ВЛИЯНИЕ ИОНОСФЕРНОЙ ПРОВОДИМОСТИ НА ПРОНИКНОВЕНИЕ ЭЛЕКТРИЧЕСКОГО ПОЛЯ ИЗ АТМОСФЕРЫ В ИОНОСФЕРУ
IONOSPHERIC CONDUCTIVITY EFFECTS ON THE ELECTRIC FIELD PENETRATION FROM THE ATMOSPHERE INTO THE IONOSPHERE

V.V. Denisenko[1], M. Ampferer [2], H.K. Biernat [3]
[1] Institute of Computatioal Modeling RAS, denisen@icm.krasn.ru
[2] Karl-Franzens-University, 04ampfer@edu.uni-graz.at
[3] Space Research Institute AAS, helfried.biernat@oeaw.ac.at

Общепринятым методом моделирования проникновения электрического поля от земной поверхности в ионосферу является решение стационарного уравнения электропроводности. Для упрощения модели мы полагаем, что это увеличение продольной проводимости происходит скачком на некоторой высоте, и выше этой поверхности проводимость вдоль магнитных силовых линий бесконечна. Такое приближение обычно используется, когда вводится интегральная проводимость ионосферы. Эта модель ионосферы позволяет получить из закона сохранения заряда специальное граничное условие в задаче для атмосферного поля. Показано, что величина ионосферного электрического поля, проникающего от земной поверхности, обратно пропорциональна интегральной педерсеновской проводимости ионосферы. Горизонтальное электрическое поле в нашей модели получилось намного меньшим, чем в модели [1], не учитывающей ионосферную проводимость выше 90 км, но намного большим, чем в модели [2], в которой педерсеновская проводимость считается бесконечной выше 150 к., Ниже 50 км все три модели дают одинаковые результаты.

Introduction. Many papers are devoted to mathematical simulation of the atmospheric electric field. In row with electric fields near thunderstorm clouds the processes of ionosphere-lithosphere coupling are under analysis. The aim of these researches is to use satellites for monitoring of earthquakes precursors. There exist data on the electric field variations near ground before earthquakes. It is interesting to know if these variations can be measure by satellites. A review on this topic can be found in [3].

The results of the simulations [1,2,4] differ much in spite of that the same steady state model of electric conductivity is used. The methods of the electric current closure by the ionosphere are principally different. Some upper boundary condition is used in our model [4] that follows from the charge conservation law for the ionosphere with infinite field-aligned conductivity. The alternative condition in [1] additionally neglects Pedersen conductivity above 90 km. One more alternative condition [2] additionally regards the Pedersen conductivity above 150 km as infinity. These conditions follow from ours if the integrated Pedersen conductivity of the ionosphere equals zero or infinity. Here we compare the results of the models [1,2,4] and analyze the error of our approximation of the ionospheric conductor with 2-D model [4].

The electric conductivity equation for the electric potential V is

$$-div(\hat{\sigma}\, grad\, V) = q, \qquad (1)$$

where $\hat{\sigma}$ **-** conductivity tensor, $-q$ **-** divergence of extrinsic currents, if those exists. It is possible to neglect the Earth's surface curvature for local events. We use Cartesian coordinates x, y, z with vertical z axis and $z = 0$ at ground**.**

The problem is simplified much if the magnetic field is vertical and conductivity depends only of the height z, since in such a case Hall conductivity σ_H does not matter and the only Pedersen σ_P and field-aligned $\sigma_{||}$ conductivities are involved in the equation (1)

$$-\sigma_P(z)\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) - \frac{\partial}{\partial z}\left(\sigma_{||}(z)\frac{\partial V}{\partial z}\right) = q, \qquad (2)$$

but when V is calculated we must add σ_H during the current density $\vec{j}$ calculation.

