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Explaining and correcting the excessive semiannual variation in the *Dst* index

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[1] It is known that the semiannual variation in the *Dst* index is excessively large compared to all other indices of geomagnetic activity. This has been interpreted in terms of a separate "non-storm component" which forms roughly one half of the whole semiannual variation in the *Dst* index. Since this component is not related to storms or the ring current it should be removed from the *Dst* index. We show how the "non-storm component" arises from the seasonal variation of the magnetic field at the *Dst* stations and from the erroneous treatment of the quiet-time curve during the construction of the index. Moreover, we reconstruct a corrected *Dst* index which is purified from the non-storm component and show that then the semiannual variation indeed attains the same level as in other geomagnetic indices. This correction will greatly affect earlier estimates of the physical causes of semiannual variation based on the *Dst* index. Since the correction will reduce the power at periods even longer than the semiannual period, in particular the annual variation, it has important consequences also on other types of studies based on the *Dst* index. **Citation:** Mursula, K., and A. Karinen (2005), Explaining and correcting the excessive semiannual variation in the *Dst* index, *Geophys. Res. Lett.*, *32*, L14107, doi:10.1029/2005GL023132.

1. Introduction

[2] One of the first features recognized in geomagnetic activity was its semiannual (SA) variation with equinoctial maxima [*Sabine*, 1856]. Three hypotheses have been proposed to explain the SA variation. In the axial hypothesis [*Cortie*, 1912; *Bohlin*, 1977] maxima are attained when the Earth is at the highest heliospheric latitudes, being exposed to fast solar wind streams. The equinoctial hypothesis [*Bartels*, 1932] assumes that activity depends on the orientation of the Earth's dipole axis. The third hypothesis by *Russell and McPherron* [1973] was the favorite explanation for SA variation for long. There, the equatorial solar magnetic field induces a seasonally varying southward component in the GSM coordinate system. However, after the analysis by *Cliver et al.* [2000] and the new physical mechanism proposed by *Lyatsky et al.* [2001] and *Newell et al.* [2002] the equinoctial hypothesis has gained more popularity.

[3] Recently, *Cliver et al.* [2001] raised the concern that the SA variation of the *Dst* index exhibits a dominant "non-storm component" unrelated to geomagnetic activity. The amplitude of the SA variation was found to be 5.3 nT when using all *Dst* data. When only the five quietest *Dst* days for each month (hereafter: quiet days) were used, the SA amplitude was 2.5 nT, i.e., 47% of the full variation. Thus, the *Dst* index exhibits a large SA variation which is not related to magnetic storms. So far there was no explanation for this "non-storm component".

[4] The solution of this problem requires a complete reconstruction of the *Dst* index. We have recently reconstructed the *Dst* index, extending it by 25 years since 1932 [*Karinen and Mursula*, 2005]. The derivation of this reconstructed and extended index, to be called here the *Dxt* index, closely follows the original recipe for the *Dst* index [*Sugiura*, 1969; *Sugiura and Kamei*, 1991; *World Data Center for Geomagnetism*, 2004]. The *Dst* index and the *Dxt* index agree to high accuracy during the overlapping time 1957–2002 [*Karinen and Mursula*, 2005]. Also, we have noted on some significant errors in the *Dst* index that have been corrected in the *Dxt* index.

[5] In this paper we show that the original recipe of the *Dst* index leaves a significant SA variation which is related to the seasonal variation of the geomagnetic field at the *Dst* stations and unrelated to storm development. This is the "non-storm component" reported by *Cliver et al.* [2001]. We show how the *Dst* index must be corrected in order to remove this component, making the *Dst* index a more truthful measure of storm evolution. After this redefinition the SA component in the *Dst* index attains the same level as in other indices.

