GEOMAGNETISM AND AERONOMY, English Translation, VOL. 35, NO. 6, JUNE 1996
Russian Edition: NOVEMBER–DECEMBER 1995

Dynamics of the midlatitude ionospheric trough during a magnetic storm: Main phase

M. G. Deminov, A. T. Karpachev, and S. K. Annakuliyev

Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences

V. V. Afonin

Institute of Cosmic Research, Russian Academy of Sciences, Moscow

Abstract. We constructed an empirical model of the change in the position of the dynamics of the main ionospheric trough minimum at altitudes of 430 ± 50 km during the main phase of a magnetic storm. By introducing an indicator of magnetic activity for the trough position, more adequate than *Kp* or *Dst*, namely, the ring current magnetic field *DR*, the model provides approximately twice the accuracy of earlier models. We found that in the premidnight hours in the main phase of an intensive magnetic storm the trough equatorward movement is steplike; that is, a strong jumplike variation in trough position occurs in a narrow interval of *DR* variations. We present a qualitative interpretation of this effect and other features that follow from the constructed model.

Introduction

The region of lowered electron concentration at subauroral latitudes, located near the equatorward boundary of the electron diffusive precipitations with an energy of about 0.5 keV, is considered the midlatitude ionospheric trough [e.g., *Rodger et al.,* 1992]. During the main phase of a magnetic storm, usually only one main ionospheric trough (MIT) is detected in this region [*Deminov et al.,* 1992]. So for this period the MIT and the midlatitude ionospheric trough are equivalent terms.

A qualitative analysis by *Deminov et al.* [1992] demonstrated that the MIT movement equatorward during the main phase of a magnetic storm is delayed in relation to an increase in the *Kp* index depending on the rate of increase in magnetic activity. This is one of the reasons for the relatively low accuracy of the empirical dependences of the MIT minimum invariant latitude Φ_T on *Kp*, which have been obtained on the basis of numerous data sets [e.g., *Rodger et al.,* 1992]. Moreover, during intense magnetic storms the MIT equatorward movement starts before the end of the growth phase of a magnetic storm; that is, it advances the *Dst* index decrease [*Deminov et al.,* 1992]. Therefore *Deminov et al.* [1992] suggested that during the main phase of a magnetic storm, Φ_T is better correlated with the ring current magnetic field *DR* than with *Kp* or *Dst*.

The goal of this paper is a qualitative check of the above hypothesis based on an analysis of the probe measurements on board the Cosmos 900 satellite at altitudes of 430 ± 50 km during the unilluminated time of day in winter in equinox during the main phases of 14 magnetic storms in 1978–1979.

Magnetic Activity Indices

Let us present the ring current magnetic field in the form

$$DR = Dst - k\sqrt{P} + 14 \qquad (1)$$

where *DR* and *Dst* are measured in nanoteslas, $P = 0.01nV^2$ is the solar wind pressure, V is its velocity, n is the concentration per cubic centimeter, and

$$\begin{aligned} k &= 0.2, & B_z &> 1 \\ k &= 0.25, & -1 < B_z &< 1 \\ k &= 0.3, & B_z &< -1 \end{aligned} \qquad (2)$$

The dependence of the coefficient k on the value and direction of the interplanetary magnetic field vertical component B_z slightly differs from that of *Kuznetsova and Shevnin* [1984]. Equation (1) for $k = 0.2$ and the substitution of 20 in the last term are used frequently [e.g., *Nishida,* 1980]. By definition, $DR \leq 0$.

0016-7932/96/3506-0010$18.00/1

Below, we consider the dependence of the invariant latitude of the main ionospheric trough $\Phi_T(T)$, measured by satellite at the universal time T, on the $Kp(T)$, $Dst(T)$, and $DR(T - T_0)$ magnetic indices. The temporal delay T_0 of the Φ_T changes relative to DR is determined from the condition of the highest correlation between $\Phi_T(T)$ and $DR(T - T_0)$. Calculations of DR for particular moments of the universal time $T - T_0$ are based on the linear interpolation of the hourly mean values of DR nearest that time. For example, if $DR = -5$, -10, and -40 for the universal time intervals 0000–0100, 0100–0200, and 0200–0300 UT, then for $T = 1.7$ and $T_0 = 0.5$, the value of DR is equal to -8.5, and for $T = 1.7$ and $T_0 = 0$, the value of DR is equal to -16. Here and below, the time is expressed in hours. For the sake of brevity the time T is omitted; that is, $\Phi_T \sim DR(-1)$ means that $\Phi_T \sim DR(T - T_0)$, where $T_0 = 1$.

