Solar flare signatures of the ionospheric GPS total electron content

J. Y. Liu,¹,² C. H. Lin,¹ Y. I. Chen,³ Y. C. Lin,¹ T. W. Fang,¹ C. H. Chen,¹ Y. C. Chen,¹ and J. J. Hwang⁴

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In this study, ionospheric solar flare effects on the total electron content (TEC) and associated time rate of change (rTEC) derived from ground-based global positioning system (GPS) receivers in the midday region are examined. The occurrence times and locations of 11 solar flares are isolated from the 1–8 Å X-ray radiations of the geosynchronous operational environmental satellite (GOES) and the SOHO Extreme Ultraviolet Imaging Telescope (EIT) images, respectively, while the TEC and rTEC are obtained from the international GPS services (IGS). Results show that the maximum value of the TEC increase solely depends on the flare class, while the maximum value of the rTEC increase is related to not only the flare class but also the time rate of change in flare radiations. A statistical analysis further demonstrates that the two maximum values are inversely proportional to the cosine of the great circle angle between the center and flare locations on the solar disc.


1. Introduction

Sudden ionospheric disturbances (SIDs) result from an interaction of solar flare radiations with constituents of the upper atmosphere, which form a major part of flare monitoring program in many observatories. The ionospheric solar flare effects or SIDs provide an interest in the reaction of the ionospheric plasma to an impulsive ionization [Mitra, 1974]. The disturbances have important effects on radio communications and navigations over the entire radio spectrum [Davies, 1990]. Davies [1990] reviewed that SIDs were generally recorded as the short wave fadeout [Stonehocker, 1970], sudden phase anomaly [Jones, 1971; Ohshio, 1971], sudden frequency deviation (or frequency shift; Doppler shifts) [Dawney, 1971], sudden cosmic noise absorption [Deshpande and Mitra, 1972], sudden enhancement/decrease of atmospherics [Sao et al., 1970], and sudden increase in total electron content (TEC) [Mendillo et al., 1974; Davies, 1980]. In the early years, the most common technique to study the ionospheric solar flare effects is to examine Doppler (frequency) shift in signals transmitted by Doppler sounding systems. However, owing to the high-frequency band (HF, 3–30 MHz) [e.g. Hunsucker, 1991] used, the Doppler sounding system observation generally suffers from the short wave fadeout and often no data was recorded even during the midway of the flare occurrence [e.g., Davies, 1990; Liu et al., 1996a].

To simultaneously monitor a large area of the ionosphere response to solar flares, the global positioning system (GPS) is ideal to be employed. The system consists of more than 24 satellites, distributed in six orbital planes around the globe at an altitude of about 20,200 km. Each satellite transmits signals in two frequencies (f₁ = 1575.42 MHz and f₂ = 1227.60 MHz). Since the ionosphere is a dispersive medium, scientists are able to evaluate the ionospheric effects with measurements of the modulations on carrier phases and phase codes recorded by dual-frequency receivers [Sardón et al., 1994; Leick, 1995; Liu et al., 1996b]. Meanwhile, owing to the transmitted frequencies being much greater than the ionospheric collision frequencies, the ionospheric absorption (signal fadeout) effects for the GPS signals are minor. Scientists report global views of ionospheric solar flare effects by means of the GPS technique [Zhang et al., 2002; Zhang and Xiao, 2003; Liu et al., 2004]. Liu et al. [2004] proposed two GPS observed quantities, the TEC and its time rate of change (rTEC), for observing ionospheric solar flare effects. They found that ionospheric responses of the two quantities depend on the local time of observation (or hour angle) and the most pronounced solar flare effects are in the midday region.

