Contribution of BeiDou to ionospheric TEC modeling and monitoring

Ningbo Wang (1), Yunbin Yuan (1), Zishen Li (2) and Xingliang Huo (1)

(1) State Key Laboratory of Geodesy and Earth Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences

(2) Academy of Opto-Electronics, Chinese Academy of Sciences

N. Wang: wnbigg@asch.whigg.ac.cn

Y. Yuan: yybgps@whigg.ac.cn
Z. Li: lizishen@aoe.ac.cn
X. Huo: xlhuo@whigg.ac.cn

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Introduction

Global Navigation Satellite System (GNSS) have become a key technology leading to significant advances in ionospheric sounding with high spatial and temporal resolution. In addition to the legacy global positioning system (GPS) and GLONASS, users now can benefit from BeiDou for ionospheric total electron content (TEC) modeling and monitoring in view of the increasing visible satellite numbers and the unique placement of BeiDou GEO and IGSO satellites.

In spite of the 3 in-orbit-validation (IOV) satellites launched in 2015, the current BeiDou constellation compromises a total of 13 active satellites: 5 GEOs (C01, C02, C03, C04 and C05), 5 IGSOs (C06, C07, C08, C09 and C10) and 3 MEOs (C11, C12 and C14). In this presentation, the ionospheric monitoring activities based on BeiDou observations at the Institute of Geodesy and Geophysics (IGG) are introduced.

a) Characteristics of BeiDou satellite and receiver differential code biases (DCBs). BeiDou DCBs are determined by IGGDCB method within the multi-GNSS experiment (MGEX) network of the international GNSS services (IGS).

b) Regional ionospheric grids for BeiDou Wide Area Augmentation System (WAAS). An adjusted spherical harmonic (ASH) function is introduced to model the ionospheric TEC over China region.

c) Observation of the ionospheric irregularities over the mid- and low-latitudes of China.

Characteristics of BeiDou DCBs

BeiDou satellite and receiver DCBs are determined by IGGDCB method based on observations collected by the MGEX network of the IGS. In the approach of IGGDCB, local ionospheric model is employed for the combined estimation of DCBs and ionospheric activities at each individual station, instead of global ionospheric modeling or using a priori ionospheric information like global ionospheric maps (GIMs). BeiDou satellite and receiver DCB estimates for a full span of three years (2013-2015) are shown in Fig.1 and Fig.2, respectively.

