

# THE INTERNATIONAL GPS SERVICE (IGS) IONOSPHERE WORKING GROUP

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**- on behalf of the IGS Ionosphere Working Group -**

*presented by*

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## ABSTRACT

The IGS Ionosphere Working Group (Iono\_WG) commenced working in June 1998. The working group's main task is the routine provision of ionosphere TEC maps with a 2-hours time resolution and of daily sets of GPS satellite and receiver hardware differential code bias (DCB) values. The computation of these TEC maps and DCB sets is based on the routine evaluation of GPS dual-frequency tracking data recorded with the global IGS tracking network.

Currently five IGS Ionosphere Associate Analysis Centers (IAACs) contribute with their ionosphere products to Iono\_WG activities. Once per week these ionosphere products are compared with a dedicated comparison algorithm. This algorithm is currently being upgraded to be able to compute a combined IGS ionosphere product from the individual IAACs inputs. This new product shall soon be made available to external users through the Crustal Dynamics Data Information Center (CDDIS).

Beyond the routine provision of ionosphere products, the Iono\_WG intends to support the ionosphere community also with other activities, e.g. by using the IGS global tracking network and capabilities to run high-rate data campaigns during events of special relevance for the ionosphere. A first such campaign was organized during the total solar eclipse on 11 August 1999, a second campaign was run recently under the name "HIRAC/SolarMax" over 7 days from 23 - 29 April 2001.

In the medium- and long-term, the working group intends to develop more sophisticated ionosphere models and to realize near-real-time availability of IGS ionosphere products.

It is the intent of this paper to give an overview over the Iono\_WG activities and to point out the importance of GPS for routine ionosphere monitoring.

# 1 INTRODUCTION

The Working Group started its routine activities in June 1998: Several so called Ionosphere Associate Analysis Centers (IAACs) provide per day twelve global TEC maps with a 2-hours time resolution and a daily set of GPS satellite DCBs in IONEX format files (Schaer et al., 1997). The routine provision of daily ground station DCBs is under preparation. Currently five IAACs contribute with ionosphere products:

- CODE, Center for Orbit Determination in Europe, Astronomical Institute, University of Berne, Switzerland.
- ESOC, European Space Operations Centre of ESA, Darmstadt, Germany.
- JPL, Jet Propulsion Laboratory, Pasadena, California, U.S.A.
- NRCan, National Resources Canada, Ottawa, Ontario, Canada.
- UPC, Polytechnical University of Catalonia, Barcelona, Spain.

The mathematical approaches used by the distinct IAACs to establish their TEC maps are quite different. Details about the individual IAACs modeling can be found in e.g. (Schaer 1999; Feltens, 1998; Mannucci et al., 1998; Gao et al.; Hernandez-Pajares M. et al., 1999).

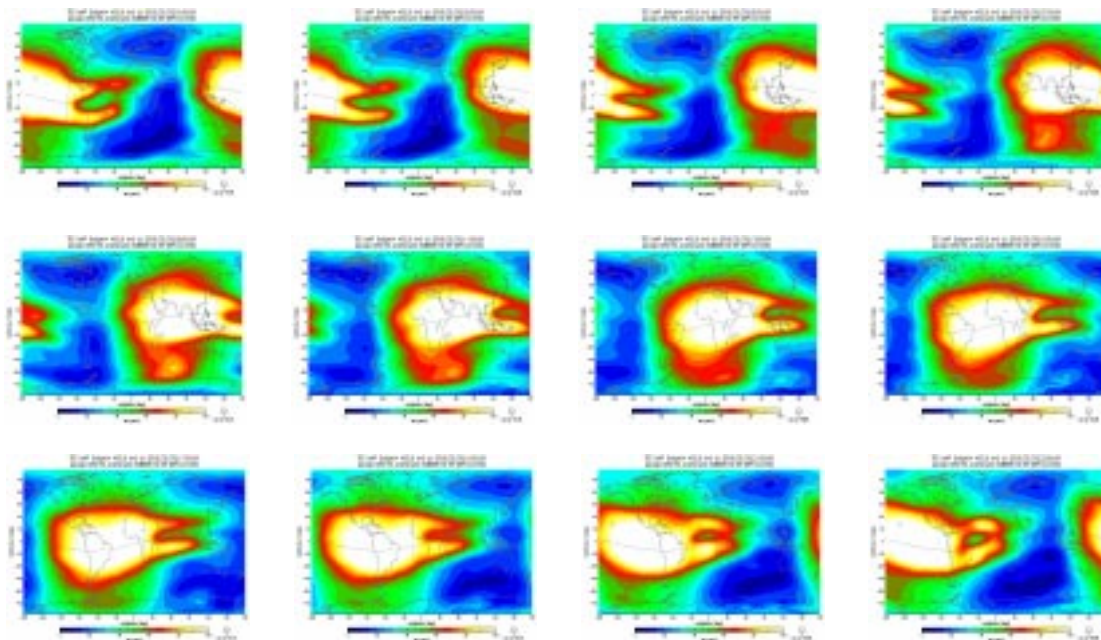
## 2 COMPARISONS

Once per week the ionosphere products from the different IAACs are compared at the Ionosphere Associate Comparison Center (IACC) at ESOC. A dedicated Fortran 77 program & Tcl was established at ESOC from scratch to do that task. In principle this algorithm computes for each of the twelve reference epochs an “unweighted mean” TEC map from the different IAAC TEC maps. Based on the residuals of the different IAAC TEC maps with respect to that “mean” TEC map a weight can be derived for each IAAC. Based on the weights thus obtained, a “weighted mean” TEC map is computed in a second step. By inspecting the residuals of the individual IAAC TEC maps with respect to that “weighted mean” TEC map per reference epoch, statistics about the agreement between the different IAACs TEC maps are established.

The “weighted mean” TEC map for each reference epoch, obtained quasi as by-product when doing the comparison in this way, 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, the IAACs use very different approaches to establish their TEC maps, resulting in very different temporal and spatial resolutions. These circumstances reflect also in the comparison results; the weighting scheme in the comparison algorithm must be improved. Software upgrades for an improved weighting scheme are currently under work. The next chapter will tell more about the new weighting scheme. As an example of results obtained with the current (old) weighting scheme Figure 1 shows the sequence of IGS “weighted mean” TEC maps of

28 March 2000, a day during a period in the current solar maximum, when the TEC level was very high.



**Figure 1:** The IGS “weighted mean” TEC maps of 28 March 2000 in [TECU]  
 (1<sup>st</sup> row: 1<sup>h</sup>, 3<sup>h</sup>, 5<sup>h</sup>, 7<sup>h</sup>; 2<sup>nd</sup> row: 9<sup>h</sup>, 11<sup>h</sup>, 13<sup>h</sup>, 15<sup>h</sup>; 3<sup>rd</sup> row: 17<sup>h</sup>, 19<sup>h</sup>, 21<sup>h</sup>, 23<sup>h</sup>).

The other important subject of comparisons are the DCBs. When directly comparing the DCB-series of the different IAACs, one can see an overall agreement in the order of about **0.3 ns**. According to a presentation of S. Schaer at the IGS Workshop, 27 - 29 September 2000, Washington, mean IAAC satellite DCB series show an agreement of about **0.1 ns**, while the day-by-day variations are significantly higher. For his analysis Schaer took three months (GPS weeks 1065 - 1077) of daily satellite DCB sets from the IAACs IONEX files and computed from these daily values IAAC-specific mean DCB sets. The five mean DCB sets thus obtained were then compared with respect to each other and also with respect to an overall mean set (*All*). Table 1 below is an extract of Schaer’s presentation and shows the obtained *rms* errors (in nanoseconds). When interpreting these numbers one has to keep in mind that some IAACs estimate their DCB sets together with their TEC maps, while others make separate program runs for this. Some IAACs introduce constraints in their DCBs estimation, while others do not.

