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Title: **OBSERVATIONAL TESTING OF MAGNETOSPHERIC FIELD MODELS AT GEOSYNCHRONOUS ORBIT**

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Observational Testing of Magnetospheric Magnetic Field Models at Geosynchronous Orbit

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Abstract. Empirical models which estimate the magnetic field direction and magnitude at any point within the magnetosphere under a variety of conditions play an important role in space weather forecasting. We report here on a number of different studies aimed at quantitatively evaluating these models, and in particular the Tsyganenko T89a model. The models are evaluated in two basic ways: 1) by comparing the range of magnetic field tilt angles observed at geosynchronous orbit with the ranges predicted for the same locations by the models; and 2) by comparing the observed magnetic field mapping between the ionosphere and geosynchronous orbit (using two-satellite magnetic field conjunctions) with the model predictions at the same locations. We find that while the T89a model predicts reasonably well the basic variation in tilt angle with local time and permits a range of field inclinations adequate to encompass the majority of observed angles on the dawn, dusk, and night sides, it is unable to reproduce the range of inclinations on the dayside. The model also predicts a smaller magnetic latitude range of geosynchronous field line footpoints than the observed two-satellite mappings indicate. Together, these results suggest that the next generation of field models should allow a greater range of stretching, especially in local time sectors away from midnight. It is important to note, however, that any increased range should encompass less-stretched configurations: although there are certainly cases where the models are not sufficiently stretched, we find that on average all magnetic field models tested, including T89a, are too stretched. Finally, in investigating how well the observed degree of field stretch was ordered by various magnetospheric indices, we find that the tilt of the field at geosynchronous orbit is a promising candidate for the incorporation into future models.

1. INTRODUCTION

A crucial element of accurate and reliable space weather forecasting is the use of realistic models of the global magnetospheric magnetic field. In many ways, a three-dimensional grid of the vector magnetic field throughout a forecasting region can be thought of as the framework, (similar to a tropospheric network of weather stations) which makes space forecasting possible. To date, the capability of different models to correctly predict the magnitude and/or direction of the magnetic field has been evaluated by comparing the model predictions to numerous, single-point *in situ* measurements [e.g., *Tsyganenko*, 1989; *Fairfield*, 1991; *Peredo and Stern*, 1991; *Peredo et al.*, 1993; *Pulkkinen et al.*, 1994; *Thomsen et al.*, 1996]. At Los Alamos, we have undertaken a series of studies aimed at evaluating the *global* configuration of a number of widely used and readily accessible magnetospheric magnetic field models, and in particular the Tsyganenko T89a model. Because of the obvious value of such field models and because of the wide variety of applications for which they are being used, it is extremely important that they be tested quantitatively with observations so that we have a good understanding of the conditions under which they are a valid representation of the field. Quantitative tests of field models in the geosynchronous region are of particular interest because of the large number of communications, weather, and military satellites which occupy that orbit; understanding, monitoring, and predicting the environment there is one of the primary goals of current space weather forecasting efforts.

In this paper we summarize our most recent efforts. We begin by describing a study which tests the ability of the T89a model to reproduce the observed range of magnetic field tilt angles at different geosynchronous satellite locations under a wide range of conditions [*Thomsen et al.*, 1996]. Section 3 describes an observational method for determining the mapping between low (ionospheric) and high (geosynchronous) altitudes, and the creation of a database of over 100 such mappings. In Section 4 we report on a study which uses this database to test the magnetic field line mappings of five different magnetic field models [*Reeves et al.*, 1995], and in Section 5 we use the database to examine the ability of different observational parameters to order the amount of stretch in the magnetic field and to identify the most appropriately stretched version of T89a [*Weiss et al.*, 1996].

2. THE GEOSYNCHRONOUS MAGNETIC FIELD CONFIGURATION

Thomsen et al. [1996] have suggested that neaı real-time, multi-point measurements of th geosynchronous magnetic field orientation coul potentially serve to help monitor the global state of th magnetosphere. Such global monitoring could b realized from local, *in situ* measurements through th use of suitable quantitative global field models. As first step toward this goal, we tested the ability of th T89a magnetic field model to reproduce the fiel orientation observed at geosynchronous orbit under wide range of conditions. The comparison was mad using data from Magnetospheric Plasma Analyzeı (MPAs) onboard three satellites (1989-046, 1990-09: and 1991-080) at different geosynchronous location and from each of the four seasons. The design an operating characteristics of the MPA have bee described in detail by *Bame et al.* [1993], and typic: examples of the observations at geosynchronous orb have been presented by *McComas et al.* [1993].

The field angles are derived from the symmetr axis of the 3-dimensional electron distributioı Assuming gyrotropicity, the 3 × 3 temperature matrix can be diagonalized, with the diagonal elements representing the eigenvalues $T_\perp$, $T_\perp$, and $T_{||}$. The eigenvalue that is most different from the other two is identified at $T_{||}$, and the corresponding eigenvector is the direction of the magnetic field. Two angles are associated with this direction: the polar angle (θ_B) between the symmetry axis and the spacecraft spin axis, and the azimuthal angle (ϕ_B) measured about the spin axis. Thus, the nominal dipole magnetic field at geosynchronous orbit has direction angles $\theta_B \sim 90°$ and $\phi_B \sim 0°$. Since an increasingly "stretched" field corresponds primarily to rotations of θ_B, we concentrate on comparing the measured values of θ_B with the model-predicted values [see *Thomsen et al.*, 1996 for further details].

