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Improvement of global ionospheric VTEC maps using the IRI 2012 ionospheric empirical model

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ABSTRACT

In this study, vertical total electron content values derived from an ionospheric empirical model (IRI 2012) are applied to global ionospheric modeling. Firstly, a comparison of VTEC maps between IRI 2012 and IGS GIMs during the year 2014 is investigated. The comparison shows that IRI 2012 is capable of representing the TEC at middle and high latitudes. Furthermore, IRI 2012 is applied to provide priori VTEC values as virtual measurements for global ionospheric modeling during the year 2014. The results show that the new approach not only eliminates the non-physical negative VTEC values but also improves the accuracy of VTEC maps. The VTEC RMS maps are improved by 3.67%, 2.95% and 22.16% in the Northern Band, Middle Band and Southern Band of the global ionosphere, respectively. This work also investigates the consistency between VTEC maps from different solutions, IGS final products and GIMs of Ionosphere Associate Analysis Centers (IAACs). The comparisons suggest that there is a slightly better consistency between the improved VTEC maps and the IGS final products. The consistencies of the VTEC maps are improved by 4.58%, 2.76% and 4.77% in the Northern Band, Middle Band and Southern Band, respectively. The annual mean values of the root mean square (RMS) of the differences between the improved VTEC maps and GIMs of IAACs are approximately 4∼6 TECU. The results indicate that the new VTEC maps using the IRI 2012 model have better agreement with the IGS final GIMs.

1. Introduction

The ionospheric total electron content (TEC) is an important parameter for satellite navigation and for scientific studies of the ionosphere and space weather (Komjathy, 1997; Schaer, 1999; Jakowski et al., 2012; Lejeune et al., 2012; Li et al., 2015; Sieradzki and Paziewski, 2016). The TEC determines the first order ionospheric delay, which is a dominant source of error in GNSS-generated navigation solutions. Existing models, such as the Klobuchar model (Klobuchar, 1987), the International Reference Ionosphere (IRI) model (Rawer et al., 1978), the Bent model (Bent et al., 1972), and the NeQuick model (Dudeney, 1978), are suitable for the scientific analysis of the general trend of the ionosphere but are limited by their accuracy in practical applications, such as precise positioning. Measurement-based TEC estimation has gained much attention as a method to meet the needs of practical applications. This is especially true because the proliferation of GNSS receivers has led to the establishment of various global and regional GNSS networks (De Franceschi and Zolesi 1998; Sakai et al., 2007; Jensen et al., 2008; Lejeune et al., 2012). Four prominent Ionosphere Associate Analysis Centers (IAACs) of the International GNSS Service (IGS) have been generating global ionospheric maps (GIMs) for over a decade. They are the Center for Orbit Determination in Europe (CODE) (Schaer, 1999), the European Space Operations Center of ESA (ESOC) (Feltens and Schaer, 1998), the Jet Propulsion Laboratory (JPL) (Mannucci, Wilson et al., 1998), and the Technical University of Catalonia (UPC) (Hernández-Pajares et al., 1999; Orús et al., 2005). The IGS final vertical TEC (VTEC) maps combined from the IAAC GIMs have become a reliable source of ionospheric information since 1998 (Hernández-Pajares et al., 2009).

Most of the GNSS receivers are basically located on the mainland in the Northern Hemisphere, and only a few receivers installed in the oceans and southern latitudes. VTEC maps over these areas will have very poor precision and may even display negative values. Multiple scholars have proposed methods to overcome this problem. Mannucci used climatological model information as simulated data to cover the gaps between measurements (Mannucci et al., 1998). Orus updated the VTEC maps using the Kriging interpolation technique and provided a better UPC GIM with an approximate 12% improvement in the self-consistency test (Orús

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et al., 2005). Yuan and Ou (2004) and Mautz et al. (2005) presented the Differential Areas and Differential Stations method and B-spline wavelets to solve the problems in ionospheric modeling due to the uneven distribution of receivers and due to data gaps, respectively. Zhang noted there are many zero values (in fact, negative values) in ESA and CODE's GIMs and proposed the inequality-constrained least square (ICLS) method to eliminate nonphysical negative values (Zhang et al., 2013). The ICLS method is based on the priori knowledge that VTEC values are always greater than zero; the ICLS method reconstructs the GIM by applying the inequality-constrained least square solution iteratively until all grid points yield positive VTEC values. Nevertheless, the computation of the ICLS method relies on the number of grid points that have negative VTEC values. If that number is large, especially during periods of low solar activity, then the matrix G (referred to Zhang et al., 2013) will be so large that the computation will be very slow.

Additional priori knowledge could be obtained from an ionospheric empirical model, such as IRI and NeQuick. Grid points with negative VTEC values could be replaced by priori VTEC values calculated from the IRI model. An improved method is hereby proposed for global ionospheric modeling that utilizes the IRI 2012 model. Then, global ionospheric maps will be generated not only without negative values but also with slightly improved precision. The remaining paper is organized as follows: In Section 2, we outline the principle methodology of global ionospheric modeling along with the IRI 2012 model. In Section 3, the improved solution strategy to process IGS GPS data is discussed, and the results are presented and analyzed. Finally, conclusions are summarized in the last section.

