Characteristics of Ionospheric Storm on October 13, 2016 at the Greenwich Meridian

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Abstract An ionospheric positive disturbance during a moderate geomagnetic storm on October 13, 2016 was studied with total electron content (TEC) from a chain of GNSS receivers and F2 layer peak parameters from two ionosondes at the Greenwich meridian. During a slow decrease of Dst, a large enhancement of the daytime TEC was observed from high to middle latitudes successively while there was small disturbance observed in low latitudes. The occurrence of TEC peak delayed with decreasing latitude. Similarly, positive disturbance of hmF2 and foF2 was recorded and their onsets were earlier in high latitude than middle latitude. These observations indicated that the ionospheric positive disturbance propagated equatorward which denied the dominant effect of prompt penetration eastward electric field (PPEF). Using the latitudinal and temporal variations of TEC peaks, the propagation velocity of the disturbance was estimated and found to decrease with decreasing latitude. Two available Fabry-Perot interferometers (FPI) at the meridian 70°W of the Greenwich showed that nighttime equatorward wind in middle latitude increased significantly after the storm sudden commencement (SSC), while no change of that was observed in low latitude. The coincidence of the directional and latitudinal features between the ionospheric disturbance and the wind observation suggested the impact of the positive storm was most likely the equatorward wind surge which raised the ionosphere to higher altitude where lower chemical loss led to increase of electron density in the daytime.

1. Introduction

The geomagnetic storms are the disturbances of the Earth’s magnetic field, and the impact of solar wind particles enhancement (Buonsanto, 1999; Gonzalez et al., 1994; Kumar & Kumar, 2019). Following geomagnetic storms, the ionosphere also has obvious disturbance. It shows the critical frequency of F2-layer (foF2) or total electron content (TEC) changes obviously. The large decrease of foF2 or TEC is the ionospheric negative storm, and the significant increase of foF2 or TEC is referred to as positive storms (Fagundes et al., 2016; Maruyama et al., 2004). In general, F region ionization is positively correlated to the density ratio of atomic oxygen [O] to the molecular nitrogen [N2]. Prölls (1987) showed that the negative storm was caused by the change of neutral gas composition. The enhanced ratio of [N2]/[O] would lead to the chemical loss rate increase, so the ionospheric electron density decreased.

There are two main physical mechanisms of ionospheric positive storms. The first is the equatorward wind surge or disturbance wind (Fuller-Rowell et al., 1994). Joule heating raises the temperature of the upper thermosphere and ion drag drives high velocity neutral winds. The heat source drives a global disturbance wind. It propagates to low latitudes and even into the opposite hemisphere. The equatorward wind pushes the ionosphere up to high altitudes where the recombination is ineffective. As a result, the electron density increases under sunlit conditions (Maruyama et al., 2004; Zhao et al., 2008). Because the equatorward wind surge blows from high to low latitudes, the ionospheric disturbance has time delay. During quiet days, the neutral winds (or background winds) are poleward in daytime and turn equatorward after sunset. During storms, the neutral winds are the combination of background and disturbance winds. The daytime neutral wind, which is caused by Joule heating in the auroral region, even turns to equatorward (Fuller-Rowell et al., 1994). Different storms have different intensity, local time, and latitude coverage. de Jesus et al. (2016) studied a positive ionospheric storm at equatorial, low and middle latitudes in African sector. The factor was the equatorward disturbance winds and huge wind circulations.
The second physical mechanism is the eastward electric field. There are two origins of such electric field, which are prompt penetration eastward electric field (PPEF; Foster & Rich, 1998; Kelley et al., 1979, 2004) and dynamo electric field (Blanc & Richmond, 1980; Fejer & Scherliess, 1995; Huang et al., 2005; Mazaudier & Venkateswaran, 1990; Richmond et al., 2003). If the eastward electric field penetrates into the dayside equatorial ionosphere, the plasma is drifted to higher altitudes caused by the $E \times B$. New electrons, which are produced by solar photoionization, fill the uplifted ionosphere, and the electron density increases (Maruyama et al., 2004; Tsurutani et al., 2008). If the factor is PPEF, the electron density increases obviously in equatorial and low latitudes. The dynamo electric field is driven by energetic storm-time particle precipitation occurring primarily on the nightside auroral to middle latitude regions. The heating leads to a pressure wave that propagates to other longitudes and latitudes. Neutral-ion drag convects the ions away from the heating region. Upward motion of the plasma was described by convection electric fields (Blanc & Richmond, 1980; Fejer et al., 2000; Maruyama & Nakamura, 2007). Jenan et al. (2021) studied an ionospheric storm at the equatorial region. The positive response during the initial phase was attributed to the PPEF, while the effects of the later phase were due to the disturbance dynamo electric fields. Lissa et al. (2020) studied ionospheric storm with two chains of GPS stations along 80°E and 120°N longitudes in the Asian sector. The main factor of this storm was the PPEF and enhanced ratio of the thermosphere neutral composition, $[O]/[N_2]$.

