Long-distance propagation of ionospheric disturbance generated by the 2011 off the Pacific coast of Tohoku Earthquake

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Propagation of the initial ionospheric total electron content (TEC) disturbances generated by the 2011 off the Pacific coast of Tohoku Earthquake at 05:46:23 UT on March 11, 2011, was investigated with ground-based Global Positioning System (GPS) receivers in the east-Asian region. It was found that the initial ionospheric disturbance formed a zonal wave front after the earthquake occurrence. Four zonal wave fronts of this initial ionospheric disturbance were observed to travel southward from Japan to Taiwan with a velocity of about 1,000–1,700 m/s. This study further found that the direction of the wave vector rotated from the south-southwest to the south-southeast as it traveled from Japan to Taiwan. The meridional propagation of the coseismic ionospheric disturbances is consistent with those observed after previous intense earthquakes. The temporal evolutions of initial ionospheric disturbances, after the earthquake, near the epicenter was observed in two-dimensions. The directivity of the disturbances was caused by a geomagnetic field effect.

Key words: Ionospheric TEC disturbance, Tohoku Earthquake.

1. Introduction

There have been various recent studies on the ionospheric total electron content (TEC) perturbations after large earthquakes by using a dense network of ground-based receivers of the global positioning system (GPS) network (e.g., Calais and Minster, 1995; Ducic *et al.*, 2003; Artru *et al.*, 2005; Heki and Ping, 2005; Otsuka *et al.*, 2006). Calais and Minster (1995) detected ionospheric perturbations using the GPS after the January 17, 1994, Northridge California earthquake (M 6.7), while Ducic *et al.* (2003) showed that ionospheric disturbances of the November 3, 2002, Denali Alaska earthquake (M 7.9) traveled with the velocity of the Rayleigh wave. Using the Japanese GPS Earth Observation Network (GEONET), Artru *et al.* (2005) observed a small-scale and long-distance propagation of a TEC perturbation associated with the June 23, 2001, Peru earthquake (M 8.2) and suggested that it could be caused by a tsunami-induced gravity wave. Heki and Ping (2005) used GEONET data to investigate coseismic ionospheric disturbances after earthquakes around Japan and showed a strong north-south asymmetric propagation of the coseismic ionospheric disturbances. They suggested that the movement of the charged particles induced by the acoustic wave along the

geomagnetic field line could be affected by the magnetic-field configuration and resulted in an asymmetry of the ionospheric disturbances in favor of propagation in an equatorward direction. Similarly, Otsuka *et al.* (2006) showed asymmetric TEC propagation after the December 26, 2004, Sumatra earthquake (M 9.0). They again showed that the TEC disturbances propagated northward/equatorward from the epicenter.

A detailed analysis of the temporal evolution of the coseismic ionospheric disturbances is necessary in order to clarify the mechanism of their directivity and propagation. In particular, a horizontal two-dimensional observation is crucial to reveal the propagation characteristics. The GPS-TEC observations after the 2011 off the Pacific coast of Tohoku Earthquake (M 9.0) provided an ideal data set with which to study the two-dimensional structures of the coseismic ionospheric disturbance with a wide field-of-view and high spatial-temporal resolution. In this study, a dense network of GPS receivers in the east-Asia region were utilized to investigate the propagation of the initial TEC perturbations generated by the earthquake. The initial perturbation was observed to travel a long distance with a high propagation velocity.

2. Observations and Results

The GPS data of GEONET in Japan, the Korea Astronomy and Space Science Institute (KASI) and the National Geographic Information Institute (NGII) in Korea, the Tai-

Fig. 1. Two-dimensional map of the total electron content derived from GPS observations with band-pass filtering (3–5 min). The red dots in (a) indicate the locations of the GPS receivers. The open star mark indicates the location of the epicenter. L1 and L2 are the lines on which the TEC data was used to examine the propagation characteristics in Figs. 2 and 3. W0, W1, W2, and W3 indicate the wave front of TEC disturbances.

