New Characteristics of Medium-Scale Traveling Ionospheric Disturbances Detected with Dense Wide-Coverage TEC Maps over North America

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Abstract

We have developed Total Electron Content Data of American-Wide GPS Network (TEC-DAWN) which provides dense wide-coverage TEC maps over North America. The TEC-DAWN maps reveal several new characteristics of medium-scale traveling ionospheric disturbances (MSTIDs). For example, nighttime MSTIDs propagating southwestward with 200-500 km wavelengths have wavefronts longer than 2,000 km. Daytime MSTIDs propagating in two different directions (southeastward and southwestward) are superimposed in the mid-to-late afternoon. TEC-DAWN can be a new powerful tool to investigate not only MSTIDs but also various ionospheric phenomena. We have opened the TEC-DAWN website to provide quick-look of the TEC maps.

1. Introduction

Medium-scale traveling ionospheric disturbance (MSTID) is one of the most common ionospheric phenomena that generally induce the perturbations of ionospheric total electron content (TEC) by ~1 TECU (several % of the background), where 1 TECU (=10^{16}electron/m^2) corresponding to ~54 ns (16.2 cm) delay at the GPS L1 signal. MSTIDs are wave-like perturbations of the ionospheric plasma that have horizontal velocities of 100–250 m/s, periods of 15–60 minutes, and wavelengths of several hundred km [1].

Since mid-1990s, several new characteristics of the MSTIDs have been revealed by the ionospheric observations with two-dimensional mapping techniques using multipoint GPS receiver networks. Clear spatial structures of the nighttime MSTIDs are first shown by *Saito et al*. [2] using the high-resolution mapping of TEC perturbations over Japan. Statistical characteristics of MSTIDs over Japan are summarized by *Tsugawa et al*. [3]. The nighttime MSTIDs are frequently observed in summer and generally have wavefronts along northwest-southeast direction and propagate southwestward. The preferred propagation direction cannot be explained by the classical theory of atmospheric gravity waves (AGWs) [4]. In contrast with the nighttime MSTIDs, the daytime MSTIDs generally propagate equatorward and appear frequently in winter. These different characteristics between daytime and nighttime MSTIDs suggest that their generation mechanisms could be different [5].

Although there have been many studies of MSTIDs, there are still many characteristics, such as the width of their wavefronts and the northern and southern limits of their propagation, that have not been determined. This is because of the limited spatial coverage of ionospheric observations. In this study, we generate dense wide-coverage TEC maps over North America using multiple GPS receiver networks (TEC-DAWN: TEC Data of American-Wide GPS Network). These TEC-DAWN maps reveal several new characteristics of the MSTIDs. The method used to process the GPS data into the TEC maps will be given, and then the typical nighttime and daytime MSTIDs observed over North America will be presented.

2. Method

The GPS data analyzed in this study are obtained via the ftp server of the Continuously Operating Reference System (CORS), the Scripps Orbit and Permanent Array Center (SOPAC), and the International GNSS Service (IGS). There are more than 1,600 permanent GPS receivers in North America as of February 2008. The distribution of the GPS receivers is shown in Figure 1. Almost all GPS receivers provide the data of carrier phase and pseudo-range measurements in two frequencies (f_1 = 1575.42 MHz, f_2 = 1227.60 MHz) every 30 seconds. Slant TEC, I_s, the integrated electron density along the entire line-of-sight (LOS) between receiver and satellite, can be derived using the following equation [6]:

$$I_s = \frac{1}{40.3}\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}[(L_1 - L_2) - (\lambda_1 n_1 - \lambda_2 n_2) + b_r + b_s] \qquad (1)$$

where L_1 and L_2 are the recorded carrier phases of the signal (converted to distance units), $\lambda_1 n_1$ and $\lambda_2 n_2$ are integer cycle ambiguities, and b_r and b_s are satellite and receiver instrumental biases terms. Vertical TEC, I, can be obtained from the slant TEC using the equation, $I = I_s \cdot S$, where S is a slant factor which is a ratio of the ionosphere thickness, 200 km, to the LOS length between 250 km and 450 km altitude. Although the integer cycle ambiguities and the satellite and receiver biases must be determined to obtain the absolute value of TEC, we do not determine these. This is because this study is focused on perturbation components of TEC caused by TIDs, so therefore we only need to study the relative changes in the TEC. We derive the perturbation components of TEC by detrending I with one-hour running average for each LOS. The relative change of TEC is obtained theoretically with a precision of 0.01-0.02 TECU, which corresponds to ~1% of the wavelength of GPS signals L_1 (0.19 m) and L_2 (0.24 m) [7]. We neglect the TEC data from small satellite elevation angles (0–30°) to reduce cycle slips and errors due to conversion from slant to vertical TEC.

