Combination of Ground- and Space-Based Data to Establish a Global Ionospheric Grid Model

Peng Chen, Wanqiang Yao, and Xuejun Zhu

Abstract—The global ionospheric maps (GIMs) that are established using ground-based Global Navigation Satellite System (GNSS) data are important means to study the variations of the ionosphere. However, the uneven distribution of ground GNSS stations, which particularly exist at large gaps in the vast ocean areas, results in low accuracy and reliability of GIMs in the marine region and other areas that lack GNSS sites. The ocean altimetry satellite’s orbit can cover most of the marine areas, and dual-frequency signals can obtained vertical total electronic content (VTEC) at the nadir track. Low-Earth-orbit occultation observations also obtain much global ionospheric uniform distribution information. The combination of the space-based ionospheric data and ground-based GNSS observation data can effectively improve the accuracy and reliability of GIM in marine areas. However, the systematic bias that exists between ionospheric data obtained by different systems must also be considered during the data combination. This paper used both ground-based GNSS data and space-based data to establish a global ionospheric model, whereas the systematic bias between the space-based ionospheric data and ground-based GNSS data can be seen as parameters to estimate. The results show that, by adding space-based data, the accuracy of GIM on the ocean areas has been improved to make up the deficiencies of the existing GIMs.

Index Terms—Constellation Observation System for Meteorology, Ionosphere, and Climate (COSMIC), global ionospheric grid model, Global Navigation Satellite System, satellite altimetry, total electron content (TEC).

I. INTRODUCTION

The ionosphere is the top part of the Earth’s atmosphere, which is 60–1000 km above the ground. At this height, the number of ions and free electrons is sufficient to affect the propagation of electromagnetic waves [11], [22]. Electromagnetic signals suffer from ionospheric delay related to the frequency of the signal. By using this feature, the ionospheric structure of the ionosphere could be detected, and the ionospheric model therefore would be established [3], [14], [15].

Global Positioning System (GPS) satellite signals for communications are also subject to the impact of ionospheric delay. Using two different frequency signals, GPS data that suffer from ionospheric delay during the propagation can be obtained, thus achieving ionospheric modeling. For a global ionospheric model, Mannucci et al. [20] proposed establishing a spherical triangle model, whereas Schaeer [22] proposed a spherical harmonic function model. In China, Yuan et al. earlier studied the ionospheric GPS-based monitoring and delay correction theory and method [25], [29]. They [25] proposed a new method to establish a large-scale high-accuracy ionospheric grid model using GPS data; the proposed model is a generalized trigonometric series ionospheric model with adjustable parameters, which accuracy is superior to the commonly used polynomial model and the triangular series model with fixed parameters. Zhang [30] systematically studied the methods to establish an ionospheric model using GPS data and compared its accuracy to that of various common ionospheric models. Liu et al. [19] compared various ionospheric models and studied the consistency of each model, proposing to establish a Chinese regional ionospheric model with a spherical harmonic function. Geng [12] studied the methods of GNSS-based global ionospheric modeling and used the Kalman filter for the parameters of a real-time sphere harmonic function model and differential code bias (DCB) estimation.

Earlier establishment of global ionospheric models only uses GPS data, but in recent years, with the improvement of the GLONASS system, global ionospheric models have been mainly using ground-based GNSS observations. However, the distribution of ground-based GNSS tracking stations is extremely uneven, which restricts the accuracy and reliability of global ionospheric models established using only ground-based GNSS data in marine areas. Ocean-altimetry-satellite ionospheric data are all located in marine areas [5]. Ionospheric data obtained using Low-Earth-orbit (LEO) ionospheric occultation are more evenly distributed around the world; thus, adding space-based ionospheric data can improve the accuracy and reliability of global ionospheric model in marine areas. Therefore, Alizadeh et al. [2] investigated the global modeling of total electron content (TEC) through combining GNSS and satellite altimetry data with the data derived from the occultation measurements of the Constellation Observation System for Meteorology, Ionosphere, and Climate (COSMIC), which proved that combined GIMs provide more homogeneous global coverage and higher reliability than the results of each single method. However, this study did not consider the different
accuracy of observational data. Moreover, the weightings to all kinds of observations were not precise enough, and the systematic bias between the satellite altimetry and GNSS was seen as constant in a day, thus reducing the accuracy of the model. In addition, Dettmering et al. [7] studied the combination of different space-geodetic observations for regional ionosphere modeling.

Based on the previous studies, this paper, using Jason-1 and Jason-2 ocean-altimetry-satellite data, COSMIC ionospheric occultation data, and ground-based GNSS observation data, creates a global ionospheric model using multisource data. It also considers the accuracy difference and systematic bias between difference types of data and uses the Helmert variance component estimation to determine precision weightings of different observations. The systematic bias of ocean altimetry satellite was seen as a constant in every model epoch (2 h), and each COSMIC satellites’ systematic bias in one day was regarded as constants and estimated by least squares. The results of using multisource data are compared with the results of using only ground-based GNSS data and CODE’s (Center for Orbit Determination in Europe).

II. MULTISOURCE DATA FUSION IONOSPHERIC MODEL

A. VTEC Obtained by Ground-Based GNSS Data

The expression to calculate the TEC using dual-frequency GNSS observations can be written as [22]

\[
TEC = \frac{f_1^2 f_2^2}{40.28 (f_1^2 - f_2^2)} (P_2 - P_1 + \Delta b_k + \Delta b_s) \quad (1)
\]

where \(P_1\) and \(P_2\) are two frequencies measured based on pseudorange observations, \(f_1\) and \(f_2\) are carrier frequencies, and \(\Delta b_k\) and \(\Delta b_s\) are the satellite and receiver DCBs, respectively. From (1), it can be seen that TEC can be obtained using dual-frequency GNSS pseudorange observations. In practice, usually, using the phase-smoothed pseudorange method reduces the measurement noise of the pseudorange [13]. In

TEC calculation, the maximum error is the satellite and receiver DCBs, but the DCBs are more stable and can be considered constant in one day [4], [17], [18]. The usual practice is to consider the DCBs as the parameters and to estimate them with the ionospheric model coefficients together by least squares.

When establishing a global ionospheric model, usually, a single-layer ionospheric model is assumed, which means that all ionospheric electronics are concentrated in an infinite thin layer at a certain height from the ground (450 km in this paper) [4], [22]. The intersection of the signal propagation path and the
single ionospheric layer is called the ionospheric pierce point (IPP). The positional relationship of receivers, satellites, and IPPs are shown in Fig. 1. The TEC along the signal propagation direction (STEC) is projected onto the zenith direction to obtain the vertical TEC (VTEC); this is the most commonly used trigonometric projection function, which is expressed as follows [22]:

\[ \text{VTEC} = \text{STEC} \cdot \cos z' \]  

(2)

where \( z' \) is the zenith distance of the satellite at the IPP.

### B. VTEC Obtained by Ocean-Altimetry-Satellite Data

The main purpose of ocean altimetry satellites is to obtain information on sea-level changes and to provide important basic information for the tidal studies of oceans and regional seas. Currently, the orbit ocean altimetry satellites are Jason-1 and Jason-2: Jason-1 was launched on December 7, 2001, whereas Jason-2 satellite was launched on June 20, 2008. With orbital inclination of 66°, the coverage of the satellites is 66° N to 66° S, their orbital altitude is 1336 km, and their cycle time is 112 min. The onboard radar altimeter has dual-band emission, with a Ku-band main frequency (13.575 GHz) and a C-band auxiliary frequency (5.3 GHz). The ionospheric effects on electromagnetic wave paths are proportional to the density of free electrons and inversely proportional to the square of the frequency of the electromagnetic wave. Thus, TEC is calculated as [21], [24]

\[ \text{TEC} = -\frac{dR \cdot f^2}{40.3}. \]  

(3)

The Jason satellites’s radar altimeter can directly access the differential group path delay of transmitted signals and then obtain an ionospheric correction \( dR \). The measurement error caused by the instrument hardware, satellite attitude, waves, or other factors is usually not more than 2–3 TECu. The credibility of Jason-satellite-derived VTEC at low latitudes and equatorial regions is high.

In this paper, the derived VTEC is smoothed with a 30-s window time to reduce the observational uncertainty without sacrificing its accuracy and with a resampling rate of 10 s.

However, the altitude of the orbit of the ocean altimetry satellite is only 1336 km; thus, the obtained ionospheric VTEC data do not include the contribution of the ionosphere above the satellite orbit. In this paper, the TEC above the ocean-altimetry-satellite orbits is considered constant in 2 h and is solved together with the model parameters.

### C. VTEC Obtained by Ionospheric Occultation Data

The running occultation system COSMIC provides about 2000 times of global occultation events each day. Its radio occultation technique has high accuracy, high vertical resolution, global coverage, and other advantages. The “ionprf” products provided by COSMIC data analysis and by the archive center COSMIC Data Analysis and Archive Center (CDAAC) provide the VTEC at the position of maximum electron density of every occultation event. In which, VTEC0 is the TEC under the LEO satellite orbit, and VTEC1 is the VTEC above the LEO satellite orbit obtained by model extrapolation. No further processing is necessary because the DCBs are already included [8], [16].

There is also a systematic bias between the VTEC obtained by COSMIC satellites and the VTEC obtained by ground-based GNSS observations. This paper deal with this systematic bias of
D. Global Ionospheric Grid Model Using Multisource Data

Fitting the VTEC values obtained by different means of observation using the appropriate model can obtain a global ionospheric model. The most commonly used global ionospheric model is the spherical harmonic function model. CODE uses a $15 \times 15$-order spherical harmonic function to create a global ionospheric grid model. The spherical harmonic function model is expressed as follows [22], [28]:

$$VTEC(\beta, s) = \sum_{n=0}^{N} \sum_{m=0}^{N} \tilde{P}_{nm}(\sin \beta) \left( \tilde{C}_{nm} \cos (ms) + \tilde{S}_{nm} \sin (ms) \right)$$  \hspace{1cm} (4)

where $\beta$ is the latitude of an IPP, $s$ is the sun angle of an IPP under a sun-fixed coordinate, $N$ is the maximum expansion
order of the spherical harmonic function, $\tilde{P}_{nm}(\sin \beta)$ is the normalized Legendre function of degree $n$ and order $m$ [1], and $\tilde{C}_{nm}$ and $\tilde{S}_{nm}$ are unknown spherical harmonic coefficients, namely the unknown ionospheric model parameters.

The temporal resolution of the model is 2 h, with a latitude interval of 2.5° and a longitude interval of 5°. The satellite and receiver DCBs, the systematic bias of ground-based GNSS VTEC with satellite altimetry, and the LEO ionospheric occultation VTEC were seen as an argument solve together. The parameters to be solved in order are the spherical harmonic coefficients, receiver DCBs, satellite DCBs, ocean-altimetry-satellite systematic bias, and the LEO occultation systematic bias.

The accuracy of the ground-based GNSS data, satellite altimetry data, and ionospheric occultation data are not consistent. During multisource data fusion, the weights of ionospheric data from different systems need to be considered. We use Helmert variance component estimation methods to determine the precise weights.

### III. Helmert Variance Component Estimation

In order to reasonably determine the weights of the types of observations, we use the Helmert variance component estimation method to estimate the variance factor of various observations from a set of initial departure a priori variance factor, given the final weights according to this variance factor, and then conduct a final adjustment [23]. The Helmert variance component estimation formula can be written as [6]

$$ S \hat{\theta} = W_\theta $$

where the specific forms of $S$, $\hat{\theta}$, and $W_\theta$ can be found in [6]. As the formula for Helmert variance component estimation is very complex, matrix inversion is needed after a continuous matrix multiplication; thus, either of the following approximate formulas are often used in the actual calculation:

$$ \hat{\sigma}^2_{0_i} = \frac{V_i^T P_i V_i}{n_i} $$

The iterative calculation process of the Helmert variance component estimation is as follows.