2. Derivation of the *Dst* Index

[6] Let us first briefly repeat the derivation of the *Dst* index [see *Karinen and Mursula*, 2005]. Firstly, the secular trend of the magnetic H component is calculated at each station by fitting a second order polynomial to 5 years of data in quiet days. This trend is removed from the observed H component, yielding the hourly deviations ΔH. Note that this removal of the secular trend leaves the seasonal variation in ΔH. Using only quiet days in the trend affects the absolute level in ΔH but not its seasonal variation.

[7] Secondly, the superposed daily (LT) variation is calculated from the ΔH in quiet days. A linear trend from one superposed night to another is then subtracted from the 24 hourly values. The 288 (12×24) rescaled hourly values for each year form a 2-dimensional S_q^o matrix which is smoothed in a 2-dimensional Fourier transformation, including only the DC and the first six Fourier components. The smoothed S_q^o values give the final quiet-time daily LT variation for each month, which is then subtracted from the hourly ΔH values to yield the disturbance variations $D(t)$ at each station. Finally, the disturbance variations from the four *Dst* stations (Hermanus, HER; San Juan, SJG;

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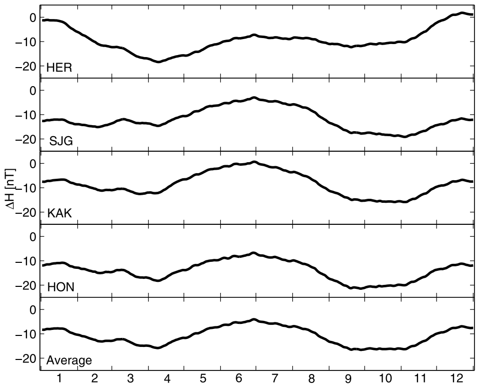

Figure 1. Seasonal variation in Δ*H* of the four *Dst* stations and in the combined Δ*H*. Hourly values have been smoothed over 31 days. Horizontal axis numbers the months. Note that, since secular variation is calculated from quiet days, the overall level of Δ*H* is negative.

Kakioka, KAK; Honolulu, HON) are normalized by the respective cosines of geomagnetic latitudes and then averaged to the final *Dst* index.

3. Seasonal Variation in the H Component

[8] At each *Dst* station there is a seasonal variation in the *H* component with the main maximum during local Summer, a lower maximum in local Winter and minima during equinoxes (see Figure 1), leading to a dominant annual and subdominant semiannual variation. (The same structure remains in Δ*H*). The Summer maximum in the *H* component is mainly due to the seasonal variation in the location of the Sq current [see, e.g., *Takeda*, 2002] which shifts the region of maximum increase in *H* away from the equator toward the Summer hemisphere. This effect is clearly visible at all low and mid-latitude stations.

[9] The relative fraction of annual vs. semiannual variation varies slightly with the location of station with respect to the moving Sq current. At higher latitude stations the annual variation is emphasized, while the SA variation dominates around the equator [see, e.g., *Campbell*, 1981]. This is also seen in Figure 1 where the annual variation dominates more clearly at HER and SJG that are higher in geomagnetic latitude than HON and KAK where SA variation is pronounced.

[10] The *Dst* index consists of three stations from the northern hemisphere (SJG, KAK, HON) and one station (HER) from the southern hemisphere. Since the seasonal maximum occurs during the local Summer, the maxima in the two hemispheres are in anti-phase and tend to decrease the annual variation when all stations are combined. (The combined Δ*H* is also depicted in Figure 1). However, equinoctial minima are in phase in both hemispheres, enhancing the SA variation in the combined curve. Thus, the annual variation is reduced and the SA variation is enhanced in the combined Δ*H*. This leaks into the *Dst* index, causing excessive SA variation.

