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GPS ionospheric tomography: A comparison with the IRI-2001 model over South Korea

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The International Reference Ionosphere model 2001 (IRI-2001) is one of the most comprehensive empirical models of the ionosphere and has been widely used to estimate the electron density profiles in the altitude ranging from about 60 to 2000 km and the total electron content (TEC) at any given location, time and date, which reflect smooth-average global ionospheric behaviors. However, whether it provides normal actual estimations in the ionosphere over some regions should be tested with real observation data. In this paper, the three-dimensional ionospheric electron density profiles over South Korea in 2003 are obtained using the ionospheric tomography reconstruction technique with the permanent Korean GPS Network (KGN) data, and its validity is further verified by another independent ionosonde data. The GPS ionospheric reconstruction results are used to compare then results obtained with the IRI-2001 model in South Korea in terms of NmF2 and TEC. The monthly averaged diurnal values of these key parameters in January, April, July and October 2003 are considered to represent the winter, spring, summer and autumn seasons, respectively. Compared with the GPS reconstruction results, averaged monthly NmF2 medians from the IRI-2001 are overestimated in daytime and underestimated in nighttime for all seasons, but the deviation magnitudes in autumn and winter are smaller than in spring and summer. In addition, averaged monthly TEC medians from the IRI-2001 are overestimated in daytime in winter, but almost always underestimated in other seasons.

Key words: IRI-2001, ionospheric tomography, GPS, South Korea.

1. Introduction

The International Reference Ionosphere (IRI) is an international joint project of the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a working group in the late 1960s to produce an empirical standard model of the ionosphere, based on all available ground and space data sources. As one of the most comprehensive empirical models of the ionosphere, the IRI, provides the electron density, electron temperature, ion temperature and ion composition at altitudes ranging from about 60 to 2000 km, and the total electron content (TEC) at any specific given location, time and date, based on the various ground and space measurements. It provides monthly averages in the non-auroral ionosphere for magnetically quiet conditions. The major data sources are the worldwide network of ionosondes, the powerful incoherent scatter radars, the Alouette and ISIS topside sounders and in situ instruments on several satellites and rockets (Bilitza, 2001). The IRI is continuously updated when the model is improved during COSPAR IRI sessions and/or IRI workshops, and the recent model version implemented in SPENVIS is the IRI-2001 (Bilitza, 2001).

The IRI-2001 has been widely used to estimate the electron density profiles and TEC at any given location, time and date in the world. For instance, the IPS (Ionospheric Prediction Service) Radio Services as the Australian Space Weather Agency (http://www.ips.gov.au/) provides hourly regional maps of TEC in near real time using the IRI model. Ezquer *et al.* (1998) used the IRI model to predict TEC for the South American peak of the equatorial anomaly, and so on. However, the IRI-2001 is an empirical model of the ionosphere and provides a smooth-average global ionospheric behavior, and its long-term reliability should be checked with real observation data, especially for some regions. In the past decades, different observing instruments have been developed and used to gather information on the ionosphere, such as ionosonde, scatter radars (Tsunoda, 1988), topside sounders onboard satellites (Reinishch *et al.*, 2001), in situ rocket and satellite observations (Klobuchar, 1991), and LEO (Low Earth Orbit) GPS occultation measurements (Jakowski *et al.*, 2002), but most instruments are expensive and also restricted to either the bottomside ionosphere or the lower part of the topside ionosphere (usually lower than 800 km), such as ground-based radar measurements. Nowadays, GPS satellites in high altitude orbits (20,200 km) are capable of providing details on the structure of the entire ionosphere, even the plasmasphere. Moreover, GPS is a low-cost, all-weather, near real time, and high-temporal resolution (30 s) technique. Therefore, more recently, GPS has been widely used to investigate the ionospheric and its related solid earth activities (e.g. Yamamoto *et al.*, 2000; Afraimovich *et al.*, 2000; Otsuka *et al.*, 2002;

Jin *et al.*, 2004; Heki and Ping, 2005). However, most of the research has been based on a 2-D single layer model (SLM) of the ionosphere at the altitude of electron density peak (generally 350 km above the Earth), which has actually restricted mapping of the vertical structure. High-resolution 3-D ionospheric information is needed so as to better monitor the ionospheric activities in full dimensions and to assess the empirical ionospheric models, e.g. IRI-2001.

The electron density F2 peak value (denoted as NmF2) greatly influences the shape of ionospheric electron density profile Ne (h), and the integrated electron density along a path through the ionosphere is the TEC. Therefore, the NmF2 and TEC are the main parameters of the ionosphere model, directly reflecting the quality of empirical ionospheric models. In this paper, the three-dimensional ionospheric electron density profiles over South Korea in 2003 are obtained using the ionospheric tomography reconstruction technique with the permanent Korean GPS Network (KGN) data, and corresponding key parameters are compared with those of the IRI-2001 model in South Korea. In Section 2, the method of 3-D ionospheric tomography is addressed in brief; reconstruction results are given in Section 3. The IRI-2001 model is compared with GPS reconstruction in Section 4 followed by a summary of noteworthy results in the Conclusion.

2. GPS Ionospheric Reconstruction Method

The Global Positioning Systems (GPS) consists of a constellation of 24 operating satellites in six circular orbits 20,200 km above the Earth at an inclination angle of 55° with a 12-h period. The satellite transmits two frequencies of signals ($f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz). Since the ionosphere is a dispersive medium, dual-frequency GPS receivers are able to evaluate the ionospheric effect with measurement of the modulations on the carrier (codes) and the carrier phases. The equations of carrier phase (L) and code observations (pseudorange P) of double frequency GPS can be expressed as follows:

$$L^i_{1,j} = \lambda_1 \varphi^i_{1,j} = \rho^i_{0,j} - d^i_{\text{ion},1,\text{j}} + d^i_{\text{trop,j}} + c(\tau^i - \tau_j) - \lambda_1 (b^i_{1,j} + N^i_{1,j}) \quad (1)$$

$$L^i_{2,j} = \lambda_2 \varphi^i_{2,j} = \rho^i_{0,j} - d^i_{\text{ion},2,\text{j}} + d^i_{\text{trop,j}} + c(\tau^i - \tau_j) - \lambda_2 (b^i_{2,j} + N^i_{2,j}) \quad (2)$$

$$P^i_{1,j} = \rho^i_{0,j} + d^i_{\text{ion},1,\text{j}} + d^i_{\text{trop,j}} + c(\tau^i - \tau_j) + d^i_{q,1} + d_{q,1,j} + \varepsilon^i_j \quad (3)$$

$$P^i_{2,j} = \rho^i_{0,j} + d^i_{\text{ion},2,\text{j}} + d^i_{\text{trop,j}} + c(\tau^i - \tau_j) + d^i_{q,2} + d_{q,2,j} + \varepsilon^i_j \quad (4)$$

Where superscript i and subscript j represent the satellite and ground-based GPS receiver, respectively; ρ_0, the true distance between the GPS receiver and satellite; d_{ion} and d_{trop}, the ionospheric and tropospheric delays, respectively; c, the speed of light in vacuum space; τ, the satellite or receiver clock offset; b, the phase delay of satellite and receiver instrument bias; d_q, the code delay of satellite and receiver instrumental bias; λ, the carrier wavelength; φ, the total carrier phase between the satellite and receiver; N, the ambiguity of carrier phase; ε, other residuals.

