An Improved Iterative Algorithm for 3-D Ionospheric Tomography Reconstruction

Yibin Yao, Jun Tang, Peng Chen, Shun Zhang, and Jiajun Chen

Abstract—The computerized ionospheric tomography usually involves solving an ill-posed inversion problem. The sparsity of Global Positioning System (GPS) stations and the limitation of projection angles lead to insufficient data acquisition, thereby preventing the accurate reconstruction of ionospheric-electron-density distributions. In this paper, we investigate and propose a 3-D iterative reconstruction algorithm based on the minimization of total variation under quiescent and disturbed ionospheric conditions. Numerical experiments on GPS simulation data and real data are discussed. In contrast to the improved algebraic reconstruction technique, the proposed algorithm exhibits significantly reconstruction accuracy.

Index Terms—Computerized ionospheric tomography (CIT), Global Positioning System (GPS), ill-posed problem, ionospheric electron density (IED), total variation (TV) minimization in three dimensions combined with algebraic reconstruction technique (ART) (TV3D-ART).

I. INTRODUCTION

COMPUTERIZED tomography (CT) technology was first successfully applied in the medical field and then extended to other applications. On the basis of the total electron content (TEC) of the propagation path of the multiple satellite ground stations, Austen et al. [1], [2] first presented the tentative idea of ionospheric imaging using CT and then used the computerized ionospheric tomography (CIT) technique to recover a 2-D image of ionospheric-electron-density (IED) distributions. Subsequently, various experimental and theoretical studies on this idea have successively been conducted worldwide [2]–[10]. Over the recent 20 years, the development of Global Positioning System (GPS) technology has enabled the acquisition of highly precise observation data on TEC for the CIT application study. Such innovations prompted the rapid development of the CIT technique. Many international and domestic scholars have proposed various CIT inversion algorithms, which are generally classified into two kinds: iterative algorithms [2], [3], [11] and noniterative algorithms [12], [13]. In the inversion of CIT images, the inverse problem is ill-posed with a limited number of viewing angles and sparse distribution of GPS stations. These features pose difficulty in accurately constructing IED distributions. Thus, subsequent studies focused on addressing these problems with good results derived by many scholars [14]–[25]. Kunitsyn et al. [15]–[18] developed the algorithm simultaneous iterative reconstruction technique (SIRT) that used Sobolev’s norm as a stabilizer. Ma and Maruyama [19] proposed a neural network reconstruction algorithm. Wen et al. [20]–[22] developed an improved algebraic reconstruction technique (ART) (IART), a hybrid reconstruction algorithm, and a two-step algorithm. Some researchers [23]–[25] applied an additional constraint to reconstruct IED distributions.

The image reconstruction algorithm for total variation (TV) minimization reconstruction is an effective method for solving ill-posed problems. A constrained optimization method with image denoising based on TV minimization was proposed by Rudin et al. [26]. Anagaw and Sacchi [27] used the TV method to process the ill-posed nature of inverse problems in seismic tomography. Persson et al. [28] developed an iterative Bayesian reconstruction algorithm for limited-view-angle tomography based on the 3-D TV norm in medical imaging field. Lee et al. [29], [30] used TV and Tikhonov regularization to reconstruct IED under nonquiescent ionospheric conditions in ionospheric tomography and found that the TV method was more resistant to noise and had highly reconstructed precision. Also, Lee and Kamalabadi [31] had done some experiments by TV method and found that it generally avoided oversmoothing of edges and captured potential localized ionospheric density structures. These experiments had shown the feasibility and superiority of the TV method. ART for CIT was first proposed by Austen et al. [2], was simple and convenient, and had been extensively applied in inverting IED distributions. Given these advantages, we apply this method, using TV minimization in three dimensions combined with ART (TV3D-ART). Numerical experiments on the simulation data and the measured data are used to validate the feasibility and superiority of the method under quiescent and disturbed ionospheric conditions.

