A space-based proxy for the Dst index

The Dst index was created to monitor and quantify disturbances in the inner magnetosphere using ground-based, magnetic field measurements. The phases and strengths of geomagnetic storms are usually defined by the evolution of Dst. The standard Dst database is computed and maintained at the World Data Center for Geomagnetism, Kyoto. We demonstrate that the Dst index can also be approximated using magnetometers on spacecraft in near-Earth orbit. Measurements used in the demonstration were obtained from boom-mounted sensors on two spacecraft of the Defense Meteorological Satellite Program. The extraction technique can be applied to magnetic field data retrieved by magnetometers on any spacecraft in low Earth orbit. This alternate method for computing a Dst-like index can be used to (1) supplement the standard Dst index in near-real-time space weather applications and (2) replace the “prompt” Dst index during periods of unavailability.

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13. SUPPLEMENTARY NOTES

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15. SUBJECT TERMS
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A space-based proxy for the $D_{st}$ index

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The $D_{st}$ index was created to monitor and quantify disturbances in the inner magnetosphere using ground-based, magnetic field measurements. The phases and strengths of geomagnetic storms are usually defined by the evolution of $D_{st}$. The standard $D_{st}$ database is compiled and maintained at the World Data Center for Geomagnetism, Kyoto. We demonstrate that the $D_{st}$ index can also be approximated using magnetometers on spacecraft in near-Earth orbit. Measurements used in the demonstration were obtained from boom-mounted sensors on two spacecraft of the Defense Meteorological Satellite Program. The extraction technique can be applied to magnetic field data retrieved by magnetometers on any spacecraft in low Earth orbit. This alternate method for computing a $D_{st}$-like index can be used to (1) supplement the standard $D_{st}$ index in near-real-time space weather applications and (2) replace the “prompt” $D_{st}$ index during intervals of unavailability.


1. Introduction

2. Background

[6] $D_{st}$ was formulated [Dessler and Parker, 1959; Sugiura, 1964] as a tool for tracking and quantifying the duration and energy content of the magnetospheric currents. The $D_{st}$ index is compiled from magnetic field records of four, off-equator stations. Secular variations of the main...
field are first removed from the H-component traces from the four stations. Subsequently seasonally dependent, quiet-day variations are subtracted from the residuals to obtain these disturbance daily variations at each station location. These variations are then divided by \( \cos \theta \), where \( \theta \) represents the geomagnetic latitudes of the stations. The perceived need for this "correction" assumes that a simple ring of current flows in the magnetospheric equatorial plane. The average of the remaining four values is the \( Dst \) index. As it became obvious that magnetospheric currents vary significantly with LT, a corrective term "partial ring current" was added to the geomagnetic vocabulary without changing the definition of \( Dst \).

[7] The terms "ring current" and "partial ring current" imply simple sets of currents. Although these terms are convenient and widely used, they describe the configuration of magnetospheric currents inaccurately. Responsible currents are actually temporally and spatially varying ensembles of currents. Modeling by Tsyganenko and Sitnov [2005, and references therein] shows that during the main phase of major geomagnetic storms, \( Dst \) is influenced in decreasing order of importance by the asymmetric (partial) ring current, the near-tail current, the symmetric ring current, and the field-aligned currents (FACs) that couple the magnetosphere to the high-latitude ionosphere and magnetopause currents. During the recovery phase the symmetric ring current is, by far, the dominant contributor.

[8] Geomagnetic storms are driven by disturbed conditions in the interplanetary medium near Earth. The initiation of most storms is marked by a sudden increase in the solar wind's dynamic pressure. Consequent magnetopause-current enhancements cause positive excursions in the \( H \) component, known as sudden storm commencements and initial phase. The main phase of a storm occurs while the interplanetary electric field (IEF) has significant dawn-to-dusk components. \( Dst \) decreases with time, becoming significantly negative with respect to the quiet-time levels. As the IEF's dawn-to-dusk component decays or reverses polarity, the slopes of \( Dst \)-versus-time traces turn positive and a storm enters its recovery phase. If interplanetary parameters return to sustained predisturbance levels, the \( Dst \) index approaches quiet-time levels over several days as the symmetric ring current ions are slowly lost via charge exchange with geocoronal neutrals.

[9] McPherron and O'Brien [2001] and Temerin and Li [2002, 2006] have developed sets of quasi-empirical formulas that compute the evolution of \( Dst \), based exclusively on measured interplanetary parameters. While these formulas reproduce the standard \( Dst \) index quite well, they have not been used in near-real-time operations. The relevant input data for these models are obtained from sensors on research satellites such as the Advanced Composition Explorer near the first Lagrange point. These satellites cannot be relied upon to produce data for years into the future. Also, because the standard \( Dst \) index has been available on needed timescales, the formulas have not yet found wide usage within the research community.