Most of the ionospheric storms were not caused by one disturbance mechanism, but by many factors (Fuller-Rowell et al., 1994; Mishra et al., 2020). In different phases of storms, different disturbance mechanisms may play a leading role. Balan et al. (2009) showed that the equatorward wind surge was more important than PPEF for positive storm in low-midlatitudes. The equatorward wind surge without PPEF may lead to stronger positive storms than with PPEF. Maruyama et al. (2004) studied a positive ionospheric storm on November 06, 2001 with a dense GPS receiver network over Japan. The conclusion was that the ionospheric storm was the effect of PPEF in the presence of equatorward wind surge. The equatorward wind surge was set up before the PPEF and persists for $>24$ hr.

In this study, an ionospheric positive storm is studied with GNSS stations, ionosondes and Fabry-Perot interferometer (FPI). Nine GNSS stations along the Greenwich meridian are selected to study TEC in middle and high latitudes ($33°$–$63°N$) during storm day. Four GNSS stations are used to study the storm TEC in low latitudes. Two ionosondes and two related GNSS stations are also used to study the impact of the ionospheric storm on foF2, hmF2, and TEC in two latitudes. The observations of meridional winds are obtained by two Fabry-Perot interferometers (FPI). The main physical mechanism of this ionospheric storm is concluded to be the equatorward wind surge. Section 2 describes the data used and method for the study. Section 3 is the interplanetary magnetic field and geomagnetic conditions. Section 4 presents the results and discussions. Section 5 is the summary.

### 2. Data Used and Method for the Study

The observations were made by GNSS stations and ionosondes as shown in Figure 1. Table 1 shows the coordinates of the stations. Nine available GNSS stations were used to derive TEC from $33°$ to $63°N$ along the Greenwich meridian. These stations belonged to the EUREF Permanent GNSS Network (EPN) (Bruyninx et al., 2019). The latitude interval between two adjacent stations was $<5°$, and the longitude deviation from $0°E$ was $<2°$. The black dots in Figure 1 is the ionosphere pivot points (IPP) where the ray path intercepted the thin shell. The distribution of the stations ensured IPP continuous coverage from $33°$ to $63°N$. The nine GNSS stations formed an observation chain at $0°E$. The diurnal variation of TEC from $33°$ to $63°N$ was obtained by joint derivation of multiple GNSS stations. Four GNSS stations were selected from IGS network in low latitudes. Two ionosondes, which were EB040 ($0.5°E$, $40.8°N$) and RL052 ($359.4°E$, $51.5°N$) from the global ionosphere radio observatory (GIRO), were used to study the disturbances of hmF2 and foF2 during the ionospheric storm. Two GNSS stations (CHIO and EBBR) near the two ionosondes were also used for comparison. The FPI observations are used to study the variations of thermospheric winds during the storm. Because there were no available FPI observations at the Greenwich meridian, two FPI stations along $~290°E$ were selected. The two FPIs located at Millstone Hill ($42.6°N$, $288.5°E$) and Arecibo ($18.35°N$, $293.3°E$), respectively.
Geomagnetic conditions are described by northward component interplanetary magnetic field (IMF $B_z$) and geomagnetic indices Dst and Kp. The IMF $B_z$ data were from OMNIWeb (https://omniweb.gsfc.nasa.gov/form/omni_min.html). The geomagnetic index was from World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/index.html).

