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# MODELING OF THE SPATIAL STRUCTURE OF THE HIGH-LATITUDE IONOSPHERE AT LEVELS OF D-, E-, AND F-REGIONS

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**Abstract. A** new version of the mathematical model of the high-latitude ionosphere is described in which two numerical models, developed earlier, are amalgamated: the first, the mathematical model of the convecting high-latitude ionosphere; the second one, the mathematical model of the high-latitude middle and upper atmospheres. The new version of the model enables one to calculate the composition of charged and neutral particles at the levels of D- and E-layers, using the detailed reaction scheme for the chemical balance between atmospheric constituents, as well as the electron concentration and electron and ion temperatures at the F- layer altitudes. The ionospheric quantities may be calculated at distances from the earth from 100 to 700 km in the three-dimensional region which includes not only the polar latitudes but also the subauroral ones.

## 1. Introduction

To calculate the HF radio wave propagation through the high-latitude ionosphere it is necessary to obtain the distribution of the electron concentration not only for the F and E regions but also for the D region. The electron concentration distributions can be obtained using the mathematical models of the high-latitude ionosphere. Unfortunately, the mathematical models of the high-latitude ionosphere developed earlier in the Polar Geophysical Institute, which enable one to calculate three-dimensional distributions of ionospheric quantities [*Mingalev et al.,* 1988; *Mingaleva and Mingalev*, 1998], had covered only the F and E regions of the ionosphere.

Over the last years in the Polar Geophysical Institute the mathematical model of the high-latitude middle and upper atmospheres has been developed by A.S. Kirillov and G.A. Aladjev. The latter model enables one to calculate the electron concentration at D-region altitudes and has been utilized for two-dimensional simulations of HF radio wave propagation [*Mingalev et al*., 1996; 1998].

In this study we make an attempt to develope a new version of the mathematical model of the high-latitude ionosphere which enables one to calculate the three-dimensional distributions of the electron concentration at levels of D-, E-, and F-regions. In the new version of the model, two mathematical models are amalgamated: the first one, the mathematical model of the convecting high-latitude ionosphere [*Mingaleva and Mingalev,* 1998]; the second one, the mathematical model of the high-latitude middle and upper atmospheres mentioned above.

## .2. The ionospheric model

### *2.1 Basic principles*

Our mathematical model encompasses the ionosphere above 36$^o$ of magnetic latitude and at distances from the earth along the magnetic field line from 70 to 700 km for one complete day. It is known that the ionospheric plasma at F-layer altitudes, due to strong magnetization, may be considered to be attached to the magnetic field lines. The magnetic field lines move in the direction perpendicular to the magnetic field **B** with the velocity of the plasma drift which is strongly affected by the electric field **E.** In the high-latitude ionosphere, the electric field **E** consists of the convection field, having a magnetospheric origin, and the corotation field. We shall consider only the steady non-substorm electric field distributions. It is known that the flow paths (or the flow trajectories), around which the magnetic field lines are carried over the high-latitude region, are closed for the steady electric field distribution. Taking into account the transport properties of the ionospheric plasma at F-layer altitudes, briefly analysed above, we base our mathematical model on the following principles.

We consider a part of the magnetic field tube of ionospheric plasma which is carried over the high-latitude region by the electric field along a flow trajectory through the moving neutral atmosphere. Using the electric field distribution we obtain the configuration of the flow trajectory and calculate the plasma drift velocity along it at the F-layer altitude. We consider the relative frame of reference moving along the obtained flow trajectory with the speed coinciding with the calculated plasma drift velocity at the F-layer altitude. In the model calculations the temporal history is traced of the ionospheric plasma in the part of the magnetic field tube during its movement along the flow trajectory. For the considered flow trajectory, we obtain variations of ionospheric quantities with time (along the flow trajectory),with the relation between the distance along the trajectory and the time containing the calculated plasma drift velocity at the F-layer altitude. In other words, the profiles against distance from the earth along the geomagnetic field line of ionospheric quantities are obtained by solving the appropriate system of transport equations of ionospheric plasma. These profiles result in a two-dimensional steady distributions of ionospheric quantities along the flow trajectory. By tracing many field tubes of plasma along a set of flow trajectories, we can construct three-dimensional steady distributions of ionospheric quantities.

