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Ionospheric disturbances in the East-Asian region during geomagnetic storm in November, 2004

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Abstract

Results of the study into variations of the ionospheric parameters during the intense geomagnetic storm on November 7–11, 2004 in the 20–80°N, 80–160°E sectors are presented. These used data from ionospheric stations and total electron content (TEC) measurements obtained from the network of the GPS ground-based receivers and the receiver onboard the CHAMP satellite. Periods of total absorption and blanketing sporadic E layers were observed at high latitudes, whereas long-lasting negative disturbances which are typical of geomagnetic storms of high intensity were detected at midlatitudes. In the afternoon hours of local time on November 8, 2004, a large-scale ionospheric disturbance was detected on the basis of foF2 and TEC measurements. The disturbance was propagating southwestward at a mean velocity of about 200 m/s. Comparison of the relative amplitude of this large-scale disturbance according to the total electron content (~70%) and foF2 (~80%) measurements made it possible to assume that the disturbance was extended in height. A similar disturbance of smaller intensity was observed on November 10.

Keywords: Ionospheric storm; Geomagnetic disturbance; Critical frequencies; F2-layer; Main ionospheric trough; "Dusk" effect

1. Introduction

The study of the influence of solar and interplanetary events on the space weather is still a very important problem of solar-terrestrial physics. In spite of the fact that there are a lot of experimental and theoretical data at present, there exist some difficulties in forecasting the solar activity effects in the ionosphere, especially during large storms. In the current solar cycle, October and November, 2003 were of unusually high solar activity. A year later, such a situation recurred in November, 2004.

Previously we presented the results of studies of variations of the ionospheric parameters in October–November, 2003 according to the data of the ionospheric station network located in the 90–130°E longitudinal band from the auroral zone down to the equator (Zherebtsov et al., 2005). We have shown that during intense storms the phenomena which are typical of the main ionospheric trough zone were observed at geomagnetic latitude of 40°. In the vicinity of the equator, the critical frequencies of the F2 layer demonstrated large-amplitude oscillations.

In this study, we continue to analyze ionospheric disturbances within the same region during the geomagnetic storm on November 7–11, 2004. The data obtained by ionosondes located within the latitude–longitude sector (20–70°N, 90–160°E) are used. Also the data on TEC variations obtained at the global GPS network of two-frequency GPS receivers presented in the Internet RINEX files [ftp://sopac.ucsd.edu/pub/] are invoked.

2. Analysis of the vertical sounding data

Yermolaev et al. (2005) presented the variations of the main parameters of the solar wind and interplanetary medium for the period of November 7–11, 2004, when an intense geomagnetic storm with two minima in Dst (−383 nT November 8, 07 UT and −290 nT November

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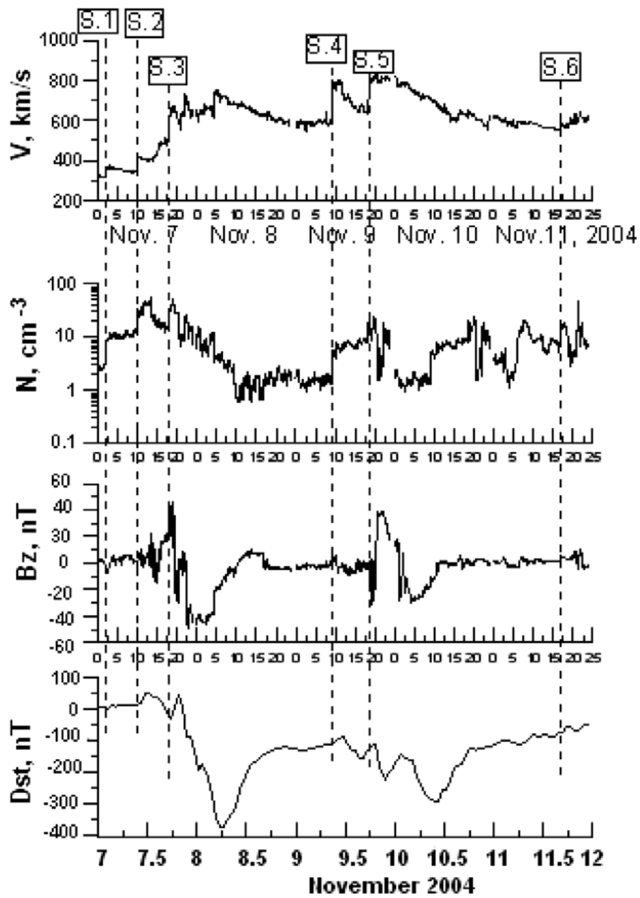

Fig. 1. Variations in the main parameters of the solar wind and interplanetary medium for the period of November 7–11, 2004 during an intense geomagnetic storm with two Dst minima.