II. CIT THEORY

CIT measures the TEC of the ray path to inverse IED distributions. Fig. 1 shows the schematic diagram of the computation domain of IED tomography. The TEC along the propagation
path between a GPS satellite and a ground receiver [32] is the combined value of the IED, expressed as

\[
\text{TEC} = \frac{f_1^2 f_2^2}{40.28 (f_1^2 - f_2^2)} \left[ (P_2 - \hat{P}_1) + B^S + B^R \right]
\]

(1)

where \(\hat{P}_1\) and \(\hat{P}_2\) are the dual-frequency pseudorange observations of the phase smoothing code and \(B^S\) and \(B^R\) are the satellite and ground receiver for the instrumental biases of the transmitter, respectively.

Ionospheric TEC is the line integral of IED along the signal propagation path [2]. It is expressed as follows:

\[
\text{TEC} = \int I(r', t) ds
\]

(2)

where \(I(r', t)\) is the IED at a position \(r'\) and time \(t\), and \(l\) is the signal propagation path.

By conducting radio telemetry measurements in a spatial environment, CIT makes use of a series of satellite signals to inverse the temporal and spatial distributions of the IED in the setting region. As shown in (2), the relationship between ionospheric TEC and IED is nonlinear. In the practical inversion procedure, the inversion region is discretized into small pixels to estimate IED. The basis function is generally classified into local and global basis functions. In this paper, we apply the local basis function, i.e., the pixel basis function, to inverse IED. We assume that the IED of each pixel is constant in the inversion region. Each set of TEC values along the propagation path from a satellite to a receiver can be expressed as

\[
\text{TEC}_i = \sum_{j=1}^{n} a_{ij} x_j + \varepsilon_i
\]

(3)

where \(i\) is the number of the ray, \(x_j\) is the IED in pixel \(j\), \(a_{ij}\) denotes the length of the \(i\)th ray path through pixel \(j\), \(n\) represents the number of all pixels, and \(\varepsilon_i\) is the observation noise of the \(i\)th ray path. Equation (3) can be further written in matrix form

\[
y_{m \times 1} = A_{m \times n} \cdot x_{n \times 1} + \varepsilon_{m \times 1}
\]

(4)

where \(m\) is the number of TEC measurements, \(y\) is a column vector of the \(m\) with the absolute TEC from GPS observations, \(A\) is an \(m \times n\) matrix corresponding to the discrete grid, \(x\) is a column vector of the \(n\) with electron density at each voxel, and \(\varepsilon\) is the noise.

III. CIT INVERSION ALGORITHM

A. IART

The classical ART [33] is a row-action algorithm that sets an initial value for each pixel before each iteration step is executed in the inversion region; it then uses an iterative method to gradually improve the initial estimation for image reconstruction. Each modification step corresponds to a single TEC measurement, and the iteration number is \(m\) at each iteration. The \(k\)th iteration of this algorithm computes the difference between the actual measured TEC and that obtained using the current estimate of the solution. Then, a correction derived from the difference is distributed over \(x^{(k-1)}\) to obtain \(x^{(k)}\). After many iterations, the results converge to a final solution. For the \(k\)th iteration

\[
x^{(k)} = x^{(k-1)} + \lambda \frac{y_i - \langle a_i, x^{(k-1)} \rangle}{a_i a_i^T} a_i^T
\]

(5)

where \(a_i\) is the \(i\)th row of matrix \(A\), \(k\) is the number of iterations, \(\lambda\) is the relaxation parameter, and \(\lambda \in (0, 1)\). On the basis of the ART algorithm, Wen et al. [20] developed an IART. The column vector \(\lambda_{k-1} = \lambda \cdot a_i^T / (a_i a_i^T)\) will be improved as follows:

\[
\lambda_{k-1} = \lambda \cdot g^{k-1} / (a_i \cdot g^{k-1})
\]

(6)

where \(g^{k-1} = [g_1^{k-1}, g_2^{k-1}, \ldots, g_n^{k-1}]^T\) and \(g_i^{k-1} = a_i x_i^{(k-1)}\).

With this method, the relaxation parameter for each pixel can be adjusted according to its estimate obtained from the last iteration.

