SIMPLE FORMULA FOR THE TOTAL ELECTRON CONTENT IN THE NeQuick MODEL: 1. *VTEC*

M. G. Deminov

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN), Moscow, Troitsk, Russia

e-mail: deminov@izmiran.ru

Receoved April 01, 2025

Revised May 05, 2025

Accepted May 22, 2025

Abstract. A simple formula for calculating the vertical total electron content, *VTEC*, based on the data on the parameters of the *E*, *F*1, and *F*2 layer maxima in the NeQuick model is presented. It is found that the error of this formula does not exceed 2% compared to a more accurate solution to the problem – obtaining VTEC as an integral of the electron concentration according to the NeQuick model along a vertical ray from the base of the ionosphere to approximately 20,000 km. The magnitude of this error varies with local time, season, and latitude, indicating the possibility of further refinement of the presented formula.

Keywords: *ionosphere, electron density, total electron content, model, formula*

DOI: 10.31857/S00167940250510e3

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are used in various economic activities including transportation monitoring, spacecraft navigation, and geodesy [Hofmann-Wellenhof et al., 2008]. GNSS data are also used for environmental monitoring, ionosphere sensing [Afraimovich et al., 2013] and many other applications.

A significant number of GNSS users still use single-frequency equipment when it is necessary to know the total electron content (*TEC*, Total Electron Content) on the satellite beam− receiver to estimate the ionospheric signal delay. One way to calculate *TEC* for given conditions is based on the use of ionospheric and plasmaspheric electron concentration models. These include the IRI [Bilitza et al., 2022], IRI-PLAS [Gulyaeva and Bilitza, 2012], NeQuick [Nava et al., 2008], and NEDM-2020 [Hoque et al., 2022] models. These are so-called climatological models that give the median electron concentration per month. Some of such models can be used to estimate daily electron concentration variations based on additional corrections that are determined from the current *TEC* values. Such space weather models include the NeQuick-G model, which introduces an additional parameter, the effective solar activity index, which depends on latitude [Angrisano et al., 2013; European Commission, 2016]. There is a simpler way to account for such a correction [Aragon-Angel et al., 2019].

In all the above cases, to obtain the *TEC*, it is necessary to calculate the integral of this concentration on the satellite beam– receiver using the electron concentration model. The main purpose of this work was to replace this integral with a simple analytical formula to calculate the *TEC* through the parameters of the ionospheric layer maxima of one of the electron concentration models. In this case, the NeQuick model was chosen as one of the frequently used models for *TEC* calculation. In addition, only the case when *TEC* is calculated for a vertical beam from the Earth's surface to the height20000 km, which approximately corresponds to the ground-based reception of a vertical signal from GPS or GLONASS navigation satellite systems, is considered.

The following are presented sequentially: a) some equations and properties of the NeQuick model, which are necessary to explain a simple analytical formula for *TEC*; b) explicit form of this formula and evaluation of its accuracy; c) discussion of the properties of this formula. Finally, the main results of this paper are summarized.

2. NeQuick MODEL

NeQuick is a model of ionospheric electron concentration that is characterized by high computational speed and is specifically designed for transionospheric radio wave propagation applications. A full description of the NeQuick version 2 model is given in [Nava et al., 2008]. Software implementation of this model is presented in Recommendation [ITU, 2013].

Only some elements of the model are given below to explain a simple analytical formula for the vertical total electron content of *VTEC* obtained for this model. For this purpose, similar notations to those used in the NeQuick model [Nava et al., 2008] are used: N is the electron concentration, h is the altitude, $N(h)$ is the altitude distribution of electron concentration, Nm, hm and B are the concentration, altitude and thickness parameter of the maximum of the ionospheric layer, which below and above the layer maximum are denoted as $B_{bot}$and B_{top}. Three ionospheric layers are used in the model: E, F1 and $F2$. The parameters of the maxima of these layers are denoted as NmE, hmE, BE; $NmF1$, $hmF1$, $B1$; $NmF2$, $hmF2$, $B2$. The Epstein layer [Rawer, 1982] is taken as the basis for the height distribution of each layer:

$$N(h, hm, Nm, B) = 4Nm \exp(x)/(1+\exp(x))^2, \quad x = (h - hm)/B \qquad (1)$$

With the additions summarized below.

