The Tsyganenko model for Earth’s magnetic field: Comparison with \textit{in situ} observations and Space Weather predictions

The Earth, with its intrinsic magnetic field, is embedded in the supersonic solar wind that originates at the Sun and is a highly-conducting plasma. It blows a bubble in the interstellar medium in which matter and fields originating on the Sun are contained. This is called the heliosphere, and it has a radius of around 100 Sun-Earth distances. Since the rotating Sun’s magnetic field is frozen into the expanding solar wind because of its high conductivity, the so-called heliospheric magnetic field (HMF) has a spiral structure. Historically the heliospheric magnetic field was called the interplanetary magnetic field (IMF). We now know that this field extends to far beyond the planets of our solar system.

The solar wind distorts Earth’s magnetosphere (see Fig. 1), compressing it in the sunward directions, and elongating it in the opposite direction. It also causes currents to flow in the magnetosphere, which in turn generates magnetic fields that changes the intrinsic field. Moreover, depending on the direction of the heliospheric magnetic at the boundary of the magnetosphere, it can cause magnetic connections between the heliosphere and the magnetosphere.

When studying the magnetosphere, it makes the most sense to do so in the so-called GSM coordinate system, or geocentric solar magnetospheric system, which includes the dipole axis of Earth’s magnetic field. However, some spacecraft data are specified in terms of the GSE coordinate system, or geocentric solar ecliptic system, which contains the direction perpendicular to the ecliptic (plane of the planets). While software to do transformation between the system is available, one needs to understand in detail how this is done.

The aim of this project is to (a) study how well the Tsyganenko model predicts the observed magnetospheric field and (b) to select parameters that would be appropriate for moderate/severe solar storms, and then see what effect it would have on Earth’s magnetic field. Part (a) has for obvious reason already been done at a level higher than required for this project and a paper is attached. Part (b) is of great interest to Space Weather studies, which is a branch of Space Physics and Aeronomy concerned with the time varying conditions within the Solar System, including the solar wind, emphasizing the space surrounding the Earth, including conditions in the magnetosphere, ionosphere, thermosphere, and exosphere. The solar wind causes current to flow in the magnetosphere, and it can also induce currents in say electrical transmission networks with devastating effects. The bigger the storm, the bigger its impact on infrastructure. This has become an active field of study, and you will gain some insight into why studying Space Weather has become so important.

Prof Kotze (SANSA Space Science) will lead the student to do runs with his Tsyganenko code, while Prof Burger will give guidance on analysing spacecraft data.

\textbf{Attached reference}

A comparison of Cluster magnetic data with the Tsyganenko 2001 model

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A comparison of Cluster magnetic data with the Tsyganenko 2001 model

E. E. Woodfield, M. W. Dunlop, R. Holme, J. A. Davies, and M. A. Hapgood

1. Introduction

As part of an investigation of the magnetic effects of external currents in the magnetosphere, we have compared two years of perigee Cluster data to the Tsyganenko 2001 (T01) field model. Cluster data are not included in the T01 database and therefore can be used to independently verify the model. The model performs very well in a global sense; nevertheless, absolute residuals between the data and the model can reach ~20 nT near perigee. These deviations take two forms: a sharp, bipolar signature and well-defined trends over a larger spatial region. The bipolar signatures in the residuals are moderately stable, repeating on the phase period of the Cluster orbit. The bipolar nature of the signatures reflects variations in the Cluster data, therefore indicating that the spacecraft may be observing a field-aligned current. Although the size of the magnetic field perturbation in this region is not well determined by T01, the location of the observed field-aligned current system is accurately predicted. The bipolar signatures are observed in close proximity to the edge of the ring current, estimated from Cluster energetic electron spectrograms, indicating that they are associated with region 2 field-aligned currents. Longer-duration trends in the residuals indicate a slight difference between the model predictions and the Cluster data for various locations and seasons. For example, throughout most of 2003 and the first half of 2004, there is a residual in the total magnetic field for an hour centered on perigee, of ~20 nT.


The geomagnetic community is actively engaged in studies of the effect of external influences on the total magnetic field of the Earth. A major aspect of this work is the investigation of the contribution of magnetospheric current systems to the Earth’s magnetic field; these current systems are, to a large extent, driven by the solar wind. In order to continue to develop our understanding, an accurate characterization of the magnetic fields generated by such external electric currents is required. As a step in this direction, we have used data from the Cluster spacecraft to investigate the accuracy of the modeled magnetospheric contribution to the whole Earth system magnetic field. Such efforts are greatly improved by close collaboration between the geomagnetic and solar-terrestrial physics communities, which can facilitate the exchange of ideas and models between the two.

