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Ionospheric effects of the solar flares of September 23, 1998 and July 29, 1999 as deduced from global GPS network data

E.L. Afraimovich *, A.T. Altyntsev, E.A. Kosogorov, N.S. Larina,
L.A. Leonovich

Institute of Solar-Terrestrial Physics SD, Russian Academy of Sciences, P.O. Box 4026, Irkutsk 664033, Russia

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Abstract

This paper presents data from first global positioning system (GPS) measurements of global response of the ionosphere to solar flares of September 23, 1998 and July 29, 1999. The analysis used novel technology of a global detection of ionospheric effects from solar flares as developed by one of the authors (Afraimovich, Radio Sci. 35 (2000) 1417). The essence of the method is that use is made of appropriate filtering and a coherent processing of variations in total electron content (TEC) in the ionosphere which is determined from GPS data, simultaneously for the entire set of visible (over a given time interval) GPS satellites at all stations used in the analysis. It was found that fluctuations of TEC, obtained by removing the linear trend of TEC with a time window of about 5 min, are coherent for all stations and the line-of-sight to the GPS satellites on the dayside of the Earth. The time profile of TEC responses is similar to the time behavior of hard X-ray emission variations during flares if the relaxation time of electron density disturbances in the ionosphere of order 50–100 s is introduced. No such effect on the nightside of the Earth has been detected yet. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Solar flares; Total electron content; GPS

1. Introduction

The enhancement of X-ray and ultraviolet radiation intensity that is observed during chromospheric flares on the Sun causes an increase in electron density in the ionosphere. These density variations are different for different altitudes and are collectively called sudden ionospheric disturbances (SID). SID observations provide a key means for ground-based detection of solar flares along with optical observations of flares and solar radio burst observations. Much research is devoted to SID studies, among them a number of thorough reviews and monographs (Mitra, 1974).

Unlike effects in the optical and radio ranges, ionospheric effects of flares are of special interest as they constitute a response of ionospheric plasma to an impulsive ionization.

Quantitative study of SID has two major implications at present. SID data in the *D*-region that were obtained predominantly by recording amplitude and phase characteristics of signals from LF and VLF radio stations can be the source of information about the X-ray part of the flare spectrum, as well as providing a tool for investigating the principal chemical processes in this region.

SID data for the *F*-region acquired by different radio probing methods were used repeatedly to estimate time variations in the X-ray and extreme ultraviolet (EUV) spectral regions and in relative measurements of fluxes in different wavelength ranges (Donnelly, 1969; Thome and Wagner, 1971; Mendillo et al., 1974).

The main body of SID data for the Earth's upper atmosphere was obtained in earlier detections of sudden frequency deviations (SFD) of the *F*-region-reflected radio signal in the HF range (Davies, 1969; Donnelly, 1969, 1971, 1976). SFD are caused by an almost time-coincident

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* Corresponding author. Fax: +7-3952-462557.
E-mail address: afra@iszf.irk.ru (E.L. Afraimovich).

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increase in E- and F-region electron densities at over 100 km altitudes covering an area with the size comparable to or exceeding that of the region monitored by the system of HF radio paths. A limitation of this method is the uncertainty in the spatial and altitude localization of the UV flux effect, the inadequate number of paths, and the need to use special-purpose equipment.

Another highly informative technique is the incoherent scatter (IS) method, one of the most universal tools for ionosphere research. In Thome and Wagner (1971), important information was obtained about the height distribution of the increase in local electron density N_e during the flares of May 21 and 23, 1967. A significant increase of N_e (by as much as 200%) was recorded in the E-region, which decreased gradually in the F-region with an up to 10–30% increase of the height and remained distinguishable up to 300 km. N_e starts to increase initially in the E-region, while at higher altitudes it is observed to be delayed, which is particularly conspicuous at the F-region heights.

The Millstone Hill IS facility recorded the flare of August 7, 1972 (Mendillo and Evans, 1974). The measurements were made in the range from 125 to 1200 km, i.e. to the altitudes exceeding greatly those of all preceding observations. The increase of N_e amounted to 100% at 125 km altitude and to 60% at 200 km.

Implementing the IS method requires extremely sophisticated, expensive equipment. There are only a few IS facilities worldwide, which are concentrated mainly in America and Europe. These systems were designed for solving a broad gamut of scientific problems and do not provide round-the-clock observations of ionospheric effects from solar flares. An added difficulty involves inadequate time resolution. Currently, it is common knowledge that the rise and fall time of the solar flare emission in the range 10–1030 Å, which has effect on the ionospheric E and F regions, is often shorter than 5–10 min, typical of the IS method's time resolution. Since the relaxation time of electron density in the E and $F1$ regions is also less than 5–10 min, most incoherent scatter measurements lack adequate time resolution for studying ionospheric effects of flares.

