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Large-scale traveling ionospheric disturbances of auroral origin according to the data of the GPS network and ionosondes

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Abstract

The intensity of large-scale traveling ionospheric disturbances (LS TIDs), registered using measurements of total electron content (TEC) during the magnetic storms on October 29–31, 2003, and on November 7–11, 2004, had been compared with that of local electron density disturbances. The data of TEC measurements at ground-based GPS receivers located near the ionospheric stations and the corresponding values of the critical frequency of the ionospheric F region f_oF2 were used for this purpose. The variations of TEC and f_oF2 were similar for all events mentioned above. The previous assumption that the ionospheric region with vertical extension from 150 to 200 km located near the F-layer maximum mainly contributes to the TEC variations was confirmed for the cases when the electron density disturbance at the F region maximum was not more than 50%. However, this region probably becomes vertically more extended when the electron density disturbance in the ionospheric F region is about 85%.

Keywords: TEC; GPS; Ionosondes; Large-scale traveling ionospheric disturbances

1. Introduction

Many papers are devoted to studying LS TIDs (Hocke and Schlegel, 1996; Oliver et al., 1997). It is found that LS TIDs are the manifestation of the atmospheric gravity waves (AGWs), which are generated in the auroral zones of the Northern and Southern hemispheres. However, the main properties of LS TIDs are still unclear mainly because the spatial–temporal resolution of the used instrumentation is insufficient, and obtained data are often ambiguous.

A new stage in the remote sensing of the ionosphere begins due to the development of the international global network of ground-based dual-frequency GPS receivers. The GLOBDET software for global detection and monitoring of natural and artificial ionospheric disturbances based on measurements of TEC variations performed in the GPS system is developed in Institute of Solar-Terrestrial Physics (Afraimovich, 2000).

One of the key problems in studying the ionosphere using transionospheric sounding is conformity of the ionospheric disturbance parameters determined from TEC measurements to local characteristics of electron density disturbances due to propagation of AGWs. To solve this problem, it is necessary to use additional data obtained with other geophysical instruments: ionosondes, incoherent scatter (IS) radars.

The aim of this paper is to compare intensity of the LS TIDs registered from TEC measurements during the magnetic storms on October 29–31, 2003, and on November 7–11, 2004, with the intensity of local electron density disturbances obtained from data of ionosondes.

2. General information about experiment and data processing

The relative amplitude R_N of electron density disturbance in the ionosphere was determined based on the measurements of the critical frequency of the ionospheric F region f_oF2 at the Irkutsk digisonde DPS-4 (52.2°N;

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104.3°E) (Reinisch et al., 1997) and at the Dyess AFB ionosonde (32.5°N; 260.3°E):

$$R_N = \frac{N_{\max} - N_{\min}}{N_{\max}} \times 100\% \tag{1}$$

where $N_{\max}$ and $N_{\min}$ are maximum and minimum values of electron density disturbance.

The parameters of the corresponding TEC disturbance were determined based on measurements at the nearest GPS stations. To demonstrate propagation of the LS TIDs we used also data of other GPS stations. The list of the GPS stations used in this paper is presented in Table 1.

The GPS standard RINEX-files contain data of highly accurate measurements of the group and phase delays at two frequencies $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz along the line of sight (LOS) between receivers on the ground and the transmitters on-board the GPS satellites which are in the zone of reception. For phase measurements with the sampling rate of 30 s the error of relative slant TEC I_s measurements does not exceed 10^{14} m^{-2} (Hofmann-Wellenhof et al., 1992). This makes it possible to detect irregularities and waves in the ionosphere over a wide range of amplitudes (up to 10^{-4} of the diurnal TEC variation) and periods (more than 5 min). The unit of TEC, which is equal to 10^{16} m^{-2} (TECU) and is commonly accepted in the literature, will be used in the following.

Methods of I_s calculating using GPS phase measurements were described in detail in several papers (Hofmann-Wellenhof et al., 1992; Afraimovich, 2000). We reproduce here only the final formula for phase measurements:

$$I_s(t) = \frac{1}{40.308}\frac{f_1^2 f_2^2}{(f_1^2 - f_2^2)}[(L_1\lambda_1 - L_2\lambda_2) + \text{const} + nL] \tag{2}$$

where $L_1\lambda_1$ and $L_2\lambda_2$ are additional paths of the radio signal caused by the phase delay in the ionosphere (m), L_1 and L_2 represent the number of phase rotations at the frequencies f_1 and f_2, λ_1 and λ_2 stand for the corresponding wavelengths, (m); *const* is the unknown initial phase ambiguity, (m); and nL are errors in determining of the phase path, (m).

