Ionospheric Response to the Geomagnetic Storm on August 21, 2003 Over China Using GNSS-Based Tomographic Technique

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Abstract—The impacts of the August 21, 2003 geomagnetic storm on the ionosphere over China have been first investigated by using the so-called computerized ionospheric tomography (CIT) technique and the observations of the Crustal Movement Observation Network of China. Tomographic results show that the main ionospheric effects of this geomagnetic storm over China are as follows: 1) the negative storm phase effect appears in the F region and 2) the positive storm phase effect occurs above the F region. Meanwhile, some key features in the ionospheric structure have been revealed in the ionospheric images during the storm; this includes the disturbances and an elongated region of the reduced electron density at the latitude around 32° N. Statistical comparisons are carried out to confirm the reliability of the global-navigation-satellite-system-based CIT reconstruction results using the profile obtained from ionosonde observations.

Index Terms—Electron density, geomagnetic storm, global navigation satellite systems (GNSS), ionosphere, tomography.

I. INTRODUCTION

THE OCCURRENCE of geomagnetic storms greatly changes the spatial distribution of ionization. This may also affect the propagation of radio signals and deteriorate the performance of global navigation satellite systems (GNSS). In the past, traditional ground-based instruments, such as incoherent scatter radars (ISRs) and ionosondes, have been extensively used for the investigation of the effects of geomagnetic storms on the ionosphere. However, ionosondes cannot be used to measure the topside ionosphere, and sometimes they suffer from absorption problems during geomagnetic storms, while ISRs are limited by geographical locations [1]. Given these limitations and the global impacts of geomagnetic storm, it is necessary to investigate the ionospheric response to geomagnetic storms using the observations which are near continuous in both temporal and spatial sense. The wide usage and rapid development of GNSS technology has opened a new avenue for the study of the ionosphere. The GNSS-based computerized ionospheric tomography (CIT) technique has recently attracted much attention to overcome the aforementioned problems based on traditional methods. Much research work [2]–[4] has been carried out since its feasibility was first verified by [5]. Recent research has demonstrated that GNSS-based CIT technique can be effectively used to investigate the impact of ionospheric disturbance in a large scale during geomagnetic storms [6]–[11].

In this paper, dual-frequency GNSS observations from the Crustal Movement Observation Network of China (CMONOC) are first used to investigate the ionospheric response to the geomagnetic storm on August 21, 2003, and the dynamics of the ionospheric variations during the geomagnetic storm has been examined. Ionospheric storm phase effects and some key features of the ionospheric structure over China are shown in the tomographic images.

II. GNSS DATA PROCESSING

A. Selected GNSS Observations

In this paper, the GNSS observation data of CMONOC are used to reconstruct the ionospheric electron density (IED) distribution. The GNSS observation stations are unevenly distributed between the reconstructed region. The sample interval of the used GNSS data is 30 s. Fig. 1 shows the distribution of the used GNSS stations.

B. Cycle-Slip Detection and Correction of GNSS Data

Routine GNSS data preprocessing is first performed to detect, remove, and/or correct outliers and cycle slips by using the algorithms described by Blewitt [12] prior to computation using the GNSS-based CIT technique. In general, cycle slips are better detectable when dealing with long rather than with short wavelengths. For this reason, the wide-lane phase combination is performed in Blewitt’s algorithm

$$\Phi_\delta = \Phi_1 - \Phi_2$$

where $\Phi_1$ and $\Phi_2$ are the actually recorded phase of the carriers. The wide-lane wavelength is obviously longer than the GNSS...
The cycle-slip criterion is fulfilled when the following derivation of STEC is commonly made using the pseudoranges and phase measurements of the dual-frequency GNSS signals. Since the GNSS phase measurements are less affected by multipath effects, the accuracy of the STEC derived from differential phases ($\text{STEC}_{\text{ph}}$) is higher than that of the STEC derived from differential pseudoranges ($\text{STEC}_{\text{co}}$). Because of the ambiguity in GNSS phase measurements, $\text{STEC}_{\text{ph}}$ only provides the relative changes of ionospheric TEC. On the other hand, although P-code pseudoranges are sensitive to multipath effects, ($\text{STEC}_{\text{co}}$) values are absolute. Taking into account these facts, an absolute STEC may be obtained by introducing an extra term $B_L$. It can be formulated as follows [13]–[15]:

$$\text{STEC} = \text{STEC}_{\text{ph}} + B_L.$$  

If $N$ measurements are obtained during a satellite pass, $B_L$ can be modeled by the following equation:

$$B_L = \sqrt{\frac{\sum_{i=1}^{N} (\text{STEC}_{\text{co}, i} - \text{STEC}_{\text{ph}, i})^2}{N}}.$$  

Due to the instrumental bias of GNSS pseudorange measurements, the derived STECs should be precalibrated. This paper used a strategy to cope with the aforementioned biases. First, the satellite and receiver instrument biases over the three days (20th, 21st, and 22nd of August 2003) were determined using the method described by Yuan and Ou [16], [17]. Mean values of the instrumental biases over the three days were then computed. They were then used to calibrate each of the differential delays for each satellite–receiver pair during the August 21, 2003 storm. Second, the bias-corrected differential delays are applied to calibrate the differential phases of the storm day by using a least squares fitting method. Absolute STECs are determined from the differential phase and time delays recorded during the storm using this procedure.

It is well known that pseudoranges from low-elevation-angle satellites are prone to multipath effects. In general, the lower the elevation angle, the larger the multipath error. On the other hand, GNSS data obtained at low elevation angles are important for getting some information about the vertical distribution of the IED. Hence, a critical problem is how to select a proper cutoff elevation angle for the CIT technique. A large cutoff elevation angle reduces the vertical resolution of the inverted results, and a small elevation angle would seriously reduce the accuracy of the IED inversion. Given the aforementioned reasons, an elevation cutoff angle of 10° is adopted in this paper.

## III. Method

### A. Derivation of STEC

To reconstruct the ionospheric IED, the computation of slant total electron content (TEC) (STEC) is necessary. The

$$N_\delta = N_1 - N_2 = \frac{L_\delta - P_\delta}{\lambda_\delta}$$  

where $L_\delta$ and $P_\delta$ are defined as

$$L_\delta = \frac{f_1 L_1 - f_2 L_2}{f_1 - f_2}$$  

$$P_\delta = \frac{f_1 P_1 + f_2 P_2}{f_1 + f_2}.$$  

During the data analysis, the so-called phase-connected arcs are built. One phase-connected arc consists of a series of data points recorded during a satellite track without detected cycle slip. The detection criterion for a cycle slip is given by the root mean square of the arc-related mean

$$\langle N_\delta \rangle_{i+1} = \langle N_\delta \rangle_i + \frac{N_\delta_{i+1} - \langle N_\delta \rangle_i}{i + 1}$$  

$$\sigma^2_{i+1} = \sigma^2_i + \frac{(N_\delta_{i+1} - \langle N_\delta \rangle_i)^2}{i + 1}.$$  

The cycle-slip criterion is fulfilled when the following $N_\delta_{i+1}$ and $N_{\delta_{i+2}}$ differ by more than $2\sigma_\delta$ from the actual mean value of the arc $\langle N_\delta \rangle_i$. Then, a new arc begins to build. If only $N_\delta_{i+1}$ and not $N_{\delta_{i+2}}$ deviates by more than $2\sigma_\delta$, $N_{\delta_{i+1}}$ is defined as an outlier. In this case, $N_{\delta_{i+1}}$ is deleted and replaced by the simple relation $N_{\delta_{i+1}} = (1/2)(N_\delta_i + N_{\delta_{i+2}})$. At each beginning of a new arc, the root mean square is initialized with $\sigma_0 = 0.5$.

### B. Tomographic Theory

Ionospheric STEC is the line integral of IED along the ray path from a satellite to a receiver, and it can be defined as

$$\text{STEC} = \int_N N_e(s) ds$$  

where $N_e(s)$ represents the IED, and $l$ is the ray propagation path of each GNSS satellite-receiver pair.
From (9), it can be seen that the relation between ionospheric STEC and IED is not linear. To simplify the IED inversion, an imaged region of the ionosphere is first discretized into some small pixels in a selected reference frame. In this paper, the study area of the ionospheric image generation covers 20° in latitude (20° N–40° N) and 20° in longitude (100° E–120° E). The altitude ranges are from 100 to 1000 km. To discretize the reconstruction area, horizontal resolution of 0.5° in latitude and 1° in longitude and a vertical resolution of 30 km are used. Within each pixel, the electron density can be assumed constant. The STEC along the ray path can then be expressed as a finite sum of the shortest integrals in all segments of the ray path. Each set of TEC values along the ray path from a satellite to a receiver can be written as

\[
\text{STEC}_i = \sum_{j=1}^{n} A_{ij} x_j + e_i. \tag{10}
\]

Equation (10) can be generally written in a simple matrix notation as

\[
y_{m \times 1} = A_{m \times n} x_{n \times 1} + e_{m \times 1} \tag{11}
\]

where \(n\) is the number of pixels in the image, \(m\) is the number of STEC measurements, \(y\) is a column vector of the \(m\) known STEC measurements, \(A\) is an \(m \times n\) matrix with \(A_{ij}\) being the length of ray \(i\) traversing pixel \(j\), \(x\) is a column vector consisting of all the unknown electron densities in all the pixels, and \(e\) is a column vector associated with the discretization errors and measurement noises.

### C. Tomographic Algorithm

In (11), matrix \(A\) is usually rank deficient. It means that only a subset of the \(m\) equations is linearly independent. Moreover, the number of independent equations is generally less than the number of the unknown parameters. Therefore, the tomographic reconstruction of the IED is an ill-posed inverse problem due to the restricted view window of the tomographic system and the irregularity and sparsity of the ground-based GNSS stations. To resolve this problem, a hybrid reconstruction algorithm (HRA) is used in this paper. In this algorithm, the truncated singular value decomposition (TSVD) method is first used to get an approximate solution of the tomographic system; the TSVD of \(A_k\) is defined as [18]

\[
A_k = \sum_{i=1}^{k} U_i D_i V_i^T \tag{12}
\]

where \(k < n\). It neglects \(n - k\) smallest singular values. Then, the pseudoinverse \(A_k^+\) is written as

\[
A_k^+ = \sum_{i=1}^{k} V_i D_i^{-1} U_i^T. \tag{13}
\]

The solution by TSVD is expressed as

\[
x_k = A_k^+ y. \tag{14}
\]

The estimates obtained from (14) are then input as initial states required by the algebraic reconstruction technique (ART)

\[
x^{(0)} = x_k. \tag{15}
\]

Next, the reconstruction is performed with the following ART algorithm:

\[
x^{(k+1)} = x^{(k)} + \lambda_k \left( y_i - a_i x^{(k)} \right). \tag{16}
\]

The column vector \(\lambda_k\) consisting of all relaxation parameters is given as

\[
\lambda_k = \gamma \cdot a_i^T / \left( a_i a_i^T \right) \tag{17}
\]

where \(a_i\) represents the \(i\)th row vector in projection matrix \(A\), and \(\gamma\), called relax parameter, is fixed in ionospheric tomography. In this paper, \(\gamma = 1\).

### IV. RESULTS AND ANALYSIS

#### A. Analysis of the Reconstructed Results

A moderate geomagnetic storm event occurred on August 21, 2003. As a result, an initial phase of the geomagnetic storm with a sudden commencement was seen after 03:40 UT. The main phase of the storm lasted from 06:00 UT to 24:00 UT and had a minimum disturbance storm time (Dst) index of −82 nT. The 3-hour Kp index reached 6 at 09:00 UT.

Fig. 2 shows the IED variations with altitude and latitude along longitude meridian of 114.5° at 15:00 UT (23:00 BT; BT...
is the abbreviation of Beijing time) during the geomagnetically active period on August 21, 2003 and geomagnetically quiet periods on the 20th and 22nd of August 2003, respectively. Comparing Fig. 2(b) with Fig. 2(a), one can see that the IED in the F region was depleted during the geomagnetic storm on August 21, 2003, which appeared to be the negative storm phase effects. The maximum depletion of the IED reached 30%. The positive storm phase effects of the ionosphere however appeared latitudinally from 20° N to 37° N and altitudinally from 500 to 700 km above the ground, and then the negative storm phase effects also appeared latitudinally from latitude 37° N to latitude 40° N. The reconstructed results show that the storm phase effects are not only latitude dependent but also altitude dependent. Similar characteristics of the geomagnetic storm can also be found in other periods. Fig. 2(b) shows an elongated region of reduced electron density at a latitude around 32° N. The IED value of the trough is about $5.7 \times 10^{11}$ e/m$^3$. In the north of the ionospheric trough, the IED increases and reaches a peak at 36° N where the peak height is about 320 km; the peak density of the ionosphere increases to $6.2 \times 10^{11}$ e/m$^3$, and then the IED begins to decrease. However, the peak IED reaches $8.0 \times 10^{11}$ e/m$^3$ south of the trough, and the peak height is about 350 km, which is higher than the north peak height of the ionospheric trough. At the same time, an intensively disturbed structure of the ionosphere appears between 20° N and 35° N; this demonstrates that the GNSS-based CIT technique is a powerful tool to monitor and investigate large-scale ionospheric structure under disturbed conditions. From Fig. 2(c), it can be seen that the IED gradient gradually comes back to the state before the storm occurred.