In this study, the diurnal variation of vertical TEC was modeled by surface harmonics expansion function (Maruyama & Ma, 2017). Azimuth ($\gamma$) and elevation ($\eta$) of the satellite were converted to longitude ($\lambda$) and latitude ($\zeta$) of the IPP and local satellite zenith angle ($\chi$) according to the following equations of the thin layer approximation that was shown in Figure 2

$$\lambda = \sin^{-1}(\sin\lambda_R \cos\alpha + \cos\lambda_R \sin\alpha \cos\gamma)$$

$$\zeta = \zeta_R + \sin^{-1}\left(\frac{\sin\alpha \sin\gamma}{\cos\lambda}\right).$$

Figure 1. Distribution of GNSS stations and ionosondes. The red dots are the GNSS stations in middle and high latitudes, the red squares are the GNSS stations in low latitudes and the blue stars are the ionosondes.
\[ x = \sin^{-1} \left( \frac{R_e}{R_e + h_s} \cos \eta \right) \]  

(3)

\[ \alpha = \frac{\pi}{2} - \eta - x \]  

(4)

where \( R_e \) is the earth’s radius; \( \lambda_R \) and \( \zeta_R \) are the latitude and longitude of the receiver, respectively; and \( h_s \) is the thin layer height, it is 400 km in this study. For the application of surface harmonics function, the coordinates of IPP were further converted to two arguments, colatitude (\( \theta \)) and angular local time (\( \phi \)) as follows:

\[ \theta = \frac{\pi}{2} - \lambda \]  

(5)

\[ \phi = \frac{7}{86,400} (2\pi + \zeta) \]  

(6)

where \( T \) is universal time (UT) in second and \( \phi \) covers a range from 0 to \( 2\phi \).

Ionosphere pierce points scattered in a wide latitude and longitude region (and thus local time), centering around the receiver location, and moving with time. The vertical TEC at IPP was represented by surface harmonics of local time in angle (\( \phi \)) and colatitude (\( \theta \)) as follows:

\[ TEC_v = \sum_{m=0}^{M} \sum_{n=m}^{N} (A_{mn} \cos m \phi + B_{mn} \sin m \phi) P_{n}^{m} (\cos \theta) \]  

(7)

where \( P_{n}^{m} \) is the associated Legendre polynomials with degree \( n \) and order \( m \). In this study, the degree \( n \) and order \( m \) were 7 and 5, respectively. The coefficients \( A_{mn} \) and \( B_{mn} \) are unknown parameters, which should be determined from the observations. The available observations are the slant TEC, \( TEC_{uv}^{obs} \). The vertical TEC was derived with the following:

\[ TEC_v = (TEC_{uv}^{obs} - b_r - b_i) \cos x \]  

(8)

where \( b_r \) and \( b_i \) are the instrumental biases of the receiver and satellite. The surface harmonics fitting (or determination of coefficients \( A_{mn} \) and \( B_{mn} \)) and estimation of \( b_r \) and \( b_i \) were simultaneously done by orthogonal network (Maruyama & Ma, 2017). The diurnal variation of vertical TEC was obtained by the solved coefficients \( A_{mn} \) and \( B_{mn} \) into Equation 7.

### 3. Interplanetary Magnetic Field and Geomagnetic Index

Figure 3 shows the interplanetary magnetic field (IMF) and geomagnetic conditions from October 12 to 14, 2016. The top panel is the z-component of the IMF observed by ACE satellite. The IMF \( B_z \) turned southward at \( \sim 06:00 \) UT on October 13, 2016. The universal time (UT) was the same as the local time (LT) at the Greenwich meridian. The southward IMF \( B_z \) was vital for the development of geomagnetic storm. The amount of solar wind energy transferred to the magnetosphere with long-duration southward IMF \( B_z \) (Arnoldy, 1971; Chao & Chen, 2013). The second panel is the Dst index. The storm sudden commencement (SSC) was at \( \sim 22:00 \) UT on October 12, 2016. The Dst started to decrease at \( \sim 23:00 \) UT, and reached about zero at \( \sim 06:00 \) UT on October 13, 2016. The initial phase was from \( \sim 23:00 \) UT on October 12 to \( \sim 06:00 \) UT on October 13. Then, the Dst decreased slowly, and the minimum of Dst was about \( \sim 105 \) at \( \sim 17:00 \)
UT on October 13. The main phase was from ~06:00 UT to ~17:00 UT on October 13, and it lasted 11 hr. The decrease rate of Dst was about 10 nT/h in the main phase of the storm. After that, Dst increased slowly, and it was about the recovery phase. The Dst returned to normal at ~00:00 UT on October 15, 2016. The bottom panel is the geomagnetic 3-hr Kp index. Kp index was designed to measure solar particle radiation by its magnetic effects. It was a proxy for the energy input from the solar wind to Earth (Matzka et al., 2021). The international Q-days (quiet days in the sense of days with low geomagnetic activity) and D-days (disturbed days in the sense of days with high geomagnetic activity) were derived from the Kp index. The international 10 Q-days (or Q10 for short) of October were used to get reference values in this study. It should be pointed out that the geomagnetic indices and the decrease rate of Dst indicated that the geomagnetic storm was a moderate one.

