

First GPS-TEC evidence for the wave structure excited by the solar terminator

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Using TEC measurements from the global network of GPS receivers, we have obtained the first evidence for the wave structure excited by the solar terminator (ST), moving over the USA, Europe, and Japan. Two main types of the observed TEC disturbance were found: large-scale (LS) 60-min variations with an amplitude of about 0.5–1 TECU and medium-scale (MS) 15-min variations with an amplitude of about 0.05–0.1 TECU. The first type of disturbances was predicted in theoretical investigations and registered earlier using different methods of ionosphere radio sounding. The second type of the observed TEC disturbance is wave packets (WPs) generated when the time derivative of TEC is at its maximum. These WPs have duration of about 1–2 h and a time shift of about 1.5–2.5 h after the ST appearance at an altitude of 100 km. That ST-generated wave packets have been found for the first time. LS TEC disturbances and MS WPs are space-fixed along the ST line over a distance exceeding 1600 km.

Key words: Solar terminator, total electron content, wave packets, GPS.

1. Introduction

Recent investigations have shown that movement of the solar terminator (ST) causes the generation of acoustic-gravity waves (STAGW), turbulence, and instabilities in the ionosphere plasma (Beer, 1978; Cot and Teitelbaum, 1980; Somsikov, 1983, 1987; Somsikov and Ganguly, 1995; Dungenbaeva and Ganguly, 2004; Antonova *et al.*, 2006). It is worth noting that among all of the sources of gravity waves, the moving ST has a special status, since it is a predictable phenomenon, whose characteristics are well known. If the ST is considered to be as a stable and repetitive source of AGWs, one can derive information about atmospheric conditions from the response of the medium to this input.

The great variety of ST-linked phenomena in the atmosphere has resulted in a number of studies being carried out on the analysis of ionosphere parameter variations obtained by different methods of ionosphere sounding (Bezrodny and Yampolski, 1976; Popov and Yampolski, 1981; Galushko and Yampolski, 1983; Mishin *et al.*, 1991; Drobzhev *et al.*, 1992; Bezotosnyi *et al.*, 1994; Beley *et al.*, 1995; Sobral *et al.*, 1997; Galushko *et al.*, 1998; Hocke and Igarashi, 2002; Galushko *et al.*, 2003). However, virtually all experimental data were obtained using indirect methods for analyzing the spectrum of ionosphere parameter variations, which can result from a number of factors. This has caused difficulties in the reliable identification of STAGWs because, in general, AGWs can be generated by different sources of either natural or of anthropogenic origin (Hocke and Schlegel, 1996).

To identify ST-generated wave disturbances it is insufficient to register the time dependence of ionosphere parameters or their spectrum. Rather, it is necessary to measure

the spatial structure of these disturbances and to compare it with spatial-temporal characteristics of ST. Another important requirement implies the continuous, global character of the observations.

Considerable progress has recently been achieved in the study of ionosphere irregularities using the new technology of GPS radio sounding, which allows data to be obtained on variations of the total electron content (TEC) with high spatial and temporal resolution. The ISTP SB RAS developed methods and a technology for the global GPS detector of ionosphere disturbances, whose high sensitivity enables the analysis of ionosphere disturbances with amplitudes as high as 10^{-3} of the TEC background value (Afraimovich and Perevalova, 2006). Compared to classical radio probing tools for the ionosphere, this technology is the first to ensure real continuous and global coverage providing monitoring of ionosphere disturbances.

The goal of this paper is to present the first evidence for the TEC wave structure excited by the solar terminator. The data were obtained at the global network of two-frequency GPS receivers. As examples we have chosen day 291 (October 18, 2001) for the USA and Europe, and several days for Japan—that is, regions with dense GPS networks.

