INTERNATIONAL STANDARD

ISO
Approved Work Item 22009

WORKING DRAFT

Space System - Space Environment (Natural and Artificial)

Model of Earth's Magnetospheric Magnetic Field

(Explanatory Report)

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Explanatory Report

1. Background

The proposed ISO standard is a magnetic field model of the Earth's magnetosphere. It is intended to calculate the magnetic induction field generated from a variety of current systems located on the boundaries and within the boundaries of the Earth's magnetosphere under a wide range of environmental conditions, quiet and disturbed, affected by Solar-Terrestrial interactions simulated by Solar activity such as Solar Flares and related phenomena which induce terrestrial magnetic disturbances such as Magnetic Storms. The model has applications in Space Weather Forecasting, human health radiation hazards determination, the estimation of spacecraft and electronic devices integrity, and in pure and applied space physics environmental research.

The model is used for instance to harden both spacecraft and the sensitive electronic devices carried by them from the effects of high-energy cosmic radiation. Space Weather Forecasting has value to the electrical utility community which can loose of millions of dollars in equipment such as transformers and in downtime due to magnetic storm induction effects at the Earth's surface. For example, during the March 1989 magnetic storm the Quebec Hydroelectric Utility grid failed costing on the order of 8600 million. Other utility grids around the world were also adversely affected by this storm. Transcontinental oil and gas pipelines are also susceptible to electromagnetic induction due to Space Weather, which causes corrosion and high-voltage hazards. Similar problems occur with spacecraft such as communications and weather satellites. These satellites are often in geostationary orbits. During a magnetic storm, the magnetospheric boundary, called the magnetopause, which ordinary acts as a deflecting shield against the Solar Wind is compressed inside the orbits of these satellites, leaving them exposed to the full impact of the Solar Wind's radiation. Often the orientation of the satellites is determined by sensing the geomagnetic field. During a magnetic storm, when the magnetopause is compressed inside a satellite's orbit, the magnetic field orientation is suddenly reversed causing the satellite to abruptly rotate, which inturn causes extended booms (e.g. gravity gradient stabilization booms and others carrying electronic sensors) to snap off, leaving the satellite dysfunctional. The strong increase of the relativistic electron fluxes in the inner magnetosphere during magnetic storm main and recovery phases is the factor which can also be responsible for the satellite dysfunction and even losses. With sufficient warning through Space Weather forecasting, such damage can be minimized or eliminated.

Noting that over the past century the degree of Solar activity in terms of the number of sunspots occurring during the maximum of the 11-year Solar Cycle has generally been increasing from one cycle to the next, with some exceptions, and noting that the Earth's dipole magnetic field strength, which accounts for approximately 90% of the Earth's total magnetic field, is currently decreasing by approximately 7.14% per century, and further noting that Earth's dipole field strength has decreased by 50% in the passed 2000 years, it is clear that the degree of penetration of energetic cosmic radiation to lower altitudes is correspondingly increasing. This in turn heats the upper atmosphere, which eventually affects the lower atmosphere and subsequently the daily weather and storm patterns at Earth's surface as well as posing human health hazards such as increased cancer risk due to increased radiation at the Earth's surface. The more energy penetrating into the Earth's atmosphere, the more active atmospheric weather patterns tend to be and the more severe are the solar related health hazards likely to be. These facts, plus our increased use of the space environment, mean substantially increased hazards related to Space Weather over the next century. Knowledge through modeling of the magnetospheric environment and the resulting ability to predict its behavior are therefore becoming critical from the points of view of space mission accomplishment, health, economics, and natural disaster mitigation. Space Weather is clearly a global phenomenon, for which it is desirable to have an internationally accepted magnetospheric model.

2. Model Requirements

The objective is to develop a magnetospheric model that accurately describes the vector-magnetic induction due to an assortment of magnetospheric currents in the solar-magnetospheric coordinate system, in the inner magnetosphere including geostationary orbit, under the full range of solar and geomagnetic activity in real-time, or near-real-time. In doing so, the model should include the following features:

1. day-side/night-side asymmetry (i.e., compression of the magnetosphere on the day-side and extension on the night-side due to the interaction of the Solar Wind)
2. daily and season variations
3. accounts for the geomagnetic dipole inclination (tilt angle) relative to the plane orthogonal to the Earth-Sun line within a range of $-35°$ to $+35°$
4. a dependence on interplanetary medium parameters (model parametrization)
5. the close relation with the International Geomagnetic Reference Field (IGRF)
6. computation of the magnetospheric induction field includes:
   (a) the magnetic field due to the Chapman-Ferraro currents on the magnetopause screening the dipole field
   (b) the magnetic field due to the geotail current system magnetic field
   (c) the magnetic field due to the ring current
   (d) the magnetic field due to Region 1 field-aligned currents and closure ionospheric currents
   (e) the magnetic field due to the magnetopause currents screening the ring current
   (f) the magnetic field due to induced currents in the solid Earth generated by external sources
7. model consists of a small set of physical input parameters, such as:
   (a) ψ - geomagnetic dipole tilt angle
   (b) $\mathbf{R_1}$ - distance to the subsolar point of the magnetosphere
   (c) $\mathbf{R_2}$ - distance to the inner edge of the geotail current sheet
   (d) $\mathbf{\Phi_\infty}$ - the tail lobe magnetic flux
   (e) $\mathbf{I_{||}}$ - the total strength of Region 1 field-aligned currents
   (f) $\mathbf{b_r}$ - the ring current magnetic field at the Earth's center

8. the input parameters depend on real-time, or near-real-time Empirical Data:
   (a) Solar Wind data
   (b) Auroral Oval size and location
   (c) AL and Dst magnetic indices
9. the model characterizes the magnetospheric magnetic field under both Solar Quiet and Disturbed conditions, without restrictions/limits imposed on the values of interplanetary medium parameters
10. although in the framework of the proposed standard, the model is intended to be used inside the geostationary orbit it must be selfconsistently enable to provide calculations in the whole magnetosphere