[11] The dominance of annual variation is even more clearly visible when Δ*H* is calculated for quiet days. This is depicted for SJG in Figure 2. We have also calculated Δ*H* separately for those quiet days that occur during storm times (during 6 days after SSC signal; storm-time quiet days) and those quiet days that are outside these times (non-storm quiet days). The former form about 27% of all quiet days. The seasonal variation of Δ*H* in quiet days closely follows that in the non-storm quiet days. In addition to the Sq current, the so called Malin-Isikara effect [*Malin and Isikara*, 1976; *Malin and Isikara*, 1999] may also cause a smooth seasonal variation with Summer maximum by turning the ring current/magnetospheric tail current away from the Summer hemisphere and thus reducing their negative effect in the Summer hemisphere. At the equator, a dominant semiannual variation would result from the M-I effect, while the annual variation would relatively increase at higher latitudes.

4. Semiannual Variation in the *Dst* Index

[12] Figure 3 depicts the seasonal variation for the *Dst* index and the *Dxt* index in 1957–2002. The seasonal pattern shows a large SA variation. The difference between equinoxes (maxima in the reversed presentation of Figure 3) and Summer (Winter) is about 14 (10) nT. Fitting the curves of Figure 3 by two sinusoids with annual and SA periods and a constant, gives the average SA amplitude in the *Dst* (*Dxt*) index of about 5.7 nT (5.8 nT). These numbers agree well with the estimate (5.3 nT) by *Cliver et al.* [2001] for *Dst* in 1957–1997.

[13] Figure 3 also depicts the SA variation in the *Dst* index using only quiet days. (Note the different level of this curve, in agreement with the different levels of the curves in Figure 2). The quiet days SA amplitude is about 2.8 nT, again in a good agreement with the estimate (2.5 nT) by *Cliver et al.* [2001]. We also note that the average amplitude of the annual variation in the *Dst* index is 3.2 nT for all days and 2.3 nT for quiet days. Thus, the fraction

Figure 2. Seasonal variation of Δ*H* at SJG in 1957–2002 for four different time selections (from top to bottom): non-storm quiet days, all quiet days, storm-time quiet days, and all days. (Latter curve is the same as in Figure 1).

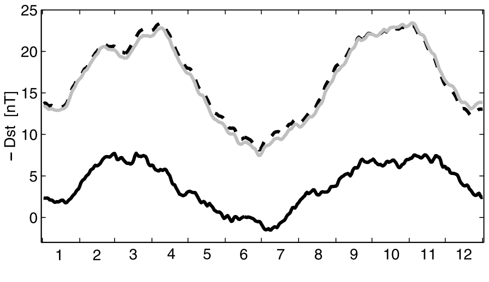

Figure 3. Average seasonal variation in 1957–2002 for the *Dst* index (grey), the *Dxt* (dashed) in all days, and for the *Dst* index during quiet days (black).

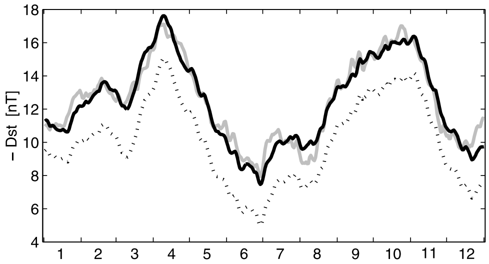

Figure 4. Average seasonal variation in 1957–2002 for the two corrected *Dcx* indices (dotted: asymmetric reduction, black: symmetric reduction) and for the *Dst* index during non-quiet days (i.e., all except for quiet days; grey).

of the annual variation is larger for quiet days than for all days, in agreement with the above discussed seasonal variation of ΔH.

[14] Let us now continue to analyse the formation of the *Dst* index, and study how the removal of the S_q^o curve affects the seasonal variation in the *Dst* index. As noted above, in the original *Dst* method, a linear trend $L(t) = a \times t + b$ is removed from the superposed daily quiet curve S_q^o using night-time values. This is important when solving the problem of the "non-storm component", since removing the linear trend from S_q^o also removes the daily ΔH level which, as shown above, varies seasonally. Thus, when S_q^o is subtracted from ΔH to form $D(t)$, the original seasonal variation in the ΔH curve remains in $D(t)$ and, thereby, also in the *Dst* index. Therefore, the *Dst* index obtains an excessive SA component.

