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IONOSPHERIC EFFECTS OF THE SOLAR FLARES AS DEDUCED FROM GLOBAL GPS NETWORK DATA

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ABSTRACT

Results derived from analysing the ionospheric response to faint and bright solar flares are presented. The analysis used novel technology of a global detection of ionospheric effects from solar flares as developed by the authors (Afraimovich, 2000a; Afraimovich et al., 2000b), on the basis of phase measurements of the total electron content (TEC) in the ionosphere using an international GPS network. The essence of the method is that use is made of appropriate filtering and a coherent processing of variations in the TEC which is determined from GPS data, simultaneously for the entire set of visible GPS satellites at all stations used in the analysis. This technique is useful for identifying the ionospheric response to faint solar flares (of X-ray class C) when the variation amplitude of the TEC response to separate line-on-sight (LOS) is comparable to the level of background fluctuations. The dependence of the TEC variation response amplitude on the flare location on the Sun is investigated.

INTRODUCTION

The enhancement of X-ray and ultraviolet radiation intensity that is observed during chromospheric flares on the Sun immediately 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) (Davies, 1969; Donnelly, 1969). Much research has been devoted to SID studies, including a number of thorough reviews and monographs (Mitra, 1974). SIDs are generally recorded as short wave fadeouts, sudden phase anomalies, sudden frequency deviations (SFD), cosmic noise absorption events, enhancements or decreases of atmospherics. SID observations provide a key means for ground-based detection of solar flares along with optical observations of flares and solar radio burst observations.

SFD (Davies, 1969; Donnelly, 1969; Liu, 1996) are caused by an almost time-coincident increase in E-and F-region electron densities at altitudes above 100 km, covering an area with 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.

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 (Mendillo et al., 1974). A serious limitation of methods based on analyzing VHF signals from geostationary satellites is their small and ever increasing (with the time) number and the nonuniform distribution in longitude. Hence it is impossible to make measurements in some geophysically interesting regions of the globe, especially at high latitudes.

A further, highly informative, technique is the method of Incoherent Scatter – IS (Thome and Wagner, 1971; Mendillo and Evans, 1974). However, the practical implementation of the IS method requires very sophisticated, expensive equipment. An added limitation is inadequate time resolution. Since the relaxation time of electron density in the E and F1 regions is less than 5-10 min, most IS measurements lack the time resolution needed for the study of ionospheric effects of flares.

Consequently, none of the above-mentioned existing methods can serve as an effective basis for the radio detection system to provide 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. It is also significant that when using the existing methods, the inadequate spatial aperture gives no way of deducing the possible spatial inhomogeneity of the X-ray and EUV flux.

The advent and evolution of a Global Positioning System (GPS) and also the creation on its basis of widely branched networks of GPS stations (at least 800 sites by February of 2001, the data from which are placed on the Internet) opened up a new era in remote ionospheric sensing. High-precision measurements of the TEC along the 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 f1=1575.42 MHz and f2=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. The TEC unit (TECU) which is equal to 1016 m-2 and is commonly accepted in the literature, will be used throughout this text.

Afraimovich et al. (2000a; 2000b) developed a novel technique for global detection of ionospheric effects from solar flares, and presented data from first GPS measurements of global response of the ionosphere to the powerful impulsive flares of July 29, 1999, and December 28, 1999, chosen to illustrate the practical implementation of the proposed method. Afraimovich et al. (2000a; 2000b) 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 LOS on the day side of the Earth. The time profile of TEC responses is similar to the time behavior of hard X-ray emission variations during flares in the energy range 25-35 keV if the relaxation time of electron density disturbances in the ionosphere of the order 50-100 s is introduced. No such effect on the night side of the Earth has been detected yet.

The objective of this paper is to use this technology for analysing the ionosphere response to faint and bright solar flares.