The semiempirical Tsyganenko magnetic field models have been widely utilized in the space physics community for many years. The 2001 version (T01) [Tsyganenko, 2002a, 2002b] is constructed by considering the mathematical form of a number of individual current systems in the magnetosphere. Data from a large number of spacecraft have been used to define the parameters of the model using a least squares fit to minimize the misfit of the full vectors of the external magnetic field.

The approach of semiempirical optimization, together with the use of a number of variable parameters to model the various current systems, contrasts with the standard method in geomagnetism which involves solving the inversion problem for the field geometry. In geomagnetism it is usually assumed that a scalar potential field can be used (i.e., measurements are taken at a distance from the source region) and that the magnetic field can therefore be described using a spherical harmonic analysis [e.g., Blakely, 1996]. In the case of the inverse problem, the input data used to set the surface boundary values for the inversion are often from ground observatories and low-altitude satellites. An example of this approach is the Comprehensive Model version 4, CM4 [Sabaka et al., 2004] which includes terms describing the ionospheric and magnetospheric contributions to the overall geomagnetic field. The Dst [Sugiura and Kamei, 1991] and F10.7 indices [Covington, 1969] are used to parameterize the conditions, however the model is only valid for very quiet conditions.

The T01 model is driven by five input parameters: solar wind dynamic pressure, solar wind speed, disturbance storm time index (Dst, or its high time resolution counterpart

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SYM-H [Wanliss and Showalter, 2006]) and the interplanetary magnetic field (IMF) components in the Y_GSM and Z_GSM directions. These quantities define the various variable coefficients within the model that are dependent on the external inputs. The model also requires a short time history of external inputs to the magnetosphere, following the understanding that the reaction of the magnetosphere depends on its previous state.

[6] In order to assess the accuracy of the T01 model, we have compared the model output to magnetic field data from the Cluster mission [Escoubet et al., 2001]. Orbits separated in time but in-phase relative to the Earth’s magnetic dipole are compared, such that a very similar region of the magnetosphere is sampled. The initial investigation focuses on two pairs of orbits. The results from this small sample are shown to recur in an analysis of 2 full years of data. A comparison with Cluster data provides an independent assessment of the accuracy of T01, since these data are not included in the empirical database of the model. This comparison also allows the actual behavior observed by Cluster to be assessed in a large-scale context.

2. Data Sources

2.1. T01

[7] Since the T01 model represents only the magnetospheric contribution to the overall magnetic field, we have used the International Geomagnetic Reference Field (IGRF) version 10 [Maus et al., 2005] as the Earth’s internal magnetic field in order to model the full magnetic field at the Cluster orbit. The IGRF is now defined to spherical harmonic degree 13 due to the inclusion of data from low altitude satellites such as Orsted, CHAMP and SAC-C. This is a significant improvement over previous versions of the model and the accuracy of the IGRF version 10 internal field is sufficient that the errors for space physics applications are negligible. The following analysis assumes that both the ionospheric and crustal contributions to the magnetic field at the altitude of the Cluster orbit are not significant.

[8] The mathematical structure of the T01 model includes all the major magnetospheric current systems: ring current, cross-tail current, magnetopause current, field-aligned currents, and the interplanetary magnetic field penetration. Important features of the structure of these currents are summarized below; for a full description the reader is referred to Tsyganenko [2002a, 2002b] and references therein. The ring current includes both an axisymmetric and a partial ring current with field-aligned closure currents. The cross-tail current sheet, which is allowed to warp in response to the geodipole tilt, has a thickness that varies both across and along the tail. The location of the inner edge of this current sheet along the Sun-Earth line varies with changing geomagnetic disturbance levels. The contribution of the magnetopause currents to the total magnetic field is represented using a potential field. This magnetic field, when added to the field from internal sources, provides the required distribution of the net normal component at the model boundary. The general magnetopause shape is defined by the empirical model of Shue et al. [1998] and is also allowed to be geodipole tilt-dependent. The field aligned current (FAC) representation includes both region 1 and region 2 field-aligned currents [Iijima and Potemra, 1976] which are allowed to vary with interplanetary conditions such that their ionospheric footprint can move in latitude. Finally, the interconnection field controlled by the interplanetary magnetic field allows the model magnetosphere to assume open configurations (by allowing a finite B normal to the magnetopause).

[9] The magnitude of the total T01 magnetic field within ±1 hour of Cluster perigee can reach of the order of tens of nano-Tesla. The majority of this is due to the ring current as, at perigee, Cluster is close to 4 R_E radial distance. This is in addition to the dominant contribution from the Earth’s internal magnetic field of hundreds of nano-Tesla (obtained from the IGRF).

