

**IGS**

**SESSION 11:  
GROUND-BASED NEUTRAL ATMOSPHERE  
AND IONOSPHERE SOUNDING**

## Session Description

Chairs: Y. Bar-Sever, M. Hernández-Pajares

The IGS tropospheric combination activity has been in transition this year. The Session will focus on the description and assessment of the new combination process, and on the operational challenges in deriving low-latency products. As always, the applications of the GPS ground-based tropospheric products need to be discussed in light of the ongoing work in climatology and data assimilation for weather forecasting. Finally, we would like to address the anticipated impact of Galileo on the estimation of trop delays, the combination process, and the possibility for new applications.

The ground-based GPS ionospheric sounding, due to the large number of available permanent stations and to the maturity of the present techniques, is now a reality. And it has important applications not just to the better understating of the Ionosphere and Space Weather mechanisms, but to practical aspects as well, such as in GNSS accurate positioning and navigation, and time transfer among others. This session will be focused to present and discuss different aspects in the context of the corresponding IGS activities, including the new and future official IGS ionospheric products, additional sources of validation, and the possibility of regional densification.

We invite Contributions concerning the above mentioned topics, as well as reports of technological advancements, new data-driven mapping functions, novel quality assessment campaigns, novel atmospheric products, and advancement in operational efficiency.

## Session Summary (Ionosphere Part)

M. Hernández-Pajares

In the session part dedicated to the IGS Ionosphere WG (IIWG) four invited presentations were performed on behalf four Ionosphere Associate Analysis Centers (IAACs), namely CODE, ESA, JPL and UPC, preceded by the IIWG position paper.

The opening of the ionosphere part was done by the IIWG chairman with the presentation of the position paper "IGS Ionosphere WG Status Report:

Performance of IGS Ionosphere TEC Maps". This paper summarized the present status of the IGS Ionosphere WG and the Final product. The first results of the IGS rapid ionospheric product were shown. Moreover alternative weighting schemes in the combination of IAAC TEC maps were discussed before concluding with some recommendations extracted from the splinter meeting, mostly concentrated on promoting the use of the ionosphere rapid product.

The first invited presentation entitled "GNSS Ionosphere Analysis at CODE" was conducted by Dr. Stefan Schaer. The CODE activities were summarized, showing, among other points, the Time Series of Global Mean TEC, the Exceptionally High TEC Levels due to X17.2 Solar Flare and the Combined GPS/GLONASS Ionosphere Analysis at CODE. Moreover, the P1-P2 DCB Values for GPS and GLONASS, an Overview of Ionosphere Products Generated at CODE and the Estimation of GNSS Satellite Antenna Phase Center Offsets and Patterns were reported as well. Finally Possible Future Developments were pointed out.

The second invited paper, "Usage of IGS TEC Maps to explain RF Link Degradations by Spread-F, observed on Cluster and other ESA Spacecraft", was presented by Dr. Joachim Feltens and co-workers. After an introduction

describing the RF link anomalies observed on the Cluster spacecraft in autumn and spring 2001-2003, they talked about the Characteristics Cluster Mission and the Observed phenomena. Afterwards they show the use of IGS TEC maps to find out whether the affected RF links passed through potential areas of Spread-F, including some significant examples. Finally the Operational consequences for Cluster and Possible consequences for future ESA spacecraft and missions were outlined.

In the third invited talk Dr. Brian Wilson and co-workers presented the "Global Ionospheric Data Assimilation & IGS Collaboration with Space Weather Programs". After enumerating the main Activities of the JPL Ionosphere Group, in the Space Weather Context, they show some examples of extreme VTEC values and plasma redistribution during the Large Geomagnetic Storm on Oct. 30, 2003. Other ionospheric phenomena with high variability such as plasmaspheric plumes and TIDs were briefly shown to the audience. In this context the need of Data Assimilation and GAIM, based on First Principles Physics Model were outlined. The remaining part of the presentation was mainly devoted to describing some main points of the GAIM research and techniques, and the Global Ground Observatory for Space Weather concept.

Finally the fourth invited work entitled "gAGE/ UPC GNSS Ionosphere Activities:

Real-time, Galileo, EGNOS and Tomography" was presented by Dr. Manuel Hernandez-Pajares and co-workers. It summarized the main activities of this IAAC, mainly focused on accurate wide area real-time ionospheric corrections with GPS (WARTK) and with Galileo (WARTK-3). Other activities such as EGNOS real-time ionospheric monitoring and GPS ionospheric tomography were briefly covered.



# IGS Ionosphere WG Status Report: Performance of IGS Ionosphere TEC Maps

Manuel Hernández-Pajares, on behalf of the IGS Ionosphere WG.  
Research group of Astronomy and Geomatics,  
Technical University of Catalonia (gAGE/UPC)  
Barcelona, Spain (e-mail: manuel@mat.upc.es)

## 1. Abstract

This paper is focused on summarizing the main activities of the IGS Ionosphere Working Group (Iono-WG) during the last year 2003. Firstly the consolidation of the IGS Global Total Electron Content maps (IGTEC) as a final Ionosphere IGS product will be shown. And secondly the performance of the first rapid IGTECs, which generation was started in testing mode in December 2003, will be discussed. Another recent achievement of the Iono-WG, such as the first IGTEC validations with ENVISAT TEC, among the future goals and corresponding tasks will be also summarized.

## 2. Introduction

The IGS Ionosphere Working Group (Iono-WG) was established by the IGS Governing Board on 28 May 1998 and commenced working in June 1998. The working group's main activity is at the moment the routine provision of IGS Global Total Electron Content (IGTEC) 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 (see Figure 1).

Currently five IGS Ionosphere Associate Analysis Centers (IAACs) contribute with their ionosphere products to the Iono-WG activities (CODE, ESA, JPL, NRCAN, and UPC, see correspondingly details of their techniques in Schaer 1999, Feltens 1998, Mannucci et al. 1998, Gao et al. 1994, Hernández-Pajares et al. 1999). Moreover there are four validation centers: ESA and JPL providing IGS TEC comparison with ENVISAT and JASON altimeters TEC, NRCAN and UPC providing weights in function of the IAAC maps quality reproducing GPS observations. Finally the final IGS TEC maps are computed and distributed from the combination center (UPC). Indeed, once per week these ionosphere products are compared with a dedicated comparison algorithm. This comparison/combination algorithm was worked out and coded in 1998 from scratch. In the meantime the original comparison/combination algorithm was upgraded with new weights computed from the results of external self-consistency validations (see Feltens 2002). The weekly comparisons are done with this new approach since August 2001. Furthermore, the IAACs TEC maps are routinely validated with TOPEX altimeter data since July 2001 and with JASON data since mid. 2003 (see general and detailed layouts in Figures 2 and 3, respectively). The official status of IGS final ionospheric product was obtained in the IGS Governing Board meeting held at Nice, April 2003, after the presentation of the combined TEC maps performance in a dedicated report (see Appendix).



