Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 57 (2016) 2470–2478

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Spatial and temporal analysis of the total electron content over China during 2011–2014

Jianchang Zheng [a,b], Biqiang Zhao [a,b,*], Bo Xiong [a,b,c], Weixing Wan [a,b]

[a] Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[b] Beijing National Observatory of Space Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[c] School of Mathematics and Physics, North China Electric Power University, Baoding 071003, China

Received 6 November 2015; received in revised form 23 March 2016; accepted 25 March 2016
Available online 31 March 2016

Abstract

In the present work we investigate variations of ionospheric total electron content (TEC) with empirical orthogonal function (EOF) analysis, the four-year TEC data are derived from ~250 GPS observations of the crustal movement observation network of China (CMONOC) over East Asian area (30–55°N, 70–140°E) during the period from 2011, January to 2014, December. The first two EOF components together account for ~93.78% of total variance of the original TEC data set, and it is found that the first EOF component represents a spatial variability of semi-annual variation and the second EOF component exhibits pronounced east–west longitudinal difference with respect to zero valued geomagnetic declination line. In addition, climatology of the vertical plasma drift velocity v_{dz} induced by HWM zonal wind field (~300 km) are studied in the paper. Results shows v_{dz} displays significant east–west longitudinal difference at 10:00 LT and 20:00 LT, and its daytime temporal variation is consistent with the second EOF principal component, which suggests that the east–west longitudinal variability is partly caused by the thermospheric zonal wind and geomagnetic declination. It is expected that with this dense GPS network, local ionospheric variability can be described more accurately and a more realistic ionospheric model can be constructed and used for the satellite navigation and radio propagation.

Keywords: Ionospheric variability; Total electron content; Empirical orthogonal function (EOF)

1. Introduction

The ionosphere manifests its great variability with latitude, longitude, time, season, solar activity, and geomagnetic activity. This variability is produced by a variety of mechanisms that caused by different processes coming from directly the change of solar radiation and indirectly the coupling with the lower and upper atmosphere and magnetosphere. Variations in the electric field, neutral winds, and neutral composition, can affect remarkably the ionosphere at multiple temporal and spatial scales. To investigate the general morphology and variability of the ionosphere, total electron content (TEC) measurements have been used since the 1970 s based on the Faraday rotation technique at middle and low latitude (e.g., Kane, 1975; Titheridge, 1973; Huang, 1984). Since TEC is one of the most important parameters of the ionosphere which can be applied in satellite navigation, and also owe to the good temporal continuity and high accuracy, it has become a powerful tool in the study of the ionospheric space weather (Mendillo, 2006).

The International GNSS Service (IGS) provides the widely used GNSS-derived global ionospheric maps (GIMs) that are 3 dimensional distributions of vertical TEC (VTEC) with resolutions of $5° \times 2.5° \times 2$ h

* Corresponding author at: Beitucheng West Road No. 19, 100029 Beijing, China. Tel.: +86 010 82998310; fax: +86 010 62010846.
E-mail address: zbqjz@mail.iggcas.ac.cn (B. Zhao).

http://dx.doi.org/10.1016/j.asr.2016.03.037
0273-1177/

(longitude × latitude × universal time) and daily sets of Global Positioning System (GPS) satellite and receiver hardware differential code bias (DCB) values from five different centers called IGS Ionosphere Associate Analysis Centers (IAACs) (Feltens, 2003). IAACs produce with their models and software routinely TEC maps and DCB sets and provide their ionosphere products to IGS Ionosphere Associate Combination Center (IACC). The IACC compares these ionosphere products with a dedicated comparison algorithm to generate a combined IGS ionosphere product. Although GIMs product has been widely used in the ionospheric research, it is essentially a data assimilation product which contains some unreal information over the region which has sparse GPS receivers (Mannucci et al., 1998). In comparison, the Massachusetts Institute of Technology (MIT) Automated Processing of GPS (MAPGPS) system provides global TEC data with higher temporal and spatial resolution (1° × 1° × 5 min). The detailed description of origin data process and bias estimation are described in Rideout and Coster (2006). The high resolution in MAPGPS is due simply to the unprecedented dense population of GPS receivers, mainly for North America. This allows a more detailed analysis of the temporal and spatial variability of the ionosphere at this area (Zhang et al., 2011).