B. TV3D-ART

The algorithm, TV3D-ART, is an interlaced iterative algorithm with the same external iteration as that used by Oliveira et al. [34]. Persson et al. [28] have effectively developed a TV3D-EM algorithm against limited-view-angle tomography and noise. In view of the gradient expressions, positivity constraints, and iterative format of the Persson method, we develop the TV3D-ART algorithm, which requires \(a\) priori constraints on the parameters of (4). The constraint equation is written as

\[
\begin{align*}
\min \| x \|_{TV} \\
\text{s. t.} \| Ax - y \| < \varepsilon, x_j > 0.
\end{align*}
\]

(7)

To solve the TV norm, referring to pixels in the context of a 3-D image is necessary. We use the subscript form, which is
expressed as \( x_{s,t,z} \); thus

\[
j = (s - 1) \cdot N \cdot P + (t - 1) \cdot P + z \tag{8}
\]

where \( s \in [1, M], t \in [1, N], z \in [1, P] \), and \( M, N, \) and \( P \) denote the number of pixels along the longitude, latitude, and altitude directions, respectively. The total number of pixels is \( n = M \times N \times P \). The function to be minimized is the \( \ell_1 \)-norm of the gradient image of IED, also known as the TV of the IED image, as given by (9), shown at the bottom of the page.

The TV minimization of IED can be accomplished by the gradient decent method. The partial derivatives in (9) are evaluated as shown by (10), shown at the bottom of the page, where \( |\nabla x_{s,t,z}| = 0 \).

The implementation of the proposed TV3D-ART is described as follows.

1) Initialize the parameters, which are the maximum iteration times \( k_{\text{count}} \), number of iterations of the TV gradient descent method \( k_{\text{grad}} \), ART iterative relaxation factor \( \lambda \), and TV minimization iterative relaxation factor \( \gamma \). The initial value of the IED image is set for vector \( \vec{N}_e \), calculated by the model of international reference ionosphere (IRI) (i.e., \( x^{(0)} \leftarrow \vec{N}_e \)) and then incorporated into the iterative loop.

2) Use ART to calculate IED (i.e., obtain \( x^{(k)}(\text{POCS}) \)).

3) Use projection on convex sets (POCS) [35] as a nonnegative constraint for the IED image; thus

\[
x^{(P O C S)}_j = \begin{cases} x^{(k)}_j & x^{(k)}_j > 0 \\ \vec{N}_e & x^{(k)}_j \leq 0. \end{cases} \tag{11}
\]

4) Calculate the distance of the gradient direction as follows:

\[
d_{\text{POCS}} = \| x^{(\text{POCS})} - x^{(0)} \| . \tag{12}
\]

5) Carry out TV adjustment by using the gradient descent method

\[
x^{(\text{TV-grad})}_j = x^{(\text{POCS})}_j - \lambda \frac{\partial \| x \|_{\text{TV}}}{\partial x_{s,t,z}} \frac{\partial x_{s,t,z}}{\partial x_{s,t,z}} \tag{13}
\]

\[
- \gamma d_{\text{POCS}} \frac{\partial \| x \|_{\text{TV}}}{\partial x_{s,t,z}} \tag{14}
\]

\[
\| x_{s,t,z} \|_{\text{TV}} = \sum_{s,t,z} |\nabla x_{s,t,z}| = \sum_{s,t,z} \sqrt{(x_{s,t+1,z} - x_{s,t,z})^2 + (x_{s,t+1,z} - x_{s,t,z})^2 + (x_{s,t+1,z} - x_{s,t+1,z})^2 + \tau^2} \tag{9}
\]

\[
\frac{\partial \| x \|_{\text{TV}}}{\partial x_{s,t,z}} \approx \frac{3x_{s,t,z} - (x_{s-1,t,z} + x_{s,t-1,z} + x_{s,t+1,z})}{\sqrt{(x_{s,t+1,z} - x_{s,t,z})^2 + (x_{s,t+1,z} - x_{s,t,z})^2 + (x_{s,t+1,z} - x_{s,t+1,z})^2 + \tau^2}}
\]