In the NeQuick model, the altitude distribution of the electron concentration below the maximum of the *F2* layer is represented as the sum of the concentrations of the *E*, *F*1, and *F2* layers of the ionosphere:

$$N_{\mathrm{bot}}(h) = N_{\mathrm{E}}(h) + N_{\mathrm{F1}}(h) + N_{\mathrm{F2}}(h), \quad (2)$$

where

$$N_{\mathrm{E}}(h) = 4NmE^{*} \exp(x_{\mathrm{E}})/(1+ \exp(x_{\mathrm{E}}))^2, \quad x_{\mathrm{E}} = (h - hmE)\xi(h)/BE, \quad (3)$$

$$N_{\mathrm{F1}}(h) = 4NmF1^{*} \exp(x_{\mathrm{F1}})/(1+ \exp(x_{\mathrm{F1}}))^2, \quad x_{\mathrm{F1}} = (h - hmF1)\xi(h)/B1, \quad (4)$$

$$N_{\mathrm{F2}}(h) = 4NmF2 \exp(x_{\mathrm{F2}})/(1+ \exp(x_{\mathrm{F2}}))^2, \quad x_{\mathrm{F2}} = (h - hmF2)/B2, \quad (5)$$

$$NmE^{*} = NmE - N_{\mathrm{F1}}(hmE) - N_{\mathrm{F2}}(hmE)\ , \quad (6)$$

$$NmF1^{*} = NmF1 - N_{\mathrm{E}}(hmF1) - N_{\mathrm{F2}}(hmF1)\ ; \quad (7)$$

function

$$\xi(h) = \exp(10/(1 + |h - hmF2|)) \quad (8)$$

ensures that the *E* and F1 layers are "damped" in the neighborhood of the maximum of the *F2* layer to avoid secondary maxima around *hmF2*. Depending on the parameters of the F1 layer, expressions (6) and (7) can be slightly modified.

The thickness parameters take different values for the bottom and top sides of each layer: BE_{bot} and BE_{top} for layer *E*, $\mathrm{B1_{bot}}$ and $\mathrm{B1_{top}}$ for layer F1, $\mathrm{B2_{bot}}$ for layer F2. Therefore, such layers are often referred to as semi-Epstein layers. In the NeQuick model, the height distribution *N* above the maximum of layer *F2* is also represented by a semi-Epstein layer, but the thickness parameter varies with height:

$$N_{\mathrm{top}}(h) = 4NmF2 \exp(z)/(1 + \exp(z))^2, \quad (9)$$

where

$$z = (h - hmF2)/H, \quad (10)$$

$$H = B2_{\mathrm{top}}\,[1 + r\,g\,(h - hmF2)/(r\,B2_{\mathrm{top}} + g\,(h - hmF2))] \quad (11)$$

и

$$r = 100, \ \ g = 0.125. \quad (12)$$

From these equations it can be seen that $\mathrm{B2_{top}}$ is the thickness parameter of the *F*2 layer near but above the maximum of this layer, where $H = \mathrm{B2_{(top)}}$. In the limit of high altitudes, the thickness parameter increases to $H = 101\mathrm{B2_{top}}$.

It can be seen from equations (2)-(12) that to obtain the full height distribution of electron concentration, it is necessary to set the parameters of the maxima of ionospheric layers and the thickness parameters of these layers. In the basic version of the NeQuick model these parameters are determined using the appropriate subroutines by the model input data: altitude, geographic latitude and longitude of the point, month of the year, world time and index *F10.*7 - the monthly average value of the solar radiation flux at the wavelength10.7 см , which is measured in 10^{-22}W/(m^2 Hz). The output of the model will be the concentration of electrons in a given month over a given location at a given world time. Note that in the NeQuick model, the parameters of the *F2* layer maximum are calculated from the ITU-R coefficients (formerly called CCIR coefficients) of the decomposition of the global distribution of the critical frequency *foF2* and the parameter *M*(3000)F2 by spherical Lejandre polynomials for each month of the year [Jones and Gallet, 1962; 1965]. In turn, such a calculation requires knowledge of the modified *modip* dipole latitude over a given point. Therefore, the NeQuick model contains 12 ITU-R coefficient files and a *modip* data file.

In the software implementation of the NeQuick model, there is a subroutine that allows one to calculate the total *TEC* electron content along a beam from one local point to another using electron concentration data. Here we consider only the variant of the vertical beam from the Earth's surface to the height20000 км , which approximately corresponds to the ground-based reception of a vertical signal from GPS or GLONASS navigation satellite systems:

$$VTEC_{\text{mod}} = \int N(h)\, dh, \quad (13)$$

where the integration is from the lower boundary of the ionosphere (usually65 km) to the height of .20000 км

3. APPROXIMATE FORMULA FOR *VTEC*

The NeQuick version 2 model is a development of the DGR model [Di Giovanni and Radicella, 1990]. The DGR model below the *F2* layer maximum uses equations that are similar in structure to equations (2)-(8), but forξ *(h)* = 1. Above the *F2* layer maximum, it is assumed that the thickness parameter is independent of height, i.e., H = $B2_{top}$ in the notations of equations (9)-(11). As a result, in the DGR model, the thickness parameters of layers *E*, F1 and *F2* below and above the maxima of these layers are independent of height. In this case, the integral (13) is calculated exactly, which gives an analytical formula for calculating *VTEC* through the parameters of maxima and thicknesses of ionospheric layers in the DGR model [Radicella and Zhang, 1995].

