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Monitoring the ionosphere based on the Crustal Movement Observation Network of China ☆

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ABSTRACT

The Global Navigation Satellite System (GNSS) is becoming important for monitoring the variations in the earth's ionosphere based on the total electron content (TEC) and ionospheric electron density (IED). The Crustal Movement Observation Network of China (CMONOC), which includes GNSS stations across mainland China, enables the continuous monitoring of the ionosphere over China as accurately as possible. A series of approaches for GNSS-based ionospheric remote sensing and software has been proposed and developed by the Institute of Geodesy and Geophysics (IGG) in Wuhan. Related achievements include the retrieval of ionospheric observables from raw GNSS data, differential code biases estimations in satellites and receivers, models of local and regional ionospheric TEC, and algorithms of ionospheric tomography. Based on these achievements, a software for processing GNSS data to determine the variations in ionospheric TEC and IED over China has been designed and developed by IGG. This software has also been installed at the CMONOC data centers belonging to the China Earthquake Administration and China Meteorological Administration. This paper briefly introduces the related research achievements and indicates potential directions of future work.

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1. Introduction

The ionosphere is defined as the upper atmosphere between the altitudes of 85 km and 1000 km, where solar radiation causes ionization [1]. The ionosphere has practical importance because among other functions, it influences radio propagation to distant places on the Earth [2]. Since the mid-to-late 1990s, first Global Positioning Systems (GPS) and then Global Navigation Satellite Systems (GNSS) have become the most important tools for continuously observing the global ionosphere at high spatial and temporal resolutions [3–8]. Recently, the BeiDou Global Navigation Satellite System (BDS), established by China, was able to improve the ability of GNSS-based ionospheric remote sensing. To setup a global public service for monitoring the ionospheric total electron content (TEC) using ground-based GNSS receivers, the International GNSS Service (IGS) working group on the ionosphere was established in 1998 [9–11]. More than four Ionospheric Associate Analysis Centers were able to provide global ionospheric map (GIM) products [3,12–14]. In this context, increasingly more GNSS receivers, mainly GPS and Global Navigation Satellite Systems (GLONASS), have been installed globally to gather data for global ionospheric remote sensing. The IGS ionosphere product uses GNSS for monitoring global variations in the ionosphere TEC by taking advantage of its high accuracy, high resolution, continuous observations, and global scale. However, there are only a few stations within China that contribute to the GIM generation; thus, the accuracy and resolution of the IGS-released ionosphere product over China are significantly lower than those in other areas. The establishment of the Crustal Movement Observation Network of China (CMONOC), comprising 260 GPS and GLONASS stations, provides a large amount of GNSS data for improving the performance of GNSS-based ionospheric remote sensing over China. These stations will be updated to track the BDS in the near future.

To model the ionosphere over China as accurately as possible, a series of approaches for GNSS-based ionospheric remote sensing and corresponding software have been proposed and developed by the Institute of Geodesy and Geophysics (IGG) at Wuhan, partly supported by the funding of CMONOC, including the retrieval of ionospheric observables from raw GNSS data, estimation of differential code biases (DCB) of the satellite and receiver, models of local ionospheric TEC, approaches for ionospheric tomography, and data processing software for GNSS-based ionospheric sensing. The above-mentioned approaches and software will be briefly introduced in this paper, and the conclusions and direction of future work will be presented in the final section.

2. Retrieval of ionospheric observables from raw GNSS data

Ionospheric observables (IO), which are the sum of the line-of-sight (LOS) ionospheric delays with the DCB in the GNSS satellite and receiver, are fundamental input for GNSS-based ionosphere sensing; IO should be retrieved from dual-frequency GNSS data as accurately as possible. For this purpose, we often rely on the so-called carrier-to-code leveling technique, the basic procedures of which are briefly revisited as follows. For a continuous satellite-receiver pass, i.e., the carrier-phase data do not undergo cycle-slip processing, we compute the geometry-free code, carrier-phase observables, and the real-value offset. By adding the (weighted) average of all epochs' offsets to the geometry-free carrier-phase data, we are able to obtain the IO of interest.

Notably, the carrier-to-code leveling technique does not seem to exploit some usable information that might be helpful for retrieving IO. Typically, the geometric effects are rather conservatively assumed to be completely unknown. As a result, tremendous LOS geometric unknowns that are pass and epoch-dependent must be introduced. Consequently, the ability of the carrier-to-code leveling technique to eliminate the particularly evident multipath effects is somewhat unfavorable.

Actually, the IGS delivers the satellite orbit and clock final products on a regular basis. Additionally, the GPS receivers serving as ionosphere sensors are commonly deployed at stationary locations with either known or unknown positions. With these general facts in mind, we retrieve the IO using the precise point-positioning (PPP) technique [15–17]. Importantly, unlike the customary PPP that categorizes the ionospheric delays as nuisance unknowns and removes them by forming ionosphere-free observables, our PPP employs the original (uncombined) GNSS data and parameterizes the IO as one type of estimable unknown. The geometric unknowns involved in the PPP are all receiver-dependent and are much smaller than the line-of-sight unknowns handled by the carrier-to-code leveling.

