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NOVEL TECHNOLOGY FOR DETECTING ATMOSPHERIC DISTURBANCES USING GPS. INSTANTANEOUS RESPONSE OF THE IONOSPHERE TO A SUDDEN COMMENCEMENT OF THE STRONG MAGNETIC STORMS

E. L. Afraimovich, E. A. Kosogorov, L. A. Leonovich, O. S. Lesyuta, and I. I. Ushakov

*Institute of Solar-Terrestrial Physics, Russian Academy of Sciences, 664033 Post Box 4026,
Irkutsk, Russia, e-mail:afra@iszf.irk.ru*

ABSTRACT

We developed a new technology for global detection of atmospheric disturbances, on the basis of phase measurements of the total electron content (TEC) using the international GPS network. Temporal dependencies of TEC are obtained for a set of spaced receivers of the GPS network simultaneously for the entire set of visible satellites. These series are subjected to filtering in the selected range of oscillation periods using known algorithms for spatio-temporal analysis of signals. An “instantaneous” ionospheric response to the sudden commencement of the strong magnetic storms were detected. On the dayside of the Earth the largest value of the net response amplitude was found to be of order 0.4 TECU (2-3 % of the background TEC value), and the delay with respect to the SSC in mid-latitudes was about 360 s. In higher latitudes the delay goes up to 15 min. On the nightside these values are 0.2 TECU and 30 min, respectively. The velocity of the traveling disturbance from the middle to high latitudes on the dayside as well as from the dayside to the nightside was about 10-20 km/s.

INTRODUCTION

Mid-latitude ionospheric effects of geomagnetic disturbances of different origins were addressed in many publications, including a number of thorough reviews (Hunsucker, 1982; Hocke and Schlegel, 1996). It is now a well-established fact that the auroral zones of the northern and southern hemispheres generate acoustic-gravity waves (AGW) and traveling ionospheric disturbances (TIDs), caused by them, of the type of solitary wave of about 1-hour duration propagating in the equatorial direction with sound and subsonic speeds (from 100 to 300 m/s). The occurrence delay τ of TIDs over various observing stations in mid-latitudes reaches 10^4 s. The propagation velocity fundamentally distinguishes the TIDs from sudden ionospheric disturbances (SIDs) which are a virtually instantaneous (τ no more than 10^{-3} s) response of the dayside ionosphere to an increase in ultraviolet radiation intensity observed during chromospheric flares on the Sun (Mitra, 1974). The physical mechanisms for generation of the above-mentioned types of disturbances were discussed in a large number of theoretical publications, and are considered to be relatively reliably established.

By analyzing the ionospheric effects from the strong magnetic storms, we detected, most likely, a new manifestation of geomagnetic disturbances in the mid-latitude ionosphere implying an “instantaneous” (compared to the above-mentioned TID effects) ionospheric response to the magnetic storm sudden commencement (SSC). For detecting this effect, we used a global spatial averaging of the variations in total electron content (TEC) obtained from the data from the international GPS network. Currently (as of February 2001) this network includes at least 800 points, the data from which are posted to the INTERNET. High-precision measurements of the TEC along the line-of-sight (LOS) between the receiver on the ground and transmitters on the GPS system satellites covering the reception zone are made using two-frequency multichannel receivers of the GPS system at almost any point of the globe and at any time simultaneously at two coherently coupled frequencies f_1=1575.42 MHz and f_2=1227.60 MHz. The sensitivity of phase measurements in the GPS system is sufficient for detecting irregularities with an amplitude of up to 10^{-3}-10^{-4} of the diurnal TEC variation. This makes it possible to formulate the problem of detecting ionospheric disturbances from different sources of artificial and natural origin.

USING THE DATA FROM A GLOBAL GPS NETWORK IN THE CONTEXT OF A GLOBDET TECHNOLOGY

Input data are represented by series of "oblique" values of TEC I(t), as well as by the corresponding series of elevations $\Theta(t)$ measured from the ground, and azimuths $\alpha(t)$ of the line of sight to the satellite measured clockwise from the northward direction. These parameters are calculated by our developed CONVTEC program by converting the GPS-standard RINEX-files (Gurtner, 1993) from the INTERNET. The GPS technology provides the means of estimating TEC variations on the basis of phase measurements of TEC (I) in each of the spaced two-frequency GPS receivers using the formula (Hofmann-Wellenhof, 1992; Pi, 1997).

