IGS IONOSPHERE MODELS COMPARISON

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Abstract

On 28 May 1998 the IGS Ionosphere Working Group was established by the IGS Governing Board. The working group's main short-term goal is the routine provision of ionospheric TEC maps with a 2-hours resolution and of daily sets of GPS satellite differential code bias (DCB) values, based on the evaluation of GPS dual-frequency tracking data. At 1 June 1998 four Ionosphere Associate Analysis Centers (IAACs) started with the delivery of their ionosphere products to the CDDIS Global Data Center. In the meantime the number of IAACs providing routinely ionosphere products has increased to five; these are: Astronomical Institute, University of Berne (AIUB/CODE); Geomatics Canada, Natural Resources Canada (NRCan/EMR); European Space Operations Centre (ESA/ESOC); Jet Propulsion Laboratory (JPL) and Polytechnical University of Catalonia (UPC).

A preliminary comparison/combination algorithm has been worked out and coded in form of the Fortran 77 program CMPCMB. Based on this algorithm a routine comparison of IGS ionosphere products has been started. At the same time the combined products are validated with independent methods with the aim to get ideas on how the comparison/combination algorithm might be improved on one hand, and on how the models of the IAACs might be calibrated on the other. The comparison/combination algorithm might then become subject of changes, e.g. after the next IGS Workshop.

It is the intent of this paper to present the current version of the comparison/combination algorithm which is presently used for the IGS ionosphere products comparison.

1 INTRODUCTION

In order to put the designated Ionosphere Associate Combination Center (IACC) ESOC into a position to start with the routine comparison of ionosphere products that are delivered routinely from the Ionosphere Associate Analysis Centers (IAACs), the new Fortran 77 program CoMParison/CoMBination (CMPCMB) had to be established from scratch.

Each IAAC delivers per day a set of 12 global TEC maps plus a daily set of satellite DCBs in form of an IONosphere Map EXchange Format (IONEX) file (ref. R6). Since already now 5 different IAACs contribute with their products to the IGS ionosphere pilot service, and further IGS Analysis Centers indicated their intention to become active as new IAACs in the future, a way had to be found how the comparison could be done efficiently. If the products of each IAAC would be compared with each other IAAC, there would be, in the case of 5 IAACs, 10 possible pairs that must be compared, and in the case of 6 contributing IAACs the number of pairs would increase to 15, and so on. To keep the extent of comparison in an acceptable frame, it was thus decided to compute per reference epoch (each of a daily IONEX file's 12 TEC maps refer to a reference epoch) from the different IAAC TEC maps a mean TEC map and to compare for that reference epoch each IAAC TEC map with that mean TEC map.

By doing the comparison in this way, one obtains, quasi as by-product, for each reference epoch a mean TEC map, which could be considered as something like a "combination" of the input IAAC TEC maps. The same holds for the comparison of DCBs, which is done basically in the same way. However, these "combined" TEC maps could only be considered as realistic, if the real quality of input IAAC TEC maps were known and could enter by proper weighting into the calculation of the mean TEC maps.

The IAACs use very different approaches to establish their TEC maps, resulting in very different temporal and spatial resolutions, and the RMS maps provided in the IONEX files represent only the internal accuracy of the respective approach. So the working group decided to start with an intense validation and calibration of the different ionosphere models in order to assess the quality of the TEC maps originating from the distinct modeling approaches. One thing that it was decided to do in parallel to the comparisons is a routine validation of the individual IAAC TEC maps, as well as of the "combined" TEC maps with TOPEX altimeter data.

It is the intent of this paper to present this comparison/combination algorithm which is currently used by the IGS Ionosphere Working Group. This algorithm must be considered as *preliminary* and will become subject of changes. The validations will help to find an optimal comparison/combination scheme for the working group's ionosphere models. Results are not presented in this paper, which will thus be restricted to the mathematical description of the comparison/combination algorithm.

2 COMPARISON STRATEGY

This chapter shall give a short overview on how the current comparison procedure works:

A) TEC maps

Comparison is done independently for each reference epoch in two basic steps:

1a) Unweighted mean

> The TEC maps of all IAACs are taken, and, moving from grid point to grid point, the *unweighted mean* of the TEC values of all IAACs at that grid point is calculated. *9999*-values are not included into the mean (*9999* stands for "no TEC value available at that grid point"). The result of this step is an unweighted mean TEC map.

1b) IAAC rms values/weights

At the same time the differences ("residuals") of the individual IAACs TEC values with respect to the unweighted mean TEC value are calculated at each grid point. For each IAAC an individual *rms*-value and a weight are then computed from the IAAC's "residuals" of all grid points according to $weight_{IAAC} = 1/(rms_{IAAC})^2$. These *rms*-values and weights are listed in the Tables 2. of the daily comparison summary (see e.g. ref. R4).