The analysis showed that the conditionξ *(h)* = 1 in equations (3) and (4) does not lead to a noticeable error in the calculation of *VTEC* by the NeQuick model for typical average conditions. In the NeQuick model, the dependence of the thickness parameter *H on* the height in the outer ionosphere is significant (see equations (9)-(12)). Nevertheless, approximating the contribution of the *F2* layer above the maximum of this layer to *VTEC* is proportional to the product (NmF2 $B2_{top}$) to the nearest constant multiplier, which depends on the coefficients *r* and *g* in equation (12). This allows us to obtain a simple analytical formula for *VTEC* by the NeQuick model, which depends only on the maximum parameters and the thicknesses of the layers *E*, F1 and *F2* and does not require the calculation of the integral (13):

$$VTEC_{sim} = 2[NmE^{*} (BE_{bot} + BE_{top}) + NmF1^{*} (B1_{bot} + B1_{top}) + + NmF2 (B2_{bot} + 1.75\ B2_{top})], \quad (14)$$

where electron concentration is measured in m^{-3}, thickness parameters are measured in m, *VTEC* is measured in m^{-2}.

In deriving this equation, it was assumed that the valueξ *(h)* = 1 (see equation (8)), i.e., the "damping" of layers *E* and F1 in the vicinity of the maximum of layer F2 can be neglected. The coefficient 1.75 was selected from the condition of minimal difference in *VTEC* calculations by equations (13) and (14). Using this coefficient, it is indirectly taken into account that in the outer ionosphere, on average, the thickness parameter of *the F2* layer is larger than near the maximum of this layer.

For estimates of the relative accuracy of formula (14), we use the deviation of $VTEC_{sim}$from $VTEC_{mod}$ in percent:

$$\delta VTEC = (VTEC_{sim} / VTEC_{mod} - 1) \cdot 100, \%, \quad (15)$$

Where $VTEC_{mod}$ is defined by equation (13). Consequently, the valueδ *VTEC* shows the relative deviation of *VTEC* according to the analytical approximation (14) from that obtained on the basis of numerical integration (13) for coincident heliogeophysical conditions.

Let us give examples of calculatingδ *VTEC* for typical average conditions. Figure 1 shows the daily variations of $VTEC_{sim}$, $VTEC_{mod}$, and δ *VTEC* at mid-latitudes (45° N, 45° E) for low (*F10*.7 = 75) and high (*F10*.7 = 175) solar activity in January (1), April (4), and July (7). In this figure, *VTEC* values are given in units of TECU = 10^{16} m^{-2}.

Fig. 1

From the data in Fig. 1, it can be seen that for all the cases given, the difference between $VTEC_{sim}$ and $VTEC_{mod}$ is less than 2% in absolute value. It can be seen that during daytime hours in Julyδ *VTEC* > 0, i.e., the analytical approximation (14) overestimates the *VTEC* values from the NeQuick model. During daytime hours in January, the analytical approximation (14) underestimates *VTEC* values: δ *VTEC* < 0.

Figure 2 shows the dependence of δ *VTEC* on geographic latitude at geographic longitude 45° E in January at noon (12 LT) and midnight (24 LT) for low (*F10.*7 = 75) and high (*F10.*7 = 175) solar activity.

Figure 2.

The data in this figure show that for all cases shown,δ *VTEC* is less than 2% in absolute value. At midnight δ *VTEC* < 0 at almost all latitudes except high latitudes in the Southern Hemisphere. At mid and high latitudes in the Northern Hemisphere in January, i.e., local winter, at noon δ *VTEC* < 0. At middle and high latitudes of the Southern Hemisphere in January, i.e. local summer, at noon δ *VTEC* > 0. The dependence of δ *VTEC* on the level of solar activity is practically absent at midnight, at noon there is a tendency to higher values of δ *VTEC* for relatively low levels of solar activity.

