Influence of the Earth's diurnal rotation on distribution of large-scale disturbances in the upper atmosphere

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Received August 6, 2007

Total Electron Content (TEC) data of the international GPS network were used to study the relation between dynamic parameters of a large-scale TEC disturbance and the motion of ionization caused by the Earth's diurnal rotation. The TEC disturbance generated in the Northern Hemisphere during the strong magnetic storm on October 29, 2003 has been examined. It was characterized as a large-scale wave of a solitary type with the annular front shape, whose apparent center was located near the geomagnetic pole. The velocity and distribution direction of the disturbance had a pronounced longitudinal dependence.

Introduction

Total Electron Content (TEC) data obtained by the GPS and GLONASS satellite navigation systems are widely used now for investigation of the structure and dynamics of the Earth's upper atmosphere. The density of receivers of the GPS network is much higher than that of all existing networks of ionospheric detectors. Taking into account that at any time the radio visibility zone of one GPS receiver includes from 5 to 8 navigation satellites, the Earth's ionosphere is now sounded simultaneously by thousands of "receiver–satellite" beams. This makes the GPS network a unique instrument for investigation of the upper atmosphere.

There were undertaken attempts [1–3] to determine spatial parameters and travel characteristics of a large-scale traveling ionospheric disturbance (LSTID), using the potential of the GPS global network and the methods of GPS interferometry developed in the ISTP SB RAS,[4] formed during the sudden magnetic storm commencement (SSC) on 10.29.2003 in the auroral zone. The geomagnetic storm of October 29, 2003, followed the very strong sunburst of X17.2 class, which took place on 10.28.2003. The storm had a pronounced SSC at 06:11 UT and was accompanied by the increase of the K_p index up to the highest value 9 ($D_{st} = -308$ nTl). Continuing the investigations,[1–3] we present the results of determination of LSTID dynamic characteristics and their possible connection with the motion of ionization attributed to the Earth's diurnal rotation.

Measurement technique

The initial data for our investigations were represented by $I_0(t)$ time series of slant TEC variations measured with double-frequency GPS detectors, as well as corresponding series of the elevation angles $\theta_S(t)$ and azimuths $\alpha_S(t)$ of the "detector–satellite" beams. When studying the global pattern of ionospheric response to the magnetic storm of 10.29.2003, the data of the global GPS network were used, located in five sectors of the Northern Hemisphere: West-American, East-American, European, Asian, and Far-East. In Fig. 1, these sectors of TEC variation detection are denoted as **A**, **B**, **C**, **D**, and **E**, while positions of GPS stations are shown by dots. The bold dashed curve shows the position of the southern boundary of the auroral oval at time 05:26 UT on 10.29.2003 (http://www.sec.noaa.gov/pmap), the cross stands for north magnetic pole (NMP). Squares mark the positions of geomagnetic-variation systems, whose data were used for monitoring the geomagnetic situation and for time reference.

To determine LSTID parameters, we selected continuous measurement series with duration no shorter than 3 h and a high quality of data (that is, without errors in phase measurements of TEC). For normalization of the disturbance amplitude, we used the transformation of the slant TEC $I_0(t)$ into the equivalent vertical value $I(t)$ [Ref. 5]. The common TEC measurement unit is TECU (Total Electron Content Unit) equals to 10^{16} m^{-2}.

To separate LSTID, TEC variations $dI(t)$ with periods 30–90 min have been filtered out from the TEC measurement series. The horizontal velocity V_h and the azimuth α of LSTID travel were calculated using the SADM-GPS algorithm.[4] This algorithm is based on calculation of space and time gradients of the electron concentration from TEC measurements at three spatially separated GPS stations (GPS grid). In each sector, all possible sets of grids were used, whose base lengths did not exceed a half of the expected LSTID wavelength.

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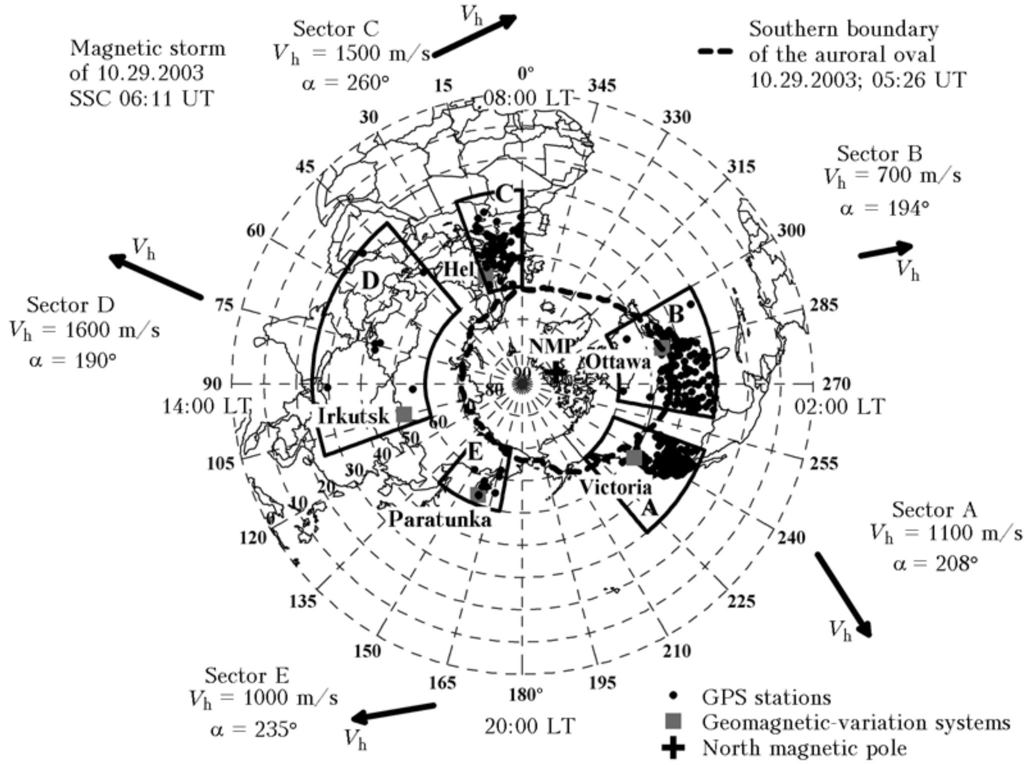

Fig. 1. Geometry of measurements during the magnetic storm of October 29, 2003.

LSTID travel in the auroral zone

In all sectors after SSC, we observed the wavy TEC disturbance with period 40–60 min. As was found in Refs. 2 and 3, the disturbance had a character of solitary wave and an annular shape. Its center lied near the geomagnetic pole. The comparison with the data of geomagnetic-variation systems has shown that the disturbance appears during the sharp change in the time derivative of the strength of the Earth's magnetic field.

The mean values of the velocity and direction of travel of detected LSTID calculated by the SADM-GPS algorithm in each sector are shown in Fig. 1 and summarized in Table. In addition, Table presents the regional average values of the amplitude ΔI and period T of the disturbance along with the number of the processed TEC series. Bold black arrows in Fig. 1 indicate the direction of the LSTID horizontal velocity, representing approximate trajectories of disturbance distribution in different regions.

The analysis of the obtained data shows that the velocity and travel direction of the disturbance have a pronounced longitudinal dependence. The lowest velocity is recorded in the night hemisphere, which is likely connected with the low plasma density in the night ionosphere. The comparison with the data of global maps of vertical TEC (GIM, ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex) confirms this assumption: the lowest TID velocity (700 m/s) was observed in the region with minimal TEC values, while the highest one (1600 m/s) was observed at the day side, where the TEC values were maximal (Fig. 2).

LSTID parameters in different sectors

Sector, region	V_h, m/s	V_h RMS dev., m/s	α, deg	α RMS dev., deg	Number of series	ΔI, TECU	T, min
A, West-American	1090	364	208	7	120	0.4	48
B, East-American	684	310	194	30	80	1.3	48
C, European	1508	540	259	46	4/86	1.2	60
D, Asian	1640	397	194	93	7/23	2.2	54
E, Far-East	1013	350	235	32	11	2.5	60

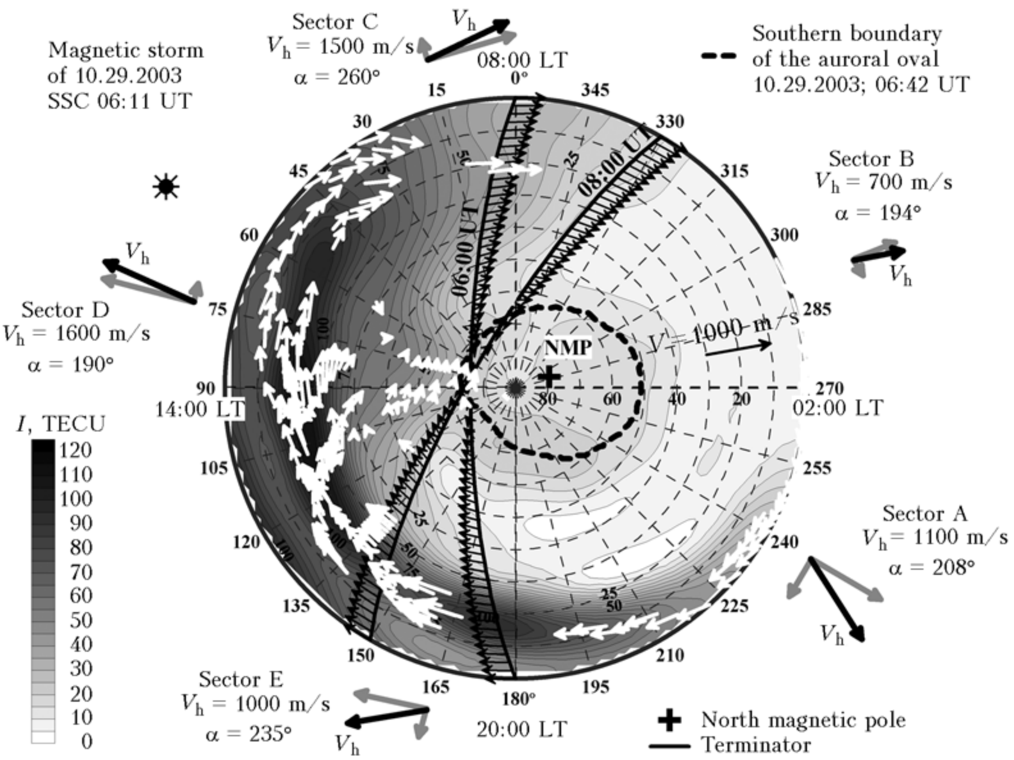

Fig. 2. Comparison of travel of TEC isolines (white arrows) with LSTID travel (black arrows along the perimeter of the figure).

Gray arrows in Fig. 2 show zonal and meridional components of the horizontal LSTID velocity.

In general, the disturbance propagates in the equatorial direction. At the same time, the effect of "swirling" of the distribution direction to the side, opposite to the direction of Earth rotation, is clearly seen. This "swirling" is caused by the significant magnitude of the zonal component of the LSTID velocity directed to the west (see Fig. 2). In morning and evening sectors, the zonal component of the velocity exceeds the meridional one. At the night and day sectors, the travel direction is close to meridional.

Travel of TEC isolines

We have supposed that the motion of background ionization influences the character of LSTID travel. To check this hypothesis, the velocity and travel direction of TEC isolines were calculated by the GIM maps. For this purpose, five reference points were chosen on every isoline, the trajectory of their motion was traced, and the velocity was calculated. The following points were taken as reference ones: the easternmost point (with the maximal longitude $\lambda_{\max}$), the westernmost point (with the minimal longitude $\lambda_{\min}$), the northernmost point (with the maximal latitude $\varphi_{\max}$), and the southernmost point (with the minimal latitude $\varphi_{\min}$), as well as the centroid of the contour. The centroid coordinates (longitude λ_c and latitude φ_c) were calculated as coordinates of the centroid of a plane figure bounded by the selected isoline[6]:

$$\lambda_c = \frac{1}{S}\int_{\lambda_{\min}}^{\lambda_{\max}} \lambda[f_1(\lambda) - f_2(\lambda)]d\lambda,$$

$$\varphi_c = \frac{1}{2S}\int_{\lambda_{\min}}^{\lambda_{\max}} [f_1^2(\lambda) - f_2^2(\lambda)]d\lambda,$$

where $f_1(\lambda)$ and $f_2(\lambda)$ are the "upper" and "lower" parts of the isoline bounded by the extreme eastern and western points; S is the area of the figure inside the isoline. For calculations, we took isolines, which crossed any meridian at no more than two points (that is, had not "tongues" and so on).