The effect of solar flares on the ionospheric F-region is also manifested as a sudden increase of total electron content (SITEC) which was measured previously using continuously operating VHF radio beacons on geostationary satellites (Mitra, 1974; Mendillo et al., 1974). A pioneering attempt was made to realize global observations of the outstanding flare of August 7, 1972 using 17 stations in North America, Europe, and Africa (Mendillo et al., 1974). The observations covered a territory whose boundaries were separated by 70° in latitude and by 10 h in local time. For different stations, the value of $\mathrm{d}I$ (TEC increase) varied from 1.8×10^{16} to $8.6 \times 10^{16}\ \mathrm{m}^{-2}$, or 15–30% of the TEC. These investigations revealed a latitudinal dependence of the amount of TEC increase. The low latitudes showed a larger increase of TEC compared with the high latitudes. Besides, the authors point out that no correlation exists between the value of TEC increase and the solar zenith angle.

A limitation of the SITEC method is the integral character of results which reflect the electron density variation in the height range from 100 to 2000 km. If, however, it is taken into consideration that only a few current methods enable flare effects to be recorded in the ionospheric F-region, SITEC observations should be recognized as one of the most convenient tools for continuous observations of the F-region. A serious limitation of methods based on analyzing VHF signals from Geostationary satellites is their nonuniform distribution in longitude. Hence it is impossible to make measurements in some geophysically interesting regions of the globe, especially in high latitudes.

Consequently, none of the above-mentioned existing methods can serve as an effective basis for the radio detection system to provide a continuous, global SID monitoring with adequate space–time resolution. Furthermore, the creation of these facilities requires developing special-purpose equipment, including powerful radio transmitters contaminating the radio environment.

The advent and evolution of a global positioning system (GPS) and also the creation of widely branched networks of GPS stations (at least 800 sites by February 2001, the data from which are placed on the Internet) opened up a new era in remote ionospheric sensing. In the very near future, this network will be extended by integrating with the Russian navigation system, GLONASS (Klobuchar, 1997). Furthermore, there also exist powerful regional networks such as the Geographical Survey Institute network in Japan (Saito et al., 1998) consisting of up to 1000 receivers. High-precision measurements of the group and phase delay 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 origins. Recently, some authors embarked actively on the development of detection tools for the ionospheric response of powerful earthquakes (Calais and Minster, 1995; Afraimovich et al., 2001), rocket launches (Calais and Minster, 1996; Afraimovich et al., 2000b), and industrial surface explosions (Fitzgerald, 1997; Calais et al., 1998). Subsequently, the GPS data began to be used in the context of the spaced-receiver method using three GPS stations to determine the parameters of the full wave vector of traveling ionospheric disturbances under quiet and disturbed geomagnetic conditions (Afraimovich et al., 1998, 2000a).

This paper reports the development of a method of global detection of the ionospheric effect from solar flares (GLOBDET) using the international GPS network. This method would improve substantially the sensitivity and space–time resolution of analysis when compared with the above-mentioned radio probing methods. General information about the flares being analyzed here and a description of the experimental geometry are given in Sections 2 and 3. The processing technique for the data from the GPS network and results of an analysis of the ionospheric effect from the solar flare of July 29, 1999 are outlined in Sections 4 and 5. Section 6 discusses the results obtained. A modeling of the physical processes involving flare effects on the ionosphere using GPS data and, moreover, the development of methods for solving their inverse problem of reconstructing emission characteristics using GPS data will be subject of future research.

2. Experimental geometry of experiments

Fig. 1 presents the geometry of a global GPS array used in this paper to analyze the effects of flare 23 September 1998 (102 stations, panel a) and 29 July 1999 (105 stations, panel b). Heavy dots correspond to the location of the GPS stations. The coordinates of the stations are not given here for reasons of space. The upper scales indicate the local time, LT, corresponding to 07:00 UT, a maximum increase in X-ray emission intensity of the flare 23 September 1998 and 19:30 UT for 29 July 1999.

As is evident from Fig. 1, the set of stations which we chose out of the global GPS network available to us, covers rather densely North America and Europe, but provides much worse coverage of the Asian part of the territory used in the analysis. The number of GPS stations in the Pacific and Atlantic regions is even fewer. However, coverage of the territory with partial LOS for the limitation on elevations $\theta > 10°$, which we have selected, is substantially wider. Dots in Fig. 1c mark the coordinates of sub-ionospheric points for the height of the $F2$-layer maximum $h_{\max} = 300$ km for all visible satellites at 29 July 1999, 19:30 UT for each GPS station. A total number of LOS (and sub-ionospheric points) used in this paper to analyze the July 29, 1999 flare is 622.

