Similarities of the total electron content behavior during geomagnetic storms

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Abstract. The study of the behavior of the ionosphere during disturbances is traditionally an important task. One of the authors in the GA 2018 paper found two groups of similar magnetic storms in 2013 and discovered a similarity in the behavior of the critical frequencies foF2 according to the data from the Sodanküla high-latitude station in the northern hemisphere, but this similarity was reduced to a negative disturbance, which is also characteristic of a large number of dissimilar magnetic storms. Nevertheless, it seemed interesting whether such a similarity could be inherent in the behavior of the total electron content TEC of the ionosphere. The study was carried out using data from three stations Juliusruh, Tromso, Longyearbyen near the 15° N meridian. It turned out that this similarity is observed in the behavior of foF2 and TEC, which is confirmed by high correlation coefficients between these parameters both during months and periods of disturbances.

1. Introduction

Despite the large number of publications, the study of the behavior of the ionosphere during disturbances is one of the main topics. A fairly common place is the statement that no two magnetic storms are alike, so each storm must be studied separately. However, great efforts are spent on finding generalizing factors that could facilitate the prediction of parameters during disturbances (e.g., [1]). The author of the paper [2] found four magnetic storms (MSs) with similar properties, and considered the behavior of the critical frequencies according to the Sodanküla station data. In the presented work, we study the behavior of the total electron content TEC during these MSs and its relationship with foF2, which is of great importance for filling the foF2 gaps during disturbances. The selected MBs are characterized by moderate intensities (a minimum value of Dst ~ -50-60 nT). Therefore, it makes sense to consider them, since in the next cycle of solar activity one should hardly expect extreme disturbances. The most recent disturbance on 24 October 2020 had a min Dst = -47 nT. Additionally, it is investigated whether it is possible to use modern models of the ionosphere to describe its behavior during disturbances. The most common is the International Reference Ionosphere IRI Model [3], in which disturbed conditions are taken into account using the “on” option. However, testing the model shows that this option does not always provide a 100% account of the disturbed conditions. Since the paper [2] refers to the high-latitude zone, it should be mentioned that in recent years the Empirical Canadian High Arctic Ionospheric Model E-CHAIM [4] has appeared, which more strongly takes into account the disturbed conditions. If we have in mind the model relationship between TEC and foF2, then it is necessary to indicate and investigate the IRI-Plas model [5], in which the N(h)-profile of the electron density is integrated to the heights of the GPS satellites measuring TEC, and the model is to be adapted to observational values TEC(obs).
2. Experimental data and models
The critical frequencies of the Juliusruh (54.6° N, 13.4° E), Tromso (69.7° N, 19° E), Longyearbyen (78.2° N, 15.9° E) stations were taken from the DIDBase (http://ulcar.uml.edu/DIDBase), TEC(obs) values were calculated from the data of IONEX files (ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/), values of geomagnetic activity indices Dst and AE were used from (wdc.kugi.kyoto-u.ac.jp/) in April, May, July and August 2013. The foF2 values for the IRI model were calculated online at the site (http://omniweb.gsfc.nasa.gov/vitmo/iri2016_vitmo.html), for the E-CHAIM model at the site (https://chain-new.chain-project.net/index.php/e-chaim/e-chaim-web-application), for the IRI-Plas model on the site (http://www.ionolab.org/index.php?language=en). These values were compared with the experimental values and with the foF2(rec) values reconstructed using the medians of the equivalent slab thickness τ(med) and TEC(obs) values. In the paper [2], two groups of similar magnetic storms were considered: April 22-25, 2013 and April 29-30 - May 1-2, 2013 and July 17-20, 2013 and August 3-6, 2013. Table 1 shows the daily average values of the Dst and AE indices. It consists of two parts on five columns for each group of storms.

Table 1. Characteristics of geomagnetic activity during the selected disturbances.

|       | April | April-May |        |        |    | July | April | April-May |    | July |     |
|-------|-------|-----------|-------|-------|----|------|-------|-----------|----|------|-----|
| Dst   | 7     | 29        | 6     | 29    | 1  | 12   | 81    | 10        | 3  | 4    | 5   |
| AE    | 57    | 30        | 84    | 294   | 1  | 224  | 227   | 228       | 2  | 28   | 16  |

In the period of the first two MBs, the behavior of the indices is similar; during the second two MBs in July, the Dst index is lower in absolute value than in August.

3. Behavior of TEC and foF2 at three stations
This behavior is shown in figures 1-3. Each graph is divided into two magnetic storms.