10, 11 UT) was observed on the Earth (Fig. 1). Obviously this great geomagnetic storm was generated by the abrupt change and high values of the IMF Bz component. In this period, the plasma parameters (V and N) were not extreme, while the Bz component of IMF reached very low values, <-45, on November 8, and also quite low values on November 10. These low Bz values activated this greatest geomagnetic storm with two main phases.

Table 1 presents the geographic and geomagnetic coordinates of the ionospheric stations. The data of the China and Japan ionosondes were taken from the following sites: http://sec.noaa.gov/ftpmenu/lists/iono_month.html; http://wdc-c2.nict.go.jp/ionog/10c_viewer/o_index.html.

Fig. 2 shows the variations of the F2 and Es layer critical frequencies during this storm including the initial and recovery phases at the stations located in the 104–160°E longitudinal sector. The variations of the critical frequencies of the ionospheric layers at the stations having closely related latitudes (Norilsk–Zhigansk and Magadan–Yakutsk) are similar and typical of high-latitude ionospheric disturbances. Norilsk and Zhigansk are located at the southern boundary of the auroral ionization zone. Magadan and Yakutsk are located in the region of the statistical position of the main ionospheric trough ($L = 3$). To simplify Fig. 2 we show only Zhigansk and Yakutsk.

In Zhigansk the rise of the Kp leads to the appearance of sporadic F2 and E layers caused by fluxes from the diffuse precipitation zone. During the first main phase of the storm on November 8, reflections from the ionospheric layers were absent due to total absorption. In the following days, only Es layers were observed during evening and night hours. During the second recovery phase of the storm, an F2 layer with very low frequencies appeared during the morning of November 11. The total absorption was then observed again. Only in the evening did the F2 layer recover.

In Yakutsk on November 8 after the total absorption, Es and F2 layers appeared during the local evening. On November 9, the critical frequencies of the day F2 layer recovered to the quiet level. In the afternoon, the typical "dusk" effect was observed. It manifested itself as a small positive disturbance and abrupt decrease of foF2 (fall of the diurnal distribution) which is associated with the formation of the main ionospheric trough (MIT) in the afternoon (Whalen, 1989). Night was dominated by the sporadic F2 and E layers with reflection frequencies of 4–5 MHz. Short periods of absorption appeared later. In the second part of the day, there began the second main phase of the geomagnetic storm which resulted in the absence of reflections at high latitudes. In the following

Table 1
The list of ionospheric stations and their coordinates

Stations	Geographic		Geomagnetic	
	Latitude	Longitude	Latitude	Longitude
Norilsk	69.20	88.26	58.71	165.7
Zhigansk	66.3	123.4	55.2	190.0
Yakutsk	62.0	129.6	50.99	194.1
Petropavlovsk	53.02	158.65	44.7	219
Irkutsk	52.5	104.0	41.1	174.8
Khabarovsk	48.5	135.1	37.91	200.4
Wakkanai	45.4	141.7	35.3	206.5
Manzhouli	44.0	117.0	32.0	189.0
Beijing	40.0	116	28.7	188
Kokubunji	35.7	139.5	25.5	205.8
Chongqing	29.0	106	18.1	177.8
Guanghou	23	113	11.7	184

