Ionospheric peak parameter foF2 and its variation trend observed by GPS

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Abstract

Knowledge of the ionospheric peak parameter foF2 (the critical frequency of F2 layer) is one of key essential factors for predicting ionospheric characteristics and delay correction of satellite positioning. However, the foF2 was almost estimated using an empirical model of International Reference Ionosphere (IRI) or other expensive observing techniques, such as ionosondes and scatter radar. In this paper, the ionospheric peak parameter foF2 is the first observed by ground-based GPS with all weather, low-cost and near real time properties. Compared with the IRI-2001 and independent ionosondes at or near the GPS receiver stations, the foF2 obtained from ground-based GPS is in better agreement, but closer to the ionosonde. However, during nighttime, the IRI model overestimated the GPS observed values during winter and equinox months. Furthermore, seasonal variation trend of the foF2 in 2003 is studied using foF2 monthly median hourly data measured over South Korea. It has shown that the systematic diurnal changes of foF2 are apparent in each season and the higher values of foF2 are observed during the equinoxes (semiannual anomaly) as well as in mid-daytime of each season.

Keywords: ionosphere; GPS; foF2; IRI.

1. Introduction

The ionospheric peak parameter foF2 (the critical frequency of F2 layer) is one of essential parameters for predicting ionospheric characteristics for radio wave propagation, position fixing in various applications such as satellite tracking, navigation, etc. Meanwhile, the critical frequency foF2 is of great influence on the shape of ionospheric electron density profile Ne (h), and is also probably related to the various physical processes of ionospheric activities. Therefore, the ionospheric peak parameter foF2 is very helpful in understanding the nature of variations of upper atmosphere. One of the most widely used empirical model of monthly mean ionosphere, is the International Reference Ionosphere (IRI) (Bilitza, 1990), which describes the median values of electron density, electron temperature, and the ion composition as a function of height, for a given location, time, and sunspot number. The IRI model is being refined and updated following the annual IRI workshops and it has led to improvements through several versions, (IRI-86, IRI-90, IRI-95, IRI-2000). In the IRI model the description of foF2 is based on detailed analysis of ionosonde data for several stations by Jones and Gallet (1962/1965) and later by Rush et al. (1983, 1984) helped in generating global maps of foF2 as a function of sunspot number and other geophysical parameters.

In addition, a feature of the ionosphere is its ability to reflect radio waves. However, only radio waves within a certain frequency range will be reflected and this range varies with a number of factors. Therefore, the most widely used instrument for ionospheric measurement is the ionosonde. The ionosonde is essentially high frequency radar that sends short pulses of radio energy into the ionosphere. If the radio frequency is not too high, the pulses are reflected back to the earth. The ionosonde records the time delay between transmission and reception of the pulses. By varying the frequency of the pulses (typically 1-22MHz), a record is obtained of the time delay at different frequencies. This record is referred to as an ionogram. The highest frequency that the ionosphere will reflect vertically is called foF2 (Aggarwal, 1985). But the ionosonde instrument is expensive and also sparse in the global. Nowadays, the 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 (30s) technique. Therefore, 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). In this paper, the GPS is the first used to investigate the ionospheric peak foF2 and its seasonal variations over South Korea.

2. The foF2 parameter from GPS observations

2.1 GPS data

The Korean GPS Network (KGN) with about 70 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), etc. (Jin and Park, 2006a).These dense GPS data can produce daily position time series, Precipitable Water Vapor (PWV), Total Electron Content (TEC), which offer opportunities to research crustal deformation, climate and space environments on the South Korean Peninsula. Here we used ground-based GPS observations of the KGN network to obtain 3-D ionospheric structure information over South Korea and further inverse important ionospheric parameters, such as foF2.