3. The Draft Model

The proposed ISO draft magnetic field model of the magnetosphere is intended to satisfy all of the requirements set forth in section 2. Although this standard is intended to characterize the inner magnetosphere, the model must also merge smoothly into magnetic field generated in other regions of Earth's environment such as the core, the ionosphere, the distant tail, near-magnetopause regions and interplanetary space. Therefore, the International Geomagnetic Reference Field (IGRF) model, which describes the magnetic field generated by the Earth's core and which is produced by International Association of Geomagnetism and Aeronomy (IAGA) and updated by IAGA every 5 years is included as part of the proposed magnetospheric model. The total magnetic field is calculated as a sum:

$$B = B_{int} + B_m \tag{1}$$

A model of the magnetic field generated by field-aligned currents, which connect the magnetosphere to the ionosphere, is also included as part of the magnetospheric model, as is a model of the magnetosheath magnetic field which takes into account the Interplanetary Magnetic Field (IMF) penetration into the magnetosphere. The model further includes a set of auxiliary physical models that characterize the magnetic field associated with various current systems on he magnetopause and within the magnetosphere itself. These include a model for the fields generated by Chapman-Ferraro currents on the magnetopause that screen the primarily dipole field of the Earth characterized by the IGRF model, a model characterizing fields generated by the geomagnetic tail current system, a model characterizing fields generated by the Ring Current system, and a model characterizing fields generated by those magnetopause currents that screen the Ring Current. The overall model is referred to as the Paraboloid Model A99 (Alexeev 99, described most completely in [Alexeev et al., 1996; Alexeev and Feldstein, 2001]). In A99 magnetospheric magnetic field induction B_m is represented in the form:

$$B_m = B_{CFD}(R_1) + B_T(R_1, R_2, \Phi_\infty) + B_{FAC}(I_{||}) + B_R(b_R) + B_{CFR}(R_1, b_R)$$

where
B_{CFD} is the magnetic field of Chapman-Ferraro currents on the magnetopause screening the dipole field;
B_T is the geotail current system magnetic field;
B_{FAC} is the field of Region 1 field-aligned currents;
B_R is the ring current magnetic field;
B_{CFR} is magnetic field of the magnetopause currents screening the RC.

The model has as its set of input parameters those listed in section 2, item 6. All the input parameters depend on empirical data such as Solar Wind data (which can be taken from the ACE or Wind satellites), Auroral Oval data, and the AL and Dst magnetic indices computed from various geomagnetic observatories scattered around the Earth's surface. The different Submodels may be used to calculate the input parameters. The model user can choose his own Submodel which describe some input parameter dynamics based on his own data set. The model magnetic field sources depend on empirical data via input parameters (model parametrization). Thus, the paraboloid Model consists of three basic elements: Empirical data, Input Parameters, and the Model itself.

Model is dynamic in the sense that it can function in real-time or near real-time depending on the availability of the empirical data. It functions through the full range of geomagnetic activity, from Solar Quiet conditions to severe magnetic storm conditions, and in the whole magnetosphere. Other magnetospheric models are commonly limited in their range of applicability with respect to geomagnetic activity and/or by the region of applicability in space.

4. The Recent Project Activities

- The project "SPACE ENVIRONMENT (NATURAL AND ARTIFICIAL). MODEL OF THE EARTH'S MAGNETOSPHERIC MAGNETIC FIELD." has been discussed and approved at the 7th 8th and 9th Meetings of WG4.
- The comparisons of the model calculations with the Large Magnetosphere Magnetic Field Data Base (Faierfield, Tsyganenko, et al., Journal of Geophysical Research, V.11, p.11319-11326, 1994) was made (see Appendix, Sec. 1).
- The detailed comparisons of the model calculations with observations in the course of several magnetic storms was made:
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  - Dremukhina, L. A., Ya. I. Feldstein, I. I. Alexeev, V. V. Kalegaev and M. Greenspan, *J. Geophys. Res., 104*, N12, 28,351, 1999.
  - V.V.Kalegaev, and A. Dmitriev, *Advances in Space Research. 26*, N1, 117, 2000.
  - Alexeev, I. I., and Y. I. Feldstein, *J. Atmos. Sol. Terr. Phys., 63/5*, 331, 2001.

- Kalegaev, V. V., I.I.Alexeev, Ya.I.Feldstein, *J. Atmos. Sol. Terr. Phys., 63/5*, 473, 2001.
- Alexeev I.I., E.S.Belenkaya, R. Clauer, *Journ. of Geoph. Res., 105*, 21,119, 2000.
- R. Clauer, Alexeev I.I., E.S.Belenkaya, *Journ. of Geoph. Res., 106*, 2001, accepted.
- Alexeev, I. I., V. V. Kalegaev, E. S. Belenkaya, S. Y. Bobrovnikov, Ya. I. Feldstein and L. I. Gromova, *Journ. of Geoph. Res., 106*, 2001, accepted.

(see Appendix, Sec.2 for details).

- The Authors' Version and Working Draft of Project have been sent to the scientists and specialists interested in the subject from 11 countries. The Authors' Version and Working Draft of Project have been refereed and corrected by the scientists and specialists from the
  - **France** (Daniel M. Boscher, ONERA-CERT/DESP)
  - **Japan** (Hiroshi Suzuki, Yukihito Kitazawa (Ishikawajima-Harima Heavy Industries Co., Ltd.), Prof. T. Iemori (Kyoto University))
  - **Russia** (Dr. Alexandr Schevurev (STC "Kosmos") and Dr. V.P. Nikitskiy (RS Corp. "Energiya"))
- In accordance with Resolution 151, taken at the recent plenary meeting of TC20/SC14 in Brazil, and with request made by James E. French (Secretary of ISO TC20/SC14), the Approved Work Item (AWI) "Space systems - Space environment - Model of the Earth's magnetospheric magnetic field" has been registered with the ISO Central Secretariat and given the number 22009.

5. Plan of Action

A draft ISO standard has been proposed by I. I. Alexeev et al. of Moscow State University's Nuclear Physics Institute and now registered as ISO Approved Work Item (AWI) No 22009. However, this model is but one of several models in current-use within the space physics community. Each model has its proponents. In order that the best overall model be standardized and in order to insure that that model achieves wide acceptance within the scientific community, and given that the international scientific expertise in the field of magnetospheric physic resides within IAGA, the evaluation of the Paraboloid model, as well as any other candidate standard magnetospheric model, be evaluated by a special Working Group set up for this explicit purpose within IAGA. During IAGA-IASPEI Joint Assembly in Hanoi (August 2001) it was approved that the evaluation of the the ISO magnetospheric model is in the field of interest of the WG 3 of Division V of IAGA. It was decided to create the scientific subcommittee of the Division V Working Group 3 of International Association Geomagnetism and Aeronomy for the examination of the ISO magnetospheric model. This activity must be joint with Division III and to take into account a Internal Field Model (IGRF) and influence of the solar wind (Division IV) on the magnetospheric model.

