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# On the global model of the ionospheric equivalent slab thickness

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# On the global model of the ionospheric equivalent slab thickness

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**Abstract**. The equivalent slab thickness τ of the ionosphere links two of its parameters: the critical frequency foF2 and the total electron content TEC and, as a consequence, allows the determination of foF2 using TEC. Interest in the parameter τ has recently increased, as evidenced by a publication in Space Science Reviews 2022, 218:37, 1-65, which provides a historical overview of τ research, presents features of τ behavior in different regions of the globe under different solar activity conditions, and indicates directions for further research. This led to the following objectives for this paper: (1) estimating the correlation coefficient between foF2 and TEC, (2) testing a unique global model τ(NSTM) - the Neustrelitz equivalent Slab Thickness Model, (3) estimating the relation between τ and the Dst index. Using data from 78 stations divided into several longitude zones, it is shown for April 2022: (1) a high correlation between foF2 and TEC on a global scale is confirmed, but there is a large dependence on data quality, (2) each longitude zone has stations for which τ(NSTM) gives good agreement with experimental values and can be used in applications, (3) the correlation coefficient ρ(τ-Dst) is found to depend on longitude, which may have a physical nature.

## 1. Introduction

Near-Earth space plays a huge role in human life. A large part of this space is occupied by the ionosphere. Nearly a century of research has led to the development of theoretical and empirical models of ionospheric parameters such as the critical frequency foF2 and the total electron content TEC. Along with foF2 and TEC parameters, the equivalent slab thickness τ, which depends on these parameters, becomes the most important characteristic. Empirical models of the parameters are known to play a major role for applications. Such models have been developed for foF2 and even TEC, but until recently there was no global model of τ, although the need for such a model is constantly declared. At present, two attempts have been made to develop such a model [1-2]. The GAMBIT system in the form of maps and in real time is presented in [1] where τ is estimated using the combination of IGS-provided vertical TEC and GIRO-provided peak density NmF2 (proportional to the square of foF2). The Neustrelitz equivalent Slab Thickness Model NSTM was developed in [2], which makes it possible to obtain specific values of τ at any point of the globe. In [3], GAMBIT was extended to a 4D-var scheme and mapped various ionospheric parameters such as MUF(3000)F2, NmF2 and TEC and their deviations from quiet state values using November 4, 2021 as an example. Results showed that τ anomalies are much stronger than the corresponding anomalies for other parameters making τ a good candidate for weather monitoring and alerts. The paper [4] gives a historical review of τ studies, presents features of τ behavior in different regions of the globe under different conditions of solar activity in the form of daily and seasonal dependences of τ, which can be used as a reference material. Herewith: (1) it is pointed out that the main application of τ is the determination of the critical frequency foF2 using the total electron content TEC, (2) it is noted that the recently developed global models of τ [1-2] have not been sufficiently tested, (3) as a direction for further research, the development of a model of τ behavior during disturbed conditions is proposed. This allows us to set the following objectives to be addressed in this paper using global foF2 and TEC data: (1) estimating the correlation coefficient between foF2 and TEC, (2) testing the model τ(NSTM), (3) estimating the relation of τ with the Dst index.

## 2. Experimental data and models

To determine τ, data from 78 ionospheric stations taken on the IZMIRAN website (https://www.izmiran.ru/ionosphere/weather/foF2/indexss.shtml) for April 2022 were used. The TEC values were calculated for the global JPL GIM map from the IONEX files on site (ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/) with a step of 2 hours. The values were determined using the formula τ=TEC/NmF2, and the monthly medians of foF2, TEC, and τ were also calculated. The values of τ(NSTM) are calculated according to the algorithm [2]. The evaluation of parameter deviations from the medians and the differences between τ(NSTM) and the experimental median τ(med) was performed using the root mean square error RSME and the normalized root mean square error NRSME. To characterize geomagnetic and solar activity, the Dst and F10.7 indices (website http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html) shown in figure 1 are used.

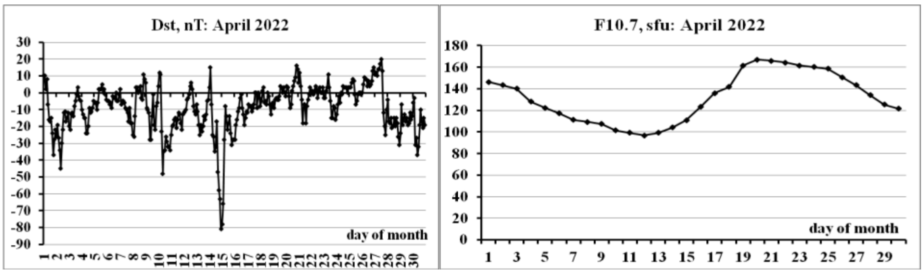


**Figure 1**. Behavior of geomagnetic indices Dst and F10.7 in April 2022.

We can see that the month is disturbed, moreover, a strong magnetic storm is also present. The behavior of the F10.7 index also shows great variability.

