Manuscript Title: The cooperative IGS RT-GIMs: a global and accurate estimation ofthe ionospheric electron content distribution in real-time

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Dear anonymous referee,

We thank the anonymous reviewer for constructive comments and suggestions. These can be very helpful to improve the quality of manuscript and also increase the readability.

We will firstly provide a point-by-point response to reviewer's comments in red font. Then the track of the changes and also the revised version of manuscript will be attached and named as "diff.pdf" and "IRTG-ESSD-v2-response.pdf", respectively.

Thank you.

Please note that reviewers' comments are in italics while our answers are not.

Yours sincerely, on behalf of the co-authors,

Qi Liu and Manuel Hernández-Pajares

Answers to Anonymous Referee 2, essd-2021-136-RC2.pdf

Comment R2.1 *The authors address in their study the generation of a specific real-time data product of IGS. This is the IGS combined Real-Time Global Ionosphere Map (RT-GIM) generated by real-time weighting of RT-GIMs computed simultaneously at four IGS real-time ionosphere centers. Because different centers use different approaches to estimate global TEC the combination of different approaches is not trivial. Consequently, the authors discuss is topic in detail. Validation of the performance of contributing ionosphere center related TEC estimates and the combined products is carried out by using independent altimeter data (1 month) from Jason-3 satellite over oceans and the dSTEC technique over continents (2 days). Comparison is also made with better conditioned post-processed GIMs. The authors finally conclude that the IGS RT-GIMs are a reliable source of real-time global VTEC information having a great potential for real-time GNSS applications.*
The results should principally be of interest for readers of ESSD.
The manuscript is well organized. Nevertheless, there are a few points which need improvement/clarification in a revised version as indicated in the subsequent comments:
Answer to R2.1 Thanks for your efficient and professional editing and kind suggestions. We have modified the manuscript and answered your questions point-by-point as following.

Comment R2.2 *Science*
Considering the Jason3-VTEC assessment the constant bias estimate includes practically the plasmaspheric electron content above 1300 km height which definitively not constant on global scale. This is clearly a weak point in the subsequent weighting practice which is based on the RMS error between VTEC (Jason) and the GIMs. This critical point concerns also the dSTEC technique if arc lengths between measurement and reference point are large, i.e. if the ray path geometry changes significantly. Additionally, mapping function errors are also included in the RMS error that is used as weighting criterium for different centers. Here arises also the question whether the different centers use exactly the same data base for the construction of their GIMs. If not, there is another source of uncertainty for estimating the weighting of different centers.
I think the authors should discuss these problems in their manuscript adequately.
Answer to R2.2 Thanks for your kind suggestions. We are focusing on the standard deviation of the difference between GIM-VTEC and Jason3-VTEC to avoid the Jason3-altimeter bias and the mean bias component of the plasmaspheric electron content in the assessment. The plasmaspheric electron content variation is up to a few TECU and is relatively a small part when compared with the GIM errors over the oceans. As a consequence, the GIM validation based on dual-frequency Jason3-altimeter measurements is sensitive to the actual error of the GIMs on the oceans where are the most challenging regions for GIMs (containing few nearby receivers in such regions) and typically far from permanent GNSS receivers potentially contributing to the GIM (see details in [1, 2]). As summarized in section 2.3, the weighting of RT-GIMs to generate the IGS combined RT-GIM is exclusively based on RT-dSTEC weighting technique and use the GF combination of phase-only observations to calculate the RMS of dSTEC error by Eq. 8.
The dSTEC observations provide the direct measurements of the difference of STEC within a continuous phase-arc involving different geometries but avoiding the huge mapping function errors by applying an elevation mask of 15 degrees. And the mapping function is used by GNSS users to convert GIM-VTEC to GIM-STEC for GNSS positioning. Therefore, the dSTEC observations, containing different geometries and mapping function values, are accurate and direct measurements for evaluating ray path GIM-STEC which is commonly used by GNSS users to calculate

ionospheric correction. In addition, the common agreed ionospheric thin layer model is set to be 450 km height in the generation of GIM to provide VTEC in a consistent way for different ionospheric analysis centers. And in this way the GNSS users are able to consistently recover a most accurate STEC from GIM-VTEC by the commonly agreed mapping function.
The GIM error versus JASON-VTEC measurements have a high correlation with the GIM error versus dSTEC-GPS based measurements, although the JASON-VTEC measurements are vertical and the dSTEC-GPS measurements are slant. As demonstrated in [2], the Jason3-VTEC assessment and dSTEC-GPS assessment are independent and consistent for GIM evaluation. In other words, the slant ray path geometry changes does not affect the capability of dSTEC reference data to rank the GIM, and the plasmaspheric component does not significantly affect the assessment of GIMs based on Jason3-VTEC data.