3. **Instrumentation**

[10] Spacecraft of the DMSP series fly in polar, circular orbits at \( \sim 847 \) km geocentric altitude with an inclination of 98.8°. This combination forces the orbital plane to precess \( 360° \) per year. Thus each spacecraft crosses the equator at approximately the same LT throughout its lifetime. The orbital period of the spacecraft is \( \sim 102 \) min. For DMSP Flight 10 (F10) and beyond, the ascending node is in the
dusk-evening LT sector. Spacecraft attitude is maintained to within 0.01° of the local vertical-forward orientation.

From 1983 to the present, eight DMSP satellites have carried fluxgate (vector) magnetometers. The sensors on F7, F12, F13, and F14 were mounted on the spacecraft frame. Instruments on F12 and beyond are similar to units flown on many NASA missions [Acuña, 1974]. DMSP magnetometers measure magnetic field vectors 12 s⁻¹ with a resolution of 2 nT in the range of 0 to 4103 nT. They have 64 offsets that extend the range to ±65,660 nT. Sensor mounting has an alignment precision of 0.5° relative to the spacecraft. Postlaunch analysis reduces the alignment precision to between 0.1° and 0.2°. The axes of the sensor and spacecraft align so that X is downward, antiparallel to local vertical, Y is parallel to the spacecraft’s velocity vector, and Z is antiparallel to the orbit normal vector. For most uses, including the present work, the measured field is averaged over 1 s and the International Geomagnetic Reference Field (IGRF) is subtracted. Data shown in this paper are differences between measured vectors and those computed using the ninth generation IGRF2000.

Magnetic field sensors were first included on DMSP payloads to identify FACs at high latitudes and to monitor secular variations of the Earth’s main field. The goal of identifying FACs has been implemented at the research but not operational level. Owing to excessive noise from the spacecraft the goal proved unachievable with body-mounted sensors. To reduce noise interference, the magnetic field sensor units were mounted on 5-m booms, starting with F15 (launched in December 1999) and continuing with F16 (October 2003) and F17 (November 2006). Boom-mounting will be provided on all future DMSP spacecraft. The F15 and F16 spacecraft cross the equator at approximately 9 a.m./p.m. and 8 a.m./p.m., respectively. The advent of high-quality magnetic field instruments on the Ørsted and the Challenging Minisatellite Payload (CHAMP) missions lessened the urgency for using DMSP magnetometer data to model the Earth’s main field. Only the cleaner and easier to handle magnetic field data from F15 and F16 are used in this paper.

4. Data Analysis

Our primary goal is to specify deviations of the magnetic-field H component from quiet-time values measured as DMSP spacecraft cross the magnetic equator. This report describes results of newly developed procedures to remove biases and signals, unrelated to geomagnetic activity, from the spacecraft-based Y (forward, horizontal) and Z (cross-track, horizontal) components. We then combine corrected magnetic-field components measured in space to calculate ΔH and compare it with the Dst index derived from ground-based data.

In the absence of geomagnetic currents, deflection vectors ΔB (= Bmeasured − BmodeI) should, in principle, be zero. In fact, we usually find nonzero values attributable to uncertainties in sensor alignment and/or calibration, spacecraft-produced magnetic fields and the IGRF model. Figure 1 shows an example of the Y and Z components of ΔB acquired during slightly more than half of an orbit of F15. In the present study each analyzed data segment starts a few minutes before a spacecraft crossed the magnetic equator and ends a few minutes after its next equatorial crossing. Data acquired at high magnetic latitudes were excluded to avoid contributions from FACs that electrically couple the ionosphere and magnetosphere. High-latitude segments were designated with reference to equatorward boundaries of auroral electron precipitation, identified in measurements from the SSJ instruments present on all DMSP spacecraft [Hardy et al., 1985]. The auroral electron boundaries are marked by vertical dotted lines in Figure 1. Since the FACs often extend a few degrees in latitude equatorward of auroral electron boundaries, the limits for selecting data are set 90 s (~5°) equatorward. The locations of these subauroral boundaries are marked by vertical dashed lines in Figure 1.

Figure 2. The DMSP magnetic deflection vector after subtracting the fitted polynomial curve from the measured deflection vector shown in Figure 1.