Using experimental dual-frequency GNSS data collected by a variety of zero- and short-baseline setups deployed worldwide, we comparatively assess the quality of the IO offered by the carrier-to-code leveling and the PPP techniques.

Fig. 1 shows a typical comparison of the IO extracted from raw GPS data based on the carrier-to-code leveling and PPP techniques. Ideally, because the distance between two receivers that form a (zero) short baseline is fairly short, the between-receiver single-differenced (SD) IO corresponding to different satellite passes will contain only the time-invariant SD receiver DCB and should overlap. Therefore, we can refer to the spread of the SD IO as a reasonable diagnostic measure when quantitatively analyzing the actual accuracy of the IO. Our main conclusions derived from the numerical investigations are (1) the code multipath effects account for the major error budget of the IO retrieval. Thus, the accuracy of the IO retrieved by the carrier-to-code leveling might be worse than four TEC units (TECu). In contrast, the PPP-derived IO is always less affected by the code multipath, and its accuracy is well below 2 TECu; (2) zero-baseline analysis suggests that the SD IO computed from daily experimental datasets that are not influenced by multipath effects may undergo very apparent diurnal variability, the magnitudes of which can reach tens of nanoseconds. This result is mainly caused by the short-term (hourly or shorter) variation in the receiver DCB.

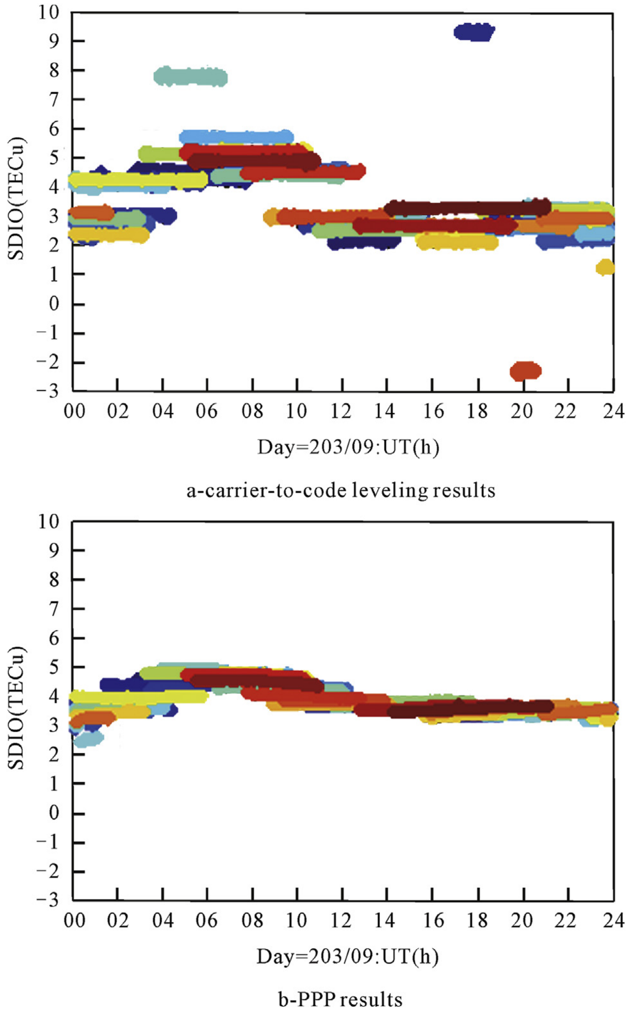

Fig. 1 – Comparison of station-differenced ionospheric observables from raw GPS data based on a-carrier-to-code leveling and b-precise point-positioning techniques.

3. Estimation of DCB in satellites and receivers

DCB is defined as the difference in the time delay between two observations obtained at the same or different frequencies [18]. The DCB is actually related to the hardware delay of a given observation [19]. The DCB can be classified into two categories: the intra-frequency bias, which is the bias between two observations at the same frequency, and the inter-frequency bias, which is the bias between observations at two frequencies [19]. Generally, the intra-frequency bias can be directly calculated by averaging the differences of the two observations, while the inter-frequency bias must be estimated by removing the differences in ionospheric delays between the corresponding observations [20]. The DCB occurs at the satellite and receiver terminals during signal transmission and reception; the biases are referred to as the satellite DCB and receiver DCB [21], respectively.