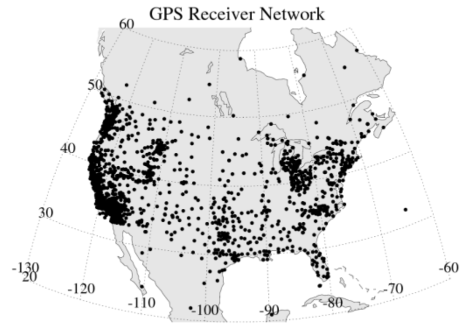

Figure 1. Distribution of GPS receiver network in North America.

The two-dimensional maps of the detrended TEC can be obtained from all available GPS LOS TEC every 30 seconds. As shown in Figure 2, the TEC map covers the wide region from 60°W to 130°W longitude and from 24°N to 54°N latitude. The size of each pixel is 0.15°×0.15° in latitude and longitude. The TEC value for each pixel is an average of perturbations for all LOS which crossed the pixel at 300 km altitude (the approximate F-region peak height). To compensate for the scarcity of the TEC data distribution, the TEC value in each pixel is smoothed temporally with the running average of 10 minutes, during which an ionospheric pierce point (IPP) moves ~50 km around the zenith of a GPS receiver. Then the TEC map in each epoch is smoothed spatially with the running average of 7×7 pixel (1.05°×1.05°) in latitude and longitude. As a result, the detrended TEC maps over North America can observe TEC variations whose time scale is between 10 and 60 minutes.

3. MSTID Observations

Figure 2 shows the time sequence of two-dimensional maps of the detrended TEC over North America in the nighttime between 03:30 UT (21:30 CST) and 06:10 UT (00:10 CST) on July 20, 2006 with a 20-minute interval. Central Standard Time, CST(=UT−6 hour), is referred to here to give a sense of a local time of center of North America. The Kp index during this day keeps between 0+ and 1, indicating that the geomagnetic activity is very quiet. Clear wave-like structures with the wavelengths of 200-500 km and the wavefronts stretching in NW–SE direction gradually appear around 03:50 UT (Figure 2b) in 70-90°W and 30-45°N, and in 110-120°W and 30-40°N. Figures 2b-e clearly show that the wave-like structures propagate southwestward with a velocity of 100-150 m/s. Judging from the wavelengths, propagation velocities and directions, these wave-like structures are identified as the nighttime MSTIDs which have been observed in Japan [2] and Southern California [5]. Focusing on the MSTID structures, it should be noted that their wavefronts can extend longer than 1,000 km as seen at 80-90°W and 110-120°W in Figure 2d. Especially, the longest wavefront at 80-90°W can extend between ~25-45°N (~35-55°N geomagnetic latitude (MLAT)), which corresponds to ~2,000 km. Comparing Figures 2a and 2b, it is also noted that their wavefronts have already been long since their appearance at 80-90°W and 110-120°W. After the MSTIDs propagate southwestward keeping their wave-like structures between 03:50 and 04:50 UT (Figures 2b-e), each structure gradually decays around 05:50–06:10 UT (Figures 2h-i).

It is recently reported that the nighttime MSTIDs have polarization electric field inside their structures [8], indicating electrodynamic forces, such as the Perkins instability, could play an important role in the generation of nighttime MSTIDs. To explain the preferred southwestward propagation direction, *Kelley and Makela* [4] have proposed a mechanism in which polarization electric fields (E_p) along the horizontal wavefront play an important role, assuming the MSTIDs structures are finite in the direction parallel to the horizontal wavefront. In this study, we reveal that the wavefront of the nighttime MSTIDs can extend longer than ~2,000 km in the NW-SE direction between 35-55°N MLAT as shown in Figure 2d. Although their NW-SE extending wavefronts could not conflict with the Perkins instability, it is difficult for the *Kelley and Makela*'s model to explain the southwestward propagation of the nighttime MSTIDs whose wavefronts extend from mid-latitudes to sub-auroral regions.