![Figure 1](image1.png)

Figure 1. Behavior of TEC and foF2 for the Juliusruh station.
Figure 2. Behavior of TEC and foF2 for the Tromso station.

It can be seen that in the first pair of MBs there is a similarity in the behavior of TEC and foF2 during both MBs, in the second pair, the behavior of only TEC and foF2 is similar. In addition, the higher the latitude of the station, the more missing foF2 values can be. To navigate the nature of the disturbances, the latitudinal dependences of TEC were calculated in the entire range from 50° to 80° N for all times of the day. Figure 4 shows these dependences for an example for UT = 12 and 22 and the days identified in [2]. At other times, the results are similar.

Figure 3. Behavior of TEC and foF2 for the Longyearbyen station.
Figure 4. Confirmation of the nature of disturbances in the entire region.
In the period of the first two MBs, similar behavior is visible. It can be seen that TEC allows one to estimate the influence of disturbances in a wider zone, and these disturbances are negative. In the period of the second two MBs, deviations from the medians are less, which corresponds to the results of [2].

4. Assessment of the possibility of using ionospheric models to describe the disturbed state

In the paper [2], it is proposed to use foF2 data to describe and predict the disturbed state by accumulating the corresponding data, but since they may not be available, in this paper it is proposed to use TEC. This is possible in two ways: 1) using the reconstructed values of foF2(rec), 2) by adapting the IRI-Plas model to TEC (obs). Additionally, it is proposed to use the E-CHAIM model. The assessment of these methods was carried out by comparing the absolute (|ΔfoF2|, MHz) and relative (σ, MHz, σ, %) deviations of the calculated foF2 values from the observational foF2(obs). Before to estimate accuracy of models during the disturbed conditions, it is necessary to have an estimation of climatological accuracy of models IRI and E-CHAIM as they are median models. For the model IRI, it is necessary, as the model IRI-2016 is essentially modified in comparison with the previous versions. For the model E-CHAIM, it is necessary, as it is a new model. Climatological estimations are given for the model IRI in table 2, for the model E-CHAIM - in table 3.

**Table 2. Accuracy of medians definition for the model IRI.**

|     | 2013 June | April | May | July | August |
|-----|-----------|-------|-----|------|--------|
|     | σ, MHz    | σ, %  | ΔfoF2 | σ, MHz | σ, % | ΔfoF2 | σ, MHz | σ, % | ΔfoF2 | σ, MHz | σ, % |
| Jul | 0.54      | 0.56  | 0.49 | 0.52  | 0.14  | 0.23  | 0.13   | 0.17 | 3.09   |
| Tro | 0.37      | 0.41  | 0.55 | 0.57  | 0.28  | 0.39  | 0.72   | 0.33 | 0.70   |
| Lon | 0.46      | 0.51  | 0.56 | 0.60  | 0.25  | 0.28  | 0.51   | 0.27 | 0.30   |

**Table 3. Accuracy of medians definition for the model E-CHAIM.**

|     | 2013 June | April | May | July | August |
|-----|-----------|-------|-----|------|--------|
|     | σ, MHz    | σ, %  | ΔfoF2 | σ, MHz | σ, % | ΔfoF2 | σ, MHz | σ, % | ΔfoF2 | σ, MHz | σ, % |
| Jul | 0.16      | 0.20  | 0.21 | 0.26  | 0.19  | 0.23  | 0.21   | 0.26 | 4.67   |
| Tro | 0.43      | 0.48  | 0.19 | 0.23  | 0.14  | 0.17  | 0.32   | 0.20 | 3.81   |
| Lon | 0.24      | 0.27  | 0.19 | 0.25  | 0.21  | 0.24  | 0.48   | 0.16 | 3.07   |

It is visible, that both models, especially, in summertime, have provided unprecedented accuracy in high latitudes even in comparison with the reference middle-latitude station Juliusruh. Table 4 gives the estimate for four magnetic storms, three stations and four options (models IRI, E-CHAIM, IRI-Plas and foF2 (rec)). It means use of the model values as the instantaneous ones.