We have created the model [5] to calculate the components $\sigma_P, \sigma_H, \sigma_{||}$ of the conductivity tensor $\hat{\sigma}$ above 90 km**,** that is based of the empirical models IRI, MSISE, IGRF. We use the empirical model [4] below 60 km and smooth interpolation between 60 and 90 km. The typical height distributions for the middle latitudes are presented in Fig. 1. Dashed lines present the effective σ_P that describes the ionospheric conductor after its acceleration during 1 hour by Ampere force [5].

The vertical component at the ground is taken as given in many models

$$-\left.\frac{\partial V}{\partial z}\right|_{z=0} = E_0(x,y), \tag{3}$$

and we do the same. The function $E_0(x,y)$ is constructed on the base of published measurements and some general ideas. It would be better to say about vertical current density that is supported by some underground generator. Since conductivity of air is given, these conditions are equivalent.

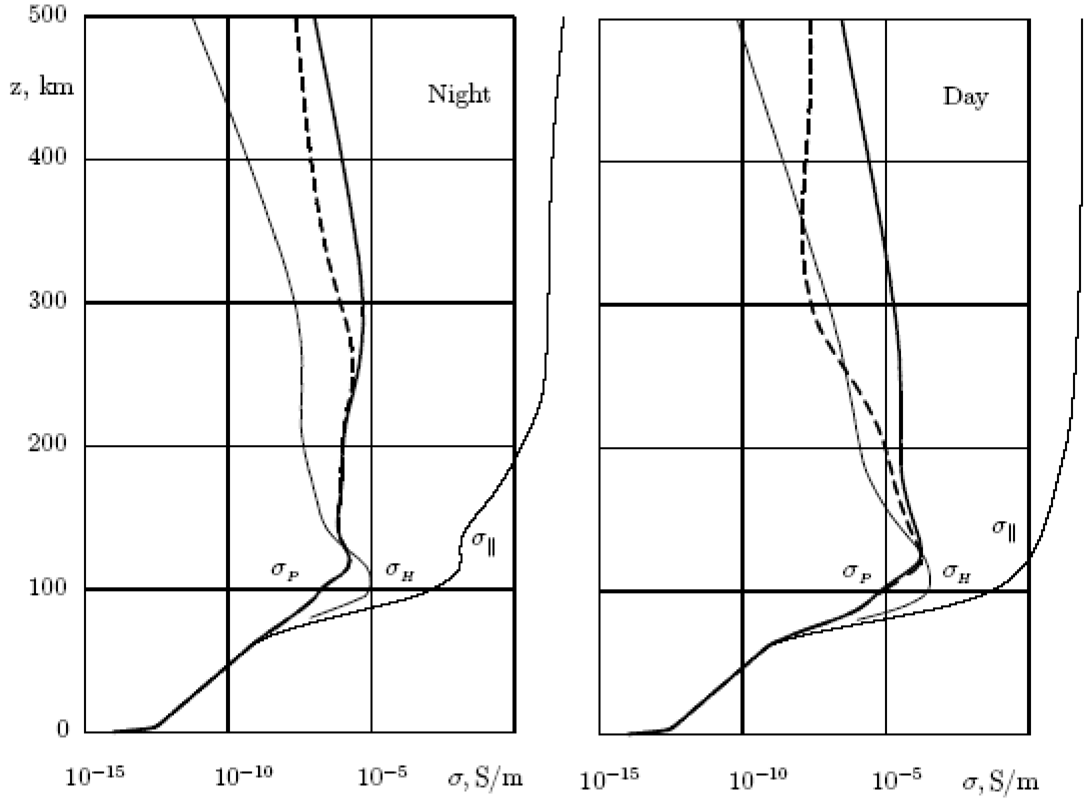

Fig. 1. Typical height distributions of the conductivity tensor $\hat{\sigma}$ components in middle latitudes.

2-D model of the ionospheric conductor. Let us consider only the ionosphere below $z = z_\infty$. For example the layer above 500 km adds less 1% to the integrated parameters of interest. The vertical current density can be given at this height

$$-\sigma_{||}(z_\infty)\left.\frac{\partial V}{\partial z}\right|_{z=z_\infty} = j_\infty(x,y), \tag{4}$$

or the currents in far conductors, which are connected with this boundary by magnetic field lines, can be taken into account as it is described below.

We cut the upper ionosphere from the lower one by the plane $z = z_{up}$ and use the approximation $\sigma_{||} = \infty$ above z_{up}. It can be seen in Fig. 1 that $\sigma_{||}$ is five orders of magnitude larger than other components of the conductivity tensor above 150 km. This approximation is not valid in the lower ionosphere and we define possible level by tests. Infinite conductivity $\sigma_{||} = \infty$ makes a magnetic field line equipotential. Hence the horizontal electric field components are independent of z and local Ohm law can be integrated over z to construct 2-D Ohm law with integral Pedersen and Hall conductivities Σ_P, Σ_H

$$\begin{pmatrix} J_x \\ J_y \end{pmatrix} = \begin{pmatrix} \Sigma_P & -\Sigma_H \\ \Sigma_H & \Sigma_P \end{pmatrix}\begin{pmatrix} E_x \\ E_y \end{pmatrix}, \qquad \Sigma_P = \int_{z_{up}}^{z_\infty} \sigma_P dz, \quad \Sigma_H = \int_{z_{up}}^{z_\infty} \sigma_H dz. \tag{5}$$

So we have 2-D model of the ionospheric conductor. Each point with coordinates x, y presents the whole magnetic field line, that includes the vertical segment $z_{up} < z < z_\infty$ and its magnetospheric continuation. Such a simplified model permits to construct the boundary condition at $z = z_{up}$ in accordance with 2-D Ohm law: the currents, which enter this layer from below through the plane $z = z_{up}$, and given currents (4), which enter this layer from above through the plane $z = z_{\infty}$, are closed by the currents $\vec{J}$ in this layer

$$Div\ \vec{J} = \sigma_{||}(z_{\infty})\frac{\partial V}{\partial z}\bigg|_{z=z_{\infty}} + Q. \tag{6}$$

When the events of interest have horizontal scale much less then the ionospheric scale that equals thousands kilometers in middle latitudes, the values of σ_P, σ_H are independent of x, y and Σ_P, Σ_H are constants. The constant Σ_H can be omitted in (6) to obtain

$$-\Sigma_P\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right)\Bigg|_{z_{up}} + \sigma_{||}(z_{up})\frac{\partial V}{\partial z}\bigg|_{z_{up}} = Q. \tag{7}$$

The possibility to represent the ionospheric influence on the electric fields below $z = z_{up}$ by this boundary condition is tested by comparison of the solutions of the problem with this condition and the solutions in the whole ionosphere and atmosphere below z_{∞}. We choose $z_{\infty} = 500$ km and the solutions of the form $f(z)\cos(x/x_0)$, where x_0 is the horizontal space scale. The equation (2) becomes the ordinary differential equation for the function $f(z)$. The boundary value problems with conditions which follow (3,7) or (3,4) can be solved numerically. We solve the problems with $x_0 = 10$, 100, 1000 km.

Results. The height distributions of the horizontal component of the electric field $E_x(\pi x_0/2, z)$ above the points $x = \pi x_0/2$, where $E_x(x,z)$ has maximal value in respect of x, are plotted in Fig. 2a. Three solutions have the same maximal values of the vertical component $E_z(0,0)$ =100 V/m. It is found that z_{up} aught be increased when x_0 is decreased. For example the height z_{up} =90 km as it was done in the models [4,6] adds only 1% error to the ionospheric value of E_x if x_0 exceeds 3 km.

The solution with $x_0 = 100$ km and boundary condition (7) is also plotted by thick line in Fig. 2b.

The solution with boundary condition that is used in the model [1]

$$-\frac{\partial V}{\partial z}\bigg|_{z=90km} = 0, \tag{8}$$

is plotted by dashed line in Fig. 2b. Thin line corresponds to the boundary condition [2]

$$V|_{z=150km} = 0. \tag{9}$$

The last would be valid if an ideal conductivity in horizontal directions exists above 150 km. The condition (8) means no vertical current from the atmosphere at 90 km. It would be valid if the medium above 90 km has zero conductivity at least in horizontal directions. The conditions (8,9) can be derived from ours (7) when Σ_P equals zero or infinity. As it is shown in Fig. 2b the neglecting the ionospheric conductivity (8) increases ionospheric E_x about thousand times. The approximation $\Sigma_P = \infty$ decreases E_x a few thousands times at $z =$ 100 km and makes it exactly zero above 150 km.

