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Comparison of observed and model magnetic fields at high altitudes above the polar cap: POLAR initial results

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Abstract. Data obtained from the high altitude, polar orbiting spacecraft, POLAR, are compared with the latest version of the data-based magnetospheric magnetic field model. The data generally agree well with the model. The major directional discrepancies at high altitudes are near the dayside cusp and on the "open" field lines over the polar cap, especially close to the boundary of the polar cap. Near the cusp, the agreement is improved if a stronger solar wind dynamic pressure and more negative IMF By and Bz are used as the model input parameters, than was actually observed. The field measured in the vicinity of the polar cusps is generally weaker than predicted by the model. Close to noon the spacecraft enters a region of additional structured field depression that appears to be the polar cusp proper. Within the limited statistics presented here, the invariant latitude of the cusp appears to be controlled by the north-south component of the IMF and the broad depression appears to be controlled by the tilt of the dipole.

Introduction

An accurate magnetic field model is an important tool for probing the physical processes in the magnetosphere. Quantitative models based on large sets of spacecraft data, combined with the standard IGRF models for the internal field have been widely used during the last years. The data-based models provide better accuracy in the regions with a good coverage by magnetometer measurements and are less well constrained in the regions with sparser sampling or no data at all.

In comparison with the low-latitude magnetosphere, the high-latitude region is still far less covered by magnetometer measurements. So far, the distant polar magnetosphere was explored only by the HEOS 2 and Hawkeye 1 spacecraft. Hedgecock and Thomas [1975] described the average magnetic field configuration in the polar and near tail regions by using HEOS data. They also compared HEOS data with the Mead-Fairfield [1975] model, showing that the model field is too strong in the high-latitude polar region. Farrell and Van Allen [1990] identified the polar cleft region at large radial distances by locating the region where Hawkeye 1 measured strong negative deviations of the magnetic field strength from that of the dipole field. These regions of negative depression relative to the dipole field strength were generally adjacent to the magnetopause. Fairfield [1991] compared the data of IMP and HEOS magnetometers with the field given by the models of Tsyganenko and Usmanov [1982] and Tsyganenko [1987]. He also found that the models frequently predicted too large a field strength in the high-latitude cusp region on the dayside, due to their inability to account for the diamagnetic currents associated with the dense polar cusp plasmas.

The POLAR Magnetic Field Experiment (MFE) [Russell et al., 1995] provides a new opportunity for the improvement of magnetic models in the magnetosphere. The POLAR spacecraft is in a high-latitude, high-altitude orbit with a perigee of 1.8 Re, an apogee close to 9 Re, and a period of 17.5 hours. In contrast to HEOS and Hawkeye, POLAR encounters the cusp at lower altitudes and seldom reaches the vicinity of the magnetopause.

In this study, we examine in detail one typical orbit, comparing the POLAR data with the T96_01 version of the data-based magnetic field model [Tsyganenko, 1996] combined with the IGRF 95 internal field. We will demonstrate the existence of a depression of the magnetic field in the vicinity of the polar cusp, as compared with the reference field given by the T96_01 and IGRF 95 models, and show how one can identify the entry into the cusp proper by using the magnetometer data. The T96_01 model is largely different from all previous representations of the distant magnetic field in that: (i) it explicitly includes a realistic analytical magnetopause, controlled by the solar wind pressure, (ii) it incorporates the effects of Region 1 and 2 Birkeland currents, (iii) it allows for an IMF-controlled interconnection between the terrestrial and solar wind magnetic fields across the boundary, (iv) it is driven by the solar wind pressure, IMF By/Bz, and the Dst-index, so that the field components are continuous functions of those input parameters, in contrast to earlier models, binned by the Kp-index only.

Model Comparison over an Orbit

To evaluate the accuracy of the model, we use the inclination and declination angles and the residuals of the total field between the data and the model ($\Delta BT = BT_{POLAR} - BT_{T96}$). The inclination angle is defined as the angle between the field and the radius vector minus 90°. Equivalently it can be defined as the angle between the local horizontal plane and the **B** vector. The declination angle is measured in the horizontal plane about the radius vector. The declination is zero when the projection of the field in the horizontal plane is northward and 90° when the horizontal component of the field points eastward in the direction of the Earth's rotation. When the magnetic field lies close to the horizontal plane, and the inclination is zero, the declination angle gives a good measure of the twist of the field from the magnetic meridian. But in the vicinity of the cusp when the inclination approaches 90°, the declination angle can be very sensitive to