4. Results and Discussions

4.1. TEC Results in Middle and High Latitudes

The vertical TEC was derived from the method of Section 2. TEC maps as a function of latitude and local time are shown in Figure 4. The x axis is the local time from 0 to 24 h, and the y axis is the latitude from 33° to 63°N. Figure 4a is the reference TEC, which is the mean value of the Q10 in October. The Q10 were from world data center (WDC) for geomagnetism, Kyoto, and the website was http://wdc.kugi.kyoto-u.ac.jp/qd-days/index.html. The Q10 in October were 6–10, 12, 19–22. Reference TEC began to increase from 05:00 LT in all latitudes, and reached their peaks at 12:40 LT–13:18 LT from 63° to 33°N, as shown by the dotted line in the panel. They decreased and remained at a small value after sunset when the solar radiation disappeared (Oryema et al., 2015).

Figure 4b is the diurnal variation of TEC on October 13. A large enhancement of TEC was observed from high to middle latitudes at the Greenwich meridian. The peak time of TEC diurnal variation delayed with the decreasing of latitude. The TEC peak times from 63° to 33°N were shown by the dotted line in Figure 4b, and it was about 11:45 LT at 63°N and 14:20 LT at 33°N. The time interval was about 2 hr and 35 min...
between 33° and 63°N. So, the disturbance gradually spread from high latitudes to middle latitudes. Because the PPEF was simultaneous in all latitudes, TEC should reach their peaks at the same time. The equatorward disturbance propagated from high latitudes to middle latitudes. The time delay of TEC peak from high to middle latitudes during the storm denied the dominant effect of PPEF. It meant the main mechanism of this positive storm was likely to be the equatorward wind surge.

Figure 4c is the TEC difference (ΔTEC) between storm day and reference. ΔTEC represents the disturbance of TEC during storm day. It showing no disturbance occurred and ΔTEC was small before 08:00 LT. The positive disturbance of TEC was obvious during the daytime at all latitudes and nighttime at middle latitudes. ΔTEC was the largest at about 12:30 LT at 46.5°N. The ΔTEC peak time also delayed with decreasing latitude.

Figure 4d shows the ratio of storm TEC to reference representing the relative increase of storm day to reference. The ratio was generally large at high latitudes and small at middle latitudes. The largest ratio was about 2.9 at 11:55 LT at 54°N meaning the storm-time TEC was tripled almost that of quiet time. The ratio was also large between 19:00 LT and 22:00 LT in lower latitudes.

Figure 5 is the variations of TEC peak time with latitude on reference and storm day. The black dotted line is the reference and the black circle line is the storm day. As shown in Figure 5, storm TEC peaks appeared earlier than that of the reference from 63° to 42°N. However, the storm TEC peak times were later than that of the reference in 42°–33°N. The slope gave a rough estimate of the velocity of equatorward wind. The large slope indicated a high-speed wind, and vice versa. The radius of Earth is about 6,371 km. The corresponding peak time was about at 11:54 LT at 60°N, and 12:18 LT at 50°N. At the height of 300 km, the propagation velocity of the disturbance was about 800 m/s from 60° to 50°N. This propagation velocity was consistent with the previous work (Richmond & Matsushita, 1975). The slope got small toward low latitudes, or the disturbance slowed down (Fejer et al., 2000; Fuller-Rowell et al., 1994). The slowdown occurred due to the ion drag of daytime high electron density of lower latitude and the Coriolis force.

