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The multi-source data fusion global ionospheric modeling software—IonoGim

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Abstract

We introduce a new global ionospheric modeling software—IonoGim, using ground-based GNSS data, the altimetry satellite and LEO (Low Earth Orbit) occultation data to establish the global ionospheric model. The software is programmed by C++ with fast computing speed and highly automatic degree, it is especially suitable for automatic ionosphere modeling. The global ionospheric model and DCBs obtained from IonoGim were compared with the CODE (Center for Orbit Determination in Europe) to verify its accuracy and reliability. The results show that IonoGim and CODE have good agreement with small difference, indicating that IonoGim owns high accuracy and reliability, and can be fully applicable for high-precision ionospheric research. In addition, through comparison between only using ground-based GNSS observations and multi-source data model, it can be demonstrated that the space-based ionospheric data effectively improve the model precision in marine areas where the ground-based GNSS tracking station lacks.

Keywords: Global ionospheric model; GNSS; IonoGim; Altimetry; Occultation

1. Introduction

Ionosphere is a part of earth upper atmosphere, 60–1000 km away from the ground; at this height, ions and free electrons are sufficient to affect the propagation of electromagnetic waves (Gao and Liu, 2002; Schaer, 1999). The ionospheric delay of electromagnetic wave is associated with the signal's frequency, which can be used to detect ionospheric structure, and ionospheric model therefore would be established (Bilitza and Reinisch, 2008; Bilitza et al., 2011; Bidaine and Warnant, 2011; Klobuchar, 1987; Hernández-Pajares et al., 2009).

The propagation of GPS satellites signals is also affected by ionospheric delay. To eliminate this ionospheric delay, two frequencies have been used in GPS. The dual-frequency observations can also be used to estimate the ionospheric delay and then to realize the ionosphere model. Mannucci et al. (1998) proposed the establishment of a spherical triangle global ionospheric model; Schaer (1999) achieved globally ionospheric modeling with the spherical harmonic functions; in the same year, Hernández-Pajares et al., 1999 proposed a multilayer global ionospheric model. In China, Zhang et al. (2001) used the GPS dual-frequency data to model the ionosphere at a regional scale; Zhang (2006) conducted systemic research on the regional and global ionosphere modeling methods using GPS data; Liu et al. (2008) compared various ionospheric models and studied the consistency of each model, proposing to establish Chinese regional ionospheric model using spherical harmonic function.

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Though some research institutions and scholars have established several ionospheric modeling software, we introduce a new global ionospheric modeling software—IonoGim, which uses ground-based GNSS observation, space-based altimetry satellite and LEO occultation ionospheric data to establish a global ionospheric model. It overcomes the low accuracy and weak reliability of existed global models in ocean area. The software takes into account the accuracies and systematic differences among different sources of data, and so it sets corresponding weights by using Helmert variance component estimation, and then estimates the systematic bias together with model parameters using the least squares. The paper firstly presents the method of establishing global ionospheric model in IonoGim, then explains its basic characteristics and main functions, finally verifies its accuracy and reliability by comparing the results with CODE's.

2. VTEC calculation and global ionospheric model

The vertical ionospheric total electron content VTEC from the height of ground to height of satellite's orbit can be obtained by using ground-based GNSS observations, ocean altimetry satellites data and LEO occultation data. Using appropriate model to fit VTEC can obtain global ionospheric model. This section describes the VTEC acquisition method using ground-based GNSS observations, ocean altimetry satellite and LEO occultation data, and spherical harmonic function commonly used in global ionospheric modeling model are also introduced.

2.1. VTEC obtained by ground-based GNSS data

GNSS dual frequency pseudo range observation equations are as follows (Mannucci et al., 1998; Schaer, 1999):

$$\begin{aligned} P_1 &= \rho + cdt_r - cdt^s + I_1 + T + b^{s,1} + b_{r,1} \\ P_2 &= \rho + cdt_r - cdt^s + I_2 + T + b^{s,2} + b_{r,2} \end{aligned} \quad (1)$$

where P_1 and P_2 are the pseudo range observations, ρ is the geometric distance between satellite and receiver, dt^s, dt_r are satellite and receiver clock errors respectively, I_1, I_2 are ionospheric delays, T is the tropospheric delay, $b^{s,1}$, $b^{s,2}$ are hardware biases in satellites, $b_{r,1}$, $b_{r,2}$ are hardware biases in receiver, and the subscripts "1" and "2" represent the two GNSS frequencies, respectively. Ionospheric delay can be expressed as:

$$I = \frac{40.3}{f^2}\int_s Neds = \frac{40.3}{f^2}TEC \quad (2)$$

where Ne is electron density, s is the signal propagation path, TEC is the total electron content along the signal propagation path, and f is the GNSS frequency.

By substituting (2) into (1), and subtracting the two equations of the formula (1), the frequency independent error terms can be eliminated, and then TEC is calculated as:

$$STEC = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}(P_2 - P_1 + \Delta b_r + \Delta b^s) \quad (3)$$

where f_1 and f_2 are the carrier frequencies, $\Delta b_r = b_{r,1} - b_{r,2}$ is defined as the receiver hardware bias, $\Delta b^s = b^{s,1} - b^{s,2}$ is defined as the satellite hardware bias.

Eq. (3) shows that TEC can be obtained with dual-frequency GNSS observations. The method of using phase observation to smooth pseudo observation is usually used for modeling to reduce the code measurement noise. In this way, the largest error are the satellite and receiver hardware biases when calculating TEC, and they are usually taken as parameters and estimated during the least squares adjustment.

When modeling global ionospheric map, it is assumed than all electrons in the ionosphere are concentrated in a thin shell at altitude H (we define H as 450 km), the intersection of signal path and this shell is called ionosphere pierce point (IPP). TEC along the signal path (STEC) can be mapped into the vertical TEC (VTEC) using the trigonometric projection functions, namely,

$$STEC = mf \cdot VTEC \quad (4)$$

where $mf = \frac{1}{\sqrt{1-\left(\frac{R}{R+H}\sin z\right)^2}}$, R is the earth radius, H is the altitude of ionospheric thin shell, z is the zenith distance above receivers.

2.2. VTEC obtained by altimetry satellite data

The main purpose of altimetry satellites is to obtain sea-level changing information. The currently running ocean altimetry satellite is mainly Jason-1/-2 series. Radar altimeter satellite with dual bands emission can directly obtain the total electron content in the vertical direction. The ionospheric effect on the electromagnetic wave path is proportional to the free-electron density, and inversely proportional to the square of frequency. For ocean altimetry satellite, vertical TEC can be calculated as (Brunini et al., 2005; Ping et al., 2004; Tseng et al., 2010):

$$VTEC = -\frac{dR \cdot f^2}{40.3} \quad (5)$$

Radar altimeter can get the differential group path of the transmitted signal to obtain the ionospheric correction dR.

However, because of its orbit height of 1336 km, obtained VTEC cannot cover information above this altitude (Brunini et al., 2005). Considering characters of TEC at high altitude, we regard VTEC above 1336 km as a daily constant and estimated it together with model parameters.

2.3. VTEC obtained by occultation data

COSMIC is one of the currently main occultation systems, which generates about 2000 occultation events every day over the world. The COSMIC system ionprf products provide the ionospheric electron density data from