1) Estimate the prior weights of different observed values, namely determine the initial value of weight to types of observations $P_1, P_2, \ldots$.
2) Conduct an adjustment for the first time, and obtain $V_i^T P_i V_i$.
3) In accordance with (6) or (7) for the first time variance component estimation, obtain the unit weight variance $\hat{\sigma}^2_{0_i}$ of various observations for the first time, and then determine the weights according to the following formula:

$$ \hat{P}_i = \frac{c}{\hat{\sigma}^2_{0_i} P_i^{-1}} $$

where $c$ is a constant. Generally, one of the $\hat{\sigma}^2_{0_i}$ values is selected.
4) The second and third steps are repeated until the unit weight variances of various observations are equal.

### IV. Data Used in Modeling

Fig. 2 shows the location maps of the global International GNSS Service (IGS) ground tracking stations in January 1, 2011. This paper used a total of 391 tracking stations, in which 146 stations receive both GPS and GLONASS data, and all tracking station observations have a sample rate of 30 s. As shown in the figure, the distribution of the IGS tracking stations is very uneven. The distribution in the Northern Hemisphere is dense and that in the Southern Hemisphere is sparse. The mid-latitude region is relatively densely distributed than the low and high latitude regions. The most intensive station distribution is in Europe and North America, but in the vast ocean areas, there is a large gap. This uneven distribution of GNSS ground tracking stations causes the existing global ionospheric model to have limited accuracy and reliability in the ocean region.

Fig. 3 shows Jason-1 and Jason-2 satellite VTEC data distributions in DOY 001, 2011. The data sampling rate of the Jason
series satellites is 1 Hz. This paper takes their median in 30 s to smooth the raw observations. The Jason series satellites obtained VTEC data within a day covering the global vast majority ocean between $\pm 66^\circ$, which is the most intensive at 50–66° S in the Southern Hemisphere.

Fig. 4 shows the distribution maps of the COSMIC satellite ionospheric occultation events. There were a total of 817 COSMIC ionospheric occultation events in doy 001, 2011. Within a day, ionospheric occultation events are more evenly distributed in both sea and land areas between $\pm 75^\circ$, adding that ionospheric data obtained from COSMIC ionospheric occultation data provide a certain help to improve the accuracy and reliability in marine areas.

V. RESULTS AND DISCUSSION

A. Analysis of GIM

Fig. 5 shows the difference between the global VTEC result using multisource data and the result using only ground-based observations in doy 001, 2011. The vertical axis is the geographical latitude, and the horizontal axis is the geographical longitude. The latitude is $-87.5$–$87.5^\circ$ and the longitude is $-180$–$180^\circ$. We can see that adding satellite altimetry and LEO occultation data make the changes in the ionospheric model; significant variations in the regions are mainly concentrated in the vast ocean areas, particularly in the southern ocean region; and the magnitude of change is $-15$–$10$ TECu. The reason is that the satellite altimetry observations are only in marine areas. LEO ionospheric occultation data are evenly distributed around the world, but the observed value is relatively small and has less impact on the final result.

Fig. 6(a) shows the difference between the global ionospheric RMS distribution obtained by multisource data and by only ground-based GNSS observation, and Fig. 6(b) shows the ocean-altimetry-satellite-derived VTEC data distribution in every 2 h. The figure apparently indicates that, with the
space-based ionospheric observations, the accuracy of global ionospheric model has improved in general, and the significant areas with improved accuracy are mainly located in the concentrated areas of the ocean-altimetry-satellite VTEC data, where the most significantly improved accuracy is the marine areas in the Southern Hemisphere, with RMS maximum reduction of 7.5 TECu, whereas the model accuracy in the land areas remained almost unchanged.

**B. Analysis of Satellite DCB Estimation**

Fig. 7 shows the comparison of the mean and standard deviation of a 31-day difference between the GPS and GLONASS satellite DCB estimations by using multisource data and using only ground-based GNSS observations in January 2011. As shown in the figure, adding the space-based ionospheric data has little effect on GPS and GLONASS satellite DCBs estimations.
C. Analysis of Receiver DCB Estimation

This section compares the receiver DCB estimation by using multisource data and by using only ground-based GNSS data, and analyzes the effect of receiver DCB estimation after adding space-based ionospheric data. The receiver DCB estimation using multisource data were compared with CODE’s results to verify the reliability of multisource-data-fusion global ionospheric model.