Such coverage of the terrestrial surface makes it possible to solve the problem of detecting time-coincident events with spatial resolution (coherent accumulation) two orders of magnitude higher, as a minimum, than could be achieved in SFD detection on oblique HF paths. For simultaneous events in the western hemisphere, the corresponding today's number of stations and LOS can be as many as 400 and 2000–3000, respectively.

It should be noted that because of the relatively low satellite orbit inclinations the GPS network (and, to a lesser degree, GLONASS) provides poor coverage of the Earth's surface near the poles. However, TEC measurements in the polar regions are ineffective with respect to the detection of the ionospheric response to a solar flare because the amplitude of background fluctuations in this case is much higher when compared to the mid-latitude ionosphere. This is particularly true of geomagnetic disturbance periods. For the same reason, equatorial stations should also be excluded from a coherent processing.

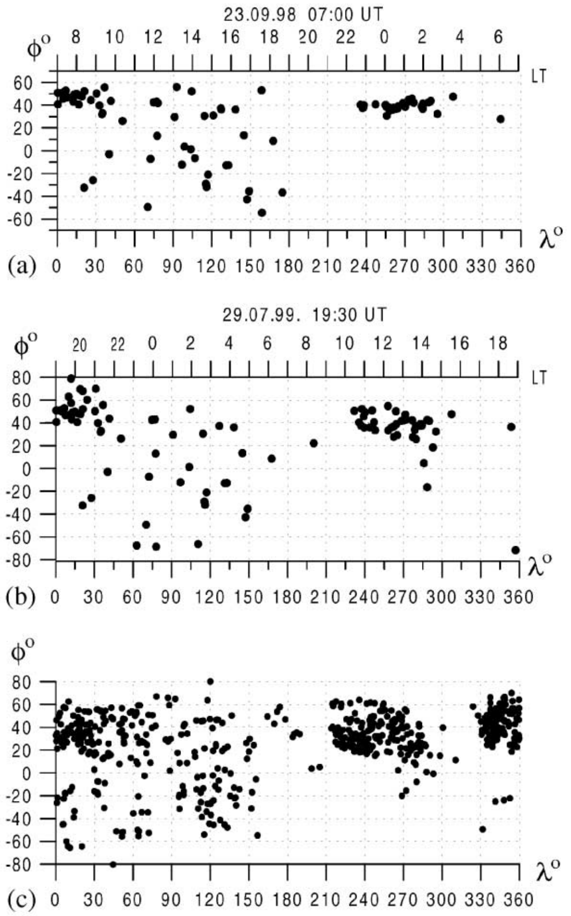

Fig. 1. Geometry of the GPS array used in this paper when analyzing the effects of flare 23 September 1998 (102 stations—a) and 29 July 1999 (105 station—b). Heavy dots correspond to the location of the GPS stations. The upper scales indicate the local time (LT) corresponding of 07:00 UT, a maximum increase in X-ray emission intensity of the flare 23 September 1998 and 19:30 UT for 29 July 1999. Dots in panel c mark the coordinates of sub-ionospheric points for the height of the $F2$-layer maximum $h_{\max} = 300$ km for all visible satellites at 29 July 1999, 19:30 UT for each GPS station. A total number of LOS (and sub-ionospheric points) used in the paper to analyze the July 29, 1999 flare is 622.

3. General data on the solar flares of September 23, 1998 and July 29, 1999

For studying the ionospheric response to the ionizing emission from solar flares, we chose relatively powerful (according to an X-ray classification) flares whose time profile was characterized by intense short-duration impulses of hard X-ray emission. The two flares selected appear in Table 1.

The study was based on events, for which flare emission data with a time resolution of about 1 s were available. The September 23, 1998 flare was recorded by X-ray telescope HXT on the YOHKOH satellite (Fig. 3b, dashed line). Operating in the flare mode, the HXT telescope provides observations in four energy channels (14–23, 23–33, 33–53, and 53–93 keV) with a resolution of 0.5 s. The second event was observed by the BATSE spectrometer on the CGRO satellite which is capable of recording solar X-ray emission with different temporal and spectral resolutions. This study utilized DISCLA data written in four channels (25–50, 50–100, 100–300, and over 300 keV) at 1.024-s intervals.