Dependence of MIT Position on Magnetic Activity

The values of Φ_T, obtained by Cosmos 900 for the main phase periods of 14 magnetic storms, correspond to the following intervals of magnetic activity variations: $-5 > Dst > -210$, $-15 > DR > -250$, $2_0 < Kp < 8_+$. These values of Φ_T correspond to two intervals of local magnetic time; 1800–2200 MLT and 2300–0500 MLT; and 10 of 14 main phase periods analyzed correspond to the 2300–0500 MLT interval. Analysis demonstrates that for these MLT intervals the Φ_T dependence on magnetic activity indices is the principal phase during the main phase of a magnetic storm.

The regression equation, obtained by the Cosmos 900 data for the 2300-0500 MLT interval, their standard deviations in latitude degrees, and the correlation coefficients R are presented below:

$$\Phi_T = 63.8 - 2.1Kp \pm 3; \quad R = 0.68 \tag{3}$$

$$\Phi_T = 63 - [1 - 2Dst - 0.001Dst^2]^{0.5} \pm 1.5; \quad R = 0.93 \tag{4}$$

$$\Phi_T = 70 - [20 - 4DR(-1) - 0.005DR(-1)^2]^{0.5} \pm 1.1; \quad R = 0.97 \tag{5}$$

Insofar as the value of Φ_T cannot increase under a DR decrease, a condition $\Phi_T = 41.4°$ under $DR < -400$ should be added to equation (5). The standard deviations and correlation coefficients of equations (3)–(5) demonstrate that $DR(-1)$ is more adequate than Kp or Dst as an indicator of the magnetic activity for trough position. For the given local time interval the most frequently used empirical model of MIT position [*Kohnlein and Raitt*, 1977] differs from equation (3) by no more than 2° latitude. The $\Phi_T - Dst$ relation has been mentioned before [*Besprozvannaya and Shchuka*, 1993; *Besprozvannaya et al.*, 1994]. The Φ_T dependence on Dst, presented by *Besprozvannaya and Shchuka* [1993], is based on an analysis of the data from the ionospheric station network for the periods near the magnetic storm development maximum. This dependence gives overestimated values of Φ_T as compared with equation (4), obtained for the entire period of the main phase of a magnetic storm. This difference between the Φ_T dependence on Dst for the entire storm period and for the storm development maximum follows from the data of the ionospheric station network presented by *Besprozvannaya et al.* [1994].

It follows from the Cosmos 900 data that at the altitudes considered a distinct peak in electron temperature usually corresponds to the trough minimum [*Deminov et al.*, 1995]; this peak is often associated with the midlatitude stable auroral red (SAR) arcs [*Rees and Roble*, 1975], so the above equations may be considered a dependence of the invariant latitudes of the electron temperature subauroral peak and, probably, of SAR arcs on magnetic activity indices during the main phase of a magnetic storm in the near-midnight and after-midnight hours.

It follows from equation (5) that the main ionospheric trough, the subauroral temperature peak, and a SAR arc under no values of DR are able to move equatorward of the limiting latitude of $\Phi_L = 41.4°$. This value of Φ_L practically coincides with the value of the SAR arc limiting latitude, observed for extremely intensive storms [*Khorosheva*, 1987]. Thus equation (5), obtained from the data set for $-15 > DR > -250$, is still valid for the entire possible range of DR variations during the main phase of the magnetic storm.

The regression equations for the 1800–2200 MLT interval are

$$\Phi_T = 66 - 1.9Kp \pm 1.9; \quad R = 0.86 \tag{6}$$

$$\Phi_T = 66 - [1 - 1.5Dst - 0.001Dst^2]^{0.5} \pm 2; \quad R = 0.85 \tag{7}$$

$$\Phi_T = 70 - [20 - ADR(-0.5) - 0.005DR(-0.5)^2]^{0.5} \pm 1.3; \quad R = 0.93 \tag{8}$$

