GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L19101, doi:10.1029/2011GL049116, 2011

East-West Coast differences in total electron content over the continental US

Shun-Rong Zhang,[1] John C. Foster,[1] Anthea J. Coster,[1] and Philip J. Erickson[1]

Received 29 July 2011; revised 2 September 2011; accepted 3 September 2011; published 7 October 2011.

[1] Total electron content (TEC) measurements made by a network of dense GPS receivers over the continental US are used to investigate ionospheric longitudinal differences. We find that the evening TEC is substantially higher on the US east coast than on the west, and vice versa for the morning TEC; the longitudinal difference displays a clear diurnal variation. Through an analysis of morning-evening variability in the east-west TEC difference, minimum variability is found to coincide with the longitudes of zero magnetic declination over the continental US. We suggest that these new findings of longitudinal differences in ionospheric TEC at midlatitudes are caused by the longitudinal difference in magnetic declination combined with the effects of thermospheric zonal winds which are subject to directional reversal over the course of a day. This study indicates that longitudinal variations in TEC measurements contain critical information on thermospheric zonal winds. The proposed declination-zonal wind mechanism may also provide a new insight into longitude/UT changes at midlatitudes on a global scale, as well as into some geospace disturbances. **Citation:** Zhang, S.-R., J. C. Foster, A. J. Coster, and P. J. Erickson (2011), East-West Coast differences in total electron content over the continental US, *Geophys. Res. Lett.*, *38*, L19101, doi:10.1029/2011GL049116.

1. Introduction

[2] Over the last decade, GPS based total electron content (TEC) measurements have been increasingly used for upper atmospheric research. Dense GPS receiver networks over different areas of the globe allow for determination of ionospheric structures, including longitudinal variations, with far better temporal and spatial resolutions than traditionally available through satellite and ground-based measurements. Subauroral plasma plumes observed during magnetic storms over the Northern America longitude sectors [*Foster et al.*, 2002], and traveling ionospheric disturbances over Japan [*Saito et al.*, 1998] are examples of the application of dense GPS receiver networks.

[3] Ionospheric longitudinal variations have recently been shown to exist, for example, the wave-4 structure at a fixed local time at equatorial and low-latitudes (see *Sagawa et al.* [2005] and *Immel et al.* [2006] for initial results). This planetary-scale phenomenon is mainly associated with electric fields generated by nonmigrating atmospheric tides in the E-region height that vary with longitude [*England et al.*, 2010]. At midlatitudes, some longitudinal variations, such as those in annual and semi-annual ionospheric changes, have been explained as the result of the separation of geographic and geomagnetic poles [*Rishbeth*, 1998]. The Weddell Sea anomaly, characterized as an evening enhancement in electron density in summer, is another midlatitude phenomenon that is associated primarily with meridional winds and magnetic declination [e.g., *Luan et al.*, 2008; *Lin et al.*, 2010; *Chen et al.*, 2011].

[4] This paper reports on a new finding of pronounced longitudinal variations in mid-latitude TEC over the continental US manifested as an east-west coast difference, based on observations of ground-based GPS receivers. The east-west difference changes sign from negative to positive depending on the local time. The physical explanation of this new result is related to changing magnetic declination over the US along with the behavior of thermospheric zonal winds and, in particular, their diurnal variations. The magnetic declination is westward on the US east coast and eastward on the US west coast, with its zero value being along the −100 to −90°E longitude. This magnetic declination/neutral wind mechanism can account for observed longitudinal differences at mid-latitudes for the US sectors, and may be applicable more generally both to other longitudes over the globe and other geospace disturbance phenomena.

2. Observation

[5] Global total electron content data obtained from the network of world wide GPS receivers [*Mannucci et al.*, 1998; *Coster et al.*, 2003] are calculated using the MIT Automated Processing of GPS (MAPGPS) software [*Rideout and Coster*, 2006]. The TEC estimates are produced with 5 minutes temporal resolution and distributed over those locations where sufficient data is available. Errors in the MAPGPS code are tracked throughout the processing, and random and correlated errors are handled separately. This allows optimal estimation of binned measurements using weighted averages and allows error values to be calculated from each binned measurement. In our data processing, we have not assumed equivalent local time and longitudinal variations; no receiver greater than 500 km away has been included in the estimation of receiver bias. The satellite biases that we use have been shown to be consistent on a monthly basis [*Wilson et al.*, 1999].

