Near-real-time Ionosphere Modeling Based on Regional GPS Data

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Abstract: We present a GPS-derived regional ionosphere model, which estimates Total Electron Content (TEC) in rectangular grids on the spherical shell over Korea. The GPS data from nine GPS stations were used. The pseudorange data were phase-leveled by a linear combination of pseudoranges and carrier phases. During a quiet day of solar activity, the regional ionosphere map indicated 30-45 Total Electron Content Unit (TECU) at the peak of the diurnal variation. In comparison with the Global Ionosphere Map of the Center for Orbit Determination in Europe, RMS differences were at the level of 4-5 TECU for five days.
Keywords: GPS, ionosphere, phase-leveled pseudorange, TEC

1. Introduction

Since Selective Availability (SA) was de-activated on 1 May 2000, the largest error source in precise positioning using GPS is the signal delay due to the ionosphere. GPS uses two frequencies in L-band: L1=1575.42 MHz and L2=1227.60 MHz. As the GPS signal travels through the ionosphere, it gets reflected. During a low solar activity, the ionospheric delay ranges from a few centimeters to several tens of meters. With a high solar activity, however, the delay can reach up to 150 m such as during the year 2002 [1].

The major factor determining the amount of the ionospheric delay is the Total Electron Content (TEC), which is dependent of the solar activity, season, time of day, receiver location and direction of the satellite, etc. The accurate measurement of TEC is important for space weather prediction, remote sensing of the Earth atmosphere, and Wide Area Augmentation System (WASS) applications [2]. Prediction of communication failures and radio interference additionally requires accurate information on TEC variations [3].

The unit for TEC is Total Electron Content Unit (TECU). One TECU corresponds to 10^{16} electrons in one square meter of surface. One TECU also translates into 0.1624 m of signal delay [4].

There exist several ionosphere models: Klobuchar model [5], Global Ionosphere Map (GIM) by Jet Propulsion Laboratory (JPL), and GIM by Center for Orbit Determination in Europe (CODE). The Klobuchar model is created by sinusoidal function fit to the broadcast information from GPS satellites, but it can correct only 50-60 % of the ionospheric delay. Using GIMs by JPL or CODE, one can achieve higher accuracy in the TEC estimates. These two GIM models are based on GPS data collected at more than 100 permanent GPS tracking stations worldwide. JPL model uses an interpolation method with triangular grids [6], whereas CODE uses spherical harmonics. Because these models are usually generated for global ionospheric models, they are at coarse grids (5°×2.5°). Thus, they are not adequate for a regional ionospheric modeling.

Some Japanese researchers average TECU in the 0.15°×0.15° rectangular grids using about 1000 GPS permanent sites in Japan [7]. This approach, however, is not appropriate for Korea, which has only 70 stations nationwide.

This study adapts a regional ionosphere model that can quickly compute accurate TEC using a small number of GPS sites. We will explain a method to reduce inherent pseudorange data noise, and then discuss the procedure to compute the slant TEC and to estimate Vertical TEC (VTEC) using rectangular grids.

2. TEC Computation

There are two major GPS observables: pseudoranges and carrier phases. One can get better estimates of TEC with carrier phases, but the fact that one has to consider cycle slips and fix integer ambiguities [4] makes it difficult to use carrier phases in estimating TEC. Even though it is not necessary to fix integer ambiguities as well as cycle slips with pseudorange data, multipath errors and inherent noises contaminate the pseudorange measurements. Thus, we used "phase-leveled" pseudoranges to reduce those noises.

The pseudorange measurement equations on L1 and L2 are:

$$P1(k) = \rho + c\left(\delta t^s - \delta t_r\right) + \frac{40.3}{f_1^2} TEC(k) + \varepsilon_{trop} + \varepsilon_{multi} + \varepsilon_{L1} \quad (1)$$

$$P2(k) = \rho + c\left(\delta t^s - \delta t_r\right) + \frac{40.3}{f_2^2} TEC(k) + \varepsilon_{trop} + \varepsilon_{multi} + \varepsilon_{L2}, \quad (2)$$

where

c	speed of light
ρ	geometric range from receiver to GPS satellite
δt^s	satellite clock offset
δt_r	receiver clock offset
f_i	frequencies of L1 and L2 (i=1,2)
ε_{trop}	tropospheric delay
ε_{mult}	multipath error
ε_{Li}	receiver noise on L1 and L2 (i=1,2).