The data shown in Fig. 1 and Fig. 2 correspond to fixed values of the solar activity index. Fig. 3 shows the dependence of daily averages of δ *VTEC* values on *F10.*7 at mid-latitudes (45° N, 45° E) in January, April, and July for almost the entire recommended range of *F10.*7 variations in the NeQuick model: 63-193. For *F10.*7 > 193, the software implementation of the model gives a warning and sets *F10.*7 = 193. From the data in this figure, it can be seen that the absolute value ofδ *VTEC* is minimum for summer, maximum for winter, and less than 1.2% for all seasons. For the conditions considered, δ *VTEC* < 0. The analytical formula (14) was selected so that on average the error of this formula is minimal, so for specific conditions this error may be of a certain sign.

Fig. 3.

In general, the data in these figures show that the approximation (14) underestimates *VTEC* local winter and overestimates *VTEC* local summer during daytime hours. Nevertheless, for all cases considered, the difference between the *VTEC* values calculated using equations (13) and (14) is less than 2% in absolute value.

4. DISCUSSION

The simple formula (14) was obtained for the satellite altitude of 20000 km. It is also applicable for the altitude interval 10000-30000 km and higher. For example, for April at noon at high solar activity (*F10.*7 = 175) at mid-latitudes for satellite altitudes 10000, 20000 and 30000 km, the value ofδ *VTEC* is equal to 0.37, -0.27 and -0.28%. This is due to the very weak dependence of *VTEC* on altitude at the considered altitudes: according to the NeQuick model, the *VTEC* value is equal to 50.43, 50.76, and 50.82 (in TECU = 10^{16} m^{-2}). For low-orbit satellites (500-1000 km), the dependence of *TEC* on the satellite altitude is significant: for the considered conditions and satellite altitudes of 500, 750, and 1000 km, the *VTEC* values are 34, 43, and 46 (in TECU) according to the NeQuick model. Therefore, obtaining an analytical formula for *VTEC* for low-orbit satellites requires special consideration because of the need to explicitly take into account the dependence of the coefficient at $B2_{top}$ on the satellite height *h* and *hmF2*, more precisely, on the difference between *h* and hmF2. This is beyond the scope of this paper.

The simple formula (14) allows us to visualize the contribution of the *E* and F1 layers to the *VTEC*. For this purpose, we use the ratio in percent:

$$REL\_TEC = [(VTEC_E + VTEC_{F1})/VTEC_{sim}]\cdot 100, \qquad (16)$$

Where

$$VTEC_E + VTEC_{F1} = 2[NmE^{*}(BE_{bot} + BE_{top}) + NmF1^{*}(B1_{bot} + B1_{(top)})],$$

the value of $VTEC_{sim}$ is determined by equation (14).

In Fig. 4 shows the dependences of REL_ *TEC* on geographic latitude at longitude 45° E in January at noon (12 LT) and midnight (24 LT) for low (*F10*.7 = 75) and high (*F10*.7 = 175) solar activity.

Fig. 4.

Figure 4 shows that at mid and low latitudes at midnight the contribution of layers *E* and F1 to *VTEC is* less than 4%, with a general tendency for this contribution to decrease with increasing solar activity index. At noon, the contribution of these layers to *VTEC* is much larger and reaches 10-15% in local summer at middle and high latitudes.

It should be noted that the above estimates are valid only for the NeQuick model, which gives the median electron concentration and has its own shortcomings. Among other things, it does not take into account the peculiarities of the auroral ionosphere, and the plasmasphere is taken into account in an approximate, rather qualitative way. Therefore, for example, the relative contribution of layers *E* and F1 to *VTEC* according to the model can significantly differ from the real contribution for specific conditions.

Comparing the data in Fig. 3 and Fig. 4, it can be seen that they are similar in many respects but differ significantly in magnitude. For example, in local summer at midday at mid and high latitudesδ *VTEC* and *REL_TEC* reach their maximum values, butδ *VTEC* is about an order of magnitude smaller than *REL_TEC* for these conditions. Consequently, insignificant (less than 2%) differences in *VTEC* values by the simple formula (14) and by the NeQuick model are mainly due to the conditionξ *(h)* = 1 (see equation (8)) in deriving formula (14). The value ofδ *VTEC* depends on the heliogeophysical conditions, which gives ways to refine formula (14). Nevertheless, the achieved accuracy of formula (14) seems to be sufficient at this stage.