## 3. Evaluation of the relationship between foF2 and TEC with an example of its use

The results representation is chosen as a function of longitude, so the stations can refer to both the northern hemisphere and the southern hemisphere. The dependence of the coefficient ρ(TEC-foF2) of the linear correlation between foF2 and TEC is shown in figure 2. The coefficients ρ(TEC-foF2) with polynomial trend (degree 2) were also calculated, which have slightly larger values than the linear correlation, and the linear correlation coefficients ρ(TEC-NmF2), which are close to those of the polynomial trend.

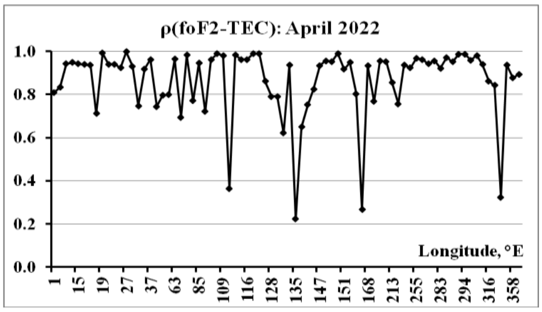


**Figure 2.** Behavior of the coefficient ρ(TEC-foF2) in April 2022 on a global scale.

It can be seen that the predominant majority of stations provide coefficients at 0.7-1.0, which is considered to be a credible relationship that determines the credibility of the parameter τ.

Ionosphere behavior depends on the longitude, so to describe its behavior often consider regions, which correspond to the greatest number of ionospheric stations. Such regions are (1) West European (1°-27° E in figure 2), (2) East European-African (27° -37° E), (3) Southeast-Australian (109° - 135° E), (4) American (213°-316° E).

We see that in each region there is a station whose data should be excluded from the statistics. Figure 3 shows the corresponding examples: for station Tromso from region 1, stations Casey and Khabarovsk from region 3, and station Tucuman from region 4.

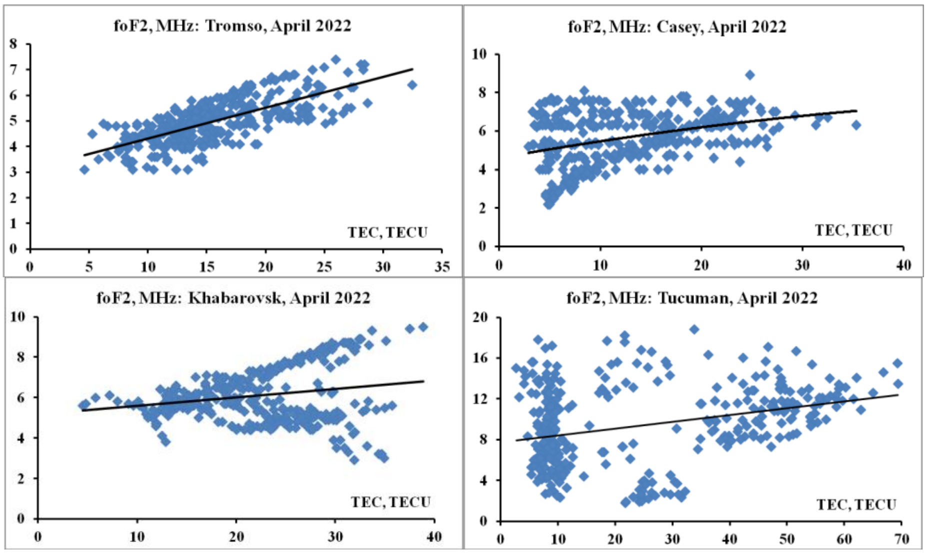


**Figure 3**. Illustration to the possibility of building a global model τ.

Consequently, when building a global model τ it is necessary to carefully select data.

Authors [4] note, that development of global model is difficult task, so they recommend to start with local and regional models.

In this paper, as a first step, it is proposed to build latitudinal dependences of τ for different meridians, obtain and compare foF2 behavior at different meridians using such τ. An example for the meridian 30° E is given below. Figure 4 gives the behavior of foF2 and TEC at the midpoint (Moscow) together with the monthly medians.