They further show theoretically that the rTEC stands for the frequency deviation of the GPS signals and is well correlated to Doppler shift in signals transmitted by Doppler sounding systems. Instead of the global view of a particular event, Zhang et al. [2002] examined several flare events and found that for the similar classes, flares occurring near the solar meridian result in stronger ionospheric responses. In this paper we examine TEC and rTEC variations in the midday region during ten X-class and one M-class solar flare events (Table 1), including the greatest flare of class...
Table 1. Parameters of the 11 Solar Flare Events

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>Flare Class</th>
<th>Start, hh:mm</th>
<th>Maximum, hh:mm</th>
<th>End, hh:mm</th>
<th>Active Region</th>
<th>( \alpha ) Angle, deg</th>
<th>Increase Rate, Watt/m²</th>
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<tr>
<td>2003/11/04</td>
<td>308</td>
<td>X28</td>
<td>1929</td>
<td>1950</td>
<td>2206</td>
<td>S19 W83</td>
<td>86.136</td>
<td>0.0314</td>
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<td>2001/04/02</td>
<td>092</td>
<td>X20</td>
<td>2132</td>
<td>2151</td>
<td>2203</td>
<td>N16 W56</td>
<td>58.637</td>
<td>0.0074</td>
</tr>
<tr>
<td>2003/10/28</td>
<td>301</td>
<td>X17.2</td>
<td>0951</td>
<td>1110</td>
<td>1124</td>
<td>S16 E08</td>
<td>17.912</td>
<td>0.0140</td>
</tr>
<tr>
<td>2001/04/15</td>
<td>105</td>
<td>X14.4</td>
<td>1319</td>
<td>1350</td>
<td>1355</td>
<td>S22 W72</td>
<td>76.338</td>
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</tr>
<tr>
<td>2003/10/29</td>
<td>302</td>
<td>X10</td>
<td>2037</td>
<td>2049</td>
<td>2101</td>
<td>S15 W02</td>
<td>15.134</td>
<td>0.0082</td>
</tr>
<tr>
<td>2003/11/02</td>
<td>306</td>
<td>X8.3</td>
<td>1703</td>
<td>1725</td>
<td>1739</td>
<td>S14 W56</td>
<td>58.029</td>
<td>0.0054</td>
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<td>2000/07/14</td>
<td>196</td>
<td>X5.7</td>
<td>1003</td>
<td>1024</td>
<td>1043</td>
<td>N17 E03</td>
<td>17.267</td>
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<tr>
<td>2002/07/23</td>
<td>204</td>
<td>X4.8</td>
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<td>0035</td>
<td>0047</td>
<td>S13 W2</td>
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<tr>
<td>2001/07/03</td>
<td>184</td>
<td>X1.5</td>
<td>0208</td>
<td>0213</td>
<td>0216</td>
<td>S18 W5</td>
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<tr>
<td>2001/04/26</td>
<td>057</td>
<td>X1.1</td>
<td>0150</td>
<td>0203</td>
<td>0210</td>
<td>N14 W15</td>
<td>20.574</td>
<td>0.0009</td>
</tr>
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<td>2004/11/06</td>
<td>311</td>
<td>M9.3</td>
<td>0011</td>
<td>0034</td>
<td>0042</td>
<td>N09 E06</td>
<td>10.824</td>
<td>0.0266</td>
</tr>
</tbody>
</table>

*Time is in Universal Time.

X28 occurring on 4 November 2003 and the well-known, fourth-greatest flare of class X17.2 on 28 October 2003, the so-called Halloween flare and storm, to find the relationship between the two quantities and the flare locations on the solar disc. Meanwhile, simultaneous observations from ground-based GPS receivers and a Doppler sounding system collocated in Taiwan during an M9.3 flare are examined to find whether the frequency deviations (or Doppler shifts) of the two transmitted signals show similar tendencies as suggested by Liu et al. [2004].

2. Observation

For a Doppler sounding system, the frequency deviation \( \Delta f_D \) from the operating (or transmitting) frequency is proportional to the rate of change of phase path of the signal and is given by [Bennett, 1967]

\[
\Delta f_D = -\frac{c}{\mu} \int_{S} \frac{\partial \phi}{\partial t} \cos \phi \, ds = \frac{c}{\mu} \int_{S} \frac{\partial N}{\partial t} \cos \phi \, ds,
\]

where \( \mu \) is phase refractive index and \( \phi \) is the angle between the wave normal and the ray direction. \( T_x \) and \( R_x \) denote the transmitter and receiver antennas. Here \( c \) is light speed in free space, \( N \) represents the ionospheric electron density, and \( s \) denotes the integration along the radiowave path from \( T_x \) to \( R_x \). Since \( \partial N/\partial t \) is a negative quantity, \( \Delta f_D \) is then proportional to \( d\phi/dt \).