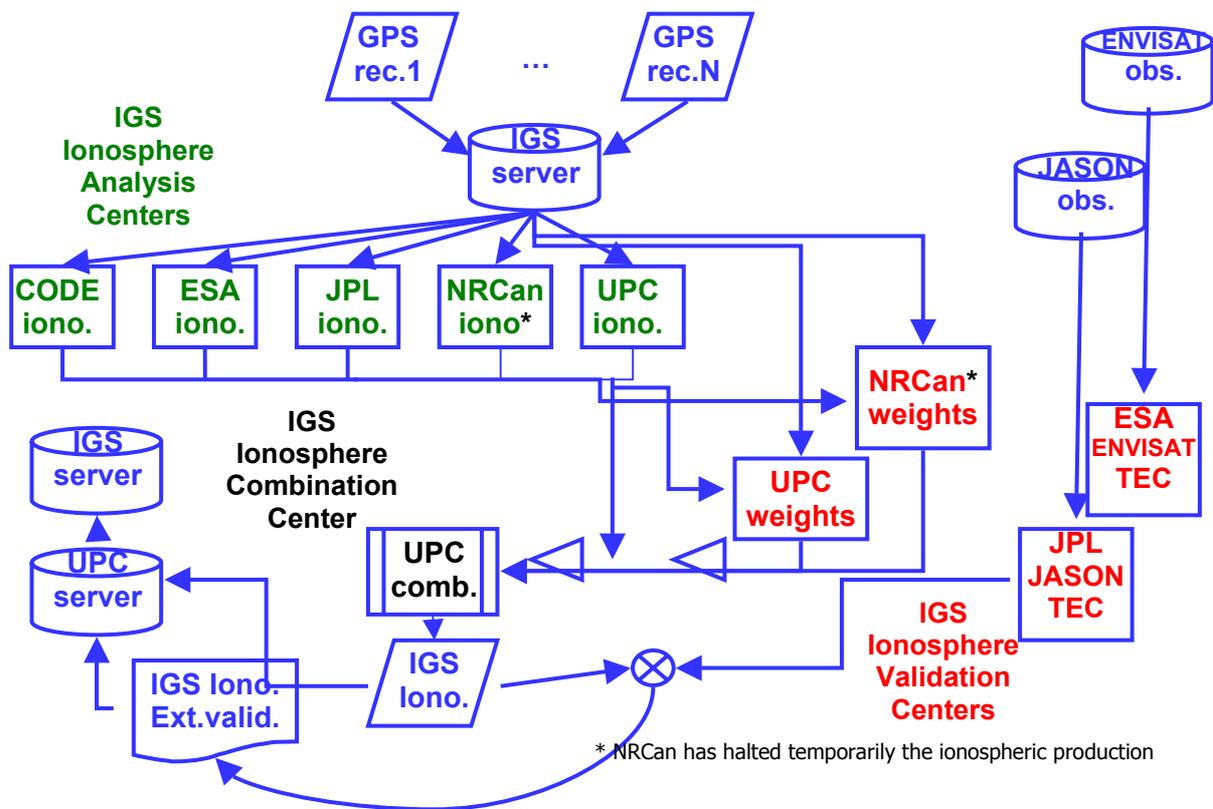


Figure 3: IGS Final Ionosphere flow chart detailing the previous layout.

The final IGS global maps, computed with a latency of about 11 days and with the resolution of 2 hours x 5 deg. x 2.5 deg. in UT x Longitude x Latitude, are stored in ionex format (Schaer et al., 1998<sup>1</sup>). They can be downloaded from the official server (CDDISA at GSFC/NASA<sup>2</sup>, being the IGS and IAAC ionex files stored in the corresponding year and day subdirectories) and or from the combination center server, presently UPC<sup>3</sup>. Please refer to the IGS Central Bureau server<sup>4</sup> in order to have more complete information of the different available products and the corresponding directories structure in the IGS servers, such as CDDIS and IGN.

The generation of a rapid IGS product (with an intended latency of less than 24 hours) have been started very recently in an initial testing phase (by using an automatic software coded from scratch), following the suggestion of the IGS GB during the meeting at Nice, in April 2003. The corresponding rapid combined global TEC maps (with the same resolution than the final ones, i.e. 2 hours x 5 deg. x 2.5 deg. in UT x Longitude x Latitude) can be accessed from the new unofficial rapid IGS server at UPC<sup>5</sup>. There

<sup>1</sup>Description available at <ftp://igsjb.jpl.nasa.gov/pub/data/format/ionex1.pdf>

<sup>2</sup><ftp://cddisa.gsfc.nasa.gov/gps/products/ionex/>

<sup>3</sup>[ftp://gage.upc.es/pub/gps\\_data/GPS\\_IONO/cmpcmb/](ftp://gage.upc.es/pub/gps_data/GPS_IONO/cmpcmb/) where the IGS ionex file is contained in the corresponding YYDOY subdirectory, being YY the year and DOY the day.

<sup>4</sup><http://igsjb.jpl.nasa.gov/components/prods.html>

<sup>5</sup>[ftp://gage152.upc.es/rapid\\_iono\\_igs/](ftp://gage152.upc.es/rapid_iono_igs/) please notice the corresponding rapid IGS ionex files igrgDOY0.YYi.Z, for year YY and day of year DOY, are stored in subdirectories for the year YEAR and day DOY.

are also additional information such as comparison with JASON TEC (performed presently with a latency of about 40 hours) and TEC movies. During the first month of generation of these preliminary rapid IGS maps, December 2003-January 2004, the combined product has been typically obtained by the noon (latencies of about 12 hours) with the two available ionosphere analysis centers (CODE and UPC). ESA and JPL made available its rapid products on a daily basis in January and February 2004, respectively (JPL made available its rapid product in a preliminary test performed during 5 days of December 2004 as well).

In this context the main purpose of this paper is to confirm the consolidation of the IGS Global Total Electron Content maps (IGTEC) as a final Ionosphere IGS product during the whole year 2003 (next section 2), and to show the performance of the first rapid IGTECs, which generation was started in testing mode in December 2003, with latencies less than 24 hours (section 3). Finally the first IGTEC validations with ENVISAT TEC, among the future goals and corresponding tasks, are going to be presented.

### **3. Final IGS Global TEC maps during 2003**

As it has been mentioned in the Introduction section, the final IGTEC are computed with a resolution of 2 hours in UT, 5 degrees in longitude and 2.5 degrees in latitude. You can find one typical example in Figure 4 (day 347 of 2003, 00UT), and another example, showing the global evolution during one day in Figure 5 (during the same day 347 of 2003, each 6 hours). At the same time the corresponding comparison with JASON TEC, used as a external source of direct vertical TEC measurements for validation, is provided in Figure 6.

Indeed, as it is well known the JASON dual-frequency altimeter provides a direct and independent VTEC below its orbit (1300 km) and over the oceans (worst case for GPS). In Figure 7 the overall performance of the IGTEC comparing its prediction with the JASON VTEC measurements is shown during practically one year of data (15-Dec-2002 to 13-Dec-2003), with more than 14,000,000 million of JASON observations compared. It can be seen than the IGS TEC (Std.Dev. 5.1 TECU) is slightly better or better than the IAACs TEC (Std.Dev. of 5.2, 5.3, 6.2, 8.1 TECU).

The temporal evolution of the performance of the IGS and IAACs “Relative Error” (RMS regarding to the JASON VTEC divided by the averaged JASON VTEC) is shown in Figure 8. It can be seen a typical daily relative error over the oceans of about 20% (15-25%). Sometimes large peaks appear coinciding with large geomagnetic storms, related to the present temporal resolution of 2 hours (see this effect in Figure 9, comparing such “Relative Error” with the Ap index evolution, such as the days 2003 302-304 geomagnetic superstorms).

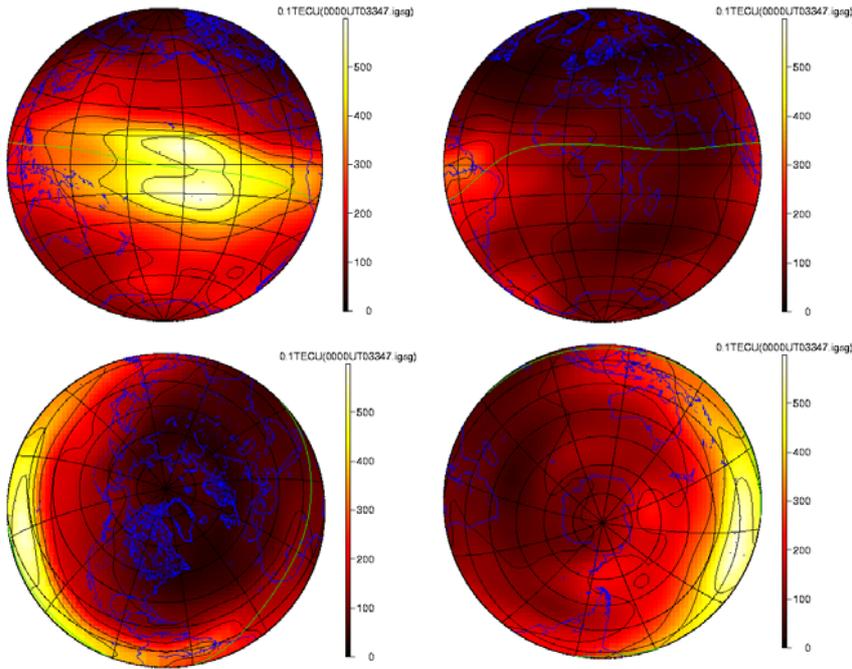


Figure 4: Example of final IGS TEC map, corresponding to day 347 of year 2003 (Lambert projection from the geomagnetic equator, first row, and from the geomagnetic poles, second row, with an scale running from 0 to 600 tenths of TECU).