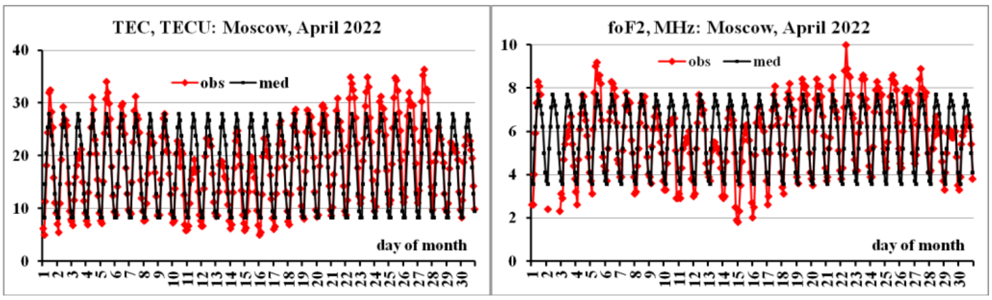


**Figure 4**. Behavior of ionospheric parameters in April 2022 from data of Moscow station.

One can see the influence of changes in solar radiation (especially in the second part of the month) and geomagnetic activity (in the middle of the month), and also synchronous variations of foF2 and TEC.

Using data from four ionosondes Murmansk (68.57° N, 33.2° E), Moscow (55.5° N, 37.2° E), Sopron (47.7° N, 16.6° E), Nicosia (35.03° N, 33.16° E), a polynomial approximation of τ(Appr) in the latitude range 30°-70° N was constructed as described in [5]. Using it, the latitudinal dependences of foF2 for different days and times of day were obtained. An example is given in figure 5 for UT=0 and 12. The median is highlighted in black. The remaining curves refer to the days in April (A7-A29).

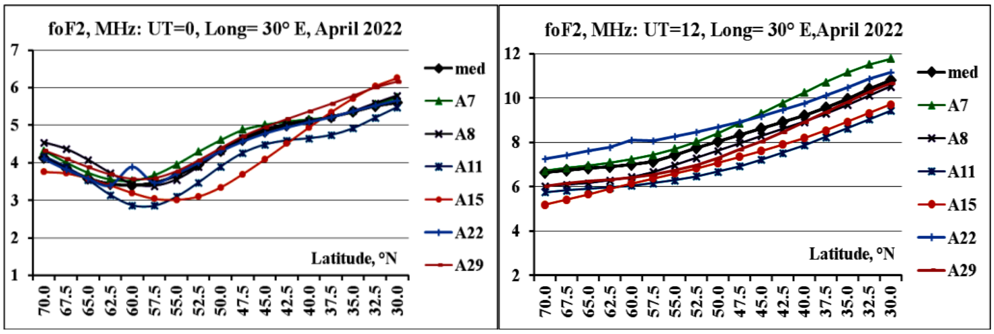


**Figure 5**. Ionospheric response to disturbances in April 2022 along the 30° E meridian.

The latitude dependence on April 7 and 8 is close to the quiet state described by the median, but a positive perturbation is seen in the afternoon at low latitudes on April 8. On April 11, we see a negative response to the magnetic storm on April 10 with a deepening of the ionization trough at night and the lowest foF2 values during the day at almost all latitudes. On April 15, a negative response to the strongest magnetic storm of this month on April 10 is seen with a shift of the trough to a lower latitude relative to the quiescent state, also a large negative perturbation by day. On April 22, a positive perturbation is observed in the daytime at all latitudes as a result of intensified solar radiation.

## 4. Results of testing the model τ(NSTM)

The τ(NSTM) model is the only global model of τ, reflects climatological features of τ behavior, and needs to be tested under specific conditions. This paper presents the results of such testing in April 2022. Figure 6 shows the RMSE deviations σ between the experimental and model values of τ as a function of longitude. The left panel additionally shows the RSME value for the model τ(NSTM) given by the authors [2]. The right panel gives the maximum values of τ(med) for each station.