To eliminate the dependence of a large number of global stations in the DCB estimation based on traditional approaches, a new method designated IGGDCB was proposed by IGG [19]. The implementation of IGGDCB consists of two procedures: first, the DCB of satellites and each receiver is individually estimated using a local ionospheric TEC model on a station-by-station basis; second, the DCB of satellites is separated from that of the receiver through an iterative reference satellite selection process based on the variability in satellite DCB stability. Independent and local ionospheric TEC modeling per ground station allows IGGDCB to eliminate the requirements of a huge dataset from a large number of geographically distributed tracking stations. The iterative method of reference satellite selection is able to reduce the impact of using satellites with unstable DCB. The IGGDCB method can work properly only when a few ground stations are available and even when some satellites with relatively unstable DCB are present. Fig. 2 shows the comparison of DCB estimates of satellites based on the proposed IGGDCB with only seven stations and the corresponding results from the Center for Orbit Determination in Europe (CODE) and Jet Propulsion Laboratory (JPL). The accuracies of the satellite DCB estimates obtained by the IGGDCB approach are similar (approximately 0.1–0.13 ns) to those obtained by the existing approaches based on a large amount of global datasets; however, the IGGDCB approach requires only a very small amount of datasets from a few ground stations. In addition, the impact of using a non-optimized satellite DCB reference for DCB estimation may be considerably reduced through the iterative reference selection process developed by IGGDCB that rejects satellites with poor DCB stabilities. Moreover, another approach for the BDS satellite estimation that is aided by neighboring GPS data has also been developed [22].

As the space environment within which the GPS satellites are present is relatively stable, long-term stability of the GPS satellite DCB is observed. At the same time, continuous GPS data collection from receivers with global coverage makes it

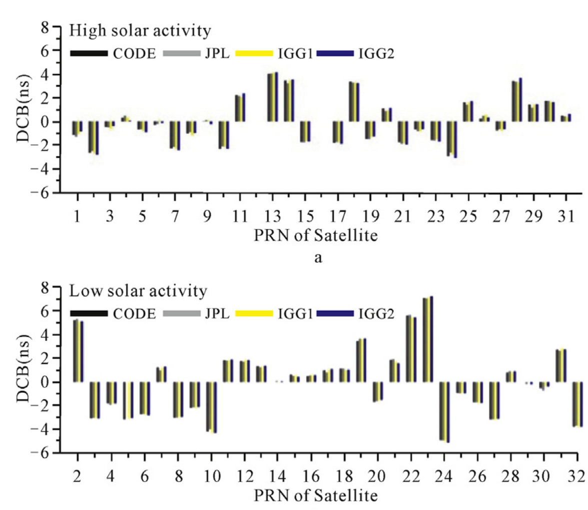

Fig. 2 – Comparison of the DCB estimates in satellites based on IGGDCB with only 7 stations and the corresponding results released by CODE and the Jet Propulsion Laboratory (JPL) [19].

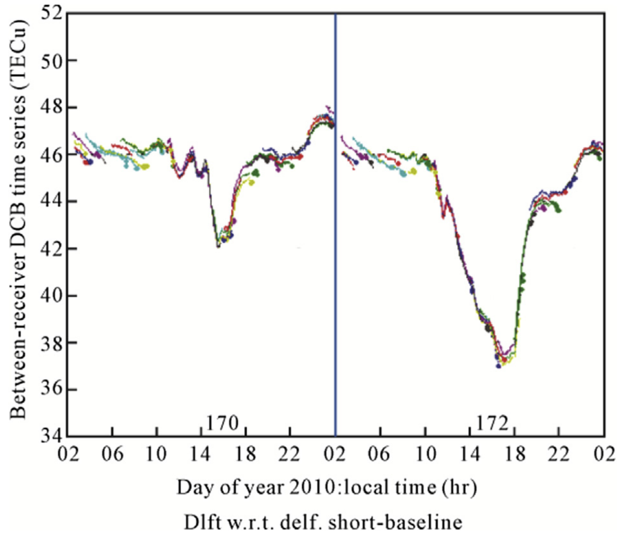

Fig. 3 – The C1–P2 receiver DCB time series (in TECu) from GPS observations collected by a shortbaseline (dlft-delf).

possible to estimate GPS satellite DCB with high accuracy. However, this result is not true for a variety of receivers' DCB. As a result of various operating environments, as well as distinct firmware versions, a receiver DCB may experience short-term variations over time. Precise modeling of receiver DCB variation can increase the reliability of ionosphere products determined from GPS data and ensure the correctness of conclusions based on these products when investigating atmosphere/space effects and geodetic phenomena [23]. Given zero/short-baseline GPS data, the between-receiver single-differenced values of these delays can be used to retrieve a time series of receiver DCB, the temporal resolution of which is equal to that of the GPS observations. In addition, the ionosphere-fixed model with estimable receiver DCB has been derived [24]. The intra-day variations in receiver DCB determined from a zero-baseline are less than 1 TECu, without apparent day-to-day repeatability (see Fig. 3). A random walk with standard deviations (STDs) of process noise between 1.0 and 1.5 mm is sufficient to characterize variation behaviors on different days; the size of the receiver DCB variation corresponding to one of the short baselines can exceed 12 TECu (roughly 2 m) in one day. To model the DCB with random walk, the empirical STD of the process noise should be set to no less than 2 mm.

4. Models of local ionospheric TEC

The IO along the LOS from a satellite to receiver can only be provided by GNSS raw data, and these observables are distributed discreetly over receiver-covered areas. Generally, a local ionospheric model (LIM) in the vertical TEC is necessary to study the variations in the ionosphere [25]. In contrast to the GIM, the local GNSS data contributes to the LIM computation, and the LIM usually has a higher accuracy. How to select a mathematical function to represent the variation in the ionosphere is one of the most critical issues for LIMs. Many functions have been studied, including polynomial functions (POLY) [26], triangle series functions (TSF) [27,28], (adjusted) low-order spherical harmonic functions (LSH) [12,29], and so on. However, the LIM is usually established under the assumption of an ionospheric thin layer; a so-called mapping function is required to convert ionospheric delay from the LOS to the vertical direction [30].

An overview of the different local ionospheric modeling methods is presented in Table 1. The POLY model is suitable for real-time monitoring and forecasting the variation in the local ionosphere. However, the model can only provide ideal precision during a short session of approximately several hours [31,32]. The generalized triangular series function (GTSF), developed from the TSF, consists of two parts: (1) two-dimensional polynomial development of the geomagnetic latitude and solar longitude; and (2) finite Fourier series of the solar longitude. The function can effectively describe the subtle variations in ionospheric TEC using data obtained over a single day. The POLY and GTSF model are based on plane geographic and geomagnetic coordinates (latitude and longitude), respectively [27], whereas the spherical cap harmonic (SCH) model is based on the spherical cap coordinates that consist of a set of spherical cap harmonic functions by solving a Laplace equation on a specific spherical cap. The SCH can efficiently model the variation in ionospheric TEC over high latitudes and the arctic region [33]. Because the coefficients of the Legendre function in SCH are non-integers, the computation process of the SCH is complicated. A LSH model has also been used for local ionospheric modeling. The LSH model has the same representation as the spherical harmonics (SH) model, but the coefficient estimations of LSH are not the solution of the Laplace function over the local region. To solve the potentially ill-conditioned problem in the LSH function, an adjusted spherical harmonics model is proposed by IGG [29]. The accuracies of different local ionospheric models, including POLY, GTSF, and LSH, are compared in Fig. 4 for the WUHN station on the 250th day of 2014.

In addition, a novel approach called differential areas for differential stations (DADS), which calculates the ionospheric TEC map over China, has been proposed [34]. In contrast to the traditional methods, a series of local ionospheric TEC models is established at each individual station, and a strategy is designed for combining those local ionospheric TEC models to generate the ionospheric TEC map over the corresponding area. The accuracy of a local ionospheric model is usually better than that of regional or global models; thus, the performance of the ionospheric TEC map can be improved. The ionospheric TEC map over China is processed using the data from CMONOC based on the DADS. Fig. 5 illustrates the variations in the ionospheric TEC at different latitudinal bands over China from 2001 to 2008 based the CMONOC data.

5. Methods of ionospheric tomography

Because ionospheric TEC is the line integral of IED along the LOS from the satellite to receiver, multi-station TEC data can be applied to study the variations in three-dimensional

Table 1 – Comparison of different methods for local ionospheric TEC modeling.

Models	POLY	GTSF	SCH	LSH (ASH)
Reference frame	Plane coordinate		Spherical cap coordinates	Spherical coordinates
Region size	Single station		Regional network	
Model session interval	5 min to several hours	24 h	12 sessions at a length of 2 h	
Suggested order and degree	$n_{max} = 3$ $m_{max} = 4$	$n_{max} = 1$ $m_{max} = 2$ $K_{max} = 4$	$n_{dmax} = 4 - 6$	$n_{dmax} = 4$

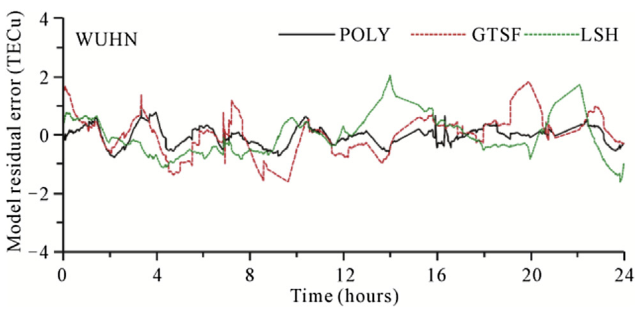

Fig. 4 – Residual errors in the different local ionospheric models for the WUHN station.

ionospheric structures. Computerized ionospheric tomography (CIT) techniques using GNSS have been developed to image the IED in three dimensions in recent years. Currently, the feasibility of ionospheric tomography has been demonstrated, and the focus has turned to limitations of the new technique [35]. For GNSS-based CIT, the reconstructed images of IED are usually distorted for the following reasons: first, the number of ground receivers is usually limited, and the distribution is not even; second, horizontal ray paths in satellite-to-receiver geometry, which are very important to improve the vertical resolution of ionospheric tomography, are absent [36]. Therefore, the CIT-based IED inversion technique must be effectively advanced.