2) Weighted mean

The TEC maps of all IAACs are taken, and, moving from grid point to grid point, the *weighted mean* of the TEC values of all IAACs at that grid point is calculated. *9999*-values are not included into the mean. The result of this step is a weighted mean TEC map.

Comparsions are then made with respect to that weighted mean TEC map, i.e. at each grid point the "residual" of each IAAC TEC map with respect to the weighted mean TEC value is computed, and for each IAAC a "residual"-TEC map is thus obtained, showing zones of good and worse agreement. Furthermore from these "residual"-TEC maps a constant offset (bias), an overall rms, and rms-values in sub-parts of the geographic grid are computed and presented in the daily comparison summary in the Tables 3. for each IAAC (see e.g. ref. R4).

B) DCBs

Currently, only sets of satellite DCB values are provided by the IAACs, and comparison is thus restricted to satellite DCBs only.

First of all the DCB set of each IAAC is referred to its mean value of *all* satellites for which *all* IAACs provide DCB estimates, in order to achieve a common reference for the comparison.

Comparison of DCBs is then basically done in the same two steps as TEC maps comparison: 1) *Unweighted mean* of all IAACs for each spacecraft for which *all* IAACs provide a DCB value and establishment of weights from the differences with respect to that unweighted mean. 2) *Weighted mean* of all IAACs for each spacecraft. Comparison of the individual IAAC DCB values with the DCB values of the weighted mean.

3 COMPARISON ALGORITHM

Expressed in Fortran do loops and in mathematical equations, the comparison strategy is as follows:

A) TEC maps

1) Unweighted mean

Run in 4 nested loops over all grid points and over all accepted IAACs (all epochs, all latitudes, all longitudes, all IAACs). Per grid point (GP) the following processing is done:

- get the TEC value for each IAAC.
- build unweighted mean over all IAACs providing non-9999 values; if all IAACs provide a 9999, set unweighted mean equal to 9999.
- update for each IAAC the squared sum $[dd]_2$ of differences with respect to the unweighted mean, if this IAAC does not provide a 9999 at this GP ($[dd]_2$ is needed for the computation of parameter $weight_2$). Find out at the same time, whether all IAACs provide non-9999 values at the current GP.
- if all IAACs provide non-9999 values at current GP, update for each IAAC the squared sum $[dd]_1$ of differences with respect to the unweighted mean over those GPs where all IAACs provide non-9999 values ($[dd]_1$ is needed for the computation of parameter $weight_1$).

  To account for the effect that the meridians and thus the GPs are closer together at high latitudes φ, the squared sums of differences are computed as follows ($[dd]_1$ and $[dd]_2$ represent directly squares of rms):

$$[dd]_2(IAAC) = \frac{\sum_j \cos\varphi \cdot d_{IAAC}^2}{\sum_j \cos\varphi} \tag{1a}$$

where

j = sum over all non-9999 values for each IAAC

$$[dd]_1(IAAC) = \frac{\sum_i \cos\varphi \cdot d_{IAAC}^2}{\sum_i \cos\varphi} \tag{1b}$$

where

i = sum over all GPs where all IAACs provide non-9999 values

For each epoch (outermost loop) weights are then calculated as follows for each IAAC:

$$weight_1(IAAC) = \frac{1}{[dd]_1(IAAC)} \tag{2a}$$

$$weight_2(IAAC) = \frac{1}{[dd]_2(IAAC)} \tag{2b}$$

$weight_1(IAAC)$ will be used for the weighted mean, $weight_2(IAAC)$ is only for information and comparison (with $weight_1$) reasons.

End of 4 nested loops to establish unweighted mean.

2) Weighted mean

Run again in 4 nested loops over all grid points and over all accepted IAACs (all epochs, all latitudes, all longitudes, all IAACs). Per grid point (GP) the following processing is done:

- get the TEC value and a $TECrms$ value for each IAAC.
- build weighted mean over all IAACs providing non-9999 values; if all IAACs provide a 9999, set weighted mean equal to 9999.

$$combTEC(GP) = \frac{\sum_i weight_1(IAAC) \cdot TEC(IAAC)}{\sum_i weight_1(IAAC)} \tag{3}$$

where

i = sum over all IAACs that provide non-9999 values at that GP

- compute differences $TEC(IAAC)$ - $combTEC$ and store them in an IAAC's TEC difference IONEX file.