The maps of distribution of travel velocities of TEC isolines (white arrows) under calm (*a*, *b*) and disturbed (*c*, *d*) conditions are shown in Fig. 3.

The black line with arrows shows the position and travel velocities of the terminator on the Earth's surface. The velocity scale $V = 1000$ m/s is specified by the black arrow. TEC isolines move along the parallel: the azimuth in all cases is close to 270° (rms deviation in determination of the azimuth is −40°). The isoline velocity depends on the latitude. At low (10–30°) latitudes, it varies from 350 to 600 m/s, and at latitudes of 60–75° it decreases to 50–100 m/s. The terminator velocity changes analogously: it is 463 m/s at the equator and 100 m/s

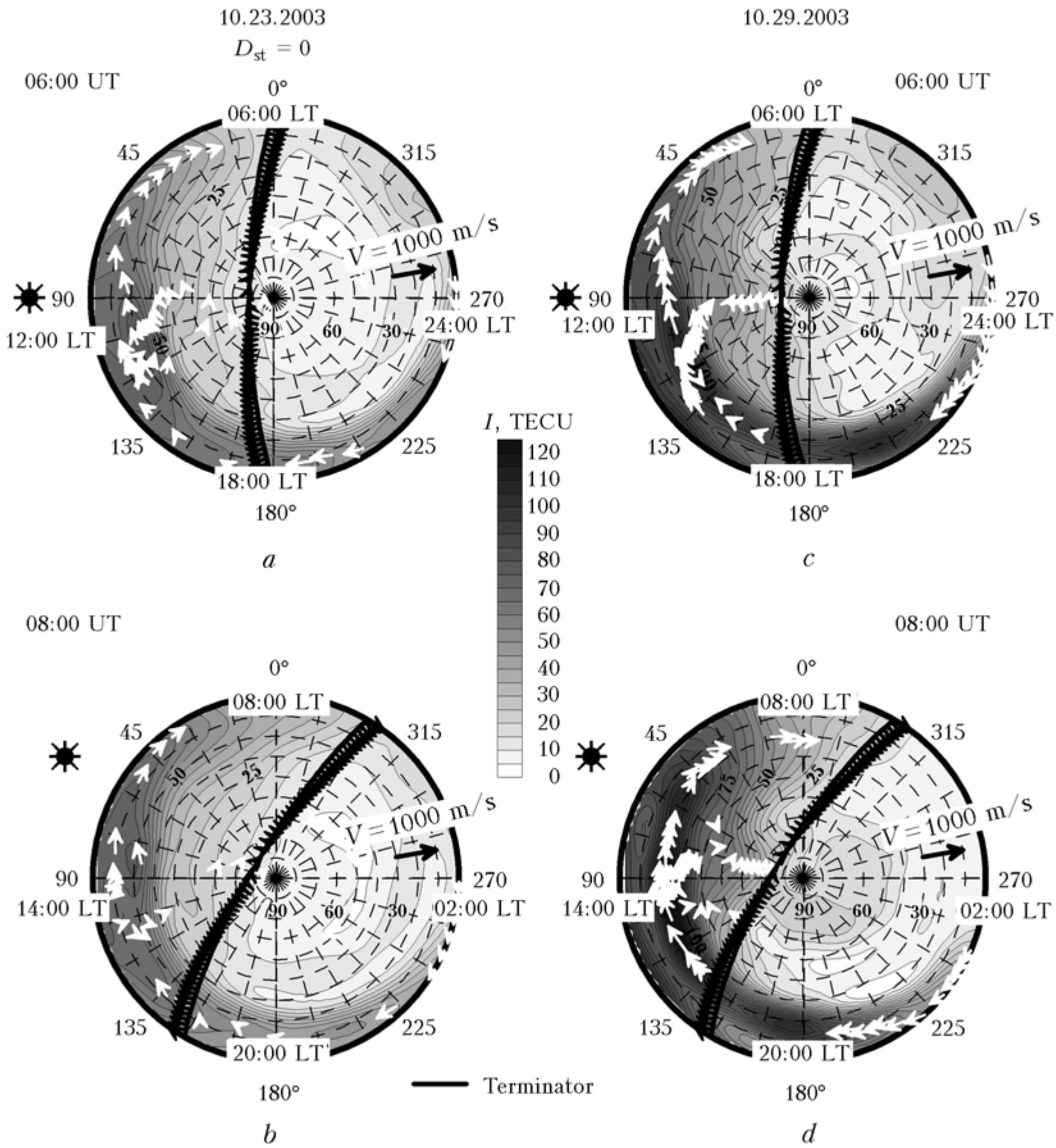

Fig. 3. Motion of TEC isolines (white arrows) under calm (*a*, *b*) and disturbed (*c*, *d*) conditions.

at a latitude of 77.5°. No marked differences have been found in the character of motion of TEC isolines in the calm day of 10.23.2003 and during the storm of 10.29.2003. Only insignificant (about 30%) increase in the absolute value of velocity was observed in low latitudes during the storm. Thus, according to our calculations, the displacement of TEC isolines is determined by the diurnal rotation of the Earth.

Results and discussion

Deflection of LSTIDs formed as a result of geomagnetic storms from the equatorial direction was noticed many time. The "swirling" of the LSTID wave front to the west was detected when investigating the effects of the magnetic storm on September 25, 1998, from the data of a network of North-American stations.[4] The direction of the wave vector changed along the wave front from 245° at a longitude of 16:00 LT to 177° at a longitude of 19:00 LT. The closer to the night local time, the closer to equatorial direction was the travel direction. In addition, Ref. 4 reported the observation of a large-scale TEC disturbance in the Southern Hemisphere, which traveled generally to the equator, but with significant (about 30°) deflection to the west. These results are in complete agreement with the data obtained in this work.

All papers presenting numerical values of the LSTID azimuth mention the azimuth deflection by 10–20° to the west.[7–10] Most authors attribute this effect to the action of the Coriolis force on propagation of acoustic-gravity waves in the atmosphere. A quite different mechanism was supposed in Ref. 11. According to Ref. 11, "swirling" of the LSTID front is a result of intense plasma flows emitted from rotating polar caps. The question on the causes of deflection of the LSTID travel direction from the equatorial one is still to be answered.

