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Ionospheric TEC Monitoring over Jeju Island using the Chinese BeiDou Satellite Navigation System

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ABSTRACT

The Chinese BeiDou Satellite Navigation System consists of three kinds of constellations: the geostationary Earth orbit (GEO), the inclined geosynchronous satellite orbit (IGSO), and the medium Earth orbit (MEO). The BeiDou has expanded its service coverage from regional to global. Recently, the BeiDou has been widely used in ionospheric total electron content (TEC) research. In this study, we analyzed the BeiDou signals for ionospheric TEC monitoring over Jeju Island in South Korea. The BeiDou GEO TEC showed a clear pattern of diurnal variations. In addition, we compared the TEC values from the BeiDou GEO, the BeiDou IGSO, GPS, and International GNSS Service (IGS) Global Ionosphere Maps (GIM). There was a difference of about 5 TEC units between the BeiDou GEO and the IGS GIM. This may be due to the altitude difference between the different navigation satellites.

Keywords: BeiDou, GEO, TEC, GIM

1. INTRODUCTION

The Global Navigation Satellite System (GNSS) is useful for efficiently calculating the total electron content (TEC) of the ionosphere. GNSS research for the ionospheric TEC began from the mid-1990s (Wilson & Mannucci 1993, Hajj et al. 1994, Coco et al. 1995, Ho et al. 1996, Calais & Minster 1996, Davies & Hartmann 1997). GNSS reference stations, evenly distributed around the world and easy to deploy on the ground, are effective in monitoring unpredictable changes in the ionosphere. The Global Positioning System (GPS) is one of the systems that contributed the most to ionospheric TEC study. The stable operation of GPS satellites and the increasing number of GNSS reference stations play a major role in analyzing the characteristics of the ionosphere.

Recently, China has developed the BeiDou Navigation Satellite. This system will be a constellation of 35 satellites, which include 5 geostationary earth orbit (GEO) satellites (58.75°E, 80°E, 110.5°E, 140°E, 160°E), 27 medium earth orbit (MEO) satellites, and 3 inclined geosynchronous earth orbit (IGSO) satellites (BeiDou ICD 2012). BeiDou is preparing full global service for positioning, navigation, and timing. A wide variety of research has also been performed on ionospheric TEC using BeiDou. Tang et al. (2014) estimated the ionospheric TEC using BeiDou observations. They used GPS TEC and the Global Ionosphere Map (GIM) to compare its performance. In addition, they presented that there is a difference of about 4 TEC Units (TECU) and 6 TECU on average between BeiDou and GIM at high and low latitudes, respectively. Hu et al. (2017) developed an ionospheric observation network using BeiDou in China to monitor the space environment. Recently, some studies have been

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conducted on combining observations of GPS, GLONASS, Galileo, and BeiDou for regional ionospheric models or global ionospheric modeling (Zhang et al. 2015, Abdelazeem et al. 2017).

In this study, we monitor changes in the ionospheric TEC using data of BeiDou GEO and IGSO satellites that is obtained from the JEJU GNSS reference station in Jeju Island. Due to the geostationary orbit characteristics of BeiDou GEOs, their signals pass through the ionosphere at specific locations. The consecutive monitoring of TEC changes at these locations plays a significant role in researching the ionosphere. Furthermore, we calculate the GPS TEC to verify the TEC produced by BeiDou GEO and compare it with IGS GIM.

2. DATA PROCESSING METHOD

BeiDou navigation satellites transmit three signals (B1~1561.1 MHz, B2~1207.14 MHz, and B3~1268.52 MHz) to the ground. In this study, we use B1 and B2 signals to calculate the ionospheric TEC. The measurement equations for BeiDou B1 and B2 are shown in Eqs. (1) and (2).

$$B_1 = \rho + c(dt^{s1} - dt_{r1}) + I_1 + T + \varepsilon_{B1} \quad (1)$$

$$B_2 = \rho + c(dt^{s2} - dt_{r2}) + I_2 + T + \varepsilon_{B2} \quad (2)$$

where ρ is the geometric distance between the satellite and the ground receiver. dt^s and dt_r are the clock offsets of each satellite and receiver, respectively. I_1 and I_2 are the ionospheric delay errors of the two signals. T is the tropospheric delay error. ε_{B1} and ε_{B2} represent the noise of the two signals, respectively.

