Performance Evaluation Method for Ionospheric Grid Information of BDS via Dual-frequency Observations

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Abstract. As one of the principal error sources in satellite navigation system, it is ionospheric delay whose correction accuracy directly affects single-frequency positioning accuracy. There are Klobuchar ionospheric model and ionospheric grid information for single-frequency users, provided by basic navigation service and enhancement service respectively in BeiDou Navigation Satellite System. Ionospheric grid information is broadcast as vertical delay estimates at specified ionospheric grid points (IGPs) with a resolution of 5°and 2.5°in longitude and latitude. To evaluate its performance, it proposed a performance evaluation method via dual-frequency observations. And the feasibility of this method was verified by the ionospheric grid information data from November 2017 to October 2018. Performance evaluation results showed that the effective coverage area of ionospheric grid information basically covers China, with a correction deviation of 1.55 TECU and a correction rate of 86.1%. And it is in winter that the correction accuracy of ionospheric grid information is lower and more fluctuating with a correction bias of 1.95 TECU and a correction rate of 81.5% and, but less than 1.47 TECU of bias and more than 86.5% of rate in other seasons. It is higher in both correction bias and correction percentage during the day than at night.

1. Introduction
The satellite navigation system augmentation system was developed due to the implementation of the Selective Availability (SA) policy of the US GPS system. Since the United States cancelled the SA policy in 2000, the accuracy of navigation and positioning has been improved to some extent. With the continuous promotion and deepening of the global satellite navigation system application, the existing satellite navigation system could not meet the requirements of some high-end users in terms of positioning accuracy, particularly for aviation users, regarding availability and integrity. To meet the needs, various satellite navigation enhancement systems have been developed, including the wide-area augmentation system (WAAS) in the USA, the European Geostationary Navigation Overlay Service (EGNOS), Multi-Functional Satellite Augmentation System (MSAS) in Japan, BeiDou Navigation Satellite System (BDS) Augmentation System (BDSAS) in China and the GPS-aided geo-augmented navigation system (GAGAN) in India.

BeiDou regional Navigation Satellite System officially has been providing service since December 27, 2012, with enhancement service provided. Currently, BDS-3 is under construction. According the
overall plan, it will provide basic services to the countries along the ‘Belt and Road and’ the neighbouring regions by 2018, and to complete the constellation deployment with the launch of 35 satellites by 2020 to provide services to global users [1]. Meanwhile, BDSAS will play an increasingly important role in the satellite navigation system development.

BeiDou Navigation Satellite System Augmentation System includes BDS Ground-Based Augmentation System (BDSGAS) and BDS satellite-based augmentation system (BDSSAS) [2]. As an important part of BDS, BDSBAS broadcasts various correction information such as ephemeris error, satellite clock error and ionospheric delay to the users via satellite navigation enhanced signal transponders on geostationary orbit satellites [3], which makes great contribution to the improvements in the positioning accuracy of BDS.

WAAS and EGNOS update ionospheric grid messages every 5 minutes, and the correction percentage is about 80% [4-5]. Ionospheric grid information of BDS is updated every 6 minutes [3], but it will take users about 4 minutes to receive the grid information due to its large amount of data [6]. Due to the limitation of the number of satellites in service in 2012, the data with only 18 ionospheric grid points (IGP) were used to evaluate the ionospheric grid information via the observations just from GEO satellites in the literature [6]. Performances of ionospheric grid information from BDS were evaluated during the solar flares on September 6, 2017 and September 10, 2017 in the literature [7], and during a geomagnetic storm in April 2017 in the literature [8], with the conclusion that ionospheric grid information from BDS performs better relative to Klobuchar ionospheric model provided by basic navigation service. So far, the performance evaluation for ionospheric grid information of BDS is relatively less and not comprehensive. So a more reasonable and comprehensive evaluation method and process are necessary for ionospheric grid information of BDS.

To summarize, it proposes a performance evaluation method via dual-frequency observations, and performance of the broadcast ionospheric grid information is evaluated by the data from November 2017 to October 2018.

2. Ionospheric Grid Information

The grid of ionospheric information covers 7.5 to 55 degrees north latitude and 70 to 145 degrees east longitude divided by 5°×2.5° to 320 IGPs, with an update frequency of 6 minutes/time. The specific grid point number is shown in Figure 1 and Figure 2.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** IGP numbers [3]. The definition of IGP numbers less than or equal to 160 is shown in the figure. When IGP≤160, the corresponding longitudes and latitudes are: L = 70 + INT((IGP-1)/10)×5, and B = 5+(IGP-INT((IGP-1)/10))×10×5. Where, INT(*) refers to round down.
Figure 2. IGP numbers [3]. The definition of IGP numbers more than 160 is shown in the figure. When $IGP > 160$, the corresponding longitudes and latitudes are: $L = 70 + \text{INT}((IGP-161)/10)\times5$, and $B = 2.5+((IGP-160-\text{INT}((IGP-161)/10))\times10)\times5$. Where, $\text{INT}(*)$ refers to round down.