2. GPS Data Processing and Results

The data we used in our work are available in the standard RINEX format with sampling intervals of 30 s from sites (<http://sopac.ucsd.edu/cgi-bin/dbDataByDate.cgi>) and (ftp://terras.gsi.go.jp/data/GPS_products/). Standard GPS technology provides the means for detecting wave disturbances based on phase measurements of slant TEC I_s . Methods for calculating I_s using GPS phase measurements are described in detail in Hofmann-Wellenhof *et al.* (1992), Afraimovich *et al.* (2003), and Afraimovich and Perevalova (2006). We reproduce here only the final formula for phase

measurements:

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

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 are 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); nL is error in determining the phase path, (m).

Phase measurements in the GPS can be made with a high degree of accuracy corresponding to the error of TEC determination of at least 10^{14} m^{-2} when averaged on a 30-s time interval, although with some uncertainty of the initial value of TEC (Hofmann-Wellenhof *et al.*, 1992). This makes it possible to detect ionization irregularities and wave processes in the ionosphere over a wide range of amplitudes (up to 10^{-4} of the diurnal TEC variation and periods (from 24 h to 5 min). The unit of TEC, which is equal to 10^{16} m^{-2} (TECU) and widely accepted in the literature, will be used in the following.

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

$$I(t) = I_s(t) \times \cos \left[\arcsin \left(\frac{r_z}{r_z + h_{\max}} \cos \theta_s \right) \right] \quad (2)$$

where r_z is the Earth's radius, and $h_{\max} = 300$ or 400 km is the assumed altitude of the ionospheric F_2 layer maximum. To obtain the absolute vertical TEC, we use the CODG global ionospheric map GIM in the IONEX format (<ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex/>).

To eliminate the variations of the regular ionosphere and trends caused by the satellite travel, we first smooth the initial series with the selected time window of 2 min and remove their linear trend with a window of about 90 min. We thus obtain the TEC variations $dI(t)$ in the range of periods 2–90 min corresponding to the AGW range of periods (Hocke and Schlegel, 1996).

Let us consider the first example. The geomagnetic situation on 18 October 2001 can be characterized as quiet: the K_p index varied from 1.0 to 1.7 (http://www.ukssdc.ac.uk/wdcc1/wdc_menu.html). The geometry of GPS measurements during morning ST moving over the U.S. West is shown in Fig. 1(a). The chosen GPS sites are marked by triangles; the names of the sites are written nearby. The coordinates of the sites are not given for reasons of space. Solid lines show the trajectory of subionospheric points for the chosen GPS satellite PRN-14 at $h = 400$ km; the motion direction is marked by arrays. The thick dotted gray line and arrow show the ST position at $H = 100$ km at 13.2 UT and direction of the ST motion. We approximately choose the altitude $H = 100$ km for the ST location, synchronization of ST appearance, and TEC disturbance commencements. Hence, the GPS ray at the chosen PRN-14 intersects the ST front.

For the PRN-14 and CTMS, MONB, KELS sites, Fig. 1(b, d) presents time dependencies of the initial TEC series $I(t)$ smoothed with the time window of 2 min and