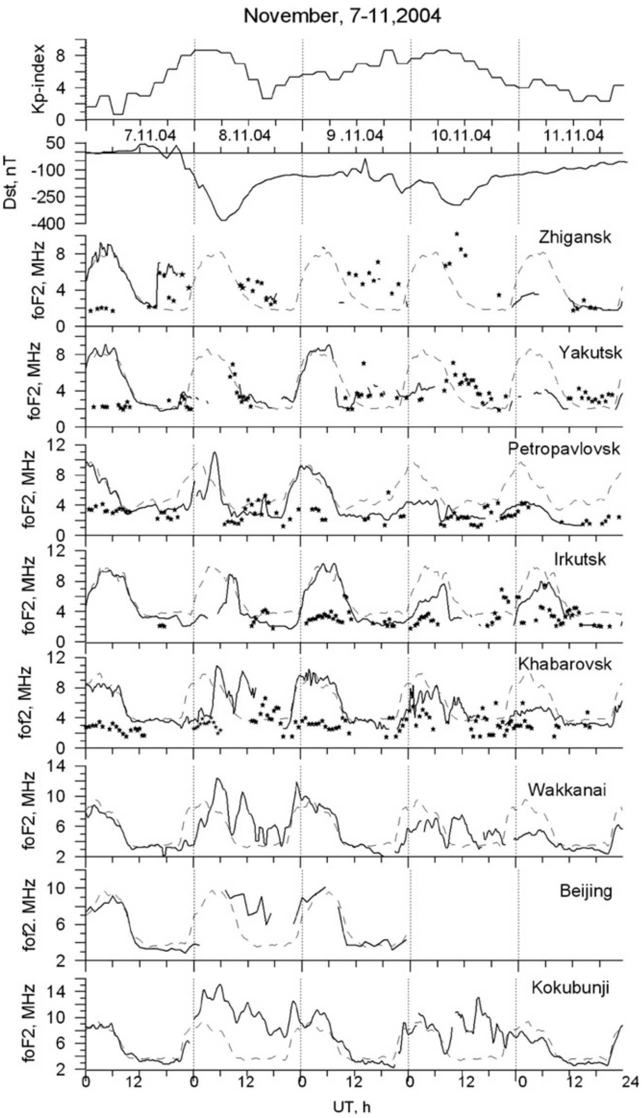

Fig. 2. Variations in the critical frequencies of the F2 and Es layers on November 7–11, 2004. The top part of the figure shows the values of the Kp and Dst indices. Dashed and solid curves show the undisturbed level and the current values of foF2; asterisks show foEs. LT = UT + (7 ÷ 9 h).

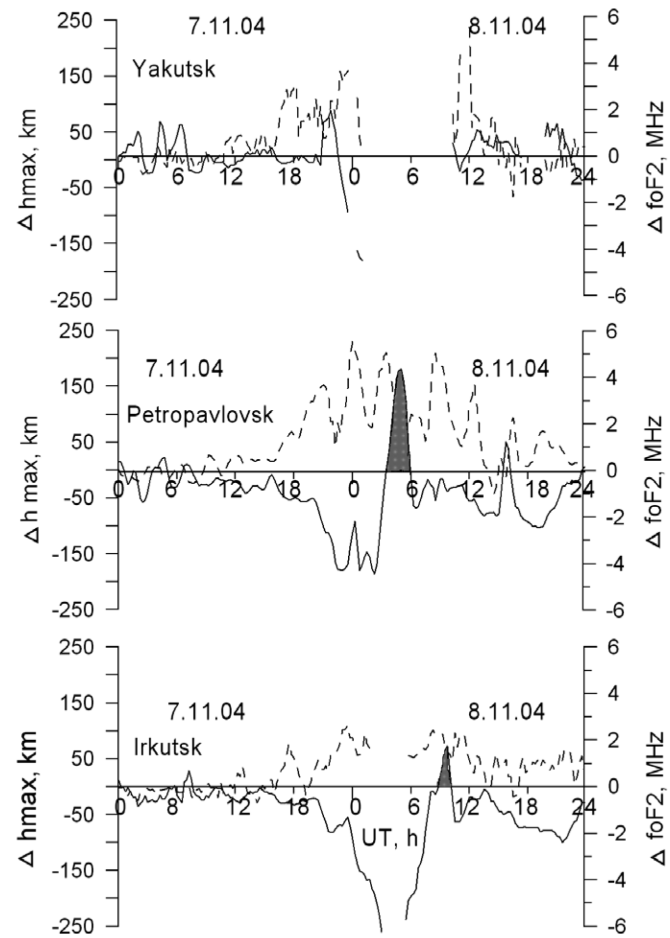

Fig. 3. Variations in the deviations of the critical frequencies and layer maximum heights on November 7–8, 2004, at Yakutsk, Petropavlovsk, and Irkutsk stations. Solid and dashed curves indicate ΔfoF2 and Δhmax F2.

two days during the second main and recovery phases of the storm, the F2 layer ionization remained extralow (about 4 MHz at noon). Intense sporadic layers that shielded the F region were observed at night.