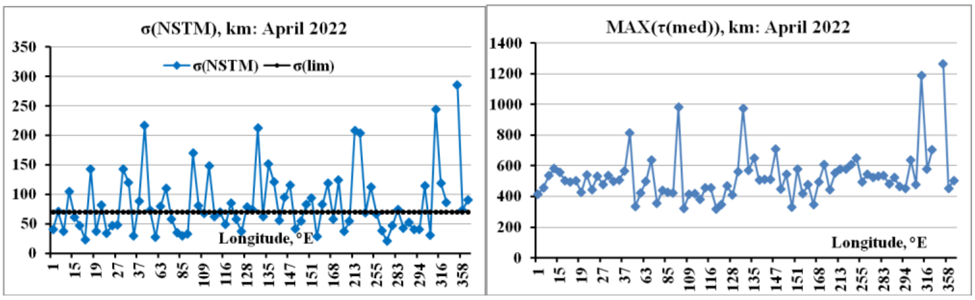


**Figure 6**. Test results of the model τ(NSTM) in April 2022.

It can be seen that in most cases σ(NSTM) is less than the specified limit. If we show the diurnal dependences of τ(NSTM), we can see a good coincidence, especially in the character of behavior. The largest discrepancies are obtained in most cases of observations of maximum values exceeding 500-600 km in the morning or evening hours, examples of which are shown in figure 7. However, there are examples when the maximum values do not exceed these limits, but the differences are observed throughout the day, as can be seen in figure 8.

A comparison of the two panels of figure 6 shows that the large deviations are mostly related to Antarctic and high-latitude stations due to data problems. One of the worst results is obtained for Kokobunji (τ drop to 76 km in evening UT time), although this station is the most reliable in Japan and in [6] its data were used just to determine τ in order to reconstruct the behavior of TEC during the period when no measurements were taken. Typical comparison patterns look as follows (figure 9).

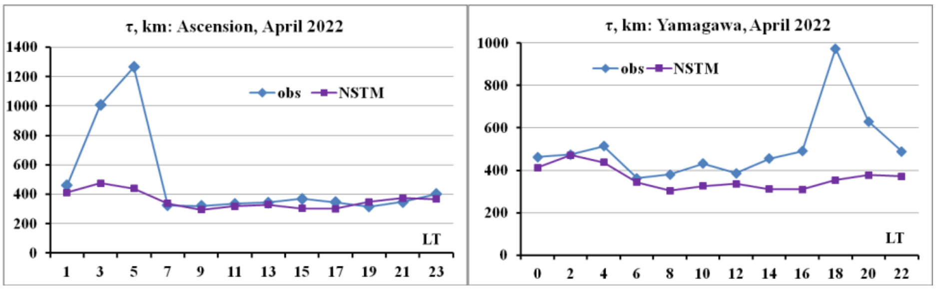


**Figure 7**. Divergences of the dawn and sunset τ exceeding of the limits σ.

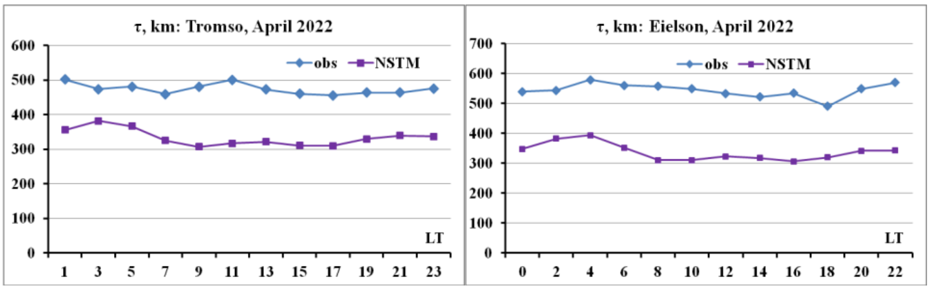


**Figure 8**. Discrepancies in τ values associated with possible uncorrected data.

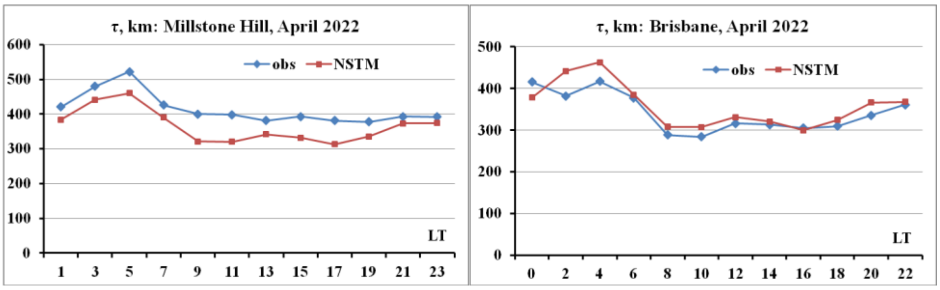


**Figure 9**. Typical correspondence between experimental and model τ.

Thus, in all longitude zones there are stations for which τ(NSTM) gives a good agreement and can serve as a reference point.