\[
- \frac{x_{s,t+1,z} - x_{s,t,z}}{\sqrt{(x_{s+1,t,z} - x_{s,t,z})^2 + (x_{s+1,t,z} - x_{s,t+1,z})^2 + (x_{s+1,t,z} - x_{s,t+1,z})^2 + \tau^2}}
\]

\[
- \frac{x_{s,t+1,z} - x_{s,t+1,z}}{\sqrt{(x_{s,t+1,z} - x_{s,t+1,z})^2 + (x_{s,t+1,z} - x_{s,t+1,z})^2 + (x_{s,t+1,z} - x_{s,t+1,z})^2 + \tau^2}}
\]

\[
- \frac{x_{s,t,z} - x_{s,t+1,z}}{\sqrt{(x_{s,t,z} - x_{s,t+1,z})^2 + (x_{s,t,z} - x_{s,t+1,z})^2 + (x_{s,t,z} - x_{s,t+1,z})^2 + \tau^2}} \tag{10}
\]
Fig. 3. Contour line of the IED distribution of the model and CIT at 16° E. The unit of IED is \(10^{11} \text{ el/m}^3\). (a) Obtained using the IRI2007 model. (b) Obtained using TV3D-ART.

Fig. 4. Comparison of the IED profiles reconstructed by two algorithms with the modeled IED profiles with the IRI2007. (a) (16° E, 54° N). (b) (4° E, 46° N).

A small angular velocity of high orbital satellites significantly deteriorates the experiment geometry and possibilities of the tomography [36]. During the course of the CIT experiment, we have taken 1 h for the observation time interval and used 1-h GPS observation data to do our experiments. The GPS station distribution of the setting region is shown in Fig. 2.

Numerical simulation experiment is a necessary step to confirm the efficiency of the proposed algorithm before applying it to real data. The procedure for the simulation experiment is described as follows.

1) The inversion region is selected, by discretizing certain intervals along the longitude, latitude, and altitude directions, respectively. The IED value is a constant in discrete pixels.

2) In accordance with the ray between a GPS satellite and a ground receiver to calculate the intercept in each pixel, projection matrix \(A\) is constructed in (4).

3) In the simulation calculation, the IED of each pixel is obtained from the IRI2007 model. Thus, the TEC without noise equals the IED multiplied by projection matrix \(A\)

\[
y_{\text{simu}} = A x_{\text{IRI}}. \tag{15}\]

4) Take fully into consideration the existence of noise and discrete errors; in fact, a fraction of such errors are introduced by (15)

\[
y_{\text{simu}} = A x_{\text{IRI}} + \epsilon_{\text{simu}}. \tag{16}\]

In order to determine the advantages and disadvantages of the reconstructed IED, the root-mean-square error (rmse) and average density error are used as the evaluation standards for CIT precision, i.e.,

\[
\sigma = \sqrt{\frac{1}{n} \sum_{j} \left( N_{e_j}^{\text{model}} - N_{e_j}^{\text{recon}} \right)^2} \tag{17}\]

\[
\rho = \frac{\sum_{j} \left| N_{e_j}^{\text{model}} - N_{e_j}^{\text{recon}} \right|}{n} \tag{18}\]

where \(n\) is the total number of pixels of the IED in the inversion region, \(N_{e_j}^{\text{model}}\) is the value of the IED in the \(j\)th pixel obtained by the model, and \(N_{e_j}^{\text{recon}}\) is the value of the IED in \(j\)th pixel reconstructed by CIT.

Fig. 3 shows that the IED distribution reconstructed by the TV3D-ART algorithm coincides well with the distribution calculated with the IRI2007 model. This result confirms the feasibility of the IED reconstruction by the TV3D-ART algorithm.

To verify the superiority of the TV3D-ART algorithm over the IART algorithm, we apply the same conditions in determining results using the two algorithms.