Wan Network (TWN) in Taiwan, and the International GNSS service (IGS), were used in this study. The total number of ground-based GPS receivers is 1,167, and their locations are represented by red dots in Fig. 1(a). The open star mark indicates the location of the epicenter of the 2011 *M* 9.0 Tohoku Earthquake. Slant TEC data along a ray path from each GPS receiver to a GPS satellite were derived from the dual-frequency ($f_1 = 1.57542$ GHz and $f_2 = 1.22760$ GHz) GPS signals. The sampling rate of the data was 30 s. The cutoff elevation angle of each GPS data was 20° to minimize errors which result from the conversion of the observed slant TEC to the vertical TEC and the multi-path of the signals (cf. Liu *et al.*, 1996; Tsai *et al.*, 2001). According to Heki and Ping (2005) and Otsuka *et al.* (2006), the typical time scale of the initial TEC perturbation after the earthquakes was about five minutes. Therefore, band-pass filtered data with a period of 3–5 min were used in this study to detect the propagation of the initial ionospheric disturbances after the earthquake. We assumed that the maximum electron density in the ionosphere at the analyzed time, was located at around 250–350 km altitude for converting the slant TEC to the vertical TEC by a slant factor described in Tsai *et al.* (2001). The altitude of the thin-shell ionosphere was assumed to be 300 km for determining the location of the sub-ionospheric point (SIP) of each ray path.

Figure 1 shows the time sequence of the two-dimensional map of the band-pass filtered TEC data from 05:46:30 UT to 06:12:30 UT. It is clearly seen that the TEC disturbance appeared around the east of the epicenter at 05:55:00 UT in Fig. 1(b). The wave fronts of the TEC disturbances expanded and propagated in the radial direction firstly around 05:58:00 UT as seen in Fig. 1(c). While the TEC disturbances further expanded, two wave fronts of TEC disturbances formed at 37°N and 39°N between 130°E and 135°E at 06:00:00 UT (Fig. 1(d)). Their wave fronts were almost in an exactly zonal direction and the western edge of the wave fronts stretched in the northwestern direction. The wave front at 37°N at 06:00:00 UT is referred to as W1, and the one at 39°N as W2. It is seen that the western

edge of W1 expanded from the center of the Japan Sea at 06:00:00 UT to the western part of Korea at 06:04:00 UT while they propagated southward. W2 was parallel to W1 with the same propagation direction. At 06:04:00 UT, a wave front of a weak TEC disturbance, W0, appeared around 32°N and 130°E , the center of Kyushu island. At 06:07:00 UT, the third zonal wave front of TEC disturbance, W3, appeared around the location of 37°N and 135°E , which also propagated in the south-southwest direction.

The W1 wave front arrived in the northern part of Taiwan around 06:12:30 UT as shown in Fig. 1(h), propagating from 37°N (Fig. 1(d)) to 26°N (Fig. 1(h)) within 12.5 min. The propagation directions of the ionospheric disturbances at 06:04:00 UT and 06:12:30 UT were in a south-southwest direction around 35°N (Fig. 1(f)) and in a south-southeast direction around 25°N over Taiwan (Fig. 1(h)), respectively. The direction of the wave vector rotated from the south-southwest to the south-southeast as it traveled from Japan to Taiwan.

To investigate the propagation velocity and the change of the wave vector direction, we chose the TEC data on the two lines, L1 and L2, perpendicular to the wave fronts. The locations of these two lines are shown in Fig. 1. The average value of the band-pass filtered TEC data along L1 and L2 within ± 2 degrees in longitude are plotted as a function of time in Figs. 2 and 3, respectively. The left-hand side y-axis in Figs. 2 and 3 is the distance from the point (20°N , 120°E) for L1 and (20°N , 130°E) for L2. The north end of the lines are (50°N , 130°E) for L1 and (50°N , 140°E) for L2. The right-hand side y-axis is the latitude along the two lines. The propagation of the four wave fronts, W0, W1, W2, and W3, are shown in Figs. 2 and 3. The propagation velocity was estimated with the lines drawn on the wave fronts. The wave front W0 appeared around 27°N at 06:08 UT and propagated southward with a velocity of 1,670 m/s on L1 as seen in Fig. 2, while the propagation velocity of W0 on L2 was 1,440 m/s as seen in Fig. 3. This means that the western part of W0 traveled southward faster than the eastern part by 230 m/s. Similar faster southward propagation is also seen for W1, W2, and W3 with the following veloc-

