Preliminary Analysis of Ionospheric Responses to Geomagnetic Storms Using the BDS GEO Satellites

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Abstract. The rapid development of Global Navigation Satellite System (GNSS) provides a reliable way to monitor the ionospheric response of geomagnetic storms. Compared with other types of satellites, the advantage of using the Beidou Navigation Satellite System (BDS) Geostationary Earth Orbit (GEO) satellites to monitor the ionosphere is that it has almost fixed Ionospheric Pierce Points (IPPs). When using the GEO satellites to monitor the ionosphere, the earth sites only need consider the ionospheric temporal change without considering the spatial change. In addition, the ionospheric delay directly calculated by the combined observations does not introduce model error and fitting error, and can obtain continuous and high-precision ionospheric delay series. According to the Disturbance Storm Time index (DST index) provided by World Data Center for Geomagnetism of Kyoto, three large geomagnetic storms occurred in 2015. This article uses the BDS dual-frequency observations to calculate the ionospheric VTEC sequences during the geomagnetic storms at the four sites KZN2, JFNG, SIN1, and CUT0, respectively; and the ionospheric responses during the three large geomagnetic storms in 2015 are preliminarily analysed. The results show that the ionospheric responses to geomagnetic storms are mainly positive and negative anomalies. Combining the results of each site during three geomagnetic storms, it is certain that different seasons have a decisive impact on the positive and negative ionospheric responses of geomagnetic storms.

1. Introduction
As an important part of the Sun-Earth space environment, the earth ionosphere refers to the whole space area between 50 km and 2000 km from the earth's surface [1]. The ionosphere is affected by solar and geomagnetic activities due to its spatial position, and expresses rich characteristics of temporal and spatial change. How does the earth's ionosphere respond to a geomagnetic storm after intense solar activity? The significance of studying this problem is to better understand the characteristics of ionospheric time-space changes and improve the model and prediction of ionospheric activities. It is also very important for satellite navigation, short wave and Loran timing, radar detection and other electromagnetic signals affected by the ionosphere [2].

With the rapid development of satellite navigation technology, it has become a very important and widely used method to measure and obtain the ionospheric delay TECs by GNSS satellites. This makes it possible to monitor the ionospheric response of geomagnetic storms using navigation satellite
signals. Scholars all over the world have done a lot of research on the dependence between the ionosphere and the earth. For example, Afraimovich E.L. et al. proposed to use the Global Electron Content (GEC) to track the changes of solar activity in 2008 [3], Ortikov M.Y. et al. used the ionosphere index to represent solar activity according to the measured data of spacecraft signal characteristics [4], Nusinov A.A. et al. proposed that the ionosphere is too researched natural detectors for the variation of EUV flux [5], Liu L.B. et al. reviewed the relationship between ionosphere and solar activity [6], Zhao H.S. et al. analyzed the variation characteristics of ionospheric TEC in high and low years of solar activity [7], Yao Lu studied the spatial correlation and number of ionospheric TEC according to the application of assimilation in seismic ionosphere [8], Yao Li studied the ionosphere response characteristics of seismic activity and solar wind disturbance [9].

However, most of the above studies are based on GPS satellites observation. Because IPPs of GPS satellites move at the speed of hundreds of meters per second, it cannot directly give the characteristics of the ionospheric changing with time at the fixed IPP. When using the model or mathematical fitting to solve the ionosphere VTEC value at the fixed IPP, the model and calculation error will inevitably be introduced. Therefore, this paper considers relying on BDS GEO satellites data for ionosphere monitoring. BDS-2 has five GEO satellites in orbit, which has irreplaceable advantages for observing the ionosphere at fixed IPP.

2. Materials and methods

2.1. GEO satellites and sites

BDS-2’s nominal space constellation includes 5 GEO satellites; BDS-3’s nominal space constellation includes 3 GEO satellites. At present, BDS is in a transitional period, and BDS-3’s GEO satellites have not been launched. Therefore, this paper intends to use BDS-2’s 5 GEO Satellite multi frequency observation data to obtain the ionospheric TEC sequence. See Table 1 for BDS-2’s GEO satellite information.

