A STATISTICAL COMPARISON OF CLUSTER MAGNETIC DATA WITH THE TSYGANENKO 2001 MODEL

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ABSTRACT

The four Cluster spacecraft have been measuring the magnetic environment of the Earth for over five years. This recently extended mission provides an ideal opportunity for a long-term study of the external contributions to the magnetic field in the near-Earth environment. Preliminary analysis of sample orbits showed significant absolute residuals (~50 nT) between Cluster magnetic field measurements taken by the flux-gate magnetometer near perigee (19,000 km altitude) and the various Tsyganenko models, both in the nightside and dayside magnetosphere. We have now extended this work by performing a comparison of a large number of Cluster magnetic field data with the Tsyganenko 2001 model, and the same differences as seen in our earlier work are often repeated in the wider data set now tested. We interpret these discrepancies in terms of the magnetospheric regions that the spacecraft pass through, using particle data from the spacecraft to identify the different regions.

1. INTRODUCTION

We have been investigating the accuracy and potential for use of the Tsyganenko models by the geophysics community to describe the magnetospheric contribution to the whole Earth system magnetic field. The Tsyganenko magnetic field models have been widely utilised in the space physics community for many years. The 2001 version (T01) [1,2] is constructed by considering the mathematical form of the individual current systems in the magnetosphere (ring current, cross-tail current, magnetopause current, field-aligned currents). In addition, a uniform magnetic field contribution from the penetration of the interplanetary magnetic field is included. Data from multiple spacecraft are then used to define the parameters of the model using a least squares fit to minimise the misfit of the full vectors of the external magnetic field.

T01 is driven by five input parameters: solar wind dynamic pressure, solar wind speed, disturbance storm time index (Dst - or its high time resolution counterpart SYM-H [3] and interplanetary magnetic field (IMF) components in the Y_{GSM} and Z_{GSM} directions. These inputs feed into various coefficients within the model – most notably two parameters which keep track of the history of external inputs to the magnetosphere, following the idea that the magnetosphere will react differently depending on what has happened previously.

In order to assess the accuracy of the T01 model we have compared the model output to magnetic field data from the Cluster mission [4]. Cluster comprises four spacecraft that orbit the Earth in an elliptical orbit with a perigee at ~19,000 km and an apogee at ~119,000 km. One orbit takes ~57 hours and precesses around the Earth in one year. We have used data from the flux-gate magnetometer (FGM) [5] supplemented by particle data from other instruments on board. A comparison with Cluster data provides an independent assessment of the accuracy of T01 since these data are not included in the empirical database.

2. METHOD

Since T01 represents only the magnetospheric contribution to the overall magnetic field we have used the International Geomagnetic Reference Field (IGRF) version ten [6] as the Earth's internal magnetic field. We have assumed that the ionospheric contribution at the altitude of the Cluster orbit is negligible.

Two methods are used to accurately compare different Cluster orbits. Firstly, we have identified pairs of complete orbits separated by an integer multiple of 24 hours to ensure that the dipole phase is as close as possible for the different orbits, i.e. the spacecraft is most likely to be going through the same magnetospheric region. The smallest separation that meets this criterion is 19 days (8 full orbits). Secondly, we have produced plots with a time axis that is relative to the time of maximum |**B**| from IGRF, in the style of a superposed epoch study.

In the following assessment the residuals are all data minus model (we have used absolute rather than percentage residuals) and 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 centred on perigee. Data from only one of the Cluster spacecraft are shown (Cluster 1).

3. OBSERVATIONS

Fig. 1 shows the results of our analysis for two dayside perigee passes separated in time by 8 orbits (one in red the other in blue) The top three panels of Fig. 1 show the X_{GSM},Y_{GSM} and Z_{GSM} residuals for both passes. The plots from the two different orbits are shifted relative to each other so that the maxima in $|\mathbf{B}_{IGRF}|$ line up with each other – hence, as mentioned previously, the x-axis is time relative to this maximum.

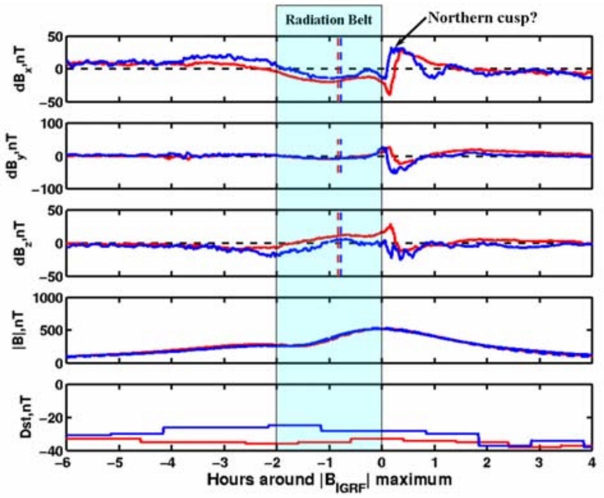

Figure 1. Residual plots for orbits 470/471 (red) and 478/479 (blue). Dashed vertical lines show perigee.