By a linear combination of Eqs. (1) and (2), we get Eq. (3), which does not contain ionosphere errors:

$$I_{ion-free}(k)=\frac{f_1^2}{f_1^2-f_2^2}P1(k)-\frac{f_2^2}{f_1^2-f_2^2}P2(k). \qquad (3)$$

The ionospheric error on carrier phases also can be obtained with the same procedure as above. Then, the ionospheric delay is transformed into TEC using the relation: 1 TECU = 0.162 m. Thus, TEC using phase-leveled pseudoranges is obtained using Eq. (4) by a linear combination of TECs obtained by pseudoranges and range-differenced carrier phases:

$$\overline{(P1-P2)}_k=(P1-P2)_k+\left\{\overline{(P1-P2)}_{k-1}+\delta(\Phi_1-\Phi_2)_{k,k-1}\right\}, \quad (4)$$

where $(P1–P2)_k$ is TEC obtained using pseudorange data at epoch k, $\delta(\Phi_1–\Phi_2)_{k,k-1}$ is TEC difference by carrier phases between epochs k and k-1. $\overline{(P1-P2)}_{k-1}$ and $\overline{(P1-P2)}_k$ are TECs by phase-leveled pseudoranges at epochs k-1 and k.

2. Ionosphere Modeling and Estimation

Two-dimensional ionosphere models are based on the assumption that all the electrons are located on a single imaginary shell. Generally, for the typical daytime profile, most of the electrons are concentrated at the medium height of 450 km above the ground [3]. Thus, we assume that all the electrons are concentrated on the imaginary thin shell at 450 km. As in Fig. 1, the point where the line of sight (from the receiver to the satellite) intersects the ionospheric shell at 450 km is referred to as Ionospheric Pierce Point (IPP) [4].

The variation of TEC at IPP is highly dependent on the solar activity and the geomagnetic field. Thus, we used a solar-geomagnetic frame, which is less variable to the ionosphere movement due to the Sun and the geomagnetic field than an Earth-fixed frame.

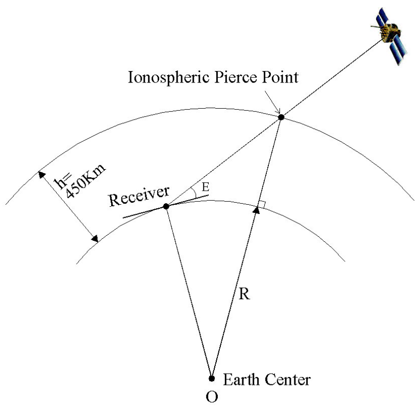

Fig. 1. Geometry of the slant TEC in the ionosphere shell.

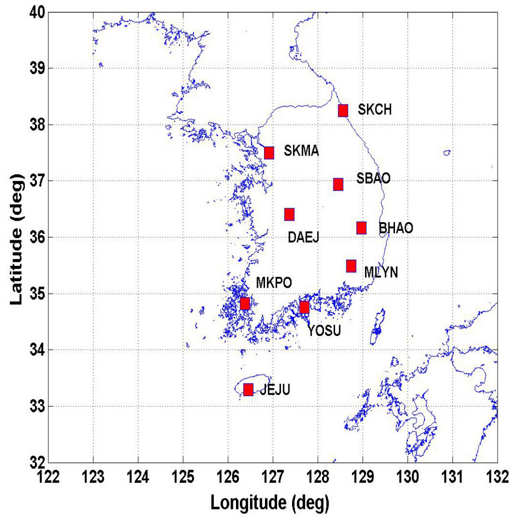

Fig. 2. Nine KAO GPS sites and rectangular grids used in the study

We designed rectangular grids of 1°×1° spatial resolution over the Korean peninsula as shown in Fig. 2. We used IPPs located in the range of 32-40° in latitude and 122-132° in longitude. Fig. 2 also shows nine permanent GPS sites used in this study, which are operated by Korea Astronomy Observatory (KAO).

Fig. 3 shows how we transform the slant TEC at IPP to Vertical TEC (VTEC) in the vertex. A mapping function is used to transform the slant TEC at IPP, $P(\varphi,\lambda)$, to the VTEC. Then, base functions W_{ij} are used to relate the VTEC at IPP to $VTEC_j$ (j=1,2,3,4) at the four surrounding vertices. The detailed explanation on the mapping and base functions can be found in [3,8].

All the nine GPS stations in Fig. 2 continuously collect data every 30 seconds. The data is delivered to the main data center at KAO via Internet or exclusive telephone lines in real-time. In our model, each TEC map was created using 120 minutes of data (phase-leveled pseudoranges).

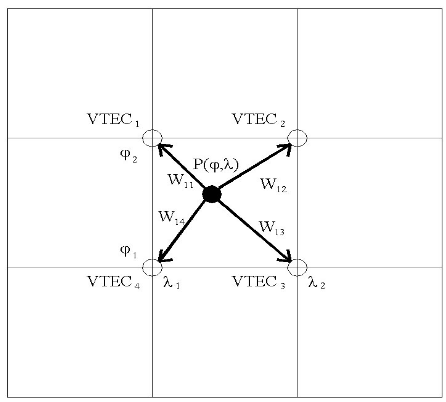

Fig. 3. Relation between slant TEC and vertical TEC at vertices.