	<b><i>NRCan</i></b>	<b><i>ESOC</i></b>	<b><i>JPL</i></b>	<b><i>UPC</i></b>	<b><i>All</i></b>
<b><i>CODE</i></b>	<b><i>0.122</i></b>	<b><i>0.106</i></b>	<b><i>0.110</i></b>	<b><i>0.370</i></b>	<b><i>0.094</i></b>
<b><i>NRCan</i></b>		<b><i>0.109</i></b>	<b><i>0.144</i></b>	<b><i>0.371</i></b>	<b><i>0.104</i></b>
<b><i>ESOC</i></b>			<b><i>0.118</i></b>	<b><i>0.373</i></b>	<b><i>0.095</i></b>
<b><i>JPL</i></b>				<b><i>0.393</i></b>	<b><i>0.117</i></b>
<b><i>UPC</i></b>					<b><i>0.296</i></b>

**Table 1:** Agreement of the distinct IAACs satellite DCB sets in [ns] (according to S. Schaer).

### 3 VALIDATIONS

NRCan and UPC have proposed two self-consistency methods. Both are in principle based on the analysis of residuals resulting from the comparison of directly from GPS-observables derived TEC values with corresponding TEC values interpolated from the IAACs TEC maps, in order to assess the quality of the distinct IAACs TEC maps. This is done with GPS data collected at ground stations equally distributed in a global geographic grid. The new geographic-dependent weighting scheme for the comparison/combination algorithm is based on the output of these two methods. A detailed description on how these two methods work can be found in (Feltens, 2000; Hernandez-Pajares, 2000; Heroux, 1999). The “weighted mean” TEC maps coming out with this new weighting scheme will then be the official combined IGS ionosphere product. In short summary, these two self-consistency methods work as follows:

I) UPC: Pairs of ionospheric GPS-signal delays  $LI = \alpha \cdot STEC + B$  between a receiver and a satellite recorded at times  $t_1$  and  $t_2$  at the same elevation are differenced (this is done over different elevations and satellite passes):

$$\Delta LI = LI(t_2, el) - LI(t_1, el) = \alpha \cdot \Delta STEC(el)$$

$\alpha$ ...multiplication factor from [TECU] into metric units

$B$ ...interfrequency bias, sum of receiver & satellite DCB

The difference  $\Delta LI$  is only a function of the *slant range TEC* ( $STEC$ ) difference.

At the same time corresponding  $STEC$ -differences are calculated with the IAAC TEC-models. The order of the differences in the  $STEC$ -differences (observed - IAAC) is an indicator of an IAAC TEC map quality.

II) NRCan: From GPS-signal delays recorded directly at a ground station,  $LI = \alpha \cdot STEC + \alpha \cdot \beta \cdot (DCB_{Sat} + DCB_{Sta})$  the terms  $(STEC_{Model} + \beta \cdot DCB_{Sat})$ , which can be computed from the IAAC IONEX-files, are subtracted. The resulting difference corresponds to the station-DCB:

$$\begin{aligned} \frac{LI}{\alpha \cdot \beta} - \left( \frac{STEC_{Model}}{\beta} + DCB_{Sat} \right) \\ = \left( \frac{STEC}{\beta} + DCB_{Sat} + DCB_{Sta} \right) - \left( \frac{STEC_{Model}}{\beta} + DCB_{Sat} \right) \\ = DCB_{Sta} + \frac{1}{\beta} \cdot \{ STEC - STEC_{Model} \} \end{aligned}$$

$\beta$ ...multiplication factor from [nanoseconds] into [TECU]

The better an IAAC-model is able to reconstruct the observed  $STEC$ , the smaller the difference  $\{ STEC - STEC_{Model} \}$  will be.