The dashed vertical lines mark perigee for each of the two passes shown. The 4th panel shows in solid lines |**B**| from Cluster, and in dashed lines |**B**| from the T01 model (the dashed lines are somewhat hidden in this case), the latter run using only the ring current contribution to the overall external field (and its included shielding which keeps the field restricted within the magnetopause, note IGRF is also included). The 5th panel shows the Dst index.

The pale blue rectangle indicates the approximate time when the spacecraft is traversing the outer radiation belt/ring current region. This was identified using electron flux data from the Imaging Electron Spectrometer (IES) component of the RAPID (Research with Adaptive Particle Imaging Detectors) instrument [7] .

The approximate location of these orbits is shown in a three dimensional view in Fig.2 in relation to |**B**| given by T01 for a set of quiet to moderate conditions (the colour scale is normalised and is meant as a guide only). The sun is to the right and slightly in front of the page in this view. The Cluster orbits in this configuration may just catch the edge of the |**B**| due to the Birkeland currents (the two yellow/green areas emanating from the polar regions).

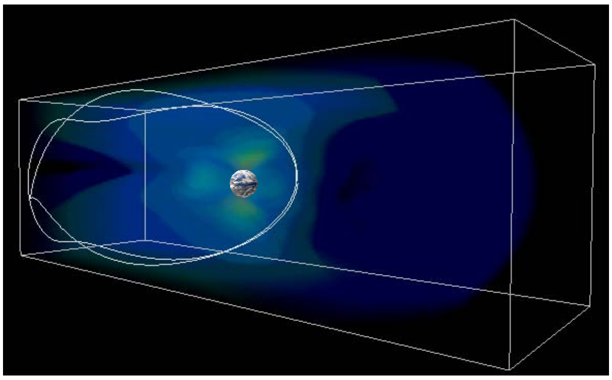

Figure 2. A representation of the two orbital paths in Fig. 1 over the T01 model magnetic field magnitude.

There is a remarkable similarity between the residuals from the two different orbits – particularly the bipolar feature just after 0 hours. This signature occurs as the spacecraft encounters the region in and around the northern cusp (Cluster passes through perigee from the south). The bipolar characteristic is significant because it shows that Cluster is passing through a tube of current, such as one would expect for a field-aligned current. The residual of the field magnitude from Cluster and from T01 shows no significant deviation where the bipolar signature is observed. This is consistent with a field-aligned current (the magnetic field change perpendicular to the main field results in only a small increase to the main field).

Fig. 3 is in the same format as Fig. 1 but for a nightside perigee pass. The residual behaviour near perigee is different here; there is a very distinctive, positive excursion in the x-component. At the same time the z-component displays a negative residual prior to perigee followed by a larger positive residual afterwards. The residual in the y-direction demonstrates more variable behaviour.

Fig. 4 shows the orbital location for the data in Fig. 3 with respect to T01 with the same set of imposed steady conditions as Fig. 2. This figure shows the Cluster orbit near perigee passing through the tailward side of the |**B**| produced by the ring current (the greenish patch directly behind the Earth).

The outer radiation belt/ring current location was identified by RAPID-IES as before and is indicated by the pale blue rectangle on Fig. 3. The major contributor to the larger residuals near nightside perigee is therefore almost certainly due to discrepancies in the modelling of the ring current.

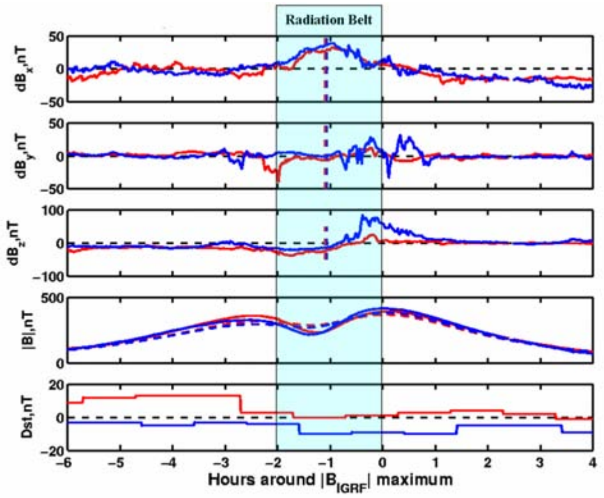

Figure 3. Residual plots for orbits 397/398 (red) and 405/406 (blue).