In practice, flare radiations, often with a broad spectrum, ionize the whole ionosphere and enhance the electron density within it, which also results in altitude descending of the reflection point \( P_R \) of signals transmitted by a Doppler sounding system. Thus equation (1) can be rewritten as

\[
\Delta f_D = -\frac{c}{\mu} \int_{T_x}^{R_x} \frac{\partial \phi}{\partial t} \cos \phi \, ds = -\frac{c}{\mu} \left[ \int_{T_x}^{P_R} \frac{\partial \phi}{\partial t} \cos \phi \, ds \right. \\
+ \left. \int_{P_R}^{R_x} \frac{\partial \phi}{\partial t} \cos \phi \, ds \right]
\]

Note that the \( P_R \) descending means the phase paths between \( T_x \) and \( P_R \) as well as \( P_R \) and \( R_x \) being shorter, which in turn gives the \( \Delta f_D \) to be positive (increased).

On the other hand, Liu et al. [2004] proposed that the two quantities, the TEC and its time rate of change, \( r_{TEC} \), observed by ground-based GPS receivers, can be employed to monitor the ionospheric solar flare effects. The two quantities can be stated as

\[
TEC = \cos \chi \int_{S}^{T_x} N \, ds
\]

and (5), a concurrent observation of a Doppler sounding system and GPS receivers in Taiwan is carried out. The operation frequency of the Doppler sounding system is 5.262 MHz and the distance between the transmitter at Liyutan University (25.0°N, 120.8°E) and the receiver at National Central University (25.0°N, 121.2°E) is about 80 km. We assume the reflection point \( P_R \) of the 5.262 MHz signals to be 200 km altitude, and the incidence angle is about 11°. Thus the Doppler sounding system performs a nearly vertical probing.

3. Result and Interpretation

To avoid the local time (solar zenith angle) effects, the GPS TEC and \( r_{TEC} \) observed around the midday regions are used to examine the ionospheric responses to ten X-class and one M-class flares occurred at various locations on the solar disc. The occurrence time and location (see Table 1) as well as X-ray radiations in 1–8 A with 1-min time resolution of each event are observed by sweeping the solar with the X-ray sensor on the geosynchronous operational environmental satellite (GOES). The midday TEC and \( r_{TEC} \) are derived from ground-based receivers of the international GPS service (IGS) and the Taiwan network.

Figure 1 illustrates the SOHO Extreme Ultraviolet Imaging Telescope (EIT) images of the fourth largest flare.
Figure 1. SOHO Extreme Ultraviolet Imaging Telescope (EIT) images of the fourth largest on 28 October 2003 (left) and the largest solar flare on 4 November 2003 (right).

Figure 2. The 1–8 Å solar X-ray radiations from GOES (bold gray curves and left axes) and ionospheric GPS TEC (dark curves and right axes) responses to flares. (a) X-ray (gray curve) and TEC (dark curve) as well as (b) rX-ray (gray curve) and rTEC (dark curve) variations on 28 October 2003 (03301). (c) X-ray and TEC as well as (d) rX-ray and rTEC variations on 4 November 2003 (03308). Note that the GOES data show data gaps/saturations during the 4 November 2003 flare.
of class X17.2 appearing at (S16, E08), near the solar meridian, on 28 October (Halloween flare) 2003 and the largest flare of class X28 occurring at (S19, W83), around the edge of the solar disc, on 4 November 2003.

Figure 2 shows that temporal variation in the increase TEC change \( \Delta \text{TEC} \) and X-ray as well as those in rTEC and X-ray are well correlated, respectively. It is surprised to find in Figure 2 that the maximum value 14.71 TECu of the TEC increase (\( \Delta \text{TEC}_M \)) of the X17.2 flare is much greater than that 4.50 TECu of the X28 (Figures 2a and 2c). Similarly, in Figures 2b and 2d, while the X28 has a greater value in the maximum time rate of change of the X-ray radiations, \( r \text{X-ray}_M \) (31.4 versus 14.0 mWatt/m²s), the X17.2 yields a greater value in the maximum time rate of change of the TEC, \( r \text{TEC}_M \) (2.29 versus 0.34 TECu/30s).