More interesting data were obtained at midlatitude stations (Petropavlovsk, Irkutsk, Khabarovsk, and Wakkanai). During the first main phase of the geomagnetic storm on November 8, there were registered extralow critical frequencies for the F2 layer (4–5 MHz as compared to 9–10 MHz in quiet time), the intensive layering of the F region, and the F1 layer appeared during the morning and daylight hours of local time. All these manifestations are unusual for November. Abnormally high values of the critical frequencies (9–12 MHz) were observed for 2–3 h at midlatitude stations in the evening (06–15 UT). They are shown by hatching in Fig. 3, where the deviations of the critical frequencies and heights of the F2 layer maximum on November 7–8, 2004, at Yakutsk, Petropavlovsk, and Irkutsk stations are presented. There is also an appreciable rise of heights (more than 100 km). We can see that the variations of foF2 and hmaxF2 are random up to 17 UT. Then they are opposite to each other.

Such an increase of the critical frequencies was detected at other stations. The second night maximum of foF2 was also observed at Khabarovsk and Manzhouli. The level of the night ionization considerably increased with decreasing latitude separating into some peaks. Positive disturbances in Kokubunji (up to 100%) appeared only in the daytime.

Fig. 4 (lower panel) presents the foF2 variations in the LT–geomagnetic latitude coordinate system during the evening maximum of foF2 on November 8. We can see that the maximum is fixed in LT. Similar variations of the electron density in this period were also detected in other longitudes according to the data of the Japanese network of GPS stations [Maruyama, 2005]. Thus, we can state that there is a powerful large-scale disturbance detected at a large number of vertical sounding stations.

During the recovery phase on November 9, the foF2 day values recovered to the quiet level with small positive

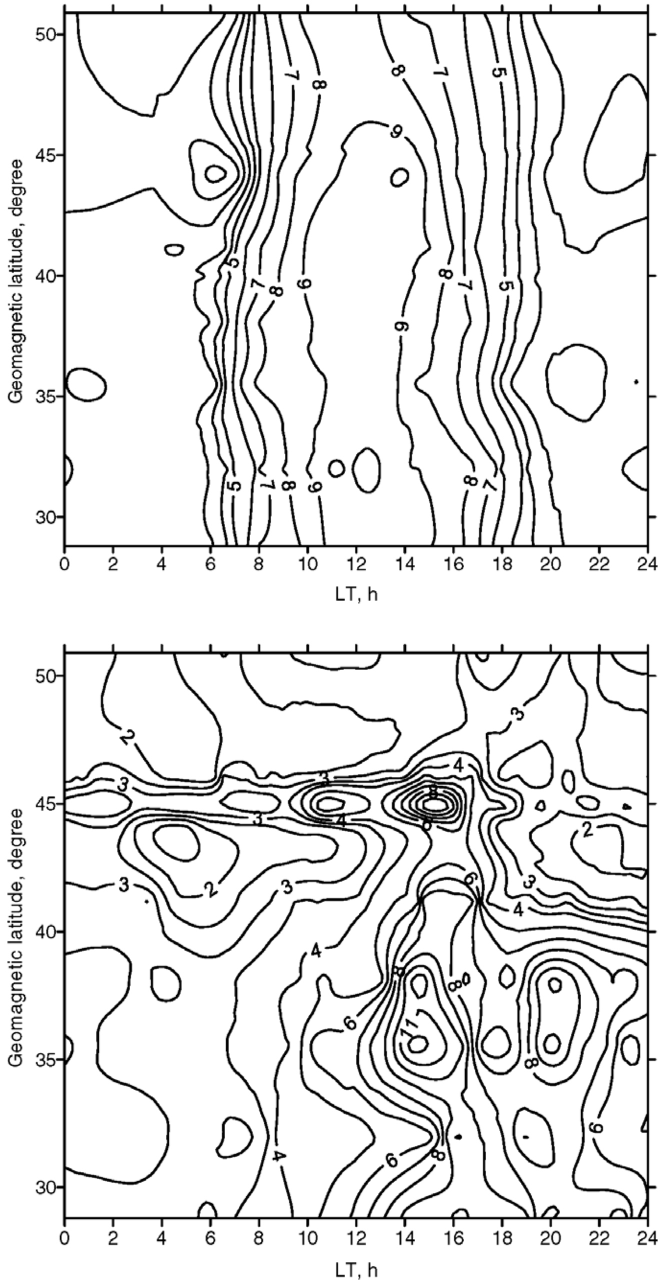

Fig. 4. Variations of foF2 in the LT – geomagnetic latitude coordinate system in the quiet day on November 5, 2004 (at the top) and disturbed day on November 8 (at the bottom).