We performed the comparison at both near-equatorial (±2°; 1989-046) and off-equatorial (-7° to -10°; 1990-095 and 1991-080) magnetic latitudes. Figure 1 summarizes the range of field inclinations, θ_B, observed at 1989-046 for four months of data, one at each solstice and equinox.

In general, the T89a magnetic field model reproduces the local time and seasonal behavior of the field inclination at geosynchronous orbit. It also generally permits a range of field inclinations adequate to encompass the majority of the observed angles. The main exception to this is on the dayside, where the T89a model exhibits very little variation in θ_B over the

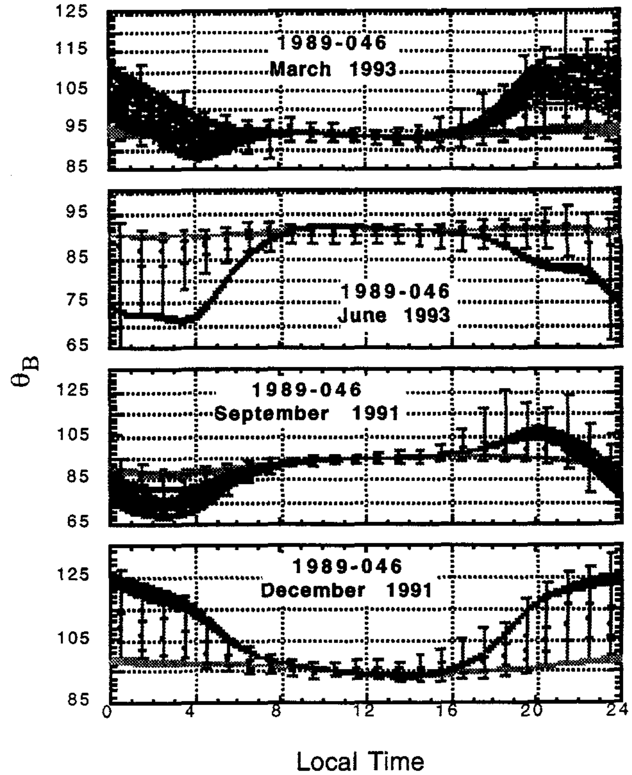


Figure 1. Range of near-equatorial magnetic field inclinations, θ_B, derived from MPA measurements from satellite 1989-046 for four months of data, one at each solstice and equinox. The solid dots show the median value of in each one-hour bin of local time. The vertical bars indicate the range between the 5th and 95th percentiles, with the cross-bars corresponding to the 25th and 75th percentiles. The dotted curves in each panel show the values that are predicted for that satellite location by the T89a parameterizations with the least amount of stretch (Kp = 0) and with the greatest amount of stretch (Kp>4+).

entire range of parameterizations. At off-equatorial locations on the dayside (not shown) the model fields are more stretched than the observations; this suggests that the model does not adequately account for dayside compression by the solar wind. At equatorial locations on the nightside there are roughly equal numbers of cases where the models are overstretched or understretched with respect to the observations. Off the equator, there is a definite tendency for the models to be more stretched than is generally seen in the observations.

3. THE DMSP-GEOSYNCHRONOUS CONJUNCTION DATABASE AND THE IONOSPHERIC FOOTPRINT OF GEOSYNCHRONOUS ORBIT

In addition to evaluating the T89a model mappings at their geosynchronous-crossing points, we can also use multi-point observations to test the *global* configurations of T89a and other models. We have compiled a database of observationally-determined magnetic field mappings between low- and high-altitude satellites, covering a range of magnetospheric activity, local times, and season, using four months of plasma electron data from two geosynchronous satellites (1989-046 and 1990-095) and three low-altitude DMSP satellites (F8, F9, and F10). Actual magnetic conjugacy between two of the satellites is determined using the similarity of plasma distribution functions at the two locations as required by Liouville's theorem for distributions along a single flux tube. Since the spectrum at synchronous orbit typically varies slowly with longitude, a single MPA spectrum at the time of conjunction is used for comparison with a number of rapidly-varying spectra from the DMS auroral zone pass; intervals of close spectral similari indicate the traversal of the DMSP satellite across tl geosynchronous drift shell. This type of two-poi spectral comparison technique has been used befo (although only in a small number of cases) to identi magnetic conjugacies of widely separated spacecra [*Sharp et al.*, 1971; *Mende and Shelley,* 1976; *Meng al.*, 1979; *Lundin and Evans,* 1985; *Schumaker et a* 1989; *Mauk and Meng,* 1991]. Further details of o experimental approach and justification of the spectr comparison technique can be found in *Hones et c* [1994].