Fig. 4 compares the simulated vertical IED distributions at the two geographic locations (16° E, 54° N) and (4° E, 46° N) with the corresponding distributions reconstructed by the TV3D-ART and the IART. Moreover, a comparison is also
made through the differences between the results obtained from the two algorithms and that of IRI2007 model. Fig. 4 shows that the IED profiles reconstructed by the TV3D-ART agree better with IRI2007 than those of the IART as a whole. In addition, it indicates that the proposed algorithm is superior to the IART in the process of CIT.

In the following section, one iteration means that all available rays are used to update the reconstruction once. To compare the convergence performances of the two algorithms, the images of IED distribution characteristics along a fixed longitude meridian of 16°E obtained from IRI2007 are compared with those of the results of the two algorithms under quiescent ionospheric conditions. Fig. 5(a) shows the results of the IRI2007 model. Fig. 5(b) and (d) illustrates the reconstruction results of the TV3D-ART and IART algorithms after ten iterations, respectively. Fig. 5(c) and (e) illustrates the reconstruction results of the TV3D-ART and IART algorithms after convergence. Fig. 5(c) shows the reconstruction results of 16 iterations by TV3D-ART, and Fig. 5(e) shows the results of 21 iterations by IART. However, the construction image by TV3D-ART is more similar to the image obtained from IRI2007. From the figure, we can see that the proposed algorithm is better based on objective quality measures than IART. At the same time, the reconstruction by TV3D-ART slightly outperforms that of IART in speed.

To further examine the effectiveness of the algorithm for a disturbed ionosphere, we design test structures by a simple plasma-bubble model. Simulated and reconstructed distributions are shown in Fig. 6. Fig. 6(a) is the original image. Fig. 6(b) and (d) illustrates the reconstruction results of the TV3D-ART and IART algorithms after 10 iterations, respectively. Fig. 6(c) and (e) illustrates the reconstruction results of the TV3D-ART and IART algorithms after convergence. Fig. 6(c) shows the reconstruction results of 27 iterations by
Fig. 6. IED profiles are given at 50° N. The unit of IED is $10^{11}$ el/m$^3$. (a) Using simulation value. (b) and (c) Reconstructed by the TV3D-ART algorithm. (d) and (e) Reconstructed by the IART algorithm.

Fig. 7. Comparison of the reconstruction rmse of the two algorithms at different longitudes.

Table I shows the error comparison for the reconstructions of the two algorithms from simulation data on total pixels.

<table>
<thead>
<tr>
<th>Error</th>
<th>TV3D-ART</th>
<th>IART</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average density error ($10^{10}$ el/m$^3$)</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>RMSE ($10^{10}$ el/m$^3$)</td>
<td>0.50</td>
<td>0.56</td>
</tr>
</tbody>
</table>

TV3D-ART, and Fig. 6(e) shows the results of 35 iterations by IART. From the figure, the reconstructed image by the TV3D-ART is more consistent with the original image after convergence.

For different longitude profiles, the rmse of the IED inversed by the TV3D-ART algorithm is slightly lower than that of the IED inversed by the IART algorithm. This result confirms that the calculation accuracy of the TV3D-ART algorithm is superior to that of the IART algorithm (Fig. 7). Table I shows...
the IED error in the total number of pixels, which also verifies the superiority of the proposed algorithm. These analysis results indicate that the computational efficiency and inversion accuracy of the TV3D-ART algorithm are superior to those of the IART algorithm.

B. Real Data Experiment

Quiescent Ionospheric Conditions: In this section, we discuss the application of the proposed algorithm to real GPS observation data and ionosonde data from Dourbes (50.1° N, 4.6° E). The dual-frequency GPS observation data from International GNSS Service (IGS) are used to analyze by the new algorithm. The time spent in reconstruction is consistent with the simulation experiment. Before inversion, data on precise ephemeris, hardware delay, and observation files are necessary to obtain the TEC value along the signal propagation path under inversion conditions. Each pixel in the inversion region is initialized by the IRI2007 model. Then, the iteration is performed by the proposed algorithm.