To solve the above problems, the improved algebraic reconstruction technique (IART) [36] and the constrained algebraic reconstruction technique (ART) algorithm (CMART) [37] have been proposed in recent years. IART improves both computational efficiency and imaging quality by introducing adaptive adjustment to relax parameters during the inversion process. IART, compared with ART, can further improve the reconstructed image of the IED, and it has a better convergence performance. Meanwhile, because of the lack of observations, some voxels are not intersected by any rays; the IED values of these voxels rely on the initialized value. Therefore, intermediate inter-voxel smoothing is necessary. CMART designs a simple 3-dimensional distance-weighted Gaussian-like boxcar average to smooth all voxels based on the continuity and smoothness of the electron density between adjacent voxels. This approach overcomes the defect that voxels without intersected rays depend absolutely on the initialized values and avoids data gaps in that region, resulting in inversion accuracy. Using the data of 88 sites from CMONOC, the slant total electron contents (STECs) obtained from GSJN, BJFS, XJRS, and HNCS are used to test the results reconstructed by the tomographic method (Fig. 6).

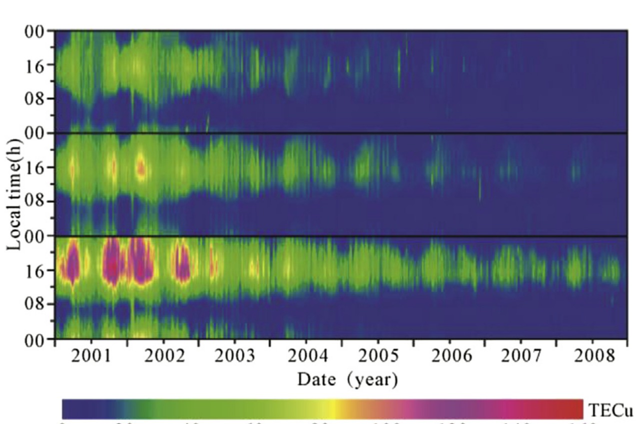

Fig. 5 – The variations of ionospheric TEC with respect to the local time at different latitudes (up: 40°N–55°N, middle: 25°N–40°N, bottom: 10°N–25°N) over China.

Recently, GNSS receivers on low earth orbit (LEO) satellites have been providing new data sources that can be added to three-dimensional tomographic imaging algorithms. GNSS occultation TEC comes from rising or setting occultation and provides the horizontal ray information that is not available from angle-limited ground-based tomography, while dual-frequency navigation receivers provide upward-looking TEC data and allow for improved three-dimensional imaging of the top of the ionosphere. It is well known that the variation in the IED over China is very complicated because the area of China spans widely across both the longitudinal and latitudinal directions [36,38–40]. Based on GPS data from CMONOC, IED have been inverted using the CIT technique, and related improvements/algorithms have been developed [36,41–43]. Preliminarily, a set of CHAMP-based GPS data has been combined with ground-based GPS observations to image the ionospheric electron density over China [41]. A time series of IED profiles over China and its surroundings are reconstructed with the IART tomographic algorithm using combined ground-based GPS observations from CMONOC and the IGS receiver network with space-based GPS measurements from the Constellation Observation System for Meteorology Ionosphere and Climate (COSMIC) [44]. The aim is to improve the determination of the IED density in images by combining LEO satellite GPS data (including the navigation data and occultation data) with ground-based GPS observations. In Fig. 7, the COSMIC electron density profiles are compared with those retrieved by ground-based data (GRND) and combined ground-based and space-based data (COMB). The results obtained by combining ground and

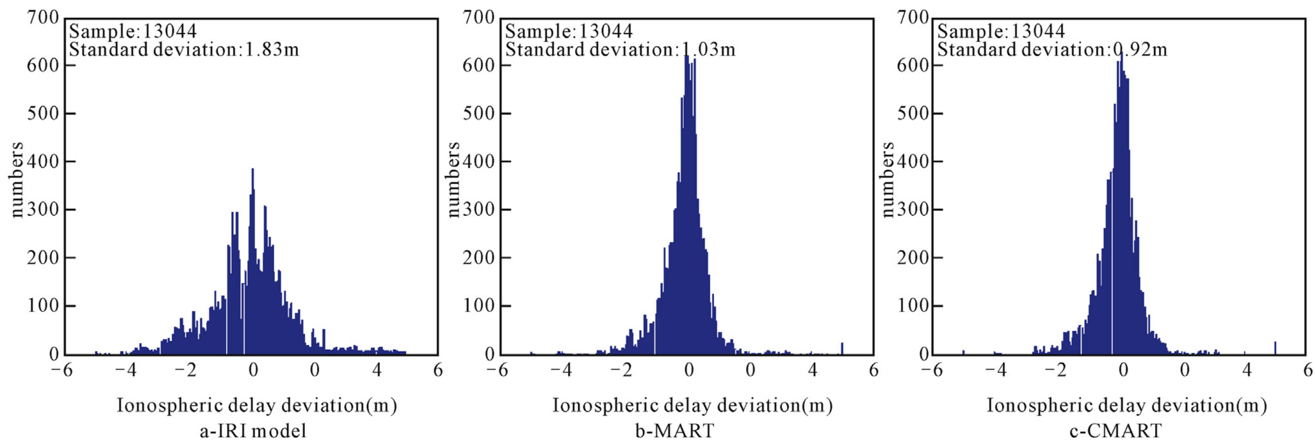

Fig. 6 – Comparisons of ionospheric delay deviations between the international reference ionosphere (IRI) model and tomographic model with observations obtained from GSJN, BJFS, XJRS, and HNCS.

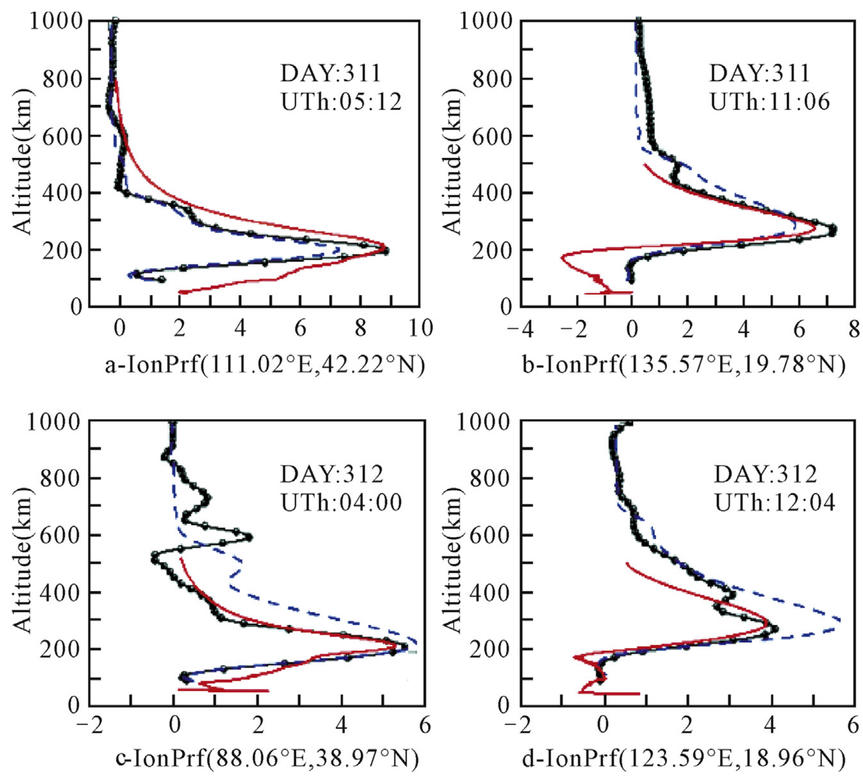

Fig. 7 – Comparisons of the IED profiles (red solid lines) from COSMIC occultation data with those retrieved by combined ground- and space-based observations (black solid lines with circle) and ground-based observations only (blue dash lines).

space-based GPS data are more similar to the COSMIC ionPrf results than the ground-based GPS data only, particularly the peak electron density. Therefore, the electron density inversion results are clearly improved by adding LEO satellite data to the ground-based data.

6. Software

To integrate the above-mentioned methods, software for GNSS-based Ionospheric Data Processing and Analysis has been developed by IGG in Wuhan, China. The functions of the software currently include (1) pre-processing the raw GPS/GLONASS/BDS data; (2) processing the carrier-to-code leveling and generating the phase-smoothed code observations; (3) retrieving the ionospheric observables; (3) local ionospheric modeling based on the polynomial or generalized trigonometric series functions; (4) estimating the DCB in satellites and receivers; (5) global ionospheric modeling based on the spherical harmonic functions; (6) generating a global ionospheric TEC map based on the improved DADS; (7) predicting the local ionospheric TEC; (8) inverting the ionospheric density based on CIT; (9) analyzing the latitudinal and longitudinal variations in the ionospheric TEC; and (10) visualizing global or regional ionospheric TEC and density products. The software is developed with C, FORTRAN, and JAVA programming and is able to be installed on Windows and Linux systems. The maximum number of processing stations is over 300. The preliminary version of this software was introduced in 2011 [45]. By supporting CMONOC, this software has also been installed at the CMONOC data centers located in the China Earthquake Administration and China Meteorological Administration, respectively. The software is also partially available for related studies and the latest version will be released in the near future; questions about this software can be directed to lizishen@whigg.ac.cn.

7. Conclusions and future work

The GNSS data from CMONOC is highly valuable for ionospheric remote sensing over China. The IGG has proposed and developed a series of approaches and algorithms for GNSS-based ionospheric remote sensing from TEC and IED, as well as self-developed software. Among these research achievements, the retrieval of ionospheric observables based on the PPP technique significantly improves the accuracy of GNSS-based ionospheric TEC, the IGGDCB approach for DCB estimation abandons the dependence on a large amount of global distributed stations, the proposed GTSF can capture the subtle variations in ionospheric TEC in local areas, and the CIT-based ionospheric IED inversion is advantageous for studying the structure of the ionosphere and explaining ionospheric phenomena. Additional information on the approaches can be found in the corresponding published papers.