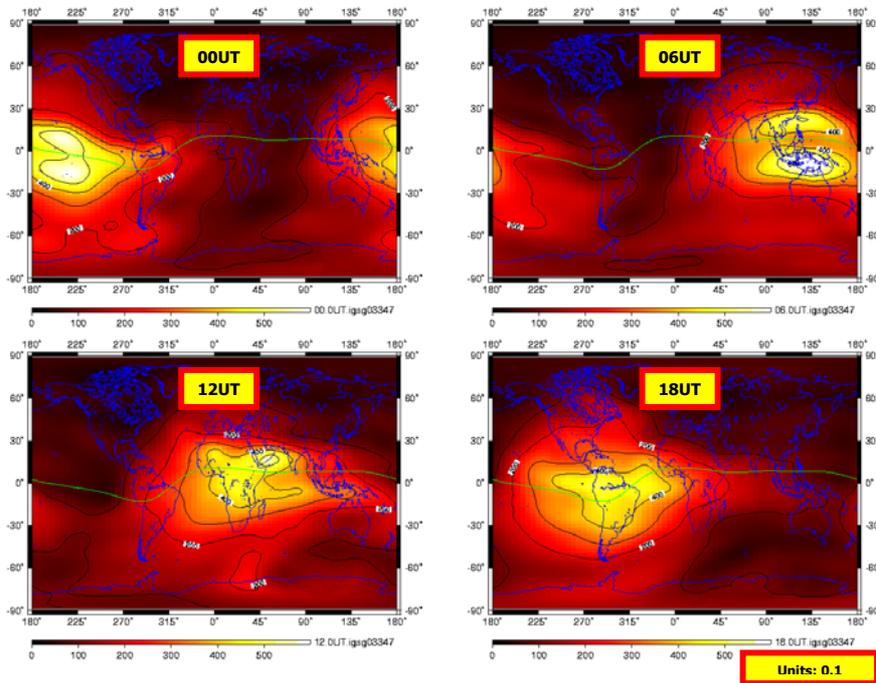


Figure 5: Example of IGS Final TEC for day 347 of 2003, shown each 6 hours.

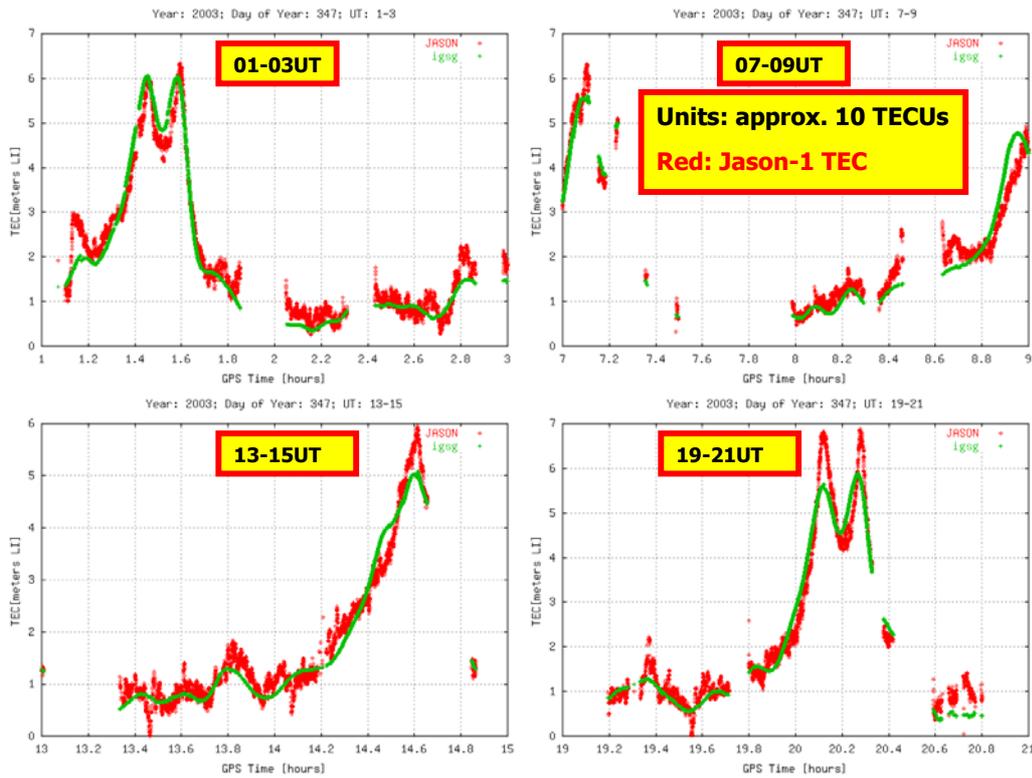


Figure 6: Example of comparison of IGS vs JASON TEC (day 347 of 2003, each 6 hours).

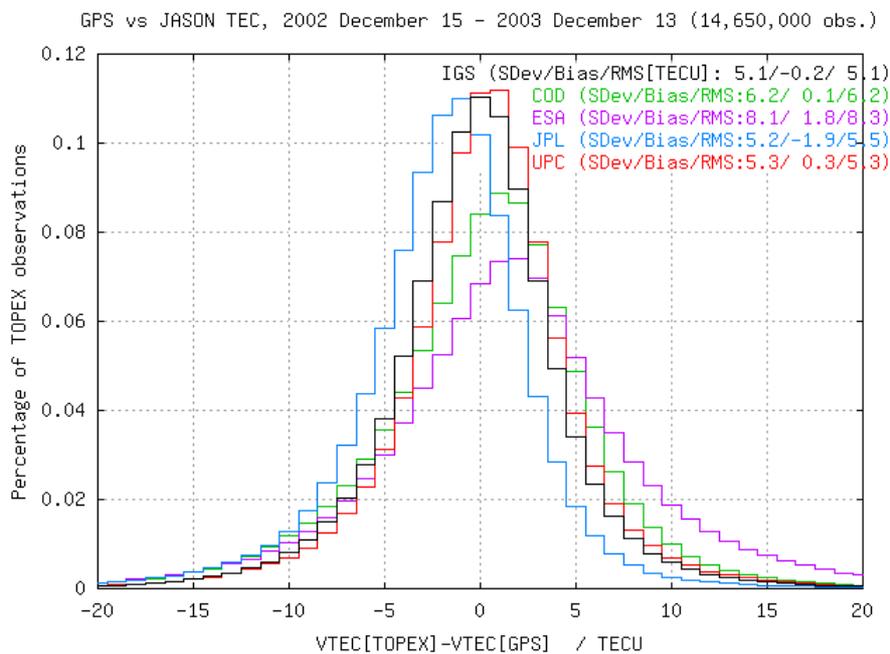


Figure 7: Final IGS TEC vs. JASON TEC in form of deviates histogram, comparing with the TEC performance of the different IAACs.

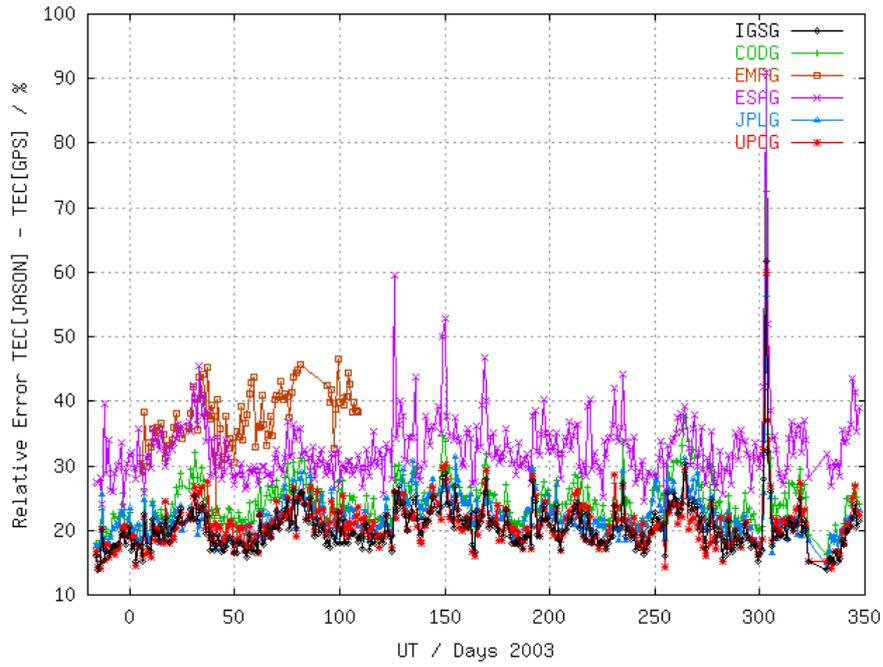


Figure 8: IGS TEC “Relative Error” vs. JASON (RMS normalized by the averaged TEC) during one year of data.