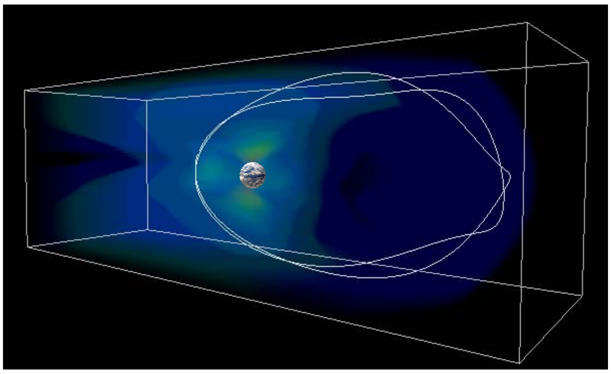

Figure 4. A representation of the two orbital paths in Fig. 3 over the T01 model magnetic field magnitude.

Very similar features in the residuals to those in Figs. 1 and 3 are frequently observed during the 3 years of data considered so far (2002, 2003, 2004). A simple average of orbits from a similar dipole phase from a quarter of a year (to maintain a similar perigee location), e.g. orbits 397/398 + 405/406 + 413/414 etc, shows that the nightside pattern of residuals is quite consistent. Fig. 5 shows the mean residuals and |$\mathbf{B}_{\text{Cluster}}$| for January, February and March of 2003. The "ring current" feature is clearly persistent (although this is only an average of 5 perigee passes due to the restrictions on orbit location that we have imposed). No sorting for geomagnetic activity or solar wind/IMF conditions has been applied here.

This pattern also persists from year to year; Fig. 6 is as Fig. 5 but for the first quarter of 2004 – when the satellites will be in roughly the same orbital location as they were the year. A similar result to Fig. 5 is apparent.

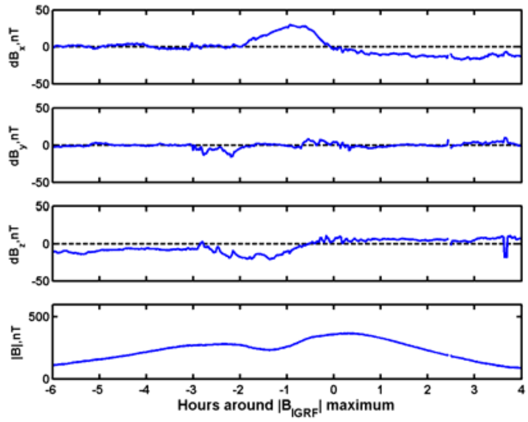

Figure 5. The mean residuals and |$\mathbf{B}_{Cluster}$| for Jan, Feb and Mar 2003.

The nightside perigee results (Figs. 5 and 6) demonstrate a consistent feature, if we then perform an average of the third quarter of 2004 (Fig. 7), when the perigee is on the dayside, we find that the bipolar signature often seen in individual pairs of dayside perigee passes (for example in Fig. 1) is not seen to be consistent.

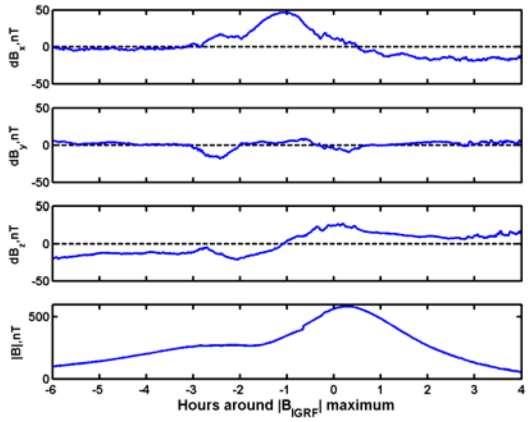

Figure 6. The mean residuals and |$\mathbf{B}_{Cluster}$| for Jan, Feb and Mar 2004.

Some small but persistent features do remain after the averaging process in all three components (marked with red arrows on Fig. 7).

If we repeat the analysis but for the same three months of 2003 (Fig. 8), this time the bipolar signature attributed to passage through the northern cusp is still visible in the mean residuals. Clearly the dayside residual feature is less consistent than the behaviour on the nightside. This would be expected if the dayside feature is due to field-aligned currents which are highly responsive to changes in the IMF conditions.