The continuous dual-frequency GPS observations can provide a precise slant TEC (STEC) of ray path after considering all kinds of possible bias and errors, such as instrument bias and clock errors (Jin *et al.*, 2004, 2006a). The STEC is defined as the line integral of the electron density as expressed by

$$STEC = \int_{R_{\text{receiver}}}^{R_{\text{satellite}}} N_e(\lambda, \varphi, h) ds \quad (5)$$

where $N_e(\lambda, \varphi, h)$ is the ionospheric electron density, λ, φ and h are the longitude, latitude and height, respectively. Using the STEC of all ray paths, the 3-D ionospheric electron density profiles can be derived through a tomography reconstruction algorithm. Here, the multiplicative algebraic reconstruction technique (MART) is used (Raymund *et al.*, 1990). The tomography reconstruction algorithm can integrate the STEC from all available GPS receivers and all GPS satellites visible from each of these receivers above a user-specified elevation cut-off angle (usually 15°). The unknown electron density profile is expressed in 4-D (longitude-latitude-height and time) voxel basis functions over the following grid: longitude 124°–130°E: in 1° increments; latitude 33°–39°N: in 0.5° increments; altitude 100–1000 km: in 25-km increments; time: 1-h increments of linear change in the electron density per voxel. Each set of slant TEC measurements along the ray paths from all observable satellites and from consecutive epochs are combined with the ray path geometry into a linear expression:

$$y = Ax + \varepsilon \quad (6)$$

where A is a matrix relating the ray paths to the voxels, y is a column vector containing the observed slant TEC values and x is the column vector of unknown coefficients of the basis functions. The inversion of this matrix gives the unknown coefficients of the electron density distribution from which the vertical electron density or vertical TEC at any grid points can be inferred. The solution is constrained using a priori information from the IRI-2001 or ionosonde. For more details about the reconstruction algorithm the reader can refer to (Gordon *et al.*, 1970; Raymund *et al.*, 1990; Jin *et al.*, 2006a).

3. Data and Results

3.1 GPS observation data

The Korean GPS Network (KGN) with more than 50 permanent GPS sites has been established since 2000 by the Korea Astronomy and Space Science Institute (KASI), the Ministry Of Governmental Administration and Home Affairs (MOGAHA), and the National Geographic Information Institute (NGI) (Jin and Park, 2006b). The spatial resolution of GPS network is about 20-50 km. Therefore, these dense GPS data can produce high-resolution daily position time series, precipitable water vapor (PWV) and total electron content (TEC), which offer opportunities to research crustal deformation, climate and space environments on the

