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

Xin Zhao¹,²,*, Shuanggen Jin², Cetin Mekik³, Jialiang Feng¹

¹ School of Environment and Chemical Engineering, Shanghai University, Shanghai 200444, China
² Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
³ Department of Geomatics Engineering, Bulent Ecevit University, Zonguldak 67100, Turkey

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A B S T R A C T

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
Current 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:

\[
P_{kj} = \rho_{kj} + d_{\text{Ion},kj} + d_{\text{trop},kj} + c (r - t_j) + d_i + d_k + \epsilon_{kj} \quad (1)
\]

\[
L_{kj} = \rho_{kj} - d_{\text{Ion},kj} + d_{\text{trop},kj} + c (r - t_j) - \dot{\lambda} (b_{kj} + N_{kj}) + \epsilon_{1kj} \quad (2)
\]

where \( \rho \) is the geometric distance between the GPS receiver and the satellite, \( d_{\text{Ion}} \) the ionospheric delay, \( d_{\text{trop}} \) the tropospheric delay, \( c \) the speed of light in a vacuum, \( r \) and \( t_j \) the clock offsets of satellite and receiver, \( \dot{\lambda} \) the differential code bias (DCB) for the satellite and receiver, \( \lambda \) the carrier wavelength, \( b \) the phase bias for the satellite and receiver, \( N \) the carrier phase integer ambiguity, and \( \epsilon \) 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 Schaefer [1], the slant TEC (STEC) can be projected into a vertical total electron content (VTEC):
where $R$ is the equatorial radius of the earth (6378 km), $H$ the altitude of the ionosphere shell and $z$ the zenith angle. The spherical harmonic functions have been proven to be suitable for both global and regional ionosphere modeling [10]. According to Haines [20], the VTEC can be expressed with spherical harmonic expansion as:

$$VTEC(\beta, s) = \sum_{n=0}^{n_{\text{max}}} \sum_{m=0}^{m_{\text{max}}} \tilde{P}_{nm}(\sin \beta)(a_{nm} \cos m s + b_{nm} \sin m s)$$

Here $\beta$ is the latitude of the IPP in solar geomagnetic frame, $s$ the sun-fixed longitude of the IPP, $a_{nm}$ and $b_{nm}$ the SH coefficients of ionospheric model, and $\tilde{P}_{nm} = \mathcal{A}(n,m) P_{nm}$ the normalized associated Legendre polynomials, where $\mathcal{A}(n,m)$ represent the normalization function, $P_{nm}$ the un-normalized Legendre polynomials.

As an external constraint, the zero-mean condition is used to separate the satellite DCB and the receiver DCB. The order/degree of the spherical harmonic expansion is usually set as 15 for a global scale, and smaller number for a regional scale. Here the order and height effects on this regional ionospheric model are discussed in next section. A least squares piecewise constant estimation method at 10-min resolution is used to calculate the ionospheric coefficients. Then, the RIGMs are derived using the obtained spherical harmonic coefficients functions. During the data processing of regional ionospheric grid model, P1P2 DCB can be calculated simultaneously in the least squares estimation.

### Results and analysis

#### 3.1. RIGM and evaluations

In this study, the regional ionospheric grid model in China and surrounding areas ($70^\circ$E–135$^\circ$E and 15$^\circ$N–55$^\circ$N) is developed from March 13, 2014 to March 18, 2014 by using the spherical harmonics function. The spatial and temporal resolution of the RIGM is $0.5^\circ \times 0.5^\circ$ and 10 min, respectively. Here spherical harmonic order/degree is set as 6 and a thin-shell University of Massachusetts Lowell conducts experimental and analytical research in atmospheric and space science. More than 80 ionosondes are maintained by different institutions around the world. Ionosonde data are provided by the Digital Ionogram DataBase (DIDBase) of SSL in Standard archiving output (SAO) format. In China, 4 ionosonde stations are continuously observing at a 15-minute temporal resolution. The electron density can be directly derived from the original data files with the corresponding altitude information. In this study, ionosonde TEC of Wuhan station (ZLT) is used as an example to validate our model results.

#### 2.3. IRI-2012 model

Recently, IRI model has been developed and updated frequently, which describes monthly average of several ionospheric parameters. IRI provides specification of ionospheric parameters such as electron density, electron temperature, ion temperature, ion composition, ion drift and so on. The new model is IRI-2012 version, which has achieved significant improvement in bottom side modeling [3]. In this study, IRI-2012 TEC is defaulted as the total electron content over the altitude range from 60 km to 1000 km.