[6] For the current study, we focus on observtions made over the US continent where a dense network of receivers exist (cf. Figure 1 of *Tsugawa et al.* [2007] for a sample distribution of receivers). TEC spatial resolution is 3° × 3° latitude/longitude, and hourly median values are used. We will present results for a representative day and an equinox month in order to illustrate both typical diurnal behavior and some statistical features of the coast-to-coast

---

[1] Haystack Observatory, Massachusetts Institute of Technology, Westford, Massachusetts, USA.

0094-8276/11/2011GL049116

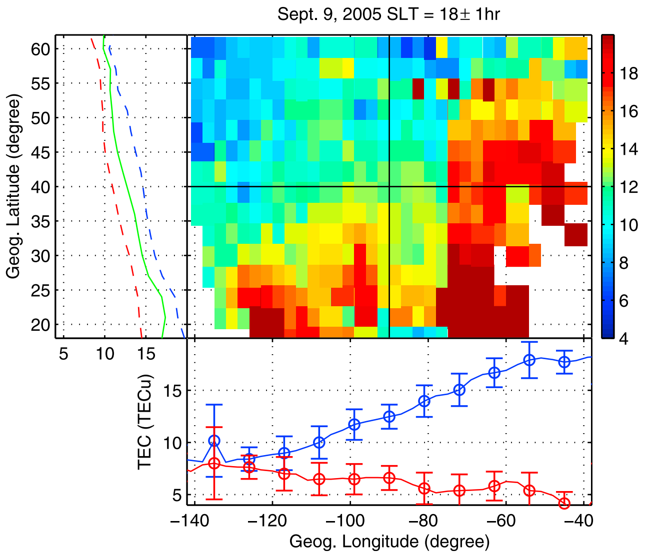

Figure 1. GPS TEC over the continental US at 1800 LT. (top right) Map of TEC distribution for 1800 LT ± 1hr; (bottom) the TEC longitudinal variation at 40 ± 5°N latitude, with a blue line for 1800 LT ± 1hr data and red line for 0600 LT ± 1hr; each data point corresponds to a median within a ±3° longitude bin (representative error bars are given also to indicate uncertainty due to data binning). (top left) The TEC latitudinal variation for three longitudinal sectors: the east side of −90 ~ −40°E (blue), the west side −140 ~ −90°E (red), and the central sector of −90 ± 7.5°E (green).

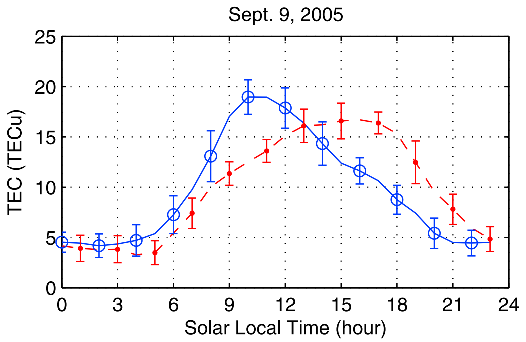

Figure 2. Diurnal variations of median TEC on both west side (solid line with circles; for −130 ~ −110°E) and east side (dashed line with dots). The representative error bars are selected to indicate uncertainty due to the spread of data within an hour for 20–60°N latitude and 20° longitude ranges.

difference in TEC; the current paper does not attempt to address a full climatology with seasonal and solar cycle dependency. We have selected September 2005, an interval during the descending phase of solar cycle 23, close to its minimum, with medium to low solar activity (median 10.7 cm solar flux index = 85). Magnetic activity was low during the month for most days, with a median daily Ap index of 11.5 and with the 3 highest daily Ap indices being 101, 75, and 52. The representative day is selected as September 9, 2005 when the daily Ap value was 17. The above data selection is appropriate for investigating underlying effects, because relatively quiet to medium magnetic activity is helpful to minimize possible large disturbance effects that may complicate the determination of the background climatology that we are examining. Furthermore, it helps reduce errors in the estimation of receiver bias.

3. Result

[7] Substantial coast-to-coast differences in TEC exist that are strongly dependent on the local time of day. These differences are either positive (higher in the east than the west) or negative. We present first results for an evening time, then address the general diurnal pattern of the differences.