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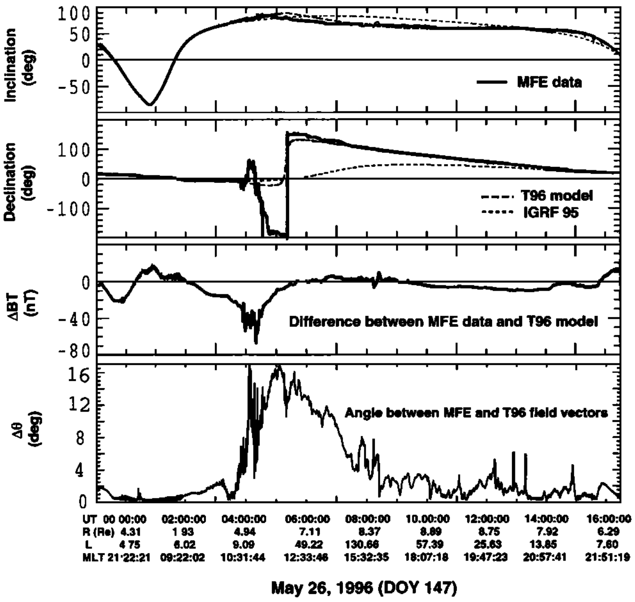

Figure 1. (top) Inclination angles from Polar MFE data (solid trace), IGRF 95 model (thin dash), and T96_01 model (thick dash); (second panel) declination angles; (third panel) difference between Polar MFE data and T96_01 model, (bottom) the angle between MFE and T96_01 field. The input parameters of the T96_01 model are: Dst=0, IMF By=-4 nT, IMF Bz=1.5 nT, Dyn=2 nPa.

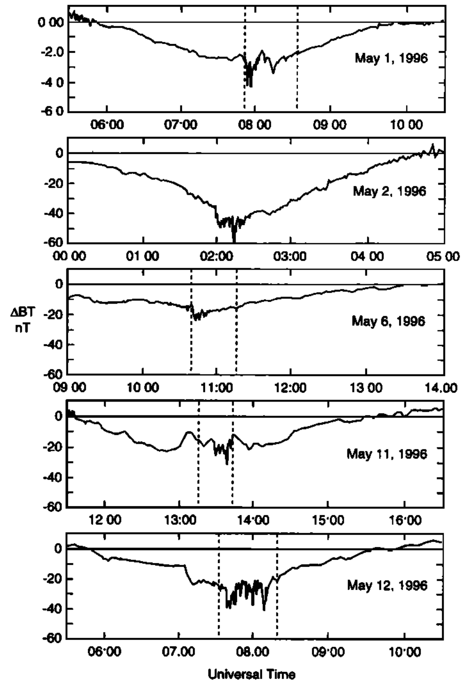

Figure 3. The residual of magnetic field magnitude between Polar MFE and T96_01 model for five orbits in May 1996 near the cusp region. The vertical lines show where magnetosheath-like electrons were observed by the HYDRA instrument.

small variations in the field direction. Thus we also show the total angle between the observed and model fields.

Figure 1 shows the inclination, declination, the difference in field magnitude (ΔBT) and the angle between the model and the measured magnetic field vectors for a typical POLAR orbit (0000-1730 UT, May 26, 1996). The solid traces are the observed angles and difference of field, dotted traces are inclination and declination of the IGRF 95 field. The dashed traces are the inclination and declination of the IGRF plus the T96_01 external magnetic field. For the T96_01 model, we use Dst=0, and the observed solar wind conditions from 0400-0700 UT. The solar wind dynamic pressure and IMF components observed by WIND spacecraft at this time were 2 nPa, and IMF By=-4 nT, Bz=1.5 nT. The standard deviation about these average values for IMF By, Bz and solar wind dynamic pressure were 1.35 nT, 2.44 nT and 0.12 nPa respectively. Overall good agreement between the data and models can be seen in this figure. For most of the time, the angular departure between the model and the measured fields is less than 4 degrees. The biggest angular departure is about 16 degrees in the region of the polar cusp and immediately above it. At low altitude below 6 Re, the direction of the field is governed principally by the internal field so no discernible difference is seen between the models and the data. Even the total field is very close to that of the model at perigee. Above 6 Re, the inclination and declination angles found from the T96_01 model agree much better with the Polar MFE data than the angles based on IGRF 95 model only, especially at high altitudes, as can be seen during the period 0600-1230 UT. From 0300 to 0600 UT in the neighborhood of the polar cusp, a depression in the field is quite conspicuous. We will examine this region in greater detail below.

