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Evaluation of regional ionospheric grid model over China from dense GPS observations

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ABSTRACT

The current global or regional ionospheric models have been established for monitoring the ionospheric variations. However, the spatial and temporal resolutions are not enough to describe total electron content (TEC) variations in small scales for China. In this paper, a regional ionospheric grid model (RIGM) with high spatial-temporal resolution (0.5° × 0.5° and 10-min interval) in China and surrounding areas is established based on spherical harmonics expansion from dense GPS measurements provided by Crustal Movement Observation Network of China (CMONOC) and the International GNSS Service (IGS). The correlation coefficient between the estimated TEC from GPS and the ionosonde measurements is 0.97, and the root mean square (RMS) with respect to Center for Orbit Determination in Europe (CODE) Global Ionosphere Maps (GIMs) is 4.87 TECU. In addition, the impact of different spherical harmonics orders and degrees on TEC estimations are evaluated and the degree/order 6 is better. Moreover, effective ionospheric shell heights from 300 km to 700 km are further assessed and the result indicates that 550 km is the most suitable for regional ionospheric modeling in China at solar maximum.

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1. Introduction

The ionospheric delay induced by the refraction is one of major error sources in Global Positioning System (GPS) measurement. Nowadays, GPS has been widely used to monitor the ionospheric variations [1]. Since 1998, the International GNSS Service (IGS) Ionosphere Working Group has been continually providing global ionosphere maps (GIMs) and ionospheric coefficients based on spherical

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harmonics expansion. These products are produced by the IGS Ionospheric Associate Analysis Centers (IAACs) using data from the global IGS tracking network [2]. Along with the increasing number of permanent GPS stations all over the world, it could be possible to establish more accurate and higher spatial-temporal resolution GIMs and regional ionosphere maps (RIMs) for ionospheric modeling and applications.

Currently, two categories of methods are used for GPS ionospheric modeling: one is the empirical models, e.g., the International Reference Ionosphere (IRI) model [3] and the Klobuchar model [4], and the other one is the observation-based ionospheric model. The widely used IRI model is developed and improved by the Committee on Space Research (COSPAR) and the International Union of Radio Science (USRI) [5]. In the latest version, the IRI-2012 has achieved a significant improvement in the auroral area, and the working group is currently devoted into developing a real-time IRI model based on updating or assimilation techniques [3]. For the observation-based ionospheric models, a number of methods have been applied in ionospheric models, e.g., the polynomial model [1], the triangle series model [6], or the low degree spherical harmonic model [7]. The European Space Operations Center (ESOC) of European Space Agency (ESA) supports a routine production of TEC-maps given as low-degree ionospheric spherical harmonics coefficients, and the differential code bias (DCB). These coefficients are included in the ionospheric map exchanging format (IONEX) files [8]. Over the recent years, a number of new approaches for ionospheric modeling have been developed and improved with new data. For example, Li et al. [9] developed a new technique to generate a global TEC using spherical harmonics plus trigonometric series functions (SHTPS) based on improved differential areas for differential stations (DADS). Their results showed similar accuracy as for the IAAC's GIM and a good agreement with TOPEX/Poseidon and DORIS results. Alizadeh et al. [10] demonstrated that the GIMs computed from a combination of GNSS, formosat-3/COSMIC, and satellite altimetry measurements significantly were improved the accuracy of the global ionospheric model, especially in the cases with sparse observations. Recently, a number of high spatial-temporal regional ionospheric models have been developed [11], and the performance of GIMs based on regional network with denser GPS observations has been validated. For example, the regional ionospheric model in South Africa was compared with the IRI and ionosonde measurements, which showed a better agreement with the ionosonde than the IRI model [12]. Moreover, Jin and Park [13] developed a 3-D GPS ionospheric tomography with real observation data in South Korea to evaluate empirical model like IRI-2001. Liang et al. [14] presented a 4-D ionospheric model from GPS radio occultation, GRACE, CHAMP and FORMOSAT-3/COSMIC data, to well describe the vertical distribution over central and south America, showing reliable results by comparison with IRI model.

Although the existing studies were devoted into establishing accurate GIM/RIGM products and validating their performance with actual measurements, but a higher spatial-temporal resolution regional ionospheric grid model (RIGM) is required for some small regions, e.g., China and neighboring areas. Currently only about 7 IGS stations located in China are used for GIMs with a spatial-temporal resolution of 5° × 2.5° and 2 h, so the IGS GIMs cannot provide more detailed ionospheric variations over China. In this paper, a higher accuracy and spatial-temporal solution RIGM based on a dense dual-frequency ground-based GPS data over China and surrounding areas is developed. The spatial and temporal resolution is 0.5° × 0.5° and 10 min, respectively. Our model is further compared to Center for Orbit Determination in Europe (CODE) products, the IRI-2012 model and ionosonde measurements. In addition, the impact of different orders and effective ionospheric shell heights on RIGM are also discussed.

2. Data and methods

The Earth's ionosphere is normally from 60 km to approximately 1000 km. When GPS signal propagates through Earth's ionosphere, it will be delayed. The signal delay can reach dozens of meters for the GPS measurements.

2.1. TEC estimation from GPS observations

Dual-frequency GPS observations can estimate TEC along the signal path with ignoring the ionospheric high-order effects. As shown in Fig. 1, the GPS stations from Crustal Movement Observation Network of China (CMONOC) and IGS are used in this study [15]. Ionospheric pierce point (IPP) trajectories from 0:00UT to 1:00UT on March 17, 2014 are shown in grey lines. The research area in this study covers 70°E–135°E and 15°N–55°N.

It is well known that GPS observations include pseudo-range and carrier phase measurements. Following Jin et al. [16,17], the observation equation for measured GPS pseudo-range P and carrier phase measurements L can be expressed as follows:

$$P^i_{k,j} = \rho^i_{0,j} + d^i_{ion,k,j} + d^i_{trop,j} + c\left(\tau^i - \tau_j\right) + d^i_k + d_{k,j} + \epsilon^i_{P,k,j} \tag{1}$$

$$L^i_{k,j} = \rho^i_{0,j} - d^i_{ion,k,j} + d^i_{trop,j} + c\left(\tau^i - \tau_j\right) - \lambda\left(b^i_{k,j} + N^i_{k,j}\right) + \epsilon^i_{L,k,j} \tag{2}$$

where ρ is the geometric distance between the GPS receiver and the satellite, d_{ion} the ionospheric delay, d_{trop} the tropospheric delay, c the speed of light in a vacuum, τ^i and τ_j the clock offsets of satellite and receiver, d the differential code bias (DCB) for the satellite and receiver, λ the carrier wavelength, b the phase bias for the satellite and receiver, N the carrier phase integer ambiguity, and ϵ the other residual errors. As for the subscripts, $k = 1, 2$ are the frequency of the GPS signal, i the sequence number of the satellite, and j the sequence number of the receiver. After gross errors and cycle slips are detected and removed before smoothing [18], the precise TEC and DCB can be estimated from dual-frequency GPS pseudo-range and carrier phase observations [19].

In the 2-D regional ionospheric modeling, electrons in the ionosphere are assumed to concentrate in a hypothetical thin shell at a specific altitude, which is called Single Layer Model (SLM). Following Schaer [1], the slant TEC (STEC) can be projected into a vertical total electron content (VTEC):