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The GPS measured SITEC caused by the very intense solar flare on July 14, 2000

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Abstract

This work studies the sudden increases in total electron content of the ionosphere caused by the very intense solar flare on July 14, 2000. Total electron content (TEC) data observed from a Global Positioning System (GPS) network are used to calculate the flare-induced TEC increment, δTEC_f, and variation rate, $dTEC_f/dt$. It is found that both $dTEC_f/dt$ and δTEC_f are closely related with the solar zenith angles. To explain the observation results, we derived a simple relationship between the partial derivative of the flare-induced TEC, $\partial TEC_f/\partial t$, which is a good approximation for $dTEC_f/dt$, and the solar zenith angle χ, as well as the effective flare radiation flux I_f, according to the well-known Chapman theory of ionization. The derived formula predicted that $\partial TEC_f/\partial t$ is proportional to I_f and inverse proportional to Chapman function $ch(\chi)$. This theoretical prediction not only explains the correlation of $dTEC_f/dt$ and δTEC_f with χ as shown in our TEC observation, but also gives a way to deduce I_f from TEC observation of GPS network. Thus, the present work shows that GPS observation is a powerful tool in the observation and investigation of solar flare effects on the ionosphere, i.e., the sudden ionospheric disturbances, which is a significant phenomenon of space weather.
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1. Introduction

The prompt response of the ionosphere to solar flare explosions, known as sudden ionospheric disturbances (SIDs), is not only an important classical topic in the solar–terrestrial relation, but also a focus of the current space weather research (*National Space Weather Program Implementation Plan*, second ed., July 2000, www.ofcm.gov). Among many observable SID phenomena (Hargreaves, 1992), the sudden increase in total electron content (SITEC) is of special importance, and has been investigated by several authors since 1970s (see the review paper by Davies, 1980). With a worldwide network of Faraday rotation stations, Mendillo et al. (1974) first obtained the global morphology of the flare-induced SITEC', although they found no obvious relationship between the observed SITEC and the solar zenith angle χ. Recently, the Global Positioning System (GPS) has been widely used in the observation of ionospheric total electron content (TEC) and especially in the study of ionospheric space weather (Ho et al., 1998; Jakowski et al., 1999). Owing to the world wide distribution of the GPS network (e.g., IGS network), the GPS TEC measurements as a powerful tool in the study of the global properties of the SITEC, have been noticed by several authors (Zhang and Xiao, 2000; Afraimovich et al., 2001a,b).

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to this solar explosion have been reported (Lee et al., 2002; Liu et al., 2002; Afraimovich et al., 2002). In the present work, we will further investigate the flare-induced SITEC from the observation of a worldwide GPS network. The data analysis results were first introduced to show the correlation between the observables and χ. To explain our observation results, we derived a simple formula for the TEC variation rate. Then the theoretical prediction was used to explain the observed correlation of TEC variation rate (and also SITEC) with flare parameters such as the solar zenith angles and the flare radiation flux. The final section is followed by a summary and conclusion.

2. Observation and initial results

On July 14, 2000, an X5 solar flare, which is the most intense flare during the past decade, occurred in the solar active region AR9077. In order to investigate the SITEC phenomenon deduced by this very intense solar flare, we analyzed the TEC data observed with a global GPS network (the IGS network augmented with a network located in China). Fig. 1 shows the location of the GPS stations and the solar zenith angles when the flare occurred.

As examples, Fig. 2 (left panel) gives the observed TEC along lines connected station–satellite pairs. We take the sub-ionospheric altitude as 120 km (about the maximum height of the flare ionization); hence we can locate the TEC measurements at selected station–satellite pairs to derive the solar zenith angles. In addition, a cut-off elevation angle of 10° is used because it cannot provide precise TEC measurement at small angles. It shows obviously in Fig. 2 the sudden increase of TEC. The SITEC phenomenon is even clearer in the curves of TEC variation rate, $dTEC_0/dt$, as shown in Fig. 2 (right panel). To distinguish the flare-induced TEC variation $dTEC_f/dt$, the background variation rate, $dTEC_0/dt$, is estimated by polynomially fitting $dTEC/dt$ in which the data in the interval of the flare are excluded, as indicated by the dashed curves in Fig. 2. From this illustration we can see the SITEC occurred at about UT 10:10 and lasted for about 20 min. At this interval, the TEC variation rate became obviously large and manifested a fine structure. This variation structure may imply the temporal evolution of the flare radiation flux. In fact, there are three marked peaks in the variation curves of $dTEC/dt$, respectively, at UT 10:19, 10:24 and 10:26.