### 4.2. TEC Results in Low Latitudes (0°–20°N)

There were no GNSS observations in low latitudes at the Greenwich meridian. Four GNSS stations were selected from IGS network. The largest longitude deviation of the four GNSS stations from the Greenwich meridian was 23°. As shown in Figure 1, the four GNSS stations could not form a meridian chain like those in middle and high latitudes. Therefore, the TEC was derived by single GNSS station in low latitudes. Figure 6 is the diurnal variation of TEC during reference and storm days. The dotted lines present the results for reference days, and the black lines are the results during the storm day. Compared with the storm TEC in middle and high latitudes, the disturbance was small in low latitudes. So, the geomagnetic storm had smaller effect in low latitudes. If the physical mechanism of the ionospheric storm was the PPEF, the disturbance should be strong in low latitudes. The assumption of PPEF is inconsistent with the TEC results in low latitudes. This was another evidence that the storm was caused by the equatorward wind surge.

### 4.3. Ionosonde Results

Two ionosondes, EB040 (0.5°E, 40.8°N) and RL052 (359.4°E, 51.5°N), were used to examine the F2 layer characteristics during the storm. The propagation process of the disturbance from 51.5° to 40.8°N was also considered by two ionosondes. Two GNSS stations (EBRE (0.5°E, 40.8°N) and CHIO (358.5°E, 51.1°N)),
which located at the same position as the ionosondes, were also selected to compare with hmF2 and foF2. Figure 7 shows the variations of hmF2, foF2, and TEC from October 12 to 15, 2016. The solid lines are the variations of hmF2, foF2, and TEC from October 12 to 15. The dotted lines are those from the reference days, which is the mean value of Q10 of October.

Figures 7a and 7b are the variations of hmF2 at 51° and 41°N. The reference hmF2 maintained low altitudes in daytime, while it was lifted to high altitudes in nighttime. The diurnal variation of reference hmF2 related to background neutral winds. During quiet days, the poleward winds depressed hmF2 to low altitude in daytime, while the equatorward winds raised the hmF2 to high altitude in nighttime. The variations of hmF2 were similar to the reference from 00:00 LT on October 12 to ~08:00 LT on October 13. The main phase of the storm began at ~06:00 LT on October 13 and the disturbance had not arrived at 51°N before 08:00 LT on October 13. The storm hmF2 at 51°N was larger than the reference hmF2 from ~08:50 LT, and then that of 41°N from ~09:30 LT. There were two positive disturbances of hmF2, which happened in daytime and nighttime, respectively. The first positive disturbance of hmF2 was from 08:00 LT to 18:00 LT on October 13. The equatorward disturbance winds blew ionosphere to higher altitude, and resulted in a positive disturbance of hmF2 in daytime. The peak height of the first disturbance occurred at noon time, and the hmF2 was close to the reference hmF2 again at ~18:00 LT. Then, there was a second positive disturbance of hmF2 from 18:00 LT on October 13 to 06:00 LT on October 14. The second disturbance was also caused by the equatorward disturbance winds. The background wind was poleward during the first disturbance, and turned to equatorward during the second disturbance. The peak height of the second disturbance was even higher than that of the first disturbance. After that, the disturbance of hmF2 became small during 08:00 LT on October 14–14:00 LT on October 15.

Figures 7c and 7d are the variations of foF2 at 51° and 41°N. The reference foF2 increased in morning and reached the largest around noon time. It decreased in afternoon and remained at a small value in nighttime. The diurnal variation of foF2 related to solar radiation. The variations of foF2 on the storm day at 51°N were also similar with reference before 09:40 LT, and it was about before 10:20 LT at 41°N. With the arrival of the disturbance, the foF2 at 51°N appeared a positive disturbance from 09:40 LT to 18:00 LT. But, the positive disturbance of foF2 at 41°N continued until 03:00 LT on October 14. The onset and peak times of the disturbance of foF2 at 41°N were later than that of at 51°N. Then, the negative disturbance of foF2 appeared on October 14, and the foF2 on October 15 was like that of the reference.