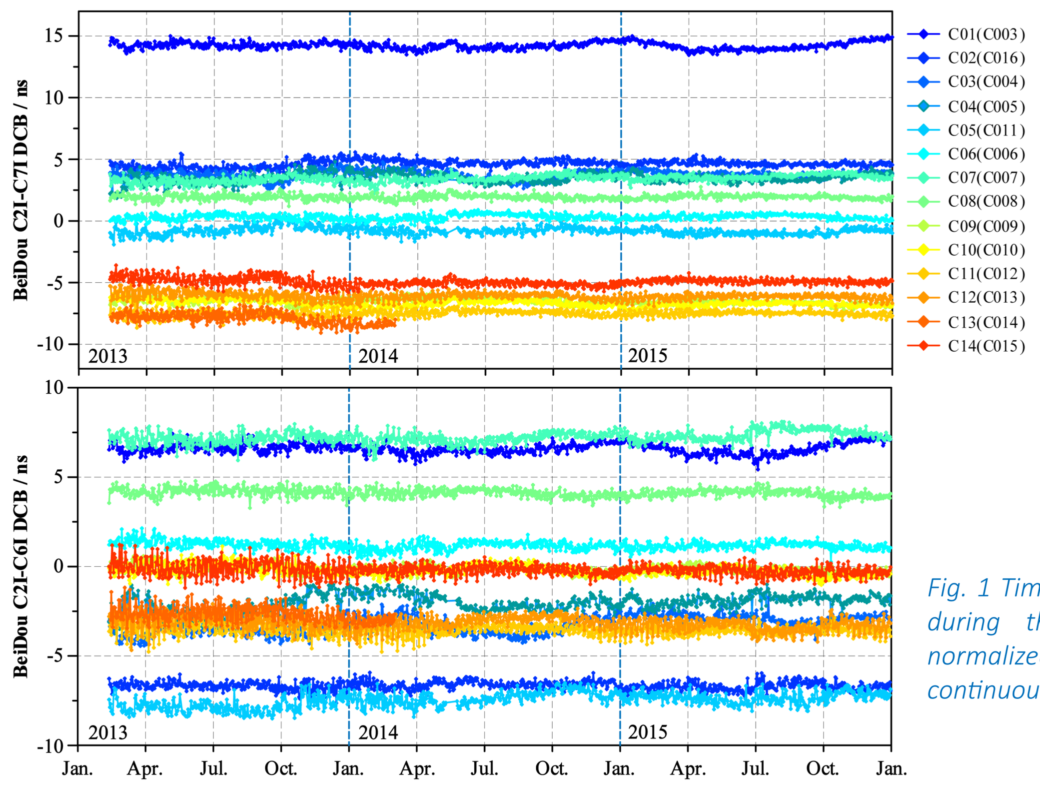

Fig. 1 Time series of BeiDou satellite C2I-C7I and C2I-C6I DCBs during the period 2013–2015. The results have been normalized by a zero-mean constraint across the 13 continuously operating satellites with the exception of C13.

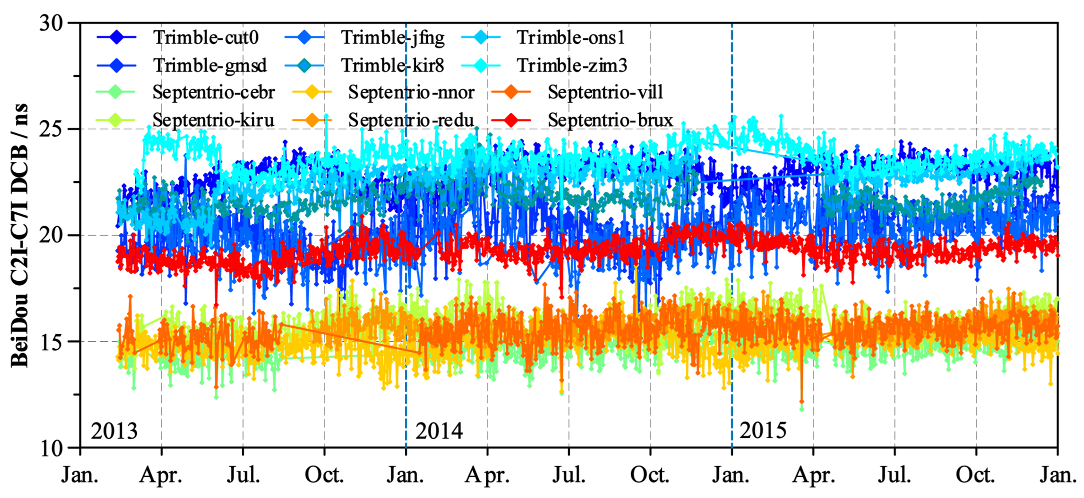

Fig. 2 Time series of BeiDou C2I-C7I DCBs for the selected receivers during the period 2013–2015.

The resulting BeiDou satellite DCBs appear to be fairly stable, which are confined to a range of ±8 ns with an exception of GEO satellite C01 (C2I-C7I value of C01 is about 15 ns). If look closely at the DCB variation of MEO (C11-C14) satellites, one may note a small oscillation with a period of approximately one week. Receiver DCBs are not as stable as that of satellite DCBs, which also exhibit some dependence on the receiver types: DCB estimates of the selected Trimble NETR9 receivers mainly vary from 18.0 to 24.0 ns, and that of Septentrio receivers vary from 13.0 to 19.0 ns.

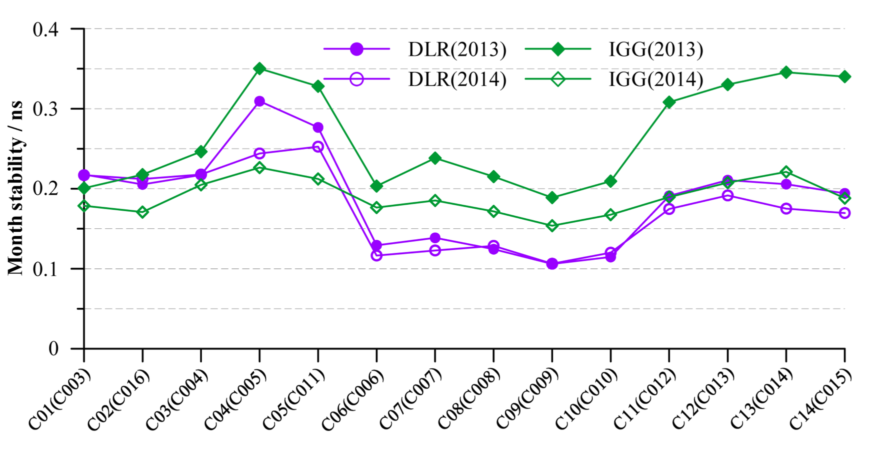

Fig. 3 Monthly stability of BeiDou satellite C2I-C7I DCBs determined by DLR and IGG for the year 2013 and 2014, respectively.