The convenience and high speed of calculating the electron concentration *N* by the NeQuick model seems to have been the main reason for the popularity of the model for practical applications. One such application has been the NeQuick-G model [European Commission, 2016], which is used as a Galileo operational model that provides ionospheric error information to single-frequency users. For this purpose, the NeQuick model replaces the *F10*.7 index with the effective solar activity index *Az*, which depends on the modified geomagnetic latitude (*modip*) in the form of a polynomial

$$Az = a_0 + a_1\, modip + a_2\, (modip)^2, \qquad (17)$$

whose coefficients are transmitted by the Galileo navigation message [European Commission, 2016]. These coefficients are determined from the condition of minimizing the error of calculating the slant *TEC* by the NeQuick-G model compared to the observations obtained with the Galileo ground receiver network [Angrisano et al., 2013; European Commission, 2016]. The simple formula (14) for calculating *VTEC* can be used and for the NeQuick-G model if the coefficients of the polynomial (17) are known. For this purpose, it is enough to replace *F10*.7 by *Az* in the NeQuick model. However, the accuracy of formula (14) for *VTEC* by the NeQuick-G model should be evaluated separately, since the range of possible values for *Az is* larger than for *F10*.7 [European Commission, 2016].

Another application of NeQuick is related to new estimates of the outer ionospheric parameters $B2_{top}$, *r* and *g* in equations (11) and (12) [Themens et al., 2018; Pezzopane et al., 2024]. For example, using data from five low-orbit satellites (COSMIC/FORMOSAT-3, GRACE, METOP, TerraSAR-X, and Swarm), it was obtained that the coefficient $g = 0.14$ (or 0.15), i.e., it is larger than in the NeQuick model, where $g = 0.125$ (see (12)). Estimates of the coefficient *r* in equation (12) from low-orbit satellite data are difficult because this coefficient becomes important above typical low-orbit satellite orbits [Pignalberi et al., 2020]. Note that changes in the coefficients *r* and *g* in equations (9)-(12) will lead to changes in the value of the coefficient 1.75 in formula (14).

These examples show that there are several ways to refine and develop the NeQuick model. Formula (14) can also be refined. However, even in this form it can be useful for *VTEC* research because of its simplicity and clarity.

5. CONCLUSIONS

Based on the analysis of the NeQuick model, a simple formula for calculating the vertical total electron content of *VTEC* from the parameter data of the *E*, F1, and *F2* layer maxima in this model is presented. It is obtained that the error of this formula does not exceed 2% in comparison with a more accurate variant of the problem solution - obtaining *VTEC* as an integral of the electron concentration by the NeQuick model along the vertical ray from the ionospheric base to about20000 км . The magnitude of this error varies with local time, season, and latitude, indicating that the presented formula can be further refined.

ACKNOWLEDGEMENTS

The computer program (NeQuick2 P.531-12 electron density model) was implemented at the Laboratory of Aeronomy and Radio Wave Propagation of the Abdus Salam International Center for Theoretical Physics, Trieste, Italy. The Aeronomy and Radiopropagation Laboratory of the Abdus Salam International Center for Theoretical Physics, Trieste, Italy.

FUNDING

The research was supported by the Program of Fundamental Scientific Research in the Russian Federation on the topic: "Study of Solar Activity and Physical Processes in the Sun-Earth System" (№ 1021100714181-3).

CONFLICT OF INTERESTS

The author declares no conflict of interest.

REFERENCES

1. *Afraimovich E. L., Astafyeva E.I., Demyanov V.V. et al*. A review of GPS/GLONASS studies of the ionospheric response to natural and anthropogenic processes and phenomena // J. Space Weather Spac. V. 3. ID A27. 2013. https://doi.org/10.1051/swsc/2013049

2. *Angrisano A., Gaglione S., Gioia C., Massaro M., Robustelli U*. Assessment of NeQuick ionospheric model for Galileo single-frequency users // Acta Geophys. V. 61. № 6. P. 1457–1476. 2013. https://doi.org/10.2478/s11600-013-0116-2

3. *Aragon-Angel A., Zürn M., Rovira-Garcia A*. Galileo ionospheric correction algorithm: An optimization study of NeQuick-G // Radio Sci. V. 54. № 11. P. 1156–1169. 2019. https://doi.org/10.1029/2019RS006875.

4. *Bilitza D., Pezzopane M., Truhlik V., Altadill D., Reinisch B. W., Pignalberi A*. The International Reference Ionosphere model: A review and description of an ionospheric benchmark // Rev. Geophysics. V. 60. № 4. ID e2022RG000792. 2022. https://doi.org/10.1029/2022RG000792