Figures 7e and 7f are the variations of TEC at 51° and 41°N. In general, the variations of TEC were consistent with that of foF2. There was an obvious positive disturbance of TEC on October 13. The peak TEC appeared...
earlier than that of peak foF2. The peak TEC at 51°N was earlier than that at 41°N on October 13. The positive disturbance of TEC at 51°N lasted to 18:00 LT, while it continued to 24:00 LT at 41°N. After that, the negative disturbance of TEC appeared on October 14.

From ~22:00 LT to ~24:00 LT on October 13, hmF2 had a second peak while foF2 and TEC had not. The reason was that the second hmF2 peak appeared in nighttime. The equatorward winds blew the ionosphere to higher altitudes, so hmF2 had second peak. There was no solar radiation in nighttime, and no new electrons were produced to fill the bottom ionosphere. So, the foF2 and TEC did not increase with hmF2.

4.4. Meridional Wind Results

Fabry-Perot interferometer (FPI) from ground-based stations and satellites provided measurement of the thermospheric wind (Conde et al., 2001; Killeen et al., 1986). There was no available wind data at the Greenwich meridian during the storm. The nearest observations were taken at two FPI stations along ~290°E,
which were located at Millstone Hill (42.6°N, 288.5°E) and Arecibo (18.35°N, 293.5°E), respectively. Their observations of meridional wind are shown in Figure 8. The black circles represent the meridional winds from 22:00 UT on October 12 to 10:00 UT on October 13. As a reference, the gray dots are the meridional winds at the corresponding time during quiet days in October. The positive/negative value represents the poleward/equatorward wind. It could be seen that the meridional wind turned from poleward to equatorward earlier at Millstone Hill than Arecibo. During 04:00–06:00 UT at Millstone Hill, the equatorward wind was about 329 m/s on storm day, while it was about 180 m/s during quiet days. The equatorward wind on the storm day was much larger than that of quiet days, implying an equatorward disturbance wind enhanced the night time circulation. As for Arecibo, there was no difference of the meridional winds between storm day and quiet days. The equatorward disturbance wind was only observed at middle latitude. It did not reach the low latitude during the storm. Being at 0°E, the longitude difference between Greenwich and Millstone Hill is ~70°. Since there was a lack of wind observations at different longitudes, it was difficult to get the real wind observations at the Greenwich meridian. Wan et al. (2018) showed that the ionospheric storm significantly enhanced TEC from ~70°W to ~45°E. We speculate that there is also an equatorward disturbance wind such as ~290°E at the Greenwich meridian during the ionospheric storm. More observation data on thermospheric winds are needed to verify the speculation at the Greenwich meridian during the storm.

4.5. Discussions

Table 2 shows the onset time when ΔhmF2 or ΔfoF2 begin to increase. The ΔhmF2 is the difference between storm hmF2 and reference hmF2 in Figure 7, as well as ΔfoF2 and ΔTEC. The onset time of ΔhmF2 was at 08:50 LT at 51°N and 09:35 LT at 41°N. For the variation of ΔfoF2, the onset time was about 09:40 LT at 51°N.
and 10:20 LT at 41°N. The onset times of ΔhmF2 and ΔfoF2 at 51°N were earlier than that of at 41°N. The factor was that the disturbance wind propagated gradually from high latitudes to middle latitudes. Thus, the ionospheric disturbance appeared first in high latitudes and then in middle latitudes (Ramsingh et al., 2015; Sastri et al., 2000). The time interval between two ionosondes implied the velocity of disturbance winds. Figure 9 is the diurnal variations of ΔhmF2, ΔfoF2, and ΔTEC on October 13. The gray lines are the results at about 51°N and the black lines are the results at about 41°N. It showed that the onset time of ΔhmF2 was earlier than that of ΔfoF2. It was explained as follows. First, the equatorward disturbance winds blew the ionosphere to higher altitudes, and hmF2 was positive disturbance. Then, new electrons were produced by photoionization of solar radiation in daytime, and filled the uplifted ionosphere (Jenan et al., 2021). The foF2 and TEC began to be positive disturbance. So, the onset time of ΔhmF2 was earlier than that of ΔfoF2. The height change was the origin of ionospheric disturbance. The ΔTEC at 51°N increased rapidly at about 08:00 LT, and it was slight earlier than that of at 41°N. With equatorward wind surge and solar radiation, the largest disturbance was at noontime. The peak times of ΔhmF2, ΔfoF2, and ΔTEC are summarized in Table 3. The peak ΔhmF2 was at 11:00 LT at 51°N and 11:30 LT at 41°N. The largest value of ΔfoF2 was at 12:40 LT at 51°N and 13:30 LT at 41°N. The peak time of ΔTEC was at 12:05 LT at 51°N and 12:50 LT at 41°N. The peak time of the disturbance at 51°N was earlier than that of at 41°N. The time interval between two latitudes was also caused by the equatorward wind surge. The peak time of ΔhmF2 was earlier than that of ΔfoF2 and ΔTEC. Delayed peak of ΔfoF2 meant the redistribution of the plasma in the new equilibrium state. The peak ΔTEC occurred earlier than that of ΔfoF2, which meant the change in the slab thickness due to the redistribution.

