Validation of new ionospheric parameter modeling

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Abstract: - The growing role of the total electron content (TEC) of the ionosphere to provide information for various technical systems and to study the ionospheric environment requires the creation of models of this parameter. Such models are constantly being developed and need to be tested. In this paper, new models of two types are validated, which are the most accessible. These two types are: 1) empirical models, 2) models determining TEC by integration of model N(h)-profile using the empirical values of the critical frequency foF2 and the height of the peak hmF2. Results are presented for two models of the first type (the Taiwan (TW) and the Neustrelitz Global Model (NGM)) and one model of the second type (the IRI-Plas version of the International Reference Ionosphere (IRI)). Since no model can give equally good results for all the geographical and geophysical conditions, testing should specify such conditions under which a particular model may provide the best fit to the experimental data. It is shown that all the models in most cases provide a better estimate of the ionospheric delay than the Klobuchar’s model traditionally used in single-frequency receivers. The TW approach is preferable to the NGM model. The NGM model is preferred for equatorial regions. The model of an equivalent slab thickness of the ionosphere τ(NGM) can serve as an empirical model of τ, therefore, be used to determine foF2, corresponding to experimental values of TEC. The IRI-Plas model gives in most cases better results than the previous versions of IRI. It provides the N(h)-profiles that correspond to additional experimental data better than profiles of IRI.

Key-Words: - Ionosphere, Modeling, Positioning, Total Electron Content, Satellite measurement

1 Introduction

The ionosphere plays an important role because of its effect on the propagation of waves of different ranges. In paper [1] are identified two categories of systems related to conditions in the ionosphere. Systems that depend on the parameters of the ionosphere include: VLF-LF communication and navigation, MF and HF communication, HF broadcasting ("short-wave" listening), OTH radar surveillance, HFDF and HF SIGINT. The systems, which are exposed to the ionosphere, include: satellite communication, satellite navigation (e.g., GPS & GLONASS), space-based radar and imaging, terrestrial radar surveillance and tracking, meteor-burst communications, and others. For many applications, particularly in the first category, it is sufficient knowledge of such parameters of the ionosphere, as the critical frequency foF2 and the height of the peak hmF2. Operation of systems of the second category requires knowledge of another parameter - the total electron content (TEC) of the ionosphere. This parameter is becoming basic because it does not only characterize the state of the ionosphere and plasmasphere but can determine the space weather by a much greater extent than foF2 and hmF2. As is known, the most significant space weather effects occur during severe disturbances. A detailed recent review of these effects and their impact on existing systems is given in [2]. Extreme disturbances described in [2] are rare, but more frequent moderate perturbations can lead to large deviations from the mean state. To account for these variations, it is necessary to know the average state. It is determined by statistical methods, and is described by empirical models. The aim of the present paper is to test new models by means of comparison with experimental data. The focus is on setting the TEC, so are identified two approaches: 1) purely empirical models, 2) the integration of the model N(h)-profile using the empirical values of parameters foF2 and hmF2. A detailed review of the existing empirical models of the TEC is given in [3]. It is shown that most of the existing models are: 1) based on the expansion of empirical orthogonal components, 2) regional models. The authors do not
give the actual values of these components and the corresponding coefficients. In addition, there is a certain difficulty in forecasting parameters out of bounds of the temporal boundaries of the data used, so this paper focuses on accessible new models [4-5]. The authors [4-5] have tested their models, but it is not enough to measure quantitative compliance. Results obtained in the present study show that there are difficulties for this type of models. Under the second approach also a breakthrough was made - a new version of the IRI model (IRI-Plas). This model is also tested with the experimental data as an alternative to the first approach.

2 The experimental data
From the huge set of existing experimental data of the TEC, the values of global maps JPL, CODE, UPC, ESA are used which are calculated from the IONEX files (ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/) for a given station, coordinates and time. The other parameters were taken from the ionospheric part of SPIDR database (http://spidr.ngdc.noaa.gov/spidr/index.jsp). Experimental and model values are compared by means of absolute (Δ, TECU) and absolute (σ, TECU) and relative (σ, %) standard deviations.