Table 1. The information of BDS-2’s GEO satellites [10].

| PRN | SVN | Satellite Type | Longitude Deg. | Launch Date |
|-----|-----|----------------|----------------|-------------|
| C01 | GEO1 | BDS-2          | 140° E         | 2010-01-16  |
| C02 | GEO6 | BDS-2          | 80° E          | 2012-10-25  |
| C03 | GEO7 | BDS-2          | 110.5° E       | 2016-06-12  |
| C04 | GEO4 | BDS-2          | 160° E         | 2010-10-31  |
| C05 | GEO5 | BDS-2          | 58.75° E       | 2012-02-24  |

GEO satellite is located at the fixed point over the equator, and its static characteristics relative to the ground make the position of the IPP of the GEO satellite observed by the receiver basically remain unchanged, which can realize the continuous monitoring of the ionosphere at the fixed IPP. Figure 1 shows the visibility (left) and IPPs (right) of BDS-2 satellites. C01-C05 are five GEO satellites. Compared with other satellites (IGSO and MEO), the observation of the monitoring site on GEO satellite is continuous, and the IPPs are basically fixed.

Figure 1. The visibility and IPPs of BDS-2 satellites observed at CUT0 site
In order to show the observation results of different geographical locations, and combined with the characteristics of GEO satellites covering the eastern hemisphere, KZN2 site of high latitude in the northern hemisphere, JFNG site of mid latitude in the northern hemisphere, SIN1 site near the equator and CUT0 site of mid latitude in the southern hemisphere are respectively selected (See Table 2 for details). All of the four sites can obtain continuous observation of GEO satellite.

Table 2. The information of 4 sites.

| No. | Site   | Coordinates     | Receiver type | Antenna type    |
|-----|--------|-----------------|---------------|----------------|
| 1   | KZN2   | 55.80° N, 49.12° E | TRIMBLE NETR9 | TRM59800.00    |
| 2   | JFNG   | 30.52° N, 114.50° E | TRIMBLE NETR9 | TRM59800.00    |
| 3   | SIN1   | 1.34° N, 103.68° E | TRIMBLE NETR9 | LEIAR25.R3     |
| 4   | CUT0   | 32.00° S, 115.90° E | TRIMBLE NETR9 | TRM59800.00    |

2.2. VTEC sequence and dTEC
BDS-2 satellites transmit signals of three frequencies, and there are three combinations when calculating ionospheric delay with dual-frequency observations, while the conversion coefficients of B1&B3 and B2&B3 are greater than those of B1&B2 when calculating TEC. According to the error propagation law, the larger the conversion coefficient is, the greater the TEC calculation error will be. Therefore, B1&B2 dual-frequency combination is selected to calculate TEC as the optimal [11]. The accuracy of VTEC calculated by B1&B2 has been evaluated. The accuracy based on carrier phase observation is less than 0.69 TECU, and the accuracy of code observation is 5.54 TECU [12].

We choose the mean values of corresponding epochs in the 10-day with quiet background conditions before each geomagnetic storm as the TEC references. The TEC is stable in the same epoch and location without specific events. Here we define the part of out of two times standard deviation threshold as the quantity of ionospheric anomaly. As described in Formula (1), if TEC is less than the lower boundary, the ionospheric storm should present a negative anomaly; otherwise, it shows positive anomaly.

$$dTEC = \begin{cases} 
T_{EC_t} - \left( \text{mean}(T_{EC_{q,t}}) + 2 \text{std}(T_{EC_{q,t}}) \right), & \text{positive} \\
T_{EC_t} - \left( \text{mean}(T_{EC_{q,t}}) - 2 \text{std}(T_{EC_{q,t}}) \right), & \text{negative} 
\end{cases}$$

(1)

2.3. DST Index
The change of the earth's magnetic field mainly comes from the influence of both inside and outside. The external cause refers to the action of the current system produced by the outside of the earth (including the solar system and the whole space), and the internal cause refers to the induced current produced by the earth itself. According to the daily variation of geomagnetism, it can be divided into quiet day and disturbed day. When the earth's magnetic field changes dramatically due to external factors, it is called geomagnetic storm. The occurrence of geomagnetic storm will cause a series of chain reactions in the space environment such as ionosphere disturbance, and then affect human activities such as radio communication and navigation positioning.