disturbances at all stations. The commencement of the second main phase on November 10 produces a decrease of the day foF2 by 4–6 MHz. An increase of foF2 coincident in time with the second minimum Dst value was observed again in the evening hours in Irkutsk and at night in Petropavlovsk. However, its amplitude was smaller than on November 8. At lower latitudes, the duration and amplitude of the ionization night enhance increased, and a second night maximum of foF2 appeared, best seen at Kokubunji station. Intense sporadic layers of the flat type in the E layer which shielded the F2 layer at the night hours of November 10 were observed in Petropavlovsk, Irkutsk, and Khabarovsk. The behavior of ionosphere in the second recovery phase was absolutely different from that during the first recovery phase on November 9, when the critical frequencies of the F2 layer were close to the quiet level at almost all stations. The foF2 day values on November 11 were considerably lower than the quiet level (by about 40%) at both high and middle latitudes. In the evening and at night the values of the F2 layer critical frequencies in Petropavlovsk and Irkutsk were considerably lower than the quiet level. At lower latitudes, the critical frequencies were close to the undisturbed values.

3. Analysis of TEC data

The vertical sounding data were supplemented with GPS information. The GPS technology makes it possible to calculate TEC variations in the ionosphere on the basis of phase difference measurements at two frequencies (Afraimovich, 2000; Hofmann-Wellenhof et al., 1992). The phase measurements in the GPS system are carried out with a high degree of accuracy when the error in TEC determination does not exceed $10^{14}\,m^{-2}$, although the initial TEC value remains unknown (Hofmann-Wellenhof et al., 1992). In this paper, we use the TEC unit (TECU) equal to $10^{16}\,m^{-2}$ generally accepted in literature. Transformation of "oblique" TEC into its equivalent "vertical" value $I(t)$ is used to normalize the TEC disturbance amplitude (Klobuchar, 1986). The procedure of preliminary smoothing of the initial data set with a chosen time window of 30 min and linear trend removal is used to eliminate the variations of the regular ionosphere as well as the trends caused by satellite motion. By these means the filtered TEC data set of $I(t)$ are separated out.

3.1. Phenomenon on November 8

The ionosonde data showed a large-scale ionospheric disturbance with a single maximum from 03 to 10 UT in the region being study. This is confirmed by the data of the ground-based GPS receivers. Fig. 5 shows the geometry of the experiment performed in Eurasia (20–70°N; 20–180°E) on November 8, 2004. Dots show the GPS stations the data of which were available from the Internet. The classical similarity method was used to determine the velocity and direction of the disturbance motion. The TEC data at three spaced receiver–GPS satellite arrays were used to select variations similar in shape for all three data set (Afraimovich et al., 2004; Leonovich et al., 2004). The time of occurrence of TEC variation maxima and the corresponding position of the subionospheric points were determined. The velocity and direction of the disturbance propagation were determined on the basis of the delays of the maxima at three spaced points. Grey arrows in Fig. 5 show approximate directions of the propagation of the disturbances detected from the TEC variations at three different receiver–GPS satellite arrays.

