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Validation of CAS's final global ionospheric maps during different geomagnetic activities from 2015 to 2017

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ABSTRACT

The Chinese Academy of Sciences (CAS) has become one of the Ionospheric Associated Analysis Centers (IAACs) of the International GNSS Service (IGS) since 2016, which utilizes the approach of spherical harmonic plus generalized trigonometric series (SHPTS) for its global ionospheric maps (GIM) generation. We presented an updated status of CAS's GIM products and evaluated the overall performance of GIMs during the period of 2015–2017 at different levels of geomagnetic activity conditions and in different latitudes, in contrast to the high-quality IGS final total electron content (TEC) maps. The results show that the root-mean-squares (RMS) of CAS's GIMs performs varies between 1.0 and 2.5 TECu and it is almost at the same level as that of the Center for Orbit Determination in Europe (CODE). The good consistency between the CAS and IGS-final GIMs has been observed in different latitudes, though the comparison results present significant dependence on the geomagnetic and solar activities. It is found that the performance of those GIMs during perturbed period is approximately 1.1–1.9 times worse than that during the quiet period. The correlations between the individual IAACs and the IGS GIMs are also investigated. The correction of CODE-GIM and Jet Propulsion Laboratory (JPL)-GIM with respected to IGS-GIM is more significant than that of Universitat Politècnica de Catalunya/IonSAT (UPC)-GIM. In general, CAS's GIM products exhibit good consistency with the IGS-final GIMs with an overall accuracy better than 2.5 TECu during the test period.

Introduction

With the development of GPS, GLONASS and follow-on Galileo and BDS, the technique of Global Navigation Satellite Systems (GNSS) has become a common and valid approach for global ionosphere monitoring with high temporal and spatial resolutions [1,2]. The International GNSS Service (IGS) ionosphere working group was established since 1998, which publicly produced and released the global ionospheric map (GIM) products using the IONosphere EXchange (IONEX) format [3–5]. GIMs can provide ionospheric total electron content (TEC) with a spatial resolution of 5 and 2.5° in longitude and latitude, respectively, and a temporal resolution of few minutes to several hours in real-time, rapid and final modes. Although the real-time GIM products have been proposed by the IGS, users now can only access the rapid and final GIMs with a latency of few days.

As of now (April 2018), there are seven IGS Ionospheric Associate Analysis Centers (IAACs) including Center for Orbit Determination in Europe (CODE), Universitat Politècnica de Catalunya/IonSAT (UPC), Jet Propulsion Laboratory (JPL), European Space Operations Center of European Space Agency (ESA), Natural Resources Canada (NRCAN), Chinese Academy of Sciences (CAS) and Wuhan University (WHU). The first four IAACs have been continually contributing GIM products to the IGS ionosphere working group since 1998 [6–9], while the other three were nominated as the new IAACs in the IGS workshop 2016 held in Sydney, Australia. Specifically, CAS was jointly managed by the Academy of Opto-Electronics (AOE) in Beijing and the Institute of geodesy and geophysics (IGG) in Wuhan, which adopts the Spherical Harmonic Plus generalized Trigonometric Series (SHPTS) method to generate the rapid and final GIMs [10].

The GIM products of the first four IAACs (CODE, JPL, UPC, ESA) have been widely used in the scientific communities, whose performance were also validated by comparing with the TEC references provided by Global Positioning System (GPS), Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS) or altimeters satellites such as TOPEX/Poseidon and JASON series [11,12]. However, few studies have been conducted to validate the accuracy of CAS's GIM (CASG) products since CAS officially started to provide GIM products to the IGS. Li et al. (2015) reported that CASG shows a mean difference

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ranging from −1.0 to −3.0 TECu with a standard deviation ranging from 1.0 to 4.0 TECu relative to GPS TEC during the period 2001–2011 [10]. Roma-Dollase et al. (2018) evaluated the consistency of the current seven GIM generation techniques by comparing with the differences of GPS slant TEC (dSTEC) and JASON vertical TEC (VTEC) over the continental and oceanic regions, respectively[13]. They reported that the relative error of CASG are 28.0% and 20.9%, respectively, compared with GPS dSTEC and JASON VTEC.

In this study, we intend to give an update status and overall performance of CAS's GIM products during the period of 2015–2017. The paper is organized as follows: Section "Data sets and methodology" presents the algorithms used in CAS for its GIM generation with the description of the data sets and analysis method for the following validation. Section "Results" gives the comparison results and proper discussions, followed by the conclusion presented in Section "Conclusions".

Data sets and methodology

The performance of CASG are validated with respect to the IGS final GIM during the period of 2015–2017. To present a comprehensive comparison, the final GIMs provided by CODE (CODG), UPC (UPCG), JPL (JPLG) and ESA (ESAG) are also included. The algorithms for generating CAS's GIM are first given, followed by the comparison of different GIM generation techniques of each individual IAAC as well as the analysis method.