[10] For the intervals covered in this paper, the interplanetary input data for the T01 model (i.e., solar wind dynamic pressure, IMF B_Y and B_Z) was level 2 data from the SWEPAM [McComas et al., 1998] and MAG [Smith et al., 1998] instruments on the ACE spacecraft. These data have been propagated to the subsolar bowshock in a simple fashion using the known distance of ACE from the Earth (230 R_E) and placing the bowshock subsolar position at 15 R_E. We have used the ambient bulk speed to calculate the convection time, taking the arrival time at the magnetosphere to be the same as that at the bowshock. A 1 hour time history of solar wind data was used to calculate the parameters g_1 and g_2 [Tsyganenko, 2002b]. The geomagnetic activity input to T01 is provided by the SYM-H index.

2.2. Cluster

[11] The four identical spacecraft that form the Cluster constellation [Escoubet et al., 2001] are in an elliptical, polar orbit with a period of approximately 57 hours, a perigee of ~4 R_E and an apogee of ~19.6 R_E. The Cluster orbit precesses such that every year all magnetic local times (MLT) are covered. The spacecraft are arranged in a tetrahedron, the spatial scale of which varies between 100 km and a few R_E. Each Cluster spacecraft has 11 experiments on board; here, we have used data from the fluxgate-magnetometer (FGM) [Balogh et al., 2001], and the Research with Adaptive Particle Imaging Detectors (RAPID) experiment [Wilken et al., 2001]. In-flight calibrations on the FGM data routinely determine the maximum offset in the data for each spacecraft to within 0.1 nT. The RAPID spectrometer provides suprathermal plasma distributions of electrons (Imaging Electron Spectrometer (IES) instrument), protons and heavier ions (Imaging Ion Mass Spectrometer (IIMS) instrument). The energy range of the IES, data from which is used in the present study, is some 40 to 450 keV.

3. Method

[12] We use a combination of two approaches to compare different Cluster orbits as consistently as possible to reveal pertinent features in the data. First, we have identified pairs of complete orbits for which the perigee times of which are separated by an integer multiple of 24 hours, to ensure that the dipole phasing is as similar as possible for each pair, i.e., the spacecraft are most likely to be going through the same magnetospheric region. The smallest separation that meets this criterion is 19 days (8 full orbits). Second, we have produced plots with a time axis that is relative to the time of
perigee for the selected orbits, in the style of a superposed epoch study.

In the following assessment of T01 performance, the residuals are formed by subtracting the model values (T01 plus IGRF) from the data (note that we have used absolute rather than percentage residuals). Geocentric Solar Magnetic (GSM) coordinates are used throughout. Cluster orbits are by convention numbered from perigee to perigee; for our purposes we have combined two half orbits to generate a set of data for a full orbit centered on perigee. Only data from the Cluster spacecraft 1 are shown, but the analysis has been carried out for all four spacecraft. We are investigating long timescale features in the data so the spin-resolution FGM data has been reduced to 1 min resolution (by selecting data points on minute boundaries). We will analyze two orbits for which the Cluster perigee was on the dawnside and two when perigee was postnoon. This is followed by a general discussion of data from the whole of 2003 and 2004.

4. Results

4.1. Dawnside Perigee

Figure 1 shows two perigee passes separated by 8 orbits. The solid line shows the Cluster spacecraft 1 trajectory for orbit A (4 December 2003), and the dashed line orbit B (23 December 2003; see Table 1 for full date and perigee time details). Universal time (UT) and radial distance to the satellite in Earth radii (r) are marked every 2 hours. The location of the spacecraft is superimposed on magnetic field lines generated from T01 (dotted lines) using the conditions: proton density $= 2.0 \, \text{cm}^{-3}$, solar wind bulk velocity $= 400 \, \text{km s}^{-1}$, Dst $= -10 \, \text{nT}$, IMF $B_Y = 0.0 \, \text{nT}$, and IMF $B_Z = 1.0 \, \text{nT}$.

Figure 1. Orbital plots in GSM coordinates for orbits A (solid line) and B (dashed line). The dotted lines are magnetic field lines traced using T01 for the conditions: proton density $= 2.0 \, \text{cm}^{-3}$, solar wind bulk velocity $= 400 \, \text{km s}^{-1}$, Dst $= -10 \, \text{nT}$, IMF $B_Y = 0.0 \, \text{nT}$, and IMF $B_Z = 1.0 \, \text{nT}$.
The corresponding tailward enhancement in magnetic field would reduce \( B_X \). An estimate can be made for the reduction in this component using a magnetic field value of \( 200 \) to \( 300 \) nT for the low-altitude region 1 field and then dividing this by the factor \((r)^{3/2}\) [Tsyganenko, 2002a]. This yields an estimate of \( 10 \) nT to \( 20 \) nT reduction in \( B_X \), which agrees with that observed. The success of T01 in modeling this feature indicates the benefit of including a magnetospheric history in the model.

