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Investigation of ionospheric TEC over China based on GNSS data

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Abstract

In this paper, the ionospheric total electron content (TEC) is derived from 250 Global Navigation Satellite Systems (GNSS) receivers over China. The GNSS TEC data are utilized to study the diurnal and day-to-day variability of ionosphere, ionospheric east–west differences and to construct regional ionospheric map. The GNSS–TEC curves clearly show sunrise and sunset enhancements in the diurnal variation. The peak value of TEC is lower in January 2015 than in May 2014. There is 2 h difference in the occurrence time of TEC maximum/minimum between May and January. Compared with the observations of Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS), the measurements from the Geostationary Earth Orbit (GEO) satellites of BeiDou Navigation Satellite System (BDS) clearly present the ionospheric day-to-day variability and east–west differences in a region with small longitude differences (3.52–11.31°). The east–west differences in TEC are more obvious in larger longitude differences at 11:30 local time on 23 January 2015. The maximum east–west difference in TEC is about 7 total electron content unit (TECU, 1 TECU = 10^{16} el m^{-2}) in longitude difference of 11.31°. Our analysis shows that the TEC for east–west small longitude differences may be associated with the east–west gradient of geomagnetic declination. Based on 250 GNSS stations, a regional TEC map constructed by Kriging method can well capture the main spatial structure of ionosphere in China. A comparison between TEC maps obtained by Kriging method and provided by Jet Propulsion Laboratory displays that there are large deviations in the North of China, which is mainly caused by the difference in the number of used GNSS stations. In addition, comprehensive investigation presents that GNSS has more advantages over GPS and GLONASS in the ionosphere research over China.

Keywords: Ionosphere; Total electron content; GNSS

1. Introduction

Ionosphere, the ionized portion of the upper atmosphere, is an important component of the near-earth space environment. It extends from 60 to 1000 km. The main source of plasma for the ionosphere is neutral molecules ionized by solar EUV and X-ray radiation (Rishbeth and Garriott, 1969). Ionosphere is an important region between low atmosphere and magnetosphere, the operation region of artificial satellites, and the medium of radio wave propagation. The disturbance of ionosphere can affect navigation systems, satellite tracking and high-frequency communications. As a result, the ionosphere physics has become an important topic of solar-terrestrial space environment research.

The total electron content (TEC), one of the most important parameters in studying the ionospheric properties,

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is widely used in satellite navigation, orbit determination and ionospheric scientific researches (Mao et al., 2008). Owing to the outstanding spatial coverage, good temporal continuity, and high accuracy, the TEC measured from dual-frequency Global Navigation Satellite Systems (GNSS) has become a powerful tool in the study of ionospheric disturbances (Hernández-Pajares et al., 2012; Xiong et al., 2014a). GNSS–TEC is used to explore the ionospheric variability with different time scales, ranging from hours to solar cycles (Rishbeth, 1998). Yue et al. (2007) investigated the spatial correlations of ionospheric day-to-day variability using the Global Positioning System (GPS) TEC and electron density observed by incoherent scatter radar. Relative larger correlations in TEC's day-to-day variation have been found between magnetic conjugate points. Based on GNSS measurements, some regional and global ionospheric maps (GIMs) have been produced (Juan, 1997; Ping et al., 2002; Wan et al., 2007, 2012; Aa et al., 2015). For instance, a regional TEC map was created by GPS observations from the State of Ohio continuously operating reference stations network (Wielgosz et al., 2003). The International GNSS Service (IGS) provides the widely used GNSS-derived GIMs that are 3 dimensional distributions of TEC with resolutions of $5° \times 2.5° \times 2$ h (longitude × latitude × universal time) (Mannucci et al., 1998). Furthermore, the TEC is also utilized to investigate the traveling ionospheric disturbances (Wang et al., 2007; Ding et al., 2011, 2012), ionospheric plasma bubble irregularity (Pi et al., 1997; Li et al., 2009), and ionospheric responses to geomagnetic disturbance, typhoon, earthquake, solar eclipse and solar flare (Liu et al., 2010; Zhao et al., 2008; Le et al., 2010; Zhang et al., 2011a; Wan et al., 2005; Xiong et al., 2011, 2014b, 2014c). In addition, some empirical TEC models have been developed and were used to an ionospheric time-delay correction for GNSS users. Klobuchar and NeQuick models have been used to eliminate ionospheric error for GPS, BeiDou Navigation Satellite System (BDS), and Galileo Satellite Navigation System (Galileo) (Nava et al., 2008).

Recently, with the continuous development of BDS, 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. The main purpose of this work is to study some ionospheric phenomena in China using the dense GNSS observations and better understand the related physical mechanisms of these phenomena. Meanwhile, we will also investigate the distinctions of GPS, Global Navigation Satellite System (GLONASS) and BDS in ionospheric studies over China. Thus, the ionospheric TEC is derived from the measurements of GPS, GLONASS and BDS, and utilized to investigate periodic variations of ionosphere and regional ionospheric map based on 250 GNSS stations from the Crustal Movement Observation Network of China (CMONOC) and Institute of Geology and Geophysics, Chinese Academy Sciences (IGGCAS). In the following sections, we will firstly introduce the used data and method of GNSS–TEC derivation. Then we give some results about ionospheric variation and map based on GNSS–TEC. Finally, a summary is presented for the main properties of investigation of ionospheric TEC over China.

2. Data and derivation of GNSS–TEC

2.1. Data

The GNSS data are from CMONOC and IGGCAS networks that consist of 250 GNSS stations covering Chinese mainland. There are 10 GNSS stations that can trace the BDS satellites. The sample period of GNSS data is 30 s (Xiong et al., 2014b). Fig. 1 illustrates the locations of GNSS stations (black asterisks) and ionospheric pierce points (IPPs) at 400 km from GPS (red dots), GLONASS (green triangles), and BDS (blue squares) measurements at 04:00 universal time (UT) on 1 January 2015. As shown in Fig. 1, Chinese sector 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. Meanwhile, we can find that different navigation satellite systems take care of different regions. GPS, GLONASS and BDS focus on the globe, high latitudes, and middle and low latitudes, respectively. As mentioned above, dense GNSS stations over China provide a good chance to study the ionospheric TEC properties. To demonstrate the performance of the Kriging method in China regional TEC map, the regional TEC maps generated by Kriging method are utilized to compare with that provided by Jet Propulsion Laboratory (JPL). The JPL products have a spatial resolution of 5° (longitude) × 2.5° (latitude) and temporal resolution of 2 h (Mannucci et al., 1998). In addition, the ionospheric F2 region critical frequency (foF2) is routinely scaled at two ionosonde stations in East Asia, which is used to evaluate the ionospheric east–west differences in Chinese sector. The ionosonde data are downloaded from the website of Space Science Lab at the University of Massachusetts Lowell (http://ulcar.uml.edu/index.html).

2.2. Derivation of GNSS–TEC

In the present paper, the GNSS–TEC consists of TECs derived by GPS, GLONASS and BDS. In the following section, we will take GPS–TEC as an example to illustrate the inversion of GNSS–TEC.

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