We use an automated spectral comparison ar selection technique to identify the intervals of clo spectral matching. The rms difference between each sec DMSP electron number flux spectrum and tl chosen MPA spectrum is calculated for a 6-min seri surrounding each close (±10° magnetic longitud conjunction. Several empirically-determined criter are applied to the resulting rms time series. The fir criterion requires that the rms difference between tw comparison spectra be less than 0.36 for them to l considered a good match; moreover, the time period f which this criterion is met must be less than 30 s ensure that the spectral matching occurs in a singl clearly defined interval (presumably when the DMS satellite crossed the geosynchronous drift shell). second set of criteria, namely that the rms difference l less than 0.42 for less than 60 s, further ensures th neighboring spectra are clearly not as well-matched as the chosen interval (we want a steep, deep minimum in the rms). The application of these stringent criteria, combined with normal DMSP and MPA data gaps, resulted in only 1 definitive mapping out of ~15 nominal conjunctions [*Weiss et al.*, 1996].

An example of the rms comparison and selection technique applied to a close magnetic conjunction between DMSP F9 and geosynchronous satellite 1989-046 on March 10, 1991 is shown in Figure 2. DMSP was traveling poleward in the southern hemisphere such that its projected position mapped to increasingly larger L-shells. The rms error between the field-aligned MPA spectrum and each DMSP spectrum between 0843:40 and 0845:40 UT is shown in the top panel. The minimum and secondary rms thresholds are marked by the solid and dashed horizontal lines, respectively. Five spectral pairs had rms values less than the minimum threshold. The second panel shows these five DMSP spectra and the MPA spectrum (heavy line) during the best-match interval. For comparison, the third panel shows 5 DMSP spectra from times

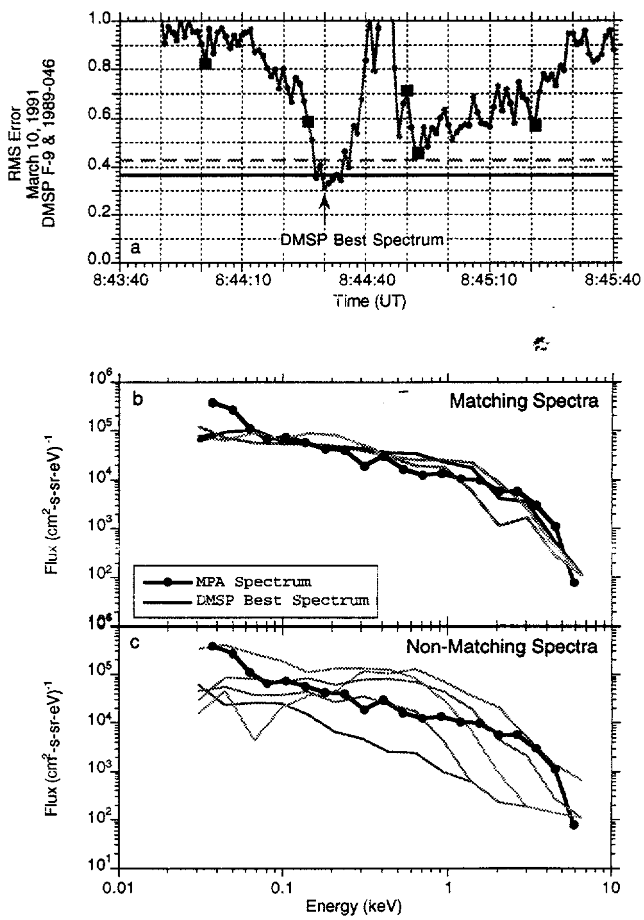


Figure 2. (a) A two-minute time series of rms difference between the logarithms of each 1-sec DMSP F9 number flux spectra and the most field-aligned 1989-046 geosynchronous spectrum. The primary and secondary rms thresholds are marked by the solid and horizontal lines, respectively, and the most closely matched spectral pair at 0844:30 is noted. (b) The five DMSP spectra within the best-match interval. (c) Five other DMSP spectra from times (marked by squares in the first panel) with larger rms values. The rms values outside this two-minute window were all > 1.0.