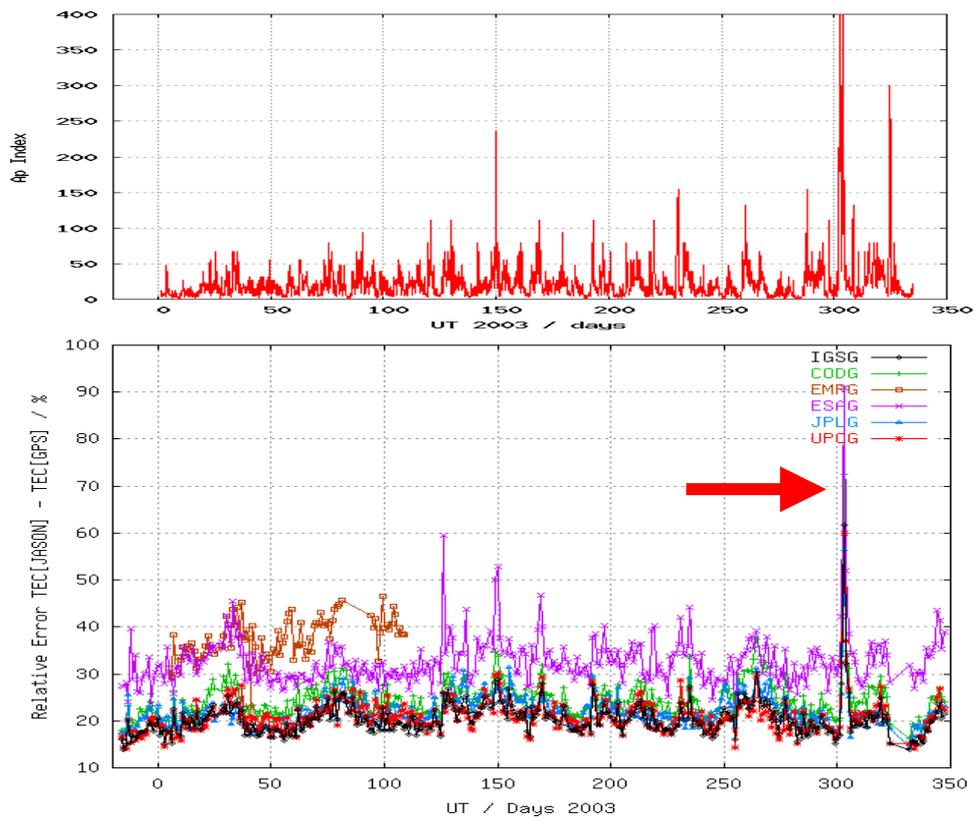


Figure 9: Ap index vs. “Relative Error” of the IGS and IAAC versus JASON TEC.

The performance dependence of the IGTEC regarding to the geomagnetic latitude is illustrated in Figures 10, 11 and 12. In Figure 10 the Standard Deviation of the JASON-IGS VTEC residuals is plotted showing that IGS presents a similar performance in the northern hemisphere compared to the best IAACs, slightly better performance at the equator, or slightly worst at southern latitudes. On the other hand the JASON-IGS TEC bias lower about 5 TECU around the equator (Figure 11) is compatible with the plasmaspheric component. The absolute bias reference is still unclear in JASON VTEC. Finally the IGS “Relative error” over the oceans is represented in Figure 12, which presents the following typical values:

- <15% at North mid and 20-25% at South mid latitudes.
- < 20% at ecuatorial latitudes.
- 20-30% at high latitudes.

Finally in this section, it is shown in Figure 13 the first comparison of IGS and IAACs TECs with ENVISAT TEC (Standard Deviation and Bias). It can be seen again the good performance of the combined final IGS product, as in the case of the previous altimeter comparisons with TOPEX and JASON. More performance details of the IGS final product (satellite and receiver DCBs, double dif. STEC, latency, with different data scarcity) and be found in the Iono-WG report (see Appendix).

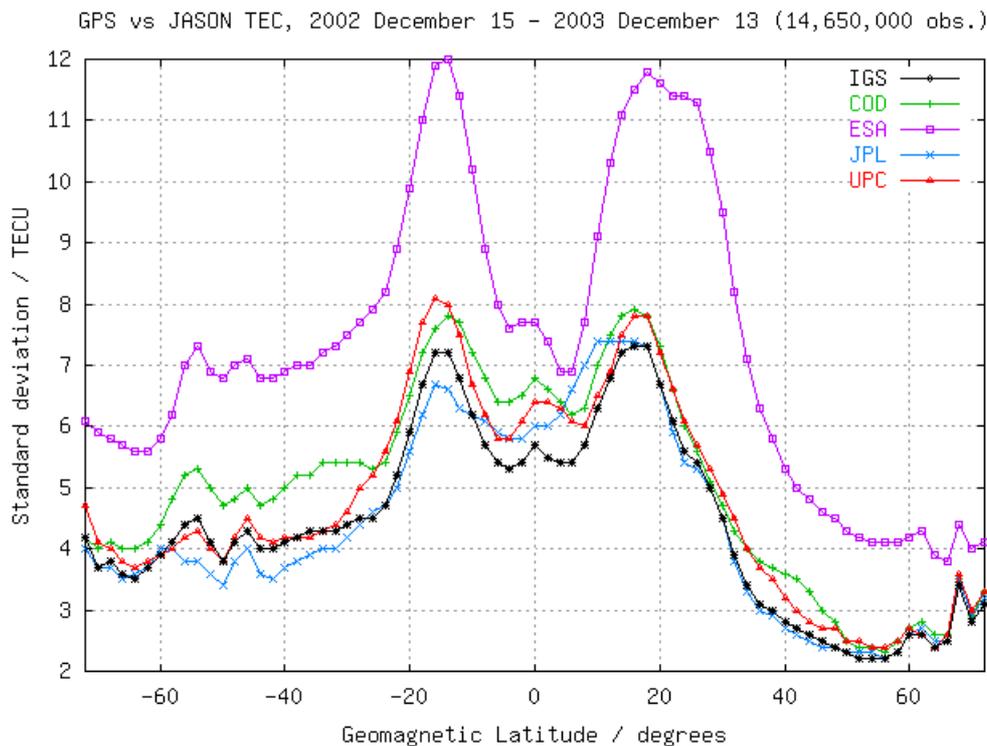


Figure 10: IGS TEC Standard Deviation vs. JASON TEC in terms of the geomagnetic latitude.

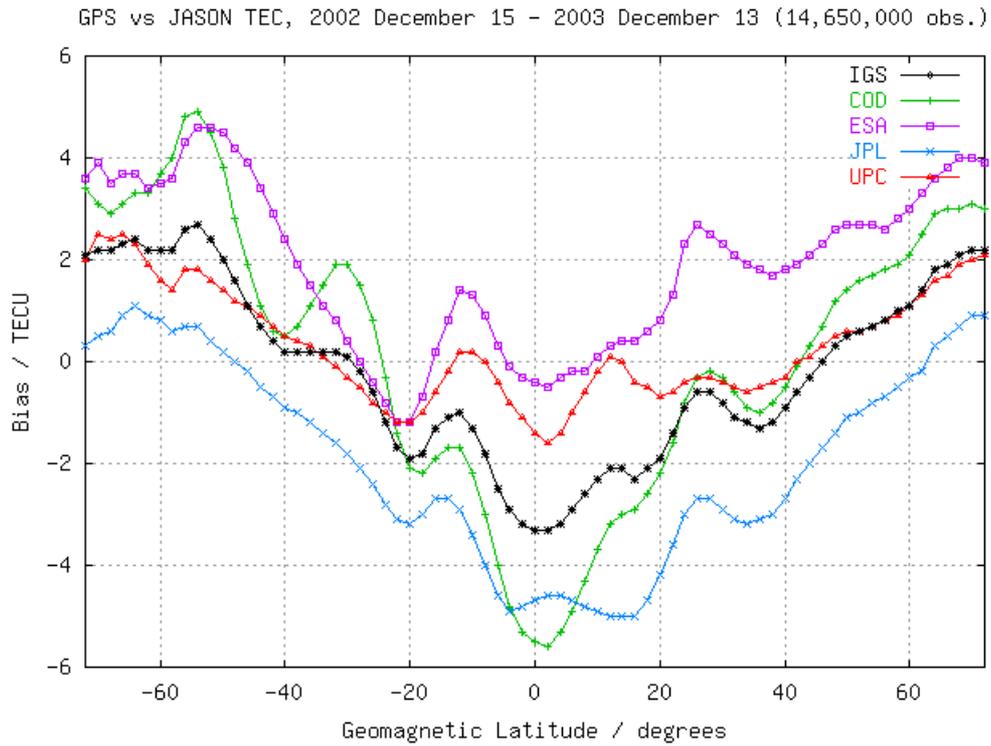


Figure 11: IGS TEC bias regarding to JASON TEC (*JASON-IGS*), represented as a function of the geomagnetic latitude.