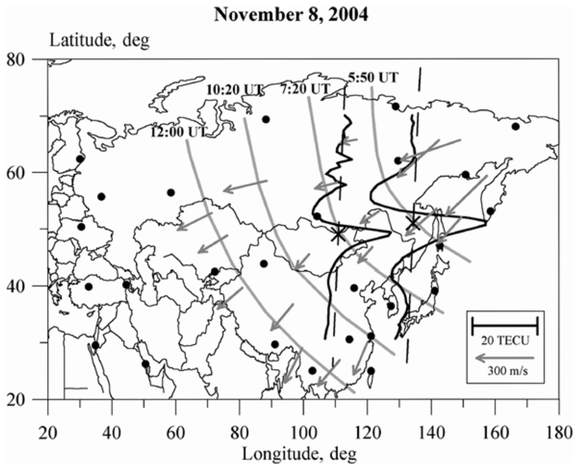

Fig. 5. Geometry of the experiment on November 8, 2004. Dots denote the GPS stations whose data are used. Grey arrows show the estimated directions of propagation of this disturbance. The length of the arrow represents approximately the value of the velocity (scale is indicated at the bottom right corner of the map). Grey lines show the rough locations of the TEC maximum at four times of UT. Heavy black lines show the TEC variations dI according the CHAMP satellite data.

The arrow length approximately represents the velocity value (the scale is shown in the bottom right-hand corner of Fig. 5). Grey lines indicate the approximate spatial positions of the TEC maximum for the four successive moments of time. They are based on the known time of the passage of the disturbance maximum over different GPS stations. The observed parts of the phase front were determined look like ring disturbance fragments with the apparent source in North-East of Asia. The disturbance existed for some hours and reached Ural in the west direction and the south region of China in the south direction. The values of the calculated velocities varied between 70 and 335 m/s. The motion azimuths were 200°–260°. Assuming that the mean velocity is approximately 200 m/s and the disturbance duration is approximately 3–4 h according to the vertical sounding data, the characteristic scale of the disturbance is ~2000 km. The obtained evaluations of the velocity and the direction of the disturbance front are close to the data presented by Maruyama (2005).

The spatial parameters of the large-scale disturbance of November 8, 2004, determined according to the data of both the ground-based network of GPS receivers and the GPS receiver onboard the CHAMP low-orbiting satellite (Afraimovich and Tatarinov, 2005), have been compared. The CHAMP satellite parameters appeared to be the most suitable for studying the ionospheric disturbance. The satellite was in a circular orbit at a height of 400 km and inclination of 87.3°. The orbiting period of the satellite was 93.55 min (GeoForschungsZentrum Potsdam // http://op.gfz-potsdam.de/). The CHAMP satellite therefore moved in the meridional direction almost at the height of the main ionization maximum.

Two black dashed lines in Fig. 5 present the projection of the CHAMP trajectory on the Earth for the time intervals 05.47–05.57 UT (on the right) and 07.19–07.29 UT (on the left). The satellite orbital velocity (~7.6 km/s) is higher than the maximum velocity of the disturbance (~335 m/s) by a factor of more than 20. Thus, the satellite provides almost instantaneous spatial cross sections of the studied disturbance. The TEC data were determined along the CHAMP-GPS PRN19 satellite line of sight. Heavy black lines show the TEC variations $dI(t)$ filtered to select the of 2–10 min periods range. Depending on the latitude of the CHAMP subsatellite point, the satellite orbiting at a high velocity results in filtered TEC variations corresponding to the spatial dimensions of the irregularities being studied in the 900–4500 km range. The spatial scale of the disturbance is ~2000 km. The scale of the TEC variations in TECU is indicated by the horizontal segment in the bottom right-hand corner of Fig. 5. The crosses on the trajectories present the approximate positions of the satellite at 05.50 and 07.20 UT at the time of observation of the TEC variation maxima. For the same times, the spatial positions of the disturbance maximum (gray lines in Fig. 5 that closely pass through the crosses) were reconstructed using the data of the ground-based GPS stations. It is clear that the spatial location of the disturbance reconstructed using the data of the the ground-based GPS stations, agrees with the data on the disturbance maximum position obtained with the CHAMP GPS receiver.