When we use dual-frequency measurements, 'Geometry-Free' linear combination is used to calculate the ionospheric TEC. In this study, carrier phase data is considered to increase TEC accuracy. The carrier phase is very sensitive to signal loss. It may cause difficulties in integer ambiguity resolution. It can also degrade the accuracy of TEC values. Eq. (3) shows a linear combination between Eqs. (1) and (2).

$$B_4 = B_1 - B_2 = (I_1 - I_2) + [c(dt^{s1} - dt^{s2}) - c(dt_{r1} - dt_{r2})] \quad (3)$$

where (dt^{s1}-dt^{s2}) and (dt_{r1}-dt_{r2}) are the B1-B2 Differential Code Bias (DCB) of the BeiDou satellite and receiver, respectively. The satellite and receiver DCBs are a significant factor in calculating the ionospheric TEC. The DCB (B1-B2) values of BeiDou satellites used in this study were calculated by the Chinese Academy of Science (CAS). The CAS provides B1 and B2 BeiDou satellite signals as C2I and C7I values. Therefore, the DCB of BeiDou satellites is expressed as C2I-C7I. Fig. 1 shows the C2I-C7I DCB values for BeiDou GEO and IGSO satellites. The satellite PRNs from C01 to C05 are BeiDou GEO satellites. The PRNs from C06 to C10 represent IGSO satellites. Currently, BeiDou has 5 IGSO satellites. In the end, it will be adjusted to 3 IGSO satellites. As shown in Fig. 1, the C2I-C7I DCB values of BeiDou GEO satellites are greater than those of IGSO satellites on average.

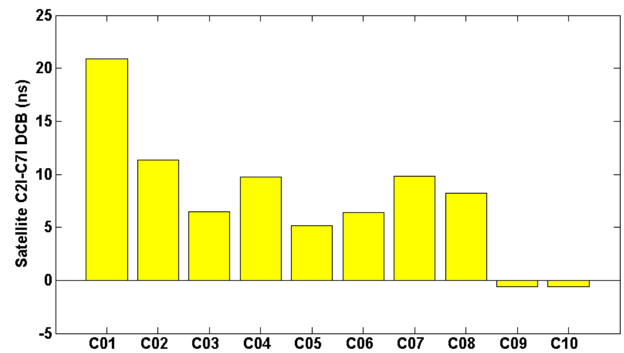

Fig. 1. BeiDou satellite C2I-C7I DCB values on 1 May, 2019.

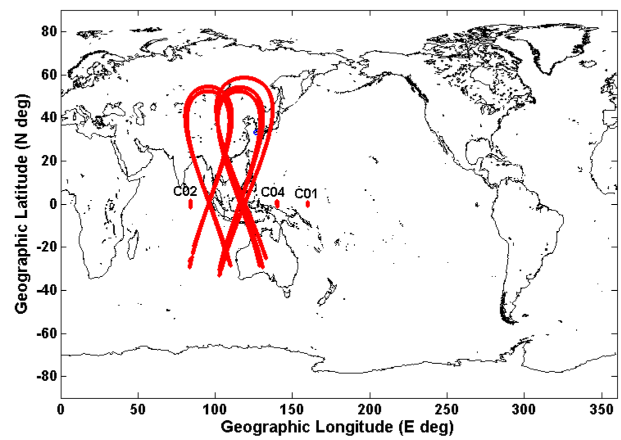

Fig. 2. The ground tracks of the BeiDou GEO and IGSO satellites at the JEJU GNSS stations on May 1, 2019.

3. RESULTS AND ANALYSIS

In this study, we processed the BeiDou data that was received at JEJU GNSS reference station from May 1, 2019, to May 31, 2019. BeiDou is useful in monitoring regional ionospheric TEC because it consists of GEO and IGSO satellites for regional navigation service.

Fig. 2 shows the ground tracks of BeiDou GEO and IGSO satellites calculated by using navigation data received from the JEJU GNSS reference station. For the receiver of the JEJU GNSS reference station, an elevation angle of the satellites is set to 10 degrees. The JEJU GNSS reference station can't receive signals from IGSO satellites below a latitude of 30°

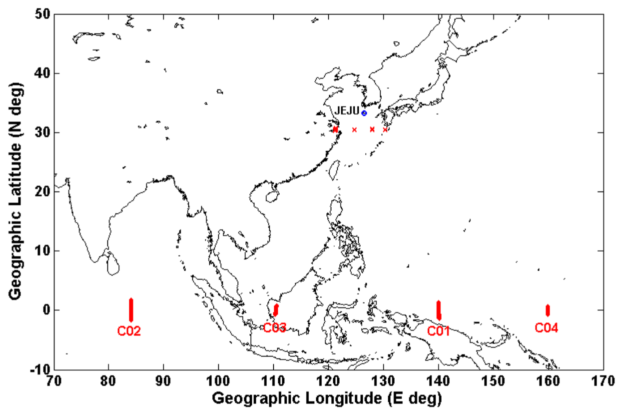

Fig. 3. BeiDou GEO's ground tracks and IPPs. The blue circle is the location of the JEJU GNSS station. The red crosses represent the IPPs of the BeiDou GEO satellites.