DST index is established to monitor the change of geomagnetism at all times. Its value is the average value of hourly geomagnetic horizontal intensity change of four geomagnetic sites with roughly uniform longitude interval measured near the equator. Its unit is nanoteslas (nT), and its range can be from tens of nT to thousands of nT. And the decrease of the value indicates that the magnetic disturbance amplitude increases gradually.

The three largest geomagnetic storms (as shown in Figure 1) occurred on March 17, 2015 (doy76), June 23, 2015 (doy174), and December 20, 2015 respectively. Every geomagnetic storm can be divided into three phases: primary, main and recovery phases. The red lines in the figure represent the main phase of the geomagnetic storm, and the blue lines before and after are the primary and recovery phases of the geomagnetic storm, respectively. This paper will analyse the ionosphere response based
on these three time periods. All DST index are from the World Data Center for Geomagnetism of Kyoto (http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html).

Figure 2. The three strongest geomagnetic storms in solar cycle 24

3. Results and analysis

3.1. Corresponding Situation of VTEC and DST

Figure 3 shows the corresponding situation of TEC and DST of KZN2, JFNG, SIN1 and CUT0 sites during the three geomagnetic storms in 2015. It can be seen from the figure that when the geomagnetic storms occur, the ionospheric TEC will be greatly abnormal. (1) when the first geomagnetic storm occurs: the TEC of KZN2, JFNG and CUT0 sites corresponding to the main phase of the storm has a process of first increasing and then sharply decreasing, while the ionospheric TEC of SIN1 site near the equator has only a small decrease, which is not obvious compared with that before and after the storm. (2) when the second geomagnetic storm occurs: the northern hemisphere in summer, the TEC of KZN2 and JFNG sites in the main phase decreased sharply, and then in the recovery phase, the TEC was always lower than the level of about 10 TECU in the quiet background. The TEC of SIN1 site in the main phase increased abruptly, and that of CUT0 site in the main phase was always lower than that of the ionosphere in the calm background. (3) when the third geomagnetic storm occurs: the TEC of the four sites increased obviously in the main phase of the storm, while the TEC of KZN2 site in the high latitude increased relatively less than that of the other three sites.

Based on the above it is certain that the occurrence of geomagnetic storm will lead to the abnormality of the ionospheric TEC, and sometimes the TEC increases sharply and sometimes decreases sharply. The reason for analysis is that in different seasons, the ion concentration and temperature over the earth are not similar, when the temperature increases, the ions move faster and become thinner, which will cause the TEC to decrease rapidly. Conversely, when the temperature decreases, the ions decelerate and the ions overlap with each other, causing the TEC to increase rapidly.
3.2. Ionospheric response

In order to further obtain the ionospheric response during the geomagnetic storm, the dTEC of the corresponding site is calculated according to formula (1), and the sunrise and sunset time of each site during the geomagnetic storm are obtained according to the time and date website (https://www.timeanddate.com/sun/). The blue line in Figure 4 represents the VTEC value of the dual-frequency ionosphere calculated by BDS. The green line is the mean ionospheric reference value in the selected calm period. The red line is dTEC, which indicates the change in ionospheric delay. The white background indicates daylight, and the gray background means nighttime. The vertical dashed, solid and dash dot lines mark the epoch of storm sudden commence (SSC), the peak of DST, and the end of the recovery phase, respectively.