5. *Di Giovanni G., Radicella S.M.* An analytical model of the electron density profile in the ionosphere // Adv. Space Res. V. 10. № 11. P. 27–30. 1990. https://doi.org/10.1016/0273-1177(90)90301-F
6. *European Commission*. European GNSS (Galileo) open service – ionospheric correction algorithm for Galileo single frequency users. Issue 1.2. 2016. https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_Ionospheric_Model.pdf
7. *Gulyaeva T., Bilitza D.* Towards ISO standard earth ionosphere and plasmasphere model / New Developments in the Standard Model. Ed. Larsen R.J. Ch. 1. London: Nova Science Publishers Inc. P. 1–39. 2012. ISBN 978-1-61209-989-7
8. *Hoque M.M.*, *Jakowski N.*, *Prol F.S.* A new climatological electron density model for supporting space weather services // J. Space Weather Spac. V. 12. ID 1. 2022. https://doi.org/10.1051/swsc/2021044
9. *Hofmann-Wellenhof B., Lichtenegger H., Wasle E.* GNSS–global navigation satellite systems: GPS, GLONASS, Galileo, and more. Wien: Springer-Verlag, 516 p. 2008. https://doi.org/10.1007/978-3-211-73017-1
10. *ITU*. Ionospheric propagation data and prediction methods required for the design of satellite services and systems. Recommendation P. 531-12, Geneva. 2013.
11. *Jones W.B., Gallet R.M.* The representation of diurnal and geographic variations of ionospheric data by numerical methods // Telecommun. J. V. 29. № 5. P. 129–149. 1962.
12. *Jones W.B., Gallet R.M.* The representation of diurnal and geographic variations of ionospheric data by numerical methods. 2 // Telecommun. J. V. 32. № 1. P. 18–28. 1965.
13. *Nava B., Coisson P., Radicella S.M.* A new version of the NeQuick ionosphere electron density model // J. Atmos. Sol.-Terr. Phy. V. 70. № 15. P. 1856–1862. 2008. https://doi.org/10.1016/j.jastp.2008.01.015
14. *Pezzopane M., Pignalberi A., Pietrella M., Haralambous H., Prol F., Nava B., Smirnov A., Xiong C.* An update of the NeQuick-Corr topside ionosphere modeling based on new datasets // Atmosphere. V. 15. № 4. ID 498. 2024. https://doi.org/10.3390/atmos15040498
15. *Pignalberi A., Pezzopane M., Themens D.R., Haralambous H., Nava B., Coisson P.* On the analytical description of the topside ionosphere by NeQuick: Modeling the scale height through COSMIC/FORMOSAT-3 selected data // IEEE J-STARS. V 13. P. 1867−1878. 2020. https://doi.org/10.1109/JSTARS.2020.2986683
16. *Radicella S.M., Zhang M.-L.* The improved DGR analytical model of electron density height profile and total electron content in the ionosphere // Ann. Geophys. – Italy. V. 38. № 1. P. 35−41. 1995. https://doi.org/10.4401/ag-4130

17. *Rawer K.* Replacement of the present sub-peak plasma density profile by a unique expression // Adv. Space Res. V. 2. № 10. P. 183–190. 1982. https://doi.org/10.1016/0273-1177(82)90387-8
18. *Themens D.R., Jayachandran P.T., Bilitza D., Erickson P.J., Häggström I., Lyashenko M.V., Reid B., Varney R.H., Pustovalova L.* Topside electron density representations for middle and high latitudes: A topside parameterization for E-CHAIM based on the NeQuick // J. Geophys. Res. – Space. V. 123. № 2. P. 1603–1617. 2018. https://doi.org/10.1002/2017JA024817