3 The empirical TW model and its agreement with experimental data
Most empirical models of TEC of the new generation are statistical. In [4] are examined several models based on approximation of experimental data by certain functions. The models were developed for a single point (Taiwan: 24N, 120E) using biases of the global JPL map. Data were chosen from 1998 to 2007 for quiet geomagnetic conditions (Dst> -30 nT). The input parameters are the local time (LT), day of the year (DOY), the index of solar activity (F10.7 or EUV). Since the choice of the best index of their huge number is not obvious, the authors [4] investigated the effect of this choice on the final result. A set of indices included average F10.7 and EUV for the period from 1 to 162 days. The most accurate matching model was daily EUV. It provided the standard deviation of RMS = 9.2TECU compared with a 15-day moving medians with their RMS = 10.4TECU and evaluation for IRI2007 according to NeQuick RMS = 14.7TECU. The daily index values of EUV (0.1-50 nm) obtained by Solar Heliospheric Observatory were taken at http://www.usc.edu/dept/space_science/semdatafolder/long/daily_avg/. Functions are based on the analysis of daily, seasonal, annual and longer variations of the TEC. As a result of analysis, variations were observed in periods of 6, 8, 12 and 24 hours with a dominant period of 24 hours. Synodic period conditioning solar variation index is about 27 days and was clearly detected in the spectrum of variations in the TEC, as well as variations in the semi- 183 days, annual (332 days) and longer (609 days). TEC is the product of 3 functions of 3 parameters (F = daily EUV, DOY and LT). For a function describing solar activity, a cubic approximation is used. Factor determining the seasonal dependence includes 3 harmonics. Multiplier of daily course includes 4 harmonics. DOY parameter is normalized to the number of days in the year. TEC parameter is given by:

$$TEC(F, DOY, LT) = f(F) \cdot g(DOY) \cdot h(LT) = \sum_{i,j,k} a_{ij} \cdot b_{ij} \cdot c_{jk} = \sum_{n=1}^{32} \alpha_n TEC_n$$

The coefficients αn are given in the table of [4]. Examples of matching model and experimental values are shown in Fig. 1 for conditions near the maximum of solar activity (2002).

![Fig. 1. Comparison of model and experimental TEC for the TW model near the maximum of solar activity](image)

Seasonal dependence of TEC is perfectly visible at a given latitude and full compliance for the autumn and winter months. In spring and summer, the model underestimates the values. Fig. 2 shows results for conditions near the minimum of solar activity.
It is seen that the values of the TEC may be 2-3 times less than during the maximum solar activity. The model can both underestimate and overestimate the experimental values. The range of the absolute deviation was 1-10 TECU. Absolute and relative standard deviations are presented in Table 1 for four months of three years.

Table 1. Absolute and relative standard deviations of the TW model

<table>
<thead>
<tr>
<th>Year</th>
<th>Mar</th>
<th>Jun</th>
<th>Sep</th>
<th>Dec</th>
<th>σ, TECU</th>
<th>σ, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>13.5</td>
<td>8.0</td>
<td>3.5</td>
<td>4.0</td>
<td>15.8</td>
<td>17.2</td>
</tr>
<tr>
<td>2006</td>
<td>3.0</td>
<td>1.7</td>
<td>2.6</td>
<td>2.2</td>
<td>14.7</td>
<td>9.5</td>
</tr>
<tr>
<td>2010</td>
<td>5.6</td>
<td>2.8</td>
<td>5.9</td>
<td>5.6</td>
<td>24.3</td>
<td>16.2</td>
</tr>
</tbody>
</table>

If we compare these results with the 50% estimate for the Klobuchar's model [6], it turns improved by 2-5 times. An important feature of the TW model is the dependence of the TEC on the daily index. Previous Figures showed the results for the medians. Fig. 3 compares the daily model and experimental values for August 2002.

We see a good correspondence of the dynamics of variations, as evidenced by quantitative estimates of the absolute deviation of 6.4 TECU, RMS absolute deviation of 8.3 TECU and the relative standard deviation 16.4%. Such results were obtained for others years. They indicate high efficiency of the TW model and the method of its developing. It can be used to test other models.

4 The empirical NGM model and its agreement with experimental data

The Neustrelitz Global Model (NGM) [5] unlike the TW model is global. Its structure can be described as follows. Model TEC(NGM) is given by the product of five factors: TEC = F1 * F2 * F3 * F4 * F5. Each multiplier reflects dependence on certain physical factor and is calculated using from 2 to 6 coefficients Ci. Coefficients are determined by the
method of least squares superimposed on experimental data for several years. F1 factor describes the dependence on the local time LT, i.e. on the solar zenith angle, and includes a daily, half-day, 8-day variation. It is calculated using the 5 coefficients (C1 to C5). Maximum daily variation recorded at LT = 14. Factor F2 describes the annual and semi-annual variations, using the coefficients of C6-C7. The coefficient C8 is included in the factor F3, which describes the dependence of the TEC on the geomagnetic latitude. The coefficients C9 and C10 correspond to accounting anomalies in the equatorial latitude. The coefficients C11 and C12 describe the dependence on the index F10.7: F5 = C11 + C12 * F10.7. The NGM model includes the model of NmF2 [7] built according to the same principle, but has 13 coefficients, because in this case the factor F1 includes 6 coefficients. Maximum daily course also accounted for LT = 14. Dependence on F10.7 is described by the factor F4. Details of the algorithm are as follows. The input parameters are: DOY - day of the year, F10.7 - monthly average F10.7 index for a given day, φ - geographical latitude of point, λ - geographic longitude, φm - geomagnetic latitude, signσ = φ/|φ|, LT (array) - array of local times. In addition, some constants are defined. These constants include: cfoF2 (array [1:13]) - coefficients for foF2, cTEC (array [1:12]) - the expansion coefficients for the TEC. Tables of these coefficients are in [5, 7]. Another important difference between the models is that the TW model uses biases of the JPL method and its value should lie close to the values of JPL map. The NGM model is based on the values of the CODE map.

