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Research on ionospheric tomography based on variable pixel height

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Abstract

A novel ionospheric tomography technique based on variable pixel height was developed for the tomographic reconstruction of the ionospheric electron density distribution. The method considers the height of each pixel as an unknown variable, which is retrieved during the inversion process together with the electron density values. In contrast to conventional computerized ionospheric tomography (CIT), which parameterizes the model with a fixed pixel height, the variable-pixel-height computerized ionospheric tomography (VHCIT) model applies a disturbance to the height of each pixel. In comparison with conventional CIT models, the VHCIT technique achieved superior results in a numerical simulation. A careful validation of the reliability and superiority of VHCIT was performed. According to the results of the statistical analysis of the average root mean square errors, the proposed model offers an improvement by 15% compared with conventional CIT models.

Keywords: Ionospheric tomography; Electron density; TEC; ART; CIT

1. Introduction

Computerized tomography technology was first successfully applied in the medical field and was subsequently extended to other applications. Specifically regarding ionospheric studies, ionospheric tomography provides significant advantages for the reconstruction of ionospheric electron density (IED) images (Kunitsyn et al., 2008). On the basis of the total electron content (TEC) of the propagation path of multiple satellite ground stations, the ionospheric tomography technique has been extensively studied since the publication of the relevant work by Austen et al. (1988). They aimed at recovering a 2-D IED image using data from a polar-orbiting satellite at an altitude of 1000 km and several ground stations. Subsequently, many early theoretical and experimental studies (Raymund et al., 1990; Fremouw et al., 1992; Kersley et al. 1993; Raymund et al., 1994; Foster et al., 1994; Kunitake et al., 1995; Markkanen et al., 1995; Kunitsyn et al., 1997; Pryse et al., 1997; Huang et al., 1999) were performed on 2-D ionospheric tomography reconstruction with the purpose of describing the basic ionospheric structure. However, owing to technical and instrumentation limitations, the IED distribution of 2-D ionospheric tomography cannot necessarily be obtained at any time and any location (Ma et al., 2005).

During the last twenty years, the development of Global Positioning System (GPS) technology has enabled the acquisition of highly precise observation data of the TEC for computerized ionospheric tomography (CIT) application studies. Therefore, research has shifted from 2-D to three-

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dimensional (3-D) ionospheric tomography in view of the high precision and near-real-time observation data acquired from high orbital satellite systems. Hajj et al. (1994) first considered combining GPS-based data obtained by a low-earth orbit LEO satellite and/or space occultation to reconstruct IED images. Since then, much GPS-based ionospheric tomographic research has been conducted in reconstructing IED distributions using a 3-D model (Bust et al., 2000; Hajj et al., 1994; Hansen et al., 1997; Hernández-Pajares et al., 1998, 2000; Howe et al., 1998; Mitchell and Spencer, 2003; Rius et al. 1998; Ruffini et al., 1998; Stolle et al., 2003; Wen et al., 2007a,b,c, 2008; Yin et al., 2004). However, the solution of GPS-based ionospheric tomography is subject to an ill-posed problem owing to certain limitations (Lee and Kamalabadi, 2009), which include the absence of horizontal ray paths from a satellite to a ground receiver, the non-uniform density of ray paths that serve as projections in the region of study, and the limited number of ground stations in addition to the finite receiving apertures (Wen et al., 2007c, 2008). Hence, the imaging quality of the inversion problem must be improved.

To resolve the above problems, various algorithms have been developed in recent years. As proposed by Yao et al. (2014), these algorithms can be divided into two categories, non-iterative reconstruction algorithms and iterative reconstruction algorithms. For non-iterative reconstruction algorithms, one of the most common approaches is the singular value decomposition method (SVD). An advantage of the SVD is that the reconstruction quality is independent of any initial solution. However, the projection matrix is usually large, so it is difficult to invert the matrix with the SVD algorithm in the inversion process. A classic iterative reconstruction algorithm, the algebraic reconstruction technique (ART) algorithm, was first presented by Austen et al. (1988). Since then, further efforts have been made, including the multiplicative ART (MART) algorithm (Raymund et al., 1990), neural network reconstruction algorithm (Ma et al., 2005), and other modified versions, such as the hybrid reconstruction algorithm (HRA) (Wen et al., 2008) created by combining SVD and ART and aimed at improving the inversion accuracy of the IED. Wen et al. (2007a) and Wen and Liu (2010) used a 2-D nine-point finite difference approximation of the second-order Laplace operator to impose constraints and introduced the constrained ART (CART) and constrained MART algorithms. Lee and Kamalabadi (2009) proposed a forward and an inverse tomographic model for obtaining 3-D images of the IED by deriving a linear algebraic relationship between integrated electron density measurements and the IED. Wen et al. (2012) first presented a new two-step tomographic algorithm with the Phillips smoothing method to resolve the ill-conditioned problem in ionospheric tomography inverse algorithms. Using the ART algorithm, Yao et al. (2014) developed a 3-D iterative reconstruction algorithm based on the minimization of the total variation under quiescent and disturbed ionospheric conditions for solving the ill-posed inversion problem of CIT. Meanwhile, Zheng et al. (2014) proposed a multiscale ionospheric tomography technique to address the ill-conditioned problem because of the poor and uneven GPS ray coverage.

To further improve the inversion accuracy of IED reconstruction and obtain a more realistic IED distribution, a new tomographic method, termed variable-pixel-height CIT (VHCIT), is presented here. In contrast to conventional CIT, which parameterizes the model with a fixed pixel height, VHCIT applies a disturbance to the height of each pixel. Namely, the height of each pixel can be considered as an unknown variable and can then be retrieved together with the electron density values during the inversion process. In the following, the basic methodology of VHCIT is detailed and applied to perform the GPS-based tomographic reconstruction of the IED using GPS observations in the China region. Finally, the features and reliability issues of the VHCIT model will be discussed in comparison with several conventional models.

2. Methods

2.1. CIT theory

The ionospheric TEC is the line integral of the IED along the GPS ray path from a satellite to a receiver that can be defined as:

$$\mathrm{TEC} = \int_p N_e(s)\mathrm{d}s \tag{1}$$

where $N_e(s)$ is the IED along the propagation path P between a satellite and a receiver.

Eq. (1) shows that the relationship between TEC and IED is linear. Thus, it should be discretized for inversion computation by assuming the IED distribution is stable during the given time period. As a result, Eq. (1) can be formulated as:

$$y_i = \sum_{j=1}^{n} A_{ij}x_j + e_i, \quad i = 1, 2, \ldots, m \tag{2}$$

Eq. (2) can be written in simple matrix notation as:

$$y_{m\times1} = A_{m\times n}x_{n\times1} + e_{m\times1} \tag{3}$$

where n is the number of pixels in the reconstructed region, m is the number of TEC measurements or ray paths, and y is a column vector of the m known TEC measurements. A_{ij} represents the element in the ith row and jth column of A, which is identical to the length of the segment with the ith ray path traversing the jth pixel, x is the vector consisting of all the unknown electron densities in all the pixels, and e is an error column vector associated with the expansion and measurement noises of the series. Additionally, the TEC in the Eq. (3)can be extracted from dual-frequency GPS measurements, in which the carrier phase smoothing using pseudorange is used in the data preprocessing to get more precise TEC as mentioned by Jin, et al. (2012).