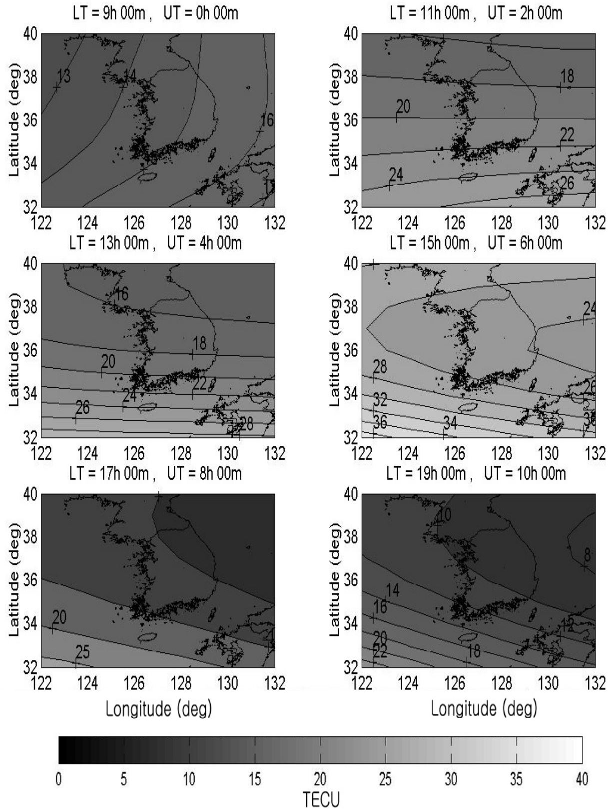

Fig. 4. Regional ionosphere map over Korea on 26 January 2003.

3. Results and Discussion

Fig. 4 shows six TEC maps for 26 January 2003. Each map is a result of two hours of GPS measurements. From Fig. 4, one can see that TEC increases toward the local daytime, and decreases as it gets close to the nighttime. The highest TEC was observed from 1-3 PM KST. TECs are higher in the southwest area than the northeast. Because the maximum TECU was around 30 in the southwest region during 1-3 PM, we believe the solar activity was moderate on the day.

It takes about ten minutes to process the two-hour's worth of phase-leveled pseudorange data and create a TEC map like the one in Fig. 4. We are improving the processing algorithm, so the processing time will further decrease. Thus, it can be easily implemented for near-real-time ionosphere modeling for improving positioning accuracy for many GPS applications.

To validate our results, we used CODE's GIM because there are no local data available to us to compare our results with. As noted earlier, the GIM is for global ionosphere models, and its spatial resolution is 5°×2.5°. When we compared five-day TEC estimates for 25-29 January 2003, the root-mean-square (RMS) differences between our model and CODE estimates were 4.7 TECU at 35°N and 5.3 TECU at 37°N. Basically there are two major differences in the CODE's model and ours: 1) CODE uses spherical harmonics and we use rectangular grids; 2) our grids (1°×1°) are finer than CODE's. Considering possible errors in interpolating from coarse grids to finer grids and the fundamental difference in the ionosphere models, the observed discrepancies at the level of ~5 TECU are smaller than we expected.

4. Conclusion

We have developed a regional ionosphere model using GPS measurements from nine permanent GPS sites in Korea. We found that the rectangular grids of 1°×1° spatial resolution are efficient in modeling the TEC variation over the Korean peninsula. The accuracy of our model, compared with a global ionosphere model, was at the level of 4-5 TECU. It takes only about ten minutes to generate a TEC map using two hours of observation from nine stations, which samples the data every 30 seconds. Thus, our regional ionosphere model can be easily implemented for near-real-time ionosphere modeling.

References

[1] Komjathy, A., B. D. Wilson, T. F. Runge, B. M. Boulat, A. J. Mannucci, L. Sparks, and M. J. Reyes, 2002. A new ionospheric model for wide area differential GPS: The multiple shell approach, *Presented at the ION National Technical Meeting*, San Diego, CA, January 28-30.

[2] Hansen, A. J., 2002. *Tomographic estimation of the ionosphere using terrestrial GPS sensors*, Ph.D. Dissertation, Stanford University, 200 pp.

[3] 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 Science*, 33(3): 565-582.

[4] Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins, 2001. *GPS theory and practice* fifth revised edition, Springer.

[5] Klobuchar, J., 1987. Ionospheric time-delay algorithm for single-frequency GPS users, *IEEE Transactions on Aerospace and Electronics Systems*, 23(3): 325-331.

[6] Wilson, B. D. and A. J. Mannucci, 1993. Instrumental biases in ionospheric measurements derived from GPS data, *Proceedings of the Institute of Navigation GPS-93*, Salt Lake City, Utah, pp. 1343-1351.

[7] Otsuka, Y., T. Ogawa, A. Saito, T. Tsugawa, S. Fukao, and S. Miyazaki, 2002. A new technique for mapping of total electron content using GPS network in Japan, *Earth, Planets and Space*, 54: 63-70.

[8] Gao, Y., X. Liao, and Z. Liu, 2002. Ionosphere modeling using carrier smoothed ionosphere observations from a regional GPS network, *Geomatica*, 56(2): 97-106.