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A neural network based error correction method for radio occultation electron density retrieval

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ABSTRACT

Abel inversion techniques have been widely employed to retrieve electron density profiles (EDPs) from radio occultation (RO) measurements, which are available by observing Global Navigation Satellite System (GNSS) satellites from low-earth-orbit (LEO) satellites. It is well known that the ordinary Abel inversion might introduce errors in the retrieval of EDPs when the spherical symmetry assumption is violated. The error, however, is case-dependent; therefore it is desirable to associate an error index or correction coefficient with respect to each retrieved EDP. Several error indices have been proposed but they only deal with electron density at the F2 peak and suffer from some drawbacks. In this paper we propose an artificial neural network (ANN) based error correction method for EDPs obtained by the ordinary Abel inversion. The ANN is first trained to learn the relationship between vertical total electron content (TEC) measurements and retrieval errors at the F2 peak, 220 km and 110 km altitudes; correction coefficients are then estimated to correct the retrieved EDPs at these three altitudes. Experiments using the NeQuick2 model and real FORMOSAT-3/COSMIC RO geometry show that the proposed method outperforms existing ones. Real incoherent scatter radar (ISR) measurements at the Jicamarca Radio Observatory and the global TEC map provided by the International GNSS Service (IGS) are also used to valid the proposed method.

1. Introduction

Radio occultation (RO) is a powerful technique that can provide vertical profiles of refractivity, temperature, pressure, and water vapor in the neutral atmosphere and electron density in the ionosphere (Fjeldbo and Eshleman, 1965; Hajj and Romans, 1998; Liou et al., 2007; Schreiner et al., 1999; Yunck et al., 1988). Such a technique has been manifested in several RO missions including the constellation of FORMOSAT-3/COSMIC satellites (Rocken et al., 2000). Nowadays, RO techniques play an important role in monitoring and predicting weather, climate, ionosphere, and space weather due to their advantage in vertical resolution and spatial coverage. Opportunities for remote sensing the earth's atmosphere and ionosphere are increasing due to the expansion of the Global Navigation Satellite System (GNSS).

Abel inversion methods have been widely utilized to retrieve EDPs from RO measurements obtained by low-earth orbiting (LEO) receivers (Hajj and Romans, 1998; Lei et al., 2007; Schreiner et al., 1999). It is well known that the most significant error in Abel inversion techniques causes by the invalidity of the spherical symmetry assumption of the ionosphere. Yue et al., (2010) and Liu et al., (2010) evaluated errors in EDPs retrieved by the Abel inversion based on FORMOSAT-3/COSMIC observations, and found that Abel retrieval techniques introduce significant errors to EDPs in low-latitude regions and at low altitudes. Several methods have been proposed to improve the electron density retrieval. Hajj et al. (1994) and Schreiner et al. (1999) assumed that electron densities in a given ionosphere layer have a given functional relationship and solved for a single unknown scale factor for each layer. Hocke and Igarashi (2002) proposed a two-dimensional inversion method to relax the spherical symmetry assumption. This method, however, requires a full latitude–height section (i.e., an annulus) of slant TEC measurements which is currently not available. Tsai and Tsai (2004) and Tsai et al. (2009) obtained ionospheric horizontal information from nearby occultations. Hysell (2007) employed the maximum entropy method to retrieve EDPs, avoiding the error propagation issue in the Abel inversion. Hernández-Pajares et al. (2000) and Garcia-Fernandez et al. (2003) assumed that the electron density is separable as a product of vertical TEC and a shape function which was estimated from slant TEC. Kulikov et al. (2011) proposed an improved Abel inversion using ionospheric

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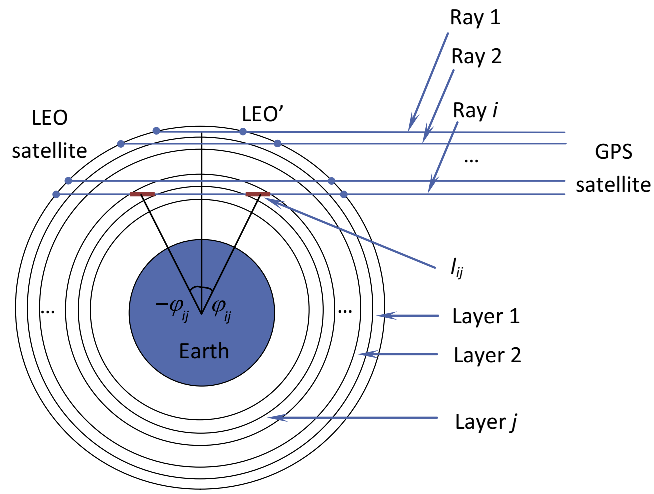

Fig. 1. Radio occultation geometry.

horizontal gradient information from vertical TECs. In addition, data assimilation methods have also been employed to overcome the limitations of Abel inversions (Angling and Cannon, 2004; Bust et al., 2004; Schunk et al., 2004; Wang et al., 2004; Yue et al., 2011, 2012).