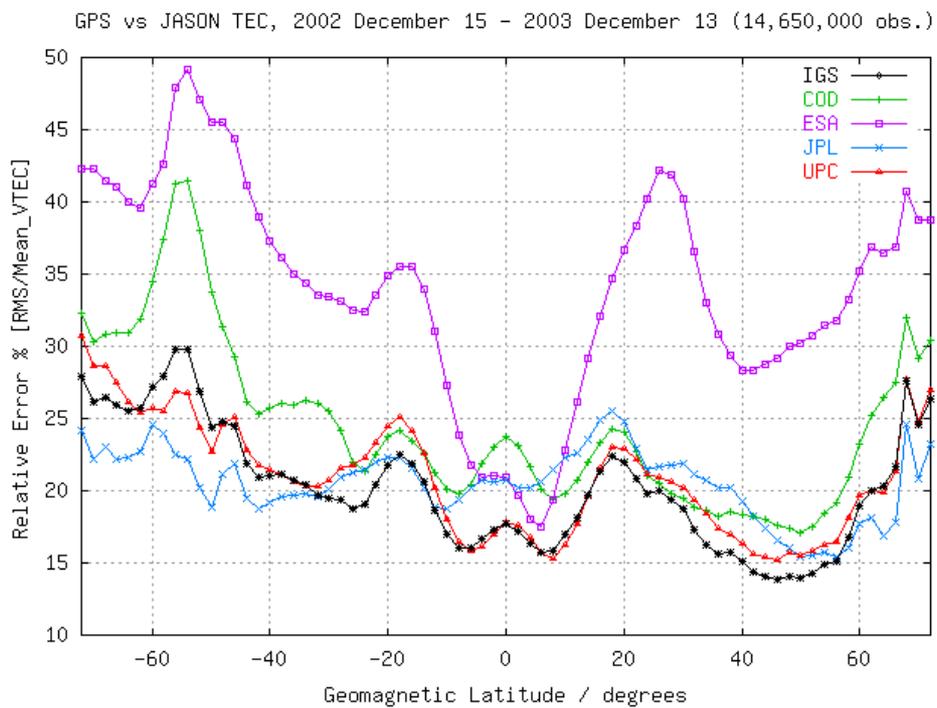


Figure 12: IGS TEC “Relative error” vs. JASON TEC plotted against the geomagnetic latitude.

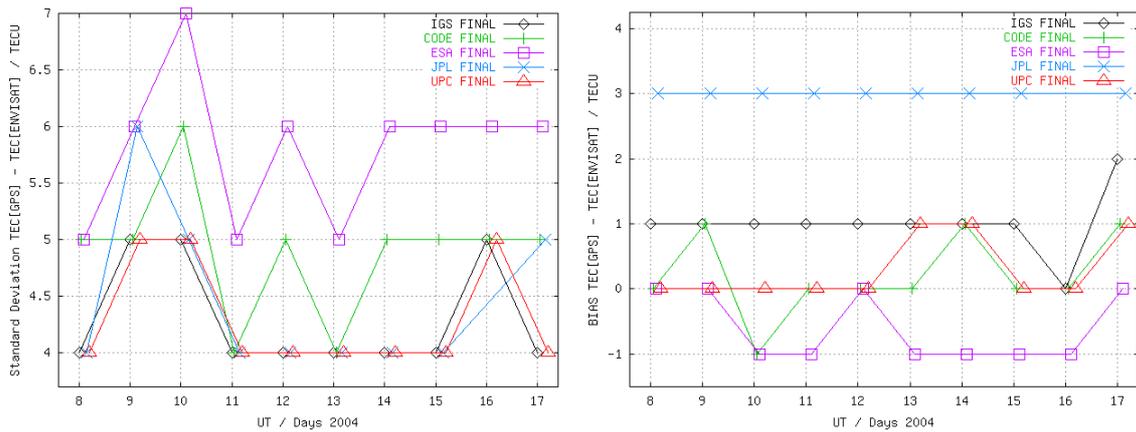


Figure 13: Standard Deviation and Bias regarding to ENVISAT TEC (8-17 January 2004).

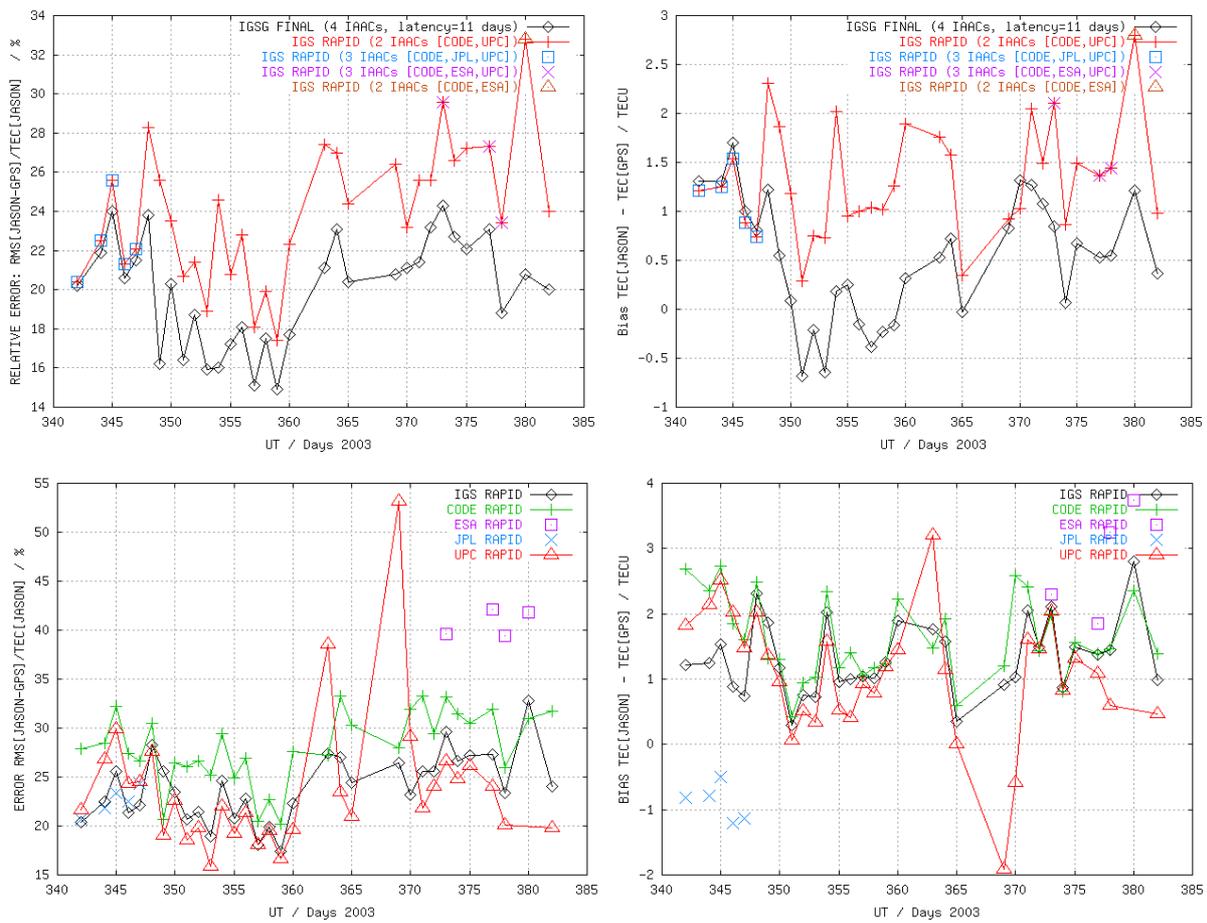


Figure 14: Rapid IGS TEC vs Final "relative error" and bias, compared with JASON TEC, from mid. December 2003 to mid. January 2004 (top hand plots). The same performance indicators are compared for the rapid IGS TEC vs. IAACs rapid TEC in the bottom plots (at left the relative error", at right the bias).