To compare the integral intensity of the studied disturbances according to the TEC data with the intensity of the electron density local disturbance, we used the TEC measurements at the PETP and IRKT GPS stations and the values of the critical frequency of the ionospheric F2 layer determined with the ionosondes in Petropavlovsk and Irkutsk. Unfortunately, at even higher latitudes the reflections from the F region were absent due to the absorption and shielding by the Es layer, and it turned out to be impossible to compare the GPS and ground-based sounding data. Solid curves in Fig. 6a and b indicate the filtered TEC variations of $dI(t)$ along the PETR-PRN06 and IRKT-PRN11 rays respectively. To estimate the relative amplitude of the disturbance we used the data of the absolute "vertical" TEC value, I_0, as the base value of TEC calculated from the data of the international IGS-GPS network (the GIM technology [Mannucci et al., 1998]). According to the data of the PETP and IRKT stations, the relative amplitude of the TEC disturbance, dI/I_0, is about 70%. The subionospheric points for the receiver–satellite beams used to obtain the TEC data were located at a distance of 280–500 km from the corresponding ionosondes. This value is much less than the spatial scale of the disturbance (~2000 km). Because of this, we can consider that the same disturbance was registered using the TEC data and critical frequencies. The lines with triangles in Fig. 6 represent the variations of foF2 critical frequency at intervals of 15 min. The scales of the corresponding values of the N_e electron density at the F2 layer maximum are shown in Fig. 6 on the right. The foF2 variations are approximately similar in shape to the TEC variations. The variations of the foF2 critical frequency correspond

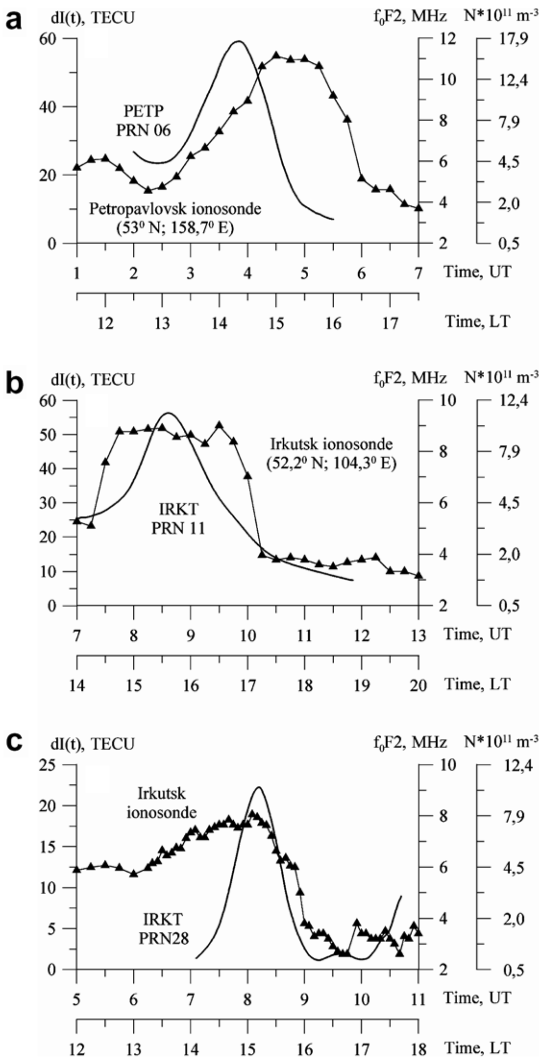

Fig. 6. Comparison of the ionospheric disturbance according to the TEC and foF2 data: (a) and (b) on November 8, 2004; (c) on November 10, 2004. TECU is equal to 10^{16} m^{-2}.

to the relative amplitude ($\Delta N/N$) of electron density disturbance of about 80% in the region of the F2 layer maximum.

3.2. Phenomenon on November 10

The positive large-scale disturbance of November 10, 2004, which had a single maximum (Fig. 6c) (as well as the disturbance observed on November 8, 2004), was studied in a similar way. The disturbance velocity and direction were also calculated using the similarity method based on the TEC data obtained at the ground-based network of GPS stations. The analysis of the TEC data showed that the disturbance velocity and azimuth are 400 m/s and 217°, respectively.

A solid curve in Fig. 6c presents the filtered TEC variations of $dI(t)$ at the IRKT-PRN28 array. The TEC maximum value was observed at approximately 08.15 UT and then there was a sharp decrease up to 20 TECU for 40–50 min. The relative amplitude of the jump in the TEC variations of dI/I_0 noted above determined using the data of the absolute "vertical" value of I_0 (Mannucci et al., 1998), was about 50%. The curve with triangles indicates the variations in the foF2 critical frequency. We can see that the foF2 and TEC variations have the maximum at the same time and are similar during the drop of the ionization. The observed decrease of the foF2 critical frequency corresponds to a relative change ($\Delta N/N$) in the electron density disturbance in the region of the F layer maximum of more than 85%.