## 5. Estimation of the relation between τ and the Dst index

Since April was a disturbed month, we can obtain a correlation of τ with the Dst index. Examples of the distribution of τ as a function of Dst are shown in figure 10.

We can see that there is a trend of increasing τ with increasing force of disturbances, but the correlation coefficient is small. For a more accurate quantification, this coefficient is usually calculated in a certain range, for example, starting from Dst=-30 nT. Such coefficient is shown for all stations in figure 11.

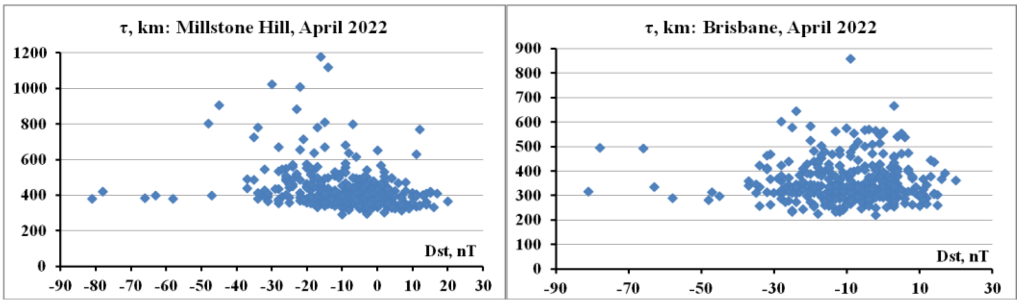


**Figure 10.** Examples of the distribution of τ as a function of Dst for two stations.

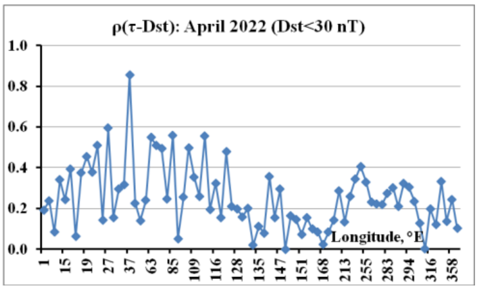


**Figure 11**. Correlation of τ with the Dst index.

There are no stable values of the correlation coefficient in regions, except for the American zone, but their coefficients are too small. Most likely, a certain trend of ρ(τ-Dst) with longitude is not random and there is a physical reason for it, but to identify it, we need to obtain results for other months.

## 6. Conclusion

The creation of a global model of the ionospheric equivalent slab thickness τ has attracted increased interest [1-5]. This is due to the fact that τ allows one to determine the critical frequency foF2 using TEC. But there is only one such model [2]. Various methods have been proposed for such applications and they are widely used. Of recent works, we can mention the paper [7] and the corresponding review in it. The paper [7] uses the determination of the critical frequency foF2(1) of one station using the critical frequency foF2(2) of another station and the TEC of both stations according to the relation foF2(1)=foF2(2)*sqrt(TEC1/TEC2) assuming constant τ, although their figure 7 shows a large difference of τ between stations. This technique was tested with data from four Brazilian stations Boa Vista (2.8°N, 60.7°W), São Luiz (2.5°S, 44.3°W), Fortaleza (3.8°S, 38.5°W), Cachoeira (22.7°S, 45.0°W) and obtained the RMSE values of foF2 significantly exceeding 1 MHz for various station combinations. By the way, the data of three of these stations (Fortaleza, Cachoeira, São Luiz,) are included in the array of 78 stations of this paper. For the first two stations, the comparison patterns of τ(obs) and τ(NSTM) are very close to the left panel of figure 7 with a dawn maximum and subsequent asymptotic behavior. For São Luiz, the maximum of τ(obs) falls in the daytime hours.

However, there is a return to the use of τ. This paper shows a high correlation between foF2 and TEC using data from 78 stations, determining a possibility to obtain foF2 using TEC, but there is a large dependence on data quality. Low quality can reduce the correspondence between τ(obs) and τ(NSTM). The data were divided into several longitudinal zones. It is shown that each zone has stations for which τ(NSTM) gives a good correspondence. It is known that values in the range of 100-1000 km were used to construct the τ(NSTM) model, but even medians can exceed 1000 km, let alone values on specific days. For stations τ of which does not exceed 500-600 km, the model can be used in applications. When studying the relationship between τ and the Dst-index, the dependence of the correlation coefficient ρ(τ-Dst) on longitude, which may have a physical nature, was found.

**Acknowledgment**
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