The diurnal variations, semiannual and winter anomalies of the ionospheric TEC based on GPS data in China*

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Abstract With the spherical harmonic (SH) function model and the dual frequency GPS P code phase data from the Crustal Movement Observation Network of China (CMONOC) during the period from year 2000 to 2002, time series of total electron content (TEC) in the area of China is calculated. The diurnal variations, semiannual, and winter anomalies of the ionosphere in the area of China are analyzed and discussed, especially according to the results of year 2001.

Keywords: **Global Positioning System, spherical harmonic function model, total electron content, semiannual anomaly, winter anomaly.**

It is generally accepted that there is a close correlation between the ionospheric activities and the human activity of production. With the rapid development of science and technology today, more and more attention is paid to the ionospheric research. Understanding of the characteristics of the ionospheric activities, such as diurnal, seasonal, semiannual and annual variations of the ionosphere, etc., is helpful not only for studying the fine structure of the ionosphere but also for the precise determination of total electron content (TEC) to serve the fields, which are affected by the ionosphere, such as geodetic survey, communication, space exploration and space navigation, etc. In the preceding work, the ionospheric activities were discussed by using the TEC data observed mainly by means of digital ionosondes, satellite beacons, and so on[1—8]. In the last decade and more, GPS (Global Positioning System) is widely utilized to monitor and investigate the activities of the ionosphere as a new tool due to its advantages such as high precision, real time, and high resolution. It has been proved that it is feasible to simulate local and regional area ionospheric activities with spherical harmonic (SH) function model[9—15]. The Crustal Movement Observation Network of China (CMONOC) has been established and is in operation. This network provides valuable data for the study of the ionospheric change in addition to its importance for the earthquake prediction in China[14—18]. In this paper, time series of total electron content (TEC) during the period from year 2000 to 2002 is calculated with SH function model and the dual frequency GPS P code phase data from CMONOC. Especially with results of some days in 2001 as examples, the diurnal variations of TEC are analyzed and discussed in detail and a method, which is utilized to calculate the vertical TEC above China, is developed in terms of qualitative analysis. On the basis of this method, the ionospheric semiannual and winter anomalies are analyzed and discussed with the time series of TEC in year 2001.

1 Outline of this research

1.1 Basic theory

The ionosphere is a layer of the atmosphere at the altitude from 60 km to 1000 km. Generally speaking, in the GPS TEC research, the ionosphere is assumed to be a thin spherical shell model located at a certain altitude (H). Taking into account the fact that the layer of the maximum electron density is usually located at altitude approximately between 300 km and 400 km above the earth's surface, the shell of a fixed altitude of 350 km is adopted in this paper, that is, $H = 350$ km. The vertical TEC is parameterized exclusively by SH expansions (see Eq. (1) below) which refer to a solar-geographical frame at the time.

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The reduction between slant and vertical TEC is conducted with a trigonometric single-layer model (SLM) mapping function[19]. The unknown ionospheric parameters are fitted with the least squares technique.

$$\mathrm{VTEC}(\varphi, \lambda) = \sum_{n=0}^{n_{\mathrm{dmax}}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\varphi) \cdot (\tilde{A}_{nm}\cos(m\lambda) + \tilde{B}_{nm}\sin(m\lambda)), \tag{1}$$

where φ is the latitude of the ionospheric pierce point (IPP), λ the longitude of the IPP, n_{dmax} the maximum degree of the SH expansion; $\tilde{P}_{nm}(\sin\varphi) = \mathrm{MC}(n, m) \cdot P_{nm}(\sin\varphi)$ is the normalized, associated Legendre function of degree n and order m; $\mathrm{MC}(n, m)$ is the normalization function[20],

$$\mathrm{MC}(n, m) = \sqrt{(n-m)!\,(2n+1)(2-\delta_{0m})/(n+m)!},$$

where δ_{0m} denotes the Kronecker delta, $P_{nm}(\sin\varphi)$ is the classical, unnormalized Legendre function, $\tilde{A}_{nm}$ and $\tilde{B}_{nm}$ are the unkown SH coefficients, i.e. the VTEC parameters to be determined[9—15].