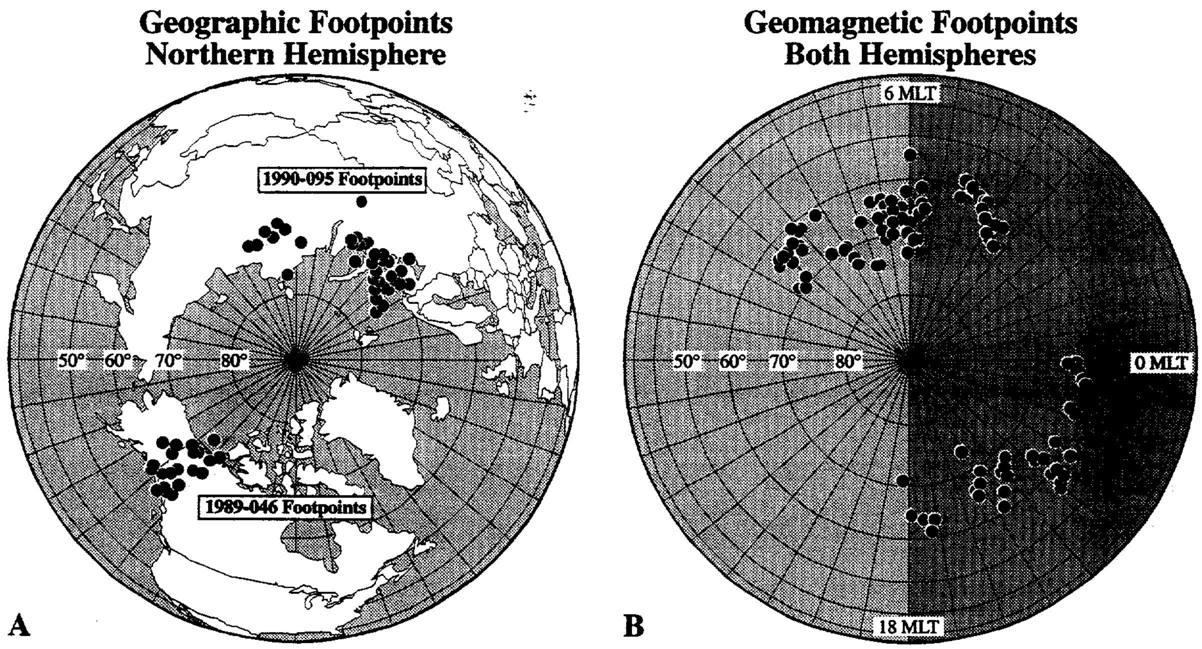


Figure 3. The location of DMSP when it measured a magnetic conjunction with a geosynchronous satellite. (a) The position of DMSP in geographic coordinates. Only northern hemisphere conjunctions are shown. (b) The position of DMSP in geomagnetic coordinates (magnetic latitude and magnetic local time). Conjunctions from both hemispheres are shown.

(marked with squares in the first panel) with higher rms values. This is a case in which the precipitating electron distribution matches the field-aligned equatorial distribution only during the short time that the DMSP satellite was magnetically connected to the geosynchronous satellite drift shell.

Observationally-determined magnetic conjunctions of this type allow us, for the first time, to examine the *model-independent* mapping of geosynchronous orbit. Figure 3a shows the locations the DMSP satellites at the times of their best spectral matches with a geosynchronous satellite. Figure 3a shows DMSP's geographic location and Figure 3b shows its location in magnetic local time and magnetic latitude. The geographic longitude of 1989-046 was such that its footpoints cluster near the Canadian-Alaskan border.

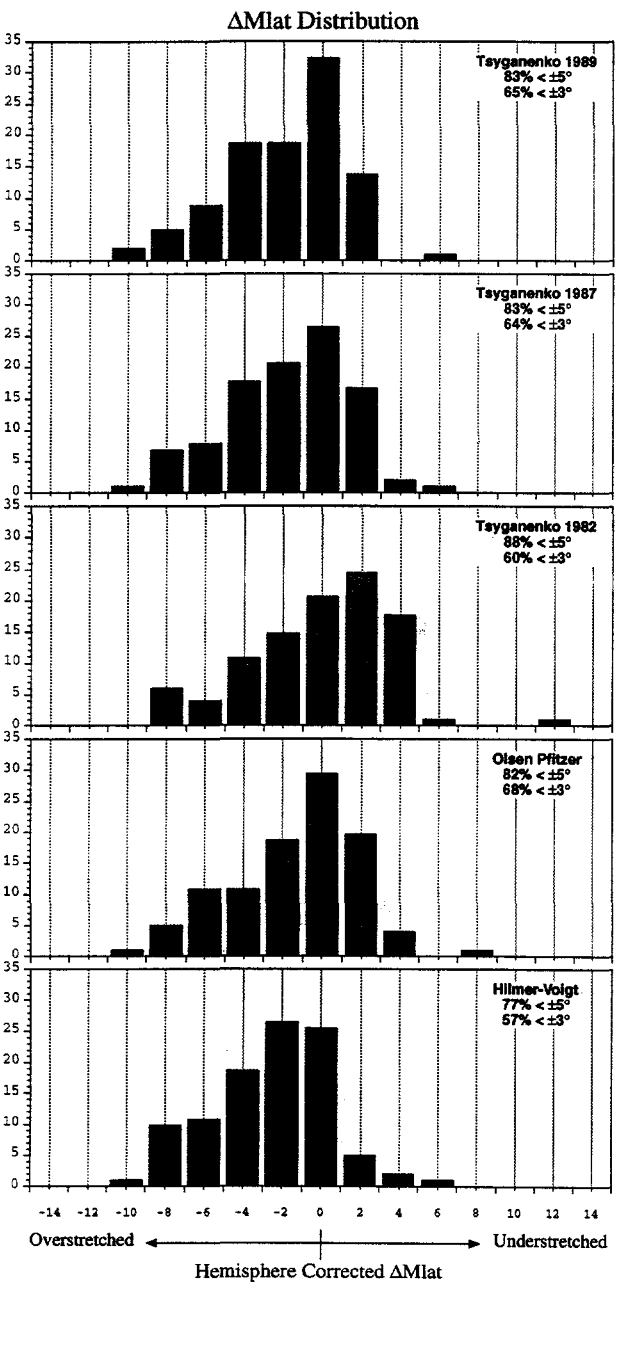
1990-095 moved in the middle of 1991 and thus has two clusters of footpoints. Although the DMSP satellites are restricted to a limited range of local time, the rotation of the Earth's dipole allows them to sample about one half of the possible magnetic local times (as shown in Fig. 3b).