Apart from constraining the problem of electron density inversion using ionospheric horizontal gradients, one way to deal with the limited accuracy of the Abel inversion is to estimate the asymmetry level of the ionosphere and use it to correct the retrieved EDP. This idea is promising because the retrieval error of a specific RO event depends on the level and characteristic of the asymmetry of the part of the ionosphere probed by RO rays. Wu et al. (2009) defined an asymmetry factor (AF) to estimate the ionospheric horizontal asymmetry and used it to reduce retrieval errors. Shaikh et al. (2014) introduced an asymmetry index (AI) and found a good correlation between the proposed index and the absolute value of the retrieval error. The proposed AI, however, cannot be directly used to correct the retrieved EDP because that absolute error is involved. Both methods only deal with errors at the F2 peak. More importantly, the former method does not take full advantage of the information about ionospheric horizontal gradients (e.g., vertical TECs) whereas the latter might not correctly reflect retrieval errors. These two methods are further analyzed in Section 3.

Artificial neural networks (ANNs) have been widely employed to forecast the F layer critical frequency f_0F2 based on the time of interest, day of year, solar activity, magnetic activity, and recent f_0F2 values (Cander et al., 1998; Poole and McKinnell, 1998, 2000; Williscroft and Poole, 1996). Most of these methods, however, require recent f_0F2 measurements which are only available at ground based measurement sites (e.g., ionosonde stations). Similar ideas were also investigated to process vertical TEC measurements (Habarulema et al., 2007; Habarulema et al., 2010; Tulunay et al., 2004; Xenos et al., 2003). Oyeyemi et al. (2006) used an ANN to predict the near real time f_0F2 everywhere on the earth given real time f_0F2 data at four base stations. Daily and monthly prediction model for f_0F2 was also developed in (Francis et al., 2000).

The paper proposes an ANN-based error correction method for the estimation of EDPs. The ANN is first trained to learn the relationship between ionospheric horizontal gradients (i.e., vertical TECs) and retrieval errors at the F2 peak, 220 km and 110 km altitudes, respectively. Afterwards, correction coefficients are estimated to correct the retrieved EDPs at these three altitudes. The paper adopts the idea of using vertical TEC measurements to correct the Abel retrieval, similar to that of Wu et al. (2009). However, the paper differs from the previous work in several aspects. First, instead of the average value, vertical TEC measurements are provided to the ANN for correction, leading to an improved accuracy. Second, the proposed method confirms that the correction at altitudes below the F2 peak can also be obtained for the correction of the whole EDP. Finally, real FORMOSAT-3/COSMIC RO data is used to verify the proposed method.

The rest of the paper is organized as follows. Section 2 briefly reviews the ordinary Abel inversion and describes the proposed method. Section 3 presents experiments and discussions. Conclusions are given in Section 4.

2. Problem formulation and method

2.1. Ordinary Abel inversion

Abel inversion is a popular method for the retrieval of electron densities at tangent points of RO rays. The method assumes that RO rays are straight lines as depicted in Fig. 1. When the LEO receiver receives GPS signals, slant TEC values along transmitter–receiver rays are obtained. Slant TEC values can be computed from the excess phase at the L1 or L2 GPS carrier frequencies or from their linear combination (Schreiner et al., 1999). The calibrated slant TEC (Schreiner et al., 1999), which is the TEC measurement along the section of a ray below the LEO, is written as an integral of electron density Ne as follows:

$$STEC_{ray} = \int_{ray} Ne(l)dl \tag{1}$$

Discretizing (1) using the spherical symmetry assumption of the ionosphere, a system of linear equations is obtained:

$$STEC_i = 2\sum_{j=1}^{i} l_{ij}Ne_j,\ i = 1 \ldots M \tag{2}$$

where l_{ij} is the length of ray i propagating in ionosphere layer j as shown in Fig. 1, Ne_j is the electron density of layer j, M is the number of rays, and $STEC_i$ is the calibrated slant TEC measurement along the section LEO–LEO' below the LEO of ray i. In the rest of the paper, this section of ray is called a RO *link*, which includes a left side and a right side with respect to the tangent point. Let the unknown vector **x** be