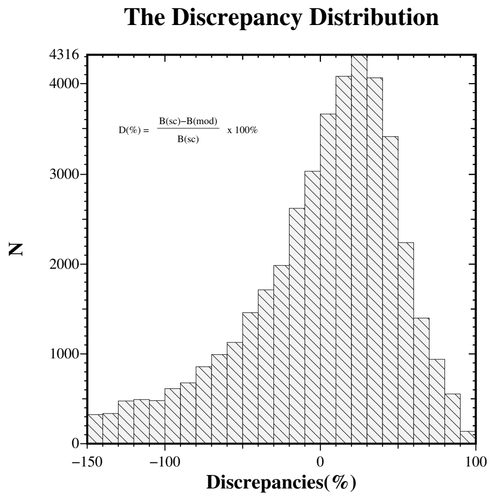


Figure 1: The distribution of discrepancies of magnetospheric field magnetic induction calculated in term of the parabolic model, compared with experimental data. $B(sc)$,nT, is the field measured onboard spacecrafts, $B(mod)$,nT, is the field calculated in terms of the parabolic model, N is for statistics.

It is expected that the subcommittee will deliberate on this matter between one and two years. IAGA meets once every two years. Thus at the next full IAGA meeting, the working group will have performed its function, which can result in one of several possible outcomes:

1) The subcommittee could decide that the state of the art of magnetospheric modeling is such that an international standard is not warranted at this time.

2) The paraboloid model of Igor Alexeev and associates may be adopted as the standard.

3) Some part of other candidate model proposed by the working group may be used in paraboloid model.

4) The subcommittee may synthesize a standard magnetospheric model by taking the best of each of the proposed candidate models.

5) The subcommittee may, using the candidate models and the criteria listed in section 2 as a guide, create a completely new magnetospheric model and adopt it as the standard.

APPENDIX. Accuracy of the Model and Comparison With Experimental Data

A1. Stationary Case. Comparison with the Large Magnetosphere Magnetic Field Data Base

The comparison with the Large Magnetosphere Magnetic Field Data Base (Faierfield et al., Journal of Geophysical Research, V.99, p.11319-11326, 1994) was made. Data base includes data of Explorer 33,35, IMPs 4,5,6,7,8, Heos 1,2 and ISEE 1, 2 in the region between 4 and 60 R_E. Calculations of the input parameters of the model were performed using solar wind data, D_{st} and AL indices which are contained in Data Base. Parameters ψ, R_1, Φ_∞ were calculated in terms of submodels presented in Appendix 1 of

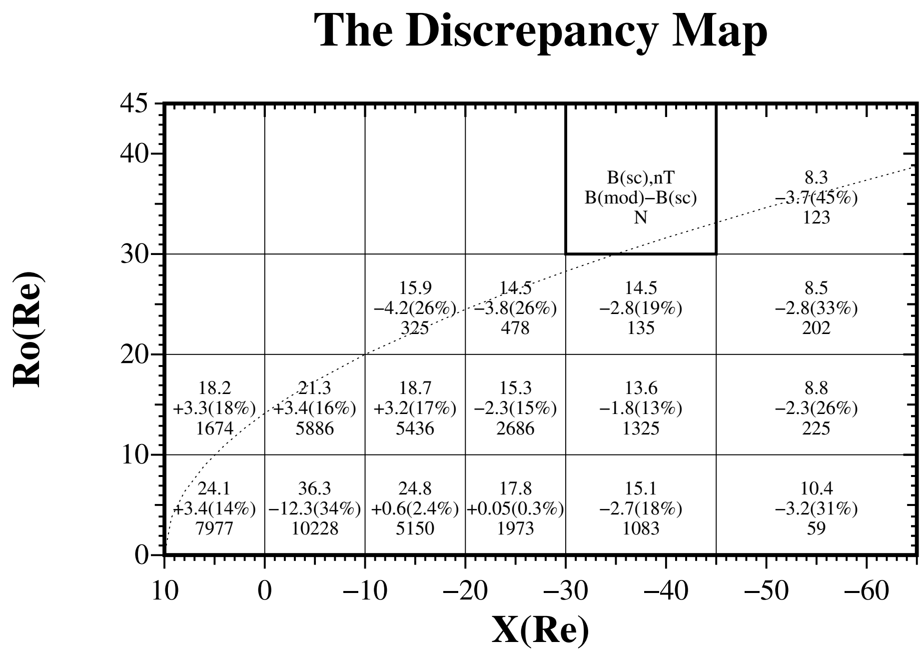


Figure 2: The distribution of the discrepancies of magnetospheric magnetic field calculated in term of the paraboloid model A99, compared with experimental data. In the singled out cell the format of data is shown: $B(sc)$,nT, is the measured onboard spacecrafts magnetic field averaged in cells, $B(mod)$,nT, is the average field calculated in terms of the paraboloid model, N is for statistics.

Working Draft. Field-aligned currents magnetic field was not taken into account in these calculations as the first step of the model evaluation.

It was supposed

$$R_2 = 1/\cos^2 \varphi_k \qquad D_{st} < -10nT$$

$$R_2 = 0.7R_1 \qquad D_{st} > -10nT$$

$$b_r = D_{st} \qquad D_{st} < -10nT$$

$$b_r = -10nT \qquad D_{st} > -10nT,$$

where φ_k is the midnight latitude of the equatorward boundary of the auroral oval.

Fig.1 and 2 represent this comparison in the form of the distribution of discrepancies. The histogram in Fig.1 shows the distribution of relative discrepancies $D = \frac{B(sc)-B(mod)}{B(sc)} \cdot 100\%$ integral over the whole experimental material (45181 measurements). The discrepancy mean value is about +3% (the distribution is asymmetric with a long negative "tail"), σ of the distribution being of $\sim$ 80%. Fig. 2 presents the distribution of absolute and relative discrepancies differential in x and ρ, where $\rho = \sqrt{y^2 + z^2}$, x, y, z are the solar-magnetospheric (GSM) coordinates. The weight of each discrepancy value (statistics) is shown in the corresponding cell in x and ρ. An examination of the Fig.2 shows that near the Earth at distances about the geostationary orbit in the magnetosphere nightside the discrepancy is, on average, 12.3 nT for $-10 < x \leq 0$ and $0 \leq \rho < 10$, and in the magnetosphere dayside it is, on average, 3.4 nT for $0 < x \leq 10$ and $0 \leq \rho < 10$.