Figs. 2b and 3b show the time dependencies of flare emission. Time profiles of soft X-ray emission were acquired by the GOES-10 satellite, the data from which are available on the SPIDER network (marked by the open circles). Dashes in Figs. 2b and 3b represent values for the hard X-ray

Table 1
Parameters of the flares being analyzed

N		September 23, 1998	July 29, 1999
1	Time of maximum soft X-ray emission (UT)	07:13	19:34
2	Flare class optical/X-ray	3B/M7.1	1N/M5.1
3	Increment of electron content (TECU)	0.4	0.5
4	Relaxation time (s)	100	65

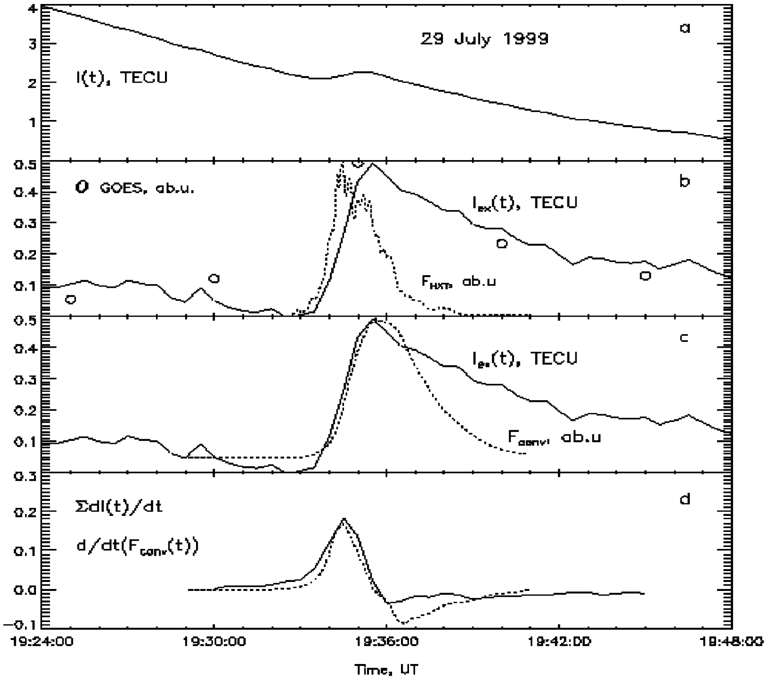

Fig. 2. Panel (a) shows the variation of TEC $I(t)$ for one of the LOS during the solar flare of July 29, 1999. Panel (b) on the same time scale shows time dependencies of the TEC $I_{\mathrm{ex}}(t)$ response upon subtracting the trend determined as a polynomial of degree 3 on the interval 19:00–20:00 UT (solid line); of hard X-ray emission F_{HXT} (BATSE, 25–50 keV—dashed line); of the values of the soft X-ray emission flux at 5-min intervals (GOES-10—open circles). Panel (c) illustrates comparison of the TEC $I_{\mathrm{ex}}(t)$ response with the result of a convolution $F_{\mathrm{conv}}(t)$ of their dependence of the hard X-ray emission flux, with the relaxation time $\tau = 65$ s. Panel (d) shows the sum of time derivatives of TEC $\sum \mathrm{d}I(t)/\mathrm{d}t$ for 622 LOS on the dayside (solid line), and the derivative of the convolution $\mathrm{d}F_{\mathrm{conv}}(t)/\mathrm{d}t$ of the X-ray emission flux (dashes).