We separate the 70-700 km distance range into two parts: first, the upper region at distances of 130-700 km; second, the lower region at distances of 70-130 km. In each part of the distance range, the mathematical model is based on the numerical solution of different systems of transport equations of ionospheric plasma.

### 2.2. The upper region ( 130-700 km )

The plasma of the upper region is assumed to consist of electrons and positively, singly charged atomic oxygen ions. It is supposed that one of the axes (axis h) of the relative frame of reference is directed upwards along the magnetic field line. The system of transport equations, describing the behaviour of the ionospheric plasma in the upper part of the considered magnetic field tube, consists of the continuity equation, equation of motion for the ion gas, and heat conduction equations for ion and electron gases. This system in the moving reference frame may be written in the following form:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial h}\left(NV_i\right) = q + q_e - l \quad , \tag{1}$$

$$m_i N\left(\frac{\partial V_i}{\partial t} + V_i\frac{\partial V_i}{\partial h}\right) - \frac{4}{3}\frac{\partial}{\partial h}\left(\mu\frac{\partial V_i}{\partial h}\right) + \frac{\partial}{\partial h}\left[Nk(T_i + T_e)\right] + m_i N g \sin I = m_i N \sum_{n=1}^{3}\frac{1}{\tau_{in}}(U_n - V_i) \quad , \tag{2}$$

$$\frac{\partial T_i}{\partial t} = \frac{1}{M}\frac{\partial}{\partial h}\left(\lambda_i\frac{\partial T_i}{\partial h}\right) - V_i\frac{\partial T_i}{\partial h} + \frac{\gamma-1}{N}\left(\frac{\partial N}{\partial t} + V_i\frac{\partial N}{\partial h}\right)T_i + \frac{1}{M}\left(P_{ie} + \sum_{n=1}^{3}P_{in}\right) \quad , \tag{3}$$

$$\frac{\partial T_e}{\partial t} = \frac{1}{M}\frac{\partial}{\partial h}\left(\lambda_e\frac{\partial T_e}{\partial h}\right) - V_e\frac{\partial T_e}{\partial h} + \frac{\gamma-1}{N}\left(\frac{\partial N}{\partial t} + V_e\frac{\partial N}{\partial h}\right)T_e +$$
$$+\frac{1}{M}\left(P_{ei} + \sum_{n=1}^{3}P_{en} + Q + Q_e - L_r - L_v - L_e - L_f\right) \tag{4}$$

where N is the $O^+$ ion number density (which is assumed to be equal to the electron concentration $N_e$ at the F-layer altitudes); $V_i$ is the parallel (to the magnetic field) component of the positive ion velocity; q is the photoionization rate; $q_e$ is the production rate due to auroral electron bombardment; l is the positive ion loss rate (taking into account the chemical reactions $O^+ + O_2 \rightarrow O_2^+ + O$, $O^+ + N_2 \rightarrow NO^+ + N$, $O_2^+ + e \rightarrow O + O$ , and $NO^+ + e \rightarrow N + O$ ); $m_i$ is the positive ion mass; k is Boltzmann's constant; $T_i$ and $T_e$ are ion and electron temperatures, respectively; g is the acceleration due to gravity; I is the magnetic field dip angle; $1/\tau_{in}$ is the collision frequency between ion and neutral particles of type n; $U_n$ is the parallel component of velocity of neutral particles of type n; M=3/2kN; $\gamma$ =5/3; $V_e$ is the parallel component of electron velocity (which is determined from the equation for parallel current); $\mu$ is the ion viscosity coefficient; $\lambda_i$ and $\lambda_e$ are the ion and electron thermal conductivity coefficients, respectively; Q and $Q_e$ are the electron heat rates due to photoionization and auroral electron bombardment, respectively; $L_r$ , $L_v$ , $L_e$ ,, and $L_f$ are the electron cooling rates due to rotational excitation of molecules $O_2$ and $N_2$ , vibrational excitation of molecules $O_2$ and $N_2$ , electronic excitation of atoms O, and fine structure excitation of atoms O, respectively. The quantities on the right-hand sides of equations (3) and (4), denoted by $P_{\alpha\beta}$ , describe the rates of energy exchange of type $\alpha$ particles as a result of elastic collisions with particles of type $\beta$.

