The Combined Real-Time Global Ionospheric Map for Operational Ionospheric Space Weather Monitoring

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Space-based radio systems in L-band, like the Global Navigation Satellite Systems (GNSSs), are severely affected by ionospheric errors, which are known to be up to tens of meters in magnitude. In the case ionospheric propagation errors are not properly corrected, performance of navigation and communication applications based on GNSS radio signals can be severely degraded. The availability of regional and global tracking networks of GNSS receivers provides the opportunity to monitor continuously the variability of ionospheric electron contents for more than 20 years, and more recently in real time. Using the global multi-frequency and multi-constellation GNSS measurements provided by the International GNSS Real-Time Service (IGS-RTS), the Chinese Academy of Science (CAS), Centre National d'Etudes Spatiales (CNES) and Universitat Politècnica de Catalunya (UPC) started to routinely generate real-time global ionospheric maps (RT-GIMs) since 2017[1,2]. Such RT-GIMs have been widely used in real-time GNSS precise positioning and ionospheric space weather monitoring, but the performance of RT-GIMs from individual analysis centers (ACs) are largely affected by the stability of RT-GNSS data streams. To provide a more stable real-time ionospheric correction stream, UPC adapted its post-processing GIM combination method, which has been successfully applied in the combination of IGS rapid and final GIMs, and used to combine the experimental IGS RT-GIM[3]. Following UPC's RT-GIM combination activity, CAS also started RT-GIM combination using real-time streams from CNES, UPC, Wuhan University (WHU), and CAS itself since late-2021 (see Table 1).

Table 1 An overview of RT ionospheric streams used for CAS RT-GIM combination and comparison

Analysis centers	Caster	Mountpoint	Interval / s	Format
CAS	products.igs-ip.net:2101	SSRC00CAS1	60	IGS-SSR
CNES	products.igs-ip.net:2101	SSRC00CNE1	60	IGS-SSR
UPC	products.igs-ip.net:2101	IONO00UPC1	15	IGS-SSR
WHU	58.49.94.212:2101	IONO00WHU0	60	RTCM-SSR
UPC-combined	products.igs-ip.net:2101	IONO00IGS1	15	IGS-SSR
CAS-combined	products.igs-ip.net:2101	IONO01IGS1	60	IGS-SSR
		IONO01IGS0	60	RTCM-SSR

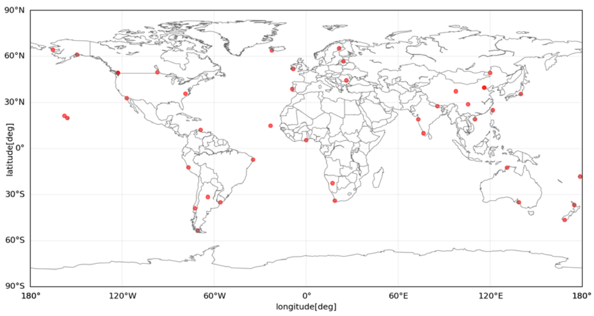

Figure 1. Distribution of RT-GNSS stations used for RT-dSTEC analysis and RT-weights computation of RT-GIMs of different ACs

A time-varying GNSS dSTEC analysis method is proposed to evaluate the quality of RT-GIMs from different ACs in real-time. Compared to conventional dSTEC assessment referring to the first epoch or the epoch with highest satellite elevation angle across the entire phase observation arc, the proposed time-varying dSTEC analysis requires limited computation load, which is also free of higher noises of those observation data with lower satellite elevation angles. Around 40 RT-GNSS stations from the IGS-RTS network are selected for RT-dSTEC analysis (see Fig. 1). The RT-dSTEC RMS are calculated by analyzing the differences between dSTEC observables derived from GPS L1/L2, BDS-2/3 B1/B3 and Galileo E1/E5a phase observation data and those computed by RT-GIMs of different ACs. RT-weight of individual AC's RT-GIM is calculated as the inverse of above squared RMS errors. The combined RT-GIM is then generated by applying the weights directly to RT-GIMs of the involved ACs, i.e., CAS, CNES, UPC and WHU.