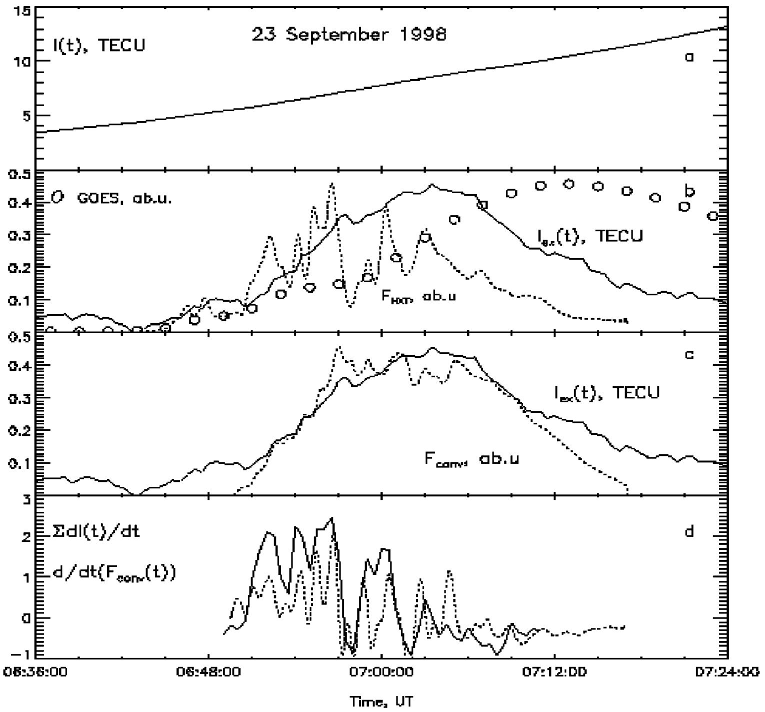

Fig. 3. Panel (a) shows the variation of TEX $I(t)$ for one of the LOS during the solar flare of September 23, 1998. Panel (b) on the same time scale shows time dependencies of the TEX $I_{\mathrm{ex}}(t)$ response upon subtracting the trend determined as a polynomial of degree 3 on the interval 06:00–08:00 UT—solid line; of hard X-ray emission F_{HXT} (HXT/YOHKOG, 23–33 keV—dashed line); of the values of the soft X-ray emission flux at 1-min intervals (GOES-10—open circles). Panel (c) illustrates comparison of the TEC $I_{\mathrm{ex}}(t)$ response with the result of a convolution $F_{\mathrm{conv}}(t)$ of their dependence of the hard X-ray emission flux, with the relaxation time $\tau = 100$ s. Panel (d) shows the sum of time derivatives of TEX $\sum \mathrm{d}I(t)/\mathrm{d}t$ for 228 LOS on the dayside (solid line), and the derivative of the convolution $\mathrm{d}F_{\mathrm{conv}}(t)/\mathrm{d}t$ of the X-ray emission flux (dashes).

emissions. A comparative analysis of these series is made in Section 5.

The events are both characterized by a low level of geomagnetic disturbance (*Dst* from −10 to −20 nT), which simplified greatly the SID detection problem.

4. Processing of the data from the GPS network

Following is a brief outline of the global monitoring (detection) technique for solar flares (GLOBDET) as developed by one of the authors (Afraimovich, 2000) on the basis of processing the data from a worldwide network of two-frequency multichannel receivers of the GPS-GLONASS navigation systems.

A physical groundwork for the method is formed by the effect of fast change in electron density in the Earth's ionosphere at the time of a flare simultaneously on the entire sunlit surface. Essentially, the method implies using appropriate filtering and a coherent processing of TEC variations in the ionosphere simultaneously for the entire set of "visible" (during a given time interval) GPS satellites (as many as 5–10 satellites) at all global GPS network stations used in the analysis. In detecting solar flares, the ionospheric response is virtually simultaneous for all stations on the dayside of the globe within the time resolution range of the GPS receivers (from 30 to 0.1 s). Therefore, a coherent processing of TEC variations implies in this case a simple addition of single TEC variations.

The detection sensitivity is determined by the ability to detect typical signals of the ionospheric response to a solar flare (leading edge duration, period, form, length) at the level of TEC background fluctuations. Ionospheric irregularities are characterized by a power spectrum (Kelley et al., 1980; Livingston et al., 1981; Afraimovich et al., 2001a), so that background fluctuations will always be distinguished in the frequency range of interest. However, background fluctuations are not correlated in the case of LOS spaced by an amount exceeding the typical irregularity size.

With a typical length of X-ray bursts and EUV emission of solar flares of about 5–10 min, the corresponding size of background ionization irregularity does not normally exceed 30–50 km; hence the condition of a statistical independence of TEC fluctuations at spaced LOS is almost always satisfied.

Therefore, coherent summation of responses to a flare on a set of LOS spaced throughout the dayside of the globe permits the solar flare effect to be detected even when the response amplitude on partial LOS is markedly smaller than the noise level (background fluctuations).

To estimate the sensitivity threshold of detection of the ionospheric response to the solar flare of a duration of 5–10 min along a separate LOS, one can take advantage of the data derived from a global averaging of TEC variation power spectra reported by Afraimovich et al. (2001a). In the cited reference, it is shown that for a magnetically quiet period at mid-latitudes, the background TEC fluctuation amplitude in the range of 5–10-min periods is about 0.01 TECU. At the time of strong geomagnetic disturbances this value can increase to 0.1 TECU.

If the SID response and background fluctuations, respectively, are considered to be the signal and noise, then as a consequence of a statistical independence of background fluctuations the signal/noise ratio when detecting the flare effect is increased through a coherent processing by at least a factor of $\sqrt{N}$, where N is the number of LOS.

Thus, in the case of an averaging of TEC variations for 100 LOS, the sensitivity threshold for a magnetically quiet and disturbed period decreases an order of magnitude (from 0.001 to 0.01 TECU).

The GPS technology provides the means of estimating TEC variations on the basis of phase measurements of TEC $I(t)$ in each of the spaced two-frequency GPS receivers using the formula (Hofmann-Wellenhof et al., 1992; Calais and Minster, 1996):

$$I(t) = \frac{1}{40.308} \times \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \left[(L_1(t)\lambda_1 - L_2(t)\lambda_2) + const + nL \right], \quad (1)$$

where $L_1(t)\lambda_1$ and $L_2(t)\lambda_2$ are the phase path increments of the radio signal, caused by the phase delay in the ionosphere (m); $L_1(t)$ and $L_2(t)$ the numbers of full phase rotations, and λ_1 and λ_2 the wavelengths (m) for the frequencies f_1 and f_2, respectively; *const* is some unknown initial phase path (m); and *nL* is the error in determination of the phase path (m).