The value in ionospheric grid information is in the scale factor of 0.125 and with unit of meters, expressing the vertical ionosphere delay of the grid point on B1I frequency. The effective value range is 0–63.625 meters, and the IGP is not monitored and not available when the value is 63.750 meters or 63.875 meters respectively.

When the ionospheric grid information is used, the vertical ionosphere delay at the Ionospheric Puncture Point (IPP) is calculated by interpolating the grid value around the IPP, and the reference height of the ionosphere thin layer is 375km [3, 9]. When at most one point surrounding the IPP is not monitored or not available, interpolation can be performed using the spatial bilinear interpolation method given in [3, 10-11]. It should be noted that when only 3 grid points are available, the weight of the unmonitored or unavailable grid points is zero. The ionosphere delay of other frequency points can be converted by multiplying by the scaling factor $k = f_1^2/f_i^2$ ($i=2, 3$; where $f_i$ is the nominal carrier frequency of the $B_i$ signal with the unit of MHZ).

3. Methodology

3.1 Dual-frequency solution for ionospheric VTEC

In this paper, Vertical Total Electron Content (VTEC) obtained by the dual-frequency solution would be used as a reference value for evaluation. According to the principle of satellite navigation and positioning, the pseudo distance difference between B1 and B2 frequency points can be calculated by using BDS pseudo distance observation equation:

$$\text{STEC} = \frac{f_1^2 + f_2^2}{40.28\cdot(f_1^2 - f_2^2)} \left[ (P_2 - P_1) - r_{\text{sat}12}^{\text{alt}} - r_{\text{recv}2}^{\text{alt}} - M_{\text{loc}12} \right]$$ (1)

Where, $r_{\text{sat}12}^{\text{alt}}$ is the delay difference of the launching channel of satellite B1 and B2 frequency points; $r_{\text{recv}2}^{\text{alt}}$ is the delay difference of receiving channel corresponding to frequency points B1 and B2 of the receiver; $M_{\text{loc}12}$ is the difference between the multipath error and random noise in the pseudo-range observations of frequency B1 and B2. After obtaining the Slant Total Electron Content (STEC) on the propagation path, the geometric mapping function [12] was adopted to convert it to VTEC at the zenith direction, i.e.

$$VTEC = \text{STEC} \cdot \cos z$$ (2)
Where, $VTEC$ is the total amount of electrons in the zenith direction of the ionosphere; $STEC$ is the total electron content on the observation path; $z$ is the zenith distance of the IPP.

### 3.2 Evaluation strategy

The ionospheric grid information updates every 6 minutes, and the ionospheric grid information received at time $t_0$ is used to correct the ionosphere delay in the next 6 minutes. Therefore, we use the data of $t_0 \sim t_0 + 6 \text{ min}$ to evaluate the ionospheric grid information received at time $t_0$. The specific evaluation process is as follows.

a. Calculate the geographic latitude and longitude of the ionospheric puncture point using Equation 3 and Equation 4.

$$\phi_M = \arcsin(\sin \phi_u \cos \psi + \cos \phi_u \sin \psi \cos A)$$  \hspace{1cm} \text{(3)}

$$\lambda_M = \lambda_u + \arcsin \left( \frac{\sin \psi \sin A}{\cos \phi_M} \right)$$  \hspace{1cm} \text{(4)}

Where, $\phi_u$ is the user's geographic latitude in the unit of arc, and $\lambda_u$ is the user's geographic longitude in the unit of arc; $A$ is the satellite azimuth in the unit of arc; $\psi$ is the geocentric angle in the unit of arc between the user and the IPP.

b. Use the rule that the ionospheric grid information is effective for interpolation when at most one point surrounding the IPP is not monitored or is not available to determine if the puncture point is available for performance evaluation. If the VTEC at the IPP can be interpolated by ionospheric grid information, the IPP participates in the assessment, otherwise it will not participate.

c. Calculate the ionospheric VTEC of IPP participating in the assessment by dual-frequency solution according to Subsection 3.1.

d. Calculate the ionospheric VTEC of IPP participating in the assessment by the spatial bilinear interpolation method with ionospheric grid information.

e. The correction accuracy is obtained by using Equation 5 and Equation 6 and the index includes the correction bias $Bias$ and correction percentage $V$.

$$Bias = \left| VTEC_{grid} - VTEC_{ref} \right|$$  \hspace{1cm} \text{(5)}

$$V = 1 - \left( \frac{VTEC_{grid} - VTEC_{ref}}{VTEC_{ref}} \right) \times 100\%$$  \hspace{1cm} \text{(6)}

Where, $VTEC_{grid}$ is the VTEC of IPP participating in the assessment by the spatial bilinear interpolation method with ionospheric grid information, and $VTEC_{ref}$ is the ionospheric reference ionospheric VTEC value replaced with the VTEC of IPP participating in assessment by dual-frequency solution.

f. The average correction accuracy of the IPPs in the grid block surrounding the IGP is obtained as the accuracy of the IGP.