It can be mentioned that if we add conductivity of the adjoint ionosphere, that means twice larger Σ_P then E_x in the ionosphere would be twice less – curve 3. If a process in the auroral zone is under analysis then the conductivity of the plasma layer Σ_P about 100 S aught be added and E_x becomes 140 times less – curve 4. Nevertheless it stays much larger than E_x in the model [2]. If we take into account the decrease of the effective σ_P, that describes the ionospheric conductor after its 1 hour acceleration by Ampere force [5], E_x would be 2.5 times larger – curve 1, but it stays much less than E_x [1].

If the magnetic field $\vec{B}$ is inclined from vertical by the angle χ, the tensor $\hat{\Sigma}$ in (5) aught be modified [5]. In our test problem the parameter Σ_P in (7) aught be substituted with $\Sigma_P/\cos\chi$ or

$\Sigma_P / \cos^2 \chi$ when $\vec{B}$ is in y, z or x, z planes. Therefore the result E_x in the ionosphere decreases in comparison with those presented in Fig. 2a by the factor $\cos\chi$ or $\cos^2 \chi$. Some more complicated model than (6) is necessary for the equatorial ionosphere [5].

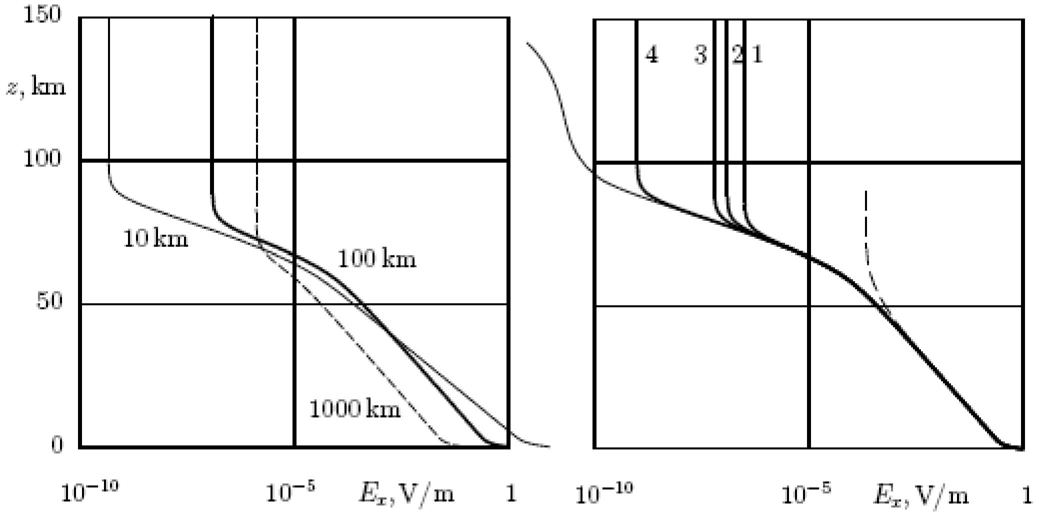

Fig. 2. Height distributions of the horizontal component of the electric field. See details in the text.

Conclusions. The new mathematical model is proposed to represent the ionospheric conductor by the boundary condition. This approximation is rather precise for large scale processes.

It is shown that two popular models of the electric field penetration into the ionosphere [1,2] are not adequate in spite of that they give good results below 50 km. Unproved upper boundary conditions are used in these models. In fact the good ionospheric conductor is excluded in [1], and unreal good conductor is added in [2]. That is why our model [4,6] predicts ionospheric electric fields not so large as the model [1] does and not so small as the model [2] does.

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