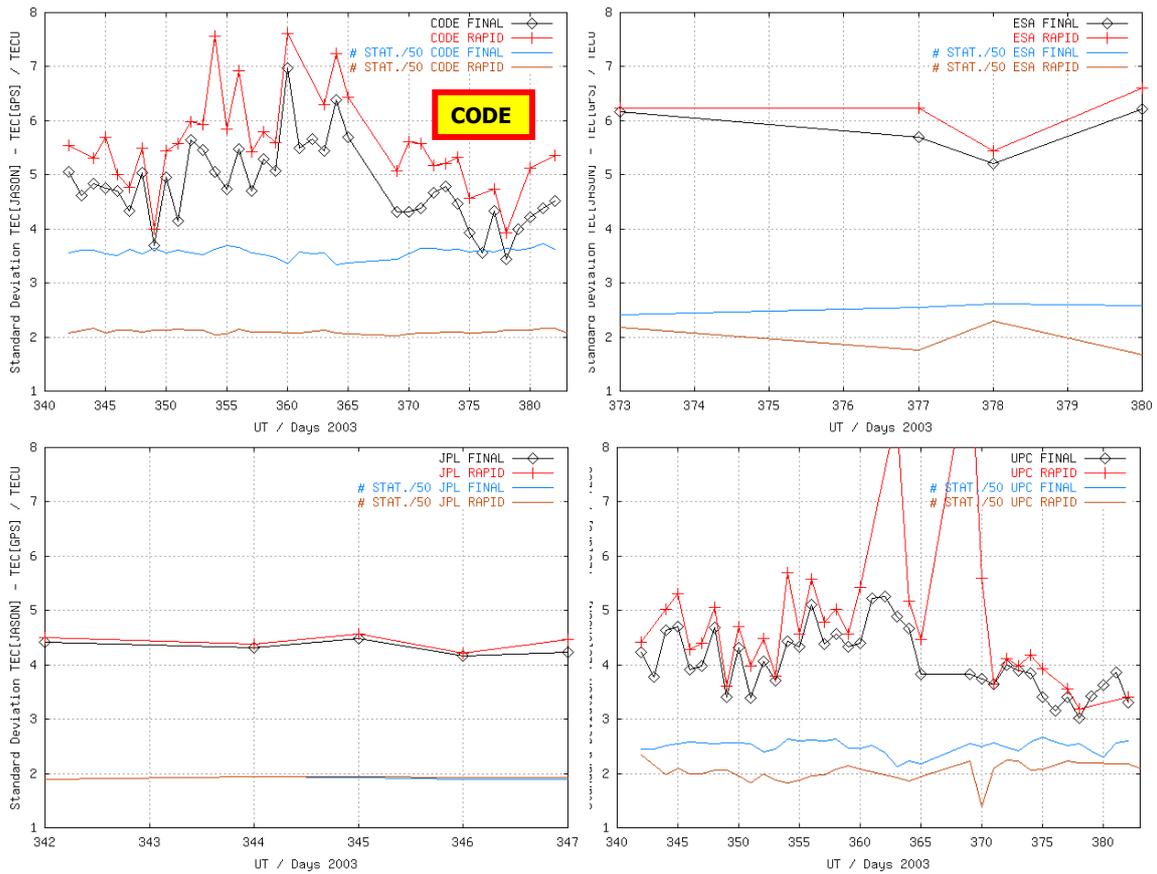


Figure 15: Std. Dev. vs. JASON and # GPS Stations.

#### 4. First results of the Rapid IGS Global TEC maps

As was mentioned in the Introduction section, the generation of rapid IGS TEC maps was started in testing mode in 8 December 2003. We are going to give the first performance results to 17 January 2004. Indeed during these 41 days it was possible to compute the rapid IGS product during 32 days (78% of availability) being the missing 9 days due to several reasons, such as power outages and lack of at least two rapid IAAC TEC maps. The typical latency has been of less than 15 hours during this first testing period.

Regarding to the TEC performance, you can see in Figure 13 (top-left hand plot) the rapid vs. final IGS TEC “Relative Error” compared with JASON TEC. The typical relative error over the oceans is of about 18-30% for the first 32 rapid IGS maps available (from December 03 to January 04) in front of 15-24% for the final IGS maps. Comparing both biases in Figure 13 (top-right hand plot), it can be seen that is - over the oceans - of about 0.5-2 TECU for the first 32 rapid IGS maps in front of -0.5-1.5 TECU for the final ones.

In order to give some additional light about these first performance results, the different rapid performances of the IAACs compared with IGS are represented in Figures 14 (bottom hand plots). The “Relative Error” is compared in Figure 14 (bottom-left hand plot), showing that the rapid IGS TEC presents accuracy close to the best IAAC TEC and maintains the integrity also under the occurrence of anomalous rapid IAAC maps (such in days 363 of 2003 and 4 of 2004). Such integrity and accuracy is

also maintained in the bias (Figure 14 bottom-right hand plot), provided by the weighting computation procedure (see Feltens 2002).

Finally in Figures 15 a first comparison between rapid and final performances are given for the four involved IAACs in the starting of the rapid product generation (CODE, ESA, JPL and UPC). The more meaningful comparison from the point of view of available TEC maps corresponds to CODE and UPC. In the case of CODE a worsening of typically about 1 TECU (or less) of the rapid regarding to the final TEC is obtained (about 20% of worsening), being the number of stations used less than the half (about 100 in front of 250). In UPC the worsening of the rapid product is typically less than 0.5 TECU (less than 10%) compared with the final product, with the exception of the two previously mentioned days (2003, 363 and 369) whose were affected by a bug in the rapid TEC map generation script of UPC, that was fixed afterwards.

## **5. Conclusions and Future work.**

After several improvements performed in the IAACs and IGS Ionosphere Map combination algorithms in 2003, the IGS final combination of TEC maps shows a good performance that is slightly better or even better than the individual IAAC maps that justified our efforts to start producing the final ionospheric product in April 2003. The rapid IGS TEC maps generation started, in testing mode, in December 2003. The first maps, mainly computed combining two available IAAC rapid TEC maps, show a good accuracy (about 10-15% worst than the final maps) with a latency less than 24 hours (as opposed to 11 days of the final product).

The future activities of the IGS Ionosphere WG<sup>6</sup> are going to be concentrated on:

1. Consolidating the Rapid IGS Ionosphere product, presently in testing phase, by incorporating four rapid IAAC TEC maps. In this way it will be possible to perform a more significant study of the TEC, including the Delay Code Biases performance study as well, during a period of time longer than the month available in the moment of writing this paper.
2. Augmenting the external data to be used for validation purposes: DORIS STEC data, provided by the International DORIS Service, and ENVISAT altimeter TEC provided by ESA, which first results have been presented as well in this work.
3. Studying further improvements of the weighting strategy.
4. Augmenting the temporal and spatial resolution of the IGS TEC maps.
5. Studying the generation of IGS 3D Ionosphere maps.

## **6. Some recommendations of the IGS Ionosphere WG (splinter meeting, 4-March-2004).**

The use of the final IGS product is quite large (154,000 IONEX files downloads in 2003, 68% from Non-IAAC users). However for the rapid product, started in Dec.2003, very few downloads are registered from the temporarily server at UPC. In this context to promote its use, the next actions items have been adopted:

---

<sup>6</sup> More details of the IGS Ionosphere WG activities, including download links, at [http://gage152.upc.es/~ionex3/igs\\_iono/igs\\_iono.html](http://gage152.upc.es/~ionex3/igs_iono/igs_iono.html)

- To send a new e-mail to the IGS e-mail list.
- Moving the igs-iono e-mailing list to igscb.
- Moving rapid product server from UPC to CDDISA.

After receiving inputs from VLBI, Altimeter and Timing users, it has been decided:

- To maintain the present generation of both final and rapid IGS TEC maps.
- To include the list of GPS receivers used for timing in the list of IAAC used stations to compute the ionospheric product, in order to ensure IGS DCB estimations for such receivers.

There was not consensus between the IAACs on increasing the temporal and spatial resolution of the present ionex files, including densification.

Finally it has been suggested in the session dealing with the final IGS considerations that the Ionosphere WG study the possibility of defining a procedure for ionospheric second order mitigation in accurate IGS positioning. This could be done in conjunction with other IAG ionospheric sub-commissions.

## **Acknowledgments**

The author acknowledges to the IAACs colleagues for their continuous support and help in the activities of the Iono-WG. This acknowledgment is extended to all the people and agencies which make possible the International GPS Service.