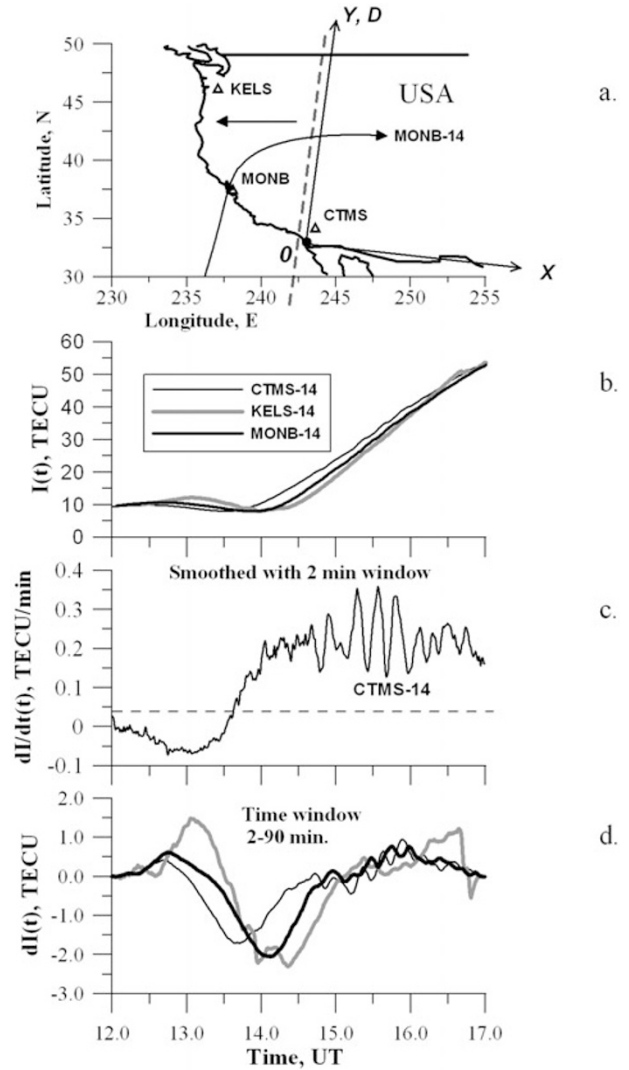


Fig. 1. Experimental geometry of GPS measurements during morning ST over the U.S. West on October 18, 2001 (a); Time dependencies of the initial TEC series $I(t)$ (b); Time derivative of the initial TEC series $dI(t)/dt$ (c); TEC series $dI(t)$ filtered in the range of 2–90 min (d).

TEC series $dI(t)$ filtered in the range of 2–90 min, respectively. Figure 1(d) presents two main types of the observed TEC disturbance: long-period (of about 60-min) variations with an amplitude of about 0.5–1 TECU and short-period (of about 15-min) variation with an amplitude of about 0.05–0.1 TECU. Long-period TEC variations are similar in shape, but they are shifted in time relative to each other according to ST appearance at different points.

Figure 1(c) presents the time derivative of the initial TEC series $\frac{dI(t)}{dt}$ smoothed with the time window of 2 min. Short-period oscillations of the TEC time derivative have the form of the wave train or wave packets (WPs). The WPs arise when the time derivative of the initial TEC series $\frac{dI(t)}{dt}$ amount to its maximum.

Figure 2(b) shows the LS structure of TEC disturbances along the morning ST over the western USA with the dense network of GPS sites. The initial TEC series $I(t)$ for PRN-14 (Fig. 2(b)) and TEC variations $dI(t)$ filtered within 20–90 min (Fig. 2(a)) are presented at different distances D from the center O (33°N ; 243°E) of the topocentric coordi-

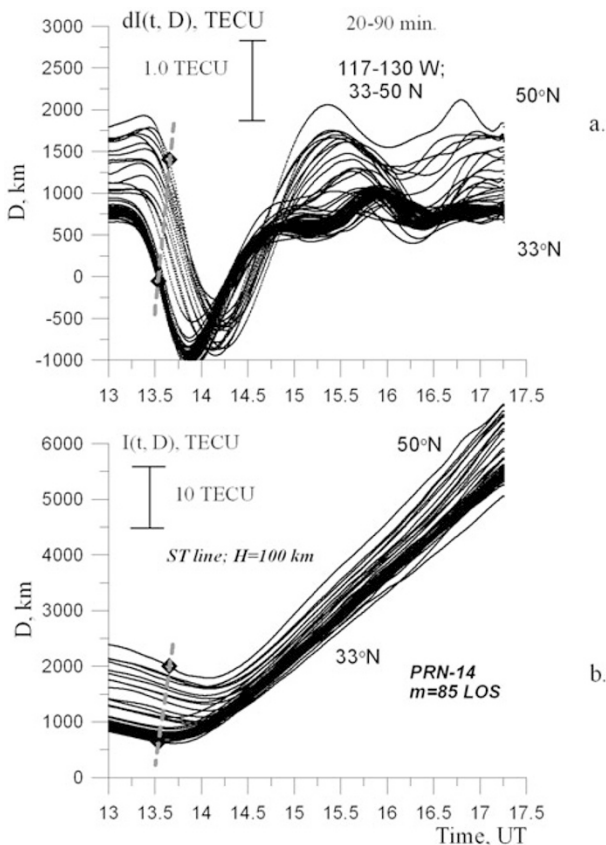


Fig. 2. Large scale structure of TEC disturbances along morning ST. Time dependencies of the initial TEC series $I(t)$ (b); TEC series $dI(t)$ filtered in the range of 20–90 min (a).