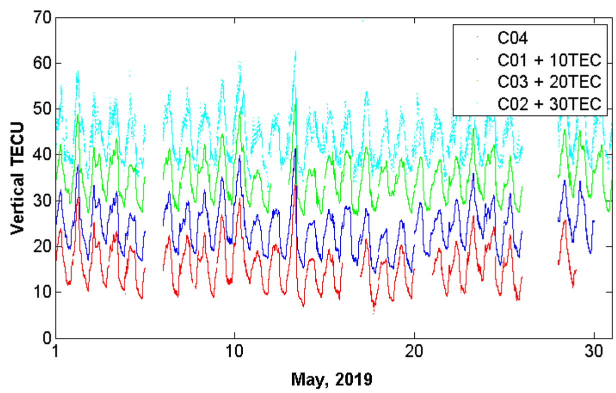

Fig. 4. BeiDou GEO TEC variations at the JEJU station from May 1 to May 31, 2019. Note that different offsets are added to the BDS GEO TEC values.

S based on the ground track. The ground tracks of IGSO satellites show two figure-eight shapes with different central longitudes relative to the Earth's equator. Signals from four BeiDou GEO satellites are observed, except for satellite C05. Since satellite C05 is located at 50°E, the JEJU reference station can't receive signals from the satellite C05.

Fig. 3 shows the IPPs of BeiDou GEO satellites calculated by using the data observed from the JEJU GNSS reference station. In this study, we calculated IPPs under the assumption that the ionospheric TEC is concentrated at a specific altitude of 300 km. As seen from Fig. 3, the orbits of GEO satellites fluctuate slightly in a north-south direction every day based on the ground tracks. The IPP is slightly affected by changes in the position of GEO satellites. The satellite C02 has a large orbital change. Changes in IPP of the satellite C02 are slightly larger than those of other satellites.

The IPPs of BeiDou GEO satellites are located at the latitude of about 30 degrees. They are spaced from each other by about 3 degrees in longitude. In general, IPP is related to the altitude for the TEC model. The altitude is set within the range of 250 km to 450 km. The IPP altitude needs to be properly set with the TEC modeling method.

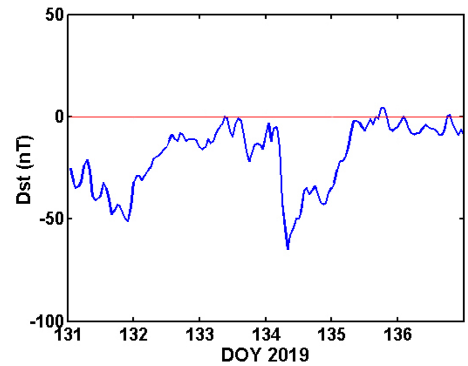

Fig. 5. Variation of the Dst index from DOY 131 to 136, 2019.

Fig. 4 shows the change in vertical ionospheric TEC estimated by using BeiDou GEO B1 and B2 observation data. Ionosphere TEC is expressed in TEC units (TECU), and 1 TECU means that 10 ^16 free electrons are distributed in a square meter of space. As shown in Fig. 4, the TEC time-series for four BeiDou GEO satellites are considered. Based on BeiDou C04, offsets of +10, +20, and +30 TECU were applied to satellites C01, C03, and C02 TEC, respectively. This is to avoid overlapping the image. We could not estimate the TEC on some dates. There was a loss of observations in some sections and a lack of navigation data from some satellites. The TEC value for the satellite C02 was more unstable compared to other satellites. This is caused by a frequent signal loss at the JEJU reference station.

3.1 BeiDou GEO TEC Changes During Geomagnetic Storms

There were two minor geomagnetic storms during May 2019. Fig. 5 presents the change in the Dst, which is an index of magnetic activity, during geomagnetic storms. Geomagnetic storms occurred on May 10, 2019 and May 13, 2019 (DOY 131 and DOY 134), and the Dst values reached below -50 nT. Using BeiDou GEO observation data during this period, we analyzed the TEC changes in Korea in terms of time series.