The magnetic field module distributions in the different cells of the magnetosphere, measured and calculated by paraboloid model are represented in the Figure 3. The measured magnetic field has also an own non-Gaussian distribution in each cell. The

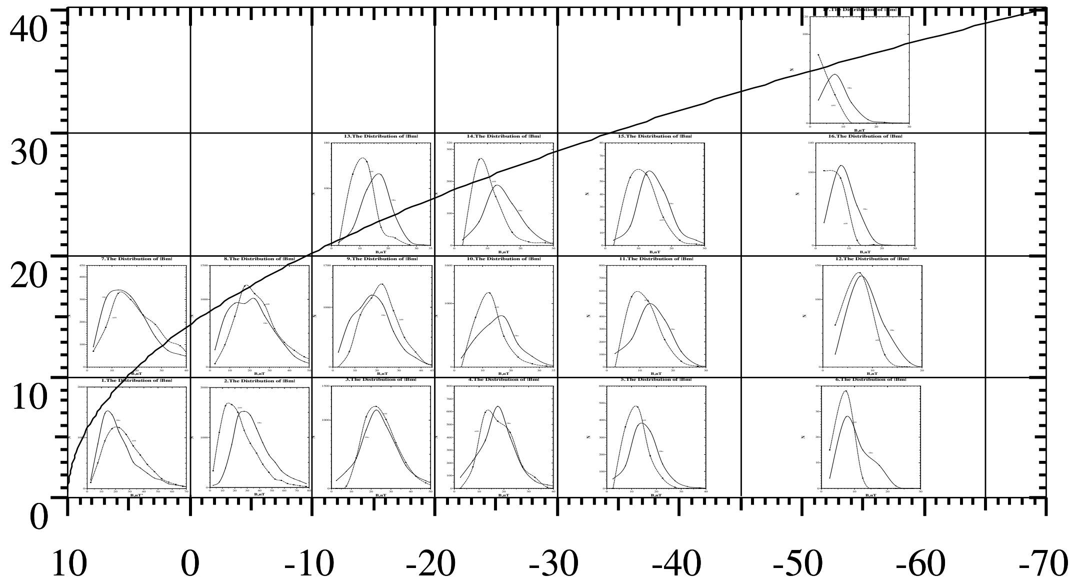


Figure 3: The magnetic field module distributions in the different cells of the magnetosphere, measured (solid line) and calculated by paraboloid model A99 (thin line).

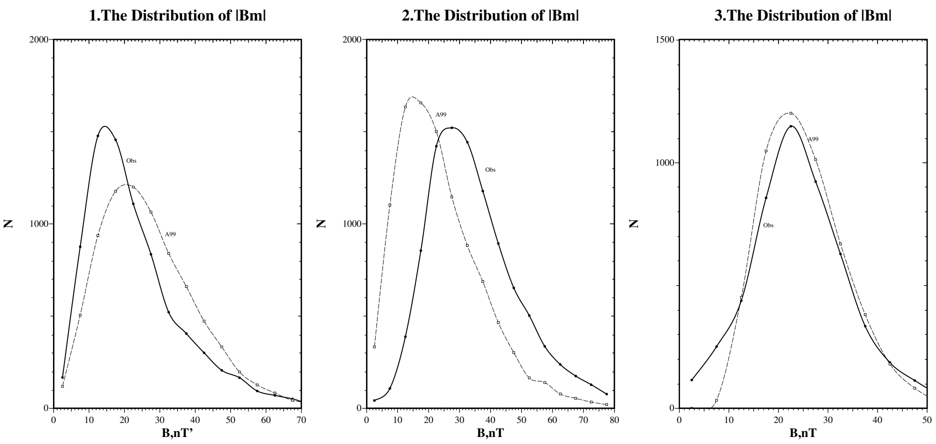


Figure 4: The magnetic field module distributions (measured and calculated by A99) in the near-Earth (x, ρ) cells (10:0; 0:10), (0:-10; 0:10), (-10:-20; 0:10) of the magnetosphere.

mean values and discrepancies represented in the Fig. 2 are the measured magnetic field distribution mean values and mean discrepancies between measured and calculated values. The calculated by paraboloid model magnetic field is distributed in a good agreement with observations.

Fig.4 represents the distributions in (x, ρ) cells (10:0; 0:10), (0:-10; 0:10), (-10:-20; 0:10) respectively. The first and second cells demonstrate the regular shifts: the magnetic field in the night side is underestimated and in the dayside is overestimated. Such behavior can be explained by field aligned currents effect which is not taken into account in these calculations. The quite good agreement exists in the third cell.

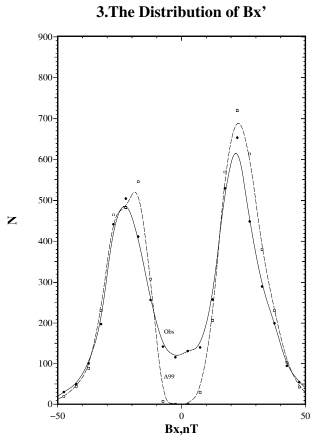


Figure 5: The same as in the Fig. 4 for GSM Bx component of the magnetospheric magnetic field.

Fig. 5 represents the same comparison for the GSM Bx component of the magnetic field in the (x, ρ) cell (-10:-20; 0:10). The distribution depression near the $Bx = 0$ corresponds the measurements which were made in the tail plasma sheet region. The A99 paraboloid model has infinite thin tail current so the Bx values which are near zero are absent.

Paraboloid model allows flexible taking into account the new magnetospheric magnetic field sources. Moreover, because each magnetospheric magnetic field source with its own screening currents is calculated separately and depends linearly on its own input parameters we can change the parametrization of current systems to match better the data. To take into account the mentioned above effects of field aligned currents and "thin" tail current the new "beta" version of paraboloid model (A01) was developed. The "thin geotail" magnetic field [*Alexeev and Bobrovnikov, 1997*] and field aligned current magnetic field [*Alexeev, Belenkaya and Clauer, 2001*] were taken into account. Fig. 6 shows the measured magnetic field module mean values in the different cells of the magnetosphere as well as mean discrepancies between the measured magnetic field and calculated by A01 (second row) and T96 (third row). The more good agreement for A01 is detected in the near-Earth region than that represented in the Figure 2. We can see that in general, the obtained in terms of A01/A99 discrepancies are of the same order as those obtained in the framework of T96 model [*Tsyganenko,* 1995].