4. Discussion and conclusions

The observed periods of full absorption and blanketing sporadic layers at high latitudes are typical of geomagnetic storms of high intensity and are due to precipitation of auroral fluxes. The variations of the AE index denote that the atmosphere considerably warms-up in the region of particle precipitation. This leads to changes in the constants of aeronomical reactions, enriching the ionosphere by molecular ions, as well as to intensification of the meridional wind that carries disturbed plasma to lower latitudes. The long-lasting negative disturbances of the electron density in the F2 layer are usually related to the changes in the circulation system and gas composition of the neutral atmosphere (Danilov and Lastovicka, 2001; Mikhailov and Foster, 1997). The importance of this factor decreases with decreasing latitude. It is notable that the critical frequencies of F2 layer recover quickly to the quiet level in the first recovery phase on November 9 at almost all stations.

As noted above, the main features of the ionospheric behavior during this storm was the appearance of large-scale ionospheric disturbances which were observed on November 8 and 10 according to the data of both the vertical sounding and global GPS networks. There were observed as a considerable increase of foF2 and TEC during evening hours of local time. The time of the disturbance appearance coincided with the time of Dst minima. The large-scale ionospheric disturbances propagated predominantly southwestward at mean velocities of 200 and 400 m/s on November 8 and 10, respectively. The characteristic spatial size along the propagation direction is about 2000 km.

The morphology of appearance of large-scale ionospheric disturbances has been discussed in many publications (Bauske and Prolss, 1997; Hocke and Schlegel, 1996; Karpachev and Deminova, 2004). It has been shown that such disturbances are related to generation of acoustic gravity waves (AGWs) in the auroral zone during magnetospheric disturbances, and the propagation of these waves to lower latitudes.

Kirchengast (1996) and Yeh and Liu (1974) suggested that the height range of 150–200 km in the vicinity of the ionospheric F region maximum mainly contributes to TEC modulation during AGW propagation. The relative amplitude of the $\Delta N/N$ disturbances described by these researchers did not exceed 20–30%. Afraimovich et al.,

(2006) analysed the theoretical and experimental investigations of the TID amplitude presented in the literature (Afraimovich et al., 2004; Hocke and Schlegel, 1996; Kirchengast, 1996; Testud and Francois, 1971;Yeh and Liu, 1974). The results of both calculations and experiments indicate that the relative TID amplitude ($\Delta N/N$) reaches its maximum value in the vicinity of 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 by a factor of two over an altitude range of about 100 km although the local electron density decreases at a much slower above the F2 maximum. Thus, the region of the ionosphere that mainly contributes to the TEC variations during the propagation of AGWs is located approximately at the altitude of the electron density main maximum, and the region of vertical extension above maximum is not more than 100–200 km.

The relative amplitude values of the disturbances on November 8 observed for according to the TEC (dI/I_0 $\approx$70%) and foF2 ($\Delta N/N \approx$80%) data indicate that the maximum deviations of $\Delta N/N$ at all ionospheric altitudes on the average were almost identical ($\sim$70–80%). It is therefore likely that the large-scale disturbance effected practically through the entire ionosphere. On November 10 the relative amplitude reached 50% and 85% according to the TEC and foF2 data, respectively. The corresponding ratio of the relative amplitudes was more then 50% at all heights. It is therefore difficult to explain the events of November 8 and 10 by AGW propagation.

Mendillo and Klobuchar (2006) assumed that such large positive disturbances are associated with a ‘‘dusk effect’’ followed by a ‘‘main ionospheric trough effect’’. However the night maximum which appears after that at midlatitudes (Khabarovsk, Wakkanai) does not fit in the above classification.

Thus the characteristics of the large-scale disturbances detected on November 8 and 10 indicate that the interaction between atmospheric, ionospheric, and magnetospheric processes is more complicated than the AGW or Mendillo and Klobuchar (2006) scenarios. There is a considerable need for additional models and morphology studies of a storms.

It should be noted that in the absence of reflections from the F2 layer ground-based ionosondes at high latitudes, the data of both ground-based and aboard low-orbiting satellite GPS receivers considerably compensates for the absence of the ionosonde information about variations of the disturbed ionosphere. The comparison of TEC and foF2 measured in Irkutsk and Petropavlovsk showed that the estimations of the time of the large-scale disturbance propagation determined using different methods are in a good agreement.

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