[16] Figures 3a, 3b, 3c, and 3d show the results of our calculation of the residuals \( dB_X, dB_Y, dB_Z \), and \( d|B| \) for both passes (\( dB = B_{\text{Observed}} - B_{\text{T01-IGRF}}, d|B| = |B_{\text{Observed}}| - |B_{\text{T01-IGRF}}| \)) for the perigee passes of orbits A and B. Figure 3e shows the total magnetic field magnitude measured by Cluster 1 and Figure 3f gives the SYM-H index. The x-axis shows time relative to perigee for each of the two orbits. The vertical dashed lines correspond to those shown in Figure 2 demarking the estimated limits of the ring current for orbit A; the vertical dotted lines correspond to the ring current limits for orbit B (RAPID data for this interval is not shown). There is a remarkable similarity between the residuals from these two orbits, particularly in \( dB_X \) and \( dB_Y \) (Figures 3a and 3b), even though they are separated by around 19 days. A prominent feature is the sharp signatures observed in all three components before \((\sim 2)\) hours and after perigee \((\sim 1)\) hour. The location of the bipolar features is closely aligned with the edge of the ring current during both perigee passes. The shape of the feature also stays remarkably similar.

[17] Both orbits could be described as geomagnetically quiet with the SYM-H index greater than \( -20 \) nT (Figure 3f). SYM-H for orbit A is \( \sim 10 \) nT higher than for the second orbit. The fact that the sharp signatures are observed in a similar form in two orbits 19 days apart indicates that this is probably a stable feature of the magnetosphere.

[18] In addition to the sharp feature in the residuals there is also a noticeable longer-lived, slow variation observed in \( dB_X \) and \( dB_Y \) through perigee, corresponding to the spacecraft being in the ring current. The correlation in \( dB_X \) between the two well-separated orbits is very good from \(-2\) hours to \(+5\) hours, and in \( dB_Y \) from \(-2.5\) hours to perigee. The same cannot be said for \( dB_Z \), particularly when the spacecraft are in the ring current region, and consequently the residual in the field magnitude is also not consistent between the two orbits. The offset between the data and the predicted value of the magnetic field within the ring current reaches a maximum of approximately \( 10 \) nT.

[19] In Figures 4a, 4b, and 4c an analysis of the model results is presented for the three component magnetic fields in orbit A. The solid line shows the external model field predicted by T01 (\( B_{\text{EM}} = B_{\text{T01}} \)), and the dotted line is the Cluster 1 data minus the IGRF (i.e., the observed external field, \( B_{\text{EO}} = B_{\text{Observed}} - B_{\text{IGRF}} \)). The dashed line shows the residuals in the field components (\( dB = B_{\text{Observed}} -\))

### Table 1. Dates, Perigee Times, and Orbit Numbers of the Four Orbits Used in This Paper

<table>
<thead>
<tr>
<th>Orbit Name</th>
<th>Date</th>
<th>UT of Perigee</th>
<th>Orbit Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4 December 2003</td>
<td>0626</td>
<td>528 and 529</td>
</tr>
<tr>
<td>B</td>
<td>23 December 2003</td>
<td>0655</td>
<td>536 and 537</td>
</tr>
<tr>
<td>C</td>
<td>21 July 2003</td>
<td>1645</td>
<td>471 and 472</td>
</tr>
<tr>
<td>D</td>
<td>9 August 2003</td>
<td>1722</td>
<td>479 and 480</td>
</tr>
</tbody>
</table>

Figure 2. (top) RAPID IES spectrogram showing differential electron flux in six energy bands for orbit A and (bottom) the 3 GSM components of the magnetic field observed by Cluster 1. Vertical dashed lines show the approximate limits of the ring current.

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Figure 3. Results from two orbits of Cluster 1 separated by ~19 days; orbit A (solid line) and orbit B (dotted line). The x-axis is time relative to the perigee for each orbit. (a, b, c, d) Shown are residuals (data-model) of the magnetic field in GSM coordinates, (e) the magnetic field magnitude from Cluster 1 for the two orbits, and (f) the SYM-H magnetic activity index for each case. The two dashed and two dotted vertical lines correspond to the estimated ring current limits for orbits A and B, respectively.