Fig. 8 illustrates the evolution of the ionosphere above Europe on December 16, 2010. The reconstruction was carried out for a whole day with different-time sampling. The TEC maps show the spatial structures. Generally, the trend of the
reconstruction IED is similar to that of TEC map. The lower color map scale at different times indicates the IED values in different sections to clearly show the region of maximum IED at each section. The IED decreases as latitude increases at the same altitude. The comparison of each subgraph shows, however, that the IED peak value occurs at 09:00 and 13:00 Universal Time (UT), and that the IED valley value occurs at 21:00 UT. Over time, the IED peak region gradually moves to the north at 01:00 UT to 09:00 UT. At 09:00 UT, the IED extends to the entire latitude range. It is also maintained over the entire latitude range at 09:00 UT to 13:00 UT. The peak region of the IED gradually moves to the south at 13:00 UT to 21:00 UT. At the same longitude, the rate of change in IED at different latitudes is varied, and the IED variations at low latitudes proceed at a faster rate than do the variations at high latitudes. These variations are specially obvious during daytime but gradually tend to coincide at night. Moreover, the IED variations are concentrated primarily at heights of 100–600 km. The IED peak height gradually decreases at 01:00 UT to 09:00 UT, remains invariant at 09:00 UT to 13:00 UT, and gradually increases at 13:00 UT to 21:00 UT. For the height changes to the ionosphere F2 layer, we can see that the height of F2 layer is gradually decreased at 01:00 UT to 09:00 UT. It is also maintained about the same height at 09:00 UT to 13:00 UT and gradually increased at 13:00 UT to 21:00 UT. The results reflect the variation characteristics of the IED vertical structure. However, the IED distributions shown in the lower line of images in Fig. 8 seem to show some ionospheric wiggles at about 500–600 km. We think that these wiggles are the imaging artifacts.

Disturbed Ionospheric Conditions: Now, we present several examples of CIT imaging of regional distributions of IED during the geomagnetic storm. Fig. 11 shows the evolution of the ionospheric trough over the part of Europe. These examples have been chosen and are for 19:00 UT, 20:00 UT, 21:00 UT, and 22:00 UT on November 20, 2003. The dimensions of the spatial resolution along the longitude, latitude, and height are $51 \times 41 \times 19$. The reconstruction is carried out for a day with a 1-h-time sampling. The ionospheric trough on TEC maps and in the submeridional vertical cross sections along $10^\circ$ E is exhibited. In general, the trend of the reconstruction IED is similar to that of TEC map. All four TEC maps show that the TEC is gradually decreased at 19:00 UT to 22:00 UT. The peak region of the TEC gradually moves to the west at this period. The height of the F2 layer is gradually decreased at 19:00 UT to 44° N, and the ionospheric trough appears at about 44° N from 19:00 UT to 22:00 UT. The NmF2 is increased from 19:00 UT to 20:00 UT at 44° N to 70° N. However, the IED distributions shown in the lower line of images in Fig. 11 seem to show some ionospheric wiggles at about 600 km. We also think that these wiggles are the imaging artifacts.

October 30, 2003, is one of the geomagnetic storms ever recorded. Fig. 12 compares the IED profiles reconstructed by the two algorithms and measured by Juliusruh ionosonde at different periods on October 30, 2003. We also find that the IED profiles constructed by the TV3D-ART algorithm are...
Fig. 11. Images of TEC distribution and IED sample distribution reconstructed on November 20, 2003. The upper line of images at different times—TEC maps. The lower line of images at different times—Vertical cross section along 10° E.

Fig. 12. Comparison of the IED profiles reconstructed by two algorithms with the IED profiles measured by Juliusruh ionosonde on October 30, 2003. (Left) At 8:00 UT. (Right) At 20:00 UT.
A new algorithm based on TV3D-ART has been successfully applied in reconstructing IED distributions from simulation data and real observation data. This algorithm uses positivity constraints, TV gradient descent, and IART to perform iteration. We examined two classes of ionospheric structures: quiescent conditions and disturbed conditions. In this paper, the inversion results have demonstrated that the proposed algorithm is characterized by high precision. The feasibility and effectiveness of the algorithm are validated by numerical experiments. In the future, this algorithm is expected to be extended to 4-D CIT, in which the time evolution of the ionosphere is considered. Moreover, we should improve the spatial resolution.