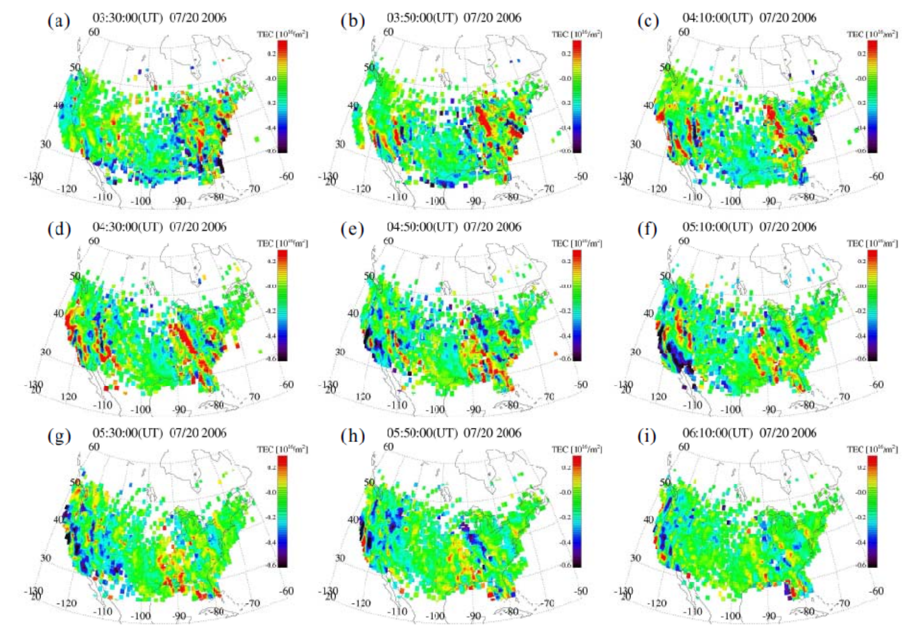

Figure 2. Time sequence of two-dimensional maps of TEC perturbation, detrended with one-hour window, in the nighttime between (a) 03:30 UT (21:30 CST) and (i) 06:10 UT (00:10 CST) on July 20, 2006, with a 20-minute interval.

Figure 3 shows the TEC maps for the daytime between 19:20 UT (13:20 CST) and 22:00 UT (16:00 CST) on November 28, 2006, in the same format as Figure 2. The Kp index during this day is between 1 and 2+, indicating that the geomagnetic activity is quiet. Consecutive wave-like structures with the wavefronts stretching in NE-SW direction are seen in the entire field of observation between 19:20–21:00 UT (Figures 3a-f). These waves propagate southeastward at the velocity of 100-200 m/s. Their wavelengths are 300-1,000 km and wavefronts are longer than 2,000 km. From their wave parameters, the wave-like structures can be identified as the daytime MSTIDs observed in Japan [3] and Southern California [5]. While the daytime MSTIDs are observed to propagate southeastward over North America until around mid-afternoon, southwestward propagating MSTIDs are also observed in the late afternoon between 21:20 and 22:00 UT (15:20 and 16:00 CST) as shown in Figures 3g-i. The two MSTIDs propagating in the different directions are superimposed on each other around mid- to late afternoon (Figures 3e-h).

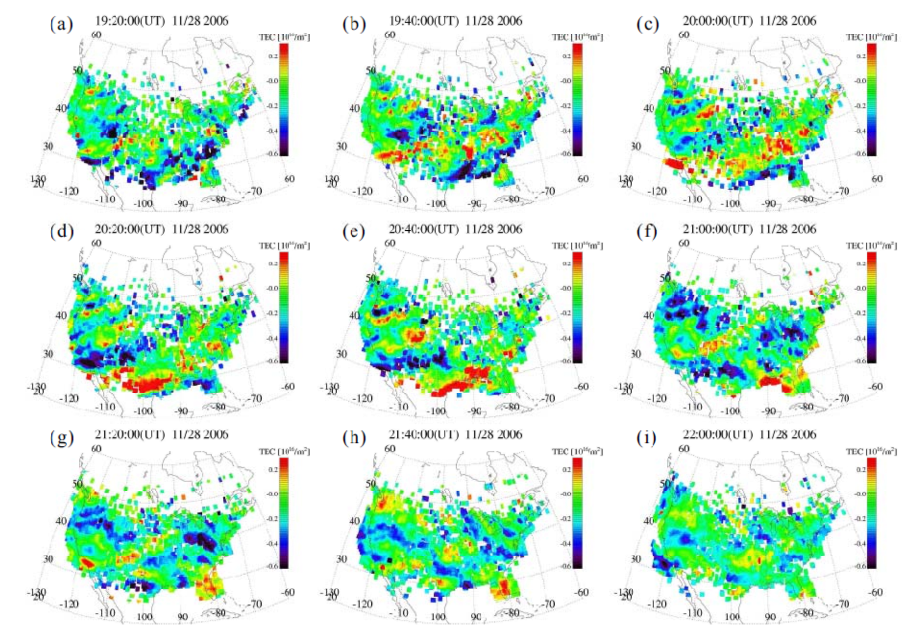

Figure 3. Same as Figure 2 for the daytime between (a) 19:20 UT (13:20 CST) and (i) 22:00 UT (16:00 CST) on November 28, 2006.

