УДК.550.388.2

Global first-principal 3D modeling of the TEC and its comparison with GPS measurements

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Аннотация. В работе представлены глобальные расчеты полного электронного содержания (*ПЭС*), полученные с помощью глобальной самосогласованной модели термосферы, ионосферы и протоносферы (ГСМ ТИП), разработанной в Западном Отделении ИЗМИРАН. Модель позволяет рассчитывать основные параметры околоземной среды в области высот от 80 км до 15 земных радиусов и, таким образом, является удобным инструментом для расчетов *ПЭС*. Представлены результаты расчетов *ПЭС*, полученные интегрированием в области высот 80-1000 км и выполнено сравнение с эмпирической моделью IRI для различных сезонов при низкой солнечной активности в спокойных геомагнитных условиях. Также смоделированы параметры группировки спутников GPS, и сделано сравнение модельных значений *ПЭС* с "*GPS*" модельными *ПЭС*, рассчитанными вдоль радиолучей от пункта наблюдения до видимых спутников.

Abstract. In this study the Global Self-consistent Model of the Thermosphere, Ionosphere and Protonosphere (GSM TIP) has been used to calculate the Total Electron Content (*TEC*). The GSM TIP model was developed in the West Department of IZMIRAN of the Russian Academy of Science. For the given input data the model calculates the time-dependent global 3D structure of the temperature, composition (O_2, N_2, O), and vector velocity of the neutral atmosphere and the densities, temperatures, and vector velocities of atomic (O^+, H^+) and molecular ions and 2D distribution of the electric field potential of both dynamo and magnetospheric origin. The distributions of these ionospheric parameters in the near Earth's space have been obtained at altitudes from 80 km up to 15 Earth radii. We present the results of the model calculations of the *TEC* and their comparison with empirical model for the different seasons of the low solar activity in quiet geomagnetic conditions. We also generate a model constellation of GPS satellites and make comparison of the model exact vertical *TEC* with "GPS" *TEC*, calculated using *TEC* along radio rays for visible satellites.

1. Introduction

In the few years the great interest has been expressed to the investigation of the *TEC* in the upper ionosphere in the global scale. It was connected with intensive progress of the space geodesy and satellite telecommunication activities. The GPS is a valuable tool for global measurements of the ionospheric *TEC* and using these data the worldwide *TEC* distribution may be obtained (*Jakowski et al.*, 2002; *Klobuchar*, 1997; *Hernandez et al.*, 1999). All the above have affected in the further modification of the IRI-model (*Bilitza*, 1992; 1994). At present the IRI model includes an approximate representation for the *TEC* up to 1000 km and also gives T_e and T_i at heights of above h_mF2. However, the altitudinal and temporal profiles of the T_e and T_i can be unrealistic (*Su et al.*, 1995; *Titheridge*, 1998). This may introduce the errors into calculations of the plasma height scale and hence in the estimation of *TEC*. This problem need be solved in the near future. But already now these additional features (*TEC*, T_e, T_i) make the IRI an attractive model for comparison with "in situ" experimental data as well as theoretical first-principal models.

Mathematical models have been played an important role in the development of our present-day understanding of the physical and chemical processes that take place within the Earth's upper atmosphere. The study of the ionosphere and thermosphere physics and indeed near-Earth space sciences, as we see above, has transited from local and regional investigations to global scale studies that require self-consistent solutions to the energetic and dynamics of the entire system. In the present study we used the model, which has been developed in the WD IZMIRAN (*Namgaladze et al.*, 1988; 1991) and applicable to the description of the N_e, T_e, T_i and other ionospheric parameters for the upper ionosphere and plasmasphere in the global scale. We have calculated *TEC* for the quiet geomagnetic conditions up to 1000 km altitude for all seasons of low solar activity ($F_{10.7} = 75$) with using our Global Self-consistent Model of Thermosphere, Ionosphere and Protonosphere (further GSM TIP) and IRI, and have made comparison between them in the global scale. In this special study we focus on *TEC* calculated from 80 km up to the height of 1000 km in order to see the perspectives for solving some problems of the construction of the *TEC* global model in the topside ionosphere.

