Some Inexactnesses of the European NeQuick Model and Possible Ways of their Correction

Sergii V. Grinchenko
Department of Physics of Ionosphere
Institute of Ionosphere, IION
Kharkiv, Ukraine
svgrinchenko@gmail.com

Abstract—**NeQuick model is used in particular in solving problems of radio wave propagation in ionosphere. It allows of calculation of the altitude profiles of electron density above any point of the globe in a wide range of altitudes at any time. The makers of NeQuick model use analytical formulas for the description of the separate E, F1, and F2 layers in constructing of the electron density profile for the whole altitude region. The formula parameters use previously calculated values of electron density and height of the layer peaks. But the insufficient correctness of algorithmization results in some inaccuracies of construction of total profile of electron density in heights of E and F1 regions. For example, there are time discontinuities of daily variations of electron density at the moments corresponding to appearance or disappearance of layer F1. The E and F1 layers practically do not manifest themselves on figures of the electron density profiles. In addition, the previously calculated F1-layer peaks do not lie on the electron density profiles. By means of the algorithm of construction of electron density profile developed by the author of this paper it is possible to describe correctly an altitude profile of electron density on its geometrical parameters of E, F1, and F2 regions. The corrected altitude profiles would change continuously with local time.**

Index Terms—**ionosphere; electron density; NeQuick**

I. General information about NeQuick model

The ionospheric models allow calculating the plasma parameters in a wide range of altitudes over the globe. The empirical model NeQuick is widely used by many research groups for studying of ionospheric effects on wave propagation. The source Fortran code of NeQuick model is relating to free software. The present Fortran compilers focused on object-oriented programming, support the every possible codes written during for the entire 70-year-old history of the Fortran. Therefore on the basis of Fortran codes it is possible to create applications using up-to-date graphics and networking technology. Critical frequency f_0F2 of F2-layer and height h_mF2 of layer peak are calculated from CCIR model.

A number of researchers make comparisons between calculations by NeQuick model and the satellite data and the data of different terrestrial radio physical methods [1-4]. There is marked a good coincidence in the F2-layer maximum and somewhat worse one in other parts of electron density profile. The largest differences are observed in the equatorial anomaly regions.

By using of the European NeQuick model it is possible to calculate both vertical and inclined profiles of electron density. When calculating the vertical profile NeQuick program uses as input the geographical coordinates of a calculation point, number of month in a year, local time and $F_{10.7}$ index of solar activity level. When calculating the inclined profile NeQuick model uses the coordinates of origin and terminus of calculation trace.

Ionospheric model NeQuick is the product of several European research organizations. The International Centre for Theoretical Physics (ICTP) – Trieste, Italy, is the leading organization at development of NeQuick model. The International Telecommunication Union Radiocommunication Sector recommends using NeQuick model for calculations of communication lines.

The ionospheric model NeQuick receives a considerable attention in the European scientific community Annually the ICTP holds seminars, assemblies, conferences devoted to development and application of NeQuick model.

II. Discontinuities of the daily electron density variations calculated by NeQuick model

The daily electron density variations have discontinuities in the morning and evening moments corresponding to appearance and disappearance of F1 layer. Fig. 1 shows the daily change of electron density calculated by the NeQuick model at Kharkiv Incoherent Scatter Radar coordinates. Estimated month – June; $F_{10.7}$ index equals 100. Electron density is measured in cm^{-3}.The decimal logarithm of electron density value is presented by corresponding color.

At the moments of appearance and disappearance of F1 layer there are discontinuities of chromaticity of drawing, i.e. discontinuities of the dependence of electron density from local time.

Fig. 2 shows the altitude profiles of the electron density corresponding to the morning discontinuity. The daggers designate peaks of E, F1, and F2 layers, precomputed at construction of NeQuick altitude profiles. Apparently from figure, in the presence of F1 layer the point corresponding to calculated F1 peak, does not lie on electron density altitude profile.