1.2 Steps of data processing

In consideration of individual GPS data processing of the fiducial stations of CMONOC for different days, the spherical harmonic function with 16 parameters is adopted in this research, i.e. $m = n = 3$, (see Eq. (1)). Taking into account the satellite and station's instrumental biases (IBs), we process the GPS dual frequency P code phase data of the fiducial stations of CMONOC for year 2001 and calculate the vertical TEC over every fiducial station all the year round. On the basis of the results, we studied the variations in the ionosphere in China. This work is a two-step process:

(1) Individual processing of the GPS dual frequency P code phase data of the fiducial stations of CMONOC for many days in year 2001 and plotting of a time series of 12 2-hour ionospheric TEC snapshots over China and its adjacent area for each day. Based on qualitative analysis, it is proved to be possible that the TEC snapshots can reflect the variations of the ionosphere over China and its adjacent area. Consequently, the mean of the TEC of all fiducial stations at an epoch is assumed to be the TEC over China and its adjacent area at this epoch.

(2) Using the method described above and the GPS dual frequency P code phase data at the fiducial stations of CMONOC for year 2001, time series of TEC above the China region all the year round is calculated and the semiannual and winter anomalies are analyzed and discussed.

2 Data processing

2.1 GPS data

We selected the GPS P code phase data of the fiducial stations of CMONOC for year 2001 in this article. The sampling interval is 30 s, which is suggested and standardized by the IGS (International GPS Service). The elevation cut-off of 20 degrees is adopted. Figure 1 shows the map of fiducial stations[16—18].

It should be pointed out that the numbers of the fiducial stations were approximately 20 in each day because of missing and poor quality of the GPS data. Especially only the IGS stations in China are utilized for days: 223, 233, 306, 312, 316 and 365. The IGS stations in China are BJFS, KUMN, LASH, SHAO, URUM, and WUHN.

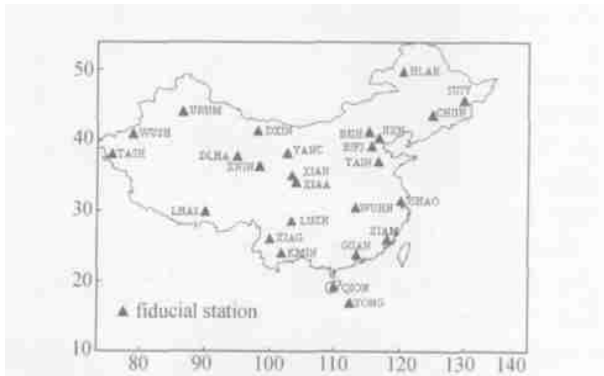

Fig. 1. The sketch map of CMONOC contribution.

2.2 The method of data processing

It is necessary to determine the quality of the data, and clean the outliers before determining the TEC parameters. The geometry-free (L4) combination is formed to eliminate the effects of the geometry, clocks, and the troposphere. Considering the satellite and station's instrumental biases (IBs) which are usually thought to be constant in a single day[10, 21], and according to the basic mathematic model in Section 1.1, the unknown ionospheric TEC parameters and IBs are fitted with the least squares technique. Then, the vertical TEC over every fiducial station for each epoch of each day is estimated. In data processing, the data of every fiducial station for each day were processed independently.

3 Results and analyses

3.1 Diurnal variations of the ionosphere

With the method described in Section 2.2, the GPS dual frequency P code phase data of the fiducial stations of CMONOC for many days in year 2001 were processed independently. At the same time, we estimated the vertical TEC over every fiducial station for these days, and sequentially we obtained time series of 12 2-hour TEC snapshots of China and its adjacent area for every day, taken at 1:00, 3:00, …, 21:00, and 23:00 UT. Because the purpose of this work is to study the long-term variations of the ionospheric TEC using the GPS P code phase data and the short-term variations of the ionosphere, such as ionospheric fluctuations etc., the solar-geographical reference frame is adopted to estimate the TEC parameters. As an example, only the research results on the diurnal variations of the ionospheric TEC for April 10 of year 2001 are given due to the space limitations. Other results will not be given owing to the similarity of all the results.

Because of missing and poor quality of the GPS data, the data of 23 stations were used from CMONOC on April 10, 2001. They are as follows: BJFS, BJSH, CHUN, DLHA, DXIN, GUAN, HLAR, KMIN, LHAS, LUZH, QION, SHAO, SUIY, TAIN, TASH, URUM, WUHN, WUSH, XIAA, XIAG, XIAM, XNIN, and YANG.