PROCESSING OF THE DATA FROM THE GPS NETWORK

The following is a brief outline of the global monitoring (detection) technique for solar flares. 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 day side of the globe within the time resolution range of the GPS receivers (from 30 s 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, so that background fluctuations will always be distinguished in the frequency range of interest. However, background fluctuations are not correlated in the case of beams to the satellite 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 ionization irregularity size does normally not exceed 30-50 km; hence the condition of a statistical independence of TEC fluctuations at spaced beams is almost always satisfied. Therefore, coherent summation of responses to a flare on a set of LOS spaced throughout the day side 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). The proposed procedure of coherent accumulation is essentially equivalent to the operation of coincidence schemes which are extensively used in X-ray and gamma-ray telescopes.

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.

The data analysis was based on using the stations, for which the local time during the flare was within 10 to 17 LT. From 50 to 100 LOS were processed for each flare. The method of coherent summation of time derivatives of the series of variations of the "vertical" TEC value was employed in studying the ionospheric response to solar flares. Our choice of the time derivative of TEC was motivated by the fact this derivative permits us to get rid of a constant component in TEC variations; furthermore, it reflects electron density variations that are proportional to the flux of ionizing radiation. Next the trend determined as a polynomial on a corresponding time interval is removed from the result (normalized to the number of LOS) of the coherent summation of the time derivatives. After that, the calculated time dependence is integrated in order to obtain the mean integral TEC increment on the time interval specified. This technique is useful for identifying the ionospheric response to faint solar flares (of X-ray class C) when the variation amplitude of the TEC response to separate LOS is comparable to the level of background fluctuations.

IONOSPHERIC RESPONSE TO A FAINT SOLAR FLARE

An example of a processing of the data for a faint solar flare July 29, 1999 (C2.5/ SF, 10:11 UT, S16W11) is given in Figure 1. One hundred LOS were processed for the analysis of this event. Panels (a) and (b) present the typical time dependencies of TEC variations for separate LOS, and their time derivatives. The BRUS (PRN14, thick line) and BAHR (PRN29, thin line) stations are taken as our example. It is apparent from these dependencies that no response to the flare is distinguished in the TEC variations and in their time derivatives for the individual LOS, because the amplitude of the TEC response for the individual LOS is comparable to the level of background fluctuations.

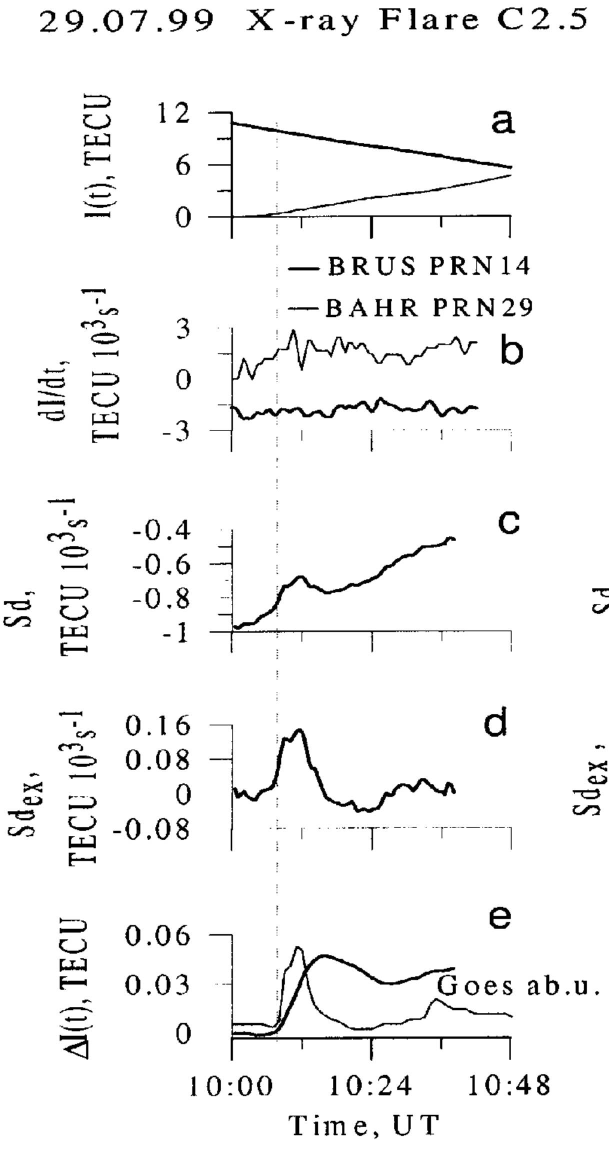

Fig.1. Faint solar flare July 29, 1999.