It can be seen from the Figure 4 that the DST peaks of the first and the third storms occurred at dawn, before which the ionosphere showed positive changes in varying degrees, and the third was more obvious; after this time, the figure (a) showed significant negative changes, except for the SIN1 site in figure (c). The ionosphere anomaly of the second storm lasted the whole cycle of the storm, and there was no significant anomaly in the main phase of the storm, but the ionosphere of the four sites after the peak value of DST showed negative changes all the time.

4. Conclusions

Three major geomagnetic storms occurred in 2015 during the 24th cycle of solar activity. Using the VTEC sequence calculated by the dual-frequency observation of the BDS-2 GEO satellite, the ionospheric responses corresponding to KZN2, JFNG, SIN1, and CUT0 four sites were studied. Compared to IGSO and MEO satellites, the main advantage of using BDS GEO satellites is that the
IPP of GEO is almost stationary, and the high-precision VTEC sequence derived from fixed IPP is always continuous. First of all, the large geomagnetic storm will definitely lead to an abnormal response of the ionosphere TEC, and sometimes the TEC increases sharply and sometimes decreases sharply. The preliminary consideration is that the temperature of the ionosphere above the earth is different and the ion velocity is different under different seasons. When the temperature increases, the ions become thinner and the TEC decreases, and vice versa, the TEC increases. Secondly, during the entire period of the geomagnetic storm, the negative change of the ionosphere is the main response of the ionospheric anomaly, which generally lasts until the end of the recovery period. Finally, the available BDS GEO observation data is limited, and the ionospheric response over the western hemisphere of the earth has not been analyzed, and there are many high-precision grid ionospheric products postprocessed, which can be used as an extension of this subject. In the future, consider combining this data to further do more comprehensive analysis, and improve the accuracy of ionospheric model algorithms and ionospheric predictions.

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References
[1] Xiong N.L., Tang C.C., Li X.J. (1997) Introduction to Ionospheric Physics [M]. Wuhan University Press.
[2] Jin S.G., Jin R., Kutoglu H. (2017) Positive and negative ionospheric responses to the March 2015 geomagnetic storm from BDS observations [J]. J. Geod., 91: 613–626.
[3] Afraimovich E.L., Astafyeva E.I., Oinats A.V., et al. (2008) Global electron content: a new conception to track solar activity [J]. Ann. Geophys., 26, 335–344.
[4] Ortikov M.Y., Shemelov V.A., Shishigin I.V., et al. (2003) Ionospheric index of solar activity based on the data of measurements of the spacecraft signals characteristics [J]. Journal of Atmospheric and Solar-Terrestrial Physics, 65: 1425–1430.
[5] Nusinov A.A. (2006) Ionosphere as a natural detector for investigations of solar EUV flux variations [J]. Advances in Space Research, 37: 426–432.
[6] Liu L.B., Chen Y.D. (2009) Statistical analysis of solar activity variations of total electron content derived at Jet Propulsion Laboratory from GPS observations [J]. J. Geophys. Res., 114, A10311.
[7] Zhao H.S., Yang L., Xu S.Y. (2017) Analysis of ionospheric TEC variation characteristics in solar activity years [J]. Journal of Navigation and Positioning, 5, 1: 24-30.
[8] Yao Lu. (2014) Application of the TEC spatial correlation and data assimilation in seismic ionospheric research [D]. Beijing: Institute of Earthquake Forecasting, CEA, 49-62.
[9] Yao Li. (2011) The Responses of Ionosphere to Seismic Activity and Solar Wind Disturbance [D]. Beijing: Institute of Geophysics, CEA, 42-67.
[10] China Satellite Navigation Office. (2017) BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1C (Version 1.0).
[11] Zhao K.J., Yang X.H., Yang H.Y., et al. (2018) Ionospheric Delay Continuous Monitoring Based on BDS GEO Satellites Dual Frequency observations [J]. Journal of Astronautic Metrology and Measurement, 38, 4: 67-72.
[12] Yang H.Y., Yang X.H., Zhang Z., et al. (2018) High-Precision Ionosphere Monitoring Using Continuous Measurements from BDS GEO Satellites [J]. Sensors, 18, 714.