2.1 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-hr period. The satellite transmits two frequencies of signals ($f1$=1575.42 MHz and $f2$=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:

$$L_{1,j}^i = \lambda_1 \phi_{1,j}^i = \rho_{0,j}^i - d_{ion,1,j}^i + d_{trop,j}^i + c(\tau^i - \tau_j) - \lambda_1 (b_{1,j}^i + N_{1,j}^i)$$
$$L_{2,j}^i = \lambda_2 \phi_{2,j}^i = \rho_{0,j}^i - d_{ion,2,j}^i + d_{trop,j}^i + c(\tau^i - \tau_j) - \lambda_2 (b_{2,j}^i + N_{2,j}^i)$$
$$P_{1,j}^i = \rho_{0,j}^i + d_{ion1,j}^i + d_{trop,j}^i + c(\tau^i - \tau_j) + d_{q,1}^i + d_{q,1,j} + \varepsilon_j^i$$
$$P_{2,j}^i = \rho_{0,j}^i + d_{ion2,j}^i + d_{trop,j}^i + c(\tau^i - \tau_j) + d_{q,2}^i + d_{q,2,j} + \varepsilon_j^i$$

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}, d_{trop}, the ionospheric and tropospheric delays;

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; and

ε, other residuals.

As the ionosphere is dispersive medium for the GPS signals, the ionospheric delay can be written as:

$$d_{ion} = \int_{Receiver}^{Satellite} (n_g - 1) dl = \frac{40.3}{f^2} \int_{Receiver}^{Satellite} N dl = \frac{40.3}{f^2} TEC$$

Combining above formulas, it can generate as followings:

$$L_4 = L_{1j}^i - L_{2j}^i = -40.3\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) TEC + B_4$$
$$P_4 = P_{1j}^i - P_{2j}^i = 40.3\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) TEC + b_4 \quad (1)$$

Where B_4 is ($-\lambda_1(b_{1j}^i + N_{1j}^i) + \lambda_2(b_{2j}^i + N_{2j}^i)$), and b_4 is $(dq_{1j} - dq_{2j}) + (dq_1^i - dq_2^i)$. The Differential Code Biases (b_4) can be estimated as constant values for each day from GPS observation, and B_4 can be obtained through the formula, $\sum_{i=1}^{N} (p_4 + L_4 - b_4)/N$, where *N* is the epoch of GPS observation. Thus, the slant TEC can be obtained. The TEC is defined as the line integral of the electron density as expressed by

$$STEC = \int_{R_{receiver}}^{R_{satellite}} N_e(\lambda, \varphi, h) ds \quad (2)$$

where $N_e(\lambda, \varphi, h)$ is the ionospheric electron density, λ, φ and h are the longitude, latitude and height, respectively. The 3D ionospheric electron density profiles are obtained through a tomography reconstruction algorithm, multiplicative algebraic reconstruction technique (MART) (Raymund et al. 1990). The tomography reconstruction algorithm can integrate the data 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 in 1° increments, latitude 33-39 in 0.5° increments, altitude 100–1000 km in 25 km increments and 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:

$$Y = Ax + \varepsilon \quad (3)$$

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 location can be inferred. The solution is constrained using a priori information from the IRI-2001 or ionosonde. Here the priori information is taken ionosonde measurements in Anyang station (37.39°N, 126.95°E) in South Korea. For more details about the reconstruction algorithm the reader is referred to (Gordon et al., 1970; Raymund et al., 1990; Jin et al. 2006b)

2.3 Results and Comparison

The critical frequency foF2 is the maximal ordinary mode frequency reflected from the ionosphere during vertical sounding and is proportional to the square root of the peak electron concentration in the main maximum of the ionosphere (Davies, 1990):

$$NmF2 = (foF2)^2/80.3 \quad (4)$$

Ionospheric electron density profiles over South Korea are obtained by GPS tomography reconstruction technique and then the ionospheric peak frequency foF2 can be further derived from the relation of foF2 and NmF2. In order to confirm the validity of the GPS tomographically reconstructed critical frequency foF2 from ground-based GPS observations, the GPS-derived foF2 is compared with independent ionosonde and IRI-2001 model. The available ionosonde Anyang station (37.39°N, 126.95°E) in South Korea provides an independent comparison with the tomographically reconstructed results from ground-based GPS observations. Figure 1 shows a comparison of the GPS reconstructed foF2 on 1 October 2003, with the available valid ionosonde data recorded at nearby Anyang station and with density profiles from IRI-2001 model. It has shown that tomographically reconstructed foF2 has a good agreement with ionosonde data from Anyang and IRI-2001 model, but is closer to the ionosonde results, especially in night time, namely GPS observed foF2 is highly consistent with the ionosonde observation. It has shown the validity of GPS ionospheric tomographically reconstructed foF2.