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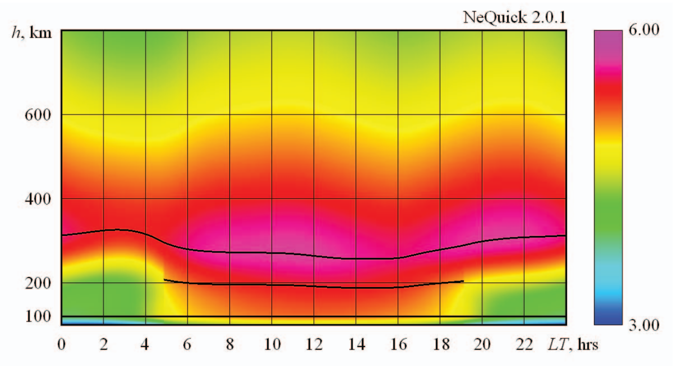

Figure 1. The discontinuities of dependence of electron density value from local time (LT) during the moments of appearance and disappearance of F1 layer

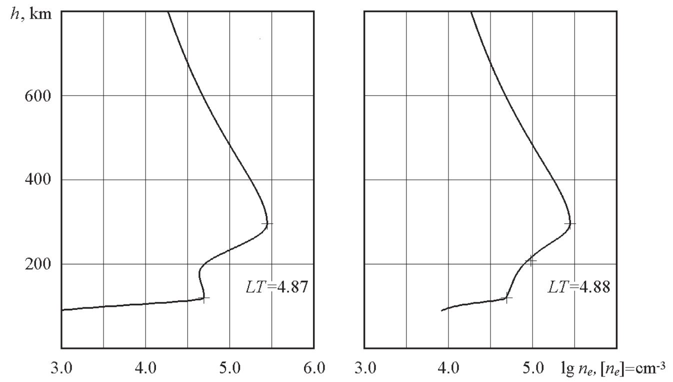

Figure 2. Abrupt change of NeQuick electron density at the moment of F1 layer appearance

In NeQuick model the height of E layer is the fixed and equal to 120 km. The height of F1 layer is calculated by the approximate formula as a half-sum of heights of E and F2 layers.

The calculations show that NeQuick model layer F1 exists in the daytime both in summer and in winter; and with a rise of solar activity the time interval of existence of F1 layer extends. This contradicts to the conventional notions about the F1 layer variations, according to which the F1 layer occurs mainly in summer daytime at low solar activity.

Although the issue of discontinuity of diurnal variations of the NeQuick model electron density seems actual, in the literature this problem was never discussed. Moreover the effect of discrete change of electron density profile in the moments of appearance and disappearance of F1 layer is present in IRI model, too.

One of problems solved in this paper is finding-out of the features of the NeQuick program algorithm, causing a discontinuity of dependence of local time in the moments of appearance and disappearance of F1 layer.

III. The Basic Formulas Used in the Construction of Model NeQuick Electron Density Profile Below the F2-Layer. The Analysis of the Analytical Description of Separate Layers of NeQuick Model

NeQuick model is based on Epstein function at the description of separate layers of electron density [5-6]:

$$f(x,y,z,w)=\frac{x}{\left(1+e^{\frac{w-y}{z}}\right)^2}e^{\frac{(w-y)}{z}}. \qquad (1)$$

For each E, F1, and F2 layers electron density is given by the formula:

$$n_e(h)=n_e(h;h_m,n_{em},B)=\frac{4n_{em}}{\left(1+e^{\frac{h-h_m}{B}}\right)^2}e^{\frac{h-h_m}{B}}, \qquad (2)$$

where h is altitude of calculation of electron density; h_m is height of the electron density maximum; n_{em} is maximum value of the electron density of the layer; B is parameter describing a thickness of the layer.