#### 2.2. Ionosonde observations

Ionosonde can determine the vertical TEC over the ionosonde station [21]. The Space Science Lab (SSL) at the University of Massachusetts Lowell conducts experimental and analytical research in atmospheric and space science. More than 80 ionosondes are maintained by different institutions around the world. Ionosonde data are provided by the Digital Ionogram DataBase (DIDBase) of SSL in Standard archiving output (SAO) format. In China, 4 ionosonde stations are continuously observing at a 15-minute temporal resolution. The electron density can be directly derived from the original data files with the corresponding altitude information. In this study, ionosonde TEC of Wuhan station (ZLT) is used as an example to validate our model results.

**Fig. 1** – GPS stations and IPP trajectories (grey lines) from 0:00UT to 1:00UT on March 17, 2014. CMONOC and IGS stations are represented in red triangles.
height is 500 km for the SLM. An example for a TEC-map on March 17, 2014 8:00 UT is presented in Fig. 2. Here the CODE GIM and the IRI-2012 model are inter-compared to our results. As for the IRI-2012 model settings, the ionosphere boundary is selected from 60 km to 1000 km. The NeQuick model is used for the Ne Topside values and the CCIR model is used for the F-peak plasma frequency foF2. Since CODE GIMs are given at 2.5° x 5° and 2 h spatial-temporal resolution, so we have interpolated the grid as 0.5° x 0.5° for comparison. Fig. 2a illustrates the snapshot of RIGM over China. More clear and defined features are observed in the RIGM than the CODE GIM and IRI-2012. To better understand the differences between the RIGMs in research area, Fig. 2d–f display their differences. The differences between this study and CODE are less than ±10 TECU in most area, while IRI-2012 TEC exceeds 10 TECU in more than half of studied area (Fig. 2d–f). The differences are bigger near China’s south-east boundary because there are neither GPS nor ionosonde data for this study.

In addition, the RMS between each model is also calculated to quantify the differences. It can be clearly seen that the RMS between this study and CODE is apparently smaller than that between CODE and IRI-2012, as well as the results between this study and IRI-2012, which indicates that this study and CODE are in a better agreement than the empirical model IRI-2012.

The ionosonde measurements are considered as the reference to evaluate the performance of our RIGM. Continuously ionosonde measurements from DIDBase are provided at 15 min interval. From Fig. 3a and b, our estimates, CODE and IRI-2012 are compared to ionosonde TEC from March 13, 2014 to March 18, 2014 at the Wuhan station (ZLT, 114.5°E and 44°N). Our results show a better correlation (0.97) to the ionosonde TEC than the CODE or IRI-2012 values. From Fig. 3d–f, it is clearly seen that our estimates and CODE products show the better correlation (0.95). The outlines in Fig. 3d and f are attributed to the boundary effect of the spherical harmonics functions for marginal areas.

For further evaluation of the regional ionospheric grid model in this study, TEC time series from this study, CODE, IRI-2012 and the ionosonde at WUHN station are presented for the same period in Fig. 4. The temporal sampling rate is 10 min for this study, 2 h for CODE and IRI-2012, and 1 h for the ionosonde data. It can be seen that our RIGM depicts a similar tendency for the diurnal variation as the ionosonde TEC. It is also obvious that our RIGM significantly exceeds the ionosonde measurements in about 5 TECU, while CODE exceeds the ionosonde measurements in about 10–20 TECU. The reason is that GPS-derived TEC is measured from 60 km to about 20,000 km, while the ionosonde measurements are less than 1000 km. There have been numerous researches for the variation of plasmaspheric TEC with ionosonde, radio occultation and satellite altimetry measurements [22–25]. The contribution of plasmaspheric total electron content (pTEC) to ionosonde results depends on the latitude, local time and season. In addition, a significant diurnal variation is observed when pTEC contributes more than 20% mostly near 30°N in the daytime of spring, while the percentage at night increases to more than 50% [26]. The ionosonde TEC in Fig. 4 exhibits the same characteristic with our RIGM results, reflecting that the CODE TEC may be overestimated at daytime.

Fig. 5 shows the diurnal TEC variation of 4 different IGS stations in China. Average values for 6 days (March 13, 2014 to March 18, 2014) are validated with the results from CODE and IRI-2012. The TEC reaches maximal at about 6:00 UT (14:00 LT) and reduces the minimal at around 20:00 UT (4:00 LT). IRI-2012 shows a less agreement with CODE than our RIGM in both mean values and variations, such as the peak value and the nighttime variation.