nate system (XOY), with coordinate axes (X, Y) directed perpendicular to and along the ST respectively (Fig. 1(a)). Thick gray dotted lines indicate the morning ST line at $H = 100$ km.

The distance D positive value corresponds to the axis Y one. Figure 2 presents the initial and filtered TEC as

$$D_i(t) = D_{0i} + k_1 I(t); \quad dD_i(t) = D_{0i} + k_2 dI(t) \quad (3)$$

where D_{0i} is the coordinate Y value for each GPS site located along the ST line (axis Y); i is the number of GPS sites (or line of sight, LOS, for the chosen satellite PRN14); $i = 1, 2, \dots, N = 85$; k_1 and k_2 are aspect ratios for $I(t)$ and $dI(t)$, respectively (marked by vertical bars in Fig. 2).

Figure 2(a, b) show that the observed LS disturbances are space-fixed along the ST line over the distance D exceeding 1600 km and travel with ST.

Figure 3 presents the MS structure for different GPS sites located along ST line (the U.S. West—left, U.S. East—middle, Europe—right) on 18 October 2001. The TEC oscillations $dI(t)$ are filtered from the initial TEC series in the time period of 2–20 min using the eight-order Butterworth band-pass filter. The diamonds mark the instant of the ST appearance at $H = 100$ km. The averaged diurnal dependences of the vertical TEC for the center of the said regions reconstructed from CODG IONEX data (<ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex/>) are plotted in the panels ((a): the horizontal gray lines on the time axis indicate the time interval using in panels (b–i)).

Names and coordinates of GPS sites and observed PRN are given on each panel. As is seen from Fig. 3, the observed MS TEC pulsations are wave packets with a duration of about 1–2 h. These WPs appeared about 1.5–2.5 h later than the ST at $H = 100$ km. The WPs arise on the stage of TEC fast increasing for morning hours (Fig. 3(a)), which corresponds to the maximum of the time derivative of the initial TEC series $\frac{dI(t)}{dt}$ for chosen PRN (Fig. 1(b)). The absolute amplitude of TEC disturbances (of about 0.05–0.1 TECU) is in accord with the relative amplitude $\frac{dI}{I}$ of about 0.2%. The main period of WPs varies from 12 to 17 min. Similar to the LS structure, WPs are space-fixed along the ST line over a distance exceeding 1000 km.

We choose the geomagnetic quiet day of October 18, 2001 ($K_p = 1-1.7$) for our detailed analysis. However, we obtained similar results for moderate geomagnetic disturbed days as well (Fig. 4). One can see TEC WPs over Japan for the disturbed days on 5 September 2004—left; on 25 September 2003—middle; on 15 November 2006—right. The well-known major earthquakes occurred in these days (<http://earthquake.usgs.gov/regional/world/historical.php>). The black triangles in Fig. 4 mark the main shocks. However, the WPs did not result from the earthquakes; rather they were generated by the ST. Figures 3 and 4 confirm that the ST-generated WPs were detected in different levels of geomagnetic activity and over different regions of the Earth.

3. Discussion and Conclusion

These data are the first evidence for the wave structure excited by the ST using TEC measurements from the global network of GPS receivers. Two main types of observed TEC disturbance were found: LS variations with an amplitude of about 0.5–1 TECU and MS wave packets with an amplitude of about 0.05–0.1 TECU. These structures are space-fixed along the ST line over a distance exceeding 1600 km. Hence, these observations confirm that the ST is a stable and repetitive source of ionospheric wave disturbances and also show that the GPS TEC representation of the ST-generated ionospheric structure suggests better possibilities for investigating this phenomenon.