The monthly stability of BeiDou satellite DCBs of DLR and IGG is illustrated in Fig.3 for the example of C2I-C7I bias. The stability of the IGG solutions in 2014 is more stable than that in 2013 (0.19 ns vs. 0.26 ns on average). Considering individual types of BeiDou satellites, the stability indices also confirm an improved performance of IGSO satellite DCBs as compared to that of GEO and MEO satellites.

Regional ionospheric grids for BeiDou WAAS

Considering the characteristics of local ionospheric TEC over China and its surrounding area, a new approach for precisely modeling the ionospheric delay is developed for BeiDou WAAS.

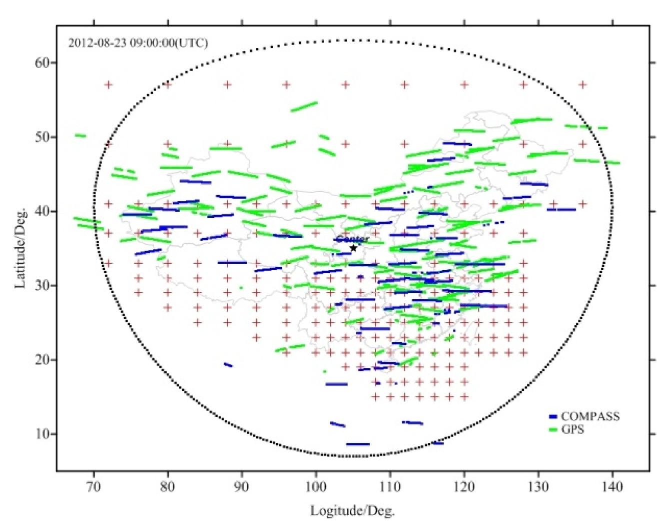

Fig. 4 IPPs of BeiDou and GPS observations with the assumption of ionospheric single layer at a height of 350 km on August 23, 2012 (09:00 UT).

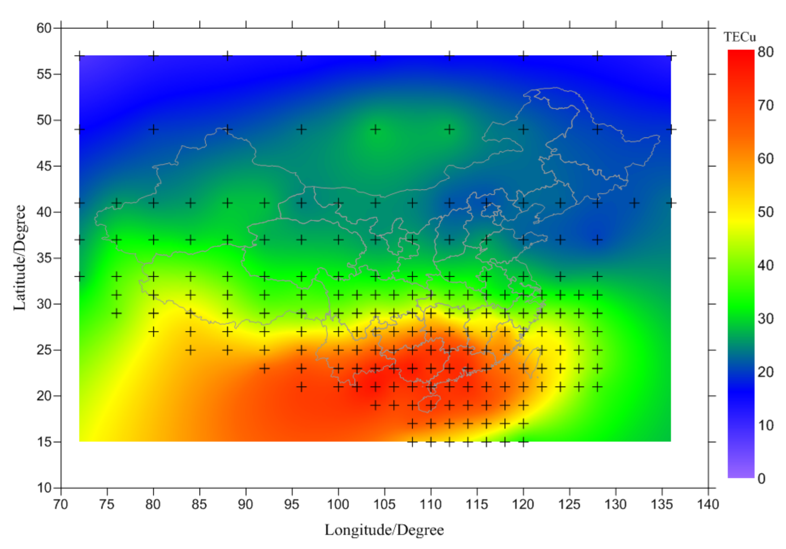

Fig. 5 The coverage and resolution of ionospheric map for BeiDou WAAS.

In this approach, the ionospheric delay is considered as the sum of the trend and stochastic terms. The trend term is represented by an adjusted spherical harmonic (ASH) function, and the stochastic term is described by a time-variant covariance function. The ASH-based ionospheric model and the covariance function are simultaneously estimated using BeiDou data, and a 15-minute moving window is selected for the ionospheric modeling in real-time mode. Ionospheric pierce points (IPPs) of BeiDou and GPS observations on August 13, 2012 (09:00 UT) are shown in Fig.4.