$B_{T01-IGRF}$ that are plotted initially in Figure 3. If T01 gave a perfect representation of the external magnetic field the solid line and the dotted line would be identical. The sharp changes noted in the residual component fields in Figure 3 are mostly bipolar in shape. This characteristic is significant: if it originates in the data, it suggests that Cluster may be passing through, or close to, a tube or sheet of current, such as one would expect for an FAC. The components of the observed external fields are indeed consistent with the spacecraft passing a sheet of current. We can further test this hypothesis by comparing the measured magnetic field magnitude with that predicted by the models. If there is little change in magnitude during the bipolar signature, it will indicate that the magnetic field change is perpendicular to the main field as expected from FAC. Using the vertical dashed lines from Figure 2 as a guide to the ring current location the bipolar signatures in the residuals are located on the edge of the ring current. This indicates these features are likely to be due to region 2 FAC. The residual in the total magnitudes (dashed line) shows that there is a general overestimate of the depression in the magnitude of the magnetic field within the ring current region by approximately 10 nT.

Figure 4a, 4b, and 4c show that there are marked deflections in the T01 predictions of the $B_{EM}$ in the same region that $B_{EO}$ shows FAC signatures. However, T01 gives a poor estimate of the field strength arising from this current system. For example at 0400 UT the T01 estimate of $B_{X,EM}$ changes abruptly (presumably indicating the poleward edge of the region 2 FAC system in the model), but $B_{X,EO}$ shows...
the majority of the increase in the magnetic field occurs at \( \sim 0420 \) UT. The clear demarcation between the FAC region and the ring current, shown by the change in the slope of \( B_x \) at \( \sim 0450 \) UT, is well matched in time for the model and the observations. So the location of the FAC region is well estimated in the model for \( B_{EM} \); however, the detailed morphology of the region is missing. In \( B_{Y,EM} \), there is very little change in the model field; this does not match the observations. Although the timing in \( B_{Z,EM} \) could be said to be approximately correct, the detailed changes in the magnitude of that component are not well predicted. In crossing the northern FAC region (\( \sim 0715 \) UT), the deviations in \( B_{EO} \) are smaller than the southern crossing, but \( B_{EM} \) shows large, well-defined changes.

4.2. Dayside, Postnoon Perigee

Figure 6 shows the perigee passes from two Cluster orbits, in which perigee was on the dayside in the postnoon sector; the solid line represents orbit C (21 July 2003) and the dashed line orbit D (9 August 2003; see Table 1 for more details). Both these orbital paths take Cluster 1 from the postmidnight sector south of the magnetic equator northward through perigee in the afternoon sector back to the postmidnight sector (north of the equator). When perigee is on the dayside, the Cluster orbit passes close to the ring current, but then often passes through one or other of the midaltitude cusps (see, e.g., the study by Vallat et al. [2005]).
Figure 7 shows the RAPID-IES data and full components in the same format as Figure 2, but for the perigee pass orbit C. Figure 7a shows that the energy spectrogram of the energetic electrons is different from that in orbit A (and orbit B). Orbit C (and D) presents a more asymmetrical appearance with time which may be an indication of a different approach of the spacecraft into the ring current. As before, the edge of the ring current is marked approximately using the vertical dashed lines.

Figure 8 presents the magnetic field residuals for this second pair of orbits in the same format as Figure 3. As in orbits A and B, the geomagnetic activity level is quiet, with SYM-H greater than $-25 \text{ nT}$. For orbit D SYM-H is around $10 \text{ nT}$ greater than that from orbit C. During the 10 hour interval centered on perigee for orbit C, the solar wind dynamic pressure was $\sim 0.5 \text{ nPa}$, IMF $B_Y$ varied between $-7 \text{ nT}$ and $-2 \text{ nT}$, and IMF $B_Z$ between $-3 \text{ nT}$ and $+3 \text{ nT}$. For the equivalent part of orbit D, the dynamic pressure was $\sim 2 \text{ nPa}$, IMF $B_Y$ varied between $-6 \text{ nT}$ and $+3 \text{ nT}$, and IMF $B_Z$ between $-3 \text{ nT}$ and $+5 \text{ nT}$.

The residuals for the two orbits, despite being separated by $\sim 19 \text{ days}$, show very similar structure. There is no obvious sharp signature in the residuals corresponding to ring current entry for either orbit C or D (in contrast to orbits A and B). It is possible that the absence of a bipolar signature in the magnetic field residuals is related to the different entry path of Cluster into the ring current. There is a very clear bipolar feature in all three magnetic field components an hour after perigee, near the time at which the Cluster 1 exited the ring current. The bipolar signature in the spacecraft data is large enough to register in both the $B_X$ and $B_Y$ components of the total field (Figure 7b).