In the manuscript, we have made some modifications for explanation:
a) We replace "The VTEC from the Jason3-altimeter was gathered as an external reference over oceans which were also the most challenging regions for GIMs (typically containing few nearby receivers in such regions)." with "The VTEC from the Jason3-altimeter was gathered as an external reference over the oceans."
b) We replace "Although the electron content above Jason3-altimeter (about 1300 km) is not available and the altimeter bias is around a few TECU, Jason3-VTEC has been proven to be a reliable reference of VTEC on a global scale (Hernández-Pajares et al., 2017). In this context, the daily standard deviation of the difference between Jason3-VTEC and GIM-VTEC was selected as the statistic for GIM assessment in Eq. 9" with "Although the electron content above Jason3-altimeter (about 1300 km) is not available and the altimeter bias is around a few TECU, the standard deviation of the difference between GIM-VTEC and Jason3-VTEC is adopted to avoid the Jason3-altimeter bias and the constant bias component of the plasmasphere in the assessment. The plasmaspheric electron content variation is up to a few TECU and is relatively a small part when compared with the GIM errors over the oceans. And Jason3-VTEC has been proven to be a reliable reference of VTEC on the oceans where are the most challenging regions for GIMs (containing few nearby receivers in such regions) and typically far from permanent GNSS receivers potentially contributing to the GIM (Hernández-Pajares et al., 2017). In this context, the daily standard deviation of the difference between Jason3-VTEC and GIM-VTEC was suitable as the statistic for GIM assessment in Eq. 9"
c) After sentence "In the dSTEC-GPS assessment, the maximum elevation angle within a continuous arc was regarded as the reference angle in Eq. 8.", we add "The dSTEC observations provide the direct measurements of the difference of STEC within a continuous phase-arc involving different geometries. And the mapping function is used by GNSS users to convert GIM-VTEC to GIM-STEC for GNSS positioning. Therefore, the dSTEC observations, containing different geometries and mapping function error, are accurate and direct measurements for evaluating ray path GIM-STEC which is commonly used by GNSS users to calculate ionospheric correction. In addition, the common agreed ionospheric thin layer model is set to be 450 km height in the generation of GIM to provide VTEC in a consistent way for different ionospheric analysis centers. And in this way the GNSS users are able to consistently recover a most accurate STEC from GIM-VTEC by the commonly agreed mapping function."
d) After the sentence "The influence of temporal resolution on RT-GIMs was also shown in this section.", we add "Before detailing the JASON3-VTEC and GPS-dSTEC assessment, it should be taken into account that the GIM error versus JASON-VTEC measurements have a high correlation with the GIM error versus dSTEC-GPS based measurements, although the JASON-VTEC mea-

surements are vertical and the dSTEC-GPS measurements are slant. As demonstrated in [2], the Jason3-VTEC assessment and dSTEC-GPS assessment are independent and consistent for GIM evaluation. In other words, the slant ray path geometry changes does not affect the capability of dSTEC reference data to rank the GIM, and the electron content between the Jason3-altimeter and the GNSS satellites does not significantly affect the assessment of GIMs based on Jason3-VTEC data."

Regarding the point on whether different centers use exactly the same data base for the construction of their GIMs or not: In our knowledge all the IGS ionospheric analysis centers use GNSS data from permanent GNSS receivers. The number of constellations in GNSS data and the distribution of GNSS receivers used by the different analysis centers are not identical (some centers are still using GPS-only data in their official product, while others are using multi-GNSS). But this is not an issue and the use of different techniques for modelling ionosphere VTEC, with complementing benefits, is one fundamental aspect to explain the good behaviour of the combined GIM.

Comment R2.3 *Data set*
The data set includes 1 month of Jason 3 vertical TEC data over oceans and 2 days of ground based GNSS data over land. Thus, the data base is very limited to derive general conclusions on physical relationships concerning the physics of the ionosphere. However, the authors use the data set to demonstrate the estimation of VTEC at 4 data different data centers and the procedure of combining their VTEC estimates in near real time. Thus, the data set is appropriate and of high quality. The question is, whether all enters use the same data set to ensure a fair comparison.