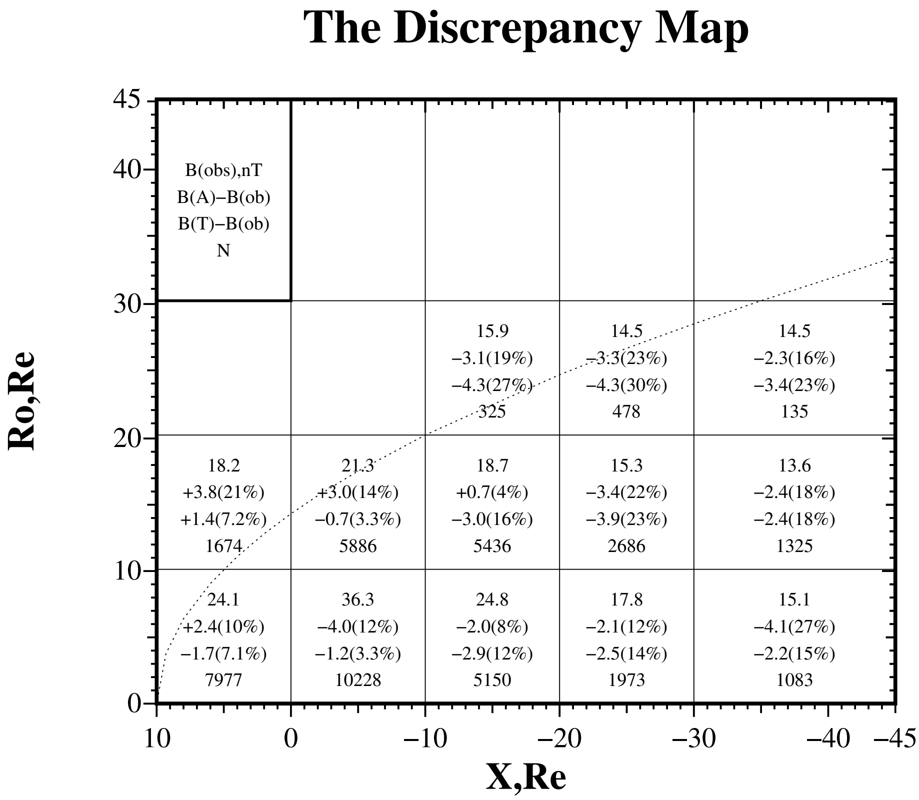


Figure 6: The same as in the Fig. 3, calculated in terms of A01 and T96 models

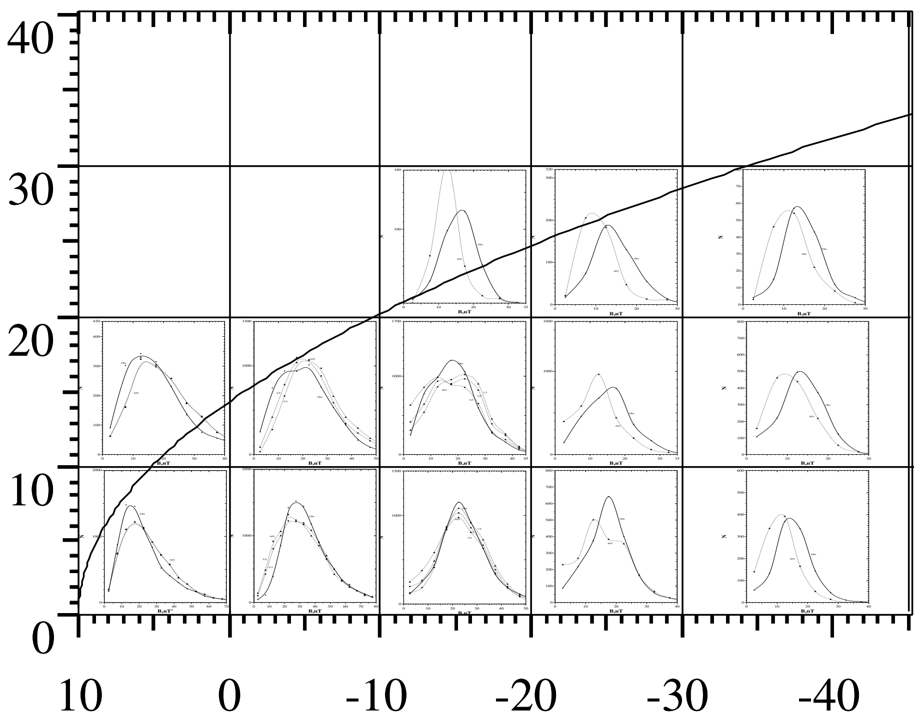


Figure 7: The magnetic field module distributions over the whole statistics in the different cells in the Earth's magnetosphere, measured and calculated by A01 model.

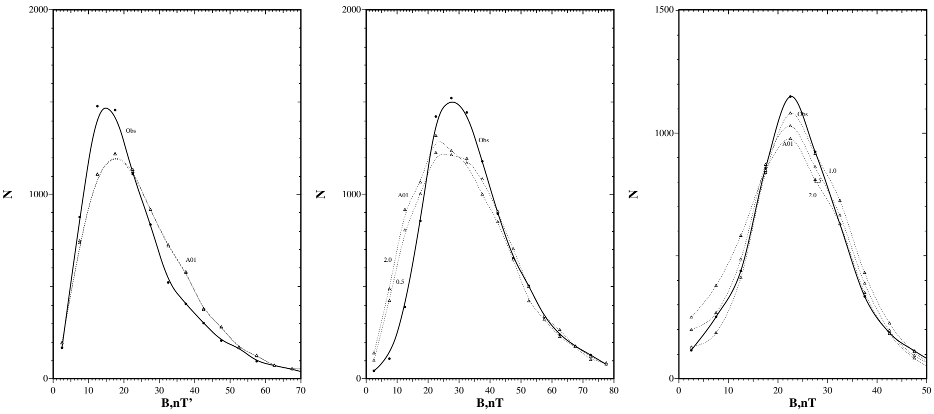


Figure 8: The same as in the fig. 4 for magnetic field module calculated by A01 model.

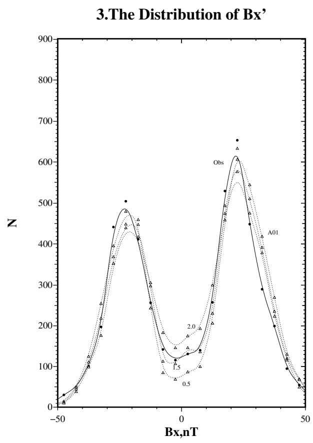


Figure 9: The same as in the fig. 8 for Bx component of the magnetospheric magnetic field.