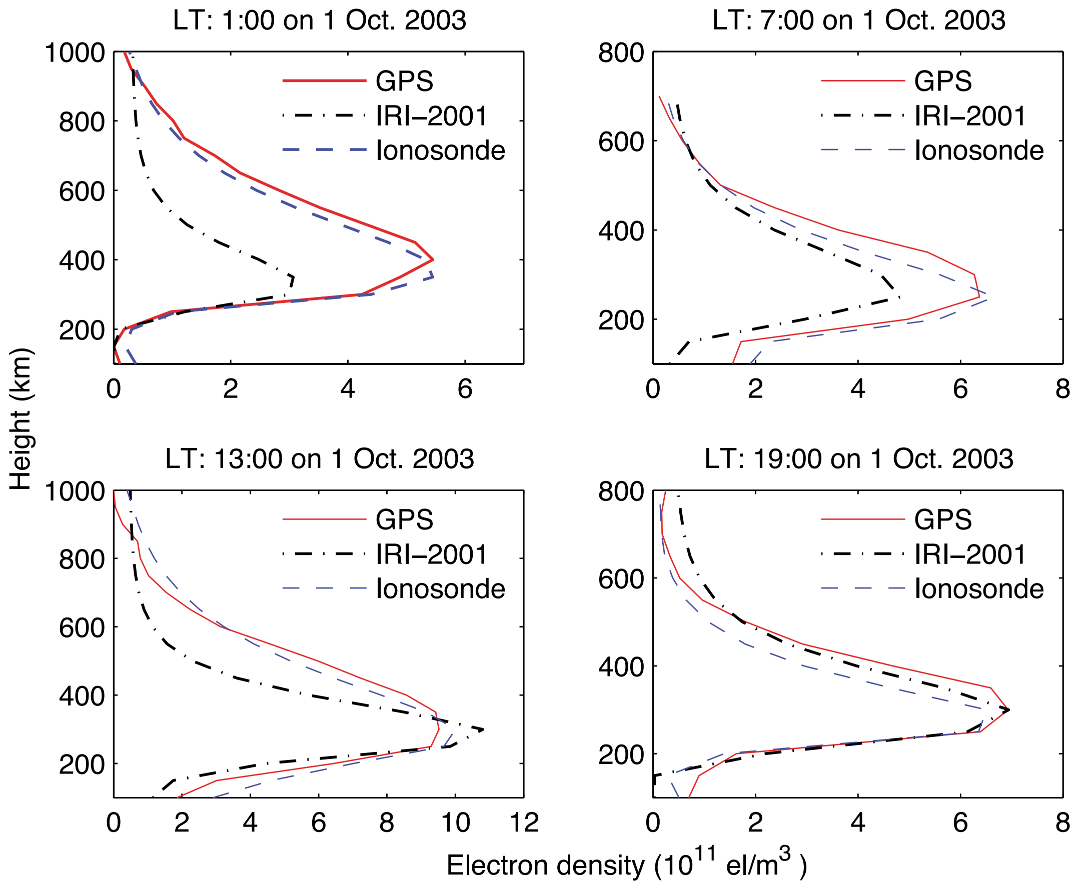

Fig. 1. Comparison of the electron density profiles derived from the ground-based GPS tomography reconstruction (solid line), ionosonde observation at Anyang stations (37.39°N, 126.95°E) (dash line) and IRI-2001 estimation (dot).

South Korean Peninsula. Here we use these ground-based GPS observations of the KGN to inverse 3-D ionospheric structure information over South Korea and then compare this with the results of the IRI-2001 model in terms of main ionospheric parameters, NmF2 and TEC.

3.2 Ionospheric reconstruction results

To obtain accurate ionospheric profiles from GPS ionospheric tomography method requires very high altitudinal and latitudinal resolution of the voxels. First, the denser GPS network in South Korea with about 20–50 km spatial resolution provides a good latitudinal resolution; second, the GPS ionospheric MART tomography greatly relies on the guess values, i.e. priori information. Here the priori information is taken from real ionosonde observations at Anyang station (37.39°N, 126.95°E) in South Korea rather than from any empirical ionospheric models. Therefore, the real iononsonde observations provide a good altitudinal resolution background of the voxels. The ionospheric electron density profiles are calculated from the ionosonde data using the SAO-X software developed by the Center for Atmospheric Research at the University of Massachusetts Lowell (http://umlcar.uml.edu/). The E-layer ionization of the ionosonde may be not included in the range of vertical profiles and then calculated from the Chapman profile model as the Chapman profile has a better density profile for the topside ionosphere than the IRI-2001 model. Thus, very good GPS ionospheric reconstruction results can be obtained with the denser Korean GPS network (KGN) data and real ionosonde observations at Anyang station as a priori information. We further verify the validity of the GPS tomographically reconstructed electron density profiles by comparing them with independent ionosonde. The available ionosonde at Anyang station in South Korea provides an independent comparison with the tomographically reconstructed electron density profiles from ground-based GPS observations. Figure 1 shows comparisons of the GPS reconstruction results at 1:00 LT (midnight), 7:00 LT (morning), 13:00 LT (noon) and 19:00 LT (evening) on 1 October 2003, with the available valid ionosonde data recorded at nearby Anyang station and density profiles from the IRI-2001 model. The GPS tomographically reconstructed density profiles are almost consistent with the ionosonde and IRI-2001, but are much closer to the ionosonde, especially in the electron density peak. The electron density F2 peak NmF2 value is a key parameter of the ionospheric electron density profile Ne (h). We further compare the GPS-derived NmF2 with the IRI-2001 and ionosonde at different times (see Fig. 2). The GPS tomographically reconstructed NmF2 has a good agreement with the ionosonde and IRI-2001 model, but is closer to the ionosonde, which again confirms the validity of GPS ionospheric tomography.

Furthermore, we obtain the diurnal GPS ionospheric reconstruction results in January, April, July and October 2003. Comparing these with the IRI-2001 and ionosonde,

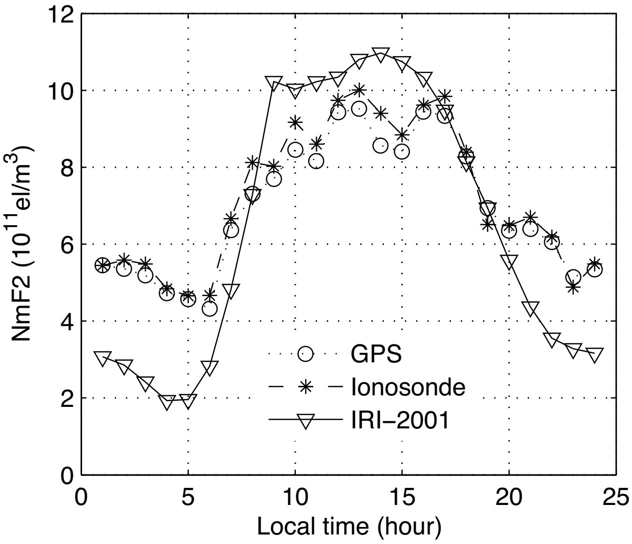

Fig. 2. Comparison of the F2-layer peak electron density NmF2 derived from the ground-based GPS tomography reconstruction (circle), ionosonde observation at Anyang station (37.39°N, 126.95°E) (star) and IRI-2001 estimation (triangle) on 1 October 2003.

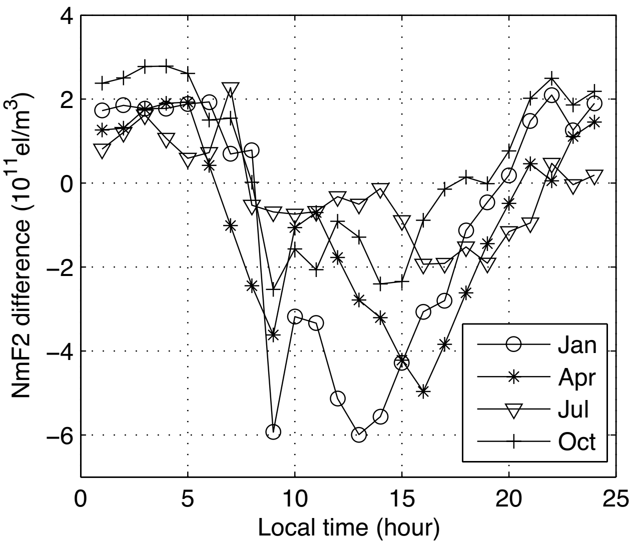

Fig. 3. NmF2 differences of monthly averaged median of GPS reconstruction with the IRI-2001 model.

GPS ionospheric tomographically reconstructed profiles are in good agreements with the ionosonde and IRI-2001 model, but almost closer to the ionosonde. Although the empirical models, such as IRI-2001, are very useful to give guidelines for monthly averages of global ionospheric behaviors and show diurnal variations well, they may not provide a good regional ionospheric behavior or cannot reproduce short (minutes to hours) events that occur sporadically. Needless to say these short period events of the ionosphere may affect the normal time density distributions. It is of interest to note that our inversion method can map the 3-D ionospheric electron density profile over a region (South Korea) in a short period of time with a good agreement with the independent ionosonde.