where $A = 2.2$ for $DR(-0.5) > -155$ and $A = 3.5$ for $DR(-0.5) < -150$. Moreover, equation (8) should be completed by the condition $\Phi_T = \Phi_L = 45.1°$ for $DR(-0.5) < -300$. Equation (8) for $-150 > DR(-0.5) > -155$ gives values of $\Phi_T = 54.5°$ and $\Phi_T = 49°$ for fixed DR; that is, a simultaneous existence of two troughs separated by latitude is possible for this narrow interval of $DR(-0.5)$ variations. Equations (6)–(8) were obtained from a limited data set for the main phases of four storms, and values of $DR < -155$ were measured during only one of these storms, so the indicated accuracies of equations (6)–(8) and the conditions for the simultaneous existence of two troughs are approximate. Nevertheless, equation (8) is apparently true for the entire possible range of DR variations during the storm main phase. For example, equation (8) almost exactly simulates the value of $\Phi_T = 45°$ for $DR < -300$, observed on February 8 around 1800 MLT (0000 UT), i.e. near the maximum of a giant storm [*Yeh et al.*, 1991].

It follows from equation (8) that under DR variations from -130 to -150 the trough position changes only slightly; that is, when the decreasing DR approaches -150, a gradual "saturation" of the equatorward trough shift occurs near the boundary latitude of $\Phi_B = 55°$. When DR diminishes from -150 to -155, there occurs a sharp equatorward jump of the trough of approximately 6° latitude. This equatorward jump may happen through an intermediate state, when two troughs exist simultaneously. Further DR decreases lead to a smooth equatorward movement trough from $\Phi_T = 49°$ until a blocking of the trough occurs when Φ_T approaches Φ_L. So in the evening hours for a decrease in DR from about -100 to the minimum possible values the strongest changes of Φ_T take place in the very narrow DR interval: that is, the trough equatorward movement is steplike in character. It is the principal quantitative difference in MIT dynamics in the evening hours from the local time near-midnight and after-midnight hours.

MIT Position Model During the Magnetic Storm Main Phase

Let us combine equations (5) and (8) and thus create a model of the MIT position during the main phase of a magnetic storm for the entire interval of the unilluminated time of day, using the magnetic activity indicator DR. Let us use as an intermediate function the hyperbolic tangent $\tanh(2t+4)$, where t is the local magnetic time, counted from the midnight, that is, t = MLT after midnight and t = MLT−24 before midnight. As a result, we obtain

$$\Phi_T(DR,t) = 70 - [20 - A DR(-T_0) -$$

$$-0.005 DR(-T_0)^2]^{0.5} \pm 1.2; \quad R = 0.96 \qquad (9)$$

$$T_0 = 0.75 + 0.25\tanh(2t+4) \qquad (10)$$

$$A = 3.1 + 0.9\tanh(2t+4), \quad \text{if } DR(-T_0) > -155$$

$$A = 3.75 + 0.25\tanh(2t+4), \quad \text{if } DR(-T_0) < -150 \quad (11)$$

From model (9) one can obtain dependences of the Φ_L limiting latitude and of the limiting value of the L shell L_L on t corresponding to this latitude:

$$\Phi_L = 43.25 - 1.85\tanh(2t+4)$$

$$L_L = 1.89 - 0.11\tanh(2t+4) \qquad (12)$$

In the same way, combining equations (3) and (6), one can get the MIT position model for the entire interval of the unilluminated part of a day, using the magnetic activity indicator Kp:

$$\Phi_T(Kp,t) = 64.9 - 2Kp-$$

$$-(1 + 0.1Kp)\tanh(2t+4) \pm 2.7; \quad R = 0.76 \qquad (13)$$

For the above reasons the standard deviations and correlation coefficients for equations (9) and (13) refer mainly to the near-midnight and after-midnight MLT hours. It follows from these equations that model (9) is much more accurate than model (13).This finding is more visually evident in Figure 1, which presents the MIT position dependences on Kp and $DR(-T_0)$ according to models (13) and (9) for $t = 0$ (solid lines) together with the Cosmos 900 data reduced to midnight (circles). The reduction procedure of a measured value of the trough position $\Phi_T(t)$ under fixed t and, for example, Kp to midnight is

$$\Phi_T(0) = \Phi_T(t) - \Phi_T(Kp,t) + \Phi_T(Kp,0)$$

where $\Phi_T(Kp,t)$ and $\Phi_T(Kp,0)$ are determined by equation (13).

The difference in trough positions between model (13) and the model by *Kohnlein and Raitt* [1977] does not exceed 2° of latitude for the entire interval $-6 < t < 6$ and for the range $2 < Kp < 8$, typical for the main phase, so the standard deviation presented for equation (13) characterizes to some degree the accuracy of the empirical dependences of Φ_T on Kp and t obtained earlier under their use for the magnetic storm main phase.

MIT Position Model for the Entire Period of Magnetic Activity Growth

It follows from equation (9) for $DR = 0$ that $\Phi_T(0,t) = 65.5°$ regardless of the local time t. However, the dependences of Φ_T on T and also on the geographic longitude Λ are essential under disturbed conditions:

$$\Phi_T(0,t,\Lambda) = 65.5 - \Delta\Phi_T(t) - \Delta\Phi_T(\Lambda) \pm 2 \qquad (14)$$

$$\Delta\Phi_T(t) = 0.7(t - 0.1t^2 - 0.01t^3) \qquad (15)$$

$$\Delta\Phi_T^N(\Lambda) = \cos(2\Lambda - 45°) - \cos(\Lambda + 40°) \qquad (16)$$

$$\Delta\Phi_T^S(\Lambda) = 2\cos(\Lambda + 35°)$$

where the N and S indices correspond to $\Delta\Phi_T(\Lambda)$ for the northern and southern hemispheres. Dependence (15) was based on a preliminary analysis of the Cosmos 900 data for the 1800–0600 MLT interval. This dependence

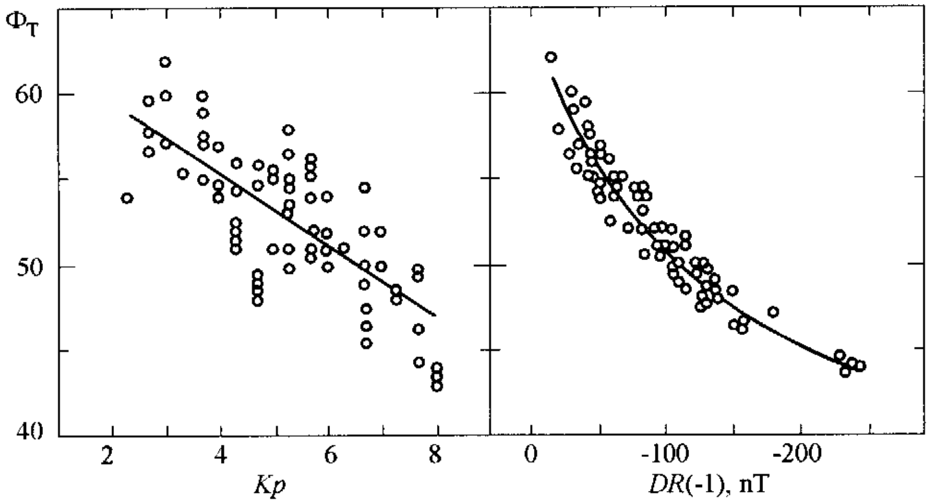

Figure 1. Invariant latitude of the main ionospheric trough minimum Φ_T versus Kp or DR at midnight during the main phase of magnetic storms according to models (13) and (9) (solid lines) and to data of Cosmos 900 reduced to midnight (circles).

differs slightly from the one presented by *Moffet and Quegan* [1983, Figure 10] for $Kp = 0$. Dependence (16) coincides with the one presented by *Deminov et al.* [1992]. The above indicated accuracy of equation (14) coincides with the one presented by *Kohnlein and Raitt* [1977] and *Deminov et al.* [1992]. Comparing equations (9) and (14) for $DR = 0$, one can conclude that the $\Delta\Phi_T(t)$ and $\Delta\Phi_T(\Lambda)$ dependences disappear if one moves from quiet conditions to the main phase of a magnetic storm, so the MIT position model for the entire expansion period of a storm may be presented in the form

$$\Phi_T(DR,t,\Lambda) = \Phi_T(DR,t) -$$
$$-[\Delta\Phi_T(t) + \Delta\Phi_T(\Lambda)]\exp(DR(-T_0)/20) \qquad (17)$$

where $\Phi_T(DR,t)$, $\Phi_T(t)$, $\Phi_T(\Lambda)$, and T_0 are determined by equations (9), (15), (16), and (10), respectively. Determining the accuracy of these models is beyond the scope of this paper. Nevertheless, one can see from (9) and (14) that in moving from quiet conditions to the main phase of a magnetic storm, the accuracy of model (17) increases.