3.1. TEC(East) > TEC(West) in the Evening

[8] In general, solar produced TEC is high in the evening. Vertical TEC distribution over the continental US (here defined as the longitude range −140 ~ −40°E) is given in Figure 1 as a function of latitude and longitude (in geographic coordinates) at 1800 LT for September 9, 2005. The figure provides three views of the longitudinal variation. The map panel clearly shows substantial east-west differences, and these appear as well in the bottom panel, showing the longitudinal variation of TEC at latitudes 40°N. TEC at 40°N increases consistently from west to east, and the difference can be up to ~10 TECu or ~100%. The left panel shows latitudinal variations for the east longitude sectors (>−90°E), the west longitude sectors (<−90°E), and the central longitude sectors (−90 ± 7.5°E), respectively. These curves indicate that the east-west difference appears consistently from higher midlatitudes to lower midlatitudes.

3.2. Local Time Dependency

[9] Local time dependency of the east-west difference in TEC is a significant characteristic. To examine this,

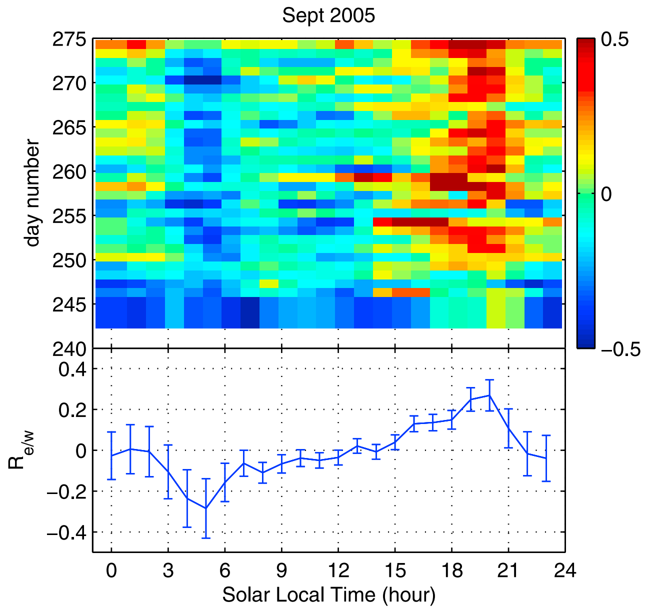

Figure 3. (top) Day-to-day change of the diurnal variation in east-to-west differential index $R_{e/w}$ over the month of September 2005, and (bottom) the diurnal variation of its monthly median. The east side is defined as −90 ~ −40°E and the west side −140 ~ −90°E.

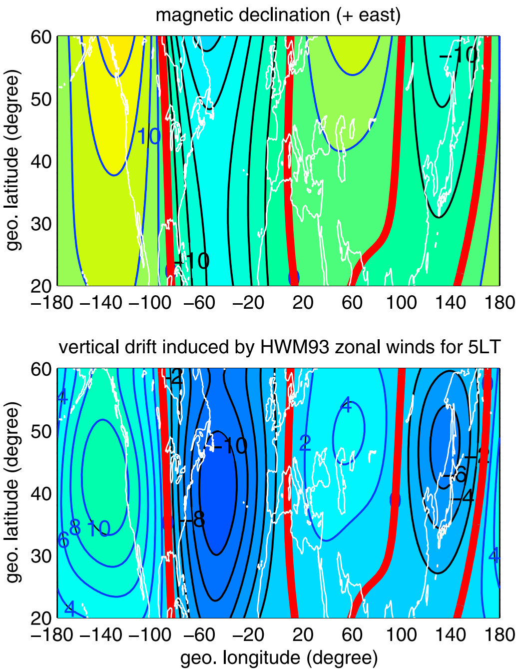

Figure 4. (top) Magnetic declination distribution and (bottom) the HWM90 zonal wind resulting vertical ion drift $Vz^{\|}_{\mathrm{zonal}}$. The magnetic declination is for 300 km for the year of 2005 as calculated by the IGRF model [*International Association of Geomagnetism and Aeronomy Working Group V-MOD*, 2010], and HWM winds are calculated for 0500 LT, September 2005 conditions.

we consider two average diurnal variations for the east (−80 ~ −60°E) and west (−130 ~−110°E) sides, respectively (Figure 2). It can be seen that on average TEC on the east side peaks in the afternoon and TEC on the west side peaks before noon; the east side TEC is higher after 1300 LT than the west side, and vice versa before 1300 LT. We also construct an hourly index $R_{\mathrm{e/w}}$, equivalent to a % east-west difference, to further quantify the east-west difference, where $R_{\mathrm{e/w}} = 2(\mathrm{TEC_{east}} - \mathrm{TEC_{west}})/(\mathrm{TEC_{east}} + \mathrm{TEC_{west}})$ and TEC data are hourly median values. Using data for the whole month of September 2005, Figure 3 presents the day-to-day variability in $R_{\mathrm{e/w}}$ as a function of solar local time (Figure 3, top), as well as the corresponding monthly average (Figure 3, bottom). On average, the highest east-west difference in TEC (by 30% as a gross average over the 20–60°N and 20° longitude span) appears positively at 2000 LT and negatively at 0500 LT; local noon and midnight are the times of zero east-west difference.