Fig. 3b shows that the footpoint of geosynchronous orbit generally lies in the auroral ionosphere. Most often it is in the region of diffuse aurora but it frequently lies in the region of discrete aurora. It is also apparent from the figure that the footpoint of geosynchronous orbit can be quite variable, spreading over more than 10° in magnetic latitude. When compared to the mapped geosynchronous magnetic latitudes using the least- and most-stretched versions of T89a, we find that the observations indicate a greater range of field-line stretch at geosynchronous orbit than the model can accommodate, especially on the dayside. This particular finding is discussed in greater detail in the following sections.

4. QUANTITATIVE COMPARISON OF DIFFERENT FIELD MODELS

We have used the DMSP-geosynchronous conjunction database to examine the field line mapping of five different magnetic field models [*Reeves et al.*, 1995; 1996]. Specifically, we compare the measured magnetic footpoints of geosynchronous orbit with the footpoints predicted by the Olson-Pfitzer [*Olson and Pfitzer,* 1974], *Hilmer-Voigt* [Hilmer and Voigt, 1995], and three of the Tsyganenko models -- T82, T87, and T89a [*Peredo et al.*, 1993, and references therein]. We used each model "as advertised"; i.e., for the Tsyganenko family of models we used the actual Kp parameter for each conjunction to specify which stretching level to use. The Hilmer-Voigt model is specified by three parameters: Dst, the stand-off distance of the magnetopause, and the equatorward boundary of the auroral oval. For the Hilmer-Voigt model we again used the parameters that were appropriate for each event. The Olson-Pfizer model has no free parameters so the same model applies to all cases.

A histogram of the difference between the measured and model footpoints for each of the five models is plotted in Figure 4. The top panel shows the statistics for the T89a model. Here, 32% of the model footpoints agreed with the measured footpoints to within ±1°, 65% were within ±3°, and 83% were within ±5°. In other words, if you need to know the location of the footpoint of geosynchronous orbit to within 1° the T89a model has a 32% probability of being correct. However, it also has a 17% chance of being off by more than 5° and the statistical uncertainty in the mapping is approximately 3°.



Surprisingly, as Figure 4 shows, no one field model performed significantly better than any of the other models. We also note that Figure 4 indicates that all of the models are, on average, too stretched. However, we have very few conjunctions in the midnight local time sector due to the limited range of local times sampled by the DMSP orbits. Therefore these results do not imply that the field models are too stretched compared to a growth phase field at midnight. Rather, we suspect that in order to better represent the conditions at midnight the modelers have made the models too stretched at other local times. Finally, we note that the footpoint of geosynchronous orbit varies over more than 10° of magnetic latitude (see Figure 3 above). This is a larger range of latitudes than any of the field models tested can accommodate, suggesting that the next generation of magnetic field models should allow a greater range of stretching.

5. EVALUATION OF MAGNETOSPHERIC STRETCHING PARAMETERS

In another study using the DMSP-geosychronous database we tested the ability of different observational magnetospheric indices to identify the most appropriate parameterization of T89a for different magnetospheric conditions [*Weiss et al.*, 1996]. The magnetospheric parameters we evaluated were Kp, AE, d(AE)/dt, Dst, the midnight equivalent auroral boundary (MEB; *Gussenhoven et al.*, 1983), and the inclination of the magnetic field at geosynchronous orbit (θ_B). *Hones et al.* [1996] showed that the actual 3-hr Kp index at the time of a conjunction was rarely the same as the Kp-version of the T89a model which came closest to connecting the two satellites. Our goal in this study is to investigate which parameters are most strongly correlated with the degree of field stretching as revealed by our 2-spacecraft conjunctions; in so doing we hope to provide guidance regarding the appropriate parameterization of T89a for various applications as well as insight into which diagnostic indices might be incorporated directly into future models.

The first step in assessing the T89a model is to determine which of the model's present stretching levels (parameterized by Kp = 0, 1, 2, 3, 4, 5) comes closest to reproducing the two-satellite mappings in our database. The method, described by *Hones et al.* [1996], consists of comparing the projected dipole magnetic latitudes of the DMSP and geosynchronous satellite positions for each parameterization of the model over the spectral matching interval. Although the mapped latitude of the low-altitude DMSP footpoint essentially does not depend on the stretching level, the latitude of the geosynchronous footpoint moves equatorward for increasingly stretched versions of the model. The stretching level for which the mapped magnetic latitudes of the DMSP and geosynchronous satellite footpoints come closest is termed the "best stretching level", or BSL.

