Monitoring Seasonal Variations of Ionospheric TEC Using GPS Measurements

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Abstract The regional ionospheric model is adopted to determine satellite-plus-receiver differential delay. The satellite-plus-receiver differential delay is estimated as constant values for each day. Dual-frequency GPS pseudo-ranges observables are used to compute vertical TEC (VTEC). All the monthly mean VTEC profiles are represented by graphs using GPS data of the Beijing IGS site between 2000 and 2004. The monthly averaged values and amplitudes of VTEC are also represented by graphs. The results indicate that the VTEC has seasonal dependency. The monthly averaged values and amplitudes of VTEC in 2000 are about 2 times larger than that in 2004. The maximum VTEC values are observed in March and April, while the minimum VTEC values are observed in December. The seasonal variations trend is found to be similar after polynomial fitting between 2000 and 2004.

Keywords GPS; differential delay; ionosphere; TEC

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Introduction

In the absence of selective availability, which was turned off on May 1, 2000, the ionosphere can be the largest source of error in GPS positioning and navigation. It can be larger than 100 m during maximum solar activity and for satellites close to the horizon[1]. Therefore, the ionospheric error must be corrected carefully. The magnitude of this error depends on total electron content (TEC). Studying TEC variation is thereby very important for establishing an accurate ionospheric model. Ionospheric TEC is not only an important data for studying ionospheric morphology, but it is also an important parameter in precise positioning, navigation and electric wave field[2]. The variation of the ionospheric TEC is caused by many factors. First, TEC is the function of local time and it will vary diurnally because electronic density is related to the solar radiant energy absorbed by the atmosphere and the solar radiant energy is relevant to local time. Second, solar radiant energy is related to solar active intensity. Solar radiant energy intensifies and the ionization degree rises during maximum solar activity and the ionization degree drops during the minimum solar activity. Therefore, TEC will vary periodically at the circle of 11 a similarly solar activity. In addition, the solar radiant energy absorbed by the Earth obviously depends on the relative position between the Earth and sun thereby making TEC vary by

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season with the Earth’s revolution around the sun\textsuperscript{[3]}. Using GPS dual-frequency data is an effective way to study TEC variations due to ionospheric dispersive effect. In recent years, many works have been done to compute TEC by using GPS data. Global ionosphere maps (GIM) are generated on a daily basis at CODE using data from about 200 GPS/GLONASS sites of the IGS and other institutions. The vertical total electron content is modeled in a solar-geomagnetic reference frame using a spherical harmonics expansion up to degree and order 15. Differential delays for all GPS satellites and ground stations are estimated as constant values for each day. Goldovsky investigated the temporal variations of ionospheric TEC. These variations included high frequency (the so-called “scintillations”), medium frequency (diurnal and seasonal effects), and low frequency (the 11-year solar cycle). But differential delay was not considered\textsuperscript{[4]}. Warnant computed differential delay by modeling the ionosphere as a polynomial in latitude and local time and obtained the absolute TEC, and then studied the seasonal variations of ionospheric TEC at Brussels\textsuperscript{[5]}. Chinese scholars have also done many research works, Xiao zuo, Zhang donghe, et al. studied the diurnal variations of ionospheric TEC\textsuperscript{[2,6]}. In this paper, differential delay is determined by modeling vertical TEC as a function of the geomagnetic latitude and the solar hour angle, and then absolute TEC is obtained. The seasonal variations are investigated in Beijing by using GPS measurements from IGS site.

1 Method of getting absolute TEC

The codes transmitted by GPS satellites at the two L-band frequencies are carefully synchronized so that they are broadcasted simultaneously. Absolute simultaneity is not possible. So the time difference between the transmitted times at the two frequencies is called the satellite differential delay. Each GPS satellite has a unique satellite differential delay. Differential frequency delays may also exist in GPS receivers. These are called receiver differential delay. Each GPS receiver has its individual receiver differential delay. Because satellite and receiver differential delay are difficult to separate, they are often called satellite-plus-receiver (SPR) differential delay\textsuperscript{[8]}. Both the satellite and receiver differential delays introduce error in the measurement of TEC. Ignoring the satellite and receiver differential delay when computing line-of-sight TEC measurements from GPS observables may result in an error of ±3 ns and ±10 ns respectively\textsuperscript{[9]}. Therefore, SPR differential delay must be considered before getting absolute TEC.