## **References**

- Feltens, J., 1998, Chapman Profile Approach for 3-d Global TEC Representation, IGS Presentation, in proceedings of the 1998 IGS Analysis Centers Workshop, ESOC, Darmstadt, Germany, February 9-11, 1998, pp 285-297.
- Feltens, J., IONO-WG Status Report and Outlook, position paper at the IGS meeting, Ottawa, Canada, 2002.
- Gao, Y., Heroux, P., and Kouba, J., Estimation of GPS Receiver and Satellite L1/L2 Signal Delay Biases Using Data from CACS, Proceedings of KIS-94, Banff, Canada, August 30 - September 2, 1994, pp. 109-117.
- Hernández-Pajares M., J.M. Juan und J. Sanz, New approaches in global ionospheric determination using ground GPS data, Journal of Atmospheric and Solar Terrestrial Physics, Vol 61, pp 1237-1247, 1999.
- Mannucci, A. J., B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqwister and T. F. Runge, 1998, A global mapping technique for GPS-derived ionospheric total electron content measurements, in Radio Science, Vol. 33, pp. 565-582, 1998.
- Schaer, S., W. Gurtner, J. Feltens, IONEX: The IONosphere Map EXchange Format Version 1, Proceedings of the IGS AC Workshop, Darmstadt, Germany, February 9-11, 1998.
- Schaer, S. (1999): 'Mapping and Predicting the Earth's Ionosphere Using the Global Positioning System', *Dissertation*, Astronomical Institute, University of Berne, Berne, Switzerland, 25 March 1999.

# APPENDIX: Performance of IGS Ionosphere TEC Maps

## IGS IONO WG Report

(Presented at the 22nd IGS Governing Board, Nice, April 6th 2003)

Manuel Hernández-Pajares,  
Research group of Astronomy and Geomatics,  
Technical University of Catalonia (gAGE/UPC), Barcelona, Spain

### 1. Introduction

The Ionosphere Working group started the routine generation of Ionosphere Vertical Total Electron Content (TEC) maps in June 1998. This has been the main activity so far performed by the five IGS Ionosphere Associate Analysis Centers (IAACs): CODE (Center for Orbit Determination in Europe, Astronomical Institute, University of Berne, Switzerland), ESOC (European Space Operations Center of ESA, Darmstadt, Germany), JPL (Jet Propulsion Laboratory, Pasadena, California, U.S.A), NRCan/EMR (Natural Resources Canada, Ottawa, Ontario, Canada) and UPC (Technical University of Catalonia, Barcelona, Spain).

The different IAAC TEC maps have been computed with different approaches but with a common formal resolution of 2 hours, 5 degrees and 2.5 degrees in UT, longitude and latitude (details can be found in e.g. Schaer 1999; Feltens, 1998; Mannucci et al., 1998; Gao et al., 1994; Hernandez-Pajares et al., 1999). The five IAACs TEC maps have been combined in an “unofficial” IGS combination product using weights obtained by two IGS Ionosphere Associate Validation Centers (IAVCs) from the corresponding performances in reproducing STEC and differences of STEC (IAVCs NRCAN and UPC respectively, see details in Feltens, 2002).

During a period of about 5 years of continuous IGS ionosphere operation, the techniques of the IAACs to obtain the TEC maps and the strategies of combination have both improved, in such a way that the combined IGS Ionosphere TEC maps are now significantly more accurate and robust (see details in Feltens 2002, 2003). The present performance is now excellent, in the opinion of the five IAACs, and so it is time to change the IGS TEC combined maps status to an official level.

In this context, the purpose of this report is to show the present performance of the combined IGS Ionosphere TEC maps, from December 15th, 2002 to March 15th, 2003, compared with the five IAACs maps, looking at:

1. Vertical TEC performance, comparing with independent estimates of TEC provided by the TOPEX altimeter. The comparison has been studied as a function of the time and of the geomagnetic latitude. The performance has been quantified over the oceans, i.e. in bad scenarios, because the TOPEX observations are typically far from the GPS sites used in the computation. Thus, it can be considered as a worst case estimate of the performance.
2. Effect of the distance from the GPS sites used to compute the maps, in the performance. We will illustrate this effect, by comparing the IGS maps with TOPEX TEC, in three areas with similar ionosphere features, and at different distances from the GPS sites.
3. Slant TEC performance (STEC), comparing predicted STEC variations with the very accurate values obtained from the direct geometric-free carrier phase observations, gathered in a well distributed subset of IGS receivers.

4. Measured vs. Formal TEC Standard Deviations.
5. Inter-frequency Delay Code Biases (DCBs) estimations of the GPS satellites.
6. Inter-frequency Delay Code Biases (DCBs) estimations for available IGS GPS sites.
7. Latency in the distribution of the combined product, computed in this case since 1999.

## 2. Vertical TEC performance from the comparison with TOPEX TEC

As it is well known in different works in the literature, the direct observations of Vertical TEC provided by the TOPEX dual-frequency altimeter since 1992 provide a valuable source of independent estimates for GPS TEC maps. These TOPEX TEC estimates are affected by an uncertainty of few TECU, and are available over the areas in which the altimeter can work, namely the oceans and seas (see for instance Ho et al 1995, Orús et al. 2002). This is another interesting aspect from the point of view of validating GPS TEC maps, because it is in these regions where, many times, there are less available GPS sites, if any. Then this comparison in a difficult scenario provides a lower boundary for the GPS TEC performance.

The comparison has been performed with the combined IGS and IAACs maps, from December 15th, 2002 to March 15th, 2003, with about 2,500,000 TOPEX observations. A general overview of this study can be seen in the histograms and Standard Deviation and Biases values, represented in Figure 1. The global performance of the IGS combined product is equivalent (in fact, slightly better) to the best IAACs performance. The details of the global trend can be better appreciated in the zoom of the left hand plot, in Figure 2. And in the corresponding right hand plot, it can be seen that IGS presents the lowest extreme residuals, or outliers.

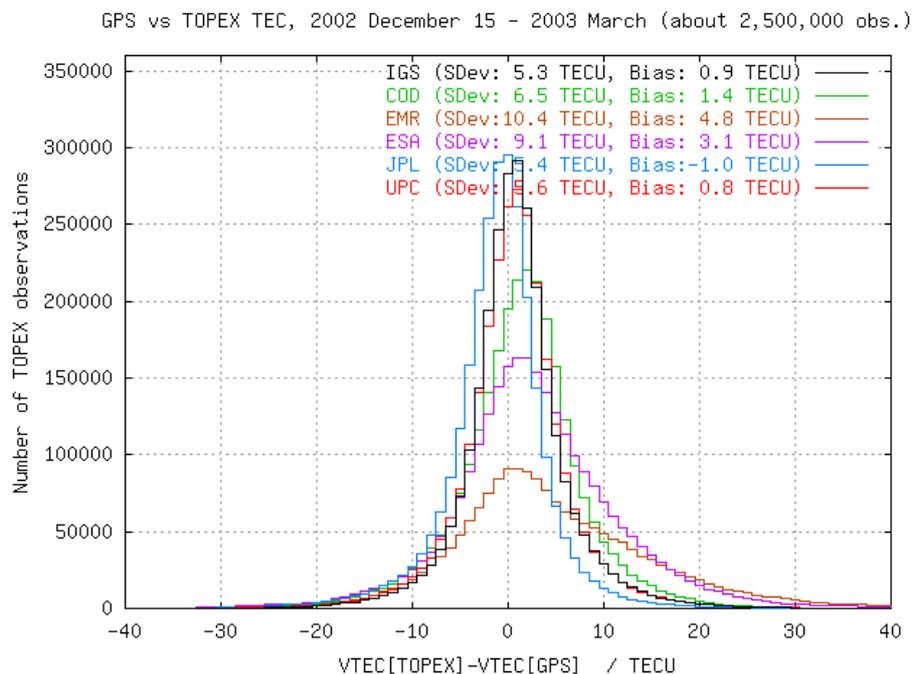


Figure 1: Histogram representing the distribution of IGS and IAAC TEC discrepancies with the TOPEX TEC, during the period 2002 December 15 to 2003 March 15, with about 2,500,000 TOPEX observations.

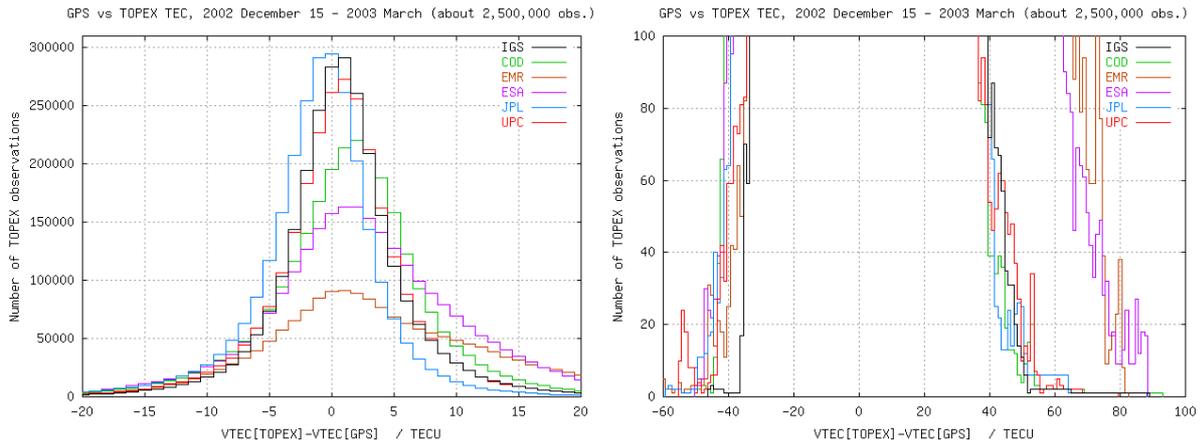


Figure 2: Details of the histograms represented in Figure 1: left plot represents a zoom of general trend; right plot represent a zoom of the extreme values, or outliers.

