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A new ionospheric tomography model combining pixel-based and function-based models

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Abstract

Considering the limitations of current single pixel-based and function-based computerized ionospheric tomography (CIT) models, this paper proposes a new tomography model – COMBI, which combines these two models. COMBI model is able to reconstruct the three dimensional distribution of electron density with fewer parameters, and easy to compute, as well as very convenient to use. Through experiments with simulated data and measured data, it is verified that the new COMBI model not only can better describe refine structure of ionospheric electron density, but also is superior to these two pixel-based and function-based CIT models in application.

Keywords: Ionospheric tomography model; Pixel-based model; Function-based models; Total electron content; Ionospheric electron density

1. Introduction

As a part of the Earth's upper atmosphere, Ionosphere is an important part of the Sun-Earth environment, and a part of the Earth's upper atmosphere. Ionization composition in ionosphere significantly affects the transmission of electromagnetic waves in the ionosphere, which causes the reflection of electromagnetic waves and the energy loss, thereby affects the activity of modern radio communications and human space.

In order to deeply study the three-dimensional structure of the ionosphere, Austen et al. (1986, 1988) first proposed the thought of Computerized Ionospheric Tomography (CIT). He obtained the spatial distribution image of ionospheric electron density using the scan of the ionospheric region came from polar-orbiting satellite. The ionospheric tomography reconstruction image can not only reflect horizontal change, but also reflect the vertical structure of ionosphere, which overcomes the limitations of single-layer ionospheric model. Many scholars conduct a plenty of studies on radio tomography (RT) method, the results of these experiments are included in the reviews (Kunitsyn and Tereshchenko, 1991; Leitinger, 1999; Pryse, 2003; Bust and Mitchell, 2008) and books (Kunitsyn and Tereshchenko, 1991, 2003; Kunitsyn et al., 2007). Wang et al. (2007) conducted experiments of ionospheric tomography using a new HF radio source. They found that reconstructed images using the HF method gave comparable results with the VHF/UHF method.

Since the Global Positioning System (GPS) established in the late 1970s, ionospheric delay in radio transmission process has caught the widespread concern, which also gave birth to the GPS ionospheric detection technology; and then the study of the ionosphere has been developed by leaps and bounds. A large amount of researchers have successively studied theoretical models and methods of GPS-based Ionospheric Tomography. Now, ionospheric models are broadly divided into two categories: one is the function-based ionospheric model (Gao and Liu, 2002; Hansen, 1998; Howe, 1997; Liu, 2004; Geng, 2011); the

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other is the pixel-based ionospheric model (Hernandez-Pajares et al., 1999; Kunitake et al., 1995; Ma and Maruyama, 2003; Rius et al., 1997a; An, 2011; Wen, 2007; Zou, 2004; Zou and Xu, 2003a,b). Jin et al. (2011) presented the current status and new developments of remote sensing using GNSS signals as well as its future directions and applications. The authors concluded that the denser ground GNSS system could monitor more detailed ground surface characteristics and processes and evolutions of the atmospheric and ionospheric profiles at global and regional scales.

In the study of function-based ionospheric tomography model, as early as 1992, Fremouw proposed to express ionospheric vertical model with empirical orthogonal function (EOF), and horizontal model with spherical harmonic function (Fremouw et al., 1992). Then Hansen (1998) first definitely gave function-based ionospheric tomography model, and obtained the ionospheric electron density distribution using the observations of WAAS system. Howe et al. (1998) extended the reconstruction height range to the entire ionosphere, and obtained time-varying three-dimensional ionospheric structure with the help of Kalman filter, using simulated GPS data. Ruffini et al. (1998) proposed correlation function model and achieved a global ionospheric reconstruction with it. Gao and Liu (2002) put forward a real-time function-based model, which improved the computational efficiency by combining the ionosphere TEC smoothing model and the function-based tomography model. Brunini et al. (2004) put forward the tensor product model of spherical harmonics and chapman profile function. Nesterov and Kunitsyn (2011) applied a method based on the choice of the smoothest solution by minimizing of a certain Sobolev's norm for the sought-for function to overcome the non-uniqueness of the solution of the problem with incomplete data is suggested.

In the study of pixel-based ionospheric tomography, Rius et al. (1997b) first reconstructed spatial–temporal distribution of global ionospheric electron density, using GPS information offered by IGS to discretize ionosphere into small grids in earth-fixed coordinate system. Hernandez-Pajares et al. (1998) successfully obtained global ionospheric electron density distribution with high resolution in clam and disturbed state, respectively; and got ionospheric electron density distribution during geomagnetic storms. Bust et al. (2000) compared the results obtained by pixel-based tomography model using GPS data with simulated results from IRI (International Reference Ionosphere) model and observations from ionosondes, and they attested that GPS-based ionospheric electron density profiles are closer to the profiles obtained from ionosondes. The IRI model is an empirical model based on a wide range of ground and space data, it describes monthly averages of ionospheric densities and temperatures in the altitude range 50–1500 km in the non-auroral ionosphere (Bilitza and Reinisch, 2008). Jin and Park (2007) reconstructed the ionospheric electron density profile of southern Korea in 2003, with the data of Korean GPS Network (KGN, Korean GPS Network); then verified the reliability of the result through a comparison with the profile obtained from ionosonde, they also made a comparison with the result from IRI-2001 model.

When using the pixel-based model to reconstruct ionospheric electron density, it is necessary to discretize ionosphere into a number of small grids, and assume that electron density in each grid is constant, and that TEC in the transmission way is equal to the sum of the products of electron density and corresponding ray-intercept in every grid. Its disadvantage is the number of discretized grids is too large, so describing a three dimensional distribution of one region needs a large amount of parameters, which is very inconvenient to use.

Function-based model (Gao and Liu, 2002; Hansen, 1998; Howe, 1997; Liu, 2004; Geng, 2011), however, utilizes a set of functions to express ionospheric electron density distribution. It is good at describing the distribution of a large region with a very small amount of model parameters; but owing to the limitation of ionospheric tomography itself, it would be very difficult to solve equations if we directly fit the observations.

This paper proposes a new tomography model which combines pixel-based model and function-based model. The new model absorbs advantages of the above two models, as well as avoids disadvantages of them. Hence, it is simple to solve equations and convenient to use. In addition, reliability of the new model is verified with simulated data and real observations.

2. Construction of the new tomography model–COMBI

The ionospheric TEC is the line integral electron density on the signal propagation path. It is expressed as

$$\mathrm{TEC} = \int_l Ne(\vec{r}, t)\,ds \tag{1}$$

where Ne is the electron density along the signal propagation path l. GNSS-based ionospheric CIT uses a series of TECs along l to inverse the temporal and spatial distributions of ionospheric electron density. The pixel-based model (Hernandez-Pajares et al., 1999; Kunitake et al., 1995; Ma and Maruyama, 2003; Rius et al., 1997a; An, 2011; Wen, 2007; Zou, 2004; Zou and Xu, 2003a,b) must discretize the reconstruction region. Assuming the electron density in each grid is constant during the reconstruction hours, the discretized equation is shown in (1):

$$TEC_i = \sum_{j=1}^{J} A_{ij} x_j + e_i \tag{2}$$

where TEC_i is the total electron content of the ith ray, and in the next experiments we wrote it as STEC (slant TEC), A_{ij} is the intercept of the ith ray path traversing the jth grid, x_j is the electron density of the ith grid, and J is the total number of grids. Assuming the number of rays simultaneously observed is m, Eq. (1) can be generally written in a simple matrix notation as: