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A new regional total electron content empirical model in northeast China

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Abstract

Using total electron content (TEC) data over one and a half solar cycles (1999–2015) provided by the Center for Orbit Determination in Europe (CODE), this paper proposes a new empirical TEC model for northeast China (40–50N, 120–130E). The model, called TECM-NEC, involves the multiplication of four separable components, including diurnal variation, seasonal variation, geomagnetic field dependency, and solar dependency. Diurnal variation is composed of three parts: the typical daily variation of TEC; corrections of Mid-latitude Summer Nighttime Anomaly (MSNA) that depend on geographic location, season, and local time; and corrections of day-to-night ratio under different seasons and solar activities. Four sub-harmonics of the year with annual, semiannual, four-, and three-month periods are used to describe seasonal variations. For geomagnetic variation, geomagnetic latitude is based on the latest International Geomagnetic Reference Field (IGRF12) model. Compared with similar empirical models, the solar proxy index F10.7P = (F10.7 + F10.7A)/2, where F10.7A is the 81-day running mean of daily F10.7, is chosen as having linear relationship with TEC for the model. This model has 43 coefficients, which are determined by nonlinear least squares fitting (NLSF) technique. The TECM-NEC model fits with the TEC/CODE input data with a bias of 0.03TECU and a RMS deviation of 2.76TECU. The proposed TECM-NEC model can reproduce the MSNA and nighttime TEC enhancements phenomenon over northeast China.

Keywords: Ionosphere; Regional empirical model; Total electron content

1. Introduction

The ionosphere, which is part of the Earth's upper atmosphere and is located from 60 km above the ground to the top of the magnetic layer, is ionized by solar radiation. Quantities of electrons exit the ionosphere, which can affect radio propagation (Yeh and Liu, 1972). Ionospheric variations are related closely to solar activity, the earth's magnetic field, and the motions of the upper atmosphere (Rishbeth and Mendillo, 2001). These variations can be divided into two classes. The first class represents regular temporal and spatial variations. Temporal variations occur mainly because of differences in the intensity of solar activity, changes in daily ground distance, and alternations of day and night. These variations have significant periods, including variations of 11-year and 27-day period, seasonal variation, and diurnal variation. Spatial variation is caused mainly by the geomagnetic field and upper atmospheric motion, which can be described by geomagnetic latitude and longitude. These temporal and spatial variations are regular or periodic. Hence, these variations can be summarized analytically from empirical data

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and predicated in advance with reasonable accuracy by ionospheric empirical models. Studying and summarizing the intrinsic variations of the ionosphere will serve as the foundation for building a reasonable empirical model. The second class represents irregular variations that result from abnormal behaviors of the sun, including sudden ionospheric disturbances or small rapid changes in electron density causing scintillation. Despite being observed regularly, these phenomena do not exhibit any behavior patterns of the magnitude or period of occurrence (Najman and Kos, 2014). These irregular variations belong to ionospheric weather rather than to climatology, which cannot be predicted by empirical models (Najman and Kos, 2014).

The total electron content (TEC) is an important physical parameter of the ionosphere, which is defined as the total number of electrons exiting along the radio path. The influence of the ionosphere on electromagnetic waves is determined mainly by TEC along the ray path and the frequency of radio waves (Klobuchar, 1996). The ionosphere is the largest error source for Global Navigation Satellite Systems (GNSS), including the GPS, GLONASS, BeiDou, and Galileo. The ionosphere can change the speed and trajectory of GNSS radio waves propagation, and in the worst case, can lead to signal interruption (Klobuchar, 1991). The correct estimation of TEC in the path of radio propagation is one of the key steps in GNSS positioning, navigation, and timing. Although affected by the ionosphere, GNSS provides a new method for obtaining TEC. As a typical dispersion medium, the ionosphere causes various propagation delays for electromagnetic waves in different frequencies. Thus, the slant TEC using to describe ionospheric propagation delay can be calculated through dual (or more) frequency measurements of GNSS. Because of the globally distributed receivers and their high frequency with continuous operation mode, GNSS-derived TEC data with high spatial and temporal resolution can be obtained on both a regional and global scale. Global and regional ionosphere maps (GIMs and RIMs) based on GNSS-derived TEC have been produced through different methods (Iijima et al., 1999; Ping et al., 2002; Otsuka et al., 2002; Meggs et al., 2004; Orus et al., 2005; Stolle et al., 2005; Fuller-Rowell et al., 2006; Zapfe et al., 2006; Sayin et al., 2008) over the last two decades. GIMs provided by the International GNSS Service (IGS) are the most well known among these maps.