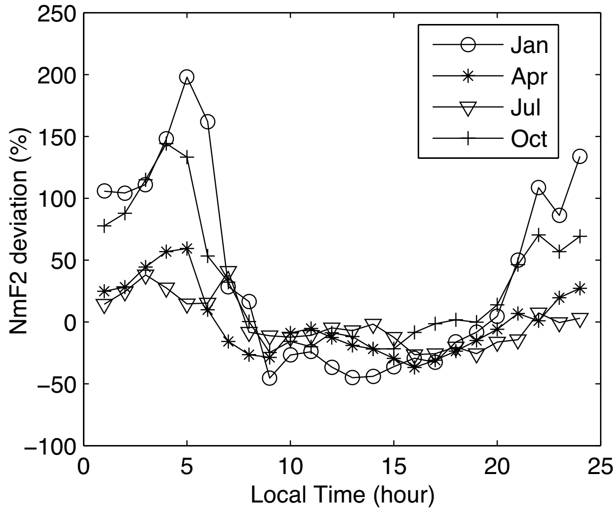

Fig. 4. Monthly averaged diurnal NmF2 variation percentage of the GPS reconstruction with respect to the IRI-2001 model.

4. Comparison of the IRI-2001 and GPS Reconstruction

In order to check the validity of the IRI-2001 for predicting the seasonal variation over South Korea, we further compare the IRI-2001 model with real GPS observation results in terms of main ionospheric parameters, the electron density F2 peak (NmF2) and TEC. The monthly averaged diurnal GPS results of these main parameters in January, April, July and October 2003 are considered to represent winter, spring, summer and autumn seasons, respectively. As GPS ionospheric reconstruction profiles are in very close agreement with the ionosonde, e.g. the F2 peak parameter NmF2, we do not compare the ionosonde with the IRI-2001, just the GPS reconstruction with the IRI-2001. Figure 3 shows the comparison of the monthly averaged diurnal NmF2 difference (DNmF2) from the GPS reconstruction with respect to the IRI-2001 model at the grid point (37.5°N, 127.0°E) in winter, spring, summer and autumn, 2003, where the standard URSI foF2 peak model for the IRI-2001 was used to estimate NmF2. The GPS-derived NmF2 is larger than the estimation of the IRI-2001 model in nighttime for all seasons (00:00–07:00 LT and 21:00–24:00 LT), but much smaller in daytime for all seasons from 08:00 to 20:00 LT, indicating that the IRI-2001 model underestimates NmF2 values in nighttime for all seasons and significantly overestimates NmF2 values in daytime for all seasons.

For a good ionospheric model, its electron density profiles $N(\varphi, \lambda, t)$ should give a good F2-layer peak electron density $NmF2(\varphi, \lambda, t)$. To assess the IRI-2001 model with the GPS reconstruction, a simple deviation percentage can be defined as following:

$$D\mathrm{NmF2}(\varphi, \lambda, t)(\%) = \{[\mathrm{NmF2}_{\mathrm{GPS}}(\varphi, \lambda, t) - \mathrm{NmF2}_{\mathrm{IRI}}(\varphi, \lambda, t)]/\mathrm{NmF2}_{\mathrm{IRI}}(\varphi, \lambda, t)\} \times 100\% \quad (7)$$

where $\mathrm{NmF2}_{\mathrm{GPS}}(\varphi, \lambda, t)$ and $\mathrm{NmF2}_{\mathrm{IRI}}(\varphi, \lambda, t)$ are the electron density peak values of GPS reconstruction and IRI-2001 estimation, respectively, and $D\mathrm{NmF2}(\varphi, \lambda, t)(\%)$ is the deviation percentage value of the GPS reconstructed