Answer to R2.3 Thanks for your understanding. Following your and also the first reviewer's suggestion, now we have extended the experiment. We add data one month before January 2021 and one month after January 2021 (from December 01 of 2020 to March 01 of 2021). The new results are similar and consistent with previous experiment. Fig. 3, Fig. 5. and Table 4 have been reproduced and the corresponding descriptions have been changed. In particular, the overall standard deviation of upc1 VTEC versus measured Jason3-VTEC drops from 4.3 to 2.7 TECU and, in agreement with that, the standard deviation of irtg VTEC versus measured Jason3-VTEC decreases from 3.3 to 2.8 TECU. Accordingly, the description of the figures and tables has also been modified. As shown and explained in Eq. 4, the whu0 is shifted by 0 hours. To see the influence of phase-shifted $\lambda_{S,t}$, the whu0 is manually shifted by 2 hours (i.e., take t_0 as 2 hours for whu0 in Eq.4) in post-processing mode. As can be seen in Fig. 3 and Table 4, the 2-hour shifted WHU RT-GIM (whu1) is slightly better than whu0.
The answer to "whether all enters use the same data set to ensure a fair comparison." has been included in the last paragraph of "Answer to R2.2".

Comment R2.4 *Wording*
Headline: The authors should avoid the term "accurate" in the headline because this requires a clear definition what accuracy means. The authors themselves conclude later in line 311 that the accuracy should be increased.
Answer to R2.4 Thank you for your suggestion. Now we replace "The cooperative IGS RT-GIMs: a global and precise estimation of the ionospheric electron content distribution in real-time" with

”The cooperative IGS RT-GIMs: a reliable estmation of the global ionospheric electron content distribution in real-time” in the headline to avoid ambiguity. Actually there is always room for improvement. And that’s why we said ”To increase the accuracy” in line 311 for the ”Future improvements might include:”.

Comment R2.5 *Abstract: The abstract should have clear and compact statements concerning the results of the paper. Thus, for instance, there is a very long sentence covering lines 15- 19 that contains several illustrations in brackets which should be avoided in the abstract.*
Answer to R2.5 Thank you for your kind suggestion. We have deleted illustrations in brackets.

Comment R2.6 *Line 8: the real-time weighting technique is sensitive to the accuracy of RT-GIMs As I understand the weighting is dependent from the accuracy, not the technique*
Answer to R2.6 Sorry for the misleading. We have deleted the ”technique” in this sentence.

Comment R2.7 *Line 203: correct ”. . . IGS-SSR is compatible with RTCM-SSR contents, while IGS-SSR. . . ”*
Answer to R2.7 Sorry for the misleading. Now we replace ”The content of ISG-SSR is compatible with RTCM-SSR contents, while ISG-SSR supports more extensions.” with ”The content of ISG-SSR is compatible with RTCM-SSR contents. And the IGS-SSR format can support more extensions such as satellite attitude, phase center offsets and variations in the near future.”

Comment R2.8 *Equations*
(6): Please check the correctness, eq. is not understandable
Answer to R2.8 Sorry for the misleading. We have reorganized the equations and the symbols.

Comment R2.9 *Figures*
Fig 5: needs precise description, the zoom refers
Answer to R2.9 Follow your and the first reviewer’s suggestion, we firstly change the zoom period in the top Figure 5(a). Now only real-time weights during 4 days are available to focus on the weight transition from USRG to UADG. The significant improvement of the transition of upc1 from USRG to UADG shown in dSTEC-GPS and Jason3-VTEC assessment is also obvious in the top figure of Fig. 5(a). Then we try to plot the daily winning epochs of RT-GIMs in Figure 5(b) from December 01 of 2020 to March 01 of 2021 to avoid the noisy evolution of weight in long-time period. For each RT-GIM, the number of daily winning epochs is computed by counting the number of epochs within the day when the one RT-GIM is better than the other RT-GIMs.

References

[1] D. Roma-Dollase, M. Hernández-Pajares, A. Krankowski, K. Kotulak, R. Ghoddousi-Fard, Y. Yuan, Z. Li, H. Zhang, C. Shi, C. Wang, *et al.*, “Consistency of seven different gnss global ionospheric mapping techniques during one solar cycle,” *Journal of Geodesy*, vol. 92, no. 6, pp. 691–706, 2018.

[2] M. Hernández-Pajares, D. Roma-Dollase, A. Krankowski, A. García-Rigo, and R. Orús-Pérez, “Methodology and consistency of slant and vertical assessments for ionospheric electron content models,” *Journal of Geodesy*, vol. 91, p. 1405–1414, 2017.