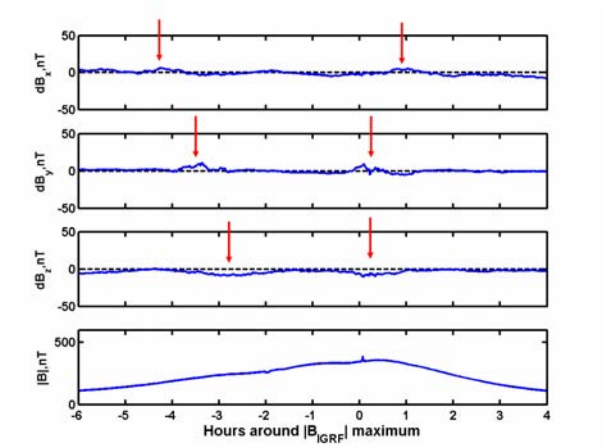

*Figure 7. The mean residuals and |**B**$_{Cluster}$| for Jul, Aug and Sept 2004.*

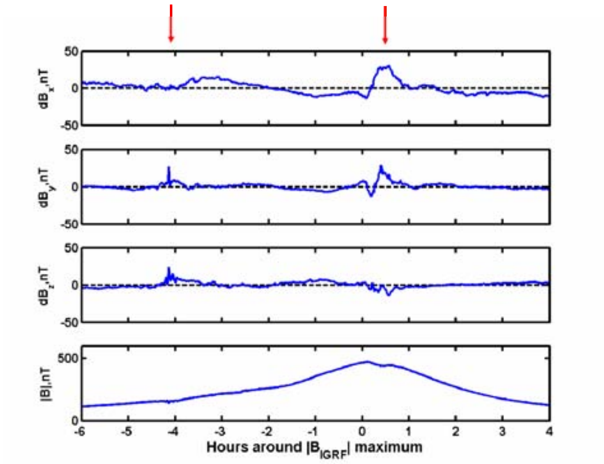

*Figure 8. The mean residuals and |**B**$_{Cluster}$| for Jul, Aug and Sept 2003.*

4. DISCUSSION

The observations from the previous section demonstrate two main features of the residuals between T01 and the Cluster 1 data: larger misfits in the two hours around perigee on the nightside, and short-lived bipolar signatures on the dayside in the approximate region of the cusp. The first of these is almost certainly related to the ring current, the second is probably due to the presence of a field-aligned current.

A breakdown of the model into T01 itself and the IGRF compared with the nightside data reveals that the positive residual "bump" in the x-component is due to T01 underestimating the effect of the ring current and therefore not adding sufficient magnetic field strength to the values given by IGRF. This could be a result of either the ring current contribution simply being too low, or the shape and location of the ring current being inaccurate, or a combination of both of these. Consideration of the data from the other three Cluster spacecraft may be able to discern if one of these factors is dominant.

Although we have not yet fully assessed the effect of magnetic activity on our observations, the nightside feature in the residuals occurs at very low activity (as defined by Dst) as well as under more active conditions. This implies that the partial ring current included in the T01 model (which only becomes important at higher activity levels) is not likely to produce the effects seen here.

The discrepancy commonly observed near dayside perigee is very different in nature to that on the nightside. It takes the form of a short-lived, bipolar variation in the residuals of all three components of the magnetic field. Analysis of the contributions of IGRF and T01 to the model magnetic field on the dayside shows that T01 misses entirely this bipolar signature. A comparison of data minus T01 (including IGRF) and data minus IGRF only show very similar results. T01 is small in this region and there is no change in the model results where this feature is observed. It is probable that this is a magnetospheric current that is not yet included in the model.

The bipolar shape of the feature indicates that the physical shape of the current causing the model misfit is a line or tube. This lends itself well to the idea that this may be a field-aligned current beyond the Birkeland currents accounted for in T01. We intend to look at the IMF dependence of this feature since field aligned currents in this region are strongly dependent on IMF orientation.

The Cluster spacecraft have provided, and continue to provide a large set of data in the ring current region. The results presented here indicate that the inclusion of Cluster data in the model dataset could enhance the model.

5. CONCLUSION

We have found persistent and significant offsets between the Tsyganenko 2001 model and Cluster magnetic field data (of the order of 50 nT). These occur in two primary areas:

1) The nightside ring current region for nightside perigee passes.
2) The cusp regions for dayside perigee passes, where a bipolar feature in the residuals of all components is observed.

There are several avenues available for advancing the current analysis. Firstly, the statistical validity of the averages can be improved by the introduction of the data from the other three spacecraft. We will also assess the impact of geomagnetic activity levels and IMF orientation on the strength of the observed offsets and also locate the local time regions where they occur. To investigate the possibility that the T01 ring current is not quite in the right location or of the most appropriate shape, we will make use of the spatially distributed nature of the four spacecraft of the Cluster mission.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the UK research council NERC for funding this work through the GEOSPACE consortium; Andy Heath for graphics software, and J. Wild for useful discussions.