To increase the contribution of CMONOC to ionosphere-related research, the following aspects should be considered: (1) quality control of IO from raw GNSS data for accuracy and reliability; (2) proper methods for combining GPS, GLONASS, and BDS data to improve the performance of ionospheric modeling, particularly data from BDS GEO and IGSO satellites; (3) improvement of the thin-layer assumption and mapping function in the ionospheric TEC model, particularly in the low latitudes; (4) extension of the CIT-based IED inversion method by using the ionospheric data from different techniques, such as ionospheric TEC from LEO satellites, ionosondes, altimeter satellites, DORIS, occultation, and others.

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REFERENCES

[1] Davies Kenneth. Ionospheric radio. London: Peter Peregrinus Ltd; 1990.
[2] Xiong Nianlu, Tang Cunchen, Li Xingjian. Introduction to ionosphere physics. Wuhan: Wuhan University Press; 1999 [in Chinese].
[3] Mannucci AJ, Wilson BD, Edwards CD. A new method for monitoring the Earth's ionospheric total electron content using the GPS global network. In: Proceeding of the 6th international technical meeting of the satellite division of the institute of navigation; 1993.
[4] Lanyi G, Roth T. Jet propulsion Lab. CIOT. A comparison of mapped and measured total ionospheric electron content using global positioning system and beacon satellite observations. Radio Sci 1988;23(4):483–92.
[5] Yuan Yunbin, Huo Xingliang, Ou Jikun. Models and methods for precise determination of ionospheric delay using GPS. Prog Nat Sci 2007;17(2):187–96.
[6] Zhang Donghe, Xiao Zuo. A method of calculating TEC with GPS data and its application to the ionospheric disturbances. Chin J Geophys Chin Ed 2000;43(4):451–8 [in Chinese].
[7] Xiao Zuo, Zhang Donghe. An approach to study the day-to-day variations of ionospheric TEC directly by GPS time-delay signals. Chin J Space Sci 2000;20(2):97–102 [in Chinese].
[8] Zhang Xiaohong, Li Zhenghang, Cai Changsheng. Study on regional ionospheric model using dual_frequency GPS measurements, Geomatics and Information Science of Wuhan University 2001;26(2):140–3 [in Chinese].
[9] Feltens J. IGS products for the ionosphere-one year of Iono_WG Activities. 1999. nng.esoc.esa.de/gps/refs/La_Jolla_SIO_Project_Report.pdf.
[10] Feltens J. IGS ionosphere models comparison. Pasadena, CA, U.S.A. 1998.
[11] Feltens J, Schaer S. IGS product for the ionosphere. Darmstadt, Germany. 1998. p. 225–32.
[12] Schaer S. Mapping and predicting the earth's ionosphere using the global positioning system. Berne, Switzerland: Astronomical Institutes, University of Bern; 1999.
[13] Hernández-Pajares M, Juan JM, Sanz J. New approaches in global ionospheric determination using ground GPS data. J Atmos Sol Terr Phys 1999;61(16):1237–47.
[14] Feltens J, Dow JM, Martín-Mur TJ, Garcia Martinez C, Bernedo P. Routine production of ionosphere TEC maps at ESOC-first results (IGS Presentation). Darmstadt, Germany: ESOC; 1998.
[15] Zhang Baocheng, Ou Jikun, Yuan Yunbin, Zhong Shiming. Precise point positioning (PPP) algorithm based on original dual-frequency GPS code and carrier-phase observations and its application. Acta Geod Cartogr Sin 2010;39(5):478–83 [in Chinese].
[16] Zhang Baocheng, Ou Jikun, Li Zishen, Yuan Yunbin. Determination of ionospheric observables with precise point positioning. Chin J Geophys 2011;54(4):950–7 [in Chinese].
[17] Zhang BC, Ou Jikun, Yuan Yunbin, Li Zishen. Extraction of line-of-sight ionospheric observables from GPS data using precise point positioning. Sci China Earth Sci 2012;55(11):1919–28.
[18] Sardon E, Rius A, Zarraoa N. Estimation of the transmitter and receiver differential biases and the ionospheric total electron content from global positioning system observations. Radio Sci 1994;29(3):577–86.
[19] Li Zishen, Yuan Yunbin, Li Hui, Ou Jikun, Huo Xingliang. Two-step method for the determination of the differential code biases of COMPASS satellites. J Geodesy 2012;86(11):1059–76.
[20] Schaer S. Differential code biases (DCB) in GNSS analysis. Miami Beach, Florida, USA. 2008.
[21] Song Xiaoyong, Yang Zhiqiang, Jiao Wenhai, Mao Yue, Feng Laiping. Determination of GPS receiver's DCB. J Geodesy Geodyn 2009;29(1):127–31 [in Chinese].
[22] Yuan Yunbin, Fan Lei, Huo Xingliang, Hsu Houtse. Determination of the differential code bias for current bds