Phase measurements in the GPS system are made with a high degree of accuracy where the error in relative TEC determination for 30-s averaging intervals does not exceed 10^{14} m^{-2}, although the absolute value of TEC does remain unknown (Hofmann-Wellenhof et al., 1992). This permits ionization irregularities and wave processes in the ionosphere to be detected over a wide range of amplitudes (as large as 10^{-4} of the diurnal variation of TEC) and periods (from several days to 5 min). The TEC unit (TECU), which is equal to 10^{16} m^{-2} and is commonly accepted in the literature, will be used throughout the text.

GLOBDET time resolution is limited by technical capabilities of the GPS system. Essentially, data with a time resolution of $\sim$ 30 s are currently available on the Internet, which is insufficient for a detailed analysis of the fine structure of the SID time dependence. Yet this limitation seems to be transient since current multichannel two-frequency GPS receivers can operate with a time resolution of up to 0.1 s. On the other hand, time resolution is determined by time constants of ionization and recombination processes in the ionosphere at a given height (Donnelly, 1969; Mitra, 1974); these parameters can be taken into account when processing the data.

5. The use of a global averaging in the GPS detection of the ionospheric effect from the solar flare

The solar flare of July 29, 1999 was used to illustrate the performance of the proposed method. Primary data include series of slant values of TEC $I(t)$, as well as the corresponding series of elevations $\theta(t)$ and azimuths $\alpha(t)$ along LOS to the satellite calculated using our developed CONVTEC program which converts the GPS system standard RINEX-files on the Internet (Gurtner, 1993). The determination of SID characteristics involves selecting continuous series of $I(t)$ measurements of at least a 1-h interval in length, which includes the time of the flare. Series of elevations $\theta(t)$ and azimuths $\alpha(t)$ of the LOS are used to determine the coordinates of sub-ionospheric points. In the case under consideration, all results were obtained for elevations $\theta(t)$ larger than 10°.

Fig. 4a presents typical time dependencies of an slant TEC $I(t)$ for the PRN03 satellite at the CME1 station (40.4°N, 235.6°E, thick line) on July 29, 1999 and for PRN21 at the CEDA station (40.7°N, 247.1°E, thin line). It is apparent from Fig. 4a that in the presence of slow TEC variations, the SID-induced short-lasting sudden increase in TEC is clearly distinguished in the form of a “step” as large as 0.4 TECU.

Such a TEC disturbance, even for a single LOS, exceeds more than an order of magnitude the sensitivity threshold of detection of the response to the solar flare for a magnetically quiet day (see Section 4).

For the same series, similar lines in panel b show variations of the time derivative of TEC $\mathrm{d}I(t)/\mathrm{d}t$ with the linear trend removed with the 5-min time window. The TEC time derivative is invoked because it reflects electron density variations which are proportional to the X-ray or EUV flux (Mitra, 1974).

The coherent summation of $\mathrm{d}I(t)/\mathrm{d}t_i$ realizations was made by the formula

$$\sum \mathrm{d}I(t)/\mathrm{d}t = \sum_{i=1}^{N} \mathrm{d}I(t)/\mathrm{d}t_i \sin(\theta_i) \quad (2)$$

where θ_i is the LOS elevation and N the number of LOS.

Multiplication by $\sin(\theta_i)$ was used to convert slant TEC variations to an equivalent “vertical” value in order to normalize the response amplitude. Reconstructing the absolute value of the ionospheric response to the solar flare requires a more accurate (than used in this paper) conversion of the

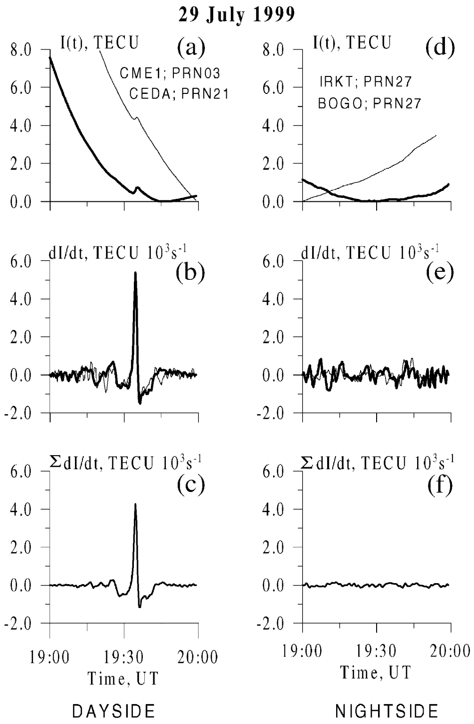

Fig. 4. Panels (a) and (b) show the time dependences of TEC $I(t)$ and variation of the time derivative $\mathrm{d}I(t)/\mathrm{d}t$ with the linear trend removed with the 5-min time window for stations CME1 (PRN03—thick line) and CEDA (PRN21—thin line) on the dayside on July 29, 1999. Panel (c) shows the normalized coherent sum of variations of the TEC time derivative $\sum \mathrm{d}I/\mathrm{d}t$ for 622 LOS. Same for the nightside (panels (d)–(f)); selected data for sites IRKT (PRN27) and BOGO (PRN27) are presented in panels (d) and (e).

slant TEC value to a "vertical" one, especially at low values of elevations of the LOS. To do this, it is necessary not only to eliminate, for this LOS to the satellite, the ambiguity of the determination of the absolute TEC value which arises when only phase measurements are used in the GPS system. The response can only be estimated reliable, with the inclusion the spatially inhomogeneous ionosphere, by using all LOS to the satellite, and by applying adequate methods of spatial interpolation. This problem is considered in a series of publications (for example, Mannucci et al., 1998), and is beyond the scope of this paper.

The normalized to $N = 622$ result of a coherent summation (2) for all LOS and GPS stations located mainly on the dayside is presented in Fig. 4c. A comparison of the resulting coherent sum (2) with the time dependence $\mathrm{d}I(t)/\mathrm{d}t$ for individual LOS presented in panels b confirms the effect of a substantial increase of the signal/noise ratio caused by a coherent processing.

It is interesting to compare, for the same time interval, the data on individual LOS and results from a coherent summation for the dayside and nightside. Fig. 4d presents typical time dependencies of an slant TEC $I(t)$ for the PRN27 satellite at the IRKT station (52.2°N, 104.3°E, thick line) and for PRN27 at the BOGO station (52.4°N, 21.0°E, thin line). Using the $I(t)$ data, it is impossible to identify any SID-induced short-lasting sudden increase in TEC. This is also true for the time derivatives $\mathrm{d}I(t)/\mathrm{d}t$ plotted in panel e. As a result, the r.m.s. of the coherent sum (2) in panel f for the nightside is of the same order of magnitude as that of background fluctuations outside the SID response interval on the dayside, which is an order of magnitude (as a minimum) smaller than the SID response amplitude (Fig. 4c).

6. Estimating the relaxation time of the ionosphere following solar flares

A comparative analysis is made of the TEC data and X-ray emission time series acquired by satellites. In carrying out a comparative analysis of the TEC and X-ray emission to flares, it is necessary to eliminate the TEC trend which is not associated with flare emission. In this case, the above procedure of determining the trend that is removed with a 5-min time window, which is significantly shorter than the flare emission duration, is incorrect. In Figs. 2 and 3, the trend to be removed was therefore defined as a polynomial of degree 3, approximating the time dependence of TEC on the intervals 19:00 and 20:00 UT, and 6:00–8:00 UT, respectively. The approximation procedure neglected the TEC values during the flares (19:30–19:48 UT, and 6:40–7:24 UT).

First we consider a simpler flare of July 29, 1999, with the X-ray emission time profile like a single impulse (dashed curve F_{HXT} in Fig. 2b). The flare is clearly seen on the time profile of TEC $I(t)$ (Fig. 2a). As is apparent from Fig. 2b, the response $I_{\mathrm{ex}}(t)$ represents an impulse with a fast growth and a relatively slow decline. The time variation of soft X-ray emission, obtained from the GOES data at large time intervals (marked by the open circles in Fig. 2b) does not contradict the behavior of the curve $I_{\mathrm{ex}}(t)$.

The rise front of hard X-ray emission F_{HXT} is steeper when compared with the response of TEC $I_{\mathrm{ex}}(t)$, and the time of a maximum is 1.05 min ahead of the TEC fluctuation maximum. These difference are natural if account is taken of the finite relaxation time of electron density disturbances caused by flare emission. This factor can be taken into account by convoluting the source function F_{HXT} with the relaxation function:

$$F_{\mathrm{conv}}(t) = \int_0^t F_{\mathrm{HXT}}(t')\exp\left[-\left(\frac{t-t'}{\tau}\right)\right]\mathrm{d}t'. \qquad (3)$$

The fitting was carried out through a convolution of the empirical hard X-ray dependence with the relaxation function. The functions $F_{\mathrm{conv}}(t)$ were calculated for different times τ, and of them, the function was selected, which was closest to the experimental dependence $I_{ex}(t)$, especially in the portions of increase and maximum.

The "best fit" of $I_{ex}(t)$ by $F_{conv}(t)$ is obtained with the X-ray signal of the 25–50 KeV energy channel when $\tau = 65$ s. The result is shown in Fig. 2c (see also Table 1). At the decay phase, the curves F_{conv} and $I_{ex}(t)$ are moving apart, which can be associated with the contribution to the ionospheric ionization from softer emission whose time profile is similar to the GOES flux profile. This value of τ is reasonable (Donnelly, 1969, 1971, 1976; Mitra, 1974), and corresponded to a statistical function of local ionosphere parameters along the LOS.