SPR differential delay is not constant, so it is difficult to determine accurately. They are commonly regarded as an unknown parameter, and are adjusted with the coefficient of ionospheric model. SPR differential delay can be expressed by the following equation\textsuperscript{[3,7]}.\footnote{The equation is shown as:}

\begin{equation}
\sum_{i=0}^{n} \sum_{k=0}^{m} E_{ik} (\varphi - \varphi_0) (S - S_0)^k + 9.524 37B \cos z = 9.524 37(P_2 - P_1) \cos z
\end{equation}

where $\varphi_0$ is geomagnetic latitude of central point in surveying area; $S_0$ is solar hour angle of central point $(\varphi_0, \lambda_0)$ at the central time $(t_0) \quad \text{and} \quad S - S_0 = (\lambda - \lambda_0) + (t_1 - t_0)$, $\lambda$ is geomagnetic longitude of puncture point, $t_1$ is observing time; $E$ is coefficient of model; $P_1$ and $P_2$ are pseudo-ranges observables; $B$ is the parameter of SPR differential delay, and its unit is meter; $z$ is zenith angle.

After getting SPR differential delay, absolute TEC can be expressed by Eq.(2):

\begin{equation}
\text{TEC} = 9.524 37(P_2 - P_1 - B)
\end{equation}

TEC is measured in TEC units(TECU), where $1 \text{TECU} = 10^{16} \text{electrons/m}^2$. For the purpose of a convenient discussion, we often use vertical TEC (VTEC) instead of TEC.

\begin{equation}
\text{VTEC} = 9.524 37(P_2 - P_1 - B) \cos z
\end{equation}

VTEC diurnal variations before and after considering SPR differential delay are presented in Fig.1 and Fig.2, using GPS measurement data from BJFS.

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**Fig.1** Diurnal variation of ionospheric VTEC neglecting differential delay
2 Seasonal variations of ionospheric TEC

The cycle of solar activity is 11 a. It is peak year in 2000 and stable year in 2004 for solar activity. In order to make the seasonal variations of ionospheric TEC clear in peak year and stable year of solar activity, monthly TEC is computed between 2000 and 2004 respectively by using GPS observations from BJFS site. TEC monthly value is represented by the TEC value of diurnal variations of the fifteenth day of that month.

The seasonal variations of ionospheric TEC in Beijing between 2000 and 2004 are presented in Fig.3 and Fig.4. From these figures, it can be seen that TEC curves are very relevant in the same season. The TEC value in 2000 is higher than that in 2004. Due to the peak year of solar activity in 2000, we can see that the magnitude of TEC greatly depends on solar activity. In order to clearly analyze the trend of seasonal variations of TEC, the average value and maximum value of TEC monthly were computed in the paper.

Fig.5 and Fig.6 depict the average value and maximum value of ionospheric monthly TEC respectively.

1) The average and maximum value in 2000 is twice larger than that in 2004. It indicates that the magnitude of ionospheric TEC depends on solar activity cycle.

2) The average value of monthly TEC varies greatly in 2000. It has increased by twice from 15 TECU in December to 45 TECU in April. However, the average value of monthly TEC remained steady in 2004, and the largest increase is 10 TECU.

3) The maximum TEC value is found in March and April between 2000 and 2004, and the maximum is 68 TECU and 25 TECU respectively.

4) The seasonal variations of ionospheric TEC are obvious. The trend of variations is similar for both the peak year and the stable year of solar activity.

3 Conclusions

The method of using GPS dual-frequency data to measure TEC is feasible. SPR differential delay must be considered before getting absolute TEC due to its great impact. We can regard the SPR differential delay as an unknown parameter that can be solved with the coefficient of ionospheric model. In this paper, ionospheric TEC in Beijing were computed between 2000 and 2004. The results show that ionospheric
TEC is greatly relevant to solar activity. The trend of seasonal variations of TEC is obvious and similar between 2000 and 2004, and TEC reaches maximum in March or April, minimum in December. Apart from BJFS site, TEC variations of other sites will be expected to investigate later.

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