Figure 5 shows the difference between the Kp-level which successfully reproduces the two-satellite conjunction (the BSL) and the actual value of Kp for all of the cases in our database. Events in the upper half of the graph are those in which the model field would not be stretched enough to reproduce the observed mappings if the actual value of Kp were used; for those in the lower half, a model field parameterized by the actual value of Kp would be overstretched. In only 13% of the cases does the actual value of Kp produce the correct mapping. In a surprisingly large number of cases, the observed two-satellite mappings fell completely outside the stretching range of T89a; i.e., the geosynchronous footpoint did not intersect the DMSP footpoint for any parameterization of the model. In 48% of the conjunctions the closest geosynchronous footpoint landed more than 0.5° equatorward of the DMSP footpoint, indicating that the observed field configuration was less stretched than the least stretched version of T89a. In 9% of the observed conjunctions the closest geosynchronous footpoint was more than 0.5° poleward of the DMSP footpoint and thus these conjunctions were more stretched than the most stretched version of the model. As discussed above,

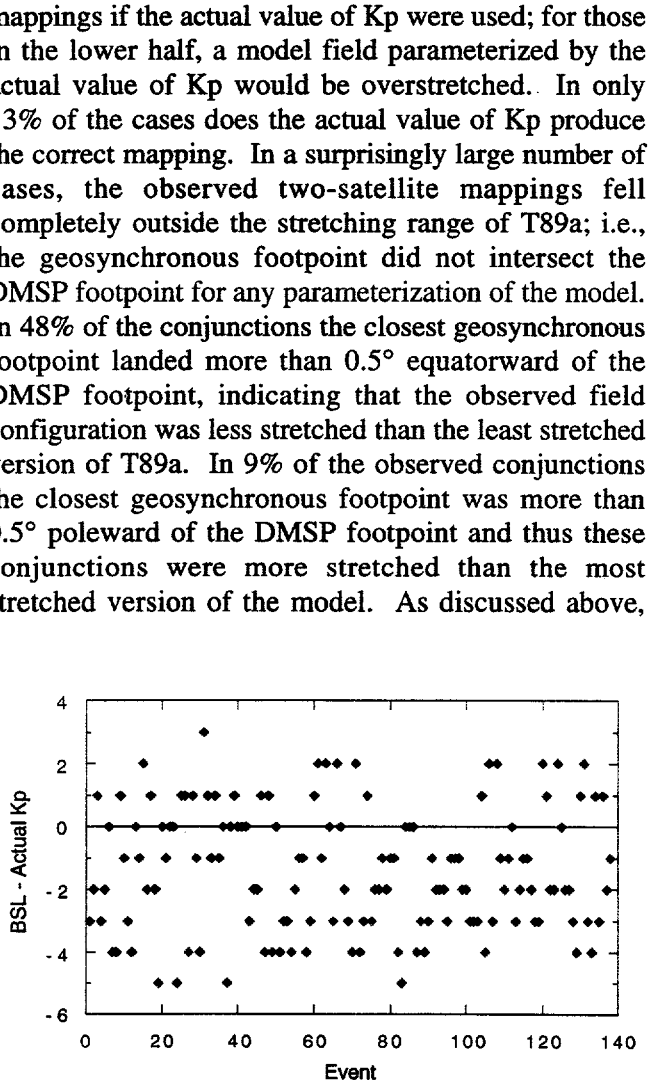


Figure 5. The difference between the T89a stretching level which came closest to connecting the two satellites and the actual Kp index for each conjunction. As in the T89a model, the actual values of Kp are grouped by integer (e.g., Kp = 1 for Kp = 1-, 1, 1+) and all values of Kp > 4+ are denoted by Kp = 5. Note the predominance of cases in the lower half of the graph in which the best stretching level is less than the actual value of Kp (i.e., using the actual value of Kp would produce model mappings which are too stretched at geosynchronous orbit than the observations indicate).

however, we don't necessarily believe that the models are too stretched at midnight, but rather that in order to better represent the conditions at midnight the models may be too stretched at other local times.

Our analysis of four of the alternative "stretching" parameters is summarized in Figure 6. The figure shows the relationships between each parameter and the BSL (i.e., between each parameter and the "observed" degree of field stretch). The conjunctions are binned according to BSL, and the median, 25th, and 75th percentile values of the parameters are plotted for each bin. The correlation coefficients are shown to the right of the plots, and the number of conjunctions in each bin is shown in the histogram at the bottom. The first parameter , θSL, corresponds to the T89a stretching level which came closest to reproducing the geosynchronous field inclination θ_B at the time of the conjunction. In about half of the cases the observed field angles fell between two (or spanned a range of) parameterizations of the model; thus, for each conjunction we defined θSL_1 and θSL_2, corresponding to the minimum and maximum T89a stretching levels that spanned the observations [see *Weiss et al.,* 1996 for details]. The second and third panels show the relationship between field stretch and the MEB and Dst indices, respectively, and the last panel shows the relationship with the Kp index.