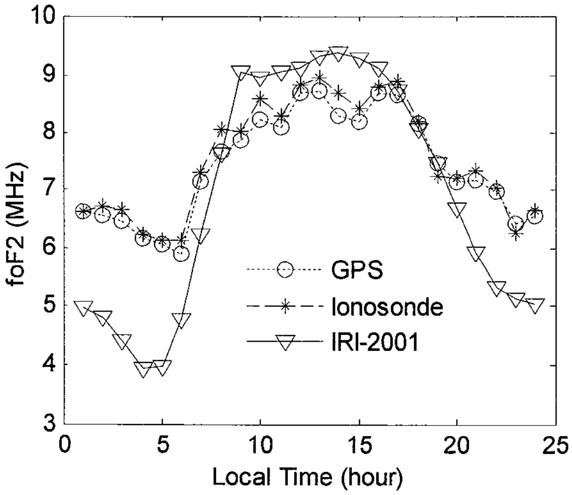

Figure 1 Comparison of the electron density F2 peak foF2 value derived from the ground-based GPS tomography reconstruction (circle), ionosonde observation at Anyang stations (37.39N, 126.95E) (star) and IRI-2001 estimation (triangle) on Oct.1, 2003.

3. Variation trend of the foF2

The daily foF2 time series in 2003 are obtained as a function of local time at intervals of 1h for each month separately. Monthly averages of the monthly median for January, April, July and October have been considered to represent winter, spring, summer and autumn seasons, respectively.

Figure 2 presents the diurnal variation of foF2 from GPS tomography reconstruction at different seasons. It can see that the greater foF2 are observed during the equinoxes (the so-called semiannual anomaly). The daytime foF2 is higher in winter than in summer from 09 to 17 LT (about 50% at 11 LT), where the night foF2 is opposite. This result maybe indicates the existence of the winter anomaly in foF2 over Anyang station during daytime in a high solar activity period in 2003. It is well known that in F region the loss rate of electron density depends mainly on the molecular nitrogen concentration [N2] with some contribution from molecular oxygen concentration [O2], while the production rate depends on the atomic oxygen concentration [O]. The composition changes are able to sufficiently explain the equinox anomaly effect of the electron density during daytime. These composition changes can be a result of the asymmetric heating of the two hemispheres, leading to neutral parameters being transported from the summer to the winter hemisphere. It was suggested that the winter anomaly is due to an increase in the [O]/[N2] ratio caused by the convection of atomic oxygen from the summer to the winter hemisphere (Torr and Torr, 1973). This is supported by the fact that the [O]/[N2] ratio is 2.3 times larger in winter than in summer (Cox and Evans, 1970). In addition, Torr and Torr (1973) also suggested that the semiannual anomaly is due to the semiannual variations in neutral densities associated with geomagnetic and auroral activity. Millward et al. (1996) using the coupled thermosphere – ionosphere–plasmasphere model (CTIP) showed that the offset of the geomagnetic axis from Earth's spin axis is the cause of the semiannual anomaly of noontime NmF2 in the South American sector.

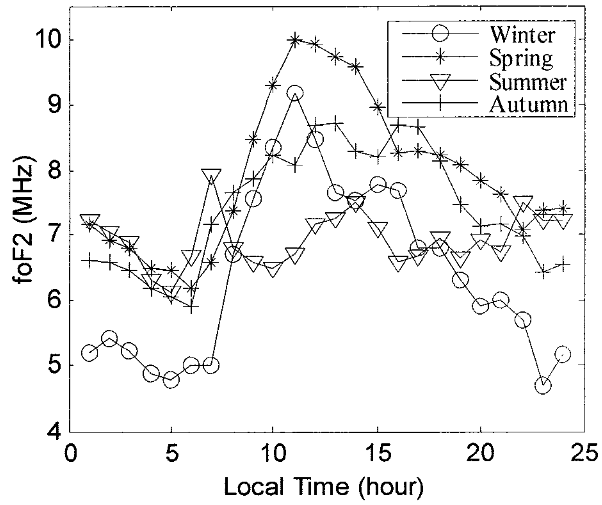

Figure 2 Monthly averaged diurnal variations of the monthly median of the ionospheric peak foF2 in Winter, Spring, Summer and Autumn.