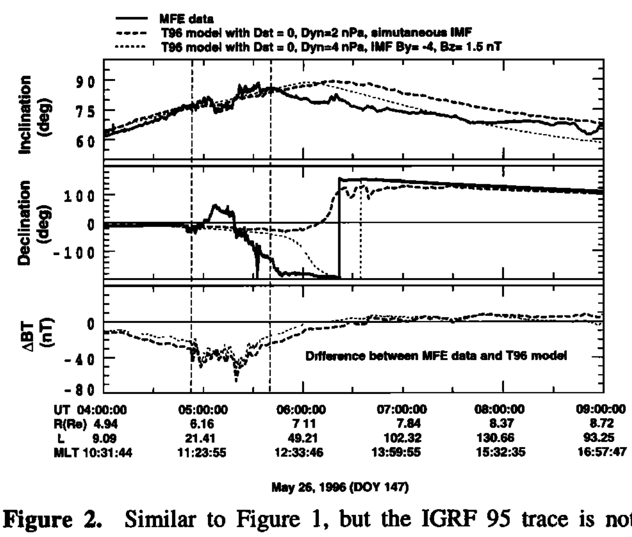

Figure 2. Similar to Figure 1, but the IGRF 95 trace is not included. The thick dashed traces are values from T96_01 model with Dst=0, Dyn=2 nPa, and simultaneous IMF By and Bz. The thin dashed traces are values from T96_01 model with parameters Dst=0, IMF By=-4 nT IMF Bz=1.5 nT, and Dyn=4 nPa.

Cusp Region

As expected and as illustrated in Figure 1, the major differences between the observed and predicted fields are concentrated near the polar cusp. The size and direction of the distortion of the field can be best visualized in terms of angles and of the residual deviation from the model. The data for the period 0400-0900 UT on May 26, 1996, are shown in Figure 2. The solid traces are the magnetometer data; thick dashed traces are the values from the T96_01 model for Dst=0, Dyn=2 nPa and simultaneous IMF By and Bz which are measured by the WIND spacecraft. The time lag we used is: ΔT=(x-10Re)/400, where x is the position of WIND spacecraft in GSM in km and ΔT is in seconds. The oscillations in the model are caused by the varying

Table 1. Polar Cusp Crossings

Date	Universal Time	Tilt Angle(°)	Footprint Magnetic Local Time	Footprint Invariant Latitude(°)	ΔBT base (nT)	ΔBT min (nT)	Solar Wind Dynamic Pressure (nPa)	IMF By	IMF Bz(nT)
05/02/96	01:58-02:38	6.87	10:57-11:29	80-82	-35	-57	3.0	2	~0
05/26/96	04:52-05:28	10.58	11:15-11:57	77-78	-30	-55	2.0	-4	-3
05/01/96	07:51-08:20	8.31	13:27-13:57	78-81	-24	-38	2.4	-2	~0
05/12/96	07:20-08:20	10.81	12:55-14:10	78-83	-20	-40	3.0	4	~0
05/06/96	10:40-11:08	16.92	14:06-14:50	79-82	-15	-22	1.5	-3	1.5
05/11/96	13:25-13:45	25.13	12:14-12:44	81-84	-15	-25	2.5	3	4

input parameters in the solar wind. The thin dashed traces are from T96_01 model with parameters Dst=0, Dyn=4nPa, IMF By=-4 nT, Bz=1.5 nT. Near the cusp region, the model overestimates the magnitude of the magnetic field by up to about 20 nT in the smoothly varying region and the field is highly twisted away from the T96_01 model predictions after the cusp itself is encountered. The deeper, structured depression of the magnetic field (up to 60 nT) from 0450-0540 UT is the cusp or cleft. This structured depression begins about 1120 MLT and extends to noon MLT. The vertical dashed lines in this figure indicate the period when the HYDRA instrument observes magnetosheath-like electrons [J. D. Scudder, personal communication, 1997]. This confirms that the deep depression occurs in the cusp. The inclination that measures the distortion of the field out of the horizontal plane indicates the field is slowly becoming oriented radially inward as the spacecraft moves poleward of the cusp. The declination angle shows that the initially northward field swung toward dusk as the cusp proper was encountered. Then it returned northward at 0520 UT and rotated dawnward and then pointed due south, turning away from southward to almost duskward by 0900 UT.

Samples of the Polar Cusp

Figure 3 shows a set of near-cusp crossings. We use Dst=0 and the real IMF and solar wind conditions in this figure. The vertical lines show the periods when magnetosheath-like plasma is seen. The broad field depression surrounding the cusp is seen on almost every pass through the cusp region. The additional structured depression in the center of the cusp region occurs much more rarely. Table 1 shows the time and location of these crossings along with the solar wind dynamic pressure and IMF By and Bz. The local time and invariant latitude are given for the northern foot of the field line traced by using the T96_01 model. The ΔBT base column gives the largest depression seen in the broad region surrounding the cusp. The ΔBT min is the depression of the field reached in the structured cusp.