To resolve this puzzle, we further examine \( \Delta \text{TEC}_M \) versus flare class (or X-ray), \( r \text{TEC}_M \) versus flare class, and \( r \text{TEC}_M \) versus \( r \text{X-ray}_M \) for all the events (Figures 3a, 3b, and 3c). The open circle symbols in Figures 3a–3c show that the \( \Delta \text{TEC}_M \) and \( r \text{TEC}_M \) of the X17.2 flare occurred on 28 October yield the greatest values but show no clear relationship with X-ray radiations. It is noted that Figures 1 and 2 imply the flare location on the solar disc to be important. We therefore take into account the angle \( \theta \) of the great circle from the center of the solar disc to the flare location and calibrate the two quantities as

\[
\Delta \text{TEC}_{\text{MC}} = \Delta \text{TEC}_M / \cos\theta \tag{6}
\]

and

\[
r \text{TEC}_{\text{MC}} = r \text{TEC}_M / \cos\theta \tag{7}
\]

The dotted symbols show that the calibrated quantities \( \Delta \text{TEC}_{\text{MC}} \) and \( r \text{TEC}_{\text{MC}} \) are generally well correlated with the flare radiations (X-ray) and time rate of change in X-ray.
(rX-ray_M), except for the rTEC_{MC} values of the X17.2 and X20 flares shown in Figure 3b and for the X17.2 and M9.3 flares shown in Figure 3c. Note that the ΔTEC of the X20 flare and the rTEC of the M9.3 flare are much less than their associated predictions (solid lines), while the ΔTEC and rTEC of the X17.2 flare are much greater than their predictions (Figure 3b and 3c).

The flare-produced frequency shifts have been simultaneously observed by the ground-based GPS receivers and Doppler sounding system in Taiwan since 2003. Because the Doppler sounding system generally suffers from the short wave fadeout significantly during X class flares, we focus on the two frequency shifts observed during an M9.3 flare occurred on 26 February 2003. It is found from Figure 4 that the two frequency shifts are generally well correlated to each other until the Doppler sounder observation encountered the short wave fadeout after about 0028 UT.

4. Discussion and Conclusion

Results shown in Figure 2 confirm that the TEC is suitable to monitor the overall variations of flare radiations, and the rTEC is useful to depict the rate of change of flare radiations. The good agreement between the simultaneous measurements of the ground-based GPS TEC and the Doppler sounding system indicates that the rTEC stands for the Doppler frequency shift of the GPS signals (Figure 4).

Donnelly [1976] and Tsurutani et al. [2005] find the strong center-to-limb effects in the solar flare EUV spectra. To see if the X-ray flare radiation is also anisotropic (the center-to-limb effect), we examine ΔTEC_{MC} versus flare class (or X-ray_M), rTEC_{MC} versus flare class, and rTEC_{MC} versus rX-ray_M for all the events (Figures 3a, 3b, and 3c).

The regression analysis for the eleven pairs of data (x:flare class in X-ray radiations, y:ΔTEC_{MC}) indicates that 96.38% of the variation of the ΔTEC_{MC} can be explained by the fitted regression line ΔTEC_{MC} = 0.102 + 0.750 X-ray (Figure 3a). Moreover, applying the Fisher’s z-transformation [Kendall et al., 1977], we have the 95% confidence interval for the correlation coefficient between flare class and ΔTEC_{MC} of (0.943, 0.994), which shows a strong linear association between the two quantities. The strong linear association demonstrates that the ΔTEC_{MC} are functions of the flare class and eruption location on the solar disc, which can be written as

\[ \Delta \text{TEC}_{MC} = 0.75 \ C_f \cos \theta \]  

where ΔTEC_{MC} is the maximum increased TEC in TECu observed in the midday region and C_f denotes the flare class in term of the X class unit.