In Beijing Time 5:00—9:00 is in the morning, 9:00—17:00 is in daytime, 17:00—21:00 is at dusk, and 21:00—5:00 is at night. Due to the difference of eight hours between Universal Time and Beijing Time, Figure 2 shows the phenomenon that the ionospheric TEC over China and its adjacent area varies from small to large value, and then from large to small value along with the earth's rotation from west to east. It is consistent with the alternation between day and night in China and in agreement with the fact that TEC is susceptible to the solar activity. From Fig.2, it can also be seen that there is a

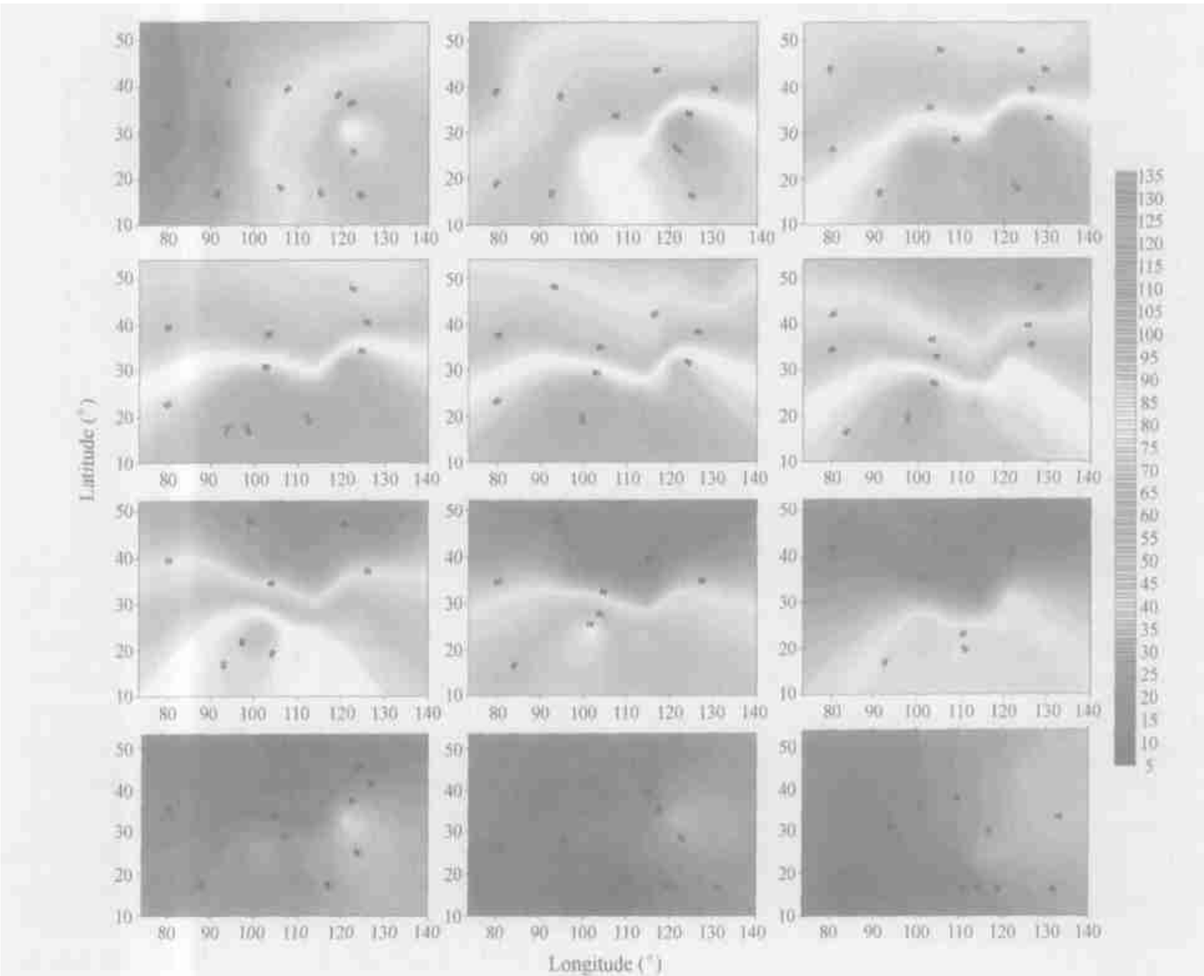

Fig. 2. Time series of the ionospheric TEC snapshots over China and its adjacent area for April 10, 2001. The 12 small figures from left to right denote the time series of 12 2-hour TEC snapshots taken at 1:00, 3:00, …, 21:00, and 23:00 UT, respectively, in units of TECU.

pronounced north-south TEC gradient and the value of the TEC in the northern part of China is generally smaller than that in the southern part. It reflects the fact that there exists a close relationship between the variations of ionospheric TEC and the latitude.