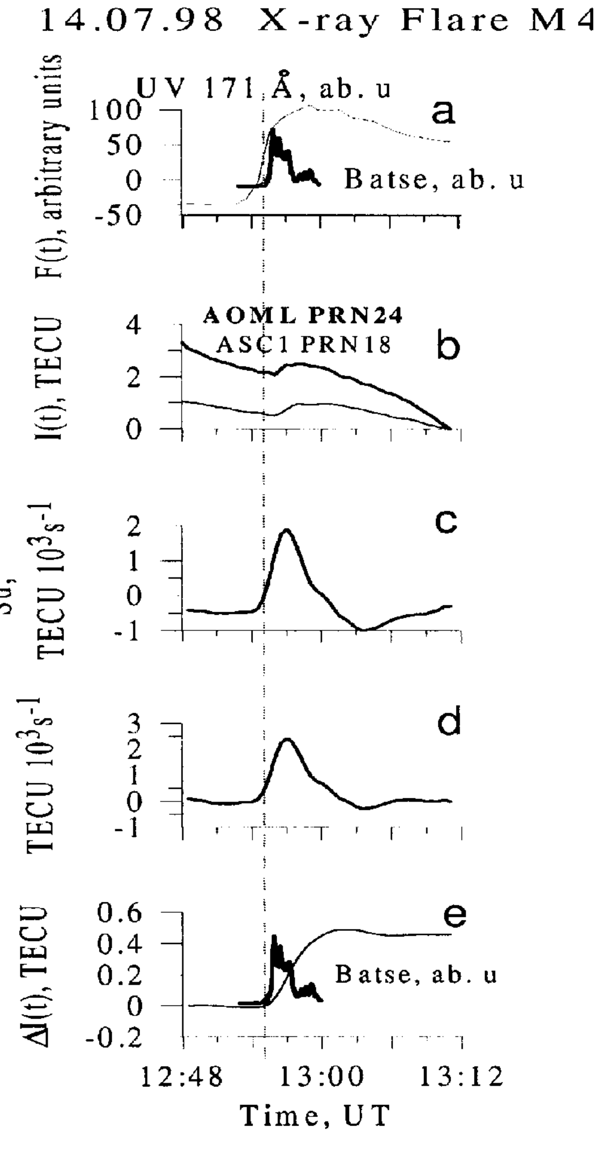

Fig.2. Bright solar flare July 14, 1998.

A response to the solar flare is clearly seen in the time dependence (Figure1c) which is a normalized result of a coherent summation of the time derivatives of the TEC variations, Sd, for all LOS. Upon subtracting the trend determined as a polynomial of degree 3 on the time interval 10:07-10:39 UT, the same curve (c) is presented in Figure 1d. Next the calculated time dependence was integrated over the time interval 10:07-10:39 UT to give the mean integral increment of TEC (Figure 1e, thick line). A comparison of the resulting dependence with the values of the soft X-ray emission flux (GOES-10) in the range 1-8 Å (Figure 1e, thin line) reveals that it has a more flattened form, both in it rise and fall. A maximum in X-rays is about 6 minutes ahead of that in TEC.

IONOSPHERIC RESPONSE TO BRIGHT SOLAR FLARES

An example of a processing of the data for the bright solar flare of July 14, 1998 (M4.6/1B, 12:59 UT, S23E20) is given in Figure 2. Fifty LOS were used in the analysis of this event. Figure 2a presents the time dependencies of hard X-ray emission (CGRO/Batse, 25-50 keV, thick line on panels (a) and (e)) and of the UV line (SOHO/SUMMER 171 Å , thin line) in arbitrary units (Aschwanden et al., 1999). It should be noted that the time dependence of the UV 171 Å line is more flattened, both in the rise and in the fall, when compared with the hard X-ray emission characteristic. The increase in the UV 171 Å line starts about 1.8 minute earlier, and the duration of its disturbance exceeds considerably that of the hard X-ray emission disturbance.