Figure 6 shows that there is a much stronger correlation between θSL and BSL, especially for T89a stretching levels ≥ 2, than between the actual 3-hr Kp index and BSL. But there is also enough scatter within each bin that a determination of the most appropriate stretching level based solely on θSL does not appear to be possible. Similarly, both the Dst and MEB parameters show good correlation with BSL, but the scatter within each bin is too great for either parameter to be used as a single-valued stretching indicator, except perhaps for the most disturbed conditions (MEB latitudes ≤ 58.5° or Dst < -45 nT). Thus, we are unable to specify any of the parameters as a unique indicator of the most appropriate T89a stretching level due to the large variability of the values of the magnetospheric observables covered by the 6 stretching levels. This is not surprising for the 30-min and 1-hour indices: the fact that differently stretched 2-satellite mappings can have the same MEB or Dst index is simply an indication that these parameters depend on things other than the shape of the magnetic field and/or that the instantaneous field configuration can differ from the time-averaged configuration due to variations in the different magnetospheric current systems on temporal scales less than 30 min and on spatial scales smaller than a few hours of LT. Although it seems reasonable

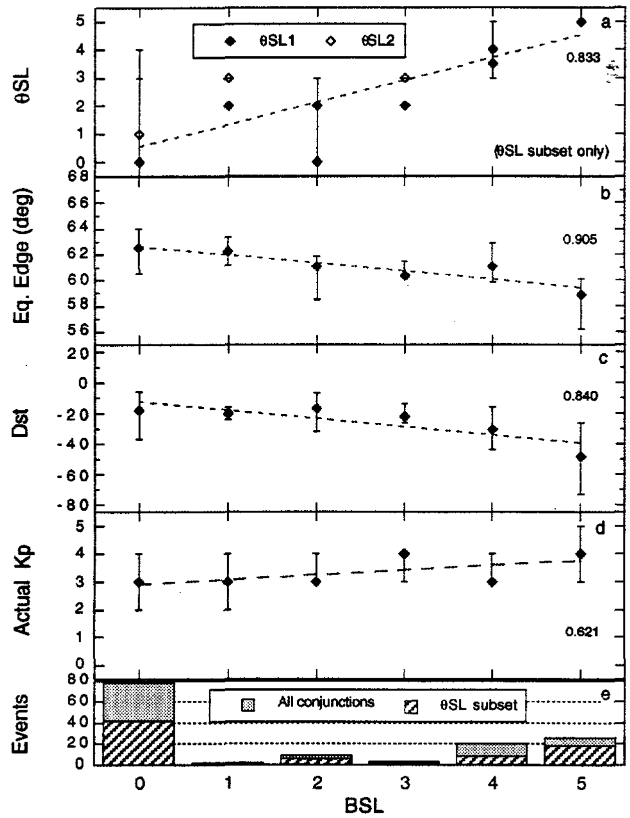


Figure 6. The relationships between the "best stretching level", BSL, and (a) the T89a stretching level which gave the best match to the observed conjunction, (b) the equatorward edge of the auroral oval at midnight, (c) the hourly Dst index, and (d) the actual value of Kp. The number of conjunctions in BSL bin are noted in (e). The QSL subset refers to the fact that only nightside conjunctions with reliable field angle determinations are used in this assessment. The diamonds denote the median values for each BSL bin , and the vertical lines show the 25th and 75th percentiles. The correlation coefficient of each parameter is given at the right of each panel.

that a 1-min resolution, substorm-related index such as AE or d(AE)/dt would be a better choice for ordering the degree of field stretch, we found these parameters to be prohibitively difficult to use as a simple pointer to the present Kp-binned T89a models. The AE index is inherently double-valued in the sense that both growth (stretched) and late recovery (dipolarized) phases can have the same instantaneous value of AE. Using the slope of AE as a pointer in theory eliminates this problem but is itself complicated by the superposition of the effects of pseudobreakups and/or multiple substorms. We found very little correlation between either of these parameters (not shown) and the T89a stretching level based on the two-satellite conjunctions.

We believe that a promising predictor of the most appropriate T89a stretching level is θSL, the value of the stretching parameter which gives the best match to the observed field orientation at geosynchronous orbit. Even this parameter does not provide a unique, one-to-one pointer, however, due to the variation of θSL values within each BSL bin. Part of this variation is due to the fact that the observed tilt angle is a continuously varying parameter which must be compared to angles predicted by six discrete stretching levels. Part of the variation, however, can also be attributed to the fundamental limitation of trying to use a time-averaged model to match the instantaneous field configuration during a single conjunction; there will almost certainly be times when the actual magnetospheric current distribution cannot be matched by the modeled currents.

SUMMARY

We have outlined a series of studies aimed at evaluating some of the widely used and readily accessible magnetospheric magnetic field models, and in particular the Tsyganenko T89a model. Detailed discussions of these studies may be found in the publications cited in the text. We have used two basic techniques for quantitatively testing the model predictions: 1) comparing the range of magnetic field tilt angles observed at geosynchronous orbit with the ranges predicted for the same locations by the models; and 2) comparing the observed magnetic field mapping between the ionosphere and geosynchronous orbit (using two-satellite magnetic field conjunctions) with the model predictions at the same locations.

Thus far our research indicates that the T89a model predicts the observed basic variation in the magnetic field tilt angle with location, and it permits a range of field inclinations adequate to encompass the majority of the observed angles for the dawn, dusk, and night quadrants. On the dayside the model exhibits very little variation in tilt over the entire range of parameterizations and cannot reproduce the observed range of tilt angles. In a related finding, we find that the observed footpoint of geosynchronous orbit (determined using the two-satellite mapping technique) varies over more than 10° of magnetic latitude -- a larger range of latitudes than any of the tested field models can accommodate. Both of these results suggest that the next generation of magnetic field models should allow a greater range of stretching.