Figure 8 is given in Figures 9 and 10 for orbits C and D, respectively. The bipolar feature is evident in the observed external $B_{EO}$ data as well as the residuals. In orbit C, the T01 estimate of the FAC location is close to that observed and the $B_{EM}$ components change in the same senses as the $B_{EO}$ components; however, the size of the FAC magnetic signature is underestimated by about a factor of two to three. In orbit D there is a very similar, large bipolar feature in $B_{EO}$ after perigee but very little indication of FAC in $B_{EM}$. Signatures from the bipolar changes in the magnetic field components do not occur in the magnitude of the total.
Figure 6. Orbital plots in GSM coordinates for orbits C (solid line) and D (dashed line). The dotted lines are magnetic field lines traced using T01 for the conditions: proton density = $2.0 \, \text{cm}^{-3}$, solar wind bulk velocity = $400 \, \text{km s}^{-1}$, Dst = $-10 \, \text{nT}$, IMF $B_y = 0.0 \, \text{nT}$, and IMF $B_z = 1.0 \, \text{nT}$.

Figure 7. (a) RAPID IES spectrogram showing differential electron flux in six energy bands for orbit C and (b) the 3 GSM components of the magnetic field observed by Cluster 1. Vertical dashed lines show the approximate limits of the ring current.
field (Figures 9d and 10d). This is consistent with the presence of FACs. The residuals of the total magnetic field in orbits C and D show that the ring current field depression is underestimated by T01 (as it was for orbit B).

4.3. Full Year Analysis

[28] The features identified in the case studies of magnetic residuals presented above are characteristic of much of the 2003 and 2004 perigee data. A summary of the perigee data from every orbit during 2003 and 2004 is presented in Figures 11 and 12, respectively; as before data are reduced to 1-min resolution. Figures 11a to 11d and 12a to 12d show the residuals between the observed field and the modeled field, dBx, dy, dBz, and dB, respectively. Figures 11e and 12e present SYM-H and Figures 11f and 12f present IMF BZ. Each parameter is color coded according to its value and plotted as a function of orbit number (x-axis) and time in hours relative to perigee (y-axis). The x-axis of each figure covers a full year starting in January. Figure 13 shows the Cluster 1 perigee locations in the GSM X-Y plane for 2003 with the orbit numbers superimposed (compare to orbit numbers in Table 1). This figure shows how the local time of perigee precesses through the magnetosphere during 2003; a very similar precession occurs in 2004.

[29] Figures 11a and 11b and to a lesser extent Figure 11c show that the bipolar signatures (indicated by the sharp changes in color) are a common feature of the residuals. A clear example of this can be seen in Figure 11b, between +1 and +2 hours away from perigee for a number of orbits around 480. A comparison with similar figures showing the components of BEO (not shown) indicate that these sharp changes are colocated with bipolar signatures in the observed external field components. Figure 11b shows that they are less frequent around the spring equinox when the Cluster perigee is on the nightside. During this time there is instead a more long-lived reversal in d By, starting ~2 hours before perigee and ending ~2 hours after. A similar slow reversal is observed in dBz (Figure 11a) from approximately orbit 475 to 500. The residuals vary from about +5 nT to −5 nT, while Cluster 1 is within the ring current region. The gradual trends observed are consistent with the changing location of the perigee of the orbits as the year progresses.
In 2003, $dB_Z$ and $dB_B$ (Figures 11c and 11d) show a well-defined trough in values spanning 1 to 2 hours around perigee. Since the perigee of the Cluster orbit is close to the magnetic equator in 2003 (and 2004), it is reasonable to assume that at this time $dB_B$ will be dominated by the $Z$ component of the magnetic field. The negative residual indicates that T01 is underestimating the field depression in this region due to the ring current. In contrast to this, away from perigee the tendency is for T01 to overestimate the magnitude of the total magnetic field although there are some exceptions to this. For example, from $-4$ to $-2$ hours relative to perigee in the first quarter of 2003 the fit of the model to the data in $dB_B$ is very good (area 1). This coincides with generally positive residuals in $B_z$ and $B_X$. There are two other areas where the residuals of the total field and the $Z$ component are close to zero. The first occurs at the same relative orbital time, $-4$ to $-2$ hours, but extends from orbit $\sim 480$ to 510 (area 2). The second extends from 4 to 6 hours after perigee for orbits $\sim 400$ to 440 (area 3); this corresponds to a region of small to positive residuals in $dB_X$. So we see that there are regions of the magnetosphere that are consistently slightly misrepresented in the model, and other regions where the model fits the data much better.

Overall 2004 was a less geomagnetically active year as reflected by fewer large negative values in the plot of SYM-H (see Figure 12e). Nevertheless, the bipolar signatures in the residuals are still apparent, in roughly the same location as in 2003. The longer-lived reversals in the $X$ and $Y$ residuals lasting some 4 hours centered on perigee are still visible on this scale, but are much smaller than the previous year. The trough in $dB_B$ close to perigee disappears part way through 2004 to be replaced by a peak in $dB_B$ of similar time extent. There is no clear indication from either the SYM-H index or the IMF $B_Z$ data of why this should occur. The other regions (areas 1, 2, and 3) identified in the 2003 data where $dB_B$ was close to zero do seem to recur in 2004, although at slightly different local times. These last three features are all apparent in $dB_Z$ as positive residuals and there are no obvious connections to the $dB_X$ and $dB_Y$ residuals in this year.