The altitude electron density profile of E, F1, and F2 regions is described by the formula:

$$n_e(h)=n_e^{\mathrm{E}}(h)+n_e^{\mathrm{F1}}(h)+n_e^{\mathrm{F2}}(h), \qquad (3)$$

where

$$n_e^{\mathrm{E}}(h)=n_e^{\mathrm{E}}\left(h;h_m^{\mathrm{E}},n_{em}^{\mathrm{E}},B^{\mathrm{E}}\right)=\frac{4n_{em}^{\mathrm{E}}}{\left(1+e^{\frac{h-h_m^{\mathrm{E}}}{B^{\mathrm{E}}}}\right)^2}e^{\frac{h-h_m^{\mathrm{E}}}{B^{\mathrm{E}}}}, \qquad (4)$$

$$n_e^{\mathrm{F1}}(h)=n_e^{\mathrm{F1}}\left(h;h_m^{\mathrm{F1}},n_{em}^{\mathrm{F1}},B^{\mathrm{F1}}\right)=\frac{4n_{em}^{\mathrm{F1}}}{\left(1+e^{\frac{h-h_m^{\mathrm{F1}}}{B^{\mathrm{F1}}}}\right)^2}e^{\frac{h-h_m^{\mathrm{F1}}}{B^{\mathrm{F1}}}}, \qquad (5)$$

$$n_e^{\mathrm{F2}}(h)=n_e^{\mathrm{F2}}\left(h;h_m^{\mathrm{F2}},n_{em}^{\mathrm{F2}},B^{\mathrm{F2}}\right)=\frac{4n_{em}^{\mathrm{F2}}}{\left(1+e^{\frac{h-h_m^{\mathrm{F2}}}{B^{\mathrm{F2}}}}\right)^2}e^{\frac{h-h_m^{\mathrm{F2}}}{B^{\mathrm{F2}}}}. \qquad (6)$$

Relations $\frac{n_{em}}{n_e(h_m-B)}=\frac{n_{em}}{n_e(h_m+B)}=\frac{(e+1)^2}{4e}$. Thus parameter B is a semithickness of the layer at which value of electron density decreases at $\frac{(e+1)^2}{4e}\approx 1.2715$ times; in this case $\lg n_{em}-\lg n_e(h_m-B)=\lg n_{em}-\lg n_e(h_m+B)=\lg\frac{(e+1)^2}{4e}$,

i. e. decimal logarithm of electron density decreases by $\lg \frac{(e+1)^2}{4e} \approx 0.10433$.

The curve $n_e(h)$ is symmetrical with respect to the line $h=h_m$: $n_e(h_m - \Delta h) = n_e(h_m + \Delta h)$.

It is clear that the curve $\lg n_e(h)$ is symmetrical with respect to the line $h=h_m$, too.

On fig. 3 we can see examples of F1 layer with parameters h_m=180 km, $\lg n_{em}$=5.3 ($[n_{em}]$=cm^{-3}), B=10 km and F2 layer with parameters h_m=260 km, $\lg n_{em}$=5.8, B=25 km.

Let us perform an elementary analysis of $\lg n_e(h)$ curve about its suitability for the description of a layer of electron density:

$$\ln n_e(h) = \ln 4 + \ln n_{em} - 2\ln\left(1 + e^{\frac{h-h_m}{B}}\right) + \frac{h-h_m}{B}, \tag{7}$$

$$(\ln n_e(h))' = \frac{1}{B} \cdot \frac{1-e^{\frac{h-h_m}{B}}}{1+e^{\frac{h-h_m}{B}}}. \tag{8}$$

Derivative $(\lg n_e(h))' = \frac{1}{\ln 10}(\ln n_e(h))' = 0$ at $h = h_m$; at $h > h_m$ derivative $(\lg n_e(h))' < 0$; at $h < h_m$ derivative $(\lg n_e(h))' > 0$. Therefore the point $h = h_m$ is the point of maximum of $\lg n_e(h)$ function.

Let's investigate an existence of the asymptotes of curve $n_e(h) = \frac{4n_{em}}{\frac{1}{e^{\frac{h-h_m}{B}}} + 2 + e^{\frac{h-h_m}{B}}}$.

At values of height h, considerably exceeding the height of electron density maximum ($h >> h_m$), the formula for the analytical description of electron density of a layer takes the form: $n_e(h) \approx \frac{4n_{em}}{e^{\frac{h-h_m}{B}}}$. At $h << h_m$ electron density $n_e(h) \approx 4n_{em}e^{\frac{h-h_m}{B}}$.