Although we have only a few data points, there is an indication of a possible correlation between the depression (ΔBT) and the Earth's dipole tilt angle. Indeed, the biggest and the smallest depressions occur when the dipole is tilted away from and toward to the Sun, respectively. The cusp is at its most equatorward latitude for southward IMF and at its most poleward position for northward IMF. This correlation is consistent with that observed by Hawkeye [Farrell et al, 1990] and previous cusp studies [e.g., Russell et al, 1971]. Such a depression has also been seen at low altitudes by Erlandson et al [1988] in the Viking observations. We have too few cases at present to determine if there are solar wind dynamic pressure effects and IMF By effects adding to the apparent tilt angle and IMF Bz effects.

Varying the Parameters of the Model

As mentioned above, we have used the parameters as: Dst=0, Dyn=2 nPa and simultaneous IMF in Figure 2, corresponding to those measured on May 26, 1996, by the WIND spacecraft. However, if we change these parameters away from their observed values, we can improve the agreement. It is our purpose here not to improve the model but rather illustrate the direction of such future improvements might take. Figure 4 shows the inclination and declination and the residual field strength for the same Dst=0 and Dyn=2 nPa, but for different IMF conditions, in the same format as in Figure 2. Here, the model field for negative IMF By and Bz (thick dashed traces) fits the MFE data much better than that for By=Bz=0 over the period 0530-0800 UT. However, as shown in Figure 2, if we compare the data with the model for Dst=0, IMF By=-4, Bz=1.5, and dynamic pressure of 4 nPa, i.e. twice larger than observed, the agreement can also be improved. For declination angles, the

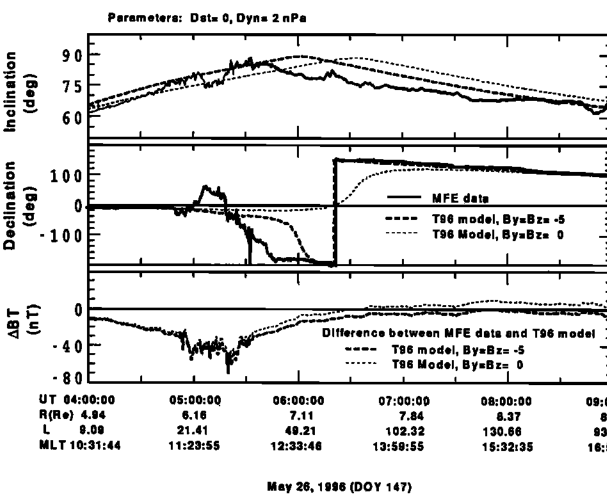

Figure 4. (top) Inclination angles from Polar MFE data (solid trace); T96_01 model with IMF By=Bz=0 nT (thin dashed trace); and T96_01 model with IMF By=Bz=-5 nT (thick dashed trace); (middle) declination angles; (bottom) difference of BT between Polar MFE data and T96_01 model.

agreement can be greatly improved over the period 0520-0830 UT, although there are still large differences in the immediate vicinity of the structured polar cusp. The agreement in the inclination angle is also improved, and ΔBT is improved at the dip by about 10 nT, in comparison with that for dynamic pressure of 2 nPa in Figure 2. In short, according to the model the field over the polar cap is distorted by the solar wind as if the solar wind and IMF had greater values than actually observed.

The most likely reason for the improvement of the results by the above modification of the input parameters is an underestimate of the near-cusp Region 1 field-aligned currents by the model. Both the IMF components (By and Bz) and the solar wind pressure were used for parameterization of the model Region 1 Birkeland current amplitude, so that larger values of the IMF clock angle and of the pressure yield larger Birkeland current, which is responsible for the 180-degrees excursion of the declination angle in Figures 2 and 4. The POLAR data imply that the dayside Region 1 current is localized even closer to the noon meridian plane, than assumed in the field model.

Summary

The early magnetic field measurements on POLAR illustrate that the T96_01 model provides a good overall approximation to the field in high-altitude, high-latitude magnetosphere. However, the T96_01 model overestimates the field in a large region surrounding the polar cusp, and within this region there is an additional deep depression near noon, which we attribute to the cusp itself. The depth of the broad depression varies with universal time, which we interpret as due to the variation of the geodipole tilt angle with respect to the solar wind direction. The structured region within this broad depression moves equatorward for increasing southward IMF Bz. The field is twisted near this region possibly due to the field aligned currents. Using the model with a higher dynamic pressure or with more negative IMF Bz, than actually observed, gives a better agreement with the data. This suggests that the actual intensity of the dayside Birkeland currents at the time of the measurements was substantially larger and/or they were concentrated closer to the dayside cusps, than according to the model.

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