[15] Originally, the reason to remove the linear trend from the S_q^o curve was the following. As mentioned above, quite a many of the quiet days used to calculate S_q^o occur during the storm recovery phase. Removing the linear trend from S_q^o aims to exactly maintain the variable daily level of the recovery phase in the *Dst* index since the original aim is to study the daily development of the ring current and magnetic storms.

5. Correcting the *Dst* Index

[16] Clearly the slope *a* of the linear trend relates to the short-term trend of ΔH within the respective month, and thereby, takes the recovery of the ring current into account. However, the intercept *b* of the linear trend includes the quiet time level of the respective month which, as seen above, varies seasonally and is mainly due to other effects than storm development. Therefore, a more correct way is to subtract only the linear slope $L(t) = a \times t$ from the S_q^o curve, thus removing the seasonally variable trend from the *Dst* index.

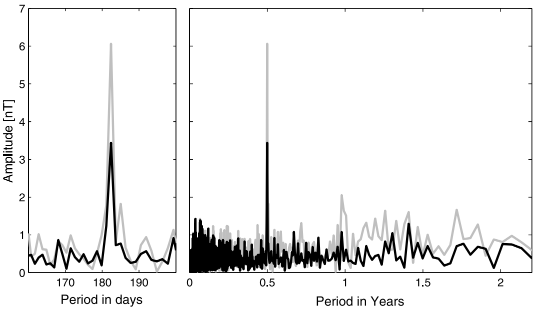

Figure 5. Amplitude spectra of the *Dxt* (grey) and the (symmetric) *Dcx* (black) indices in 1932–2002 for periods around half a year (left), and from half a year up to about 2 years.

[17] We have corrected the *Dst* index for its excessive seasonal variation by calculating a new, corrected *Dst* index to be called *Dcx* (corrected, extended *Dst*) using this method. Figure 4 depicts the seasonal variation of this corrected index. The average (sinusoid) amplitude of SA variation in *Dcx* is only 3.2 nT, i.e., roughly one half of that in the *Dst* index. The difference between these two amplitudes, about 2.5 nT, is then the estimated SA amplitude of the "non-storm component". This estimate is in a good agreement with the 2.8 nT amplitude of the SA variation for quiet days (2.5 nT according to *Cliver et al.* [2001]).

[18] We have depicted in Figure 4 also the difference between the curves for all days and quiet days which gives the SA variation in the *Dst* index for the non-quiet, i.e., more disturbed days. The sinusoid amplitude of SA variation for this curve is 3.1 nT, i.e., almost exactly the same as for the *Dcx* index. Note that even the form of the curves in Figure 4 agrees with each other in great detail, but deviates notably from that of the curves, especially the quiet-days curve, in Figure 3. These facts prove that the *Dcx* index describes closely the level of the real SA variation related to geomagnetic activity, after the excessive quiet-time "non-storm component" has been removed. Note also that the overall level of the *Dcx* index in Figure 4 is much above (more negative than) the level of the *Dst* index for quiet days, and is rather close to the level of the non-quiet-day *Dst* index. This gives further evidence that the SA variation in the *Dcx* index indeed comes from the more disturbed days.

[19] The overall level of the *Dcx* index in Figure 4 is slightly but systematically below (less negative than) the level of the non-quiet-day *Dst* index. This is due to the asymmetric treatment of the night-time activity in the above procedure, leading to the "asymmetric" *Dcx* index described above. When the slope $L(t) = a \times t$ is removed, the two successive nights are set on the level of the first night. If we, after removing the trend, set both nights to their average level, we treat the two night symmetrically and attain a "symmetric" *Dcx* index. As seen in Figure 4, the form of the SA variation in the symmetric and asymmetric *Dcx* indices is exactly the same but the symmetric *Dcx* index is about 2.4 nT higher and matches the level of the non-quiet *Dst* index perfectly. Thus, the symmetric way of correcting the *Dst* index is more appropriate.