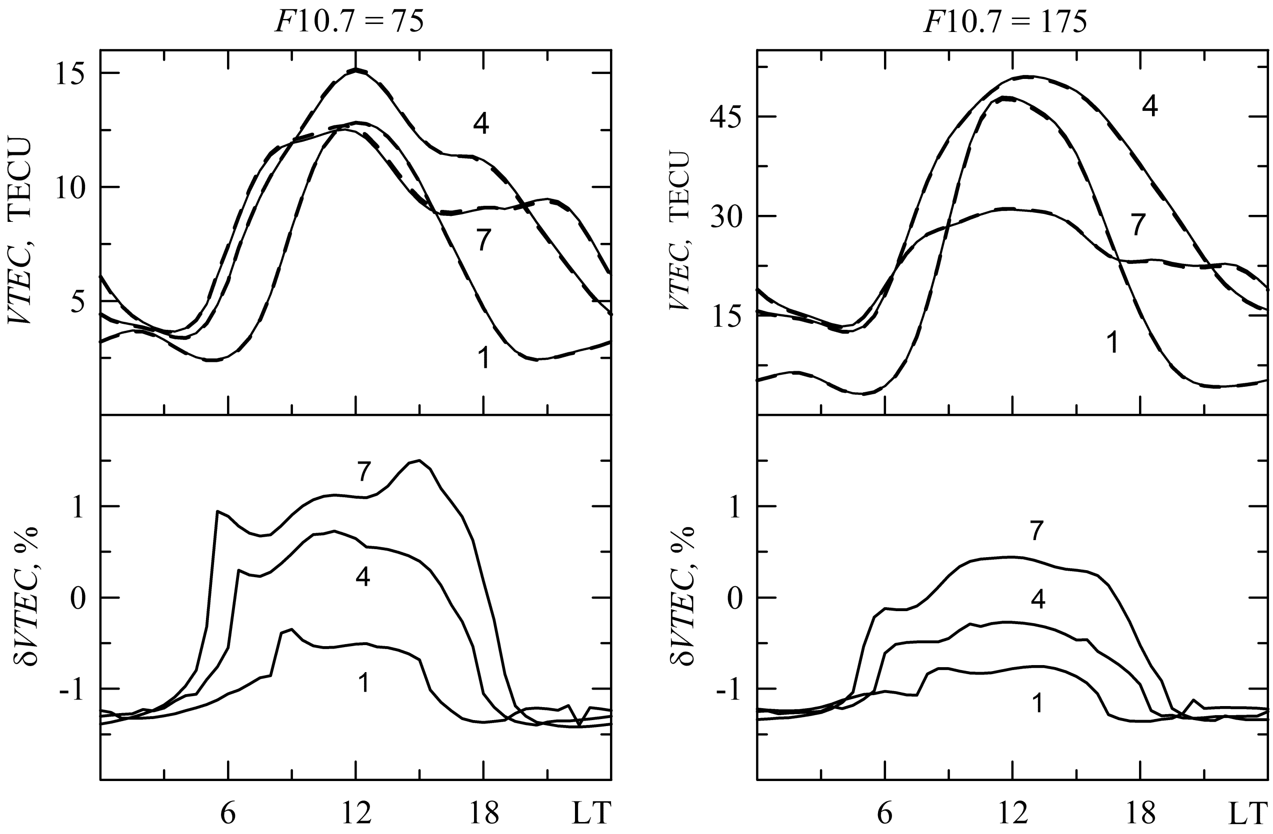
FIGURE CAPTIONS

Fig. 1. Daily *VTEC* variations (by formula (14) - solid lines and by NeQuick model - dashed lines) and δ *VTEC* at mid-latitudes (45° N, 45° E) for low (*F10*.7 = 75) and high (*F10*.7 = 175) solar activity in January (1), April (4), and July (7).

Fig. 2. Dependences of δ *VTEC* using equation (15) on geographic latitude at geographic longitude 45° E at noon and midnight in January (solid and dashed lines) for low (*F10*.7 = 75) and high (*F10*.7 = 175) solar activity.

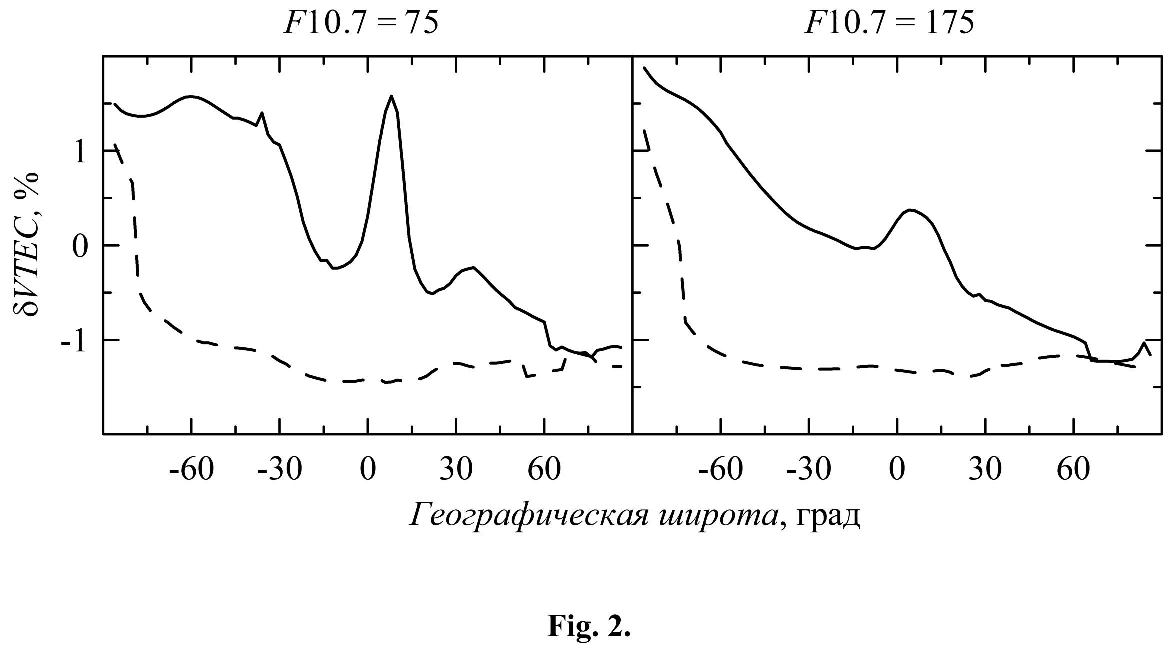
Fig. 3. Dependences of daily averages of δ *VTEC* values on the solar activity index *F10*.7 at mid-latitudes (45° N, 45° E) in January (1), April (4), and July (7).