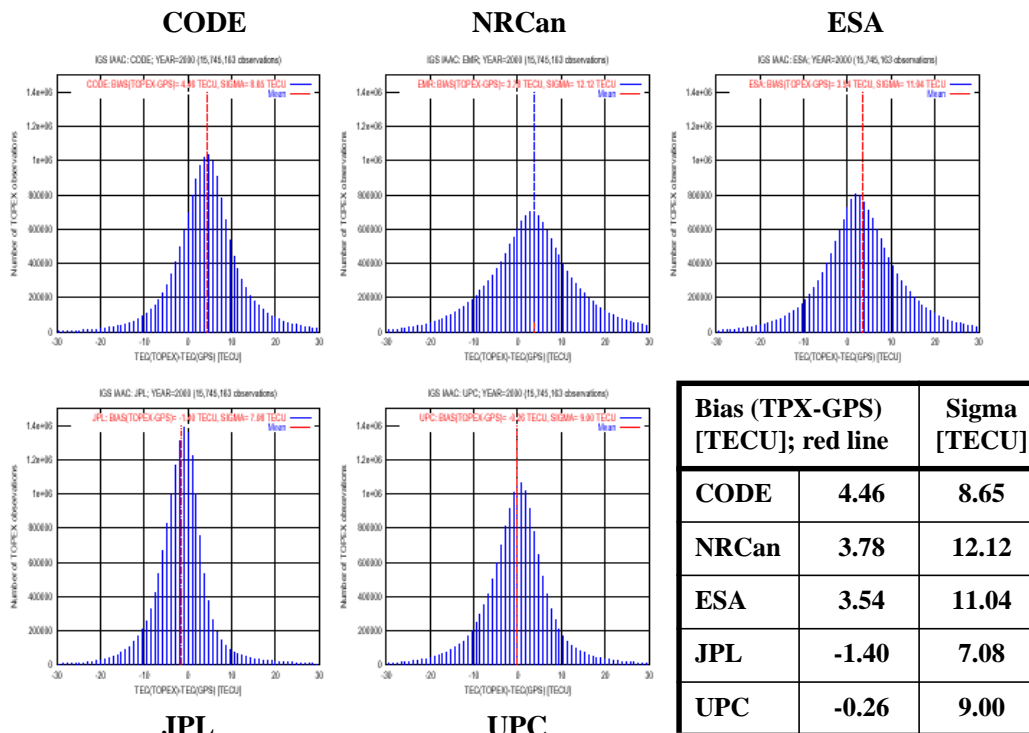
In this way station-DCB time series can be established, giving an indication of an IAAC-TEC map quality.

Per geographic area the IAAC weights are then computed as:

$$weight(IAAC, area) = \frac{1}{rms(IAAC, area)_{UPC}^2 + rms(IAAC, area)_{NRCan}^2}$$

Beyond that, the Iono\_WG intends to perform other kinds of validation, which are in short:

1) JPL proposed to make validations by comparing IAACs model vertical TEC values with TEC values derived from TOPEX (and Envisat, once launched) altimeter data. This type of validation shall soon be attached to the weekly comparison program runs. Figure 2 below shows in form of histograms the results of an analysis made at UPC with TOPEX data for each of the five IAACs for the year 2000; the Number of TOPEX observations are shown on the ordinate and the differences  $\{TEC(TOPEX) - TEC(GPS)\}$  in [TECU] are shown on the abscissa. When interpreting these histograms it should be taken into account that, in these plots, a negative bias means that the estimated TEC with GPS ( $h < 20200$  km) is greater than the TOPEX TEC ( $h < 1300$  km). Then a positive bias means directly a mean underestimation of the TEC with GPS at least equal to the bias (the TOPEX accuracy seems to be 2 TECU).



**Figure 2:** TOPEX- vs GPS-TEC for the year 2000 (figure made at UPC).

2) DLR Fernerkundungsstation Neustrelitz has proposed to make a validation with ionosondes data: Ionosondes data provide information about the critical frequency  $f_0F_2$  of the  $F_2$ -layer. On the other hand the electron density  $N_mF_2$  is proportional to the square of the critical frequency  $N_mF_2 \sim (f_0F_2)^2$ . By using TEC values derived from the different IAAC TEC-models, equivalent slab thickness values  $TEC/N_mF_2$  could be computed. The equivalent slab thickness is a quite sensible indicator for the GPS-derived TEC-values, especially at low TEC-levels, having typically values of 200 - 400 km over daytime. Systematic studies could find out typical daily and seasonal variations of that parameter, e.g. higher daytime values in summer than in winter.