Overall, the 2 years show some broadly similar features in the residuals including the bipolar signatures identified as FACs. Other larger/longer-lived features are
also present in both years but the overall performance of T01 seems to be significantly better in 2004. The reason for this is not yet clear.

5. Discussion

The comparison of four case events and 2 full years of Cluster spacecraft 1 magnetic field data with predictions from the Tsyganenko 2001 model indicate the frequent occurrence of sharp features in the residual values (data minus model) in all three GSM magnetic field components. These signatures are often bipolar in form and are observed again 19 days later indicating the presence of a stable or recurring current structure. The comparison also reveals longer duration features in the residuals close to perigee that are not necessarily consistent between pairs of in-phase orbits but can be observed over a longer time period.

5.1. Sharp Residual Features

Initially, we presented dawnside perigee passes from two orbits, separated by ~19 days (sufficient to bring the dipole back in phase). The residuals between the Cluster magnetic field data and the T01 model output revealed two bipolar features in all three components, one prior to perigee and one after. These features were repeated in almost the same form in both orbits, 19 days apart. In orbits A and B, the preperigee feature shape is due to the data, since the model exhibits only smooth changes (Figures 4 and 5). The same figures show that the postperigee feature is heavily influenced by rapid changes in the model field but is still mainly in the data.

We then presented data from two dayside, postnoon perigee passes, which again revealed very distinct bipolar signatures but this time only after perigee. Again, these residual signatures are mostly due to the observed data since the T01 results significantly underestimated the magnetic changes in this region. The bipolar shape of the signatures seen in the data implies that Cluster 1 may be passing through an FAC which is not adequately reproduced by the model. In addition, the total magnetic field magnitude (and its residual) shows no prominent features at the time these bipolar signatures are observed. The constant value of the field magnitude through the bipolar feature is consistent...
with the idea of electric current flowing along magnetic field lines. Therefore we believe these features to be signatures of FACs; their consistency over time leading toward the conclusion that they are due to the large-scale Birkeland current system.

The addition of particle data from the same spacecraft facilitates an accurate determination of the magnetospheric location of these bipolar signatures. The Cluster RAPID-IES instrument shows the enhanced energetic electron flux of the ring current/outer radiation belt. This places the observed FACs on or near the edge of the ring current. The morphology of the Birkeland current system suggested by Iijima and Potemra [1976] has the region 2 system closing via the ring current. It is therefore possible that the FACs we have observed were part of the region 2 current circuit. This is in agreement with Vallat et al. [2005] where the authors used the four Cluster spacecraft to estimate the current using the curlometer technique [e.g., Dunlop et al., 2002]. They found FAC signatures at the edge of the ring current and associated these currents with the region 2 system. A curlometer analysis has not been included here since the quality is expected to be low in view of the spacecraft configuration in some of the relevant regions in these orbits.

The T01 model takes a detailed approach to modeling the region 1 and 2 Birkeland currents, including the change of ionospheric latitude with activity, dipole tilt-related deformation and the observed day-night asymmetry [Tsyganenko, 2002a]. It is a difficult task to model these FAC systems realistically, and any attempt to include them in a global model is almost certain to be a simplification as a matter of necessity. In general we find that T01 models the location of the observed FAC system signatures well but the magnitude and fine structure are not so well reproduced. It is unrealistic to expect the model to be able to accurately estimate the detailed structure; however, it is of prime concern to obtain a realistic prediction of the magnitude that the effect the FAC system has on the magnetic field. As the individual events showed, the intensity of the magnetic field perturbation due to the FAC system varies greatly. This increases the need for accurate and large data sets to be used in generating a model. The results presented here demon-

Figure 11. Plots for the whole of 2003. Each vertical strip is a section of an orbit; the x-axis is the orbit number, y-axis is time relative to perigee, and the color scale is the value of (a) dB_X, (b) dB_Y, (c) dB_Z, (d) d|B|, (e) SYM-H, and (f) IMF B_Z.
strate the need for empirical models of the external field to exploit Cluster magnetic field measurements, especially in the Birkeland current region.

[38] The time that the FACs are encountered with respect to perigee alters over the course of a year as the plane of the Cluster orbit precesses through 24 hours in local time. It would be expected, given the day-night asymmetry mentioned above, that orbits with a dayside perigee would observe any region 2 current signatures further towards the poles [see, e.g., Tsyganenko, 2002a, Figure 4]. This is in agreement with our results; the FAC signatures occur further away from perigee from about July to December (Figures 11 and 12).