Fig. 4. Dependences of REL_ *TEC*, the relative contribution of *E* and F1 layers to *VTEC*, on geographic latitude at longitude 45° E in January at noon and midnight (solid and dashed lines) for low (*F10*.7 = 75) and high (*F10*.7 = 175) solar activity.



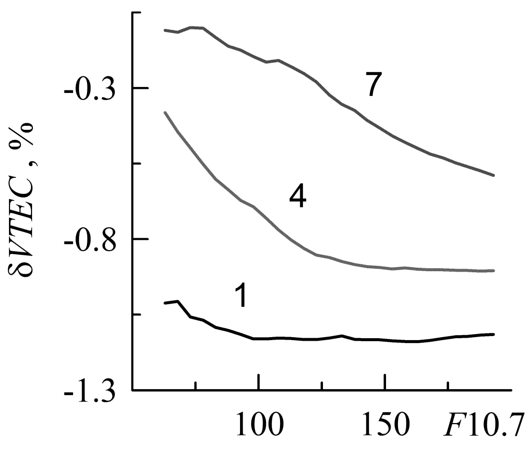
F10.7 = 75
F10.7 = 175
VTEC, TECU
δVTEC, %
15
10
5
45
30
15
1
0
-1
4
7
1
6
12
18
LT

Fig. 1.



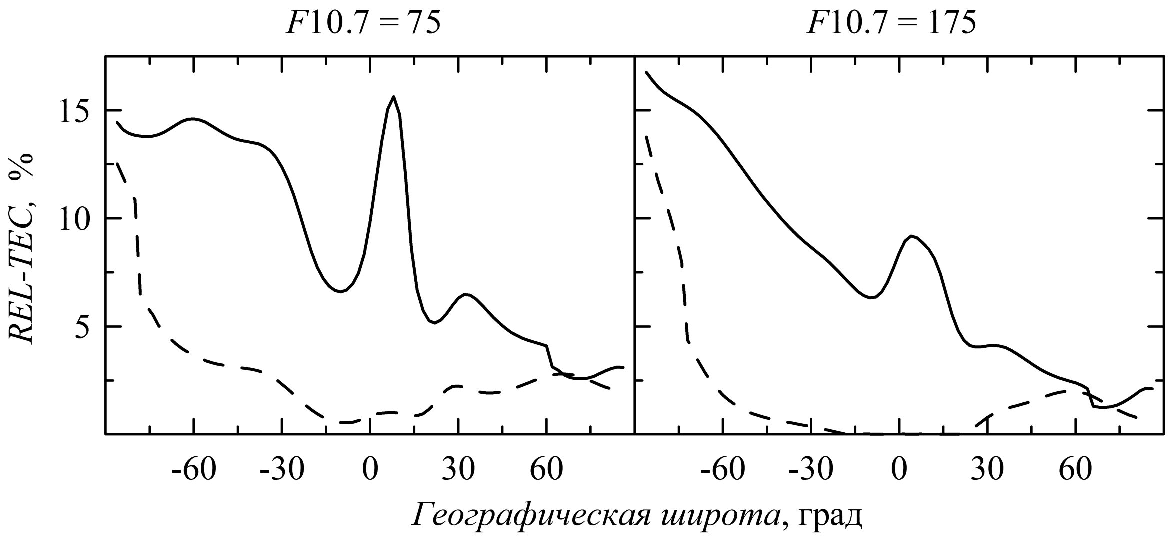
F10.7 = 75
F10.7 = 175
δVTEC, %
1
0
-1
-60
-30
0
30
60
Географическая широта, град

Fig. 2.



-0.3
-0.8
-1.3
δVTEC , %
7
4
1
100
150
F10.7

Fig. 3.



F10.7 = 75
F10.7 = 175
REL-TEC, %
15
10
5
-60
-30
0
30
60
Географическая широта, град

Fig. 4.