Fig. 8 shows the comparison of the receiver DCB estimation using multisource data and the same results using only ground-based GNSS data. The figure indicates that the difference of GPS and GLONASS receivers’ DCBs estimation were both less than $-0.06$–$0.10$ ns in January 2011, most of them within the $\pm 0.02$ ns. The comparison results indicate that, after adding the space-based ionospheric data, the receiver DCB estimation results have been less affected. However, the standard deviation of GPS and GLONASS receivers’ DCBs estimation within 31 days has decreased in general, which indicates that the receivers’ DCB estimation has better stability after adding the space-based ionospheric data.

The ten tracking stations whose standard deviation of GPS receiver DCB estimation reduced the most in 31 days are ohi2, maw1, ohi3, kerg, vesl, cas1, rio2, roth, mac1, and syog, whereas the ten tracking stations whose standard deviation of GLONASS receiver DCB estimation reduce the most in 31 days are ohi2, ohi3, maw1, cas1, thl, faal, reen, nurk, ntus, and aspa. Fig. 9 shows the distribution maps of these tracking stations. From the figure, it is shown that the tracking stations are mainly located in the Southern Hemisphere near the ocean areas. This indicates that adding the space-based ionospheric observations also improves the receiver DCB estimation, and results in stability of tracking stations near marine areas.

D. Analysis of Systematic Bias Estimation

Fig. 10(a) shows the average of 12 Jason’s systematic biases versus the universal time during 31 days and the variation of one daily average of Jason’s systematic bias during 31 days. From the figure, the variation of systematic bias of Jason satellites in one day is similar to the variation law of the plasmaspheric electron content. The plasmaspheric electron content reached the maximum in the afternoon and gradually decreased at night. The systematic bias of Jason satellites varied in 31 days and is generally stable; however, there also exist some sudden changes, and the cause of the changes still needs further research.

Fig. 10(b) shows the systematic bias estimation of COSMIC ionospheric occultation data between ground-based GNSS data for January 2011. The figure shows that the mean of systematic bias estimation of five COSMIC satellites in 31 days is more stable. The mean systematic biases of five COSMIC satellites is $-1.75$, $-2.13$, $-2.14$, $-2.41$, and $-2.14$ TECu, and the standard deviations is $0.26$, $0.27$, $0.48$, $0.34$, and $0.29$ TECu, respectively.

The systematic bias estimation indicated that Jason’s VTEC is greater than the VTEC obtained by ground-based GNSS data, whereas the VTEC results obtained by COSMIC satellite is less than the ground-based GNSS.

VI. CONCLUSION

This paper provided a solution for the limited accuracy and reliability of existing global ionospheric models that use ground-based GNSS data in the coverage of marine areas. By adding VTEC data obtained by ocean altimetry satellite and COSMIC ionospheric occultation, the accuracy and reliability of the global ionospheric model in marine areas are improved. The systematic biases of the ocean-altimetry-satellite data and the LEO occultation ionospheric data between ground-based GNSS observations are taken into account, and they are estimated together with the ionospheric model parameters by least squares. Taking into account the different accuracy of various ionospheric data, the Helmert variance component estimation method is used to determine the precise weight for all types of observational data.

Using the DOY 001–031, 2011 data for example, the impact on the global ionospheric model of adding the ocean-altimetry-satellite data and COSMIC occultation data is analyzed. The accuracy of global ionospheric model in marine areas has improved to some extent after adding the ocean-altimetry-satellite and COSMIC ionospheric occultation data, particularly in the Southern Hemisphere near the Antarctic region. With the number of satellites performing the ionospheric measurements further increased and the quality of ionospheric measurement data improved, adding space-based ionospheric data will further improve the accuracy of global ionospheric model, particularly in the vast oceans and other ground GNSS tracking station missing regions.
In addition, adding the DORIS system ionospheric data further improves the accuracy and reliability of the global ionospheric model in vast ocean regions.

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