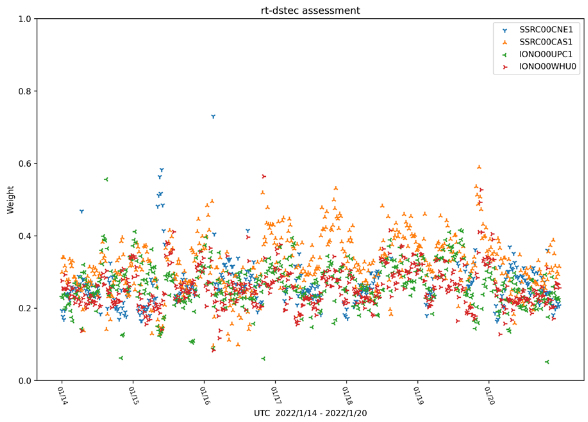

Figure 2. RT-weights of RT-GIM of CAS (SSRC00CAS1), CNES (SSRC00CNE1), UPC (IONO00UPC1) and WHU (IONO00WHU0) during January 14-20, 2022

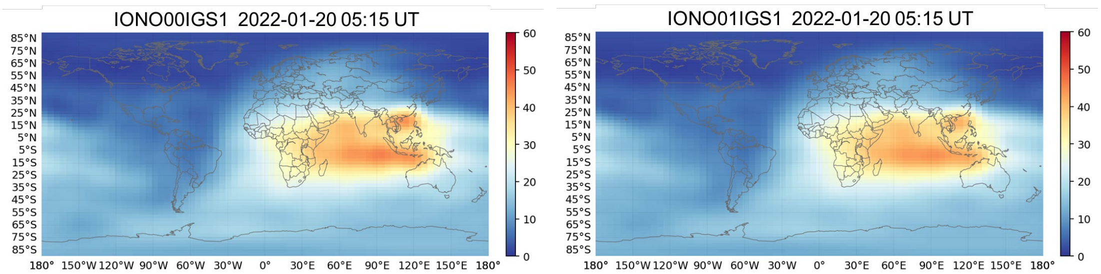

Figure 3. Real-time global VTEC maps from UPC-combined (IONO00IGS1) and CAS-combined (IONO01IGS1) RT-GIMs on January 20, 2022 at 05:15 UT

RT-weights of RT-GIMs of CAS, CNES, UPC and WHU during January 14-20 of 2022 are shown in Figure 2, with an interval of 15 minutes for RT-weight computation. The weight of CAS RT-GIM is pronounced, indicating the smaller RMS errors in RT-dSTEC analysis compared to RT-GIMs from the other three ACs. The result is slightly different from the analysis presented in [3], where UPC's RT-GIM exhibits the highest weight, followed by CNES, CAS and WHU. Aside from the different analysis periods, such inconsistency also relates to 1) different sets of RT-GNSS stations, 2) different observation data (GPS-only for UPC, whereas multi-GNSS for CAS), and 3) slightly different RT-dSTEC computation method in the RT-weighting analysis. An example of real-time global VTEC maps from CAS-combined and UPC-combined RT-GIMs are plotted in Figure 3, and similar global VTEC distributions can be found from both data sources. CAS combined RT-GIM streams are transmitted in both RTCM-SSR (IONO01IGS0) and IGS-SSR (IONO01IGS1) standards, which are freely accessible from the IGS data streaming server (products.igs-ip.net:2101) since January 2022.