Figures 8 and 11 show the vertical electron density profiles (EDP) from 06:00 LT to 16:00 LT of two ionosondes. The dotted line is the profile on

|         | RL052 (LT/h) | EB040 (LT/h) | Time difference (min) |
|---------|--------------|--------------|-----------------------|
| ΔhmF2   | 08:50        | 09:35        | 45                    |
| ΔfoF2   | 09:40        | 10:20        | 40                    |
October 12, and the solid line is the profile on October 13. The $x$ axis is the frequency and it is proportional to the electron density. The $y$ axis is the altitude. The integral of the electron density profile along the altitude could be considered as TEC. Since the disturbance had not arrived at 06:00 LT on October 13, there was not significant difference between the EDP on the 13th and that on the 12th. The geomagnetic storm had affected the ionosphere at $A_A 51^\circ N$ at 08:00 LT, while it had not affected at $A_A 41^\circ N$. The onset time of $A_A \Delta TEC$ at $A_A 51^\circ N$ was earlier than that at $A_A 41^\circ N$. At $A_A 51^\circ N$, the slab thickness of EDP, $hmF_2$, and $foF_2$ at 10:00 LT on the 13th were much larger than that on the 12th, and TEC on the 13th was also larger than that on the 12th. At $A_A 41^\circ N$, the slab thickness of EDP and $hmF_2$ on the 13th was larger than that on the 12th at 10:00 LT, while there was no change in $foF_2$. The TEC at 10:00 LT on the 13th was also larger than that on the 12th at $A_A 41^\circ N$. It meant that the onset time of $A_A \Delta TEC$ was earlier than that of $A_A \Delta foF_2$ at $A_A 41^\circ N$. Figure 10 also showed the $foF_2$ at 13:00 LT was larger than that at 12:00 LT, while the slab thickness of EDP at 13:00 LT was less than that at 12:00 LT. The changes of slab thickness and $foF_2$ made the TEC at 13:00 LT less than that at 12:00 LT. It also could be seen in Figure 11, the $foF_2$ at 15:00 LT was slight larger than that at 14:00 LT on the 13th, while the slab thickness at 15:00 LT was much less than that at 14:00 LT. The change of slab thickness caused the TEC at 15:00 LT smaller than that at 14:00 LT. So, the change of TEC was the combined effects of F2 layer peak and the slab thickness of the ionosphere.

At $A_A 41^\circ N$, moderate positive disturbances of $foF_2$ and TEC (Figures 7 and 9) continued for >12 hr after reaching the peak around 12:00 LT. The positive disturbance during night time at $A_A 41^\circ N$ was also caused by the equatorward wind surge. But at $A_A 51^\circ N$, $foF_2$ and TEC returned to normal level quickly and went to the negative disturbances. The positive disturbances and negative disturbances competed to each other. During the main

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**Figure 9.** The $\Delta hmF_2$, $\Delta foF_2$, and $\Delta TEC$ at $A_A 51^\circ N$ (gray line) and $A_A 41^\circ N$ (black line) on October 13. Panel (a) is the diurnal variation of $\Delta hmF_2$, Panel (b) is the diurnal variation of $\Delta foF_2$, and Panel (c) is the diurnal variation of $\Delta TEC$.