The procedure of determining the disturbance-associated characteristics is based on selecting several series of TEC I(t) measurements having a length of 1 hour at least. To exclude the influence of signal reception conditions we used only the observations with satellite elevations $\Theta(t)$ larger than 30^0. To eliminate the variations of a regular ionosphere, as well as trends introduced by the satellite motion, we apply the procedure of removing the linear trend with a preliminary smoothing of the initial series, with the selected time window of a duration of about 30 min.

The GLOBDET software package (Afraimovich, 2000a), which has been used in this study, performs a global coherent accumulation of TEC series over a time interval of interest (Afraimovich, 2000b)

$$S(t) = \sum_{i=1}^{m} dI_i \times k_i$$

where dI_i is the filtered TEC series; k_i is the correction factor for the geometry of the beam connecting the "satellite-receiver"; and m is the number of beams.

The correction factor k_i is calculated for converting the "sloping" TEC to an equivalent "vertical" value by the expression (Klobuchar, 1997)

$$k_i = \cos[\arcsin(\frac{R_z}{R_z + h_{\max}} \cos\Theta_i)]$$

where R_z is the Earth's radius, km; and h_{max} is the height of the ionospheric F2 layer maximum.

The TEC values are in TECU units ($1 \text{TECU} = 10^{16} m^{-2}$).

RESULTS OF OBSERVATIONS

Ionospheric Response To The SSC Of A Strong Magnetic Storm Of April 6, 2000

For the time interval 16:00-18:00 UT, Figure 1 presents the variations in magnetic flux (a) at geostationary orbit of the GOES10 station (135^0 W), and of the H-component of the magnetic field at station Irkutsk (52.2^0 N; 104.3^0 E) (b) for April 6, 2000.

The time of the geomagnetic disturbance SSC, determined from these data and from the data from other ground-based magnetic observatories, including those located in the western hemisphere (on the dayside), corresponds to 16:42 (16.7) UT. The time of SSC is shown on panels (a-d) by a vertical dashed line.

The geometry of the part of the global GPS network that was used in this study when analyzing the ionospheric response to the SSC of the strong magnetic storm of April 6, 2000 (180 stations), is presented in Figure 1e. Dots correspond to the location of GPS stations; we do not give here their coordinates for reasons of space. The upper scale indicates the local time LT, corresponding to the time 16 UT. As is evident from Figure 1e, our selected set of GPS stations cover reasonably densely North America and Europe, and much less densely the Asian part of the territory used in the analysis. An even smaller number of GPS stations are in the Pacific and Atlantic Oceans. However, coverage of the territory with partial LOS to the satellites for our selected limitations to the LOS elevations $\Theta > 30^0$ is substantially wider. Panel f shows the coordinates of subionospheric points for the height of the F2-layer maximum h_{max} = 300 km for all satellites visible at the SSC time for each of the GPS stations marked on panel e (a total of 746 beams).

An analysis of the TEC data from the selected GPS stations revealed that almost all stations over the time interval 16:30-18:30 UT, containing the SSC time, show a single negative disturbance of about 20-min duration.