Fig. 2. TEC-time-distance/latitude diagram on L1 from 05:36 UT–06:48 UT (14:36 JST–15:48 JST). The location of L1 is shown in Fig. 1. The left y-axis represents the distance from the starting point of L1 (20°N, 120°E) and the right y-axis represents the latitude along the L1. The vertical dashed line indicates earthquake onset time, and the slant dashed lines (W0, W1, W2, and W3) denote propagation velocities of the wave front of the ionospheric TEC perturbations.

Fig. 3. The same format with Fig. 2 but on L2. The location of L2 is shown in Fig. 1. The left y-axis represents the distance from the starting point of L2 (20°N, 130°E).

ities. The wave front W1 traveled southward with a velocity of 1,380 m/s on L1 and 1,110 m/s on L2. W2 traveled southward with a velocity of 1,270 m/s on L1 and 1,090 m/s on L2. W3 traveled southward with a velocity of 1,130 m/s on L1 and 1,040 m/s on L2. The horizontal wavelengths of the four wave fronts were calculated along L1 in Fig. 2. The horizontal wavelength is defined as twice the distance between the minimum and maximum of the TEC perturbations. The horizontal wavelengths of W0, W1, W2, and W3 were 300 km, 210 km, 270 km, and 260 km, respectively.

3. Discussion

TEC disturbances triggered by earthquakes have been observed in previous studies (Calais and Mister, 1995; Calais *et al.*, 1998; Ducic *et al.*, 2003; Heki and Ping, 2005; Otsuka *et al.*, 2006; Liu *et al.*, 2010). However, this is the first time the two-dimensional propagation of TEC dis-

turbances has been detected with wide coverage and high spatial and temporal resolution by dense GPS receiver networks. The ionospheric disturbance started about 7 min after the earthquake and lasted for several hours afterwards (Saito *et al.*, 2011). Tsugawa *et al.* (2011) have reported the zonal propagation velocity of TEC disturbances using high-pass filtered data with a cutoff period of 10 min along 37°N latitude from 05:00 UT to 09:00 UT after the 2011 Tohoku Earthquake. Their result showed a fast westward propagation of the ionospheric disturbance at a velocity of about 3,500 m/s from 140°E to 130°E around 06:00 UT. This propagation of the disturbance corresponds to the radial and north-westward expansion of the disturbance shown in Figs. 1(c) and 1(d). After this zonal expansion, zonal wave fronts were formed and propagated southward to Taiwan with a velocity of about 1,000–1,700 m/s (Figs. 1, 2 and 3). Previous studies (Calais *et al.*, 1998; Afraimovich *et al.*, 2001) have reported the horizontal propagation velocity of wave fronts generated by earthquakes to be around 1,100 to 1,660 m/s, which was close to the sound of speed in the thermosphere and ionosphere, consistent with our results here. It implies that the wave fronts seen in the 3–5 min band-pass filtered GPS data correspond to the acoustic waves generated by the earthquake.