Although the empirical models, such as IRI-2001, are very useful to give guidelines for monthly averages of global ionospheric behavior and show diurnal variations well, but they may not provide a good regional ionospheric behavior or cannot reproduced 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 ionospheric peak frequency foF2 over a region (South Korea) in a short period of time with a good agreement with the independent ionosonde. Furthermore, the empirical model IRI-2001 maybe underestimates or overestimates the real foF2 values. Therefore, we further compare with the mean foF2 behaviors between the GPS and IRI-2001 model in different seasons. Figure 3 shows the foF2 differences of monthly averaged median of GPS reconstruction with the IRI-2001 model at the grid point (37.5°N, 127.0°E) in winter, spring, summer and autumn, 2003. It can be seen that the GPS-derived foF2 is larger than the estimation of the IRI-2001 model in nighttime for all seasons (00–07 LT and 21-24 LT), but smaller in daytime for all seasons from 08 to 20 LT, indicating that the IRI-2001 model underestimates foF2 values in nighttime of all seasons, and significantly overestimates foF2 values in daytime of all seasons.

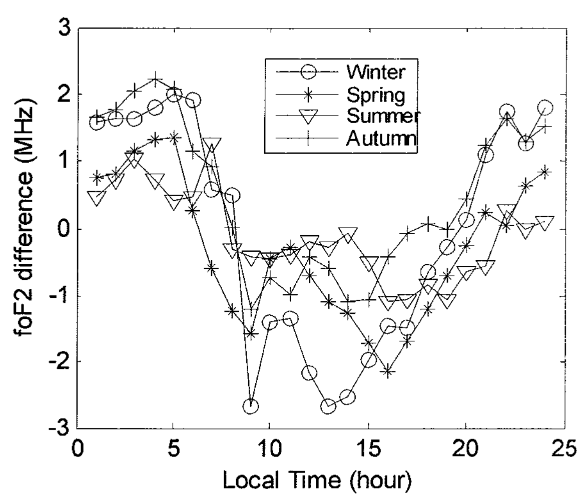

Figure 3 The foF2 differences of Monthly averaged median of GPS reconstruction with the IRI-2001 model.

4. Conclusion

The ionospheric peak parameter foF2 (the critical frequency of F2 layer) is the maximal ordinary mode frequency reflected from the ionosphere during vertical sounding and is proportional to the square root of the peak electron concentration in the main maximum of the ionosphere. Therefore, the ionospheric peak parameter foF2 is of great influence on the shape of ionospheric electron density profile Ne (h), and is also probably related to the various physical processes of ionospheric activities. And thus, it is important to observe the foF2 as one of essential parameters for predicting ionospheric characteristics for radio wave propagation and positioning delay corrections, such as GPS positioning and navigation. In this paper, the ionospheric peak parameter foF2 over South Korea is the first observed by ground-based GPS technique with all weather, low-cost and near real time properties. Compared with the IRI-2001 and independent ionosondes at or near the GPS receiver stations, the foF2 obtained from ground-based GPS observation data is in better agreement, but closer to the ionosonde. Furthermore, the daily foF2 time series are extracted from ground-based GPS measurements in January, April, July and October in 2003 and the monthly averaged diurnal values of the monthly median of January, April, July and October have been considered to represent the winter, spring, summer and autumn seasons, respectively. The result shows that the systematic diurnal changes of foF2 are apparent in each season and the higher values of foF2 are observed during the equinoxes (semiannual anomaly) as well as in mid-daytime.

In addition, as compared to the IRI-2001 model, the GPS-derived foF2 is larger than the estimation of the IRI-2001 model in nighttime for all seasons (00–07 LT and 21-24 LT), but smaller in daytime for all seasons from 08 to 20 LT, indicating that the IRI-2001 model underestimates foF2 values in nighttime of all seasons, and significantly overestimates foF2 values in daytime of all seasons.

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