The neutral atmosphere is assumed to consist of the species O, $O_2$ ,and $N_2$ , subscripts *n* of which in equations (2)-(4) are 1,2, and 3, respectively . The parameters of the neutral atmosphere, expressions for the quantities which appear in the system (1)-(4), spatial distributions of zonal and meridional components of the neutral wind, numerical method, and other details are taken from previous models [*Mingalev et al*., 1988: *Mingaleva and Mingalev*, 1998].

### 2.3. The lower region ( 70-130 km )

The plasma of the lower region is assumed to consist of electrons, positevely, singly charged ions, and negatively, singly charged ions. The neutral atmosphere is assumed to consist of the main, minor, and excited neutral constituents. Taken into account is the presence of positive ions $O^+(^4S)$, $O^+(^2D)$, $O^+(^2P)$, $O_2^+$, $NO^+$, $N_2^+$, $N^+$, and $H^+$ as well as two cluster positive ions. The negative ions include $O_2^-$, $O^-$, $CO_3^-$, $NO_3^-$, $CO_3^- {*} H_2O$, and $NO_3^- {*} H_2O$. The minor and excited neutral constituents contain $N(^4S)$, $N(^2D)$, $N(^2P)$, NO, $NO_2$, $NO_3$, $N_2O_5$, $O_3$, OH, $HO_2$, $H_2O_2$, $HNO_2$, $HNO_3$, $HNO_4$, $O(^1D)$, and CO. The concentrations of positive and negative ions and minor and excited neutral constituents, mentioned above, are calculated by solving the appropriate system of transport equations. The concentrations of the main neutral constituents ($N_2$ , $O_2$ , O, and H) are assumed to be the given quantities. When the concentrations of positive and negative ions are calculated, the electron concentration $N_e$ is obtained from the condition that the ionosphere is electrically neutral, i.e.

$$N_e = \sum_{i=1}^{10} N_i - \sum_{j=1}^{6} N_j \quad , \tag{5}$$

where $N_k$ is the number density of particles of type k; the summation with respect to i is applied to all types of positive ions; the summation with respect to j - to all types of negative ions.
The concentration of the component of type k in the vertical (z) direction is described by the continuity equation

$$\frac{\partial N_k}{\partial t}+\frac{\partial}{\partial z}\left(N_k V_k^z\right)=q_k-l_k \qquad (6)$$

where $V_k^z$ is the vertical component of the velocity of particles of type k; $q_k$ and $l_k$ are the production and loss rates of particles of type k. The transport in the horizontal directions is assumed to be negligible as a consequence of slight inhomogeneity of the middle atmosphere in the horizontal directions as compared with inhomogeneity in the vertical direction.

The vertical velocity ($V_k^z$) is written as the sum of three parts

$$V_k^z=(V^z)_{av}+(V_k^z)_M+(V_k^z)_T \qquad (7)$$

where $(V^z)_{av}$ is the mean velocity of atmospheric mass motion, $(V_k^z)_M$ is the molecular diffusion velocity of particles of type k, and $(V_k^z)_T$ is the velocity given to particles of type k by means of eddy mixing or turbulent processes in the middle atmosphere.

$(V^z)_{av}$ is usually assumed to be negligible in model studies because of scarce information on large-scale circulation in the middle atmosphere. $(V_k^z)_M$ is determined from the equation of motion for particles of type k that is similar to the equation (2) in which the inertial and viscous terms are omitted. $(V_k^z)_T$ is determined by the ordinary expression containning the vertical eddy diffusion coefficient [*Shimazaki*, 1971]. The temperatures of the neutral constituents, ions, and electrons are assumed to be the given quantities. Ionization and dissociation processes by solar UV and X-ray fluxes as well as by precipitating energetic electrons are taken into account by the mathematical model.