However, any increase in the stretching range of future field models should certainly incorporate less-stretched configurations. Although there are some cases where the models are not sufficiently stretched, we find that on average all magnetic field models tested are too stretched. When we compared the observed and predicted field line mappings for T89a, we found that even the least stretched parameterization of that model generally predicted a field configuration which was more stretched than the observed mappings indicate. This problem may have arisen from modelers trying to better represent the conditions at midnight and thereby making the models too stretched at other local times.

In testing the ability of different observational magnetospheric parameters (AE, the local geosynchronous field direction, the equatorward edge of the auroral oval, and Dst) to order the observed degree of field stretch, we could not identify a unique, one-to-one pointer to the most appropriate stretching level of T89a. However, both the tilt of the field at geosynchronous orbit and the equatorward edge of the diffuse aurora at midnight show a strong correlation with the correct degree of stretch and indices based on these parameters are thus promising candidates for incorporation into future models.

The two-satellite mapping technique provides an excellent opportunity for testing future magnetic field models. The database can be extended to include a larger number of cases (especially those with available solar wind data) and it may be possible to get broader coverage in local time and L by using other high-altitude satellites such as CRRES or POLAR. The existing DMSP-geosynchronous conjunction database is available for use at http://nis-www.lanl.gov/nis-projects/mpa/geo_dmsp.html.

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REFERENCES

Bame, S. J., et al., Magnetospheric plasma analyzer for spacecraft with constrained resources, *Rev. Sci. Instrum., 64*, 1026, 1993.

Fairfield, D. H., An evaluation of the Tsyganenko magnetic field model, *J. Geophys. Res., 96,* 1481, 1991.

Gussenhoven, M.S., D. A. Hardy, and N. Heinemann, Systematics of the equatorward diffuse auroral boundary, *J. Geophys. Res., 88*, 7171, 1983.

Hilmer, R. V. and G.-H. Voigt, A magnetospheric magnetic field model with flexible current systems driven by independent physical parameters, *J. Geophys. Res., 100,* 5613, 1995.

Lundin, R., and D. S. Evans, Boundary layer plasmas as a source for high-latitude, early afternoon , auroral arcs, *Planet. Space Sci., 32*, 1389, 1985.

Mauk, B. H. and C.-I. Meng, The aurora and middle atmospheric processes, in Auroral Physics, edited by C.-I. Meng, M.J. Rycroft and L.A. Frank, p. 223, Cambridge University Press, New York, 1991.

McComas, D. J., S. J. Bame, B. L. Barraclough, J. R. Donart, R. C. Elphic, J. T. Gosling, M. B. Moldwin, K. R. Moore, and M. F. Thomsen, Magnetospheric Plasma Analyzer: Initial three-satellite observations from geosynchronous orbit, *J. Geophys. Res.*, 98, 13453, 1993.

Mende, S.B and E.G. Shelley, Coordinated ATS 5 electron flux and simultaneous auroral observations, *J. Geophys. Res.*, 81, 97, 1976.

Meng, C.-I., B. Mauk, and C.E. McIlwain, Electron precipitation of evening diffuse aurora and its conjugate electron fluxes near the magnetospheric equator, *J. Geophys. Res.*, **76**, 7669, 1971.

Olson, W. P. and K. A. Pfitzer, A quantitative model of the magnetospheric magnetic field, *J. Geophys. Res., 79,* 3739, 1974.

Peredo, M, D. P. Stern, and N. A. Tsyganenko, Are existing magnetospheric models excessively stretched?, *J. Geophys. Res., 98,* 15343, 1993.

Pulkkinen, T.I., H.E.J. Koskinen and R.J. Pellinen, Mapping of auroral arcs during substorm growth phase, *J. Geophys. Res.* 96, 21087, 1991.

Reeves, G. D., L. A. Weiss, M. F. Thomsen, and D. J. McComas, A quantitative test of different magnetic field models using conjunctions between DMSP and geosynchronous orbit, *Workshop on Radiation Belt Modeling,* Brussels, Belgium, 17-20, October, 1995.

Reeves, G. D., L. A. Weiss, M. F. Thomsen, and D. J. McComas, Quantitative verification of the magnetic conjugacy of geosynchronous orbit and the auroral zone, *to be submitted, J. Geophys. Res.,* 1996.

Schumaker, T.L., M.S. Gusenhoven, D.A. Hardy and R.L. Carovillano, The relationship between diffuse auroral and plasma sheet electron distributions near local midnight, *J. Geophys. Res.*, 94, 10061, 1989.

Sharp, R.D., D.L. Carr, R.G. Johnson, and E.G. Shelley, Coordinated auroral electron observations from a synchronous and polar satellite, *J. Geophys. Res.*, 76, 7669, 1971.

Thomsen, M. F., D. J. McComas, G. D. Reeves, and L. A. Weiss, An observational test of the Tsyganenko (T89a) model of the magnetospheric field, *accepted, J. Geophys. Res.,* 1996.

Tsyganenko, N.A. A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, **37**, 5, 1989.

Weiss, L. A. , M. F. Thomsen, G. D. Reeves, and D. J. McComas, An examination of the Tsyganenko (T89a) field model using two-satellite magnetic conjunctions, submitted, *J. Geophys. Res.*, 1996.