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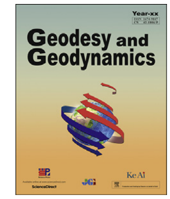

Ionospheric disturbances following the March 2015 geomagnetic storm from GPS observations in China

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A B S T R A C T

When strong solar activities and geomagnetic storms happen, satellite communications and navigation system will be strongly disturbed. It is of great significance to monitor ionospheric disturbances, because empirical models cannot capture ionospheric anomalous disturbances well. Nowadays, dual-frequency Global Positioning System (GPS) observations can be used to estimate the ionospheric total electron content, correct the ionospheric delay and analyze the response of the ionosphere to geomagnetic storms. In this paper, the ionospheric response to the geomagnetic storm occurred in March 2015 is investigated using GPS observations provided by Crustal Movement of Observation Network of China. The result shows that this storm increases the electron density in the ionosphere quickly and disrupts the structure of the northern equatorial anomaly region at the beginning. In the main process stage, compared with that in the quite periods, the Vertical Total Electron Content (VTEC) around the longitude of 120°E decreases by 50% and the amount of depletion is larger in the high latitude region than that in the low latitude region. We also find the height of the peak electron density in F2 layer increases during the geomagnetic storm from the electron density profiles derived from GPS occultation mission.

1. Introduction

When the GPS (Global Positioning System) signal propagates through the atmosphere and ionosphere, it will be delayed by the atmospheric and ionospheric refraction [1–5], which will cause the phase advance and code delay [6–9]. The signal distortion and additional phase delay will affect the accuracy of navigation and positioning. In practical application, dual-frequency GPS observations are usually used to minimize the ionospheric effect on GPS measurement [10–12], while empirical ionospheric models, such as IRI-2012 [13] and NeQuick [14], are not accurate under the extreme conditions and even cause a great deviation. Geomagnetic storms will normally cause a great change of the ionospheric TEC (Total Electron Content) or electron density. In this case, signal phase shift and amplitude perturbations derived from the traditional ionospheric models are not accurate. Estimating the variation of ionospheric TEC and studying the response to geomagnetic storms are helpful to understand the ionospheric temporal and spatial variations and improve the ionospheric modeling and forecasting [15,16].

During the geomagnetic storm, the ionosphere was strongly disturbed, which caused the severe changes in TEC. Study on the ionospheric response to the geomagnetic storms is indispensable for correcting the disturbance of electromagnetic signal. In 1994, Fuller-Rowell [20] carried out four numerical simulations using the coupled thermosphere-ionosphere model and illustrated the ionospheric response to the geomagnetic storm. The study about geomagnetic storm has been continuing for decades. However, due to the limited observations, the underlying mechanisms and spatial–temporal

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evolution of ionospheric storms have not been fully elucidated. Studying ionospheric variations and coupling mechanism requires multi-directional and multi-angle observations. With the development of satellite navigation technology, the information such as TEC can be obtained from dual-frequency GPS observations. The high-resolution ionospheric information can be extracted from dense GPS network, which is of great significance in monitoring and studying ionospheric change during the magnetic storm [22,23]. However, GIM (Global Ionospheric Maps) from IGS (International GNSS Service) has a low space resolution of 2.5° × 5° and a time interval of 1 h. For example, only 7 IGS stations in China are used for GIM. In this paper, a dense and continuous GPS network with over 200 stations in China and 30 IGS stations are used to obtain TEC and Regional Ionospheric Maps, which are used to investigate ionospheric disturbances during the March 2015 geomagnetic storm and some valuable results such as the disturbances about the TEC and the variation of the Hmf 2 were found. In this paper, based on the TEC derived from dense continuous GPS observations, we will illustrate the ionospheric response to geomagnetic storm.

2. Geomagnetic storm and observation data

2.1. Geomagnetic storm in March 2015

One of the most violent geomagnetic storms occurred on March 17, 2015, which is during the 24th solar cycle. During this storm, the geomagnetic index Dst dropped to −223 nT and the space environment was disturbed violently. Besides these, the strong ionospheric disturbance also appeared during this storm. Many studies about the effects of this geomagnetic storm have been published, such as the large-scale or small-scale response, global or regional response, and ionospheric or plasmaspheric response [23–29]. This geomagnetic storm, which occurred in the declining phase of the solar cycle, is caused by the interaction of the twice- CME (Coronal Mass Ejections) events. Following subsequent high-speed solar wind compression, it showed significant variation characteristics of multistage processes [30].

Fig. 1 shows the changes of geomagnetic indices Dst, AE, Ap and Kp for a few days before and after the March 2015 storm. Seen from Fig. 1, each index was stable before geomagnetic SSC (Sudden Storm Commencement). These significantly higher indexes (the left vertical dotted line in Fig. 1) reveal the beginning of strong magnetic storm. The SSC occurred at 06:00 UT, 17th March 2015 and the magnetic field intensity is showed in Fig. 1b, where the AE is with obvious enhancement. As the number of energetic particles increases, the ring current from east to west increases. Because the current generated a magnetic field in opposition to the geomagnetic production, the Dst index declined and at the same time the Kp index significantly increased to 8, as shown in Fig. 1d.

The Dst index decreased continuously and reached the lowest peak which was −223 nT at 23:00 UT, 17th March 2015. The main phase lasted about 12 h. Moreover, the AE index also appeared an extreme value after the peak showing in Fig. 1b. Then geomagnetic storm began to recover and the Dst index returned to a stable state with little fluctuations until the 19th March 2015.

2.2. Continuous GPS observations in China

The continuous GPS observation data are provided by the CMONC (Crustal Movement Observation Network of China), including more than 200 GPS continuous stations and 30 IGS stations in China and surrounding areas (Fig. 2). In addition, the distribution data of the VTEC and electron density can be obtained from GIM and the COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) respectively, which will be used to further analyze the ionospheric changes and response to geomagnetic storms in March 2015.

3. Fundamental theory

Based on the dual-frequency GPS observation from CMONC, we can establish 2-dimensional RIM (Regional Ionospheric Maps) over China with the temporal resolution of 10 min and the spatial

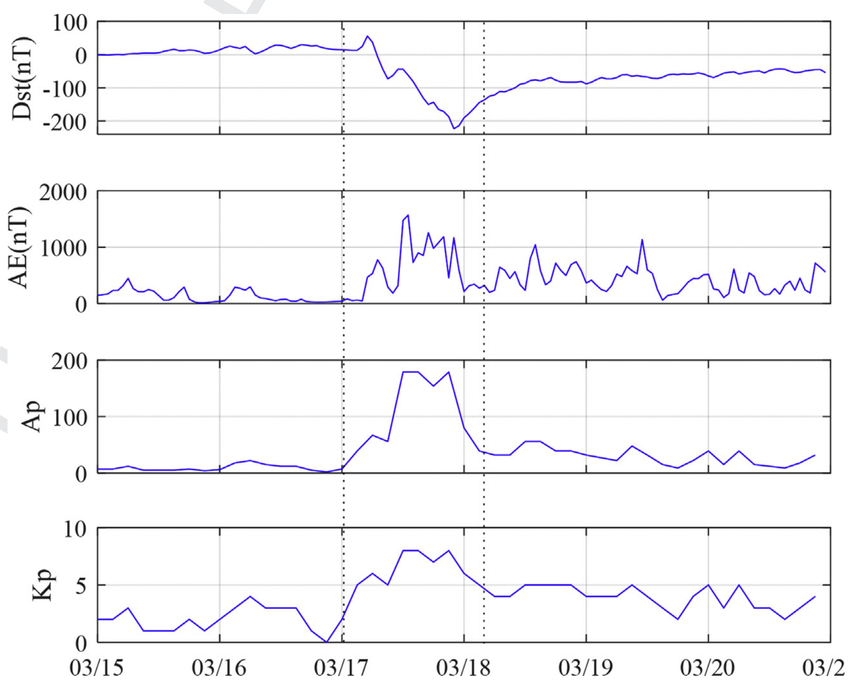

Fig. 1. The geomagnetic indices in March 2015 (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec1.html).

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