Based on the above discussions, the mean of vertical TEC of all stations at an epoch is assumed to be the vertical TEC above China at this epoch. Figure 3 shows the variation of the ionospheric TEC with time for April 10, 2001. This figure suggests that there is the maximum TEC at 6:00 a.m., Universal Time or 14:00 p.m., Beijing Time and the minimum TEC at 21:00 p.m., Universal Time or 5:00 a.m., Beijing Time.

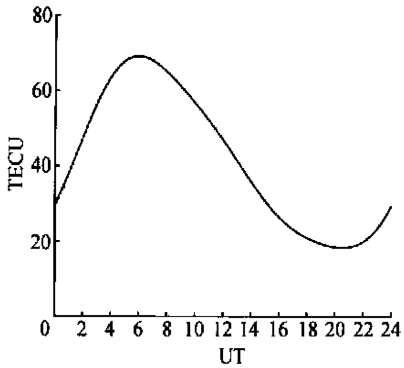

Fig. 3. The time variation of the mean of the ionospheric TEC over China region for April 10, 2001.

Now we can conclude that some characteristics of the variations of the ionosphere above the area of China may be reflected from the TEC obtained with the method described above.

3.2 Semiannual and winter anomaly

On the basis of the research in Section 3.1, we processed the GPS dual frequency P code phase data of all fiducial stations of CMONOC for year 2001 and obtained the mean vertical TEC estimated at each epoch of each day in China.

In China, March and April are in spring, September and October in fall, May, June, July, and August in summer, and January, February, November, and December in winter[6]. In Fig. 4: the abscissa denotes the Universal Time for every day, the ordinate denotes the month and the shades denote the value of TEC (see the right panel in Fig. 4). Figure 4 shows the seasonal behaviour of the ionospheric TEC in China. It is clear in Fig. 4 that there exists a semiannual variation of TEC, that is, the ionospheric TEC peak values appear in spring and fall, and the vale values in summer and winter. Figure 4 also shows that the daytime ionospheric TECs are higher in November and December in winter than in summer. This phenomenon is named the winter anomaly. It is also apparent in Fig. 4 from left to right that the winter anomaly is not the nighttime phenomenon but the daytime phenomenon[22].

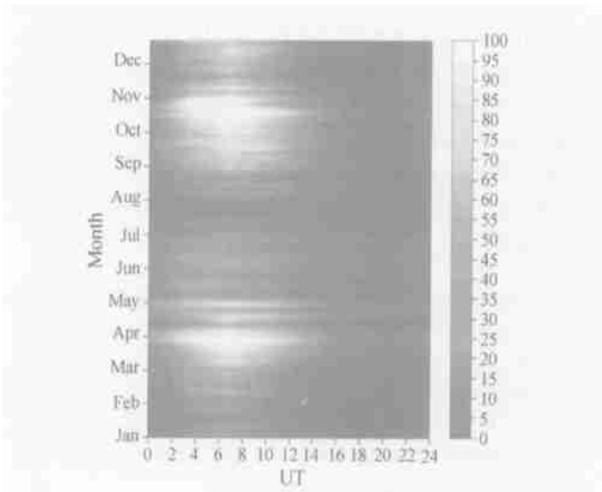

Fig. 4. The seasonal variations of the ionospheric TEC over China region in year 2001.

We also processed the GPS dual frequency P code phase data of CMONOC for years 2000 and 2002, and obtained similar results that were not shown here due to the limited length of the paper. They indicate that the results of this article are not obtained casually, and can effectively reflect the variations of the ionospheric TEC in China for the time period.

Although these phenomena have also been observed by other observation means, this research shows that GPS has its advantages such as high time-space resolution, and has the exclusive value and the bright future in monitoring and investigating the ionospheric activities.

4 Summary

This work attempts to study the variations of the ionospheric TEC above China by GPS. The preliminary results show that it is feasible to monitor and investigate the behaviors of the ionosphere, such as diurnal variation, semiannual and winter anomalies, by using the dual frequency GPS P code phase data of CMONOC and adopting reasonable calculation and analysis methods.

It should be noted that the results obtained in this paper are still preliminary reports about TEC behaviors during the peak period of this cycle of solar activity. Other behaviors during the periods of low solar activity will be reported elsewhere when more data are collected and analyzed.