This analysis revealed that the relative amplitude $\frac{dI}{I}$ of the variation in ST-generated LS disturbances in the middle latitudes can be compared with the TEC variation amplitude increase during a magnetic storm main phase and corresponds to changes in the local electron density up to 5–7% (Afraimovich *et al.*, 2008). The obtained results concerning the LS structure agree with theoretical indications of ST effects (Cot and Teitelbaum, 1980; Somsikov, 1983, 1987; Somsikov and Ganguly, 1995; Dungenbaeva and Ganguly, 2004; Antonova *et al.*, 2006) and do not contradict the experimental results obtained by Mishin *et al.* (1991), Beley *et al.* (1995), and Galushko *et al.* (1998, 2003). In particular, these results confirm the conclusion by Galushko *et al.* (1998) that ST-generated AGWs can be observed at sunrise better than at sunset (corresponding data will be presented in future publications). Using the GPS/MET observation at heights from 300 to 600 km, Hocke and Igarashi (2002) found the LS structure that may result from the disturbance

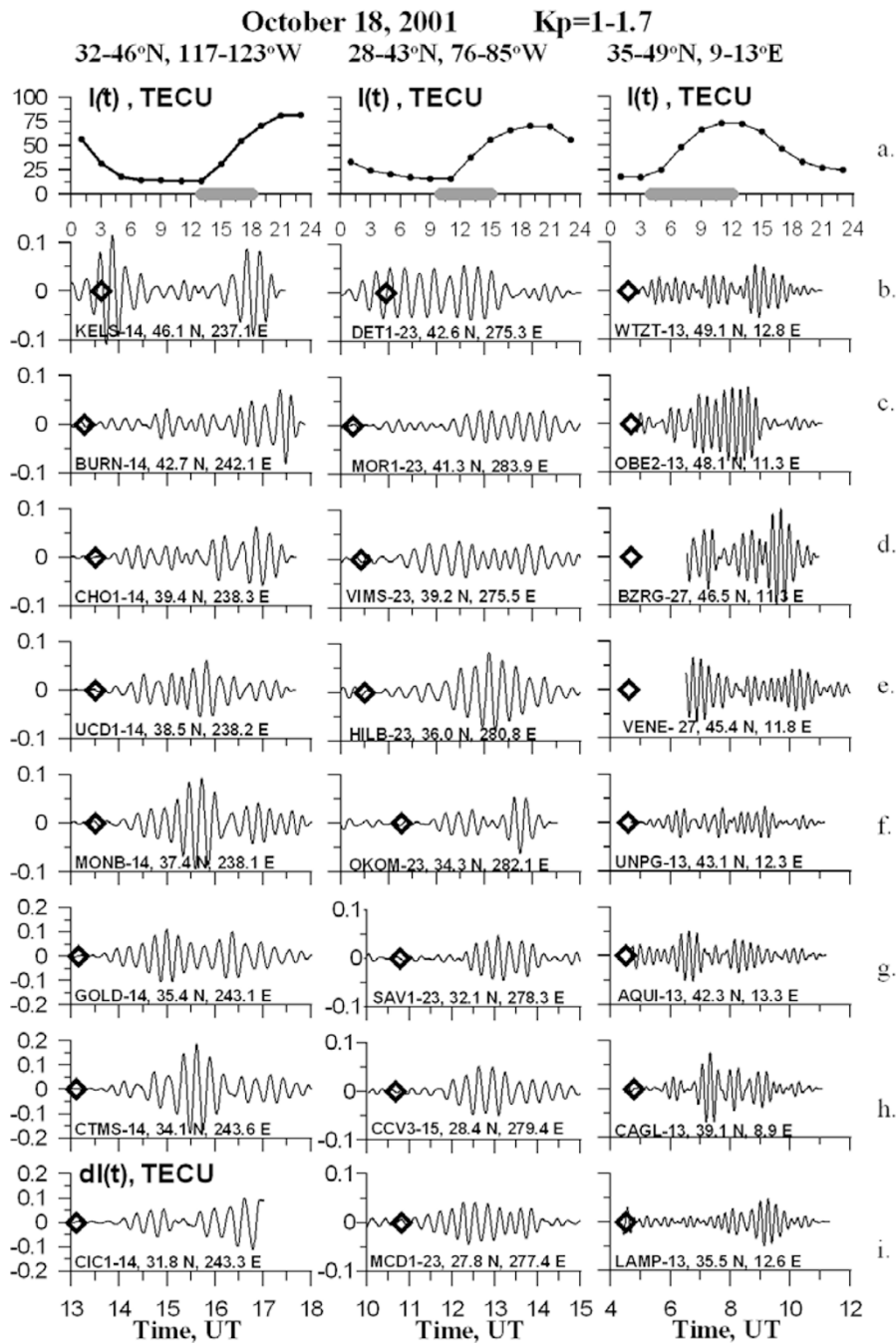


Fig. 3. TEC wave packets for GPS sites located along morning ST over U.S. West—left; over U.S. East—middle; over Europe—right.

of the thermosphere and ionosphere during the sudden sunrise at the dawn side.