V. CONCLUSION

A new algorithm based on TV3D-ART is better in general. It also can be seen that the result of reconstruction using TV3D-ART algorithm is closer to the ionosonde profiles at different periods. These results confirm the effectiveness of CIT, which is used to monitor temporal and spatial variations in IED. Fig. 13 shows a comparison of the estimated NmF2 from Athens ionosonde and inversion using TV3D-ART algorithm and IART algorithm for the 0–23 h UT on October 30, 2003. CIT results are well consistent with the ionosonde data and display similar patterns of NmF2 distribution. Moreover, we should improve the spatial resolution.

ACKNOWLEDGMENT

The authors would like to thank IGS for providing the Global Positioning System data and Global Ionospheric Radio Observatory (GIRO) for providing the ionosonde data. The authors would also like to thank the anonymous reviewers for their constructive comments in improving this paper.

REFERENCES


[10] H. S. Zhao, Z. W. Xu, J. Wu, and Z. G. Wang, “Ionospheric tomography by TV3D-ART algorithm and IART algorithm for the 0–23 h UT on October 30, 2003. CIT results are well consistent with the ionosonde data and display similar patterns of NmF2 distribution. Moreover, we should improve the spatial resolution.

Fig. 13. Comparison of CIT and ionosonde data, October 30, 2003, NmF2 obtained from CIT and Athens ionosonde.


Yibin Yao received the B.Sc., M.S., and Ph.D. degrees with distinction in geodesy and surveying engineering from the School of Geodesy and Geomatics, Wuhan University, Wuhan, China, in 1997, 2000, and 2004, respectively. He is currently a Professor with Wuhan University. He has been the author of more than 90 publications since 2001. His main research interests include Global Navigation Satellite System ionospheric/atmospheric/meteorological studies, theories and methods of surveying data processing, and Global Positioning System (GPS)/Meteorology and high-precision GPS data processing.

Dr. Yao has been awarded with Luojia Professor of Wuhan University, supported by the Program for New Century Excellent Talents in University, selected into High Level Talents Project of Hubei Province in the new century, etc.

Jun Tang received the B.Sc. degree in surveying and mapping engineering and the M.Sc. degree in geodesy and surveying engineering from the East China Institute of Technology, Fuzhou, China, in 2006 and 2009, respectively. He is currently working toward the Ph.D. degree in geodesy and surveying engineering in the School of Geodesy and Geomatics, Wuhan University, Wuhan, China.

His research interests include ionospheric modeling using diverse data, multidimensional ionospheric tomography based on the Global Navigation Satellite System (GNSS) observations, and GNSS applications.

Peng Chen received the B.Sc. and M.Sc. degrees from the School of Geosciences and Info-Physics, Central South University, Changsha, China, in 2006 and 2009, respectively, and the Ph.D. degree in geodesy and surveying engineering from the School of Geodesy and Geomatics, Wuhan University, Wuhan, China, in 2012. He is currently a Lecturer with the Xi’an University of Science and Technology, Xi’an, China. His main research interests include global ionospheric modeling using multisource geodesy observations, 3-D ionospheric tomography based on Global Navigation Satellite System observations, and ionospheric anomaly analyses under abnormal conditions.

Shun Zhang received the B.Sc. degree in surveying engineering from Southeast University, Nanjing, China, in 2010. He is currently working toward the Ph.D. degree in geodesy and geomatics engineering at Wuhan University, Wuhan, China.

His current research area is the effects of solar activity on the ionosphere.

Jiajun Chen received the B.Eng. degree in geodesy and geomatics from Wuhan University, Wuhan, China, in 2012, where she is currently working toward the M.Sc. degree in the School of Geodesy and Geomatics. Her current research interests mainly involve 3-D ionospheric tomography with Global Navigation Satellite System observations and detection and analyses of ionospheric anomalies during geomagnetic storms or earthquakes.

Ms. Chen was awarded with Outstanding Bachelor’s Degree Thesis in Hubei Province, in 2012.