It is known that the properties of the ionosphere greatly depend on latitude zone. Strict boundaries between the zones do not exist, however, one distinguishes between high-latitude, mid-and low-latitude, equatorial zone.

4.1 The results for the mid-latitude stations
Comparisons for the mid-latitude areas are illustrated by the example of the European station Juliusruh. Since all models are medians, the comparison is carried out for the monthly medians. Typical examples are given in Figs. 4-5 for conditions that are close to the maximum (2001) and minimum (2007) of the solar activity. Fig. 4 shows the behavior of the TEC in the daily course for two experiment maps JPL and CODE and three models: NGM, IRI2001 [8] and IRI-Plas [9].

We can see that all the model values are close to the values of the JPL map, although such a picture can be linked to a specific month.

Fig. 4. Examples of the behavior of experimental and model TEC values in the diurnal run near the maximum (2001) and minimum (2007) solar activity

Fig. 5 displays absolute and relative deviations of the model from the experimental values of maps CODE in the annual run.

Fig. 5. Examples of comparison of the results for maximum and minimum solar activity for the mid-latitude station

One can see how the results depend on the level of solar activity. TEC values themselves (Fig. 4) are much less during the minimum than for maximum. The NGM model can provide some results that are better than the IRI model, but in some cases (autumn-winter) it provides results at the level of the model [8]. At other times, the relative deviations of all models are similar or better than for the IRI2001 model [8]. During periods of high activity the IRI-Plas model has the advantage.

4.2 The results for the high-latitude stations
It is known that high-latitude ionosphere has a large variability. If the comparison results of mid latitudes may be similar to multiple stations, then at high latitudes, since such variations, large differences can
be expected, so in Figs. 6-7 results are reported for several stations with different coordinates and for two levels of solar activity.

**Fig. 6.** Absolute and relative standard deviations of TEC for two high latitude stations and maximum solar activity

![Image](image.png)

**Fig. 7.** Absolute and relative standard deviations of TEC for two high latitude stations and minimum solar activity

![Image](image.png)

It is turned that the results for the high-latitude stations are not very different from the results of the mid-latitude station at a certain increase of deviations with latitude. The maximum deviations are of the IRI2001, illustrating the benefits of the IRI-Plas model before IRI2001. When comparing the results for the models IRI-Plas and NGM, the IRI-Plas model has the advantage. In conditions of low solar activity for all stations there are moments when deviations for the NGM model is smaller than for the IRI model. The absolute deviation is less than for the maximum activity, relative - more. Large deviations are common to all models in the winter months.

### 4.3 The results for the low latitude stations

More great features are inherent in the behavior of the ionosphere in the low-latitude and equatorial regions. Results for the low-latitude zones are illustrated by the data of the Grahamstown station, for the equatorial region - according to the Ascension Is station in Figs 8-9.

**Fig. 8.** Absolute and relative standard deviations of TEC for the low latitude Grahamstown station near maximum and minimum solar activity

![Image](image.png)

**Fig. 9.** Absolute and relative standard deviations of TEC for the equatorial Ascension Is station near maximum and minimum solar activity

![Image](image.png)

The NGM model is preferable for equator. The results for individual stations do not give the whole picture. It is interesting to identify deviations in behavior depending on the latitude. The results are shown in Fig. 10. The absolute deviations of the TEC decrease with the increase of the absolute values of latitude, the relative ones increase, but the relative deviations practically do not exceed 30%. Results for the wider area are shown in the Figs 11-12. They refer to a specific month and longitude zone: Europe (longitude ~30º, April 2002 and July
The U.S. (longitude ~100º, April 2002 and November 2003). Cases were selected on the basis of the largest number of stations. In addition, it should be noted that all the months contained disturbed conditions.

Results depend on season. In April, both models (IRI-Plas and NGM) give much better results than the IRI2001 for both longitude areas. Results for July give an advantage of NGM before the IRI.

5 Using TEC to determine the parameters of the ionosphere

In this Section, we evaluate the possibility of using the TEC to determine the parameters of the ionosphere such as NmF2 and N(h)-profile. As indicated in Section 2, the NGM model includes the model of NmF2. Testing of this parameter lies outside the brackets of this work. We only note that the results are similar to ones for the TEC. It is important that having NmF2(NGM) and TEC(NGM), we can calculate the equivalent slab thickness of the ionosphere \( \tau = \text{TEC(NGM)}/\text{NmF2(NGM)} \). The parameter \( \tau \) can play an important role in determining foF2, therefore, also requires an empirical model. Until now, this role could perform value of \( \tau(\text{IRI}) \) (e.g. [10-11]). In the paper [12], it is shown that the median \( \tau(\text{med}) \) allows to determine foF2 during disturbances or fill data gaps of foF2. Examples are given in Fig 13 for mid- and high-latitude stations for one of the perturbations (4-8 April 2000). The experimental values and medians are shown for TEC. For foF2 are given experimental values (symbol «obs»), the values for the initial IRI model, the values calculated using the median \( \tau(\text{rec}) \) and the medians (med).
Experimental values of $\tau(\text{obs})$, than $\tau(\text{IRI})$. Important to evaluate how much the model $\tau(\text{NGM})=\text{TEC(NGM)}/N_mF_2(\text{NGM})$ is closer to $\tau(\text{obs})$ than $\tau(\text{IRI})$. Such an assessment is done by comparing the critical frequency reconstructed from the experimental values of the TEC of different maps using the corresponding $\tau$, the model values and their deviations from the experiment. These deviations are calculated for each day, so the designation "ins" (from "instantaneous") is used and calculated monthly average. For the NGM model, $\text{foF}_2$ (ins) are obtained from the TEC(CODE) with $\tau(\text{NGM})$. Results are presented in Fig. 14 for various latitudinal areas and two levels of solar activity.

![Fig. 14. The annual course of deviations |$\Delta\text{foF}_2(\text{ins})$| for various stations and solar activity levels](image)

Graphs are shown for the conditions under which the model $\tau(\text{NGM})$ may yield better results than the IRI model.

Another important parameter is $N(h)$-profile. The IRI-Plas model allows the use the TEC to build these profiles. However, the values of the TEC defined by maps JPL and CODE may differ. In [13], it is proposed to use the plasma frequency, measured by satellites, to select profiles. Examples of comparison of model and experimental TEC are shown in Fig. 15 for the Chung Li station and the TW model and the Grahamstown station and the NGM model. Values of TEC(fne) correspond to $N(h)$-profiles passing through fne(sat) measured by DMSP satellites.

![Fig. 15. Comparison of experimental TEC (JPL and CODE maps) values, model values (NGM and TW) and TEC(fne) values corresponding to plasma frequency fne measured by DMSP satellites](image)

We see that in the first case, the TEC for the profiles passing through the experimental plasma frequency for UT = 1 is close to the values of the TW model, and for UT = 13 is close to the NGM model. Examples of respective profiles are shown in Fig. 16 for the original model IRI, for the model, adapted to the experimental values of the JPL and CODE maps, and profiles that pass through the plasma frequency fne. They are closest to the profiles corresponding to TEC of empirical models (TW for top profiles and NGM for low ones).

![Fig. 16. N(h)-profiles corresponding to various options of TEC determination](image)

In general, we can say that the profiles of the original model may be far from the model profiles corresponding to the model TEC and passing through the plasma frequency.
6 Conclusion
The important role of the TEC in applications stimulates the creation of new approaches and models. Test calculations conducted for this paper show that these new approaches and models can significantly improve the definition of the ionospheric delay and propagation conditions in space. Of course, one approach and one model cannot be equally well suited for all latitudinal zones and geophysical conditions, so testing models pursues such goal, as the definition of the conditions under which a particular model can give the best results. In this regard, the approach of [4] was better than [5]. At the same time, the NGM model includes both parameters TEC and NmF2. Although both parameters can have large deviations from the experimental values, the parameter τ(NGM) is closer to the experimental values than τ(IRI) as the TEC and NmF2 deviations have the same sign. The biggest advantage of this model is in the equatorial region. The IRI-Plas model in most cases provide better results than previous versions the IRI model. Using the TEC allows us to build N(h)-profiles, which are closer to additional experimental data than the profiles of previous versions the IRI model.

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References: