \( D_{st} \) index decreases with the increase of solar activity related to the start of the solar cycle 17. With the increasing height of the subsequent solar cycles the \( D_{st} \) values decrease fairly systematically during the two next solar maxima and the \( D_{st} \) index reaches a local minimum of \(-28.1 \) nT in 1960. Soon thereafter the \( D_{st} \) index raises rapidly to its absolute maximum \(-6 \) nT during the subsequent solar minimum in 1965. Thereafter, during solar cycles 20–22, the \( D_{st} \) indices at solar maxima decrease again slowly but systematically, reaching the overall minimum of \(-28.6 \) nT in 1989, close to the maximum of solar cycle 22. However, the \( D_{st} \) indices at solar minima show no clear trend but remain roughly at the same level during the last three minima.

5.3 Comparison with \( A_p \) index

The so-called \( K \)-related indices (Mayaud, 1980) form a uniform series of geomagnetic activity. The \( K \)-related indices have been calculated since 1932 and thus can be used to study the long-term evolution of geomagnetic activity over the same time interval as covered by the new reconstructed \( D_{st} \) index. Figure 6 correlates the annual averages of the quasi-linear \( A_p \) index with the absolute values of the simultaneous reconstructed \( D_{st} \) indices, separately for the early and later periods. (Only gapless data were used to calculate the annual averages of the \( D_{st} \) index. A similar procedure could not be followed for \( A_p \) because it is a daily index.) As seen in Fig. 6 the correlation between the two indices is
strong and fairly similar for both time intervals. The correlation coefficients are $R=0.77$ in 1932–1956 and $R=0.82$ in 1957–2002. (The corresponding correlation coefficients using daily averages are $R=0.78$ for both periods.)

The similarity of correlations in the two periods gives further evidence for the correctness of our construction of the $D_{st}$ index and especially its extension into the early period. Note also that the correlation coefficient between the annually averaged $A_p$ and the original $D_{st}$ indices is smaller ($R=0.80$) than for the reconstructed index in 1957–2002 using gapless data.

We have used the best fitting linear correlation equations included in Fig. 6 in order to model the $A_p$ index using the the reconstructed $D_{st}$ index. This “model” $A_p$ index and the observed $A_p$ index are shown in Fig. 7. The annual sunspot numbers are included in Fig. 7 for comparison. Figure 7 shows that there is a good overall agreement between the observed $A_p$ index and the modelled $A_p$ index, i.e. the reconstructed $D_{st}$ index. Large differences are found during the declining phase of solar cycles (in particular in 1951–1952, 1973–1974, 1983) when recurrent high-speed streams occur in the solar wind. Such streams typically cause rather weak magnetic storms and other types of geomagnetic activity (e.g. substorms) that are more restricted to higher latitudes and do not affect very strongly at the low-latitude $D_{st}$ index stations. On the other hand, large storms mainly occur around solar maxima. Since a similar difference between the the observed and modelled $A_p$ index is found both in the early period (1951–1952), as well as in the later period (1973–1974, 1983), we find that the conditions of the solar wind causing geomagnetic activity, on the one hand, and large magnetic storms, on the other have, remained quite similar over the studied 71-year time interval. We would also like to note that, in agreement with the modern view of the solar cycle, the difference between the observed and modelled $A_p$ index (a proxy of the strength of high speed streams) seems to be a good predictor of the height of the coming solar cycle.

Note that the two $A_p$ curves in Fig. 7 depict a fairly similar long-term evolution during the 71-year interval. The observed $A_p$ index includes all of the above-mentioned properties of the long-term $D_{st}$ activity: systematic increase from 1930s to a maximum in 1960; rapid decrease to a minimum in 1965; increase of activity during subsequent cycle maxima and rough levelling off during minima. However, the overall range of observed $A_p$ values is somewhat larger than the range of modelled $A_p$ values. The largest $A_p$ values are above the corresponding model values and the smallest $A_p$ values are below the model values. This is also seen in Fig. 6 where the points with the largest (smallest) $A_p$ values are well above (below) the best fitting line. Accordingly, the long-term fluctuations are slightly (relatively) larger in the $A_p$ index than in the $D_{st}$ index.

Note also that the observed $A_p$ index is systematically lower (see Fig. 7) than the modelled $A_p$ index in the beginning of the early period (1933–1940; ascending phase and maximum of SC 17). Also, the absolute minimum in the observed $A_p$ index is already reached in 1933. We are confident that this difference lasting 8 years is not technical, i.e. due to the method of reconstructing the $D_{st}$ index or due to the above-mentioned question related to the first four years, and hardly due to statistical fluctuation. Rather, it may indicate a problem in the $A_p$ index ($K$-indices more generally) or an interesting deviation in the physical relations between the two indices at this time. Taking into account that the increase of geomagnetic activity in 1930s is part of a longer increase present in the $aa$ index since the beginning of the century (see, e.g. Clilverd et al., 1998; Lockwood et al., 1999), the observed difference would motivate an extension of the $D_{st}$ index (or a related proxy) even to earlier years.
5.4 Superposed epoch analysis of geomagnetic storms

We have studied the $D_{st}$ index and the magnetic storms also by using the superposed epoch (SPE) analysis method. We have included in the analysis all the SSC (sudden storm commencement) storms mentioned in the SSC list by NGDC (2004), and used the SSC times as the superposed epoch zero times. (There are 729 SSC storms in the list in the early period and 1497 in the later period.) For each storm, the $D_{st}$ indices from one day before the SSC time until 6 days after it were included in the SPE analysis. Figure 8 depicts the resulting SPE storm curves for the reconstructed $D_{st}$ index in the early and the later period separately, as well as for the original $D_{st}$. (This analysis includes full $D_{st}$ data, not only gapless data.) Note how closely the SPE storm curves for the original and reconstructed $D_{st}$ indices in 1957–2002 follow each other over the whole 7-day storm time. In fact, the average difference between the two curves is only $0.08\,nT$, i.e., much smaller than the average difference between the two $D_{st}$ time series. This is due to the fact that the SPE method randomizes the statistical differences between the two indices for each SPE hour. In fact, this agreement also verifies that there are no large systematic differences between the two $D_{st}$ indices.

On the other hand, the SPE storm curve for the early period deviates from the later period in several ways. Statistically, the average difference between the two curves is $1.07\,nT$. Compared to the above-mentioned result that a difference due to statistical fluctuations is at most $0.08\,nT$, the difference between the two SPE curves for the two periods is significant. In the compression phase before the SSC and, in particular, at the $D_{st}$ minimum the SPE curve for the early period is a few $nT$ above the curve for the later period. Accordingly, on average, the storms in the early period seem to be slightly less intense than in the later period. This is consistent with the fact that the $D_{st}$ indices (e.g., the annual values, see Fig. 5) include considerably larger values in the later period than in the early period. However, in the late recovery of the storm, since SPE day 4 onwards, the $D_{st}$ index in the early period remains lower than in the later period. This feature recovers the above-mentioned similar overall averages of the $D_{st}$ indices in the two periods, and suggests that, on average, storms may recover slower in the early period. These differences, although rather small for conclusive evidence, may still be indicative of a systematic long-term change in the interplanetary conditions. The weaker main phase and the longer recovery phase in the early period suggests that the storms at that time were more typically driven by recurrent streams (often producing HILDCAA, high intensity long duration continuous AE activity, type storm recovery phases (Tsurutani and Gonzales, 1987; Soraas et al., 2004)), rather than by strong CMEs, as typical in more recent times.

As a final study, we have depicted in Fig. 9 the annually calculated superposed storm curves, with the SPE day running vertically and years horizontally. The $D_{st}$ values are given in colour code with strongly negative values in blue, weakly negative values in yellow and positive values in red. (Here, as in Fig. 8, we have used all $D_{st}$ data, not only gapless data.) Figure 9 shows clearly the strong solar cycle variation in the storm development, with blue colour dominating after the SPE zero time in solar cycle maximum years and yellow colour in minimum years. The strongest and most persistent blue colours are found during the maximum of SC 19, in agreement with the annual $D_{st}$ maximum in 1960 (see Fig. 7). Strongly stormy years are also found around the maxima of solar cycles 17, 21 and 22. However, strong storm activity in SC 17 is quite surprising, taking into account the rather low annual averages during this cycle. Note also that the most stormy years during this cycle occur rather late in the declining phase of the cycle and that there are only rather a few stormy years in this cycle. In fact, these properties are most closely reproduced during cycle 21 while the storm activity in cycles 19 and 22 lasts longer and extends over the whole sunspot maximum.

There are also some differences in the storm activity level during solar minimum times. We find three periods of exceptionally high $D_{st}$ values (weak activity) after the SPE zero time. These appear in Fig. 9 as large yellow regions in early 1930s, in mid-1960s and in mid-1990s. Note that these seem to appear every third solar minimum, when the lowest values of the $A_p$ index are also found (see Fig. 7). This gives additional support for the suggested 3-cycle periodicity in solar activity and, for example, cosmic rays (Ahluwalia, 1998). Moreover, the higher $D_{st}$ level during these times is also found before the SPE zero time and, especially, at the SPE zero time when the $D_{st}$ attains typically positive values. On the other hand, during solar maximum years, in particular during the strongest maxima discussed above, the SPE zero time $D_{st}$ level is clearly lower, weakly negative.
6 Conclusions

We have reconstructed the geomagnetic $D_{st}$ index for 1932–2002, thus extending it by 25 years, i.e. by more than one full solar magnetic cycle. The extension was done by using data from the original set of four low-latitude stations for 1941–1956, and by using the nearby CTO station as a predecessor of the HER station for 1932–1940. Although we have followed the original $D_{st}$ formula as closely as possible, the $D_{st}$ index cannot, because of inadequate information, be fully reproduced and therefore remains partly unscientific. As a comparison, we give here a complete formula for our reconstruction of the $D_{st}$ index. Despite the open questions related to the formula of the original $D_{st}$ index, the reconstructed index is quite similar to the original one during the overlapping time interval (1957–2002). The average difference between the two indices is only about 3 nT and their correlation coefficient is about 98.7%.

We note that the reconstructed $D_{st}$ index corrects for some known errors in the original $D_{st}$ index, such as the erroneously large daily UT variation in 1971. Despite the fair overall agreement, the reconstructed index deviates from the original index even on the level of annual averages for some years. All annual averages of the reconstructed index are negative and for 1962–1966 they are systematically lower (more stormy) than those of the original index. Accordingly, we disagree with the uniquely positive annual average of the original index in 1965, which most likely is erroneous. We also find somewhat higher (less negative) values than in the original $D_{st}$ index for the three lowest annual averages in 1960, 1989 and 1991. Out of these the lowest annual average is found in 1989 rather than in 1991.

The reconstructed $D_{st}$ index presents a homogeneous, 71-year series which can be used, for example, to study the long-term development in the ring current and in the evolution and structure of storms. The annual averages of the geomagnetic $A_p$ index and the reconstructed $D_{st}$ index correlate very well over this time interval, except at the beginning of the series in 1933–1940 and in the declining phase of solar cycles 18, 20 and 21, where high speed solar wind streams cause enhanced geomagnetic activity. While the reconstructed $D_{st}$ indices in 1932–1956 and 1957–2002 are statistically quite similar, we find differences in the average storm development during the two periods using the superposed epoch method. During the early period in 1932–1956 the storms are less intense but tend to have a longer recovery phase, suggesting that there are more HILDCAA-type medium activity intervals during the early period than more recently. We also study the annually averaged storm structure using the superposed epoch method and find that the most stormy years occur during the declining phase of solar cycles 17 and 21 and around the solar maxima of cycles 19 and 22. On the other hand, the least stormy years are found in early 1930s, mid-1960s and mid-1990s, in agreement with the lowest cycle minima of the $A_p$ index.

Note: The extended and reconstructed $D_{st}$ index described and studied in this paper will be released to the geophysical community via the World Data Center system as soon as possible. At the same time we will introduce a new symbol for
our index in order to avoid confusion with the original $D_{st}$ index. At present, our best candidate for the coming name is the $D_{st}$ index, emphasizing the fact that the time range of the $D_{st}$ index was greatly extended.

Topical Editor T. Pulkkinen thanks M. Campbell, M. Happgood and another referee for their help in evaluating this paper.

References


WDC-C1.: Hourly mean geomagnetic data, World Data Center for Geomagnetism (WDC-C1), http://swdcdb.kugi.kyoto-u.ac.jp, Kyoto, Japan, 2004.