The GIMs and RIMs of TEC products provide opportunity for the construction of new TEC empirical models. For example, Jakowski et al. (2011) proposed a global two-dimensional empirical ionospheric model called Global Neustrelitz TEC Model (NTCM-GL) based on nonlinear least squares methods, which used GIM TEC data derived by CODE at the University of Berne for ten years (1998–2007). A et al. (2012) built a global model of TEC using the method of empirical orthogonal function (EOF) based on TEC data set derived from Jet Propulsion Laboratory (JPL) for more than 10 years, 1999–2009. Wan et al. (2012) constructed another global ionospheric TEC model also based on EOF analysis. Mukhtarov et al. (2013) proposed a new global empirical TEC model by using the TEC data set provided by the CODE during 1999–2011. New regional ionospheric TEC models have also been built in China (Mao et al., 2008), Australia (Bouya et al., 2010), Southern Africa (Habarulema et al., 2010, 2011), Europe (Jakowski et al., 1998; Jakowski, 1996), and the polar regions (Jakowski et al., 2011).

These TEC empirical models summarized above are all built based on the statistical analysis of long-term GNSS-derived TEC data, and different theory-based functions are used to model the intrinsic variations of TEC (Bilitza, 1999; A et al., 2012; Mukhtarov et al., 2013). The global empirical models typically represent the overall features of global TEC quite well, but are limited because of issues on the accuracy of GNSS-derived TEC data on the global scale and other factors, such as anomalies of ionosphere, asymmetry of the northern and southern hemispheres, and abnormal diurnal cycle in polar area. Thus, for a certain area, the regional empirical model generally exhibits higher accuracy than the global empirical model when they utilize similar theory-based functions.

In this paper, we propose a new regional empirical TEC model in northeast China (40–50N, 120–130E) called TECM-NEC, which uses long-term TEC data from CODE. This model requires 43 coefficients, which are determined using nonlinear least squares fitting technique. This model can provide a simple and easy long-term prediction of temporal and spatial variations of regional TEC in northeast China under quiet geomagnetic conditions.

2. Modeling data set and preprocessing

In this work, the TECM-NEC model is constructed based on regional TEC maps over northeast China provided by CODE. The TEC/CODE data are available at FTP address, ftp://ftp.unibe.ch/aiub/CODE/. TEC/CODE data from 1 January 1999 to 30 June 2015, which span one and a half solar cycles (16.5 years), are used in this paper. At CODE, the GIMs are generated daily using data from GPS/GLONASS sites of IGS and other institutions. The estimated accuracy of GIM/CODE keeps within several TECU, which makes GIM/CODE become one of the most precise TEC maps of IGS (Mukhtarov et al., 2013; Jakowski et al., 2011). Analysis and validation of different GIMs over China can be found in Xiang's work (Xiang et al., 2015). It indicated that CODE has slightly better performance than other GIMs at middle latitude over China in terms of relative error and standard deviation. The TEC/CODE data are stored in Ionosphere Exchange format (IONEX) files and arrayed in terms of the coordinate system of geographical latitude and longitude. The range of longitude is 180W–180E with a spacing of 5°, whereas the range of latitude is 87.5N–87.5S with a spacing of 2.5°. Thus, a map of TEC/CODE refers to 5183 TEC grid points. Note that the content of CODE IONEX files