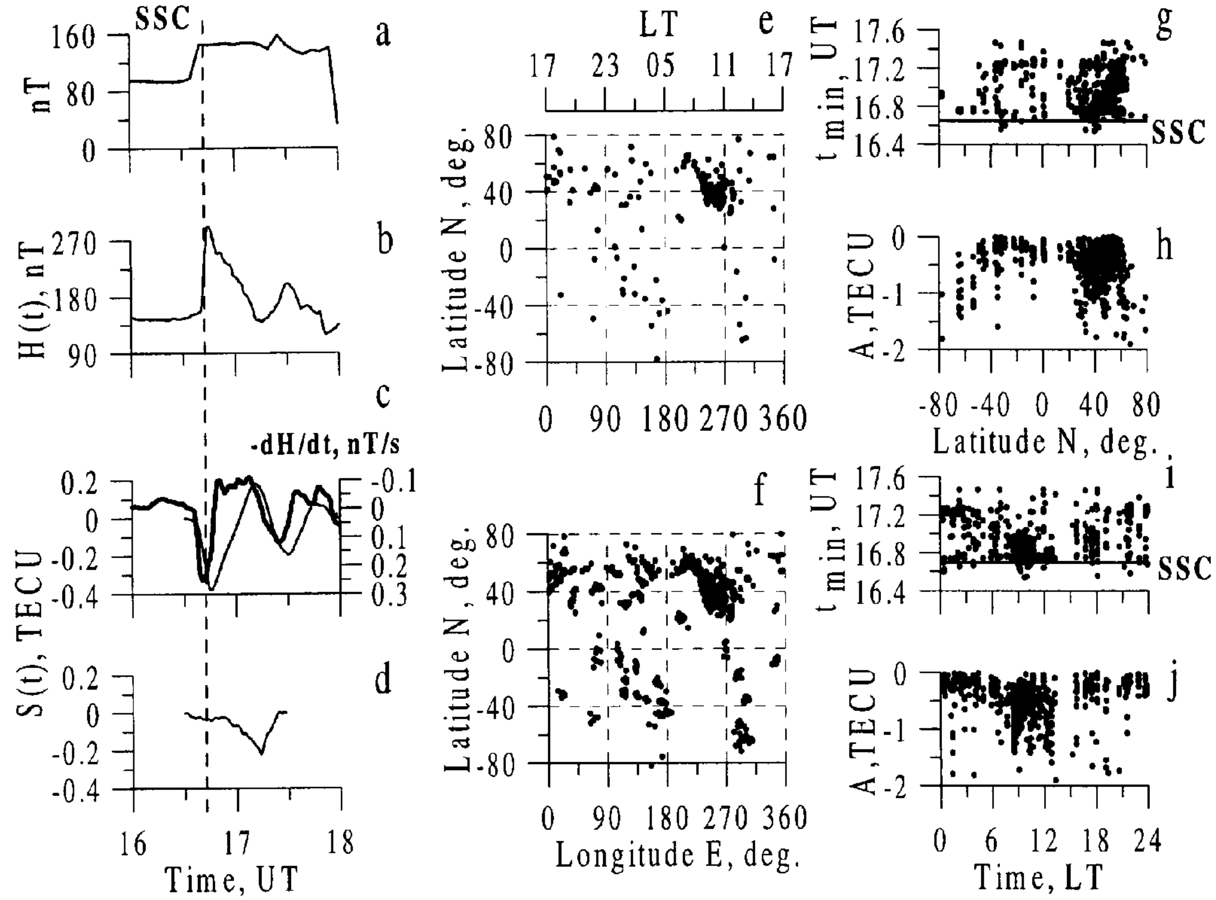

Fig. 1. Instantaneous ionospheric response to the strong magnetic storm of April 6, 2000

Upon removing the trend and smoothing with a time window of 30 min, we were able to determine for each beam to the satellite the amplitude A and the time t_{min} at which a minimum TEC value was attained. Figure 1 presents the latitudinal dependencies (obtained for each beam) of the t_{min} (g) and of the amplitude A (h) of the ionospheric response to the magnetic storm SSC, as well as the distributions of t_{min} (i) and A (j) as a function of local time LT. The SSC time is shown in panels g and i by a horizontal straight line.

The scatter of the position of t_{min} and A is due to the fact that when the trend is removed with a time window of 30 min, the response to the SSC is always overlapped by existing TEC oscillations with similar periods and with a random phase. Therefore, identifying the response requires a coherent combination of TEC variations for all LOS. The result of such a global spatial averaging of S(t) for 472 LOS on the dayside is shown in panel c (thin line). A similar result for 245 LOS on the nightside is presented in panel d.

For comparison, panel (c) presents the inverted curve dH/dt (heavy line). The correlation coefficient between S(t) and dH/dt is 1. The delay between the minima of the S(t) and dH/dt series was 7 min (line 3 in the Table).

Ionospheric Response To The SSC Of The Other Magnetic Storms

The similar results were obtained at the analysis of "instantaneous" ionospheric response to the SSC of the strong magnetic storms of January 6, April 23, 1998; June 8, July 13, 14, 15, 2000.

For the time interval 8:00-10:00 UT, Figure 2 presents the variations in magnetic flux (a) at geostationary orbit of the GOES10 station (135^0 W), and of the H-component of the magnetic field at station Irkutsk (52.2^0 N; 104.3^0 E) (b) for June 8, 2000. The result of such a global spatial averaging of S(t) for 406 LOS on the dayside is shown in panel c (thin line). A similar result for 632 LOS on the nightside is presented in panel d.