5.2. Longer-Duration Features in the Residuals

[39] In the individual events studied in sections 4.1 and 4.2 there were offsets between the T01 model output and the Cluster 1 data that extended around perigee while Cluster 1 was inside the ring current. These offsets were longer-lived (∼2 hours) than those mentioned in the previous section. There was a reasonable degree of consistency in dB_X and dB_Y between the in-phase orbits in each case (Figures 4, 5, 9, and 10). The same could not be said of dB_Z and d|B| in the first perigee pass. The recurrence of these ring current residuals persists in the 2 year long analysis. In the corresponding parts of Figure 11 (orbit A, numbered 528/529, and B, 536/537, for the dayside perigee orbits, C, 471/472, and D, 479/480, for postnoon perigee) there are positive followed by negative residuals within one orbit (or vice versa as applicable) which correspond to the recurring ring current residuals. Figure 11 shows that these continue over greater times than just the 19 days examined here in detail but also that the morphology of the residuals changes as the Cluster orbital path precesses in local time. These patterns in the residuals indicate that there is a small but systematic offset in the model from the magnetic field that is measured by Cluster when it is inside the ring current during large periods of 2003.

[40] The T01 model achieves better results during 2004, producing smaller residuals throughout the year, possibly due to the overall slightly quieter magnetic conditions (compare Figures 11e and 12e). Since no data from 2003

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**Figure 12.** Plots for the whole of 2004. Each vertical strip is a section of an orbit; the x-axis is the orbit number, y-axis is time relative to perigee, and the color scale is the value of (a) dB_X, (b) dB_Y, (c) dB_Z, (d) d|B|, (e) SYM-H, and (f) IMF B_Z.
or 2004 are included in the T01 database, perhaps the 2004 conditions more closely resemble those included in the database (which covers 1984 to 1999). Both 2003 and 2004 are in the declining phase of solar cycle 23 which peaked in April 2000.

[41] The other clear feature in the 2003 data is the ~1 hour long burst of negative residuals in the total magnetic field around perigee. This is consistent throughout the entire year (with a couple of brief exceptions). This trend then reverses dramatically approximately halfway into 2004 such that there is a burst of positive residuals around perigee for the rest of the year. The dominant component of the total field at this location is the Z direction (perigee is close to the magnetic equator); dB\textsubscript{Z} also undergoes a change in the second half of 2004. What causes this sudden alteration in the pattern is unclear, but it means that an improvement to T01 to remedy the original trough of negative residuals is probably not viable, at least until the source of the change in 2004 can be identified.

[42] Outside of the ring current region and beyond the FAC signatures there are other regions that show very small residual values and semi-persistent behavior as mentioned in section 4.3. These occur in dB\textsubscript{Z} and can be matched primarily to positive residual regions in dB\textsubscript{Z} (Figures 11c and 12c) but also in places dB\textsubscript{X} and dB\textsubscript{Y}. These features last for approximately three months and also appear in both years of data. There is an initial indication that at least one of these patches (between ~2 and ~4 hours relative to perigee in 2003, for approximately orbits 390 to 420) shows a reaction to changes in the IMF B\textsubscript{Z}. The IMF B\textsubscript{Z} changes sign in a periodic manner during this time; corresponding changes in the sign of the residual are also observed. This is an interesting point and worthy of further investigation.

6. Conclusion

[43] An investigation of Cluster data in comparison with the T01 model has been carried out. We have found commonly observed offsets between the Tsyganenko 2001 model and Cluster magnetic field data (of the order of 20 nT) which take the form of bipolar signatures. These can be observed in a similar form 19 days later when the dipole phase of Cluster is most closely matched. These are found to be indicative of field-aligned currents, probably part of the region 2 current system. The T01 model gauges the location and duration of the FAC signatures well in general but our results show the magnitude of the magnetic field changes is not so well predicted. Our results indicate that the T01 model would benefit from the inclusion of Cluster magnetic field data in the calculation of the model parameters. The location of these bipolar features has been identified to be close to the edges of the ring current, using electron energy spectrograms from the same spacecraft. This is consistent with our suggestion that the bipolar signatures are the result of region 2 currents. On the dayside the effects are slightly more complex, being influenced by the presence of the midaltitude cusp region, and are asymmetrically sampled by Cluster. Nevertheless, these FAC observations are also observed to follow the expected day-night asymmetry of the region 2 system.

[44] Less systematic trends in the offsets between the data and the model have also been found when Cluster is both
inside and outside the ring current region. However, not all of these are consistent from year to year, and it would therefore be hard to improve upon T01 without an accurate indication of their physical source. Future work will therefore investigate the cause of these longer-term trends along with the factors controlling the magnitude of the region 2 FAC magnetic signatures.

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**References**


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