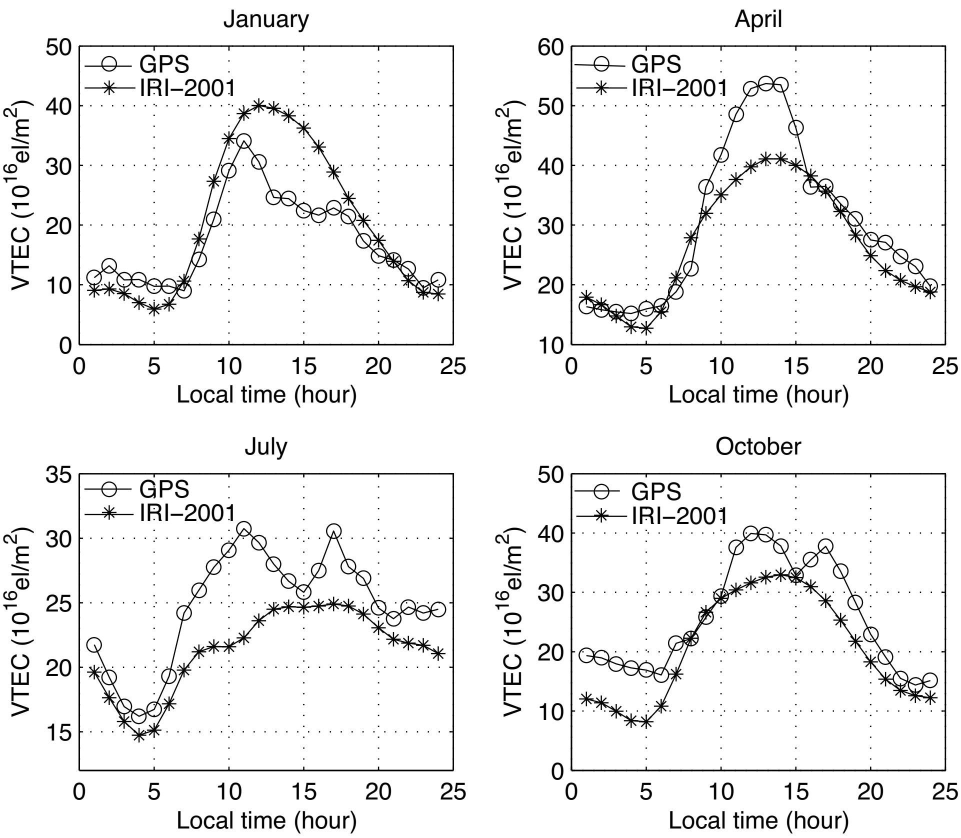

Fig. 5. Comparison of TEC at grid point (37.5°N, 127.0°E) between the GPS reconstruction and IRI-2001.

$\mathrm{NmF2_{GPS}}(\varphi, \lambda, t)$ with respect to the IRI-2001 estimated $\mathrm{NmF2_{IRI}}(\varphi, \lambda, t)$. Thus, the monthly averaged diurnal percentage variations of the monthly median $\overline{D\mathrm{NmF2}(t)(\%)}$ can be obtained. Figure 4 shows a comparison of the monthly averaged density peak deviation percentage as calculated from GPS reconstruction with respect to the IRI-2001 at the grind point (37.5°N, 127.0°E) in winter, spring, summer and autumn, 2003. It can be seen that the IRI-2001 model underestimates the NmF2 values by ~30% in nighttime for all seasons and significantly overestimates NmF2 values in daytime for all seasons, especially in the autumn and winter.

The $\mathrm{TEC}(\lambda, \varphi, h)$, relating with latitude φ, longitude λ and height h, is the integrated electron density along a path through the ionosphere, namely

$$\mathrm{TEC} = \int_{R_{\mathrm{receiver}}}^{R_{\mathrm{satellite}}} N_e(\lambda, \varphi, h) ds \tag{8}$$

where $N_e(\lambda, \varphi, h)$, ionospheric electron density, was obtained from the GPS tomography reconstruction in small cells (i, j, k) of $0.5° \times 1.0° \times 25$ km pixels. Therefore, the vertical $\mathrm{TEC}(\lambda, \varphi, h)$ can be written as follows

$$\mathrm{VTEC}(\lambda, \varphi, h) = \sum_i \sum_j \sum_k (N_e)_{i,j,k} h_{i,j,k} \tag{9}$$