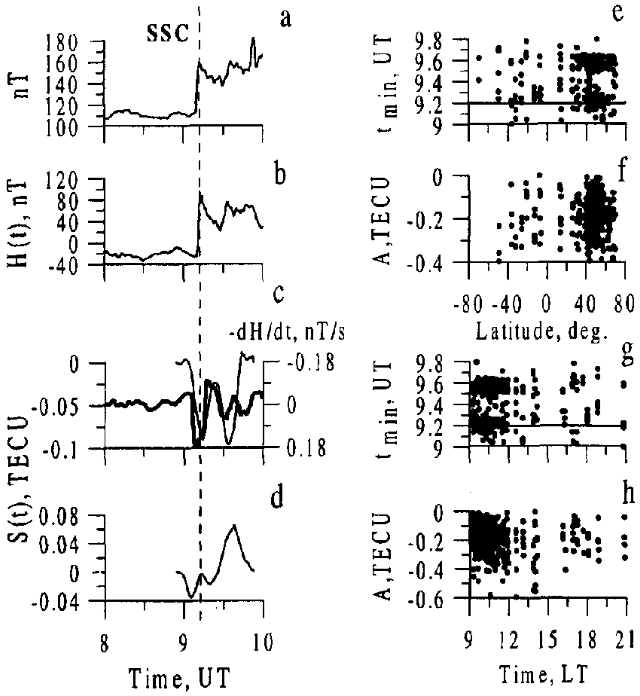

Fig. 2. Instantaneous ionospheric response to the strong magnetic storm of June 8, 2000

For comparison, panel (c) presents the inverted curve dH/dt (heavy line). The correlation coefficient between S(t) and dH/dt is 0.9. The delay between the minima of the S(t) and dH/dt series was 3.5 min (line 4 in the Table). The SSC time is shown in panels e and g by a horizontal straight line. The basic values characterising the magnetic storms under consideration are presented in the table: Dst at the SST time (according to the data from the GOES 8 and 10 satellites); SSC time; $\max \frac{dH}{dt}$ is a maximum value of the derivative H(t); ΔT is the time interval under investigation; m is the number of averagings of the beams, in the case of a global coherent accumulation on the dayside; and $|A_\Sigma|$ is the modulus of a maximum amplitude of the response for the S(t) series. It is shown in percentage how much our measured value of the TEC amplitude differs from the background mean value of $\bar{I}_0$ calculated from the IONEX-files (Mannucci, 1998); τ is the delay between the minima of the S(t) and dH/dt series; and r is the correlation coefficient between S(t) and dH/dt.

Table: Statistics of experiments

N	Date	Dst, nT	SSC time, UT	$\max \frac{dH}{dt}$, nT/s	ΔT, UT	m	$\lvert A_\Sigma \rvert$, TECU	τ, min	r
1	6.01.1998	100	14:16	0.06	14 -15:30	395	0.1	6	0.8
2	23.04.1998	563	18:25	0.08	18-19:30	401	0.1	3	0.8
3	6.04.2000	135	16:42	0.25	16:30-18	472	0.4 $\bar{I}_0$=14.53 2.6 %	7	1
4	8.06.2000	160	9:12	0.17	8:54-9:54	406	0.1 $\bar{I}_0$=35,3 0.3 %	3,5	0.9
5	13.07.2000	88.32	9:42	0.1	9:19-10:32	227	0.2 $\bar{I}_0$=35,3 0.3 %	3	0.9
6	14.07.2000	101.45	15:32	0.1	15-16	350	0.1 $\bar{I}_0$=37,3 0.4 %	4.5	0.8
7	15.07.2000	166.5	14:37	0.4	14-15:21	203	0.1 $\bar{I}_0$=35,3 0.3 %	9.5	0.9