The magnetic field module distributions in the different cells of the magnetosphere, measured and calculated by paraboloid model are represented in the Figure 7. The magnetic field distributions measured in the near-Earth's cells represented in the Figures 8 (magnetic field module) and 9 (Bx component). The distributions of the magnetic field calculated for the different parametrizations of the tail current and field aligned currents demonstrate the more good agreement with experimental data than that obtained in the framework of A99 paraboloid model.

The results represented on the Fig. 6 shows that paraboloid model, analytical and based on the small number of the input parameters, describes the large array of experimental data with approximately the same accuracy as the T96 model, which constructed as approximation of that array by the chosen by author functions with the chosen number of parameters. Fig. 10 represents the distributions of measured and calculated by A99 and T96 models magnetic fields (module and Bx component, respectively).

In the Table 1 the comparison of magnetic field calculated by paraboloid model (A99) Tsyganenko model (T96) and measured magnetic field from Large Magnetosphere Magnetic Field Data Base averaged by the levels of disturbances is presented. We can see that only for very quite conditions T96 model gives the better results than A99. For Kp between 1^- and 2^- the results are comparable, but for disturbed conditions ($Kp > 2$)

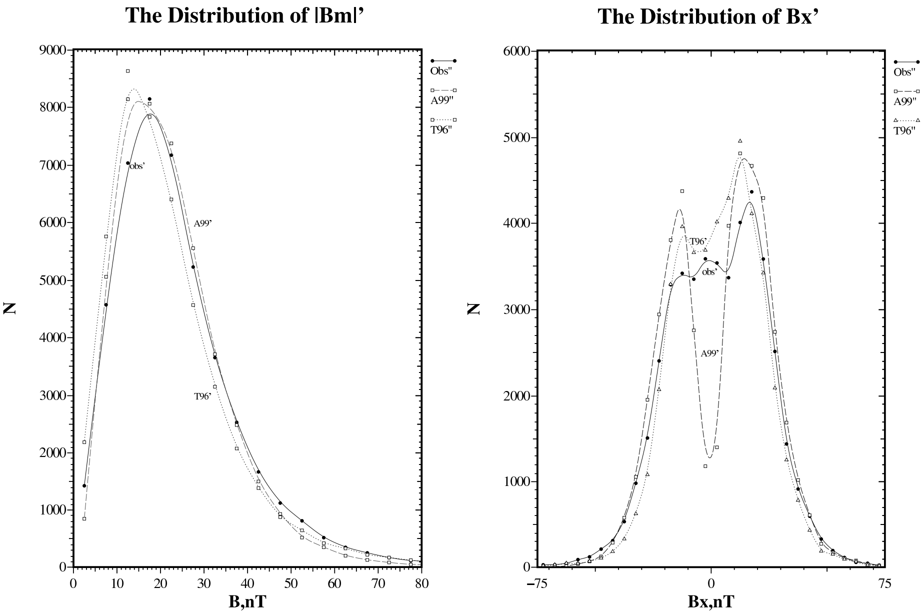


Figure 10: The same as in the fig. 8 for Bx component of the magnetospheric magnetic field.

Kp	A99	T96	Data
$0, 0^+$	13.8	14.9	15.5
$1^-, 1$	16.9	16.3	17.6
$1^+, 2^-$	18.3	18.6	20.3
$2, 2^+$	21.6	20.6	22.6
$3^-, 3, 3^+$	25.3	24.1	26.3
$4^-, 4, 4^+$	30.0	28.1	31.3
$5^-, 5$	34.8	33.4	35.4

Table 1: Comparison of magnetic field calculated by paraboloid model (A99) Tsyganenko model (T96) and measured magnetic field from Large Magnetosphere Magnetic Field Data Base averaged by the levels of disturbances.

A99 gives the better results than T96. The T96 (as the earlier Tsyganenko models) was constructed using the minimization of the deviation from a data set of the magnetospheric magnetic field measurements gathered by several spacecrafts during many years. The disturbed periods are relatively rare events during the observation time, so their influence on the model coefficients is negligibly small. That is why the T96 model's applicability is limited by Dst, Bz_{IMF}, and the solar wind dynamic pressure low values.

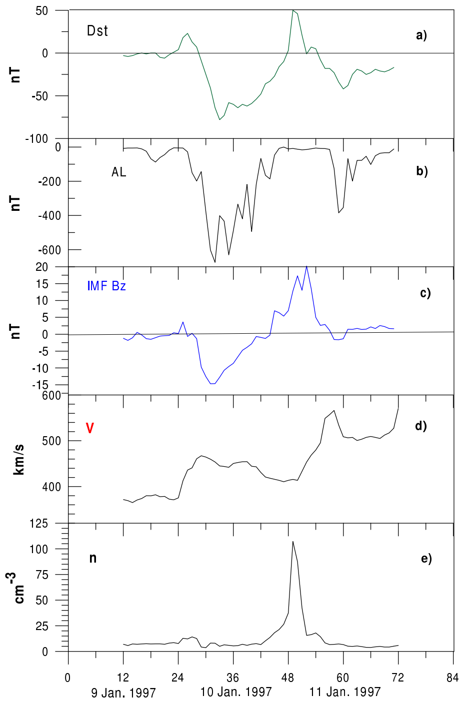


Figure 11: Empirical data used for the calculations of the model input parameters: (a) Dst, (b) AL, (c) IMF B_z component of the solar wind, (d) velocity, and (e) density for January 9–12, 1997.

A2. Nonstationary Case. Case study for January 9–12, 1997

The dynamics of the magnetospheric current systems was studied in [*Alexeev et al.*, 2001] in terms of A99 model for the specific magnetospheric disturbance on January 9–12, 1997 caused by the interaction of the Earth's magnetosphere with a dense solar wind plasma cloud. A dense cloud of the solar wind plasma was of rather complicated structure. A southward interplanetary magnetic field (IMF) in its leading part caused a significant substorm activity during the interaction with the magnetosphere. A strong increase of the relativistic electron fluxes at the geosynchronous orbit was observed [*Reeves et al.*, 1998]. The trailing half of the magnetic cloud contained a strong northward IMF and was accompanied by a large density enhancement that strongly compressed the magnetosphere. Because of the significant compression of the magnetosphere, several magnetopause crossings by the geostationary orbit took place. This storm causes also the crash of geostationary satellite Telstar 401 leading to significant financial losses.

Figure 11 shows the Dst and AL indices (Figures 11a and 11b). The hourly averaged Wind data on the plasma and magnetic field are presented in Figures 11c–11e. The time delay ($\sim$ 25 min) between the measurements in the Earth's vicinity and on board the Wind spacecraft is taken into account.