Recently, with the continuous development of GNSS ground network, there are more than 1500 GNSS stations in China. More and more GNSS-TEC data can be used in the ionospheric scientific researches and improvement of GNSS positioning. Routinely, 250 GNSS stations from the Crustal Movement Observation Network of China (CMONOC) can be obtained since the year 2011, which enable us to better investigate the regional ionospheric variability in details. In this paper, first we construct TEC maps derived from CMONOC, then ionospheric spatial and temporal variations and physical causative mechanism of different spatial patterns are investigated by using empirical orthogonal function (EOF) analysis. The quick convergence of the EOF expansion makes it very convenient to construct an empirical model for the original data set and decomposition of spatial and temporal variations. EOF analysis is extensively used into empirical ionospheric modeling and the investigation of ionospheric climatology (e.g., Zhao et al., 2005; Mao et al., 2008; Wan et al., 2012; Meza and Natali, 2008). A new kind of midlatitude longitudinal variation caused by magnetic declination (e.g., Horvath and Essex, 2003; Horvath, 2006; He et al., 2009; Zhang et al., 2011, 2012), has been revealed with this method based on high spatial–temporal resolution observations. Given the fact that the typical configuration of the geomagnetic field over East Asian area is analogous to that over the North American continent, but different in that the America Sector is characterized with a substantial offset between the geomagnetic and geophysical poles, it is of particular interest to investigate the detailed midlatitude structures and their variability. The contents of this paper are organized as follow: we describe the measurements database and mathematical formulation in Section 2, scientific discussions of the results are given in Section 3 and finally conclusions are summarized in Section 4.

2. Data and derivation of GNSS-TEC

The 30s GNSS data are from CMONOC network that consist of 250 GNSS stations covering Chinese mainland. Fig. 1 illustrates the locations of GNSS stations (black asterisks) and ionospheric pierce points (IPPs) at 400 km from GPS (blue dots) at 04:00 universal time (UT) on 1 January 2013. China is almost fully covered by the IPPs of GNSS at a certain instant. There are sparse GNSS stations in the South China Sea, northeast and west of China.

All GPS stations provide the measurements of the pseudorange and the carrier phase at two L-band frequencies. The pseudorange TEC (*STECa*) and phase TEC (*STECr*) along the path from a satellite to a receiver can be obtained by differencing the code and carrier phase measurements at the two frequencies (Mannucci et al., 1998). The pseudorange TEC is expressed as

$$STECa = \frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)}\left[(P_1 - P_2) - c(b^{s,1} - b^{s,2}) \right. \\ \left. - c(b_{r,1} - b_{r,2})\right], \tag{1}$$

Here f_1 and f_2 are the dual frequencies of GPS signals, P_1 and P_2 are the recorded pseudoranges, c is the speed of light, and $b^{s,1} - b^{s,2}$ and $b_{r,1} - b_{r,2}$ represent the interfrequency biases for the satellite and receiver, respectively. The phase TEC is as follows:

$$STECr = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}\left[\left(\frac{c\Phi_1}{f_1} - \frac{c\Phi_2}{f_2}\right) - \left(\lambda_1 N_{r,1}^s - \lambda_2 N_{r,2}^s\right)\right]. \tag{2}$$

where Φ_1 and Φ_2 are the carrier phases, λ_1 and λ_2 are the wavelengths, $\lambda_1 N_{r,1}^s - \lambda_2 N_{r,2}^s$ is the integer cycle ambiguity. The interfrequency biases and integer cycle ambiguity can be considered as constants for a period without cycle slip disrupting the continuity of observation. At a time i during the continuous measurements of N epochs, a more accurate slant TEC (*STECi*) can be obtained by smoothing the *STECr* based on the *STECa* (Hernández-Pajares et al., 2011, 2012; Xiong et al., 2014).

$$\begin{aligned} STEC_i &= STECr_i + \frac{1}{N}\sum_{i=1}^{N}(STECa_i - STECr_i) \\ &= \frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)}\left\{\left(\frac{c\Phi_{2,i}}{f_2} - \frac{c\Phi_{1,i}}{f_1}\right)\right. \\ &\quad + \frac{1}{N}\sum_{i=1}^{N}\left[(P_{1,i} - P_{2,i}) + \left(\frac{c\Phi_{1,i}}{f_1} - \frac{c\Phi_{2,i}}{f_2}\right)\right] \\ &\quad \left. - c(b^{s,1} - b^{s,2}) - c(b_{r,1} - b_{r,2})\right\} \end{aligned} \tag{3}$$