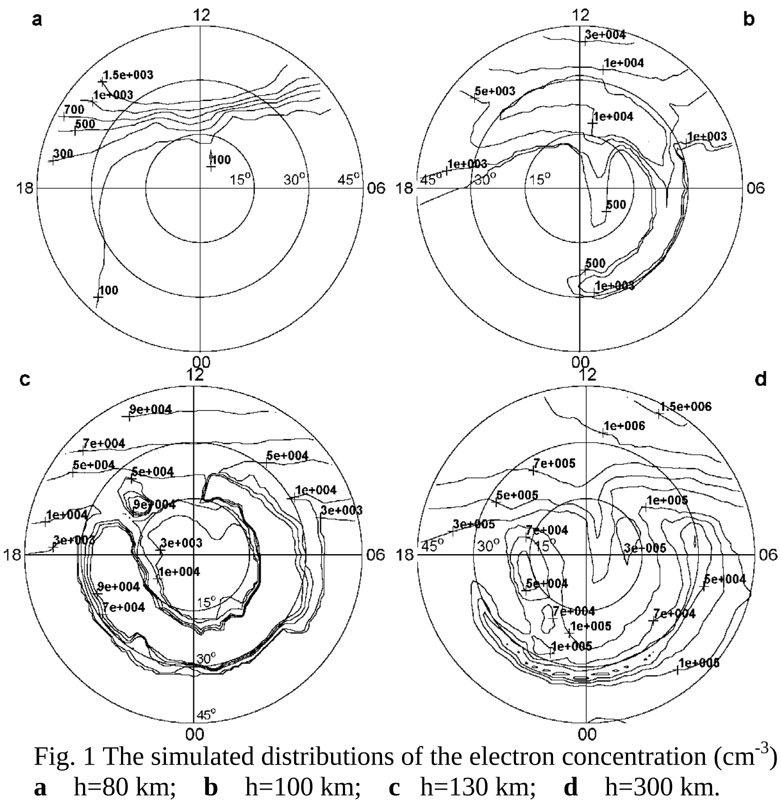


Fig. 1 The simulated distributions of the electron concentration ($cm^{-3}$) at levels:
**a** h=80 km; **b** h=100 km; **c** h=130 km; **d** h=300 km.

### *2.4. Outputs of the model*

The new version of the mathematical model of the high-latitude ionosphere enables one to calculate the three-dimensional steady distribution of the electron concentration at distances from the earth from 70 to 700 km not only at polar latitudes but also at the subauroral ones. Besides, the new version of the model produces distributions of the positive ion velocity and ion and electron temperatures at distances from the earth from 130 to 700 km. Moreover, the model allows one to calculate the concentrations of positive and negative ions and minor and excited neutral constituents, taken into account by the model, at distances from the earth from 70 to 130 km at polar and subauroral latitudes.

## 3. Testing the model

The developed mathematical model can describe different combinations of the geomagnetic activity level, solar cycles and seasons. For examination of the model, the simulations were performed for the autumn (25 October) and high solar activity ($F_{10.7}$ =193) conditions under middle geomagnetic activity ($K_p$ = 3). The results of simulation were obtained by using the electric field distribution which is the combination of the pattern B of the empirical models of high-latitude electric fields of *Heppner* [1977] and the empirical model of ionospheric electric fields at middle latitudes, developed by *Richmond* [1976] and *Richmond et al*. [1980]. The spatial configuration of the electron precipitation zone as well as intensities and average energies of the precipitating electrons were chosen as consistent with the statistical model of *Hardy et al.* [1989].

Figure 1 presents some of the simulation results obtained. From Fig.1a we can see that the electron concentration at D-region altitudes is distributed in accordance with the illumination of the ionosphere by the solar radiation. At the level h = 100 km (Fig. 1b), we can see a band of increased electron concentration in the morning sector which is a natural consequence of the bombardment of the atmosphere by the most energetic auroral electrons. At the level h = 130 km (Fig.1c), the precipitating auroral electrons produce a considerable enhancement of the electron density near the auroral oval. The results of Fig.1d illustrate the efficiency of the convection of ionospheric plasma at the F-layer altitudes, in particular, the formation of the tongue of ionization, extended from the local noonside of the earth across the polar cap to the nightside. The remarkable feature presented in Fig.1d is the existence of the main ionospheric trough lying equatorward of the auroral oval on the nightside.

## 4. Conclusions

The new version of the mathematical model of the high-latitude ionosphere has been briefly described in which two numerical models, developed earlier, have been amalgamated: the mathematical model of the convecting high-latitude ionosphere; the mathematical model of the high-latitude middle and upper atmospheres. The developed new version of the model enables one to calculate the three-dimensional steady distribution of the electron concentration at distances from the earth from 70 to 700 km at the polar and subauroral latitudes. In addition, the model produces distributions of the positive ion velocity and ion and electron temperatures at distances from 130 to 700 km and the composition of the atmosphere, including positive and negative ions and minor and excited neutral constituents, at distances from 70 to 130 km. The testing of the model has been performed which has demonstrated the possibility of the model to reproduce main characteristic features of the high-latitude ionosphere which are well known from observations.

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