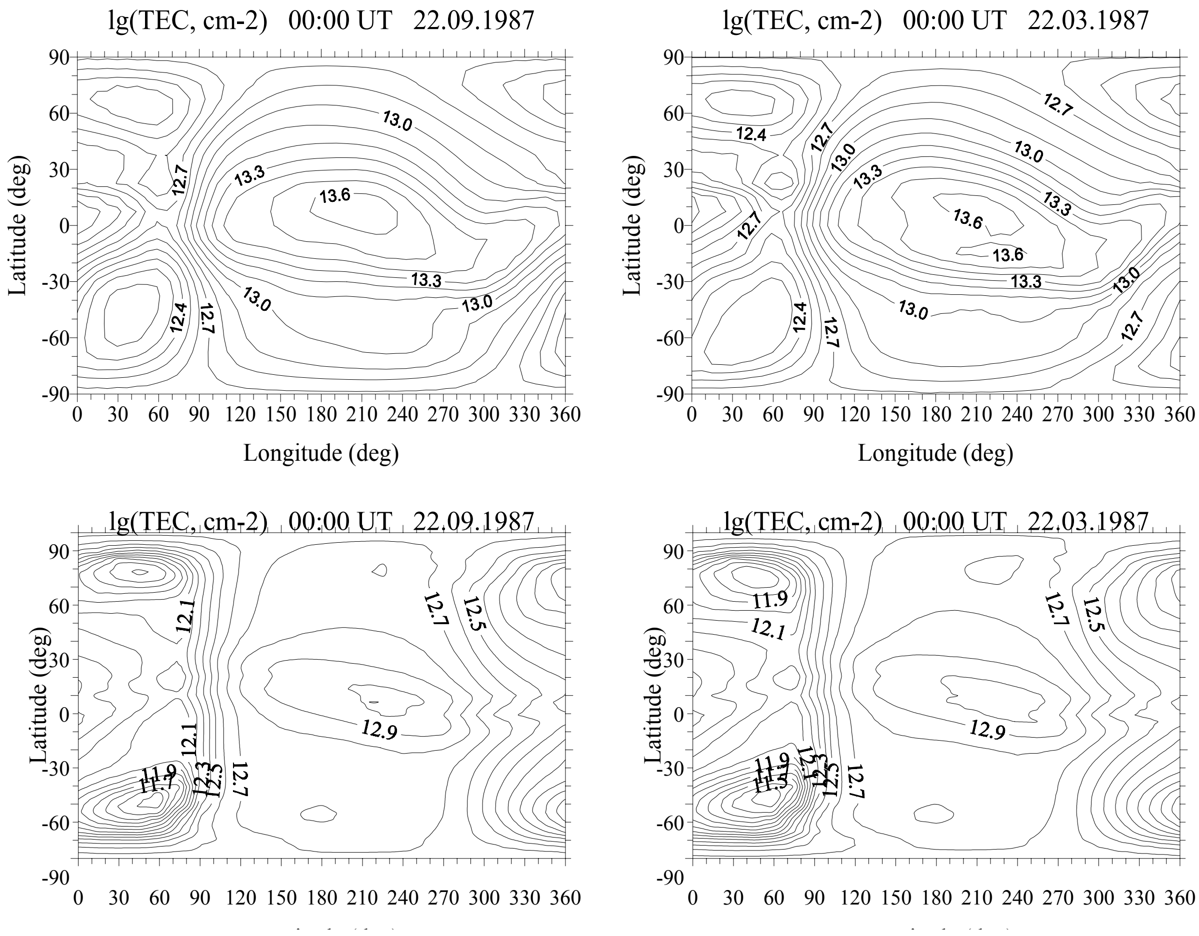

Fig. 1

2. Brief GSM TIP description

For the given input data the model GSM TIP calculates the time-dependent global 3D structure of the temperature, composition (O_2, N_2, O), and vector velocity of the neutral atmosphere and the densities, temperatures, and vector velocities of atomic (O^+, H^+) and molecular ions and 2D distribution of the electric field potential both of dynamo and magnetospheric origin.

The solution is performed numerically on a global grid with resolutions of 5° in latitude and 15º in longitude in spherical geomagnetic coordinate system. In the vertical dimension, the thermospheric code uses 30 grid points between 80 and 520 km altitude above the Earth's surface. The ionospheric part of the code (F2 region and upper ionosphere) has variable spatial steps along the geomagnetic field lines from a base altitude of 175 km to a maximum distance of 15 Earth's radii. Note here that ionospheric code does not need the upper boundary conditions.

Model inputs are: 1. the solar UV and EUV spectra, 2. the precipitating electron fluxes, and 3. the distribution of the field-aligned currents of the first and second zones.

The model has been described in detail in (*Namgaladze et al.*, 1988; 1991) and its application has been presented in the papers (*Korenkov et al.*, 1996; 1998).

It should be particularly emphasized that in this study we have used the method of numerical calculation of the electric field another than it was presented in our papers mentioned above, in which the 3D equation of the current density conservation was solved by reducing this equation to the 2D form taking an integral over the thickness of the ionospheric current-conducting layer along height in the geomagnetic spherical coordinate system using the thin shell dynamo model. In this paper the transition from 3D model equation to 2D form has been obtained by integrating one along the geomagnetic field lines (*Klimenko et al.*, 2006).

3. Main input data and boundary conditions

The GSM TIP model requires the following key inputs: 1. the values of field-aligned currents (FACs) of the first zone ($5 \cdot 10^{-8}$ A/m^2) and second zone ($3 \cdot 10^{-8}$ A/m^2) for all seasons; 2. in both hemispheres we have auroral oval electron precipitations with the characteristic energy of 3 keV, and soft electron flux (0.2 keV) in the cusp region; 3. solar EUV fluxes were constructed using the model by *Nusinov* (1984) and UV fluxes are as by *Mount and Rottman* (1983) data. For the calculation of the thermospheric parameters the lower boundary conditions were predefined and the upper boundary condition is a diffusive equilibrium for the neutral composition. The lower boundary condition assumes a photochemical equilibrium for the ion composition. More detailed description of the initial and boundary conditions can be found in (*Korenkov et al*., 1998).

4. Results and discussion

Results of our calculations for the global maps are presented in Fig. 1, 2 in the geographic Cartesian coordinate system. In all figures the results of the calculations using the IRI model are shown at the top panels, and calculations obtained using the GSM TIP – at the bottom panels. The comparison may be made between models to illustrate the GSM TIP and IRI current capabilities.

Figures 1, 2 show the global distributions of lg (TEC, cm^{-2}) at low solar activity for four seasons: spring and autumn (Fig. 1) and winter and summer (Fig. 2).

The comparison of the appropriate panels in Fig. 1 (top and bottom in the left, and top and bottom in the right) shows a good qualitative agreement. The quantitative analysis shows some discrepancies between the models. The GSM TIP gives more lower values of the TEC then the IRI as a whole with the exception of the high latitude regions, where TEC for both models are practically coincides. Fig. 2 illustrates the same as Fig. 1 but for winter (in the left) and summer (in the right). From these panels it is obvious that the GSM TIP underestimates TEC especial at night, but the TEC values in the summer polar region are larger then the TEC obtained from the IRI. It may be noted that the equatorial anomaly is very weak in both models for the low solar activity.

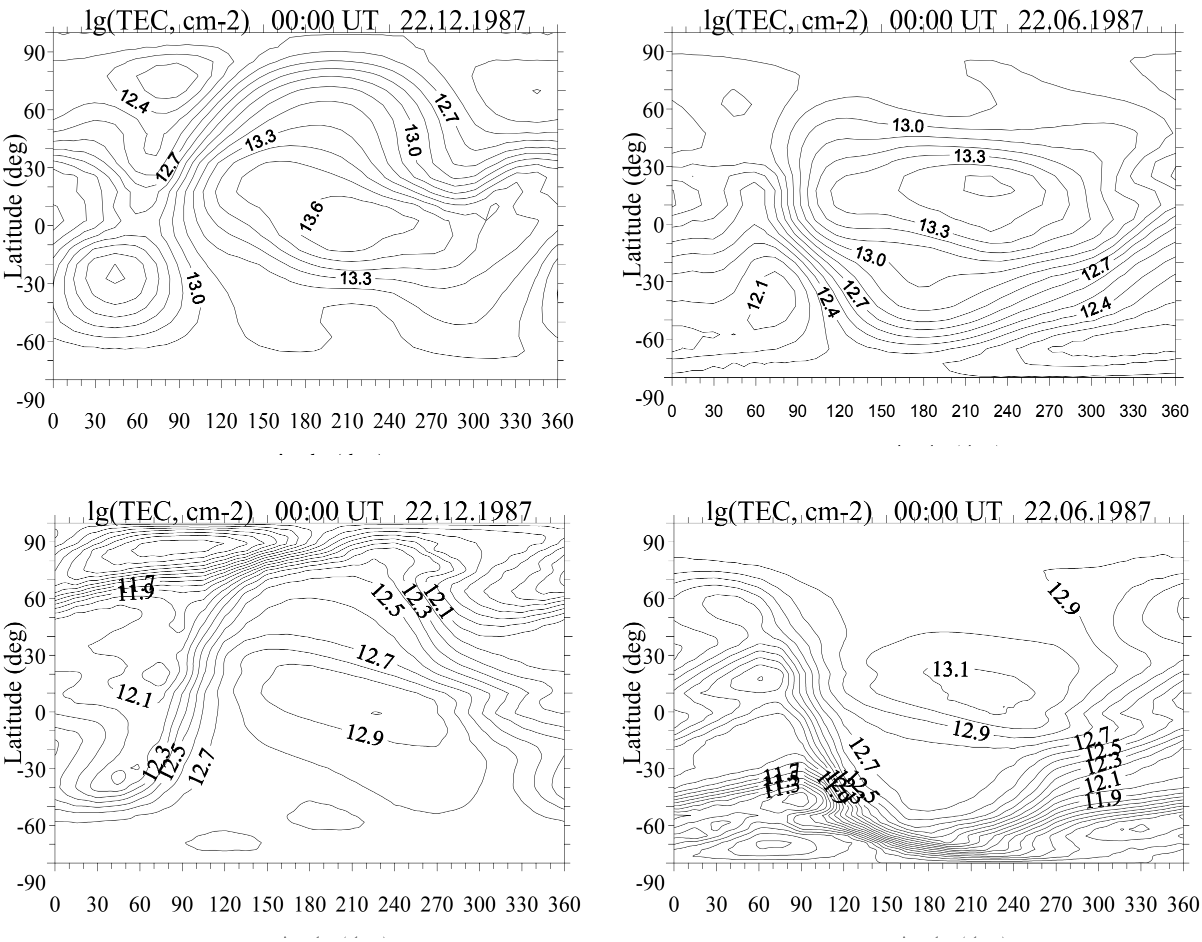

Fig. 2

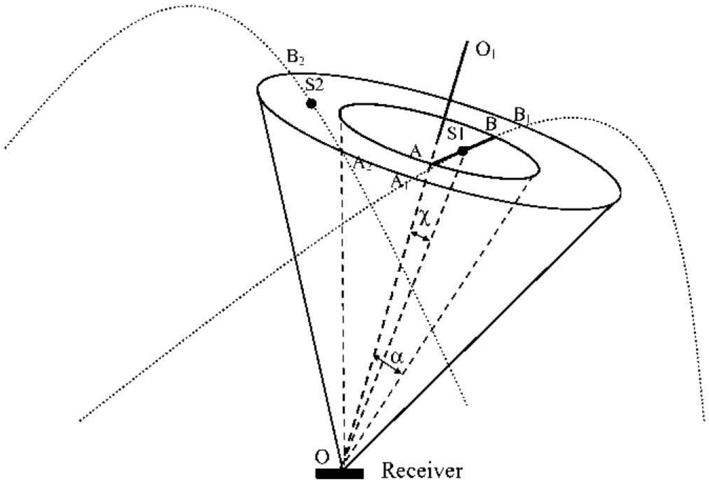

Fig. 3

Fig. 3 shows a schematic picture of the satellite observations geometry. One can see that at small view angles (α) only one satellite S_1 would be observed and its signals would be received only during its motion along the stretch of path AB. With an increase of the α angle the other satellites are falling down into the field of view of the receiver (for example, the stretch of path of S_2 satellite A_2B_2) and the observation time of the S_1 satellite increases (the stretch of path A_1B_1).

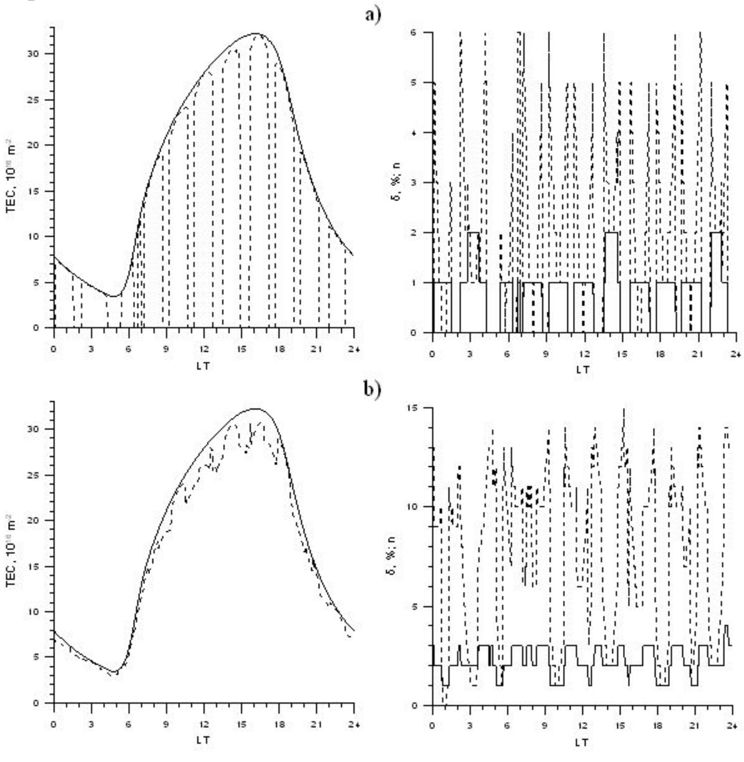

Fig. 4

Diurnal variations in "exact" *TEC*, satellite *TEC*, and also relative errors are shown in Fig. 4 for Kaliningrad station (55° N, 20° E). The left panels show diurnal variations of *TEC* in the TECU units. The right panels show the modulus of the relative error in percents (dashed curves) and the number of observed satellites (solid curves) for various angles of the view cone of the receiver: a) 20°, b) 40°.

5. Conclusion

In this study we have presented the global distributions of the *TEC* obtained using the first principal model GSM TIP and empirical model IRI for all seasons of low level solar activity ($F_{10.7}$ = 75) in quiet geomagnetic conditions. The comparison between calculation results of the models has shown that the theoretical model GSM TIP gives the smaller values of the *TEC* then the IRI model in all cases. However, the influence of the auroral precipitation and magnetospheric convection is more noticeable in the GSM TIP. In this paper we have presented the model simulations of *TEC* along the radio ray between the receiver and satellite with the following determination of the vertical *TEC* and "true model" *TEC* calculated using the Global Self-consistent Model of the Thermosphere, Ionosphere and Protonosphere. The errors of the quasi-experimental method of *TEC* determination have been studied for two view angles of the receiving device during day for the Kaliningrad station of the European region.

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