Furthermore, the diurnal amplitude and initial phase are obtained from the above mentioned TEC values. Fig. 6 shows

![Fig. 2](image_url) 
**Fig. 2** – TEC distribution (top panels) and residuals between GPS models and IRI-2012 (bottom panels) at 0.5° x 0.5° on March 17, 2014 at 8:00 UT.
the diurnal amplitude and the initial phase for RIGM, CODE and IRI-2012 at the 4 IGS stations in China for the 6 days. The better agreement is with CODE (Fig. 6), and IRI-2012 shows a relatively poor agreement with CODE.

3.2. Degree/order and single-layer height effects

For a global scale TEC distribution, the usually spherical harmonic expansion order/degree is set as 15, such as IGS GIM. However, in a regional ionospheric modeling, the suitable expansion order/degree of spherical harmonics depends on the research area, e.g., degree and order 3 for Korean Peninsula [27] and order and degree 4 for Chinese and adjacent area [18]. In this study, different orders and degrees from 2 to 20 for 4 representative epochs on March 17, 2014 are calculated to evaluate the effects from the spherical harmonics expansion, and compared with CODE in Table 1. The ionospheric shell height is set as 450 km. The RMS is calculated at all studied grid points of TEC maps to evaluate the performance of each expansion order/degree. Theoretically, higher spherical harmonics order and degree are better due to the higher resolution of spherical harmonics function. While from the
test results, order and degree 6 has a relatively better agreement with CODE GIM. The main reason of the relative disagreement between TEC results from orders and degrees is probably lacking of observations in south-west and south-east China. The unknown parameters will increase with increasing order and degree, which leads to the ill-condition equation. Therefore, the order and degree 6 is recommended to establish a regional ionospheric grid model in China.

The ionospheric shell height is the key parameter when converting STEC into VTEC. The optimal ionospheric shell height is normally influenced by the solar activity, the season and the local time. In the region of large spatial gradient of TEC like China, it could be wrongly estimated by inappropriate shell height [28]. The ionosphere shell height is set as 506.7 km for CODE GIMs from the modified single layer model (MSLM). In this section, the effect of different ionospheric shell heights on RIGM is discussed. Table 2 shows the TEC differences between our RIGM and CODE at the 4 IGS stations in China on March 13, 2014. Different shell heights are tested from 300 km to 700 km. The

![Fig. 5](image)

Fig. 5 – Average diurnal TEC time series from our RIGMs, CODE and IRI-2012 at the 4 IGS stations from March 13, 2014 to March 18, 2014.

![Fig. 6](image)

Fig. 6 – Amplitude and initial phase of diurnal TEC variations from RIGM, CODE and IRI-2012 at 4 IGS stations (BJFS, WUHN, LHAZ, URUM) in China. The amplitude $A$ and initial phase $\phi$ are defined as $VTEC = Asin(2\pi(t - t_0)/p + \phi)$ from 6 continuous days (from March 13, 2014 to March 18, 2014), where $t_0$ is 0:00UT on Mar 13, 2014 and $p$ is the period of 24 h.
spherical harmonic expansion order/degree is set as 6. The shell height at 550 km has a relatively better agreement to CODE. On a year (2014) of solar maximum, it is easy to understand that the higher solar radiation excites more electrons and free ions, leading to a higher value of both the plasmaspheric TEC and the ionospheric TEC. While the percentage of plasmaspheric TEC to total TEC is relatively lower since the ionospheric TEC has a higher increase, which leads the effective ionospheric shell height to be lower. On the contrary, the optimal altitude should increase as the solar minimum contributes to higher percentage of plasmaspheric TEC. The best shell height ranges from 500 km to 700 km in consideration of all factors [28]. In this study, we recommend a single-layer altitude for China with 550 km, in spring season and at solar maximum.

4. Conclusion

The existing global/regional ionospheric models such as CODE GIMs have low spatial and temporal resolution. In this paper, a regional ionospheric grid model (RIGM) with a higher spatial and temporal resolution (0.5° × 0.5° and 10 min) is established in China and surrounding areas (70°E–135°E and 15°N–55°N) from the dense ground-based GPS measurements, collected by CMONOC and IGS stations. Compared to CODE GIMs, our results not only have a better agreement than the IRI-2012 model, but also better description of the regional features of ionospheric variations in China and surrounding areas. Our model is also validated by ionosonde measurements. RIGM is better in describing the diurnal variations of TEC. Moreover, the effect of spherical harmonics expansion order/degree and shell height is discussed. The order 6 and the optimal ionospheric shell altitude of 550 km are recommended for the RIGM estimation.

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References


Xin Zhao, is a Master student of Shanghai University and Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China. His main topics are focused on Satellite Navigation, Space Geodesy and GNSS Ionospheric Sounding.