4. Discussion

[10] The above discussion indicates that the observed longitudinal difference in TEC and its variation with local time are substantial and repeatable with clear patterns. We suggest these are due to the combined effect of magnetic declination and thermospheric zonal winds. The magnetic declination, as shown in Figure 4 (top), is westward (negative) on the east side of the US continent and eastward (positive) on the west side, being zero along ~−90°E longitude. The magnetic field-aligned ion drift $V^{\|}_{\mathrm{zonal}}$ (positive for upward drift) induced by thermospheric horizontal zonal winds U_e (positive for eastward winds), $V^{\|}_{\mathrm{zonal}} = -U_e \sin D \cos I$, with I being the magnetic inclination, is either upward or downward depending on the sign of declination angle D and the sign of zonal winds U_e. For winds with a westward component, $V^{\|}_{\mathrm{zonal}}$ is upward on the west side of the zero declination longitude, and downward on the east side. The downward field-aligned drift $V^{\|}_{\mathrm{zonal}}$ moves the ions to lower altitudes where their recombination rate, exponentially increasing toward lower altitudes, is higher so that they are lost more quickly than they would be at higher altitudes and thus TEC in that region is reduced. A zonal wind induced upward drift gives rise to higher TEC than in the downward drift regions. As a result, westward winds produce higher TEC on the west side of the US than on the east side. Similarly, eastward winds cause the opposite effect. The observed longitudinal difference over the US continent is a result of this mechanism, which can readily explain the shift of the time in the diurnal TEC maximum between the east and west sides (Figure 2).

[11] Some early modeling work has demonstrated the magnetic declination and wind effect in general [*Challinora and Ecclesa*, 1971]. Here to provide a quantitative sense of the effect, HWM90 model winds [*Hedin et al.*, 1991] are calculated for September 2005 conditions. This is a westward wind system for 0500 LT. The vertical component of the field-aligned ion drift $Vz^{\|}_{\mathrm{zonal}}$ (Figure 4, bottom), directly responsible for upward or downward motion causing the height change in the recombination rate of the ions, is up to −10 m/s on the east side of the zero declination longitude and +10 m/s on the west side. Within 0.5 hour, the 20 m/s difference in $Vz^{\|}_{\mathrm{zonal}}$ can cause ~36 km difference in the height of the ions, which is sufficient to produce a pronounced TEC difference. Zonal winds at midlatitudes reverse their direction once during a day. Typically (as shown in the HWM90 model), the winds are westward in the morning hours and eastward in the evening hours. The reverse of this wind direction causes an opposite east-west difference in TEC.

[12] In Figure 1 (bottom), the red line is obtained for 0600 LT in a similar manner as the blue line for 1800 LT at 40°N. The average TEC levels for the two lines are different because of different local times, so we normalize TEC over different latitude ϕ at each local time to the same [−0.5 0.5] range, N(ϕ). This allows us to evaluate morning-evening variability, $\delta(\phi) = |\mathrm{N}(\phi)_{\mathrm{morning}} - \mathrm{N}(\phi)_{\mathrm{evening}}|$, as a function of longitude. We expect to see a longitude area of minimum variability, and according to our discussion above, this area should be close to the zero declination zone. Three latitude zones are selected: 60-45°, 50-30°, 35-20°. The monthly median $\delta(\phi)$ values for September 2005 over these zones are shown in Figure 5. The morning-evening variability, due to the directional reversal of zonal winds, increases toward each end of the longitude where D is large. The minimum of variability $\delta(\phi)$, however, is indeed close to −90 ~ −100°E longitudes where D ~ 0 and the directional reversal of zonal winds impose minimum impacts. The location of the minimum tilts slightly toward east from higher- to lower- midlatitudes, a feature consistent with the zero declination orientation.