An inhomogeneous grid is designed for BeiDou WAAS over China and its surrounding area. The coverage and resolution of ionospheric map is shown in Fig. 5. The intervals of latitudes are 8^0 at high latitudes (greater than 42^0N), 4^0 at middle latitudes (from 34^0N to 42^0N) and 2^0 at low latitudes (lower than 34^0N).

Table 1 Performance of the regional ionospheric maps generated with BeiDou- or GPS-only observations during August 23-27, 2012 (unit: m).

Test stations	ULAB	HLAR	BJFS	JXHK	YNTC	GDST	TWTF	QION
GPS	0.15	0.13	0.12	0.12	0.26	0.19	0.14	0.25
BeiDou	0.29	0.43	0.30	0.34	0.42	0.43	0.50	0.40

GPS TEC generated from 8 IGS and the Crust Movement Observation Network of China (CMONOC) stations are used as references. The selected test stations cover the low-, mid- and high-latitudes of China. Performance of the ionospheric maps generated with BeiDou- or GPS-only observations during August 23-27, 2012 are shown in Table 1. Root-mean-square (RMS) values of the differences between GPS-based grids and GPS TEC are confined to a range of 0.1-0.3m, and that between BeiDou-based grids and GPS TEC vary from 0.3 to 0.5m for the test period.

Observation of the ionospheric irregularities over China

The IGS Ionosphere Working Group has recommended to start a new TEC fluctuation product over North Pole to study the dynamic of oval irregularities since 2012. Similarly, the low-latitudes of China are also confronted with serious ionospheric irregularities, and GNSS observations from CMONOC network provide an opportunity for ionospheric space weather monitoring over China low-latitude regions.

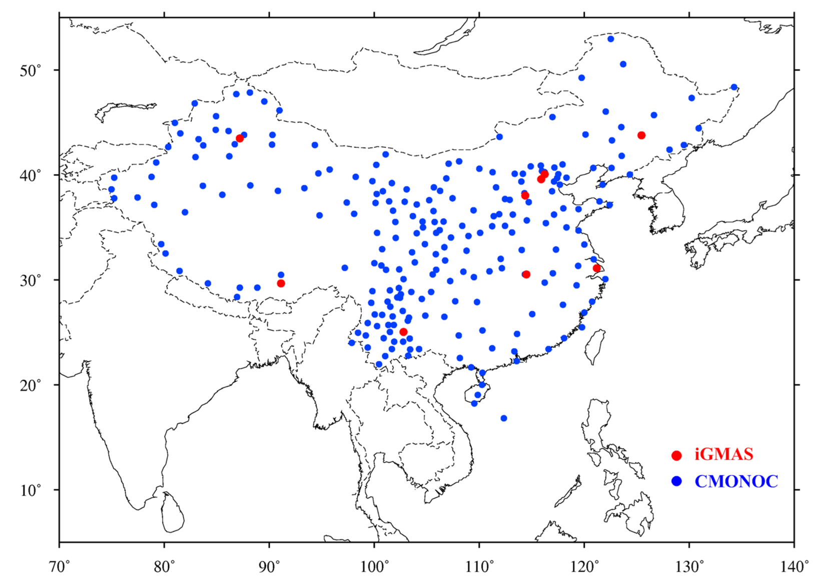

Fig. 6 Distribution of CMONOC and iGMAS stations.

Distribution of the selected CMONOC stations is given in Fig.6. GPS and GLONASS observations provided by CMONOC network allow to detect the ionospheric irregularities over China low-latitude regions.

There are 10-15 iGMAS (the international GNSS Monitoring and Assessment System) stations in the mainland of China at present, supporting to tracking BeiDou, GPS, GLONASS and Galileo signals. BeiDou signals can also be used for the observation of ionospheric irregularities.

Five statistical indexes are used to analyze the TEC fluctuation activity, including:

a) ROT: rate of TEC change; b) ROTI: standard deviation of the detrended ROT;
c) dTEC: detrended TEC; d) Dif1Rot: first difference of ROT;
e) ACEVS: Auto-covariance estimation of variable samples (ACEVS) method;

Case studies of the ionospheric irregularities observed over China mid- and low-latitude regions are shown in Fig.7 and Fig. 8, respectively.