2. Basic methodology of TEC modeling

2.1. GIMs derived from GPS measurements

The Ionosphere Working Group of IGS, which was created in 1998, is responsible for generating reliable VTEC maps, as well as their corresponding ranking and final product combination. The IGS VTEC maps have been generated by IAACs without interruption for scientific or application uses since 1998 (Hernández-Pajares et al., 2009). IAACs compute global ionospheric VTEC maps independently using different approaches. CODE uses a spherical harmonic (SH) expansion referring to a solar geomagnetic frame for representing GIMs (Schaer, 1999). In this paper, the spherical harmonic functions used for global ionospheric modeling are the same as those used by CODE and ESA. The basic equations are presented for ionosphere modeling, as follows (Blewitt 1990; Miyazaki et al., 1997; Ma and Maruyama, 2003):

$$P_f = \rho_0 + c(\Delta t_r - \Delta t_s) + T + I_f + c(b_{r,f} + b_{s,f}) + \varepsilon_f \tag{1}$$

where the subscript f indicates the frequency dependency of the terms; P is the code measurements; ρ_0 is the geometric range between the receiver and a satellite; c is the speed of light; Δt_r and Δt_s are the respective clock errors of receiver and satellite with respect to GPS time; T is the tropospheric delay; I is the ionospheric delay; b_r and b_s are the respective hardware delays of receiver and satellite; and ε contains the multipath effect, measurement noise, and other error sources.

Code measurements are smoothed by the carrier-phase measurements to obtain high-precision code observables. The code observables are actually replaced by the carrier-phases, shifted by the average value of code minus the phase in a continuous arc (Dach et al., 2007), as shown in Eq. (2):

$$\begin{aligned} \tilde{P}_1 &= \bar{P}_1 + \Phi_1 - \bar{\Phi}_1 + \frac{2f_2^2}{f_1^2 - f_2^2}\left(\left(\Phi_1 - \bar{\Phi}_1\right) - \left(\Phi_2 - \bar{\Phi}_2\right)\right) \\ \tilde{P}_2 &= \bar{P}_2 + \Phi_2 - \bar{\Phi}_2 + \frac{2f_1^2}{f_1^2 - f_2^2}\left(\left(\Phi_1 - \bar{\Phi}_1\right) - \left(\Phi_2 - \bar{\Phi}_2\right)\right) \end{aligned} \tag{2}$$

where $\tilde{P}_1,\tilde{P}_2$ are the smoothed code measurements; $\bar{P}_1$, $\bar{P}_2$ and $\bar{\Phi}_1,\bar{\Phi}_2$ are the mean code measurements and mean phase measurements in a continuous arc, respectively; f_1 and f_2 are the respective carrier frequencies of the L1 and L2 signals, respectively; and Φ_1, Φ_2 are the corresponding phase measurements at an epoch.

The non-dispersive terms are eliminated by the difference between the carrier-smoothed code measurements, as shown in Eq. (3).

$$\tilde{P}_1 - \tilde{P}_2 = I_1 - I_2 + c\left(b_{r1} - b_{r2} + b_{s1} - b_{s2}\right) + \Delta\varepsilon_{12} \tag{3}$$

Following the conventional notations, the differences between the receiver hardware delays and between the satellite hardware delays are referred to as the receiver and satellite differential code biases (*DCB*), respectively. We follow the widely used thin shell approximation of the ionosphere and use the same mapping function MLSM (Schaer, 1999) as that used in CODE to transform Slant TEC to VTEC. Ignoring the noise term, Eq. (3) can be rewritten as Eq. (4), where mf is the ionospheric mapping function, which depends on the zenith distance z at the station, and VTEC is the vertical TEC at the ionospheric pierce point (IPP).

$$\tilde{P}_1 - \tilde{P}_2 = \frac{40.3\left(f_2^2 - f_1^2\right)}{f_1^2 f_2^2} \cdot mf(z) \cdot VTEC + c(DCB_r + DCB_s) \tag{4}$$

An SH function is used to model VTEC referring to a solar geomagnetic frame as the following Eq. (5) (Schaer 1999), where φ is the geomagnetic latitude of IPP; λ is the sun-fixed longitude of IPP; n and m are the degree and order of the model, respectively; $\tilde{P}_{nm}$ is the normalized associated Legendre function of degree n and order m; and a_{nm} and b_{nm} are the unknown SH coefficients and GIM parameters, respectively.

$$VTEC(\varphi, \lambda) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\varphi)\left(a_{nm}\cos(m\lambda) + b_{nm}\sin(m\lambda)\right) \tag{5}$$

In this work, GPS data of approximately 330 IGS stations are used for modeling, and a minimum elevation cutoff of 20° is applied to avoid particularly noisy measurements. VTEC modeling is in a solar-geomagnetic reference frame using spherical harmonic expansions up to a degree and order of 15.

Since solar activities and the geomagnetic field of the earth are the primary drivers of ionospheric variation, global VTEC distribution exhibits daily variation with the earth's rotation. When the space weather is quiet, global VTEC varies more slowly in the solar geomagnetic reference frame. We consider the SH coefficients to vary linearly with time, which means that the parameters are linearly interpolated between consecutive nominal epochs (Schaer, 1999). Additionally, we divide all of the data from a given day into 12 sessions, and each session contains two hours of data. Thus, there are 13 groups of SH coefficients to be estimated, which is the same approach used by CODE. The DCB of satellites and receivers will be estimated along with the SH coefficients, where a DCB datum is defined by a zero-mean condition imposed on all of the satellite biases.

2.2. TEC values from the expanded IRI model

The international reference ionosphere (IRI) is the internationally recognized empirical model. It was developed and improved by a joint work group of the Committee on Space Research