To normalize the amplitude of TEC disturbances, we use the transformation of oblique TEC into the equivalent vertical value $I(t)$ (Klobuchar, 1986):

$$I(t) = I_S(t) \times \cos\left[\arcsin\left(\frac{r_z}{r_z + h_{\max}}\cos\theta_s\right)\right] \tag{3}$$

Table 1
The list of the used GPS stations and their geographical coordinates

GPS station	Latitude, °N	Longitude, °E
IRKT	52.22	104.32
KSTU	55.99	92.79
PUB1	38.29	255.65
SUM1	34.83	257.49
URUM	43.81	87.60

where r_z is the Earth's radius, and $h_{\max} = 300$ km is the assumed altitude of the ionospheric F2 layer maximum.

To eliminate the variations of the regular ionosphere and trends caused by the satellite motion, we use the procedure of preliminary smoothing of the initial series with selected time window of 30 min and removal of the linear trend with a window of about 120 min. Thus, we filter the TEC variations d$I(t)$ in the range of periods 30–120 min corresponding to the LS TID range of periods (Hocke and Schlegel, 1996).

To determine the relative amplitude R_I of TEC disturbance following formula was used:

$$R_I = \frac{\mathrm{d}I_{\max} - \mathrm{d}I_{\min}}{I_0} \times 100\% \tag{4}$$

where d$I_{\max}$, d$I_{\min}$ – maximum and minimum values of TEC variations d$I(t)$; I_0 – value of the absolute vertical TEC (the Global Ionospheric Maps technology (Mannucci et al., 1998)) available from the Internet (ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/). We used the maps obtained by Jet Propulsion Laboratory (JPLG files). In the formula (4) we assume that I_0 value corresponds to zero level of d$I(t)$ series.

3. Experimental results

In this paper we selected LS TIDs registered during the magnetic storms on October 29–31, 2003 (Dst = −347 nT, $Kp = 9$) and on November 7–11, 2004 (Dst = −383 nT, $Kp = 9$). The absolute amplitude of these disturbances was 2–16 TECU.

3.1. The disturbance registered on 29 October 2003 in eastern Asia

During the magnetic storm on 29 October 2003 we detected LS TID using f_oF2 measurements at the Irkutsk ionosonde and using TEC data at GPS stations IRKT and KSTU (Table 1).

The solid and dashed lines in Fig. 1 show the filtered TEC variations d$I(t)$ at two LOSs IRKT–PRN03 and KSTU–PRN03 (PRN represents the number of GPS satellite). It is obvious that these two d$I(t)$ series recorded at different LOSs are almost similar, especially in the time interval from 6:30 to 8:00 UT. Moreover one can see a time shift between these series. Such the shifts allowed Afraimovich et al. (2005) to obtain the LS TID horizontal velocity V_h and propagation direction α counted clockwise from the north. They were close to 1185 m/s and 199°, respectively. The relative amplitude of TEC variations R_I (4) at LOS IRKT-PRN03 was about 5% ($I_0 \approx 40$ TECU).

The solid line with triangles in Fig. 1 shows the variations in the critical frequency f_oF2. The scale of the corresponding approximate values of the electron density N at the F region maximum is shown on the right in Fig. 1. The f_oF2 variations indicate a high degree of similarity with the TEC variations in the time interval from 07:00 to 08:00

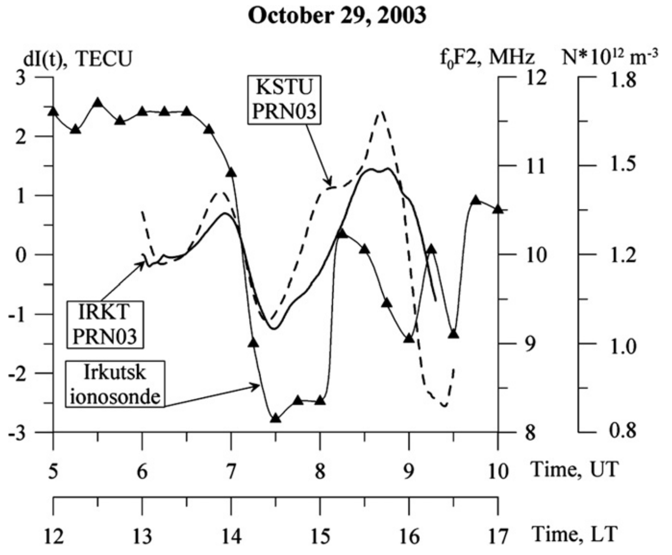

Fig. 1. Comparison of the variations in TEC and f_oF2 for the magnetic storm of October 29, 2003, in eastern Asia – filtered TEC variations d$I(t)$ from GPS LOSs KSTU-PRN03 (dashed line) and IRKT-PRN03 (solid line), and f_oF2 variations from Irkutsk ionosonde (line with triangles).

UT. The relative amplitude of electron density disturbance R_N (1) in the F region maximum reached 50%.

3.2. The disturbance registered on 30 October 2003 in North America

To study this disturbance, we used TEC measurements at GPS stations SUM1 and PUB1 (Table 1) and the values of the ionospheric F region critical frequency f_oF2 measured at the Dyess AFB ionosonde (32.5°N; 260.3°E) during the magnetic storm on October 30, 2003.

Afraimovich and Voeykov (2004) showed that the LS TID propagated from north-east to south-west of North America ($\alpha \approx 235°$) with the horizontal velocity $V_\mathrm{h} \approx 1200$ m/s. To illustrate the disturbance propagation the filtered TEC variations d$I(t)$ at two LOSs SUM1–PRN27 and PUB1–PRN27 are presented in Fig. 2 (solid and dashed lines, respectively). The relative amplitude of TEC variations R_I at LOS SUM1–PRN27 was about 9% ($I_0 \approx 100$ TECU). The shape of f_oF2 variations (the line with triangles in Fig. 2) is close to that of TEC variations. The relative amplitude of the electron density disturbance R_N at the F region maximum was about 40%.

3.3. The disturbance registered on 10 November 2004 in eastern Asia

The LS TID was detected using the TEC data at GPS stations IRKT and URUM (Table 1) and using the f_oF2 measurements at the Irkutsk ionosonde during the powerful magnetic storm of November 10, 2004.

Detailed analysis of the disturbance was presented by Polekh et al. (2006). The authors obtained that the LS TID propagated southwestward ($\alpha \approx 217°$) with horizontal

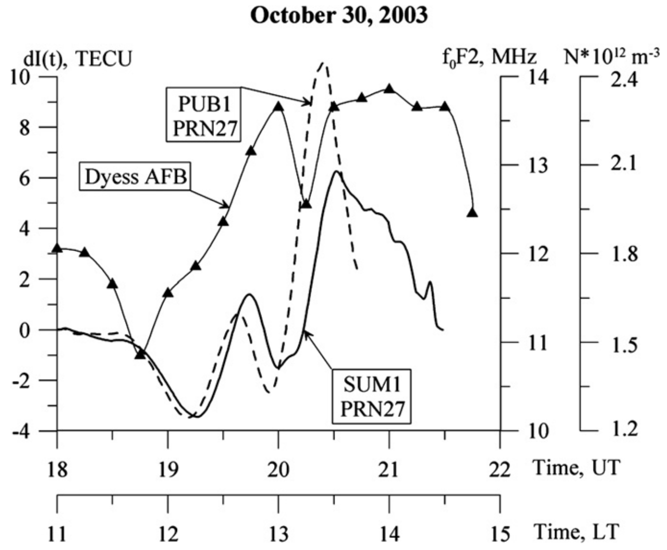

Fig. 2. Comparison of the variations in TEC and f_oF2 for the magnetic storm of October 30, 2003, in North America – filtered TEC variations d$I(t)$ from GPS LOSs PUB1-PRN27 (dashed line) and SUM1-PRN27 (solid line), and f_oF2 variations from Dyess AFB (line with triangles).

velocity 432 m/s. The disturbance movement is clearly seen from Fig. 3 where filtered TEC variations d$I(t)$ at two LOSs IRKT–PRN28 and URUM-PRN28 (solid and dashed lines, respectively) are presented. The maximum of TEC variations (IRKT–PRN28) was observed at approximately 08:15 UT and was followed by a sharp decrease – about 16 TECU for 40–50 min. The relative amplitude of the observed decrease in the TEC variations R_I was about 57% ($I_0 \approx 30$ TECU). The solid line with triangles in Fig. 3 shows the variations in the critical frequency f_oF2. It is clear that the f_oF2 variations are

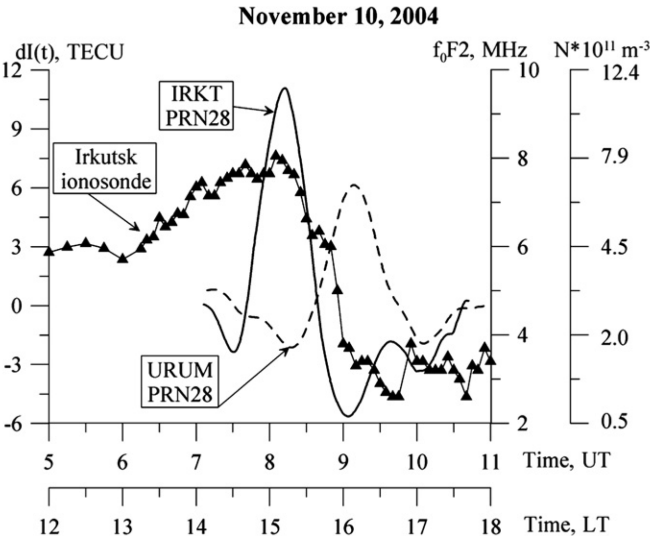

Fig. 3. Comparison of the variations in TEC and f_oF2 for the magnetic storm of November 10, 2004, in eastern Asia – filtered TEC variations d$I(t)$ from GPS LOSs URUM-PRN28 (dashed line) and IRKT-PRN28 (solid line), and f_oF2 variations from Irkutsk ionosonde (line with triangles).

similar to the TEC variations at IRKT–PRN28. The observed change in the critical frequency f_oF2 corresponds to the relative amplitude of the electron density disturbance at the F region maximum $R_N \approx 85\%$.

4. Discussion

For the first two disturbances registered during the magnetic storms on October 29–31, 2003 the ratio $R_{I/N} = R_I/R_N$ of the relative disturbance amplitude according to the TEC ($R_I \approx 5$–9%) and f_oF2 data ($R_N \approx 40$–50%) varied from 0.1 to 0.2 (Sections 3.1 and 3.2).

Since the values of R_I and R_N are not very close the corresponding disturbances could not have constant relative amplitude of electron density irregularity through the whole range of the ionospheric altitudes. On the contrary, the altitude dependences of the relative amplitude should have a maximum near to the F region maximum. This confirms the assumption made in (Kirchengast, 1996; Yeh and Liu, 1974) that the ionospheric region with vertical extension from 150 to 200 km located practically at the altitude of the F-layer maximum mainly contributes to the TEC variations during propagation of AGWs.

Our data quite agree with the results of the theoretical and experimental studies performed previously. The theoretical estimates of the TID amplitude were obtained in a number of papers including the extensive reviews (Hocke and Schlegel, 1996; Kirchengast, 1996; Testud and Francois, 1971; Yeh and Liu, 1974). Fig. 4 (line 3) presents the altitude variations in the relative amplitude R_N of the electron density disturbance calculated in (Yeh and Liu, 1974). More detailed calculations were given in (Kirchengast, 1996); Fig. 4 shows the results of the calculations made for the average level of geomagnetic disturbance (Ap = 3) – afternoon (14:30–18:30 UT) and noon of September 6, 1998 (lines 1 and 2, respectively).

To verify these results experimentally, it is necessary to use the IS radar data since only this instrument has a necessary sensitivity during detecting of the ionospheric AGW response in the wide altitude range (from 150 to 800 km) and a sufficient spatial–temporal resolution. Such experiments were described in a number of papers. In Fig. 4 the set of data 4 shows the average values and rms deviations of the R_N dependence measured with the IS radar in France on September 13, 1967 (Testud and Francois, 1971). The data of R_N measurements, obtained for 45 clearly defined cases of AGW with periods from 30 to 150 min at the EISCAT radar during low geomagnetic activity, are presented in the review (Hocke and Schlegel, 1996). These data are in good agreement with the theoretical dependence 1 (Fig. 4).