Discussion

Let us consider possible causes of MIT dynamics during the expansion phase of a magnetic storm, which follows from model (17). In quiet conditions, $\Phi_T(0,t,\Lambda)$ depends on the local time and longitude. In particular, during the evening hours the trough is located more poleward than during the near-midnight and after-midnight hours. Such dependence on the local time is typical for many auroral structures, including the equatorial boundary of the electron diffusive precipitation (EDP) [*Gal'perin et al.*, 1990]. During that period the vertical component of the interplanetary magnetic field B_z is usually directed northward, i.e., $B_z > 0$, and the electric field of the magnetospheric convection at auroral and subauroral latitudes is weakened. On that background a dependence of Φ_T on the horizontal component B_y of the interplanetary magnetic field additionally appears with a correlation coefficient of $R = 0.66$ [*Ben'kova et al.*, 1989]. Moreover, even relatively weak fluctuations of the convection electric field and of the thermospheric wind velocity may lead to a significant scatter of the measured Φ_T values in relation to the model. The standard deviation presented for equation (14) characterizes that scatter under $DR = 0$.

The beginning of the growth phase of a magnetic storm is related to the high-speed plasma flux of the solar wind approaching the Earth [*Nishida*, 1980] and is accompanied by an increase in Kp and Dst under almost unchanged DR and Φ_T. There is no correlation of Φ_T with Kp or Dst during this period [*Deminov et al.*, 1995]. A reversal of the magnetic field vertical component B_z from north to south in this solar wind plasma initiates (via the electric field in the magnetotail) a beginning of the injection of the plasma sheet energetic ions into the magnetosphere [*Nishida*, 1980]. These ions are a source of the magnetospheric ring current and, moreover, a main reason for the existence of the Alfvén layer, which forms a pronounced boundary of the high-latitude plasma convection [*Nishida*, 1980] and, as a result, EDP and MIT [*Gal'perin et al.*, 1990]. Thus the injection of the plasma sheet ions to the Earth, intensification of the magnetospheric ring current, reduction of the *DR* field, and the equatorward shift of EDP and MIT are due to one and the same cause. That is why Φ_T correlates with $DR(-T_0)$. Features of the drift trajectories of the plasma sheet injected ions, and of redistribution of the magnetic convection electric field, are evidently the principal reasons for the increase in the T_0 delay before Φ_T changes relative to *DR*, if one moves from the evening to the near-midnight and after-midnight hours (see equation (10)).

As a result, the equatorward trough movement begins in the evening hours earlier than in the near-midnight and after-midnight hours, and the difference in trough position between these sectors of local time, typical for quiet conditions, starts to decrease. Moreover, an increase in magnetic activity leads to a weakening of the Φ_T dependence on longitude [*Deminov et al.*, 1992] and the horizontal components of the interplanetary magnetic field B_y [*Ben'kova et al.*, 1989]. Such weakening of the above indicated factors after the B_z reversal southward is taken into account in model (17) by the exponential multiplier at $\Delta\Phi_T(t)$ and $\Delta\Phi_T(\Lambda)$. During intensive storms the southward B_z reversal, and the beginning of *DR* depletion and of the trough drift equatorward occur before the end of the growth phase of a magnetic storm. At the beginning of the main phase of an intensive magnetic storm, usually $DR < -20$ and the dependences of Φ_T on local time and longitude typical for quiet conditions are already weakened. During the main phase of the storm, both in the evening and in the near-midnight and after-midnight hours, out of many parameters on which Φ_T depends, the *DR* parameter is in fact, the only one left. That is evidently the reason for the increased accuracy of model (17), while switching from quiet conditions to the magnetic storm main phase. For the Φ_T and *Kp* dependences the opposite tendency is characteristic, probably because of a relation between the Φ_T variation delay time relative to *Kp* and the rate of change of *Kp*, the relation being different for different storms [*Deminov et al.*, 1995]. In the vicinity of the minimum of a strong storm development, *DR* depends on *Dst* to a more significant degree than on the solar wind pressure. In this period the correlation of Φ_T with *Dst* is almost as high as the one with *DR*. During the entire period of magnetic storm activity growth the correlation of Φ_T with *DR* is considerably higher than that with *Dst* for the above noted reasons.