- 3) UPC proposed to compute TEC-values with the IRI model and to introduce these into the distinct IAAC models as “observables”. In this way it can be seen how good the different IAAC models are able to adapt to the IRI TEC surface. - The IRI would here be used simply as a pure mathematical reference.
- 4) ESA intends to use the different IAACs-models in ERS/Envisat orbit determinations and to analyze the order of orbit determination residuals resulting from the usage of the different IAACs-models.

## 4 SPECIAL ACTIVITIES

On the occasion of the solar eclipse on 11 August 1999 the Iono\_WG organized and coordinated a special observation campaign. This event was a unique opportunity to demonstrate the power of the GPS technique in monitoring the ionospheric ionization. As the zone of totality crossed Europe, the rather dense portion of the IGS network provided excellent conditions for monitoring the eclipse: ca. 60 IGS ground stations along the eclipse path from North America over Europe to the Middle East recorded on that day high-rate dual-frequency GPS-data (1 sec resp. 3 sec.). These solar eclipse data were archived at the Crustal Dynamics Data Information System (CDDIS) NASA/GSFC U.S.A. and can be accessed for analyses via *anonymous ftp* at *cddisa.gsfc.nasa.gov* in directory */gps/99eclipse* (Feltens and Noll, 1999).

The current solar maximum represents another unique chance to establish such a high-rate tracking database for ionosphere analyses. The two regions of major interest are in this case:

1. the polar regions and
2. low latitudes including the crest regions at both sides of the geomagnetic equator.

The “HIRAC/SolarMax” campaign was thus organized by the Iono\_WG and lasted from 23 - 29 April 2001. On 26 April a large solar flare was observed which impacted the ionosphere on 28 April. A list of the stations and a map can be accessed as pdf files via

[ftp://cddisa.gsfc.nasa.gov/pub/gps/01solarmax/solarmax\\_table.pdf](ftp://cddisa.gsfc.nasa.gov/pub/gps/01solarmax/solarmax_table.pdf)

[ftp://cddisa.gsfc.nasa.gov/pub/gps/01solarmax/solarmax\\_map.pdf](ftp://cddisa.gsfc.nasa.gov/pub/gps/01solarmax/solarmax_map.pdf)

This IGS activity were coordinated with other ionospheric observation programs or measurement campaigns using ionosondes, EISCAT, high resolution magnetometers, etc. to obtain a comprehensive view of the geomagnetic and ionospheric state. The high-rate GPS and GLO-NASS data are also archived at the CDDIS and are available through *anonymous ftp* at *cddisa.gsfc.nasa.gov* in directory */gps/01solarmax* (Feltens, Jakowski and Noll, 2001).

Similar campaigns are also planned for the future.

## 5 CONCLUSIONS AND LOOK INTO THE FUTURE

The IGS Ionosphere Working (Iono\_WG) commenced its activities in June 1998. Main task is the routine establishment and provision of ionosphere products using IGS global GPS tracking data. The worldwide IGS GPS and GLONASS ground stations network (about 180 sites) provides the unique opportunity for a global ionosphere monitoring on routine base. Currently five so called Ionosphere Associate Analysis Centers (IAACs) contribute to this routine processing. The individual IAACs ionosphere products are compared once per week at the Ionosphere Asso-

ciate Comparison Center (IACC) at ESOC. However, the comparison algorithm currently used is, with regard to the kind of weighting used, not optimal. - A new comparison program version with an improved weighting scheme, based on self-consistency test validations, is currently under testing and will be available soon. Once these software tests are completed, it is intended to start with the routine delivery of an official IGS ionosphere product.

The next important task will be a significant reduction of the time interval between the recording of the GPS observables and the delivery of ionosphere products derived from these GPS data; currently these are 11 days.

In the medium and long-term the Iono\_WG models shall be extended and improved, e. g. with regard to special models for certain regional and local areas, or at the IAACs the development of more complex mathematical ionosphere models. Final target should then be an independent IGS ionosphere model.

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