The model input parameters were defined by the solar wind density and velocity, by the strength and direction of the interplanetary magnetic field, and by the auroral AL index. Figure 12 presents the time variations of the model input parameters: the tilt angle (Figure 12a) and the magnetic field flux across the magnetotail lobes (Figure 12b). Figure 12c shows b_r, calculated using Burton equation and Dessler-Parker-Skopke equation. Figure 12d shows the distances to the magnetopause subsolar point and to the earthward edge of the tail current sheet.

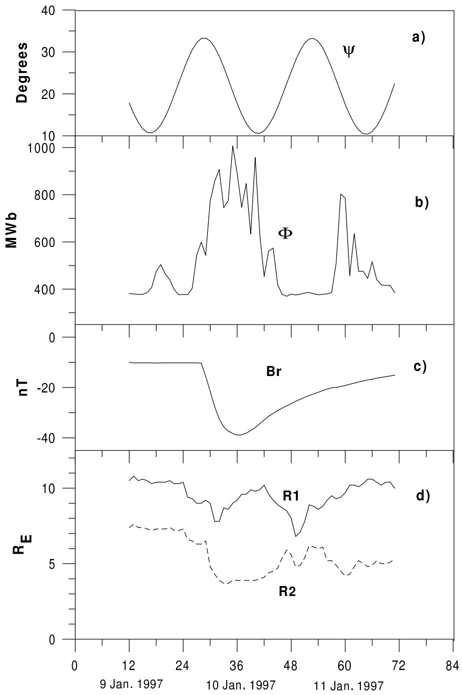


Figure 12: The model input parameters for January 9–11, 1997: (a) the tilt angle, ψ; (b) the magnetic field flux through the magnetotail lobes, Φ_∞; (c) the ring current magnetic field at the Earth's center b_r; and (d) the distances to the magnetopause subsolar point (solid curve), R_1, and to the earthward edge of the magnetotail current sheet (dashed curve), R_2.

To investigate the Dst sources during the January 9–12, 1997, event the ground magnetic field was analyzed in terms of the paraboloid model of the magnetosphere A99, which allows us to distinguish the contributions of different large-scale current systems. The paraboloid model calculations are demonstrated in Figure 13 at the left panel. The magnetospheric magnetic field variation is calculated at the geomagnetic equator at each hour of magnetic local time (MLT) and averaged over the equator. Figures 13a–13c (left panel) present the Dst sources Bcf, Br, and Bt and their parts arising owing to the Earth currents. Figure 13d compares the Dst and the calculated magnetic field. A good agreement is obtained for both the relatively quiet and disturbed periods. The calculations in terms of the paraboloid model give an RMS deviation from Dst (δB) of ~ 8.7 nT.

We can see from the analysis of magnetic storm on January 9–12, 1997, that the magnetospheric dynamics depends on all the magnetospheric magnetic field sources, which appear to be comparable by the order of magnitude. The paraboloid model can be successfully applied, especially in the disturbed periods, when the empirical models are often not valid.

The same magnetic storm was investigated by [Turner et al., 2000] in terms of T96 model. The important feature of the T96 model is (as reported by the author in the T96_01 model's description) its applicability only for 20 nT $>$ Dst > -100 nT, 0.5 nPa$<$ p_{sw} $<$ 10 nPa, and -10 nT$<$ Bz_{IMF} $<$ 10 nT. In the course of the storm under consideration (January 9-12, 1997) the upper value of p_{sw} is significantly beyond the 10 nPa limit. During the most disturbed interval of the magnetic storm under consideration (the first hours of 11 January 1997) T96 model was out of order (see Figure 13, right panel).

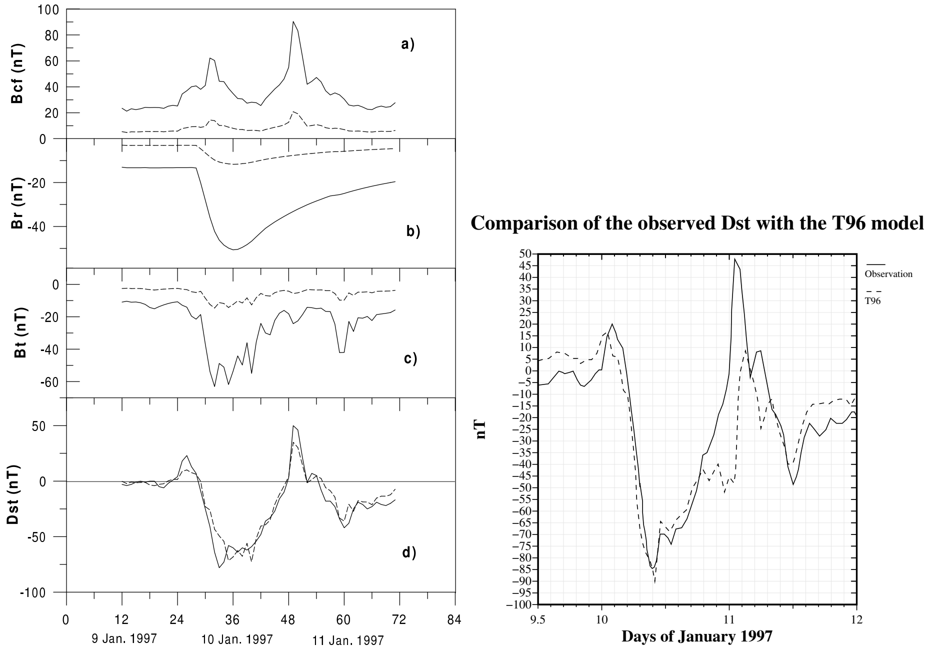
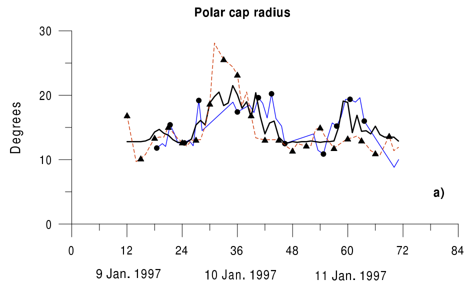


Figure 13: **Left:** (a) Magnetic field of currents on the magnetopause, (b, c) the ring current magnetic field and tail current magnetic field, respectively, at the Earth's surface (solid curves) and the corresponding magnetic field due to currents induced inside the Earth (dashed curves), and (d) Dst (heavy solid curve) and total magnetic field, B_M (dashed curve), calculated at the Earth's surface by A99 in the course of the magnetic storm on January 9–12, 1997. **Right:** Dst (heavy solid curve) and total magnetic field, B_M (dashed curve), calculated at the Earth's surface by T96 in the course of the magnetic storm on January 9–12, 1997 [*Turner et al.*, 2000].