During the main phase of a magnetic storm, model (17) for the premidnight hours (1800–2200 MLT) coincides with equation (8), which demonstrates a "saturation" of the trough equatorward shift in the vicinity of $\Phi_B = 55°$ when the decreasing *DR* approaches a value of -150. It follows from the Cosmos 900 data that under such a "saturation" the main ionospheric trough often deepens additionally in the relatively narrow region and assumes the structure of a narrow ionization trough. This effect, evidently, is due to a formation of ions of moderate energies near the inner boundary of the plasma sheet but equatorward from the EDP in the polarization jet; a peak of increased northward electric field is formed [*Gal'perin et al.*, 1990]. The jet is typical for the premidnight sector [*Spiro et al.*, 1979], is often associated with the narrow ionization trough [*Gal'perin et al.*, 1990], and can lead to a significant reduction in velocity of the equatorward movement of EDP and MIT [*Deminov and Shubin*, 1987]. The last fact means that if a polarization jet has formed, its position changes only slightly even though the inner boundary of the plasma sheet ions continues to shift deeper into the magnetosphere. It follows from model (17) that the optimum conditions of formation of an intensive polarization jet during the main phase of an intensive storm are realized in the vicinity of $\Phi_B = 55°$ or $L_B = 3$.

The above situation would be maintained until the maximum plasma sheet ion concentration crosses the L shell at which the trough and the polarization jet are located, because the efficiency of the polarization jet formation depends on the value and sign of the concentration gradient of these ions in the equatorial plane of the magnetosphere [*Deminov and Shubin*, 1987]. Further disappearance of the polarization jet near $L = 3$ would lead to an almost jumplike equatorward shift of EDP, to the formation of the polarization jet and trough equatorward from the new position of EDP, and to the gradual disappearance of the trough near $L = 3$. This process would look like a jumplike equatorward shift of the trough through an intermediate state, when the simultaneous existence of two troughs separated by latitude is possible.

Further depletion of *DR* would lead to a smooth drift of the new trough down to the limit value of $L_L = 2$. The end of such a process probably was observed on February 8, 1989, in the vicinity of 1800 MLT (0000 UT) for $DR < -300$, when the maximum ring current density appeared at $L = 2.6$ [*Hamilton et al.*, 1988], the EDP and the adjoining polarization jet appeared at $L = 2.4 - 2.5$ [*Yeh et al.*, 1991], and the deep trough was registered at $L = 2$ [*Yeh et al.*, 1991]. As far as the EDP approximately corresponds to the plasmapause [*Gal'perin et al.*, 1990], i.e., to the boundary of the large-scale high-latitude convection relative to the cold plasma, the trough was inside the plasmasphere and, moreover, was not directly related to the polarization jet. The energy density of the ring current ions at $L = 2$ was significant, and under the mean energies $E < 30$ keV, this density was mainly provided by the O^+ ions [*Hamilton et al.*, 1988]. The latter fact means that the Coulomb interactions of the ring current O^+ ions with the ambient electrons inside the plasmasphere, heating of the ambient electrons in the region of this interaction, formation of the electron temperature peak and of SAR arcs at ionospheric heights through the heat transfer along the L shell from the heat region [*Kozyra et al.*, 1987], the increase in the recombination coefficient of the ionospheric electrons at F region heights due to the vibrationally excited constituents, such as N_2^* and O_2^*, in the region of the electron temperature maximum [e.g., *Rodger et al.*, 1992]; all these events are evidently the principal chain in the process leading to formation of the ionospheric trough during the main phase of a magnetic storm in the premidnight hours under $DR(0.5) < -160$. In the after-midnight hours the EDP, the adjoining MIT, and probably the plasmapause are located almost at the same L shells during the entire main phase of a magnetic storm. This statement does not contradict the results presented by *Gal'perin et al.* [1990], so the difference between the extreme positions of the trough in the morning and evening hours ΔL_{L} is less than the corresponding difference in the plasmapause position ΔL_p. It follows from equation (12) and the above presented estimates that approximately $\Delta L_{\mathrm{L}} = 0.22$ and $\delta L_p = 0.7$.

Conclusions

1. We developed an empirical model of the variations in the MIT minimum for the unilluminated part of the day at altitudes of 430 ± 50 km during the main phase of a magnetic storm. By the standard deviation value the new model provides approximately twice the accuracy of the models developed earlier. This was achieved by introducing into the model a more adequate, than Kp or Dst, magnetic activity indicator for the trough position: a magnetic ring current field DR. We found that the model has no limitations on the magnetic storm intensity.