The ST-generated WPs (the second type of the observed TEC disturbance) have been found for the first time. The term “wave packets” was first applied to ionospheric disturbances by Hines (1960). Following Hines (1960) and Francis (1974), we decided to use this term for the revealed processes. The investigation reported here has revealed that this designation describes most adequately the phenomenon considered. Particularly, WPs have a limited duration (of about 1–2 h) and follow the ST. Hence, WPs are wave processes for an observer in the fixed coordinate system on the Earth’s surface.

These WPs have duration of about 1–2 h and a time shift

of about 1.5–2.5 h after the ST appearance at $H = 100$ km. The more-pronounced WP effect can be observed at sunrise; the WP amplitude increases with increasing TEC gradient. The absolute amplitude of TEC WPs is sufficiently small and varies from 0.1 to 0.2 TECU for October 18, 2001 (Fig. 3), and from 0.02 to 0.03 TECU for 3 days over Japan (Fig. 4), which corresponds to the relative amplitude $\frac{dI}{I}$ by about 0.3% and 0.2%, respectively. Most likely this is the main reason why such a phenomenon has been unknown to date.

The obtained results are in agreement with the theoretical indications of ST effects (Somsikov, 1983) and do not contradict the results obtained by Somsikov (1992) and Drobzhev *et al.* (1992), which are based on limited statisti-