DISCUSSION AND CONCLUSIONS

An analysis of the data in Figures 1, 2 suggests the conclusion that the ionospheric response to the SSC has the form of a single negative disturbance of about 20-min duration. On the dayside of the Earth the largest value of the net response amplitude was found to be of order 0.4 TECU (2-3 % of the background TEC value, for the magnetic storm of April 6 2000),and the delay with respect to the SSC in mid-latitudes was about 360 s. In higher latitudes the delay goes as long as 15 min. On the nightside these values are 0.2 TECU and 30 min, respectively. Of special note is that the onset of negative TEC disturbance on the dayside, marked according to the level of 0.25 from a maximum deviation (Figure 1, panel c), coincides with the magnetic flux SSC (panel a) and is 120 s ahead of the SSC time determined from the data from ground-based magnetic observatories. The velocity of the traveling disturbance from middle to high latitudes as well as from the dayside to the nightside is estimated at about 10-20 km/s. Thus our detected disturbance (a global delay τ no more than 10^2 - 10^3 s) is inexplicable in terms of the AGW model, and it should be sought when modeling a electromagnetic set of phenomena accompanying a strong geomagnetic disturbance. It is not improbable that in the analysis of the mechanism it would be useful to take into account some important characteristics of the "global detector" which we are using, such as primarily the sensitivity, continuity and global character. However, it may well be of crucial importance that, unlike conventional techniques of ionospheric observations, the altitude limit of which does not exceed 500 km (ionosondes, HF Doppler measurements) or 1000-2000 km (incoherent scatter radars, and stations for recording the rotation of the polarization plane of the VHF signal from geostationary satellites), the system of GPS satellites and ground-based GPS receivers enables a global detection of the Earth's ionospheric and plasmaspheric disturbances (for example see the similar method suggested by Davies, 1977) up to heights as high as 20,000 km.

Effects, caused by electric fields in the ionosphere, influence the behaviour of its parameters and manifest themselves differently, depending on the latitude, which is associated primarily with the geomagnetic field geometry (Bryunelli, 1988). Under quiet conditions, the electric field generated at the magnetopause during the interaction of the solar wind with the geomagnetic field, is almost entirely shielded from the penetration to the mid-latitudes by the polarization electric field produced by drifting energetic charged particles. This field is partially shorted out through the conducting ionosphere via field-aligned currents connecting the Alfven layer with the equatorial boundary of the auroral oval. Under conditions of geomagnetic disturbances, the shielding effect can be substantially reduced both because of the nonstationarity of the original magnetospheric electric field (the polarization field does not rearrange itself immediately after changes in the original field but within a time on the order of 1 min) and as a consequence of an increase in conductivity of the lower-lying ionosphere (due to precipitation) which shorts out the polarization field (Jaggi, 1973). As a result, the magnetospheric electric field during disturbances can penetrate the middle and low latitudes.

During magnetic disturbances when there is a significant enhancement of the electric field, strong variations in the height of the F2 layer maximum are often observed, which can be caused by the vertical component of the ExB-drift of ionospheric plasma (Tanaka, 1973). According to Bryunelli (1988), ionospheric effects of magnetospheric electric fields at mid-latitudes are caused by the divergence of the upward directed ion flux produced by the horizontal electric field. The electric field-induced transport during a disturbance in the F2 region with the ExB-drift velocity is effective both in the daytime and at night. The electric field can reach 10-15 mV/m (Ogawa, 1975) at mid-latitudes (the undisturbed values of the field are smaller by a factor of 2-3). The influence of the vertical component of the ExB-drift on the height distribution of electron density was investigated by different methods (Tanaka, 1973). As a consequence of the virtual independence of the ExB-drift velocity from the F2 height, the electron density distribution profile is displaced under the action of the electric field as a single whole without changing its form substantially (Bryunelli, 1988). The eastward and westward directed electric fields cause the F2 layer maximum to rise and fall, respectively. The h_mF2 variations correlate quite well with changes of the zonal electric field, with a slight delay on the order of 20 min at night, and with a shorter delay in the daytime. The N_mF2 variations during an instantaneous change of the field in earlier studies are less pronounced, and manifested themselves in a decrease of critical frequencies by about 0.1-0.3 MHz. According to the assumption made in (Park, 1974), such effects corresponded to electric fields with the amplitude of 5-10 mV/m.

An unambiguous interpretation of ionospheric effects by the action of electric fields in earlier studies is made difficult by the fact that similar effects can also cause IGW generated by auroral electrojets during substorms. The pivotal criterion in the separation of the effects of electric fields and IGW is the delay between geomagnetic and ionospheric effects. In the former case where ionospheric effects are caused by IGW, the delay average 45-60 min (Afraimovich, 2000c).

The analysis made above which describes the occurrence of ionospheric effects on abrupt changes of the electric field, and the data on TEC variations together with dH/dt obtained in this study, bear witness to the fact that electric fields of magnetospheric origin with typical nonstationarity times of 30-60 min penetrate the mid-latitude ionosphere during dramatic magnetic disturbances.

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