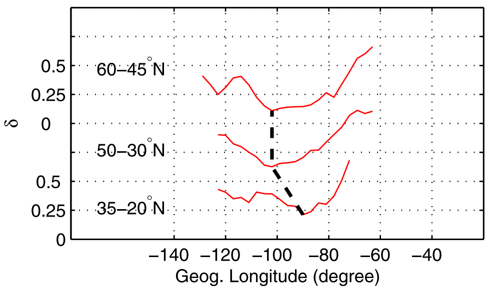

Figure 5. Morning-evening variability $\delta(\phi)$ of TEC derived for the month of September 2005 at three latitude zones, indicating minima of variability, near $-90 \sim -100$°E tilting toward east where declination is close to zero. Guided by Figure 3, the morning and evening hours are selected as 0500 ± 1.5 LT and 2000 ± 1.5 LT.

[13] Our discussion has focused on zonal wind effects. Meridional winds contribute to the vertical ion drift, however, their effect is not important for our primary emphasis of longitudinal differences, since we have seen no evidence of a clear longitudinal change in them at midlatitudes during non-storm conditions. We have used geographic latitudes. In fact, the (corrected) magnetic latitude is highest near the zero declination over the continental US and it differs by merely 3–7° between −60 °E and −130°E. Therefore the magnetic latitude variation does not contribute significantly to the observed longitudinal difference. Further, latitudinal variations shown in Figure 1 (left) indicate that the east-west coast difference is latitude independent. In this study, we focus on conditions of fall equinox at low solar activity to illustrate the primary mechanism. More extensive climatology of the east-west coast TEC difference over the US continent is needed. It may be directly associated with the zonal wind climatology, and this investigation is beyond the scope of the paper. But we notice that the large TEC difference does exist throughout the years 2007–2009. This seasonal persistency and local time dependency is different from the Weddell-Sea-anomaly-like behavior which is a summer nighttime phenomena. In the northern hemisphere, magnetic declination changes its sign 4 times such that there are two zones of negative declination and two zones of positive declination. A global pattern of longitudinal variations at midlatitudes may therefore be expected, since similar longitudinal variations at a given local time may exist in European and Asian sectors. However, the magnitude of these predicted variations can be different due to different magnetic field configurations (see Figure 5) and the fact that the distance to the magnetic pole varies with longitude [*Rishbeth*, 1998]. The directional reversal in declination causes a large difference in TEC through the zonal wind induced ion drift, and therefore it might be feasible to derive zonal wind information based on electron density differences across the zero declination longitude. In fact, decades ago similar ideas to deduce equivalent meridional winds from the height of the F2-peak were introduced and widely used [*Rishbeth et al.*, 1978]. Finally, a combined declination-zonal wind effect can certainly take place during space weather disturbances and may be responsible for some longitudinal features of disturbances; in particular, when the midlatitude ionosphere acts as the source for some geospace disturbances (such as by *Foster et al.* [2002]), these disturbances can contain some regional/longitudinal/UT signatures.

5. Conclusion

[14] Ground-based TEC observations using a network of dense GPS receivers over the continental US indicate a pronounced longitudinal variation. In particular, the evening TEC is substantially higher on the US east coast than on the west, and vice versa for the morning TEC, showing a clear diurnal variation in the east-to-west TEC difference. Through an analysis of morning-evening variability in the east-west TEC difference, minimum variability is found to coincide with the longitudes of zero magnetic declination over the continental US. It is suggested that these longitudinal differences are caused by the difference in magnetic declination which gives rise to upward and downward ion drifts across the zero declination for a given thermospheric zonal wind direction. Thermospheric zonal winds are subject to directional reverse over the course of a day, therefore producing a diurnal variation in the longitudinal difference. This declination-zonal wind mechanism may also provide a new insight into longitude/UT changes at midlatitudes on a global scale, as well as into some geospace disturbances.

[15] **Acknowledgments.** We thank the members of the MIT Haystack Observatory for maintaining the Madrigal Database. The original GPS data are from the International GNSS Service (IGS) for providing GPS data. Observations and research are supported by the US National Science Foundation under Cooperative Agreements ATM-0733510 and ATM-0856093.

[16] The Editor thanks Yuichi Otsuka and an anonymous reviewer for their assistance in evaluating this paper.

References

Challinora, R. A., and D. Ecclesa (1971), Longitudinal variations of the mid-latitude ionosphere produced by neutral-air winds—I. Neutral-air winds and ionospheric drifts in the northern and southern hemispheres, *J. Atmos. Terr Phys.*, *33*, 363–369.