### 4. Data

The dual-frequency observations from continuous dual-frequency receivers distributed throughout China, and the ionospheric grid information from D2 navigation message from November 2017 to October 2018, including both the normal period and the ionospheric disturbance period, were adopted as follow-up experimental data. Then, the VTEC via B1B2 dual-frequency observations was calculated as the reference value in the performance evaluation of ionospheric grid information.

### 5. Results and discussion

#### 5.1 Correction accuracy of IGP
Figure 3 shows the correction bias of ionospheric grid information at 9:00 BDT on October 31, 2018. It can be seen that the effective coverage area approximately covers for one half of the ionospheric grid information coverage area, which basically covers the Chinese region, and only some sea areas and areas near the boundary are not covered. Within the effective coverage area, the correction accuracy of the ionospheric grid information in the mainland and surrounding areas is good, with the bias within 3TECU, most within 2TECU, and some areas in South China Sea with poor correction accuracy, with the correction bias even up to 5.5TECU. The reasons for the large invalid coverage area and the poor correction accuracy in some areas of the south China sea are limited distribution of measurement stations, resulting in the lack of ionospheric puncture points or the insufficient number of effective puncture points in this area, or the poor quality of data received due to the too small satellite altitude Angle. If the sea area and overseas stations can be strengthened, the service scope and accuracy of ionospheric grid information will be improved significantly.

5.2 Daily change of correction performance

Figure 4 shows the average VTEC and correction accuracy of ionospheric grid information within 24 hours at BDT. The figure shows that the correction bias of ionospheric grid information are higher during the day (about BDT 0:00-12:00) than at night (about BDT 12:00-24:00) with a max value at about BDT 8:00, and is about 2.2TECU. There is a relatively gentle change at night with a bias of about 1.45TECU, especially from12:00 to14:00 and 20:00 to 22:00 BDT. The correction percentage of ionospheric grid information is higher in the daytime than at night, with a relatively flat single-peak structure throughout the day. It reaches its peak at about 7:00 BDT, about 91%, and its lowest point at 22:00 BDT, about 72%. From the analysis, correction bias and percentage of ionospheric grid information are higher than those during the day night, for the reason that the mean VTEC as the reference value and correction bias both change over time, although the VTEC and fixed deviation has a relatively consistent trend, however the VTEC changes proportion bigger, which leads to that the correction percentages with large deviation are still bigger in numerical value.
Figure 4. Correction bias and percentage of ionospheric grid information on October 31, 2018.

5.3 Seasonal change of correction performance

Figure 5 and Figure 6 respectively show the distribution of corrected errors and corrected rates of ionospheric grid information in different months. It can be seen that the variation of correction bias fluctuates greatly in November and December 2017. Moreover, in November, December 2017 and January 2018, the correction bias is large and the correction accuracy is poor. In November, December
and January, 2017, the correction percentage fluctuates more greatly, with low correction rate and poor correction accuracy.

Figure 6. Monthly distribution of correction percentage of ionospheric grid information. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the ‘+’ symbol.

Table 1. Correction accuracy of ionospheric grid information in different seasons

|                  | Spring (Feb-Apr) | Summer (May-July) | Autumn (Aug-Oct) | Winter (Nov-Jan) | Average |
|------------------|------------------|-------------------|------------------|------------------|---------|
| **Bias (TECU)**  |                  |                   |                  |                  |         |
| Average          | 1.45             | 1.34              | 1.47             | 1.95             | 1.55    |
| Max              | 1.93             | 1.62              | 1.87             | 2.54             | -       |
| Min              | 1.19             | 1.12              | 1.22             | 1.32             | -       |
| **Correction Accuracy (%)** |                  |                   |                  |                  |         |
| Average          | 86.8             | 89.1              | 86.9             | 81.5             | 86.1    |
| Max              | 90.2             | 90.9              | 89.0             | 87.7             | -       |
| Min              | 83.5             | 86.5              | 83.1             | 76.6             | -       |

Table 1 shows the difference in correction accuracy of ionospheric grid information in different seasons within the effective coverage area. As can be seen from the above table, the average annual deviation of ionospheric grid information is 1.55TECU, of which the average correction bias of ionospheric grid information in winter is 1.95TECU, and the correction bias of other seasons is better than 1.50TECU. The annual average correction percentage of ionospheric grid information is 86.1%, including 81.5% in winter and no less than 86.8% in other seasons. In summary, the correction accuracy of ionospheric grid information in winter is lower than those in other seasons, and it has stronger fluctuation.

6. Conclusions
BDSAS has been playing an increasingly important role in the satellite navigation system development. Ionospheric grid information is an important message broadcasted in BDSAS to make great contribution to the improvements in the positioning accuracy of BDS. However, the performance evaluation for ionospheric grid information of BDS is relatively less and not comprehensive. The performance evaluation method for ionospheric grid information of BDS via dual-frequency
observations was designed to meet the above. Moreover, as we shall see, the performance evaluation method performs pretty well with ionospheric grid information data, such as that from November 2017 to October 2018.

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