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International Reference Ionosphere as a potential regularization profile for computerized ionospheric tomography

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Abstract

In recent years, radio ray tomography of the ionosphere has developed into a very useful technique for the study of the ionosphere. Compact generalized singular value decomposition (CGSVD) is used to study the feasibility of using the International Reference Ionosphere (IRI) model as a regularization profile for ionospheric tomography experiments. TEC data obtained from a meridional chain of three LEO satellite receivers located in Alaska, USA are used for reconstruction of the poleward edge of the mid latitude ionosphere and the high latitude ionosphere. Results show that the IRI has the potential of becoming a useful regularization profile for computerized tomographic reconstruction of the ionosphere. The error estimates for reconstructed images with IRI and Chapman as regularization profiles show that the IRI is a better profile to use under quiet and moderate geomagnetic conditions. Under severe geomagnetic conditions, the IRI and Chapman regularization profiles produce reconstructed images of comparable quality. It has also been observed that the foF2 values obtained from reconstructed images that use the IRI as a regularization profile are closer to measured values than those obtained from the images reconstructed with the Chapman regularization profile.

Keywords: Computerized ionospheric tomography; Compact GSVD; International reference ionosphere; Regularization

1. Introduction

Although individual and coordinated TEC measurements provide information about the temporal and horizontal distribution of electron content on various time scales, TEC cannot be used for investigating the vertical structure of the ionosphere using conventional techniques. The more advanced technique of ionospheric tomography can be used to study the vertical structure of the ionosphere in a given space-time segment utilizing TEC as the measured parameter. In recent years, the radio ray tomography of the ionosphere has developed into a very useful technique for the study of the ionosphere. Austen et al. (1986, 1988) first proposed the application of computerized tomography for reconstruction of the electron density distribution below and above the F2 peak by utilizing TEC observations. Pryse and Kersley (1992) reported preliminary experimental results based on the method proposed by Austen et al. (1986, 1988). Andreeva et al. (1990), Kunitsyn and Tereshchenko (1992) proposed a phase-difference approach making use of relative TEC derivatives and obtained experimental ray tomographic (RT) images of the ionosphere for the first time. The genre of computerized ionospheric tomography (CIT) that followed Austen et al. (1986, 1988) basically adheres to the principle of measurement of total electron content at a meridional chain of ground receivers using a TRANSIT satellite and then inverting the same to reconstruct a two dimensional electron density versus height profile. Raymund et al. (1990) applied computerized ionospheric tomography to realistically simulate the ionospheric electron density variations over 16° in latitude within the height range of 50 to 1000 km.

A number of theoretical as well as experimental CIT schemes have so far been reported in the literature

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(Raymund et al., 1990; Fremouw et al., 1992; Na and Lee, 1990, 1991, 1994; Afraimovitch et al., 1992; Andreeva et al., 1990, 1992, 2001; Kunitsyn and Tereshchenko, 1991, 1992; Klobuchar et al., 1992; Pryse and Kersley, 1992; Kunitake et al., 1995; Kersley et al., 1997; Zhou et al., 1999; Andreeva et al., 2000; Tsai et al., 2002; Kamalabadi et al., 2002; Bhuyan et al., 2002, 2004). The Algebraic Reconstruction Technique, ART (Austen et al., 1988), the Multiplicative Algebraic Reconstruction Technique, MART (Raymund et al., 1990; Kersley et al., 1993), and the Maximum Entropy Method, MEM (Fougere, 1995) are some of the widely used CIT algorithms. Kunitsyn et al. (1995) proposed the DART algorithm (Decomposed Algebraic Reconstruction Technique) and obtained good results for ionospheric tomography problems.

The most common inversion techniques applied to radio tomography are iterative in nature. The iterative algorithms start from some initial profile and the iteration continues until a pre-defined stop criterion is met. The choice of the model layer to be used as start profile poses a central problem in these algorithms since the ultimate result depends more or less on it. On the other hand, in the stochastic inversion methods, the results are obtained in terms of matrix operations. One of the advantages of stochastic inversion methods is that it allows regularization to be used for feeding suitable a priori information to the inversion algorithm (Nygren et al., 1996). The incorporation of a regularization profile, which usually does not include features of interest, can substantially improve the reconstruction results. This approach allows the direct reconstruction of features not described by the regularization profile but contained in the measured data (Raymund et al., 1994). Pryse et al. (1998) gave a comparative estimate of the different reconstruction techniques. It should be noted that the iterative algorithms can also incorporate regularization and can have well defined error bounds.

In this paper, we investigate the feasibility of using the International Reference Ionosphere model (Bilitza, 2001) vis-à-vis the Chapman profile as a regularization profile for CIT experiments by reconstructing slices of the ionosphere utilizing TEC data obtained at a meridional chain of three LEO satellite receivers located in Alaska, USA. Bust et al. (2001) presented a method that combined IRI-95 density predictions with ionospheric tomography data and obtained improved density predictions. Though the primary objective of the present work, that is to obtain a truer representation of the ionosphere, is the same as that of Bust et al. (2001), the approaches are different.

2. Compact GSVD method

Bhuyan et al. (2002, 2004) reported a CIT algorithm based on the generalized singular value decomposition (GSVD). In this study, a modified version of the GSVD algorithm reported earlier has been used. In the inversions of TEC (y') for the reconstruction of electron density distribution (x'), more stable estimates are usually obtained by minimizing an objective function

$$F = (A'x' - y')^T C_{y'}^{-1}(A'x' - y') + \alpha^2 (x' - x_o)^T C_{x'}^{-1}(x' - x_o) \tag{1}$$

where $C_{x'}$ is the covariance matrix, the diagonal elements representing uncertainty about the prior estimate x_o, $C_{y'}$ is the covariance matrix representing the variance of the error in data. In practice, determining the model error covariance matrix $C_{x'}$ is not so easy (Bust et al., 2001). In this study, the model error covariance is assumed to be Gaussian in nature and a few percent of the predicted electron density. Bust et al. (2001) devised a method to combine IRI-95 predictions of electron density with ionospheric tomography data to provide an improved electron density estimate and also discussed a technique for ionospheric data ingestion capable of ingesting GPS, CIT, ionosonde, and incoherent scatter radar (ISR) data. Several issues regarding faithful estimation of electron density had been addressed. In our case, however, due to the lack of a suitable dataset, no such attempts for data ingestion has been made. To model the IRI-95 error covariance, Bust et al. (2001) assumed that the covariance is statistically homogeneous; the spatial correlations are separable horizontally and vertically, the vertical correlations are given by a Gaussian, and the horizontal correlation are given by an elliptical Gaussian in geomagnetic coordinates.

We make the transformations

$$A = C_{y'}^{-\frac{1}{2}} A' C_{x'}^{\frac{1}{2}} \tag{2a}$$

$$x = C_{x'}^{-\frac{1}{2}} (x' - x_o) \tag{2b}$$

$$y = C_{y'}^{-\frac{1}{2}} (y' - A'x_o) \tag{2c}$$

where $C_{x'}^{-\frac{1}{2}}$ and $C_{y'}^{-\frac{1}{2}}$ are the Cholesky factors of the covariance matrices $C_{x'}$ and $C_{y'}$ respectively. Then the objective function takes the form

$$F = \|Ax - y\|_2^2 + \alpha^2 \|x\|_2^2 \tag{3}$$

The GSVD can be used to solve the damped least squares problem as proposed by Tikhonov (1963). The Tikhonov regularized solution of the above equation is

$$x_{\alpha,L} = (A^T A + \alpha^2 L^T L)^{-1} A^T y = A^{\#}_{\alpha,L} y \tag{4}$$

or, explicitly we can write

$$x_{\alpha,L} = \sum_{i=1}^{P} \frac{\lambda_i^2}{\lambda_i^2 + \alpha^2 \mu_i^2} \frac{U_i^T y}{\lambda_i} B_i + \sum_{i=P+1}^{N} (U_i^T y) B_i \tag{5}$$

In the Compact GSVD (CGSVD) (Hansen, 2001) algorithm, it is assumed that $M \geqslant N \geqslant P$ (Bhuyan et al., 2004). This is true for regularization problems. Also, the matrix B (in Eqs. (7) and (8) of Bhuyan et al., 2004) is replaced by

$$B_1 = \mathrm{inv}(B^T) \tag{6}$$

In our formulation, P is always put equal to N. Then, the solution of the inversion problem can be written as