Short-duration disturbances on TEC dependencies, which are associated with the ionization by flare emission, are more pronounced on the time derivatives $\mathrm{d}I(t)/\mathrm{d}t$. Fig. 2d compares the result of summation (2) of the series of the derivatives $\sum \mathrm{d}I(t)/\mathrm{d}t$ for all visible satellites from GPS stations located on the dayside, with the derivative $\mathrm{d}/\mathrm{d}t(F_{conv})$ presented in Fig. 2c. It can be seen that the growth stage of the coherent sum $\sum \mathrm{d}I(t)/\mathrm{d}t$ for the entire sunlit side of the Earth is described adequately by the function $\mathrm{d}/\mathrm{d}t(F_{conv})$. Note that the accuracy of estimating the duration τ determined from the coincidence of peaks of the time derivatives is determined by time resolution of TEC measurements (30 s in the case under consideration).

The flare of September 23, 1998 was of a longer duration, and, despite a somewhat higher intensity, its response was relatively small on TEC time dependencies for separate paths (Fig. 3a). Nevertheless, by subtracting the polynomial of degree 3, it was possible to identify the TEC response $I_{ex}(t)$ (Fig. 3b). In this event, the time dependence of soft X-ray emission is much different from the temporal behavior of the response $I_{ex}(t)$ which grows faster than does the GOES signal (marked by the open circles), attains a maximum 9 min earlier, and decreases much more rapidly.

The signal of hard X-ray emission F_{HXT} (dashed line) shows a number of peaks leading the TEC fluctuations $I_{ex}(t)$. The convolution with the hard X-ray emission signal F_{conv} agrees satisfactorily with the response $I_{ex}(t)$, with $\tau = 100$ s. The curves in Fig. 2c are most similar for the M1 (23–33 KeV) channel of the HXT/YOHKOH X-ray telescope. The estimated $\tau = 100$ s is confirmed by comparing the combined time derivative of TEC $\sum \mathrm{d}I(t)/\mathrm{d}t$, with the derivative $\mathrm{d}/\mathrm{d}t(F_{conv})$.

A comparison of the time profiles of the TEC response and hard X-ray emission shows that corresponding electron density disturbances are recorded with confidence by a global GPS network. For hard X-ray emission, the highest correlation is attained for photon energies of about 30 KeV, with relaxation times τ in the range 65–100 s. These estimates are in reasonably good agreement with results obtained previously when analyzing the SID effect (Donnelly, 1969, 1971, 1976; Mitra, 1974).

Unfortunately, the lack of data on UV emission of the flares under investigation, the most probable ionizing factor at ionospheric heights above 100 km, gives no way of making absolute estimates of the TEC increment and comparing them with measured values. It is pointed out in Mitra (1974) that although UV emission is essentially responsible for SID in the F-region, TEC variations are also correlated quite well with X-ray flares. This is also confirmed by simultaneous measurements of X-ray and EUV flare emission characteristics by the Solar Maximum Mission satellite (Vanderveen et al., 1988).

7. Conclusions

According to the concept developed in Afraimovich et al. (2000), a global GPS network can be successfully used as a global detector of the ionospheric response to solar flares.

A continuous operation of such a detector is of great interest within the context of the advancement of space weather monitoring systems (see National Space Weather Program. The Implementation Plan, 1997). Such experiments are of importance in the study of flare effects in the geospace, and of the physical processes on the Sun. Furthermore, they are useful for estimating the relationship of X-ray and EUV emissions during flares.

In this paper, we have analyzed the ionospheric response to powerful solar flares of September 23, 1998 and July 29, 1999. It was found that fluctuations of TEC and its time derivative obtained by removing the linear trend of TEC with a time window of about 5 min are coherent for all stations and LOS to GPS satellites on the dayside of the Earth, regardless of the station's location, local time and elevation of the LOS. The time profile of TEC responses is similar to the time behavior of hard X-ray emission variations during flares if we introduce the relaxation time of an electron density disturbance in the ionosphere of a duration of 50–100 s. No such effect was detected on the nightside of the Earth.

For powerful solar flares like the one examined in this report, it is not necessary to invoke a coherent summation, and the SID response can be investigated for each LOS. This opens the way to a detailed study of the SID dependence on a great variety of parameters (latitude, longitude, solar zenith angle, spectral characteristics of the emission flux, etc.). With current increasing solar activity, such studies become highly challenging. In addition to solving traditional problems of estimating parameters of ionization processes in the ionosphere and problems of reconstructing emission parameters (Mitra, 1974), the data obtained through the use of GLOBDET can be used to estimate the spatial inhomogeneity of emission fluxes at scales of the Earth's radius.

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