The quality of CAS combined RT-GIM is evaluated in both GPS RT-dSTEC and single-frequency precise point positioning (SF-PPP) assessments by comparison with the existing combined RT-GIM provided by UPC. As shown in Figure 4, RMS differences between GPS RT-dSTEC references and those derived from combined RT-GIMs mainly vary between 2.0 and 6.0 TECu for the selected test period. CAS combined RT-GIM shows comparable performance with UPC combined RT-GIM, which confirms the robustness of the proposed method for RT-GIM combination. In addition to the combined RT-GIMs from CAS and UPC, the IGS rapid GIM and GPS broadcast Klobuchar model are also involved in GPS SF-PPP analysis. In Figure 5, the horizontal and vertical RMS errors of GPS single-frequency PPP augmented with different ionospheric corrections are presented. Note that the selected stations have good global coverage, which are sorted following their geographic latitude from the high-latitude of southern hemisphere to the high-latitude of northern hemisphere. Overall, The mean horizontal RMS errors are 2.13m for Klobuchar model, 0.58m for igrg, and 0.62m for CAS- and UPC-combined RT-GIMs across all test stations. For the mean vertical RMS errors, the values are 3.87m, 0.69m, 0.71m and 0.71m for Klobuchar mode, igrg and two combined RT-GIMs, respectively. The analysis proves the good performance of CAS combined RT-GIM compared to the UPC combined one, which also shows that quality of the IGS combined RT-GIM is almost approaching the rapid one.

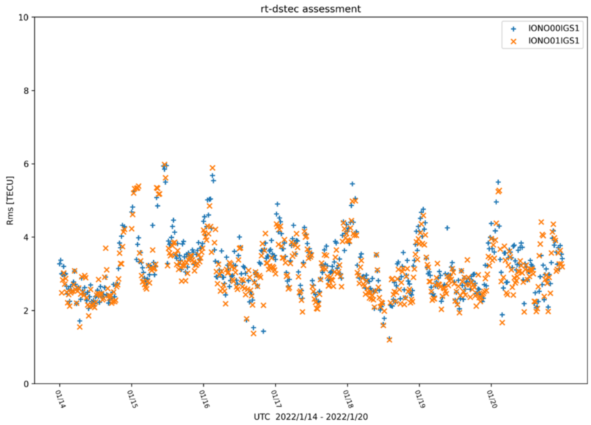

Figure 4. RMS series of CAS-combined (IONO01IGS1) and UPC-combined (IONO00IGS1) RT-GIMs derived from the RT-dSTEC analysis during January 14-20, 2022

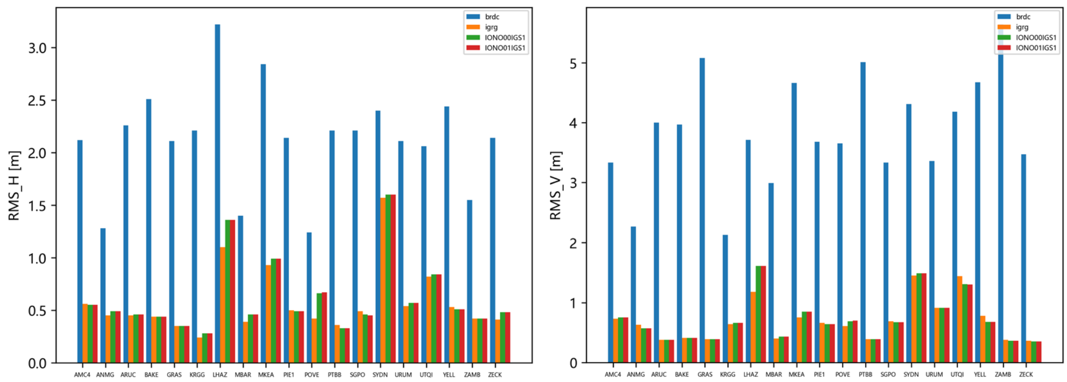

Figure 5. Horizontal and vertical RMS errors of GPS single-frequency PPP augmented with different ionospheric corrections

In summary, a time-varying GNSS RT-dSTEC analysis method is proposed for RT-GIM weighting and combination at CAS. The quality of CAS combined RT-GIM is evaluated in both GPS dSTEC and SF-PPP assessments. Aside from proving the combined RT-GIMs to the IGS, an experimental operational ionospheric space weather monitoring system has also been set at CAS, based on the routinely generated RT-combined GIM. In addition to the long-term analysis of the combined RT-GIM (e.g. covering different seasons), its effects on single- or multi-GNSS PPP applications at different geographic locations should be also analyzed, which is the work are focusing on.

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