Panel (b) presents the typical time dependencies of the TEC variations for separate LOS. The AOML (PRN24, thick line) and ACSI (PRN18, thin line) stations are taken as examples. A response to the bright flare is clearly distinguished for separate LOS. The normalized sum of the time derivatives of the TEC variations, Sd, for all LOS is presented in Figure 2c; panel (d) plots the same curve (c), upon subtracting the trend determined as a polynomial of degree 3 on the time interval 12:48-13:12 UT. Next the resulting time dependence was integrated in order to obtain the mean integral increment of TEC (Figure 2e, thin line).

It might be well to point out that the time dependence of the mean integral increment of TEC has a more flattened form in the rise than the emission flux characteristics; however, the onset time of its increase coincides with that of hard X-ray emission, and is delayed by about 1.8 minutes with respect to the UV 171 Å line.

A total of 11 events was processed (see Table 1). The class of X-ray flares was from M4.5 to M7.4. It was found that the mean TEC variation response in the ionosphere depends on the flare location on the Sun (central meridian distance, CMD) - Figure 3a.

Table 1: Bright solar flares

№	Data dd.mm.yy	Flare max time UT	X-ray/optic class	Δ I(t) TECU	LAT CMD Degree
1	23.09.98	07:13	M7.1/3B	1.00	N18 E09
2	14.11.99	16:07	M5.6	0.31	N18 E60
3	29.07.99	19:36	M5.1/1N	0.5	N25 E51
4	17.11.99	09:57	M7.4/2B	1.1	N17 E21
5	28.02.99	16:39	M6.6/2B	1.00	N28 W06
6	27.08.99	13:07	M5.5/2N	0.53	S23 W09
7	19.09.00	08:26	M5.1/1N	0.46	N14 W46
8	16.07.00	02:03	M5.5/1N	0.08	N09 E81
9	14.07.98	12:59	M4.6/1B	0.50	S23 E20
10	28.12.99	00:48	M4.5/2B	0.27	N20 W56
11	12.07.00	18:49	M5.7/2F	0.30	N16 W64

DISCUSSION

The results presented here are consistent with the findings reported by Donnelly (1971, 1969, 1976), Donnelly et al., 1986, Donnelly and Puga (1990) where a study of EUV flashes of solar flares observed via sudden frequency deviation (SFD) was made. In the cited references it was shown that the relative strength of impulsive EUV emission from flares decreases with increasing CMD and average peak frequency deviation is also significantly lower for SFD's associated with Hα flares at large CMD. Donnelly (1971) is of the opinion that the percentage of Hα flares with SFD's tends to decrease for large CMD of Hα flare location - Figure 3b. Similar effects at the center and limb were observed in the ratio of EUV flux to the concurrent hard X ray flux (Kane and Donnelly, 1971). Using a fourth-order polynomial to fit the results in Figure 3b with CMD in degrees (Donnelly, 1976) gives

$$A(CMD) \sim 1 - 0.0484 \cdot CMD + 0.001426 \cdot CMD^2 - 1.79\ 10^{-5} \cdot CMD^3 + 7.43 \cdot 10^{-8} \cdot CMD^4 \qquad (1)$$

Equation (1) implies that on the average the impulsive EUV emission is more than an order of magnitude weaker for flares near the solar limb than for flares at the central meridian. Donnelly (1976) have assumed that this is a result of the low-lying nature of the 104K-106K flare source region and from absorption of EUV emission in the surrounding cool non-flaring atmosphere. Figure 3c presents the result of a modeling of the SFD occurrence probability at the time of the solar flare as a function of CMD (solid lines) in arbitrary units, as well as the amplitude of the TEC response in the ionosphere to solar flares (in the range of X-ray class M4.5-M5.7 (dots), and M6.6-M7.4 (crosses) as a function of CMD. The modeling used equation (1). This figure suggests that the results of our measurements do not contradict the conclusions drawn by Donnelly (1976) that the relative strength of impulsive EUV emission from flares decreases with increasing CMD. It should be noted that in the case of solar flares whose class is similar in X-ray emission, the dependence under study resembles cos(CMD) rather than a polynomial of degree 4. The fitted cos(CMD) curve for solar X-ray M4.5-M5.7 flares is plotted in Figure 3a (solid line) and 3c (dashed line).