**Table 4.** Comparison of the accuracy of the description of the disturbed state using various model options.

|     | 2013 June | April | May | July | August |
|-----|-----------|-------|-----|------|--------|
|     | σ, MHz    | σ, %  | ΔfoF2 | σ, MHz | σ, % | ΔfoF2 | σ, MHz | σ, % | ΔfoF2 | σ, MHz | σ, % |
| Jul | 0.65      | 0.66  | 0.36 | 0.35  | 0.58  | 0.75  | 0.39   | 0.37 | 0.56   | 0.49   | 0.38   |
| Tro | 0.81      | 0.81  | 0.45 | 0.45  | 0.71  | 0.89  | 0.52   | 0.52 | 0.66   | 0.61   | 0.51   |
| Lon | 14.6      | 14.6  | 8.0  | 8.1   | 13.8  | 17.2  | 10.0   | 10.1 | 13.3   | 12.3   | 10.1   |
|     | 1.11      | 0.62  | 0.57 | 0.51  | 0.75  | 0.77  | 0.90   | 0.67 | 0.88   | 0.52   | 0.68   |
|     | 1.11      | 0.62  | 0.57 | 0.51  | 0.75  | 0.77  | 0.90   | 0.67 | 0.88   | 0.52   | 0.68   |
|     | 1.11      | 0.62  | 0.57 | 0.51  | 0.75  | 0.77  | 0.90   | 0.67 | 0.88   | 0.52   | 0.68   |
|     | 1.11      | 0.62  | 0.57 | 0.51  | 0.75  | 0.77  | 0.90   | 0.67 | 0.88   | 0.52   | 0.68   |
σ, % 18.1 10.2 9.4 8.4 13.7 14.0 16.4 12.2 17.1 10.0 13.1 9.6
\(|\Delta f_{O2}\)| 0.51 0.39 0.40 0.25 0.36 0.27 0.45 0.31 0.57 0.51 0.61 0.47
3 σ, MHz 0.62 0.53 0.51 0.36 0.46 0.37 0.53 0.43 0.78 0.70 0.87 0.75
σ, % 10.7 9.1 8.9 6.2 8.6 6.9 10.0 8.0 15.0 13.4 16.9 14.5
\(|\Delta f_{O2}\)| 0.62 0.53 0.46 0.40 0.56 0.28 0.34 0.27 0.36 0.22 0.30 0.28
σ, MHz 1.11 1.02 0.99 0.96 0.68 0.37 0.46 0.37 0.45 0.28 0.45 0.37
σ, % 20.0 18.4 17.8 17.4 12.9 7.0 8.6 7.0 9.3 5.8 9.2 7.6

The table shows that there are no significant differences between the stations. In most cases, the largest absolute and relative deviations correspond to the IRI model, the smallest - to the procedure for using \(\tau(\text{med})\) and TEC (obs). If we compare the two models E-CHAIM and IRI-Plas, then for the mid-latitude station, the results are slightly better for the IRI-Plas model, because the station is located near the low-latitude boundary of validity of the E-CHAIM model. For Longyearbyen station, the results are better for the E-CHAIM model. The average values for all magnetic storms do not exceed 0.7 MHz for the IRI model, 0.5 MHz for the E-CHAIM and IRI-Plas models, and 0.4 MHz for the \(f_{O2}\) values. For relative deviations, this is 16% for the IRI model, 12-13% for the E-CHAIM and IRI-Plas models, and 10% for the \(f_{O2}\) values. These estimates show, that the disturbed condition essentially differs from climatological norms, therefore they can be considered as the bottom limit of accuracy.

5. About the similarity of TEC behavior
The results obtained indicate that the greatest similarity is observed in the behavior of TEC and \(f_{O2}\). This is confirmed by the correlation coefficients between TEC and \(f_{O2}\), estimated for a month and for more complete periods of disturbances, which are shown in figure 5. The respective periods of April 21-30, 2013 and July 5-17, 2013 are shown in figure 6. Blue curves show monthly values, red curves - for periods of disturbances.
In the high-latitude zone at night, the decrease of correlation may be associated with the presence of auroral ionization. In almost all cases, the correlation coefficients during disturbances are not lower than monthly values, i.e. the correlation does not decrease.

6. Conclusion

The importance of studying the behavior of the ionosphere during disturbances is emphasized like the reference [6]. An attempt is made to find out whether the search for similar disturbances gives any advantages. It is shown that the greatest similarity is observed in the behavior of TEC and foF2. This confirms the results obtained earlier in [7] during also a specially selected disturbed period on March 7–17, 2012 according to data from Longyearbyen, Juliusruh, Pruhonice stations for stronger disturbances. In the paper [7], a high synchronicity of TEC and foF2 variations was shown. An important result of this work is the assessment of the possibility of using the IRI-Plas and E-CHAIM models to describe the state of the ionosphere during disturbances. The advantage of the IRI-Plas model is associated with the assimilation of the observational TEC values into the model, the advantage of the E-CHAIM model is associated with the strong consideration of geomagnetic indices.

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