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**Table 3**

|                   | RL052 (LT/h) | EB040 (LT/h) | Time difference (min) |
|-------------------|--------------|--------------|-----------------------|
| $\Delta hmF_2$    | 11:00        | 11:30        | 30                    |
| $\Delta foF_2$    | 12:40        | 13:30        | 50                    |
| $\Delta TEC$      | 12:05        | 12:50        | 45                    |
phase, the positive disturbances played a leading role and it was the positive storm. For the recovery phase, the negative disturbances were gradually dominant at high latitudes but not at middle latitudes. Therefore, it turned to negative storm at higher latitudes while it was still positive storm at lower latitudes.

It was also showed in Figure 4c. The zero-value line of ΔTEC was the boundary between positive and negative ΔTEC. The negative ΔTEC meant the negative storm, and vice versa. The positive disturbance was dominant during the main phase, the positive storm was observed in high and middle latitudes. Then, the negative ΔTEC first appeared at about 14:00 LT at 63°N, and then extended to lower latitudes. Negative ΔTEC appeared at about 24:00 LT at 50°N, while it remained positive in <50°N. A negative storm prevailed in the middle and high latitudes on October 14. It indicated that the positive and negative mechanisms coexisted and competed to each other. The relative contribution varied with location, local time, storm phase, and other factors (Kumar & Kumar, 2019; Liu et al., 2014).

Figure 10. The electron density profiles of RL052 (359.4°E, 51.5°N) on October 12 (dotted line) and October 13 (solid line). The x axis is the frequency, and the y axis is the altitude.
5. Summary

An ionospheric positive disturbance during a moderate geomagnetic storm was studied with TEC from a chain of GNSS receivers and F2 layer peak parameters from two ionosondes at the Greenwich meridian on October 13, 2016. There was a large enhancement of TEC from high to middle latitudes while small disturbance was observed in low latitudes. The TEC ratio of storm to quiet days even reached to 3. The TEC reached the peaks almost same time from high to middle latitudes during quiet days. However, the TEC peak delayed with decreasing latitude on the storm day, and the time interval was about 2 h and 35 min between $33^\circ$ and $63^\circ$ N. It meant that the disturbance first appeared at high latitudes and then propagated to middle latitudes. The thermospheric winds were observed by two FPIs at about $290^\circ$ E. At Millstone Hill, the maximum wind speed of the equatorward wind was about 180 m/s during quiet days, while the equatorward wind even reached to 329 m/s on the storm day. The equatorward wind increased significantly at middle latitude during the storm day, while no change was observed at low latitude. The directional and
latitudinal features of ionospheric disturbance were consistent with the wind observations. The dominant driving force of this positive ionospheric storm was most likely to be the equatorward wind surge rather than PPEF. The mean velocity of disturbance was roughly estimated by the slope of the latitudinal variation of TEC, and it was about 800 m/s from 60° to 50°N. The equatorward wind speed slowed down with decreasing latitude due to the ion drag.

Two ionosondes were also used to study the variations of hmF2 and foF2. During the main phase (06:00 LT-17:00 LT on October 13), the hmF2, foF2, and TEC had significant positive disturbance. The equatorward wind surge blew the electrons to higher altitudes and the chemical loss rate reduced. Then, new electrons were produced to fill the lower altitudes by solar radiation, the ΔfoF2 and ΔTEC increased. The onset and peak times of the disturbance at 51°N were earlier than that of at 41°N. This further proved that the main physical mechanism of this positive storm was most likely the equatorward wind surge. The onset and peak times of ΔhmF2 were also earlier than that of ΔfoF2 and ΔTEC. The height change caused by the disturbance wind was the origin of this ionospheric storm. During the recovery phase (17:00 LT-24:00 LT on October 13), the ΔhmF2 increased due to the equatorward winds at two latitudes. The foF2 kept a higher level than normal to 24:00 LT at 41°N, while it decreased to a lower level than normal since 19:00 LT at 51°N on October 13. Then, the negative storm was observed both at the middle and high latitudes on October 14.

Data Availability Statement

The data used for this study were obtained from EUREF Permanent GNSS Network (http://epncb.oma.be/). The ionosonde data are obtained from Global Ionosphere Radio Observatory (http://giro.uml.edu/). The FPI data are from the OpenMadrigal project (http://cedar.openmadrigal.org/openmadrigal).

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