3 of 7
Note that our fitting procedure differs significantly from that in 2002. Figure 3 shows the result of subtracting fitted polynomial values at equator crossings. Differences were sorted by hour of day and longitude are closely linked to the UT hour of the day. A daily variation was expected since the hour of day and longitude are closely linked. At the time of the data in Figure 1, theDst index was near zero. On the basis of geophysical considerations, the DMSP magnetic field deflections ΔBy and ΔBz should also be near zero. Figure 1 shows they are not zero. However, the observed finite values were found repeatable from orbit to orbit. The present work began after we noticed that DMSP ΔBm, the component closest to the direction of B at the magnetic equator, varied in time in ways that were strikingly similar to those of Dst.

The obvious next step was to subtract constant offsets from the polynomial values of ΔBy and ΔBz at the magnetic equator. When historic values of Dst were near zero, the subtraction of constants appropriate for each component at different spacecraft locations also brought the component values at the magnetic equator to near zero. The constants applicable to the morning and evening sides of the orbit were different and varied from spacecraft to spacecraft but remained consistent from year to year. The constants ranged in absolute value between 20 and 70 nT. Most likely they reflect factors not accounted for in preflight calibrations of the sensors and/or surveys of spacecraft-generated magnetic fields.

We next examined differences between Dst and polynomial-fit values for the spacecraft ΔBy and ΔBz at the magnetic equator crossings as functions of the day of the year. Annual variations exist at the magnetic equator. When historic values of Dst were near zero, the subtraction of constants appropriate for each component at different spacecraft locations also brought the component values at the magnetic equator to near zero. The constants applicable to the morning and evening sides of the orbit were different and varied from spacecraft to spacecraft but remained consistent from year to year. The constants ranged in absolute value between 20 and 70 nT. Most likely they reflect factors not accounted for in preflight calibrations of the sensors and/or surveys of spacecraft-generated magnetic fields.

At low and middle latitudes, the components of ΔB vary more slowly than at high latitudes. However, some variations about uniform trends remain. To determine the trend and exclude small-scale variations, a least squares polynomial was fitted to the data values for each component observed during the ~60 min intervals DMSP satellites spent at subauroral latitudes. Polynomials of order 7 and 5 were applied to ΔBy and ΔBz measurements, respectively. To insure the goodness of the procedure, we then calculated root-mean-square (rms) differences between the polynomial fits and original data. If the rms for ΔBy and ΔBz exceeded 15 and 20 nT, respectively, we reset the fitting boundary to 180 s (~10°) equatorward of auroral electron boundaries and repeated the polynomial fitting procedure. If the rms difference still exceeded the specified limits, the particular half-orbit of data was excluded from further processing. Note that our fitting procedure differs significantly from that described by Higuchi and Ohtani [2000] for processing DMSP magnetometer data.

Figure 2 shows the result of subtracting fitted polynomials from ΔBy and ΔBz data. At low and middle latitudes the values are nearly zero. Nonzero values at high latitude are due to the FACs. Developing this procedure was partially motivated by a perceived need to establish baselines for calculating auroral FACs and Poynting vectors during magnetic storms [Huang and Burke, 2004].

The present report uses the values of the polynomial fits to ΔBy and ΔBz at crossings of the magnetic equator along with the LT, date, and time of crossing. Polynomial-fit values are used to suppress small-scale variations due to a variety of factors. At the time of the data in Figure 1, theDst index was near zero. On the basis of geophysical considerations, the DMSP magnetic field deflections ΔBy and ΔBz should also be near zero. Figure 1 shows they are not zero. However, the observed finite values were found repeatable from orbit to orbit. The present work began after we noticed that DMSP ΔBm, the component closest to the direction of B at the magnetic equator, varied in time in ways that were strikingly similar to those of Dst.

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Figure 4. $Dst$ index and the $\Delta H$ component of the DMSP F15 magnetic field measurement as the a.m. and p.m. magnetic equator are crossed with adjustments as described in the text.