Thus, the vertical TEC can be obtained from the GPS reconstructed 3-D electron density at any specific grid point. Although the IRI model can calculate the TEC by actually updating F2 peak parameters with measured peak values, we focus here on evaluating the average behaviors of the IRI-2001 model with empirical standard models' parameters. We therefore do not use the measured peak values (e.g. ionosonde) and just used empirical standard models' peak values for IRI TEC calculation. Figure 5 is the comparison of TEC at grid point (37.5°N, 127.0°E) estimated from GPS and IRI-2001 in different seasons. Both show the diurnal behavior of the monthly TEC median of the ionosphere averaged over 1 month. Independently of the season, the maximum TEC values are arrived at about the noon, between 11:00 and 15:00 LT. The IRI-2001 gives a smoother TEC than the GPS reconstruction. However, averaged monthly TEC medians from the IRI-2001 model are overestimated in daytime in winter, but underestimated at other times for all seasons. In addition, the maximum GPS-derived TEC values are found during equinoxes (spring equinox especially). Furthermore, the daytime TEC values in winter (January) are slightly greater (about 5–16%) than those in summer (July) from around 10:00 to 12:00 LT, namely the so-called winter anomaly. However, the nighttime behavior shows that TEC values are higher in summer than in winter, which indicates that this phenomenon vanishes at night near the maximum of the solar cycle in 2003.

Similar with the NmF2 deviation percentage as Eq. (4), the monthly averaged diurnal variation percentages of the GPS reconstruction TEC with respect to the IRI-2001 model are obtained (Fig. 6). It has been seen that the IRI-2001 significantly overestimates the TEC in daytime in winter and almost underestimates the TEC in other time by about 30%.

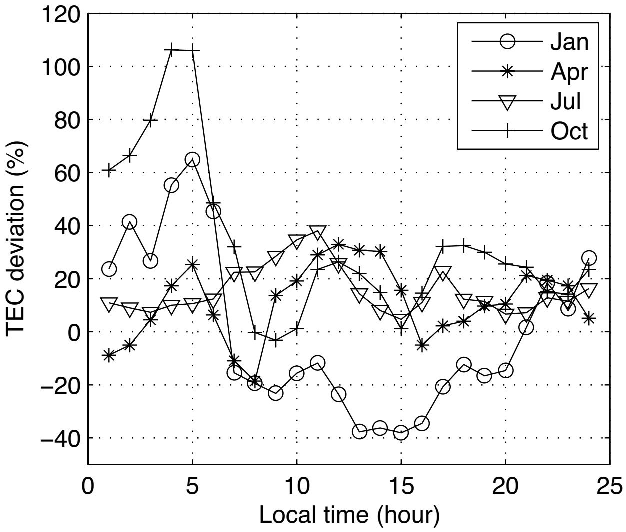

Fig. 6. Monthly averaged diurnal TEC variation percentage of GPS reconstruction with respect to the IRI-2001 model.

5. Conclusion

The IRI-2001 is one of the most comprehensive empirical models of the ionosphere and has been widely used to estimate the electron density profiles and TEC at any given location, time and date. However, whether it provides normal actual monthly averages in the ionosphere over some regions should be tested with real regional observation data. In this paper, the 3-D ionospheric electron density profiles over South Korea are obtained using the ionospheric tomography reconstruction technique with the permanent Korean GPS Network (KGN) data. Compared with the profiles obtained from independent ionosondes at or near the GPS receiver stations, the GPS reconstruction electron density profiles are in better agreement, showing the validity of the GPS ionospheric tomographic reconstruction. These results are further used to evaluate empirical ionospheric models in terms of the main ionopsheric parameters, the electron density F2 peak value NmF2 and the TEC. The GPS-derived monthly averaged diurnal values of these key parameters in January, April, July and October 2003 are considered to represent winter, spring, summer and autumn seasons, respectively. Comparison of the IRI-2001 and GPS reconstruction in different seasons shows that averaged monthly NmF2 medians from the IRI-2001 model are overestimated in daytime and underestimated in nighttime for all seasons, but the deviation magnitudes are smaller in autumn and winter than in spring and summer. In addition, averaged monthly TEC medians from the IRI-2001 model are overestimated in daytime in winter, but almost underestimated in other time. Therefore, the empirical ionospheric model, IRI-2001, cannot accurately predict the regional variation of the ionosphere over South Korea, and it is necessary to use local real observation data to estimate the ionospheric parameters.

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