Fig. 6 shows the TEC changes calculated using observations from three BeiDou GEO satellites (C04, C01, and C03) from DOY 131 to 136 in 2019. In Fig. 6, offsets of +7 TECU and +14 TECU were applied to the TEC values of BeiDou C01 and C03 satellites, respectively. We analyzed the changes in BeiDou TEC during the period of geomagnetic storms. The TEC values increased significantly at DOY 131 and 134 due to the direct influence of the storms. The ionospheric TEC increased about 10 TECU on average compared to the quiet

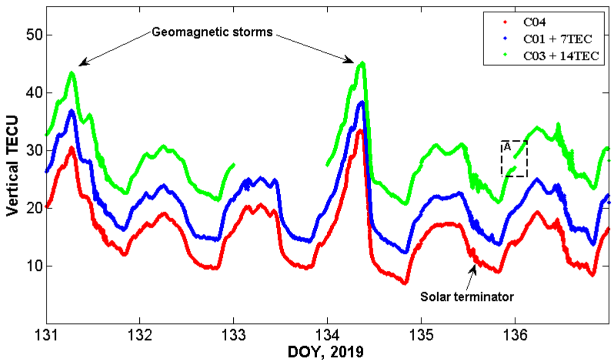

Fig. 6. BeiDou GEO TEC time series from DOY 131 to 136, 2019.

days.

An interesting thing is the TEC disturbance occurred at DOY 135 and 136, which lasted up to 2 hours. The TEC disturbance occurred from 10:00 to 12:00 UT (19:00 ~ 21:00 KST). Afraimovich et al. (2010) reported that solar terminator was the cause of instability and disturbances in the ionospheric plasma and acoustic gravity waves. Therefore, these TEC disturbances observed by BeiDou GEO satellites may be related to the solar terminator.

The daily changes in TEC generally maintain continuity. The BeiDou GEO C03 satellite, however, observed TEC discontinuities at the end of DOY 135 and the beginning of DOY 136. Fig. 6 shows such TEC discontinuities marked as a black dotted box. TEC discontinuities between two different days were not observed in BeiDou C01 and C04. These discontinuities, which were only observed by C03, are speculated as large changes in satellite C2-C7 DCB values. In this study, we assumed that the C2-C7 DCB values of BeiDou satellites have not changed significantly for almost one month and applied the DCB values of the satellites and receivers on May 1, 2019. If there were significant changes in the receiver DCB values, the TEC discontinuities would also have appeared in C01 and C04 satellites, as well as in C03 satellite. Therefore, the main cause of TEC discontinuities would be the change in C03 satellite DCB values estimated on a daily basis.

3.2 Comparison of BeiDou TEC and GPS TEC

To verify the BeiDou TEC, we calculated TEC using GPS data of the same period. We also computed the vertical TEC at a location of the JEJU GNSS station from the IGS GIM with a time resolution of 2 hours and a spatial resolution of 5°×2.5°.

Fig. 7 shows the changes in TEC over time using BeiDou GEO, IGSO, and GPS data obtained from JEJU GNSS reference station on May 1, 2019. The BeiDou and GPS TEC values were both calculated every 30 seconds. As shown

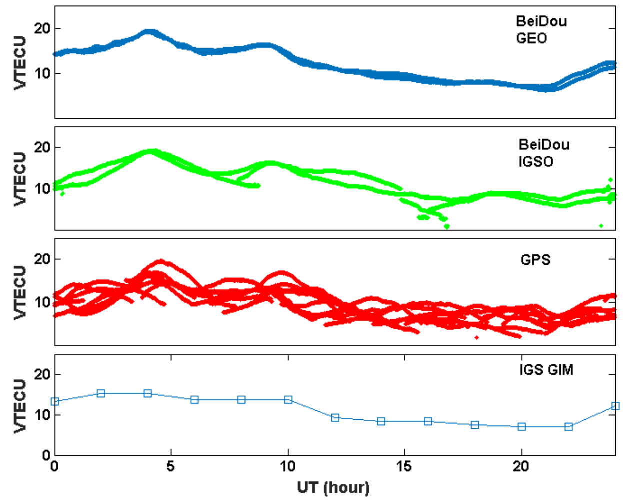

Fig. 7. TEC changes for BeiDou GEO, BeiDou IGSO, GPS, and IGS GIM on May 1, 2019.

in Fig. 7, the TEC of BeiDou GEO shows a distinct diurnal variation, changing from 7 TECU to 20 TECU. BeiDou IGSO shows similar TEC daily changes to BeiDou GEO, and sudden TEC changes which are observed at certain periods caused by signal loss due to low satellite elevation angles. The third and fourth panels in Fig. 7 represent the diurnal variations of GPS TEC and IGS GIM, respectively. The GPS TEC changes from 2 TECU to 20 TECU. The diurnal pattern of them is very similar to that of BeiDou TEC. However, GPS and BeiDou GEO and IGSO satellites have different orbit characteristics. Therefore, it is impossible to observe TEC values at certain points continuously.