[20] We have also calculated the amplitude spectra for the *Dxt* index and the (symmetric) *Dcx* index during the

Table 1. Normalized Amplitudes of Semiannual and Annual Variations for Different Geomagnetic Indices in 1957–1994

Geomagnetic Index	0.5-Year Amplitude	1-Year Amplitude
Ap	0.13	0.04
Aa	0.13	0.04
AE	0.10	0.13
Dst	0.23	0.13
Dxt	0.22	0.12
Dcx	0.13	0.05

extended interval 1932–2002 (see Figure 5). We find that the correction decreases the spectral peak at the SA period from 6.1 nT to 3.4 nT, implying that roughly 45% of the seasonal variation in the *Dst* index results from the "non-storm component", in an excellent agreement, e.g., with the 47% (2.5 nT/5.3 nT) estimate by *Cliver et al.* [2001].

6. Comparison With Other Indices and Periods

[21] The fact that the SA variation is excessively strong in the *Dst* index is demonstrated by a comparison with other geomagnetic indices. In order to make the different indices comparable at the absolute level, we have first, before calculating the amplitude spectra, scaled each index by its standard deviation.

[22] Table 1 tabulates the SA and annual amplitudes obtained from the spectral peaks for the three *Dst* indices (original, reconstructed, and corrected) and for the *Ap*, *Aa*, and AE indices during the same period 1957–1994. One can see that the SA amplitude is largest of all in the *Dst* (and *Dxt*) index, being almost 80% larger than, e.g., in the *Ap* and *Aa* indices. After the correction, the SA amplitude in the *Dcx* index is very close to the level in all other indices. This verifies that the correction of the *Dst* index has been made in a reasonable way and that the SA variation after the correction is due to the same (mainly external) causes as in the other indices.

[23] As shown in Figure 5, the correction of the *Dst* index does not only affect the SA variation. In particular, the annual variation suffers a large decrease, even relatively larger than the SA variation (see also Table 1). This is understandable from the way the *Dst* index is calculated since the annual (semiannual) variation is the fundamental (second harmonic, respectively) sinusoid to be fitted in the S_q^o matrix. Figure 5 also shows that the correction reduces the amplitude of even longer periods in the *Dst* index, e.g., the mid-term quasi-periodicities in the period range of 1–2 years [see, e.g., *Mursula et al.*, 2003; *Mursula and Vilppola*, 2004]. Thus, the correction changes the spectral content of the *Dst* index over a wider period range. Therefore, it is clear that correcting the *Dst* index will have an effect on different types of studies made using the *Dst* index, not only those where the SA variation of the index has been studied.

7. Conclusion

[24] We have discussed the excessively large semiannual variation in the *Dst* index, which appears as the so called "non-storm component" and forms roughly one half of the whole semiannual variation. Since the "non-storm component" is unrelated to the development of storms or the ring current, it has to be removed from the *Dst* index.

[25] We have shown here that "non-storm component" arises from the seasonal variation of the magnetic *H* component at the *Dst* stations and from the erroneous treatment of the quiet daily curve in the original *Dst* method. We have corrected the *Dst* index by modifying this treatment, and calculated a corrected and extended version of the *Dst* index called the *Dcx* index from 1932 onwards. After this correction the "non-storm component" disappears from the *Dcx* index and the semiannual variation attains the same level as in other geomagnetic indices.

[26] The reduction of the semiannual amplitude in the *Dst* index will obviously affect most earlier estimates of the physical causes of semiannual variation based on the *Dst* index. (E.g., the analysis by *Chen* [2004] depends on the absolute *Dst* level and will be affected. On the other hand, *Cliver et al.* [2000] subtracted the non-storm component whence their results are probably unaffected). Moreover, since the correction of the *Dst* index reduces the amplitude of periods even longer than the semiannual period, it also affects other types of studies based on the *Dst* index, not only those where the semiannual variation has been studied.

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