Although this is only a preliminary research, we are fully convinced that the dual frequency GPS P code phase data of CMONOC will be more and more abundant in the future, and these abundant resources will give a new opportunity for the further study of the ionospheric activities with GPS data. The research findings will also provide references for related fields, in which high accuracy ionospheric corrections are involved, such as geodetic survey, etc.

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References

1 Torr M. R. and Torr D. G. The seasonal behaviour of the F2-layer of the ionosphere. J. Atmos. Terr. Phsy., 1973, 35(12): 2237—2251.

2 Rishbeth H. How the thermospheric circulation affects the ionospheric F2-layer, J. Atmos. Terr. Phys., 1998, 60: 1385—1042.

3 Zou L., Rishbeth H. and Müller-Wodarg I. C. F. Annual and semiannual variations in the ionospheric F2-layer: I. Modelling. Ann Geophysicae, 2000, 18(8): 927—944.

4 Rishbeth H., Müller-Wodarg I. C. F. and Zou L. Annual and semiannual variation in the ionospheric F2-layey: II. Physical discussion. Ann Geophysicae, 2000, 18(8): 945—956.

5 Ma R. P., Xu J. and Liao H. The characteristics and a possible mechanism of semiannual variation of f_0F_2. Chinese Journal of Geophysics (in Chinese), 2002, 45(6): 766—772.

6 Chen Y. H., Wang W. and Liu L. A statistical TEC model based on the observation at Wuhan ionospheric observatory. Chinese Journal of Space Science (in Chinese), 2002, 22(1): 27—35.

7 Suo Y. C. Seasonal variation of f_0F_2. Chinese Journal of Radio Science (in Chinese), 1995, 10(4): 83—89.

8 Suo Y. C., Li Y. and Wei M. There is seasonal abnormal phenomenon in nighttime f_0F_2. Chinese Journal of Space Science (in Chinese), 1989, 9(1): 64—69.

9 Feltens J. and Schaer S. IGS products for the ionosphere, IGS position paper. In: Proceedings of the 1998 IGS Analysis Centers Workshop. Darmstadt: European Space Operations Centre (ESOC), 1998, 225—232.

10 Schaer S., Beutler G. and Rothacher M. Mapping and predicting the ionosphere. In: Proceedings of the 1998 IGS Analysis Centers Workshop. Darmstadt: ESA/ESOC, 1998, 307—318.

11 Wilson B. D., Mannucci A. J. and Edwards C. D. Subdaily northern hemisphere ionospheric maps using an extensive network of GPS receivers. Radio Science, 1999, 30: 639—648.

12 Yuan Y. B. and OU J. K. Preliminary results and analyses of using IGS GPS data to determine global ionospheric TEC. In: Progress in Natural Science, 2003, 13(8): 446—450.

13 Wang X. Y. and Zhu W. Methods and progress on monitoring ionosphere activity by GPS. Progress in Astronomy (in Chinese), 2003, 21(1): 33—40.

14 Yuan Y. B. and OU J. K. Differential areas for differential stations (DADS): A new method of establishing grid ionospheric model. Chinese Science Bulletin, 2002, 47(12): 1033—1036.

15 Wang G. and Wei Z. A method and results of setting up grid ionospheric delay model. Chinese Bulletin of Surveying and Mapping (in Chinese), 2000, 44(9): 1—2.

16 Ma Z. J., Chen X. L. and Ye S. H. et al. Contemporary crustal movement of continental China obtained by global positioning system (GPS) measurements. Chinese Science Bulletin (in Chinese), 2001, 46(13): 1118—1120.

17 Chen J. Y. Introduction to the crustal movement observation network of China. Chinese Bulletin of Surveying and Mapping (in Chinese), 1997, 43(2): 8—15.

18 Gu G. H., Zhang J. and Wang W. Progress in predicting earthquake using GPS space geodesy technique. GNSS World of China (in Chinese), 2003, 1: 9—13.

19 Ou J. K. Atmosphere and its effects on GPS surveying. LGR-Series, TU Delft, 1996 (14): 19—29.

20 McCarthy D. D. IERS Conventions, IERS Technical Note 21, Central Bureau of IERS, Observation of Paris, France, July 1996.

21 Yuan Y. B. and OU J. K. The effects of Instrumental Bias in GPS observations on determining ionospheric delays and the methods of its calibration. Acta Geodaetica et Cartographica Sinica (in Chinese), 1999, 28(2): 110—114.

22 Xiong N. L., Tang C. and Li X. An Introduction to Ionospheric Physics (in Chinese). 1st ed., Wuhan: Wuhan University Press, 1999, 181—182.