Afraimovich et al. (2004) obtained similar results based on measurements performed at the Irkutsk IS radar (Zherebtsov et al., 2002). The corresponding R_N dependence measured during the moderate magnetic storm of April 17, 2002 ($Dst \approx -100$ nT, $Kp \approx 7$), is shown in Fig. 4 by asterisks and the smoothed dashed line 5.

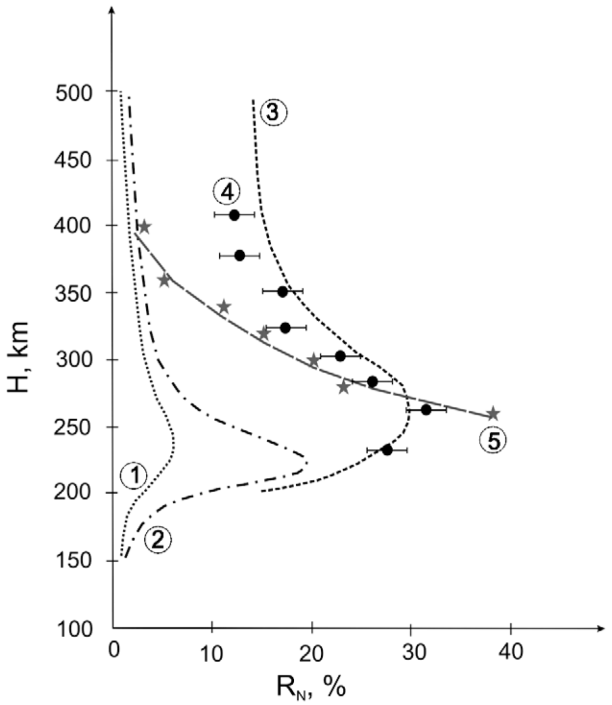

Fig. 4. The altitude dependences of the relative amplitude of the electron density disturbances. Modeling dependences obtained by Kirchengast (1996) (lines 1 and 2) and Yeh and Liu (1974) (line 3). Experimental dependences presented by Testud and Francois (1971) (data set 4) and Afraimovich et al. (2004) (asterisks and line 5).

The results of the calculations and experiments indicated that the maximal value of the relative amplitude R_N is reached near to the F2 layer maximum and varies from 5 to 40% depending on the geophysical conditions. Above the maximum, the disturbance amplitude rapidly decreases with altitude, decreasing twice in the altitude range of about 50–100 km, in spite of the fact that the local electron density above the F2 maximum decreases much slower. Thus, the ionospheric region that mainly contributes to the TEC variations during the propagation of AGWs of different origin is located approximately at the altitude of the electron density maximum, and the region vertical extension is not more than 150–200 km.

At the same time for the disturbance registered on November 10, 2004 (Section 3.3) the relative amplitude reached $R_I \approx 57\%$ and $R_N \approx 85\%$ according to the TEC and f_oF2 data, respectively. The corresponding ratio $R_{I/N}$ of the relative amplitudes was about 0.7. There is sufficient difference between the ratios $R_{I/N}$ for November 10, 2004 ($R_{I/N} \approx 0.7$) and for the other cases ($R_{I/N} \approx 0.1 \div 0.2$). The observed difference is apparently related to the fact that the disturbance observed on November 10, 2004 should be more extended in the vertical than two previous disturbances.

5. Conclusions

In this paper the comparison analysis of the data of TEC measurements from the ground-based GPS receivers located near the ionospheric stations and the corresponding values of the ionospheric F region critical frequency f_oF2 was carried out. For all events mentioned above, the variations in TEC and f_oF2 were similar. The previous assumption that the region of thickness 150–200 km in the vicinity of the ionospheric F region maximum mainly contributes to the TEC modulation was confirmed in the cases when the electron density disturbance at the F region maximum was not more than 50%. However, this region probably becomes more extensive in vertical when the electron density disturbance in the F region is about 85%.

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