According to Fig. 2, the wave period of TEC disturbances, T , was around 120 s. A dispersion relation was derived relating the vertical wavelength ($\lambda_m = 2\pi/m$) and the horizontal wavelength ($\lambda_k = 2\pi/k$) being: $\omega^4 - \omega^2 C_0^2 (k^2 + m^2) + \omega_b^2 C_0^2 k^2 - \omega_a^2 \omega^2 = 0$, where $\omega (= 2\pi/T)$ is the wave frequency of TEC disturbances, $C_0 (= \sqrt{\gamma g H})$ is the speed of sound, $\gamma = 1.4$ is the ratio of specific heats, g is the gravitational acceleration, $H (= k_B T / Mg)$ is the scale height, k is the horizontal wavenumber, and m is the vertical wavenumber. Also, $\omega_b (= \sqrt{\gamma - 1} g / C_0)$ is the Brunt-Väisälä frequency, and $\omega_a (= C_0 / 2H)$ is the acoustic frequency. The NRLMSISE-00 model, an empirical model of the neutral atmosphere based on observational data (Picone *et al.*, 2002), was used to obtain the atmospheric parameters in this study. At the height of 300 km, the periods $T_a = 2\pi/\omega_a = 730$ s and $T_b = 2\pi/\omega_b = 810$ s. Since T is considerably smaller than T_a , we can conclude that the initial TEC disturbances relate almost entirely to the branch of acoustic waves. The vertical wavelength of the initial TEC disturbances was around 120 km as calculated by the dispersion relation.

After the initial ionospheric disturbances propagating in a radial direction from the east of the epicenter, the zonal wave fronts were formed and traveled southward as seen in Fig. 1(d). This zonal alignment of the wave front is similar to that of medium-scale traveling ionospheric disturbances (MSTIDs) in the daytime at a mid-latitude region. These are caused by the fact that an atmospheric gravity wave, propagating in the meridional direction, receives less effect of drag from the ionized atmosphere because the mobility of the ionized atmosphere is high along a geomagnetic field line. Heki and Ping (2005) and Otsuka *et al.* (2006) showed that the amplitude of TEC disturbances generated by earthquakes depend on the propagation direction: equatorward propagating waves have much larger amplitudes than those propagating in other directions. In this study, we

have observed the stronger southward/equatorward propagating TEC disturbances. This also indicates that the directivity of the disturbance propagation is affected by the magnetic field effect, propagating in a field-aligned direction. However, the declination angle at 35°N and 130°E is -6.35° calculated by the IGRF-10 model (Maus *et al.*, 2005), which means that the initial TEC disturbance did not propagate fully along the magnetic field lines. It is clarified by this study that the evolution and propagation of fast propagating phenomena following an earthquake is not as simple as might be expected. At first, a zonal wave front is formed by the radial expansion of the disturbance. The velocity of the expansion is up to 3,500 m/s as shown by Tsugawa *et al.* After the formation of the zonal wave front, this propagated equatorward/southward with a velocity of about 1,000–1,700 m/s.

On the other hand, for all of the wave fronts shown in Figs. 2 and 3, their western parts had a larger propagation velocity than their eastern parts. This means that the propagation velocity was greater in the area far away from the epicenter. The difference in velocity between L1 and L2 is about 8%–20% compared with the velocity on L1. This difference in the southward propagation velocity of the wave fronts is consistent with the rotation of the wave vector of the ionospheric disturbances as it traveled from Japan to Taiwan, as seen in Fig. 1. As a result, the wave fronts rotated to the east as they traveled to the south. This evolution of such phenomena cannot be fully explained by a geomagnetic field effect.

4. Summary

The propagation of the initial ionospheric TEC disturbances generated by the 2011 off the Pacific coast of Tohoku Earthquake at 05:46:23 UT on March 11, 2011, has been investigated using ground-based Global Positioning System (GPS) receivers in the east-Asian region. Five GPS receiver networks in the east-Asian region were used to reveal the two-dimensional structures and propagations of the TEC disturbances. The major findings in this study are summarized as follows:

1. The initial ionospheric disturbances formed zonal wave fronts after they propagated in a radial direction from the vicinity of the epicenter.
2. The initial disturbances propagate southward with velocities of 1,000–1,700 m/s, which are close to the speed of sound in the thermosphere and ionosphere. The horizontal and vertical wavelengths of TEC disturbances were 200–300 km and 120 km, respectively.
3. The direction of their wave vectors rotated from the south-southwest to the south-southeast as they traveled from Japan to Taiwan.

The zonal alignment of the wave front could be caused by the drag effect of the atmospheric wave by the ionized atmosphere. However, the change of the wave vector cannot be explained by this effect. Further analyses of the observational data and more theoretical studies are necessary to clarify the physical mechanisms involved.

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