To seek the correlation between the observed SITEC and the observation locations, we calculated the geographical distribution of the largest peak values of the flare-induced TEC variation rate, $dTEC_f/dt$ at UT 10:24, as well as the flare-induced TEC increment, δTEC_f, shown as solid lines in Fig. 3. Here, $dTEC_f/dt$
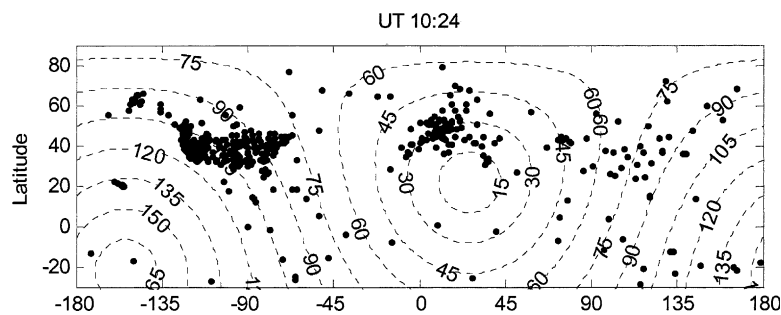

Fig. 1. Geographical distribution of the GPS receivers. The contours indicate the distribution of the corresponding solar zenith angle at the time UT 10:24, July 14, 2000.
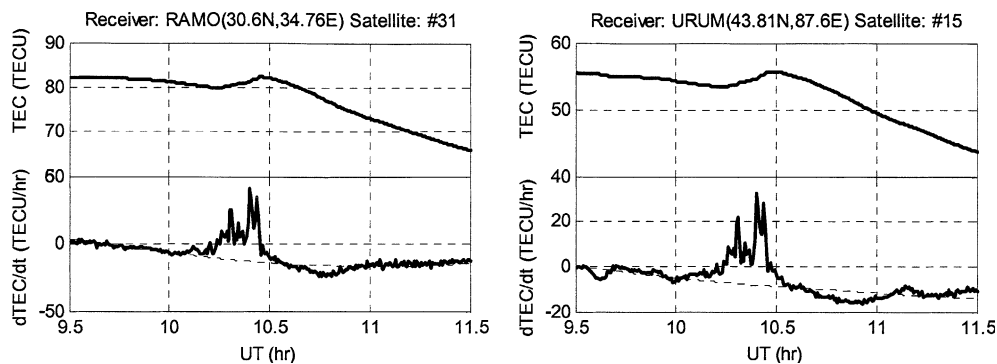

Fig. 2. The GPS measured TEC and its vacation rate along lines,connected the two station–satellite pairs during the period around the very intense solar flare on July 14, 2000.
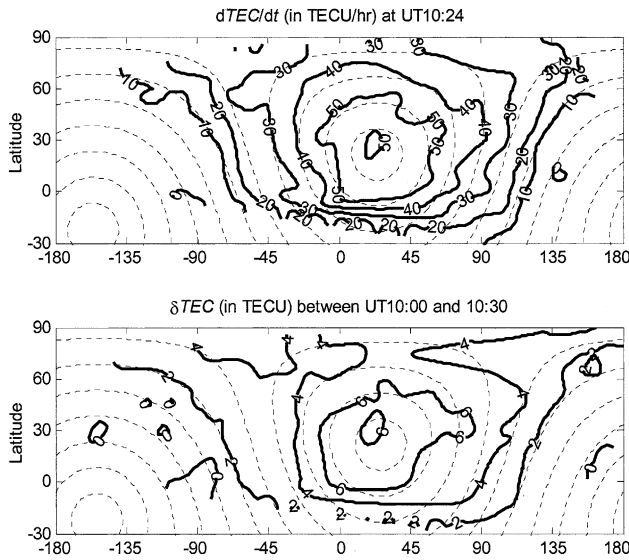
Fig. 3. Contours of dTEC$_f$/dt at UT 10:24 (top panel) and ∂TEC$_f$ (bottom panel). For comparison, contours of the solar zenith angle χ are also given as the dashed lines.

is the difference between the observed dTEC/dt and the fitted dTEC$_0$/dt, and δTEC$_f$ is estimated as the integration of dTEC$_f$/dt in the flare interval. For comparison, the contours of χ are also shown in Fig. 3 as dashed lines. Thus, we can see that both kinds of contours are very similar in shape, implying that both dTEC$_f$/dt and δTEC$_f$ are closely related to χ.

3. Discussion and further results

3.1. Theoretical analysis

As well known, the variation rate of the ionospheric electron density, N, is given by the continuity equation,

$$\frac{\partial N}{\partial t} = Q - L + M, \tag{1}$$

where Q, L and M are, respectively, the electron production, loss and immigration rate. During a solar explosion, the sudden increase of the solar radiation produces a flare-related increment, Q_f, on the electron production, and creates a corresponding increment, N_f, on the electron density. The flare explosion is a very rapid process; its effects on the electron loss and immigration may be ignored in the continuity equation. Therefore from Eq. (1) we have,

$$\frac{\partial N_f}{\partial t} = Q_f. \tag{2}$$

According to the Chapman ionization theory, we express the flare-related electron production as,

$$Q_f = Q_{fm} \exp(1 - y - e^{-y}), \quad Q_{fm} = \frac{\eta' I_f}{H \mathrm{ch}(\chi)},$$

$$y = \frac{h - h_m}{H}, \tag{3}$$

where η' represents the efficiency of ionospheric ionization; I_f is the effective radiation flux of solar flare in the ionospheric altitudes; H is the scale height of the background atmosphere; h_m is the reference height where production is largest; $\mathrm{ch}(\chi)$ is the Chapman function. Usually $\mathrm{ch}(\chi) \approx \sec(\chi)$ is a good approximation but it may bring a considerable error when χ is greater than 80° (Rishbeth and Garriot, 1969).

Substituting Eq. (3) into Eq. (2) and integrating along altitude h, we obtain,

$$\frac{\partial \mathrm{TEC}_f}{\partial t} = \frac{\eta I_f}{\mathrm{ch}(\chi)}, \tag{4}$$

where TEC$_f$ is the TEC increment produced by flares. Here in the integration, we replaced $\mathrm{ch}(\chi)$ as its value at h_m, because it varies very slowly with height. Furthermore, we change the lower limit of the integration 0 into $-\infty$, because Q_f in Eq. (3) decrease rapidly to zero at lower altitudes. Thus, the altitude integration is carried as,

$$\eta = \frac{\eta'}{H} \int_{h=0}^{h=\infty} \exp(1 - y - e^{-y}) \, \mathrm{d}h$$

$$= \eta' \int_{-\infty}^{\infty} \exp(1 - y - e^{-y}) \, \mathrm{d}h$$

$$= 2.7183 \eta'.$$

Integrating Eq. (4) in the flare interval, one can find

$$\partial \mathrm{TEC}_f = \frac{\eta \int I_f \, \mathrm{d}t}{\mathrm{ch}(\chi)}. \tag{5}$$

Eqs. (4) and (5) show that the flare-induced TEC variation rate ∂TEC$_f$/∂t and TEC increment ∂TEC$_f$ are, respectively, proportional to I_f and total flux (integration of I_f), and both inverse proportional to the Chapman function $\mathrm{ch}(\chi)$. This makes possible to study the TEC variation with χ using the TEC observation at different places (with different χ), as well as to study the evolution of the effective flare radiation.

It should be pointed out that only the variation rate, dTEC$_f$/dt, along moving lines between certain station–satellite pairs is observed for the present GPS observation. Thus, dTEC$_f$/dt is different from ∂TEC$_f$/∂t in Eq. (4) because there exist TEC gradients. Fortunately, the contribution from the TEC gradients is often negligible, thus dTEC$_f$/dt, is a good approximation of ∂TEC$_f$/∂t, and the same approximation is valid for ∂TEC$_f$.

4. Variation of SITEC vs. solar zenith angles

According to Eqs. (4) and (5), both ∂TEC$_f$/∂t and ∂TEC$_f$ are inversely proportional to (χ) at a certain time

(hence a certain flare radiation flux). To demonstrate this theoretical prediction, we show in Fig. 4 the scatter plot of both peak $dTEC_f/dt$ and δTEC_f vs. the reciprocal Chapman function, $ch^{-1}(\chi)$, observed at different stations at UT 10:24. A very clear linear correlation with correlation coefficients larger than 90% is immediately obtained from such illustration. It should be pointed out that the remaining dispersion in Fig. 4 is probably due to the measurement error as well as the approximation that we replace $\partial TEC_f \partial t$ with $dTEC_f/dt$ and ignore the flare effects on the electron loss and immigration rate.

Using the Faraday rotation measurements made at 17 stations in North America, Europe and Africa, Mendillo et al. (1974) studied the SITEC produced by the great solar flare of August 7, 1972. Contrary to our results, they found no correlation between TEC increments and solar zenith angles. The possible reason may be that their estimation of ∂TEC is lack in precision. In addition, the size of the database they used is much smaller than ours. They use 17 stations of Faraday measurements, and their observation covers a range of χ from 31.71° to 73.09°, or $\sec(\chi)$ from 1.18 to 3.44. In the present work, we use 677 stations of GPS receivers, and each station consists of 4–8 channels. Our observation covers a χ range from 0° to about 140°, corresponding to $ch(\chi)$ range from one to almost infinite.