satellites. Geoscience Remote Sens IEEE Trans 2014;52(7):3968–79.
[23] Zhang Baocheng, Ou Jikun, Yuan Yunbin, Li Zishen. Calibration of slant total electron content (sTEC) and satellite-receiver's differential code biases (DCBs) with uncombined precise point positioning (PPP) technique. Acta Geod Cartogr Sinica 2011;40(4):447–53 [in Chinese].
[24] Zhang Baocheng, Yuan Yunbin, Ou Jikun. Short-term temporal variability of GPS receivers' differential code biases (DCB): retrieving and modeling. in press Chin J Geophys 2015 [in Chinese].
[25] Zhang Yong, Zhang Bin, Ma Nengwu. On models of ionospheric delay correction for single-frequency GPS receiver. J Geodesy Geodyn 2012;32(2):69–73 [in Chinese].
[26] Coco DS, Coker C, Dahlke SR, Clynch JR. Variability of GPS satellite differential group delay biases. IEEE Trans Aerosp Electron Syst 1991;27(6):931–8.
[27] Yuan Yunbin, Ou Jikun. A generalized trigonometric series function model for determining ionospheric delay. Prog Nat Sci 2004;14(11):1010–4.
[28] Georgiadiou Y. Modeling the ionosphere for an active control network of GPS stations, 7. LGR-Series-Publications Delft Geodetic Computing Centre; 1994. 1.
[29] Li Zishen. Study on the mitigation of ionospheric delay and the monitoring of global ionospheric TEC based on GNSS/Compass. Wuhan: Chinese Academy of Sciences; 2012 [in Chinese].
[30] Tu Rui, Zhang Qin, Huang Guanwen. On ionospheric delay processing methods for single frequency precise point positioning. J Geodesy Geodyn 2010;30(2):99–103 [in Chinese].
[31] Zhang Hongping, Ping Jinsong, Zhu Wenyao, Huang Cheng. Brief review of the ionospheric delay models. Prog Astronomy 2006;24:16–26.
[32] Yuan Yunbin. Study on the methods of correcting ionospheric delay and monitoring ionosphere using GPS data. Wuhan: Chinese Academy of Sciences; 2002 [in Chinese].
[33] Liu Jingbin, Chen Ruizhi, Wang Zemin, Zhang Hongping. Spherical cap harmonic model for mapping and predicting regional TEC. GPS Solutions 2010;15(2):109–19.
[34] Yuan Yunbin, Ou Jikun. Differential areas for differential stations (DADS): a new method of establishing grid ionospheric model. Chin Sci Bull 2002;47(12):1033–6.
[35] Wen Debao, Zhou Yiyan. Result analysis of ionospheric tomography inversion from GPS data over China. J Geodesy Geodyn 2010;30(3):55–8 [in Chinese].
[36] Li Hui, Yuan Yunbin, Yan Wei, Li Zishen. A constrained ionospheric tomography algorithm with smoothing method, Geomatics and Information Science of Wuhan University 2013;38(4):412–5.
[37] Wen Debao, Yuan Yunbin, Ou Jikun, Huo Xingliang, Zhang Kefei. Three-dimensional ionospheric tomography algebraic reconstruction technique. GPS Solutions 2007;11(4):251–8.
[38] Huo Xingliang, Yuan Yunbin, Wen Debao, Luo Xiaowen. The diurnal variations, semiannual and winter anomalies of the ionospheric TEC based on GPS data in China. Prog Nat Sci 2005;15(1):56–60.
[39] Yuan Yunbin, Ou Jikun. The first study of establishing China grid ionospheric model. Salt Lake City, Utah. 2001.
[40] Wen Debao, Yuan Yunbin, Ou Jikun, Zhang Kefei. Ionospheric spatial and temporal variations during 18 August 2003 storm over China. Earth Planets Space 2007;59:313–7.
[41] Wen Debao, Yuan Yunbin, Ou Jikun, Zhang Kefei, Liu Kai. A hybrid reconstruction algorithm for 3-D ionospheric tomography. Geoscience Remote Sens IEEE Trans 2008;46(6):1733–9.
[42] Yuan Yunbin, Wen Debao, Ou Jikun, Huo Xingliang, Yang Rengui, Zhang Kefei. Preliminary research on imaging the ionosphere using CIT and China permanent GPS tracking station data. Springer; 2007.
[43] Wen Debao, Yuan Yunbin, Ou Jikun. Monitoring the 3-dimensional ionospheric electron density distribution using GPS observation over China. J Earth Syst Sci 2007;3:235–44.
[44] Li Hui, Yuan Yunbin, Li Zishen, Huo Xingliang, Yan Wei. Ionospheric electron concentration imaging using combination of LEO satellite data with ground-based GPS observations over China. IEEE Trans Geoscience Remote Sens 2012;50(5):1728–35.
[45] Zishen Li, Huo Xingliang, Yan Wei, Li Hui, Yuan Yunbin. Exemplary monitoring system of space (ionosphere) weather based on GNSS. In: Electric information and control engineering (ICEICE); 2011. International Conference on, Wuhan, China.

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