The daytime MSTIDs are considered to be caused by AGWs [5]. The local time variation of the observed MSTID propagation direction can be explained by the wind filtering effect of the AGWs. In this study, the TEC maps reveal, for the first time, that the two MSTIDs propagating southeastward and southwestward are superimposed on each other around mid- to late afternoon. Considering the long wavefronts in zonal direction and the two different propagation directions, the MSTIDs may be caused by the AGWs launched at the two different locations at auroral latitudes.

4. Concluding Remarks

We have developed TEC Data of American-Wide GPS Network (TEC-DAWN) which provides dense wide-coverage TEC maps over North America, and observed both nighttime and daytime MSTIDs. The TEC-DAWN maps have a spatial coverage much wider than other methods used in the previous MSTIDs observations. One of new findings of this study is that the wavefronts of the MSTIDs can be longer than 2,000 km at mid-latitudes. We have been processing both old and current GPS data to derive TEC maps, and developing the database of TEC-DAWN maps. We have opened the TEC-DAWN website (http://stdb2.stelab.nagoya-u.ac.jp/GPS/TEC-DAWN/) to provide quick-look of the TEC maps. Snapshots of detrended (one-hour window) and absolute TEC maps every 10 minutes can be browsed at this website. Although not mentioned in this paper, we have also observed large-scale TIDs associated with geomagnetic storms, fast equatorward motion of clear mid-latitude ionospheric trough, and "unknown" ionospheric disturbances with the TEC-DAWN maps. The TEC-DAWN maps can be a new powerful tool to investigate not only MSTIDs but also various ionospheric disturbances.

5. Acknowledgments

The GPS data were obtained via the ftp servers of CORS (ftp://www.ngs.noaa.gov/cors/rinex/), SOPAC (ftp://garner.ucsd.edu/pub/rinex/), and IGS (ftp://cddisa.gsfc.nasa.gov/pub/gps/data/daily/).

6. References

1. Hocke, K., and K. Schlegel, "A review of atmospheric gravity waves and traveling ionospheric disturbances: 1982– 1995", *Ann. Geophys.*, 14, 917–940, 1996.

2. Saito, A., S. Fukao, and S. Miyazaki, "High resolution mapping of TEC perturbations with the GSI GPS network over Japan", *Geophys. Res. Lett.*, 25, 3079–3082, 1998.

3. Tsugawa, T., N. Kotake, Y. Otsuka, and A. Saito, "Medium-scale traveling ionospheric disturbances observed by GPS receiver network in Japan: A short review", *GPS Solutions*, 11, 139–144, doi:10.1007/s10291-006-0045-5, 2006.

4. Kelley, M. C., and J. J. Makela, "Resolution of the discrepancy between experiment and theory of midlatitude F-region structures", *Geophys. Res. Lett.*, 28, 2589–2592, 2001.

5. Kotake, N., Y. Otsuka, T. Ogawa, T. Tsugawa, and A. Saito, "Statistical study of medium-scale traveling ionospheric disturbances observed with the GPS networks in Southern California", *Earth Planets Space*, 59, 95–102, 2007.

6. Mannucci, A. J., B. A. Iijima, U. J. Lindqwister, X. Pi, L. Sparks, and B. D. Wilson, "GPS and ionosphere", in *Review of Radio Science 1996–1999*, edited by W. R. Stone", pp. 625–665, URSI, Ghent, Belgium, 1999.

7. Spilker, J. J., and B. W. Parkinson, "Overview of GPS operation and design", in *Global Positioning System: Theory and Applications*, vol. 1, pp. 29– 56, Am. Inst. of Aeronaut. and Astronaut., Reston, Va, 1996.

8. Shiokawa, K., Y. Otsuka, C. Ihara, T. Ogawa, and F. J. Rich, "Ground and satellite observations of nighttime medium-scale traveling ionospheric disturbance at midlatitude", *J. Geophys. Res.*, 108(A4), 1145, doi:10.1029/2002JA009639, 2003.