Fig. 5. The effective flare radiation flux obtained by the coherent summation of $dTEC/dt$ (bottom panel). Its integration (SITEC) is shown in the top panel.

5. Fine structure of the flare radiation flux

Afraimovich et al. (2001b) suggested a method to express the flare effect on the ionosphere by coherent summation of $dTEC_f/dt$. From Eq. (4) we can obtain I_f by the coherent accumulation of the observed TEC variation rates,

$$\eta I_f = \sum \frac{\partial TEC_f}{\partial t} \bigg/ \sum \frac{1}{ch(\chi)}. \tag{6}$$

Here, the effective radiation flux ηI_f refers to the flare-induced TEC variation rate when $\chi = 0$, hence the coherent accumulation is an essential improvement to understand the total effect of radiation bursts at zero solar zenith angles. By the accumulated summation using Eq. (6), the evolution of effective flux radiation ηI_f of the flare obtained is obtained and shown in the bottom panel of Fig. 5, and the corresponding TEC at zero solar zenith angle is derived by integrating ηI_f and shown as the curve in the top panel of Fig. 5.

6. Summary and conclusion

During the very intense solar flare on July 14, 2000, the flare explosion produces sudden increase of the ionospheric ionization and lead to the SITEC observed with a global GPS network. According to the simple Chapman ionization theory, we obtained that both the flare-induced TEC variation rate and TEC increment is proportional to the flare radiation flux I_f and inverse proportional to the Chapman function $ch(\chi)$. We first statistically analyzed the relationship between the flare-induced TEC variation rate $dTEC_f/dt$ (as well as the TEC increment ∂TEC_f) and the solar zenith angle χ,
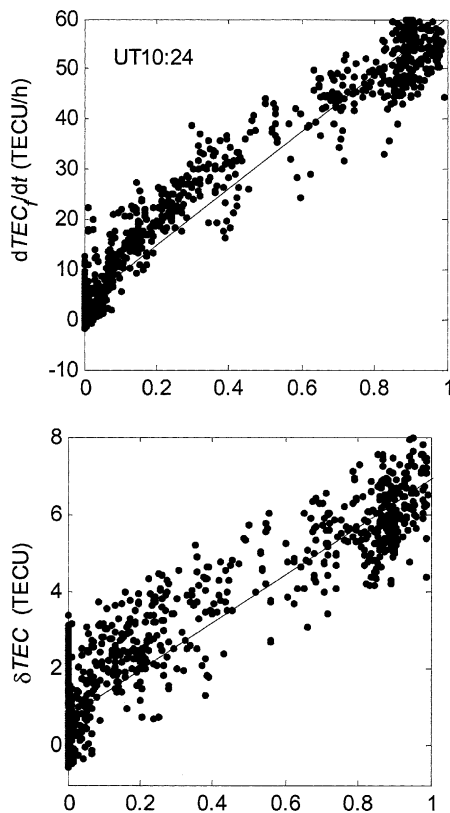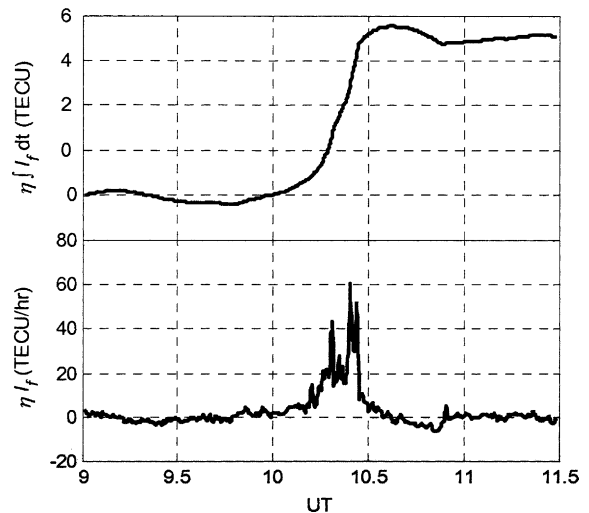

Fig. 4. The observed $dTEC_f/dt$ (left panel) and ∂TEC_f (right panel) vs. $ch^{-1}(\chi)$, which shows a very good linear correlation between them.

and the results quite agree with the theoretical predictions. Based on this theoretical and observational analysis, we proposed a method of coherent summation $dTEC_f/dt$ observed by a global GPS network to express effective flux radiations of the solar flares. Owing to its advantages for high. precision, large distribution range, and good temporal resolution, the TEC observation with GPS networks is a powerful tool in the study of SIDs caused by solar flares. This is of significance in the space weather research.

Acknowledgements

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