IGS GIM also shows distinct diurnal variations as in the case of BeiDou and GPS TEC. One important thing is that IGS GIM has a maximum of about 15 TECU. There is a clear difference between IGS GIM and BeiDou GEO TEC. This difference can be attributed to the different altitudes of the GNSS satellites. Therefore, the altitude difference between BeiDou GEO satellites and GPS MEO satellites can affect TEC values.

Fig. 8 shows the IPP distributions of GPS and BeiDou GEO and IGSO. The dotted green line indicates the IPP distribution of GPS satellites. The GPS IPPs are widely and evenly distributed due to the satellite orbit characteristics. On the other hand, the IPPs of BeiDou GEO and IGSO shown in red dotted lines, are completely different from GPS IPPs. The IPPs of BeiDou GEO are distributed in 4 different points. The IPPs of BeiDou IGSO show loops in the shape of figure-eight (ring). The latitude of the intersection point is about 30° N.

As a result, BeiDou GEO and IGSO can be efficient for continuous observations of ionospheric TEC at certain points, as shown in the IPP distributions of BeiDou GEO and IGSO.

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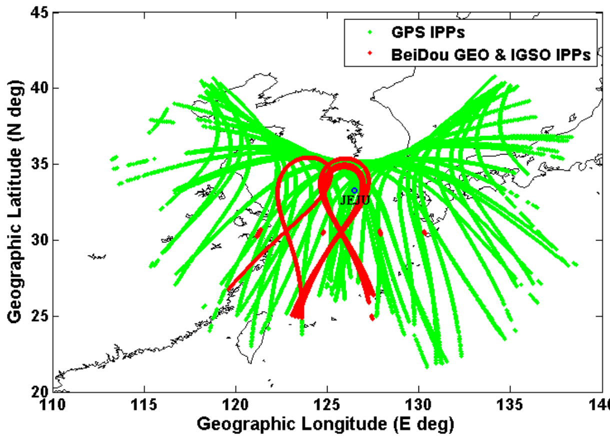

Fig. 8. IPP distribution for BeiDou GEO, BeiDou IGSO, and GPS on May 1, 2019. The green and red dots represent the IPPs location for GPS, BeiDou GEO, and IGSO, respectively.

4. CONCLUSIONS

In this study, we calculated the ionospheric TEC using BeiDou GEO and IGSO data obtained from JEJU GNSS station from May 1 to May 31, 2019. BeiDou GEO and IGSO satellites are operated as regional navigation systems. They are efficient for monitoring changes in the ionospheric TEC in specific areas. We calculated BeiDou GEO and IGSO TEC, except for data loss and signal loss from certain satellites in some sections. In addition, we considered two elements to verify the BeiDou TEC values. First, we monitored changes in TEC during the period of geomagnetic storms. There were two weak geomagnetic storms during the data processing period. The BeiDou GEO TEC on the corresponding days increased about 10 TECU compared to the quiet days. Therefore, we suggest that BeiDou can be used to monitor changes in the ionospheric TEC with changes in the space environment.

Second, we calculated the TEC from BeiDou GEO, BeiDou IGSO, GPS, and IGS GIM. We also compared these values to verify the accuracy of BeiDou TEC. The different TEC values showed distinct diurnal variations. In particular, there was a difference in TEC between BeiDou GEO and IGS GIM. It might be attributed to the altitude difference between the two different navigation systems.

We expect that BeiDou data can help scientific research on ionospheric changes, disturbances, and structural heterogeneity.

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AUTHOR CONTRIBUTIONS

Methodology, B.K. Choi and W.K. Lee; software, B.K. Choi; formal analysis, B.K. Choi and D.H. Sohn; investigation, S.M. Yoo, K.M. Roh, J.M. Joo, and M.B. Heo; visualization, B.K. Choi.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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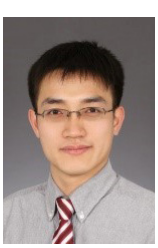

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