Algorithms for CAS's GIM generation

SHPTS method is adopted by CAS to generate the GIM product, which can be divided into four steps: (1) extracting ionospheric information from observation data using the classic carrier-to-code leveling (CCL) method; (2) estimating satellite and receiver Differential Code Biases (DCB) with IGGDCB (IGG stands for the Institute of Geodesy and Geophysics in Wuhan) method [14]; (3) ionospheric TEC modeling based on Spherical Harmonic (SH) function and Generalized Trigonometric Series (GTS) function on global and regional scales, respectively; (4) generating GIM with the improved different areas different station (DADS) method proposed by Yuan and Ou [15].

Currently, the approaches for extracting ionospheric TEC from raw GNSS observation can divided into two categories, one is based on CCL and the other is based on the uncombined precise point positioning (UPPP) [16,17]. Since the precise satellite orbit and clock products and the known position of the receiver has been introduced in the UPPP approach as the prior constraint, the accuracy of ionospheric TEC from UPPP approach is generally better than that from CCL approach. However, in order to wean the GIM generation from the precise satellite orbit and clock, the CCL approach is still adopted by CAS.

The satellite and receiver DCB is also assumed as daily constant in the CAS's GIM generation and estimated using the approach of IGGDCB [14]. Although the subtle variation of receiver DCB in intra-day scale was confirmed by Zhang et al. (2015,2017), the effect on the accuracy of GIM generation is able to be ignored in our experience at present [18,19]. The distribution of global ionospheric TECs are modelled by the SH function in SHPTS approach, which is described as follows.

$$V(\varphi,\lambda)=\sum_{n=0}^{n_d\max}\sum_{m=0}^{n}\widetilde{P}_{nm}(\sin\varphi)\times(\widetilde{A}_{nm}\cos(m\lambda)+\widetilde{B}_{nm}\sin(m\lambda)) \tag{1}$$

where $V(\varphi,\lambda)$ is the vertical ionospheric TEC at ionospheric intersecting pierce point (IPP); φ and λ denote the geographic latitude and longitude of IPP; $\widetilde{P}_{nm}=N_{nm}P_{nm}$ is the normalized associated Legendre function of degree n and order m; N_{nm} is the normalization function; P_{nm} is the classical, un-normalized Legendre function; $\widetilde{A}_{nm}$ and $\widetilde{B}_{nm}$ are the SH coefficients to be estimated using real data.

The variation of regional ionospheric TECs are modelled by the GTS function, which is given in Eq. (2) as follows.

$$V(\varphi,h)=\sum_{n=0}^{n_{\max}}\sum_{m=0}^{m_{\max}}\{E_{nm}(\varphi-\varphi_0)^n h^m\}+\sum_{k=0}^{k_{\max}}\{C_k\cos(k\cdot h)+S_k\sin(k.\,h)\} \tag{2}$$

where $V(\varphi,h)$ is the vertical ionospheric TEC at ionospheric intersecting pierce point (IPP); φ and φ_0 denote the geographic latitude of IPP and the station; h is the current local time of IPP; $n_{\max}$ and $m_{\max}$ are the maximum degree of the polynomial development; $k_{\max}$ is the maximum degree of the finite Fourier series; E_{nm}, C_k and S_k are the coefficients of the local ionospheric model to be estimated.

SHPTS method utilizes the SH the GTS functions for global and regional ionospheric TEC modeling, respectively. SH function is beneficial for the global TEC modeling, and GTS is capable of capturing the subtle variation of TEC in a local scale. To solve the problem that the ionospheric TEC and its RMS can't be estimated accurately in the area without real data, the improved DADS method introduces the SH-based model as a background ionospheric model and improves the distance-related function to the elevation-related function. The ionospheric VTEC at the grid point near the GNSS stations is estimated by adjusting the VTEC from each corresponding local ionospheric model using an elevation-dependent weight. The accuracy of ionospheric VTEC estimated around the contributing stations in the DADS can be improved, this is because that the local ionospheric model is generally more accurate than the global ionospheric model. The VTEC maps of CODE and ESA, by contrast, are generated on a daily basis using GPS, BDS and GLONASS dual-frequency data from about 300 globally distributed stations of the IGS and other institutions.

It has been demonstrated that the accuracy of ionospheric TEC estimated from SHPTS-based GIM over the real data covered area has been improved, by using local ionospheric model to capture subtle variations in the ionospheric TEC instead of the global ionospheric model [10].

GIM products of the individual IAAC and IGS

The GIM products of the selected five IAACs are downloaded from the NASA's Crustal Dynamics Data Information System (CDDIS) archive [20], which are also compared with the IGS final GIMs.

Table 1
Summary of the different GIMs assessed in this work (as of 2017).

GIM ID	IGSG	CASG	CODG	ESAG	JPLG	UPCG
Raw iono. extraction	Weighted mean	CCL	CCL	CCL	CCL	L4 combination
TEC modeling method		SHPTS	SH	SH	spherical triangles with splines	Tomographic with splines
Iono. layer		single-layer (450 km)	modified single-layer	single-layer	three-shell (250, 450, and 800 km)	2-layer voxel model
Handling of negative TEC		Inequality-Constrained Least Square	Kalman filter, LS and PWL algorithm	Kalman filter, LS and PWL algorithm	Use pixel-based algorithms	Use pixel-based algorithms
Time resolution	2 h	2 h/0.5 h	1 h	2 h	2 h	2 h
References Number	[4]	[10]	[8]	[21]	[26]	[6]