Comparison of the motion of TEC isolines calculated by us with the LSTID travel (see Fig. 2) shows that the longitudinal travel of the ionization maximum for 24 hours can affect the zonal transport of the TEC wave disturbance. The effect is especially strong near the terminator, where variations of the electron concentration are most pronounced. The zonal transport manifests itself in the displacement of the LSTID annular front center relative to the magnetic pole. In addition, the cyclic motion of the TID annular disturbance as a whole, following the displacement of the background ionization, is observed.

Conclusions

The data of TEC measurements on the GPS global network during the magnetospheric storm of 10.29.2003 have been used to study the influence of the diurnal motion of the background ionization on the dynamic characteristics of TEC large-scale wave disturbance. It has been shown that the disturbance velocity and travel direction had the pronounced longitudinal dependence. The lowest velocity (700 m/s) was observed at the night hemisphere, where TEC values are minimal, while the highest velocity (1600 m/s) was measured at the day hemisphere, where TEC values are maximal. The effect of "swirling" of the travel direction of auroral LSTID to the side opposite to the Earth rotation was noticed. The "swirling" is caused by the significant value of the zonal component of the LSTID velocity directed to the west. In the day and night sectors, the travel direction was close to meridional, while in the morning and evening sectors the zonal component of the velocity exceeded the meridional one.

Comparison with the GIM maps has shown that the zonal transport of the wave disturbance is likely caused by the longitudinal motion of the ionization maximum connected with the diurnal rotation of the Earth.

Acknowledgements

The authors are grateful to specialists of the Laboratory of Geodynamic Investigations of KOMPS of the Geophysical Service of the Russian Academy of Sciences for initial data of the Kamchatka Regional GPS Network and to specialists of the Scripps Orbit and Permanent Array Center (SOPAC) for the initial data of the Global GPS Network.

The work was supported in part by the Russian Foundation for Basic Research (Grants No. 05-05-64634 and No. 06-05-64577) and by the SB RAS Integration Project No. 3.24.

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