2. We generalized the model over the entire expansion period of a magnetic storm. We found that the model accuracy increases from quiet conditions to the main phase of a storm.

3. We discovered that the equatorward trough movement in the premidnight hours during the main phase of an intensive storm has a steplike character; that is, a strong jumplike change in trough position takes place in the narrow interval of DR variations. In this DR variation interval an intermediate state is possible, when two troughs separated by latitude exist simultaneously.

4. We give a qualitative interpretation of the above effect and other consequences of the developed model.

Acknowledgments. This paper was supported by the Russian Fund for Basic Research (project J 41100).

References

Ben'kova, N. P., et al., IMF influence on the main ionospheric trough position according to Interkosmos 19 satellite data, *Geomagn. Aeron.*, *29*, 5, 863, 1989.

Besprozvannaya, A. S., and T. I. Shchuka, Dynamics of the main ionospheric trough during global storms with developed ring current, *Geomagn. Aeron.*, *33*, 6, 145, 1993.

Besprozvannaya, A. S., T. I. Shchuka, P. V. Kishcha, et al., Influence of the *DR*-current on the dynamics of the nighttime ionospheric trough in the periods of magnetic storms in September 1989, *Geomagn. Aeron.*, *34*, 4, 166, 1994.

Deminov, M. G., and V. N. Shubin, Dynamics of the subauroral ionosphere in disturbed conditions, *Geomagn. Aeron.*, *27*, 3, 398, 1987.

Deminov, M. G., A. T. Karpachev, V. V. Afonin, and Ya. Shmilauer, Variations of the main ionospheric trough position depending on longitude and geomagnetic activity, *Geomagn. Aeron.*, *32*, 5, 185, 1992.

Deminov, M. G., et al., Dynamics of the midlatitude ionospheric trough during storms, 1, A qualitative picture, *Geomagn. Aeron.*, *35*, 1, 73, 1995.

Gal'perin, Yu. I., L. D. Sivtseva, V. M. Filippov, and V. L. Khalipov, *Subauroral Upper Ionosphere*, 192 pp., Nauka, Novosibirsk, 1990.

Hamilton, D., et al., Ring current development during the great geomagnetic storm of February 1986, *J. Geophys. Res.*, *93*, 14,343, 1988.

Khorosheva, O. V., Magnetospheric disturbances and related dynamics of the ionospheric electrojets, auroras and plasmapause, *Geomagn. Aeron.*, *27*, 5, 804, 1987.

Kohnlein, W., and W. J. Raitt, Position of the midlatitude trough in the topside ionosphere as deduced from ESRO 4 observations, *Planet. Space Sci.*, *25*, 3, 600, 1977.

Kozyra, J. U., E. G. Shelley, and R. H. Comfort, The role of ring current O^+ in the formation of stable auroral red arcs, *J. Geophys. Res.*, *92*, 7487, 1987.

Kuznetsova, T. V., and A. D. Shevnin, Calculation of the DCF field on the terrestrial surface depending on IMF direction, in *Geomagnetic Variations and the Electric Field*, p. 35, IZMIRAN, Moscow, 1984.

Moffet, R. J., and S. Quegan, The midlatitude trough in the electron concentration of the F layer: A review of observation and modeling, *J. Atmos. Terr. Phys.*, *45*, 5, 315, 1983.

Nishida, A., *Geomagnetic Diagnosis of the Magnetosphere*, 299 pp., Mir, Moscow, 1980.

Rees, M. H., and R. C. Roble, Observations and theory of the formation of stable auroral red arcs, *Rev. Geophys.*, *13*, 1, 201, 1975.

Rodger, A. S., R. J. Moffett, and S. Quegan, The role of ion drift in the formation of ionization troughs in the mid- and high-latitude ionosphere: A review, *J. Atmos. Terr. Phys.*, *54*, 1, 1, 1992.

Spiro, R. W., R. A. Heelis, and W. B. Hanson, Rapid subauroral ion drifts observed by Atmosphere Explorer C, *Geophys. Res. Lett.*, *6*, 8, 657, 1979.

Yeh, H.-C., J. C. Foster, F. J. Rich, and W. Swider, Storm time electric field penetration observed at midlatitude, *J. Geophys. Res.*, *96*, 5707, 1991.

(Received March 10, 1995.)