Chen, C. H., J. D. Huba, A. Saito, C. H. Lin, and J. Y. Liu (2011), Theoretical study of the ionospheric Weddell Sea Anomaly using SAMI2, *J. Geophys. Res.*, *116*, A04305, doi:10.1029/2010JA015573.

Coster, A. J., J. C. Foster, and P. J. Erickson (2003), Monitoring the ionosphere with GPS, *GPS World*, *14*(5), 42–45.

England, S. L., T. J. Immel, J. D. Huba, M. E. Hagan, A. Maute, and R. DeMajistre (2010), Modeling of multiple effects of atmospheric tides on the ionosphere: An examination of possible coupling mechanisms responsible for the longitudinal structure of the equatorial ionosphere, *J. Geophys. Res.*, *115*, A05308, doi:10.1029/2009JA014894.

Foster, J. C., P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich (2002), Ionospheric signatures of plasmaspheric tails, *Geophys. Res. Lett.*, *29*(13), 1623, doi:10.1029/2002GL015067.

Hedin, A. E., et al. (1991), Revised global model of thermosphere winds using satellite and ground-based observations, *J. Geophys. Res.*, *96*, 7657–7688.

Immel, T. J., E. Sagawa, S. L. England, S. B. Henderson, M. E. Hagan, S. B. Mende, H. U. Frey, C. M. Swenson, and L. J. Paxton (2006), Control of equatorial ionospheric morphology by atmospheric tides, *Geophys. Res. Lett.*, *33*, L15108, doi:10.1029/2006GL026161.

International Association of Geomagnetism and Aeronomy Working Group V-MOD (2010), International Geomagnetic Reference Field: The eleventh generation, *Geophys. J. Int.*, *183*, 1216–1230, doi:10.1111/j.1365-246X.2010.04804.x.

Lin, C. H., C. H. Liu, J. Y. Liu, C. H. Chen, A. G. Burns, and W. Wang (2010), Midlatitude summer nighttime anomaly of the ionospheric electron density observed by FORMOSAT-3/COSMIC, *J. Geophys. Res.*, *115*, A03308, doi:10.1029/2009JA014084.

Luan, X., W. Wang, A. Burns, S. C. Solomon, and J. Lei (2008), Midlatitude nighttime enhancement in F region electron density from global COSMIC measurements under solar minimum winter condition, *J. Geophys. Res.*, *113*, A09319, doi:10.1029/2008JA013063.

Mannucci, A. J., B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqwister, and T. F. Runge (1998), A global mapping technique for GPS-derived ionospheric total electron content measurements, *Radio Sci.*, *33*, 565–582.

Rideout, W., and A. Coster (2006), Automated GPS processing for global total electron content data, *GPS Solut.*, *10*, 219–228, doi:10.1007/s10291-006-0029-5.

Rishbeth, H. (1998), How the thermospheric circulation affects the ionospheric F2-layer, *J. Atmos. Sol. Terr. Phys.*, *60*, 1385–1402.

Rishbeth, H., S. Ganguly, and J. C. G. Walker (1978), Field-aligned and field-perpendicular velocities in the ionospheric F2-layer, *J. Atmos. Terr Phys.*, *40*, 767–784.

Sagawa, E., T. J. Immel, H. U. Frey, and S. B. Mende (2005), Longitudinal structure of the equatorial anomaly in the nighttime ionosphere observed by IMAGE/FUV, *J. Geophys. Res.*, *110*, A11302, doi:10.1029/2004JA010848.

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

Tsugawa, T., Y. Otsuka, A. J. Coster, and A. Saito (2007), Medium-scale traveling ionospheric disturbances detected with dense and wide TEC maps over North America, *Geophys. Res. Lett.*, *34*, L22101, doi:10.1029/2007GL031663.

Wilson, B. D., C. H. Yinger, W. A. Fees, and C. Shank (1999), New and improved: The broadcast interfrequency biases, *GPS World*, *10*(9), 56–66.

A. J. Coster, P. J. Erickson, J. C. Foster, and S.-R. Zhang, Haystack Observatory, Massachusetts Institute of Technology, Off Route 40, Westford, MA 01886, USA. (ajc@haystack.mit.edu; pje@haystack.mit.edu; jcf@haystack.mit.edu; shunrong@haystack.mit.edu)