The Figure 13 right panel represents calculations made by T96 model in [Turner et al., 2000]. The reason for the residual difference between the calculations presented in [*Alexeev et al.*, 2001] and those made by *Turner et al.* [2000] was investigated in [*Alexeev et al.*, 2001]. This is the tail current inner edge dynamics which are taken into account in the paraboloid model in accordance with the auroral oval expansion due to the substorm activity. In the calculations made by *Turner et al.* [2000] the dynamics of the inner edge of the tail current sheet are neglected.

Thus the discrepancy of the results obtained in [*Alexeev et al.*, 2001] and in that of *Turner et al.* [2000] is explained mainly by the use of different quantitative models and associated with the difference of the tail current parameterization. The quality of a model and its flexibility are defined by the possibility of reflecting the dynamics of the large-scale current systems. The empirical models do not yet allow one to determine correctly the time dependence of each large-scale current system. In the paraboloid model the submodels are used for the calculation of the parameters of the large-scale magnetospheric current systems. These submodels can take into account the significant features of various magnetospheric current systems.

The analysis of the magnetic disturbances during the January 9–12, 1997, event shows that in the course of the main phase of the magnetic storm the contribution of the ring current, the currents on the magnetopause, and the currents in the magnetotail are approximately equal to each other by an order of magnitude. Nevertheless, in some periods one of the current systems becomes dominant. For example, an intense Dst positive enhancement (up to +50 nT) in the course of the magnetic storm recovery phase in the



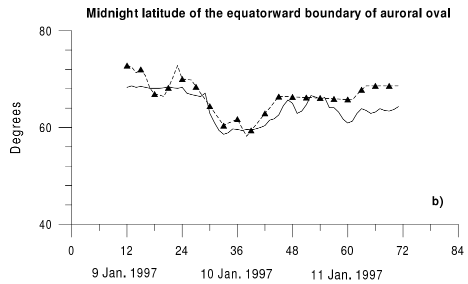


Figure 14: (a) Comparison of the polar cap radius calculated from the magnetic flux value Φ_∞ (solid curve) with radii obtained from the measurements on board DMSP F10-F13 (marked with triangles) and from the Polar Ultraviolet Imager (UVI) images (marked with circles). (b) Comparison of the midnight latitude of the equatorward boundary of the polar oval calculated in terms of paraboloid model (solid curve) and that calculated by the data measurements on board DMSP F10-F13 (marked with triangles).

first hours on January 11, 1997, is associated with a significant increase of the currents on the magnetopause, while the ring current and the magnetotail current remain at a quiet level. Such analysis can be made only in terms of the modern dynamical models such us paraboloid models, where the different magnetic field sources can be calculated separately. A comparison of the calculated *Dst* variation with measurements indicates good agreement.

This analysis allows us to investigate the level of applicability of the different kinds of magnetospheric models. The T96 model is not applicable for disturbed periods and does not take into account the time dependence of the important parameters of the magnetospheric current systems. For this reason the most essential part of the magnetotail current system was excluded from the consideration made by *Turner et al.* [2000]. The paraboloid model depends on the parameters of magnetospheric origin and takes into account the movements of the magnetotail in accordance with the level of geomagnetic activity.

To estimate the accuracy of our model calculations of the magnetospheric field at geosynchronous orbit, a comparison with the data obtained on board the geostationary satellites GOES 8 and 9 was performed. For the verification of calculations of the magnetotail current contribution to *Dst*, the obtained values of the model parameters were used to calculate the auroral oval boundaries, which were compared to the boundaries obtained using the DMSP precipitation data and the Polar UVI images.

Figure 14a compares the polar cap radius calculated by paraboloid model to the radii obtained from the observations on board DMSP F10-F13 and on board Polar. Figure 14a shows good agreement between the calculations and the experimental data obtained from the independent sources. So, the model estimation of Φ_∞ can be used to identify the polar cap boundaries. Figure 14b compares the midnight latitude of the equatorward boundary

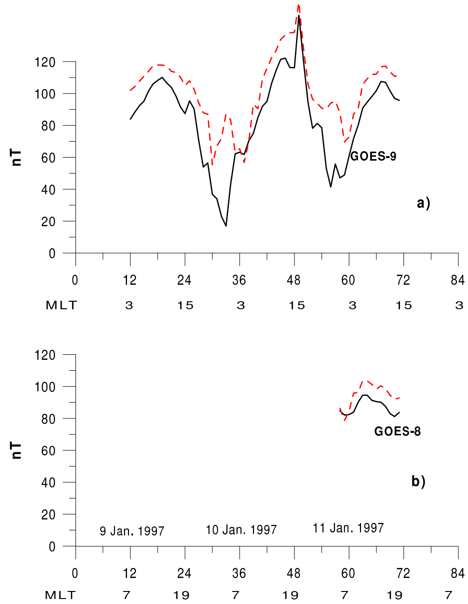


Figure 15: Comparison of the magnetic fields calculated in terms of the paraboloid model and measured during the magnetic storm on January 9–12 , 1997, along the (a) GOES 9 orbit and (b) GOES 8 orbit.

of the auroral oval calculated by paraboloid model to those determined using the particle spectra measured on board the DMSP F10-F13 satellites. The obtained agreement with observations confirms our suggestions about Φ_∞ and R_2 made above.

Figure 15 presents the calculations of the magnetic field along the GOES 9 and 8 spacecraft orbits. To take into account the magnetic field of the interterrestrial sources, the International Geomagnetic Reference Field (IGRF95) model was used. The agreement of calculations with the measured magnetic field confirms the initial assumptions of the relative roles of the magnetospheric current systems in the course of magnetic storm.

The usage of the paraboloid model allows one to make an important physical conclusions about the development of the different magnetospheric magnetic field sources during disturbances. We can see that during the main phase of a weak magnetic storm the magnetotail current and the ring current create disturbances of approximately equal intensities. The paraboloid model describes well the magnetic field variations on the Earth's surface and at the geosynchronous orbit during the interaction of a solar wind plasma cloud with the magnetosphere on January 9–12, 1997. The root mean square deviation between the model calculations and the measured field is equal to 8.7 nT. The tail current contribution to the storm maximum disturbance is about -60 nT (for the Dst maximum equal to -78 nT).

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