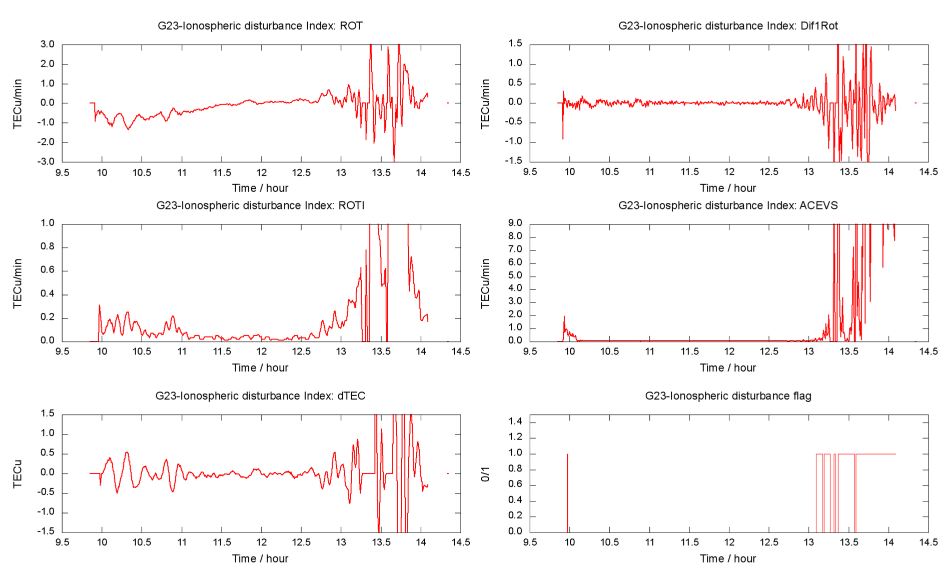

Fig. 7 Observation results of the ionospheric irregularities at QION on March 23, 2013 (G23 satellite).

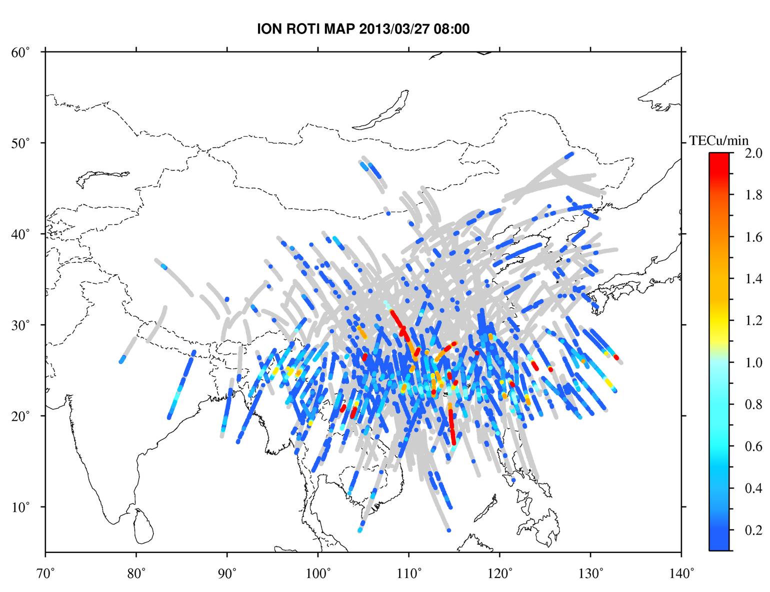

Fig. 8 The ROTI map over China mid- and low- latitude regions on March 23, 2013 at 08:00 UT (1 hour interval).

Summary and outlook

a) IGG/CAS provides BeiDou (also GPS, GLONASS and Galileo) satellite and receiver DCB products to MGEX since mid-October 2015 routinely. Good agreement of BeiDou satellite DCBs with that of DLR is obtained (0.33ns and 0.39ns for BeiDou C2I-C7I and C2I-C6I, respectively).

b) The correction accuracy of BeiDou-based ionospheric grids performs at the level of 0.5m over China region, meaning that BeiDou observations can contribute as independent sources for regional ionospheric modeling.

c) GPS and GLONASS observations provided by CMONOC network allow to detect the ionospheric irregularities over China low-latitude regions. With the development of BeiDou-2, more BeiDou observations will be used for analysis in the near future.

Further reading

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