In Figure 3b, the regression analysis for the whole data set produces the correlation coefficient between x:flare class in X-ray radiation and y:rTEC_{MC} as 0.673 and indicates that the fitted regression line rTEC_{MC} = 0.243 + 0.056 X-ray explains only 45.33% of the variation of rTEC_{MC}. However, after removing the outlier, the extreme large rTEC_{MC} of the X17.2 flare, the correlation coefficient between flare class and rTEC_{MC} is enhanced to be 0.751. If we remove one more influential observation with the X20 flare, the related correlation coefficient becomes as high as 0.917, which implies a strong linear association between the X class and rTEC_{MC}.

In Figure 3c, the regression analysis produces 95% confidence intervals for the correlation coefficient between x:the maximum time rate of change in X-ray radiation (rX-ray_M) and y:rTEC_{MC} as (−0.254, 0.810) and

\[ \Delta \text{TEC}_{MC} = 0.75 \ C_f \cos \theta \]  

where ΔTEC_{MC} is the maximum increased TEC in TECu observed in the midday region and C_f denotes the flare class in term of the X class unit.

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where ΔTEC_{MC} is the maximum increased TEC in TECu observed in the midday region and C_f denotes the flare class in term of the X class unit.

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(-0.144, 0.871) based on the whole data set and the data set without the outlier, the extreme large rTEC\(_{MC}\), of the X17.2 flare, respectively. This means that rX-ray\(_{M}\) and rTEC\(_{MC}\) may not be linearly correlated. However, after removing one more influential observation with rTEC\(_{MC}\) of the M9.3 flare, the regression analysis based on the remaining nine pairs of data indicates that the fitted regression line \(rTEC_{MC} = 0.292 + 43.423 \times rX-ray\) explains 75.27% of the variation of rTEC\(_{MC}\). Moreover, the related 95% confidence intervals for the correlation coefficient between the two quantities is given by (0.573, 0.964), which indicates a moderate to strong linear association between rX-ray\(_{M}\) and rTEC\(_{MC}\).

[18] Both the rTEC\(_{M}\) and rTEC\(_{MC}\) of the X20 flare are much less than the linear prediction (Figure 3b), which might result from that the flare erupted gradually having a very small rX-ray\(_{M}\) (see Table 1 and Figure 3c). On the other hand, although the associated rX-ray\(_{M}\) is rather large, the rTEC\(_{M}\) and rTEC\(_{MC}\) of the M9.3 flare are much less than the prediction, which is possibly due to the relative small flare class (i.e., flare radiations) (Figure 3c). By contrast, Figures 3b and 3c display that the rTEC\(_{M}\) and rTEC\(_{MC}\) of the X17.2 flare are much greater than the predictions. It can be seen in the X17.2 flare that occurred on 28 October 2003, both the observed \(\Delta TEC_{M}\) and rTEC\(_{MC}\) yield the greatest values among the 11 events. Note that there are double sudden-increases (peaks) in the rTEC at about 1103 and 1105 UT, while the rX-ray radiation only has a single peak at about 1105 UT (Figure 2b). It is interesting to find that the EUV radiation in the X17.2 flare also has double peaks at about 1103 and 1105 UT (see Tsurutani et al., 2005, Figure 3). The double peaks in the rTEC confirm both the X-ray and EUV radiations to be important. It might be the enormous EUV radiation significantly contribute to the \(\Delta TEC_{M}\) and rTEC\(_{MC}\) of the X17.2 flare (B. T. Tsurutani, private communication, 2005). Nevertheless, after removing the outliers of the X20, X17.2, and M9.3 flares (Figures 3b and 3c), we find that the rTEC\(_{M}\) is a function of the flare class and the time rate of change of flare radiations.

[19] In conclusion, this study shows that the solar disc location of the flare has significant effect to the ionospheric response. The linear relation between the flare X-ray radiations and the cosine-angle-corrected TEC increases suggest that the center-to-limb effect of the flare radiation spectra also exists in the X-ray radiation.

References