The available ionosonde station at Wuhan in China region provided independent comparisons with the tomographically obtained electron-density profiles. Fig. 3 provided verification of the outputs of CIT, for 14:30 UT–15:00 UT (22:30 local time (LT)–23:00 LT) time period on August 20, 21, and 22, 2003, with the available valid ionosonde data recorded at Wuhan station. From Fig. 3, the agreement between the profiles obtained from tomographic reconstruction and those from ionosonde data can be seen. This validated the reliability of the tomographic results.

The previous tomographic results show only the nighttime density profiles. To further examine the ionospheric response to the storm event in daytime and dusk, Fig. 4 shows a series of typical tomographic images of the ionosphere over China along a longitude chain of 114.5° E for the 06:00 UT–12:00 UT period during the storm on August 21, 2003. The label in the top-right corner represents the universal time. From Fig. 4, one can see that the disturbed structure of the ionosphere shown in Fig. 3(b) can be clearly seen, and the dynamics of the ionospheric response to the geomagnetic storm is also shown. However, the IED gradient in Fig. 4(a) obtained at 05:30 UT–06:00 UT (13:30 LT–14:00 LT) is smaller than those in Fig. 4(b) and (c). The ranges of the disturbed ionospheric structure widened with time. This characteristic of the disturbed structure is also seen in the reconstructed image in nighttime density profile [in Fig. 3(b)].

To validate the reliability of the reconstructed results shown in Fig. 4, three comparisons are made in Fig. 5. Fig. 5 shows that the profiles obtained from the CIT at three time periods (05:30 UT–06:00 UT, 08:30 UT–09:00 UT, and 11:30 UT–12:00 UT)
agreed with those from ionosonde data recorded at Wuhan station. The comparison verified the validation of the tomographic reconstruction in Fig. 4.

**B. Statistics of the Reconstructed Errors**

To show the superiority of the aforementioned HRA, the statistics of the reconstructed error in the tomographic inversion is made. Table I gives the statistics results. From Table I, we can see that the maximum of the reconstructed IED error is $1.24 \times 10^{10} \text{e/m}^3$, the minimum of the reconstructed IED error is $-1.16 \times 10^{10} \text{e/m}^3$, and the average of the reconstructed IED error is $1.5 \times 10^{10} \text{e/m}^3$, which are very small compared with the typical peak density of $1.78 \times 10^{12} \text{e/m}^3$. By comparison with the TSVD and ART alone, the reconstructed results of HRA are obviously improved.

**V. DISCUSSION AND CONCLUSION**

A GNSS-based CIT technique has been firstly applied to investigate the ionospheric response to the geomagnetic storm on August 21, 2003 over China. The reconstructed images of the IED show that a large-scale ionospheric disturbance is evident in China with ionization depletion in the F region and ionization enhancement above the F region, which represent a negative and a positive storm phase effect, respectively. Similar to early theoretical analyses by Buonsanto and the references therein, the negative storm phases that occurred in the F region during the geomagnetic storm on August 21, 2003 could be attributed to an increased input of energy to the region and an expansion of the neutral atmosphere. Such a rapid expansion may cause upwelling, which in turn induces a dramatic depletion of the atomic to molecular neutral density ratio. This change in chemical composition may cause an increased recombination in the ionosphere and a reduction in ionization concentration. The positive phases are generally believed to be caused by uplifting of the F region by equatorward winds in the early stage of a storm development. The reconstructed results suggest that one may monitor and investigate the disturbed variations of the IED in China during geomagnetic storm with the CIT method and dual-frequency GNSS data from CMONOC. This is helpful in understanding finer structures of the ionosphere during geomagnetic storms. The tomographic results have illustrated that the intense disturbance of the ionosphere in China occurred during the storm, and the ionospheric storm phase effects are not only latitude dependent but also altitude dependent.

We are convinced that these results are beneficial to the understanding of the characteristics and variation mechanism of the ionosphere in China during geomagnetic storms, and they are capable of providing a valuable experimental support for understanding the complex behavior of the F region during geomagnetic storms.

**REFERENCES**


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