From the asymptotic approximations of $n_e(h)$ there are obtained asymptotes of $\lg n_e(h)$. At $h >> h_m$ the logarithm $\lg n_e(h) \approx \lg 4 + \lg n_{em} - \frac{h-h_m}{B}\lg e$. At $h << h_m$ the logarithm $\lg n_e(h) \approx \lg 4 + \lg n_{em} + \frac{h-h_m}{B}\lg e$.

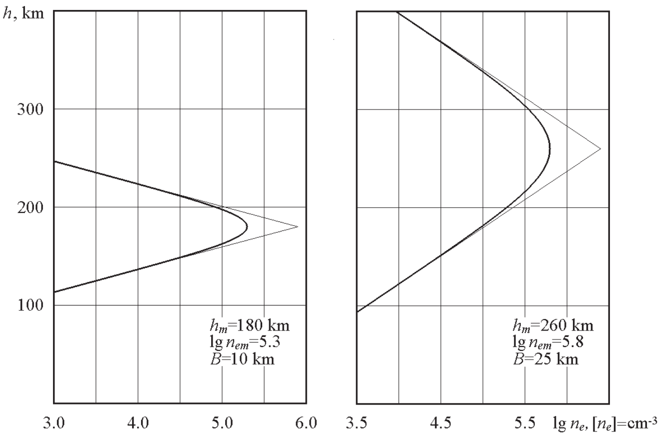

Figure 3. Examples of electron density graphs of F1 and F2 layers and their asymptotic straight lines

The straight line $\lg n_e(h) \approx \lg 4 + \lg n_{em} - \frac{h-h_m}{B}\lg e$ is an incline asymptote of the decimal logarithm of electron density layer above the maximum. The straight line $\lg n_e(h) \approx \lg 4 + \lg n_{em} + \frac{h-h_m}{B}\lg e$ is an incline asymptote below the maximum. Both straight lines are crossed in a point $(h_m; \lg 4 + \lg n_{em})$.

IV. Modeling of altitude electron density profile as the sum of the profiles of separate layers

When the E and F2 layers exists at all hours, then the F1 layer exists only during the daytime. Therefore, in the daytime electron density $n_e(h) = n_e^{\mathrm{E}}(h) + n_e^{\mathrm{F1}}(h) + n_e^{\mathrm{F2}}(h)$ and in the rest of time $n_e(h) = n_e^{\mathrm{E}}(h) + n_e^{\mathrm{F2}}(h)$. In the moments of appearance or disappearance of F1 layer the electron density profile has a jump (see Fig. 4).

As a result of addition of layers the peaks of E and F1 layers of total electron density profile shift from the original positions.

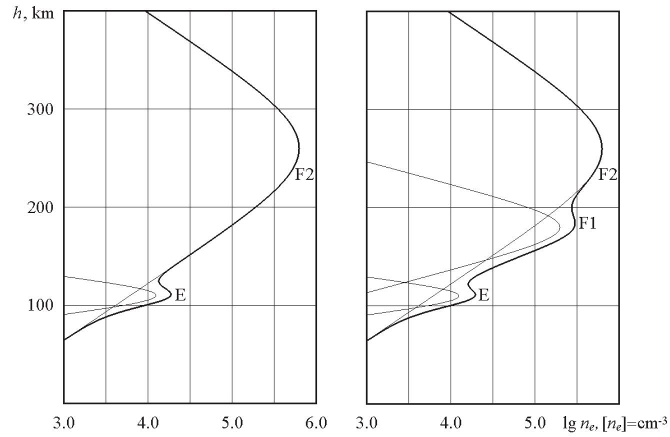

Figure 4. Discrete change of electron density profile in the moments of appearance or disappearance of F1 layer

An analysis of the program code shows that the program has algorithms that prevent the displacement of the layer peaks. When the E peaks are practically not displaced, then the calculated F1 layer peaks still do not lie on themselves electron density profiles. A by-effect of these algorithms is the fact that there almost are not obtained E and F1 layers on the NeQuick profile of electron density (see Fig. 2).