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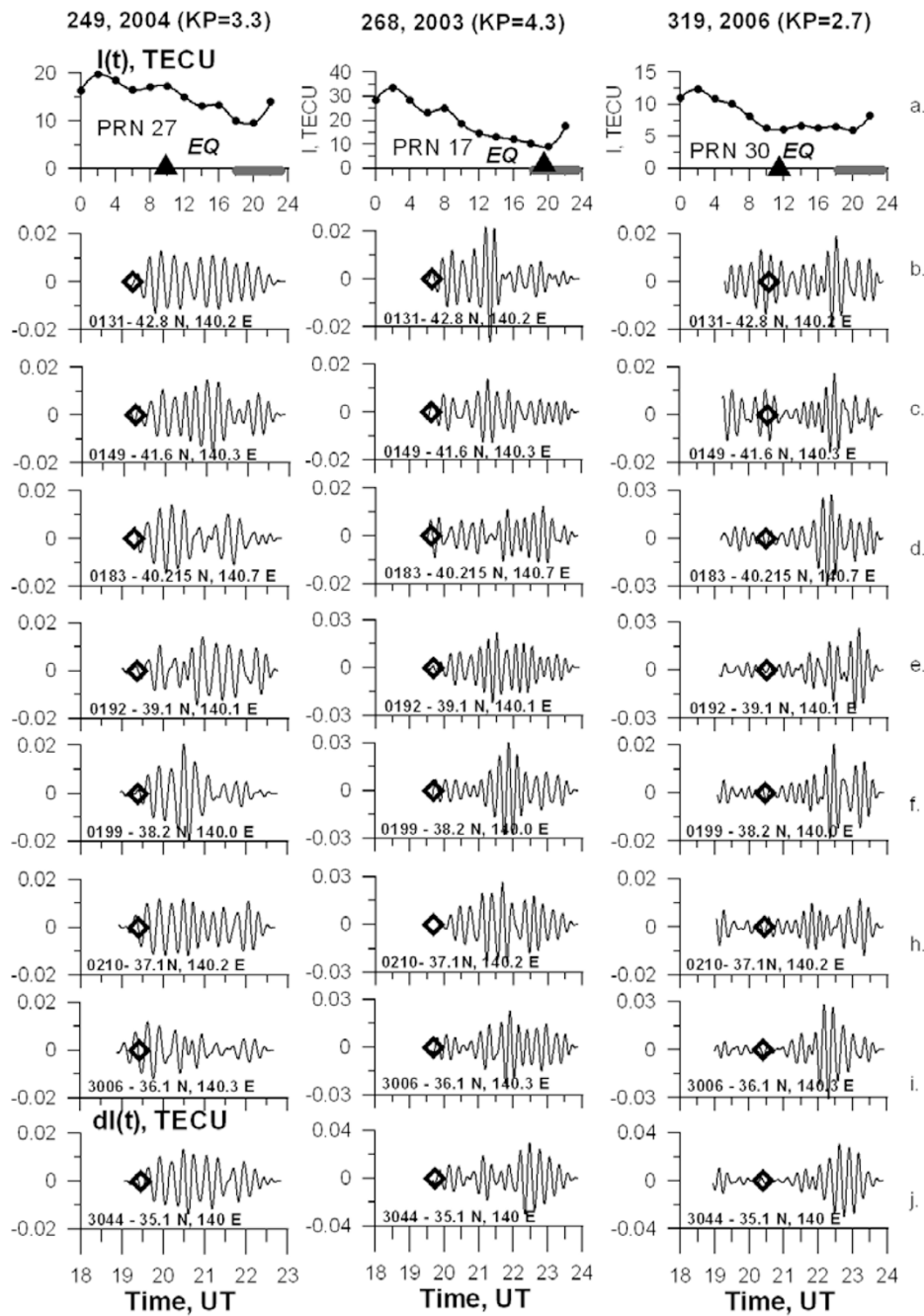


Fig. 4. TEC wave packets for GPS sites located along morning ST over Japan on September 5, 2004—left; on September 25, 2003—middle; on November 15, 2006—right.

cal material. Drobzhev *et al.* (1992) and Bezotosnyi *et al.* (1994) studied the dynamic spectra of the radio-wave reflection virtual heights obtained by vertical sounding of the ionosphere. It was shown that during transient hours of the day under magnetically quiet conditions, the low-frequency maximum of the spectra shifts to the higher-frequency region. Our results reinforce this conclusion.

The comparison between our detected WP and the data from Hines (1960) and Francis (1974) suggest that an additional amplitude modulation mechanism exists for wave processes that permits obtaining the closest TEC oscillations in the form of a single WP in the atmosphere. Taking

the auroral electrojet as a source of AGW, Francis (1974) showed that the ground-reflected waves gain the properties of a WP, when propagating through the atmosphere into the *F*-region. However, the 2001 October 18 event considered in this paper occurred in the mid-latitude region and at a sufficiently magnetically quiet period, when the conditions of realization of the Francis's mechanism are not satisfied.

The results obtained here do not completely correspond to the known mechanisms of the ionospheric irregularity generation and propagation in various latitudes and can contribute to the development of the theory. Our results are important for developing ionospheric irregularity physics and

modeling transionosphere radio wave propagation. Space-temporal features and the nature of the LS TEC and MS TEC structures will be analyzed in detail in future investigations.

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