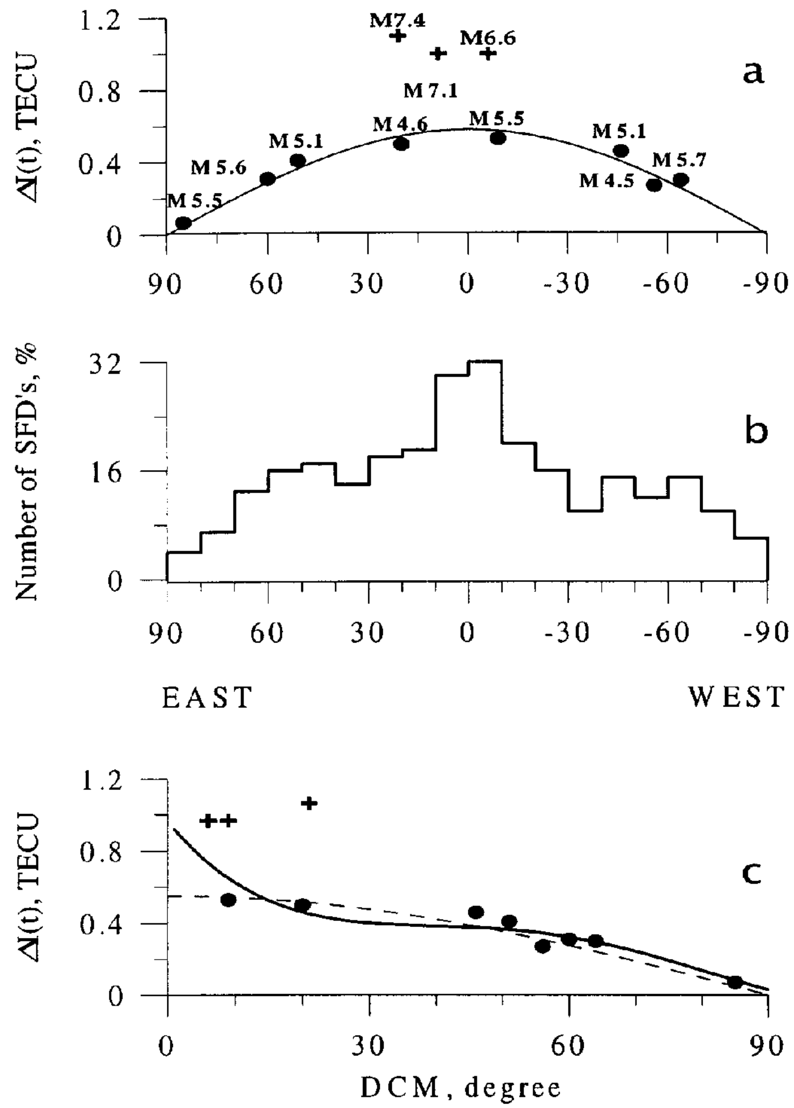

Fig.3. CMD dependence of the increment of the mean amplitude of the TEC response to solar flares.

SUMMARY

This paper suggests a new method for investigating the ionospheric response to faint solar flares (of X-ray class C) when the variation amplitude of the TEC response to individual LOS is comparable to the level of background fluctuations. The dependence of the TEC variation response amplitude on the flare location on the Sun is investigated. In the case of solar flares whose class is similar in X-ray emission, the dependence under study resembles cos(CMD).

The high sensitivity of GLOBDET permits us to propose the problem of detecting, in the flare X-ray and EUV ranges, emissions of non-solar origins which are the result of supernova explosions.

For powerful solar flares it is not necessary to invoke a coherent summation, and the ionospheric response can be investigated for each beam. 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, the data obtained through the use of GLOBDET can be used to estimate the spatial inhomogeneity of emission fluxes at scales of the order of the Earth's radius.

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