V. Proposals for the Correction of NeQuick Model

The following defects of NeQuick program were revealed. At calculation of electron density in the morning moments of appearance of F1 layer and evening moments of his disappearance there are discontinuities of daily electron density variation. On any NeQuick electron density profile there almost are not obtained E and F1 layers. In addition, pre-calculated F1 peaks does not lie in themselves electron density profile. The reason of this is the insufficient correctness of algorithmization of construction of electron density profile in E, F1 regions.

As the less significant incorrectnesses it is possible to mention the facts, that the E peak height is fixed and equal to 120 km, and the F1 peak height is calculated by the approximate formula as a half-sum of the heights of the E and F2 layers. According to the NeQuick model F1 layer exists in the daytime in summer and winter and with the increase of solar activity the time interval of existence F1 layer expands. This contradicts to the conventional notions of F1 layer variation.

To eliminate the noted incorrectnesses of NeQuick model it is possible by means of the developed algorithm of construction of electron density profile in E, F1, and F2 regions on characteristic points of layers and valleys. This algorithm allows to construct an altitude electron density profile at heights h_mE, h_mF1, h_mF2 of E, F1, and F2 peaks, at heights h_vE, h_vF1 of E and F1 valleys, and also at corresponding values n_{em}E, n_{em}F1, n_{em}F2, n_{ev}E, n_{ev}F1 of electron density.

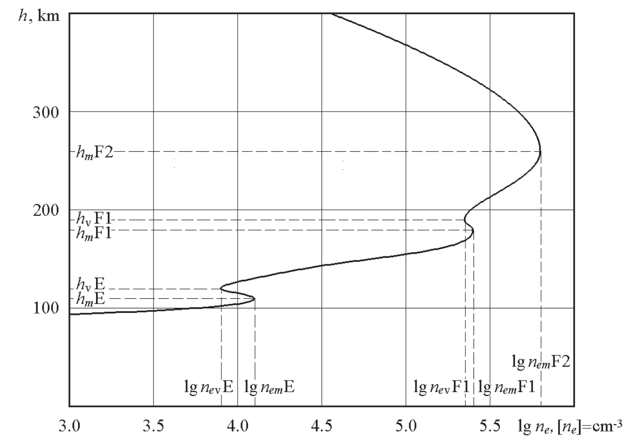

Figure 5. Construction of electron density profile on characteristic points of layers and valleys

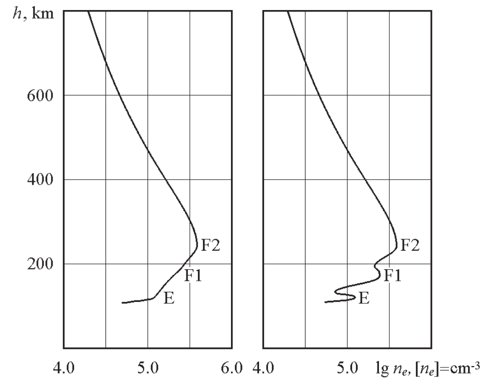

Figure 6. Calculation of the altitude profile of the electron density within the original NeQuick model and taking into account the correction in E and F1 regions

To demonstrate the working capacity of algorithm of construction of a profile the following values of input parameters have been set: h_mE = 110 km, h_mF1 = 180 km, h_mF2 = 260 km, h_vE = 120 km, h_vF1 = 190 km, lg n_{em}E = 4.1, lg n_{em}F1 = 5.4, lg n_{em}F2 = 5.8, lg n_{ev}E = 3.9, lg n_{ev}F1 = 5.35 ([n_e] =cm^{-3}). The results of calculation are presented on Fig. 5 and show conformity of the calculated profile of electron density to the set characteristic points of the profile.

At the altitude profile of electron density constructed according this algorithm, firstly, the points of layers do not lie away from curve of electron density, and, secondly, there are valleys of E and F1 regions.

The principal difference between the proposed algorithm for construction of electron density profiles n_e (h) from the known consists that the parameters setting a profile n_e (h), are visually evident and will easily be defined from the experimental data.

Figure 6 presented on the left the calculation of the altitude profile of electron density within original NeQuick model (φ=49.7; λ=36.3; *mth*=06; $F_{10.7}$=72) and on the right – calculation with the account of correction of E and F1 layers, using the mentioned algorithm.

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