The final step in our analysis was to compute the $\Delta H$ component of the magnetic field at DMSP altitude and compare it with the standard $Dst$ index. This was done by subtracting the bias values and average hourly variations from each of the $\Delta B_y$ and $\Delta B_z$ values. These deviation components were then added to IGRF field components to create the “effective,” measured y and z components ($B_{y,measured}^\prime$ and $B_{z,measured}^\prime$). The spacecraft-based value for the deviation in the horizontal field is

$$\Delta H = (B_{y,measured}^2 + B_{z,measured}^2)^{1/2} - (B_{y,model}^2 + B_{z,model}^2)^{1/2} \quad (1)$$

Examples of $\Delta H$ derived from DMSP F15 and F16 data are plotted together with the $Dst$ index in Figures 4 and 5, respectively. DMSP $\Delta H$ values and the $Dst$ index are very similar during quiet times. During storms, trends found in DMSP $\Delta H$ values appear similar to but not identical with those in the $Dst$ trace. $\Delta H$ components from the morning and evening sides are plotted separately and differ noticeably during the main phase of storms. We attribute most of this difference to effects of the partial ring current in the evening sector and its absence in the postdawn sector. Magnetic deflections measured at individual $Dst$ stations manifest similar evening-morning differences during the main phases of storms. The $Dst$ index is computed as the arithmetic average of all $Dst$ stations on the assumption that they are adequately distributed in longitude to represent a true globally averaged deflection. Since equatorial sam-

Figure 5. DMSP F16 magnetic field data for the same time period and in the same format as Figure 4.
plings of \( \Delta H \) by DMSP satellites in the evening and morning sectors are separated by \( \sim 50 \) min in UT, a different averaging scheme must be devised to create a more accurate proxy \( Dst \) during the main phase of storms.

5. Discussion

5.1. DMSP “Dst-Like” Index Versus the Standard \( Dst \)

[23] Our technique for obtaining a DMSP “Dst-like” index has some similarities to those used to convert ground-based magnetic field measurements into the standard \( Dst \) index. Both data sets have systematic corrections that must be applied to the initial measurements. Both methods of analysis seek to estimate the perturbations at the geomagnetic equator due to magnetospheric current sources. While currents near the magnetospheric, equatorial plane significantly affect ground-based magnetometer morning differences reflect the asymmetry of the magneto-spheric current system during the main phase of storms. We analyzed data from the main and early recovery phases of all geomagnetic storms during the 2002–2005 interval. The survey showed that (1) DMSP \( \Delta H \) values obtained in the morning sector were less negative than both \( Dst \) and values measured on the eveningside, (2) \( \Delta H \) obtained in the evening sector was more negative than \( Dst \), and (3) after the recovery phase was underway for 2–4 hours, morning and evening DMSP \( \Delta H \) values converged with each other and \( Dst \). The morning/evening difference reflects the asymmetry of the magneto-spheric current system during the main phase of storms when large quantities of plasma were energized and injected into the inner magnetosphere.

[24] Most storm-injected ions drift westward across the evening-afternoon sector of the inner magnetosphere. Some energetic ions become trapped on closed paths around the Earth. Conversely, most energetic electrons drift eastward across the morning sector. The pressure of the ring-current ions \( (P_e) \) exceeds that of the electrons \( (P_i) \). Force balance requires that the current density \( j_\perp \) perpendicular to the local magnetic field \( B \)

\[
j_\perp = -\frac{\nabla (P_i + P_e) \times \vec{B}}{B^2}
\]

With the strongest pressure gradients developing in the midnight-dusk sector, we expect that magnetic perturbations at the Earth’s surface, produced by ring current particles, should be stronger at these local times. After injection drivers diminish or stop, some particles continue to drift out of the magnetosphere while the rest become confined to trapped orbits. Thus the recovery phase ring current evolves toward the symmetric, near-equatorial configuration initially suggested by Chapman [1951]. Observed differences between the DMSP \( \Delta H \) measured in the dusk and dawn sectors may offer advantages. DMSP data, in coordination with other space- and ground-based measurements can be used to improve models of the asymmetric ring current’s birth-death cycle.

6. Conclusions

[25] This paper demonstrates substantial agreement between our DMSP \( \Delta H \) and the standard \( Dst \) index. With further development, a DMSP index could provide an alternate method of computing \( Dst \) for use in space weather models. The major advantage is that the DMSP data are rapidly available within the operational space weather community and the DMSP index can be derived with much less human involvement. In addition, the DMSP magnetometers are space assets whose availability is guaranteed for the next decade. The major disadvantage is that the index can only be updated at intervals of several minutes as various contributing spacecraft cross the magnetic equator. Ground-based magnetic field data are updated at 1-min...
intervals. This disadvantage can be reduced by the inclusion of magnetic field data from other satellites in low-Earth-orbit. In particular, if data from the Iridium series of spacecraft [Anderson et al., 2002] were added, the spacecraft-based index could be updated every 5 min. Currently, the resolution of data sampled by Iridium magnetometers is inadequate for computing a Dst-like index. However, this deficiency can and may well be remedied in the near future.

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