- compute at current GP weighted rms of combined TEC as:

$$combTECrms(GP) = \sqrt{\frac{\sum_i \frac{\{TEC(IAAC, GP) - combTEC(GP)\}^2}{\{TECrms(IAAC, GP)\}^2}}{\sum_i \frac{1}{\{TECrms(IAAC, GP)\}^2}}} \tag{4a}$$

where

i = sum over all IAACs that provide non-9999 values at that GP

Concerning the rms maps currently delivered by the distinct IAACs it must be said that they look very different, representing the internal accuracy of each individual estimation method. The same holds principally also for the DCB-rms values delivered in the IONEX files (see Equation (11) below). The anticipated validation will provide the real accuracies for the TEC maps originating from the different IAACs. Until such objective accuracy parameters have been found, Equation (4b) would be an alternative to calculate an rms of the combined TEC at each grid point, since no individual rms values enter into that formula.

$$combTECrms(GP) = \sqrt{\frac{\sum_i weight_1(IAAC) \cdot \{TEC(IAAC, GP) - combTEC(GP)\}^2}{n_{IAACs} - 1}} \tag{4b}$$

where

i = sum over all IAACs that provide non-9999 values at that GP

n_{IAACs} = number of all IAACs that provide a non-9999 value at that GP

- compute overall rms for each IAAC only over those GPs where all IAACs provide non-9999 values. Again, to account for the effect that the meridians and thus the GPs are closer together at high latitudes φ, the squared sum of differences is computed as follows ($[dd]$ represents directly a squared rms):

$$[dd](IAAC) = \frac{\sum_i \cos\varphi \cdot \{TEC(IAAC, GP) - combTEC(GP)\}^2}{\sum_i \cos\varphi} \tag{5}$$

where

i = sum over all GPs where all IAACs provide non-9999 values

For each epoch (outermost loop) an overall rms is finally calculated as follows for each IAAC:

$$rms(IAAC) = \sqrt{[dd](IAAC)} \tag{6}$$

End of 4 nested loops to establish weighted mean.

B) DCBs

1) First of all find out for which satellites all IAACs provide a DCB value.

2) Refer independently for each IAAC its DCB values to the reference $\Sigma_{DCBs} = 0$ for those satellites for which all IAACs provide a DCB value in order to achieve a common reference for comparison. Also the DCB values of the satellites for which not all IAACs provided a DCB value are referred to this new reference.

3) Compute unweighted mean DCB values for all those n_d satellites for which all IAACs provide a DCB value and compute then for each IAAC a weight for weighted mean:

$$uwmean_{sat} = \frac{\sum_k DCB(IAAC)_{sat}}{n_{IAACs}} \tag{7}$$

where

k = sum over all IAACs per satellite

n_{IAACs} = number of all IAACs

$$[dd](IAAC) = \sum_{sat} \{DCB(IAAC)_{sat} - uwmean_{sat}\}^2 \tag{8}$$

where

sat = summation over all n_d satellites per IAAC

$$weight(IAAC) = \frac{n_d - 1}{[dd](IAAC)} \tag{9}$$

4) Compute per satellite the weighted mean of all IAAC-*DCB*s, also of those for which not every IAAC has provided a value:

$$combDCB_{sat} = \frac{\sum_j weight(IAAC) \cdot DCB(IAAC)}{\sum_j weight(IAAC)} \tag{10}$$

where

j = sum over all IAACs that provide a DCB value for that satellite

5) Compute differences $DCB(IAAC)_{sat}$ - $combDCB_{sat}$ and store them in the IAAC's *TEC* difference IONEX file.

6) Compute for current satellite the weighted *rms* of combined *DCB* as:

$$combDCBrms_{sat} = \sqrt{\frac{\sum_j \frac{\{DCB(IAAC)_{sat} - combDCB_{sat}\}^2}{\{DCBrms(IAAC)_{sat}\}^2}}{\sum_j \frac{1}{\{DCBrms(IAAC)_{sat}\}^2}}} \tag{11}$$

where

j = sum over all IAACs that provide a DCB value for that satellite

In a similar way as the individual *TEC rms* values, also the *DCB rms* values of the different IAACs represent the internal accuracy of their respective estimation method. A formula similar to the above Equation (4b) might thus provide more objective *DCB rms* values as Equation (11) may do.

7) Finally, refer the weighted mean *DCB* values again to $\Sigma_{DCBs} = 0$.

4 CONCLUSIONS

The IGS Governing Board has established the IGS Ionosphere Working Group on 28 May 1998. The working group's main short-term goal is the routine provision of ionospheric TEC maps and of sets of GPS satellite DCB values. A very important component of the working group's activities is the routine comparison of the ionosphere products delivered by the different IAACs. To do this task, a comparison algorithm has been worked out and coded, and was presented in this paper. This comparison algorithm provides, so to say as by-product, also something like a "combination" of the IAACs individual ionosphere products. However, this comparison/combination algorithm is based on the concept of weighted means and must be considered as *preliminary*, since the IAACs use very different approaches and estimation schemes in their ionosphere processing. Intense activities to validate and calibrate the different ionosphere models have recently been started within the working group in order to assess the quality of the TEC maps/DCBs originating from the distinct modeling approaches. It is the working group's intent that these validations will lead to a final scheme to combine the IAACs individual ionosphere maps and DCBs to a new common IGS ionosphere product.

5 REFERENCES

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