On the other hand, in Figure 3, the standard deviation of the discrepancies of the GPS maps relative to TOPEX is shown as a function of the geomagnetic latitude. The standard deviation of the IGS maps is typically similar to the best IAAC (northern hemisphere, 3-9 TECU), sometimes slightly better (equator, about 6 TECU), sometimes slightly worse (Southern Hemisphere, 4-6 TECU).

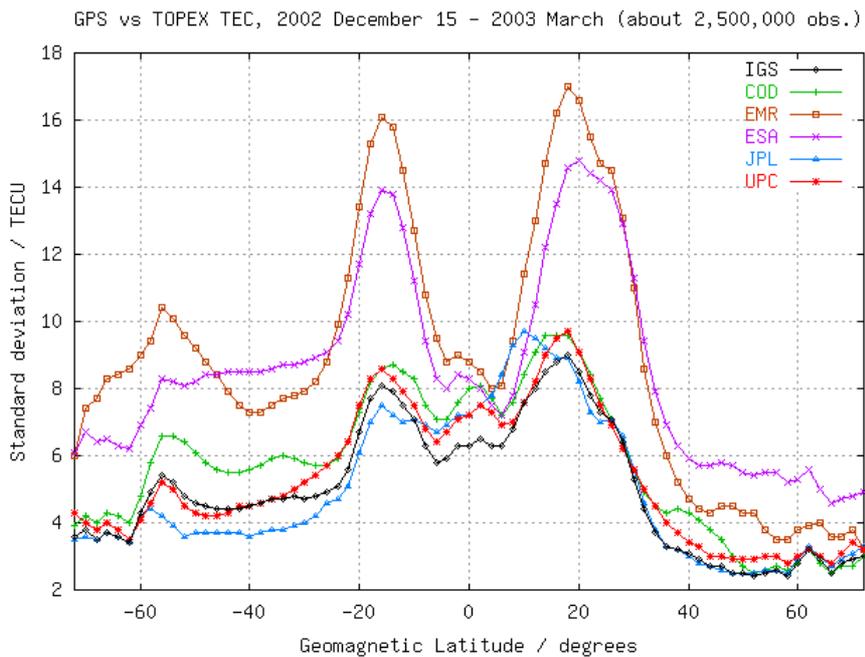


Figure 3: Standard Deviation of the difference between TOPEX TEC and GPS TEC as a function of the geomagnetic latitude for the Combined Ionosphere IGS and IAACs maps (2002 Dec. 15th - 2003 March 15th, 2,500,000 TOPEX observations).

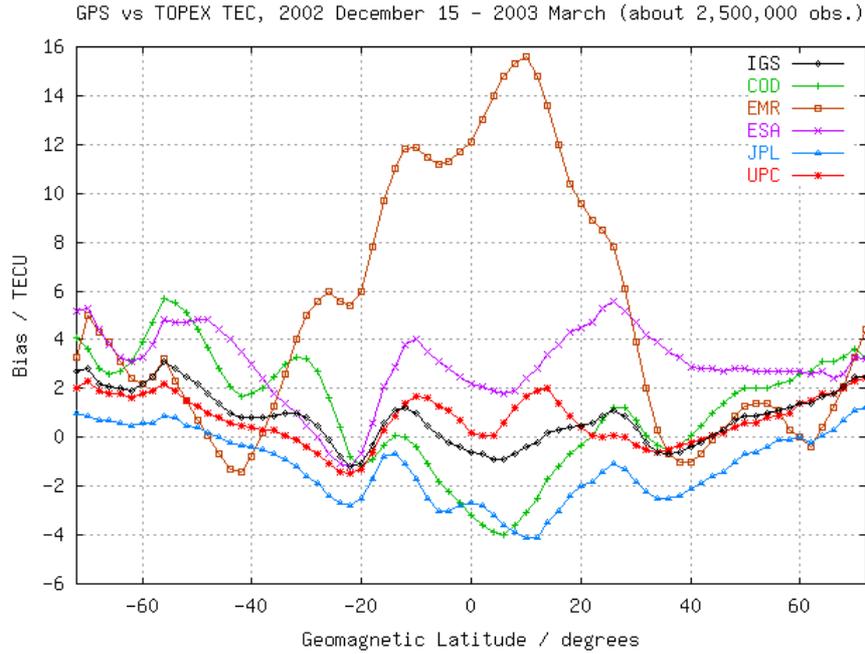


Figure 4: Bias of the difference TOPEX-GPS TEC as a function of the geomagnetic latitude for the Combined Ionosphere IGS and IAACs maps (2002 Dec. 15th - 2003 March 15th, 2,500,000 TOPEX observations).

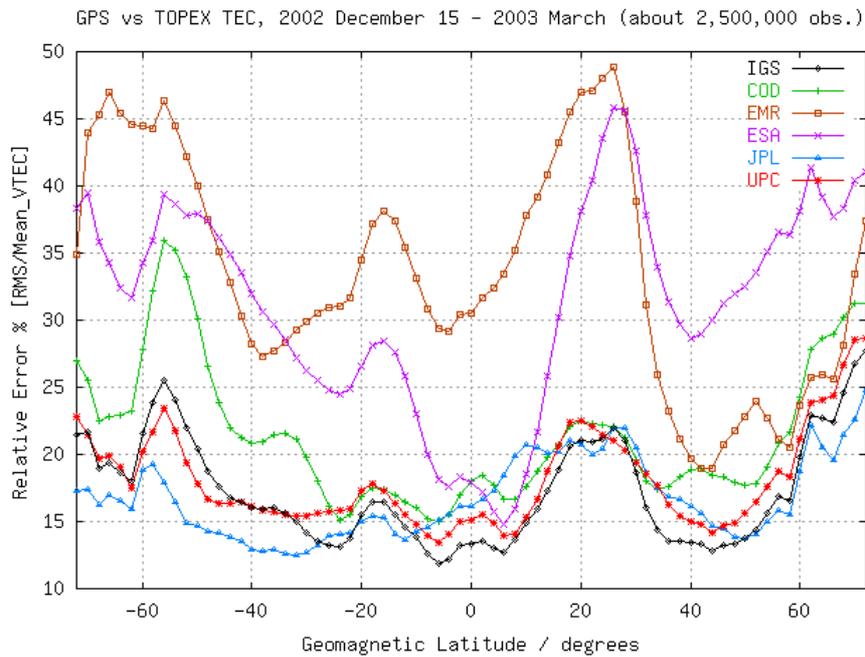


Figure 5: Percentage of "Relative Error" (defined as  $RMS \cdot 100 / \text{Mean Vertical TEC}$ ) of the GPS TEC maps regarding to TOPEX, as a function of the geomagnetic (2002 Dec. 15th - 2003 March 15th, 2,500,000 TOPEX observations).

Figure 4 shows the corresponding bias (TOPEX-GPS) in terms of the geomagnetic latitude. It can be seen that the IGS bias performance is not bad, because: (1) It decreases 2-3 TECU at the equator, and this change is compatible with the upper plasmaspheric electron content not measured by the TOPEX altimeter (see for instance Orús et al. 2002). And (2), at high latitude, in which the plasmaspheric content should be negligible, the values provided by the IGS maps can be considered zero at the level of the TOPEX error of few TECU.

To conclude the comparison in terms of the geomagnetic latitude, in Figure 5 shows the GPS TEC maps “relative error” percentage, defined as the ratio between the RMS and the mean TEC in each bin. It reproduces, qualitatively, the relative performance previously commented on for the standard deviation. In general the relative error during this period, end of 2002 and beginning of 2003, and over the oceans, is about 13% at Northern Mid-Latitudes, 13-17% at Southern Mid-Latitudes, reaching more than 20% in the Northern Ionosphere Anomaly. At high latitudes the relative error reaches 20% or more as well.

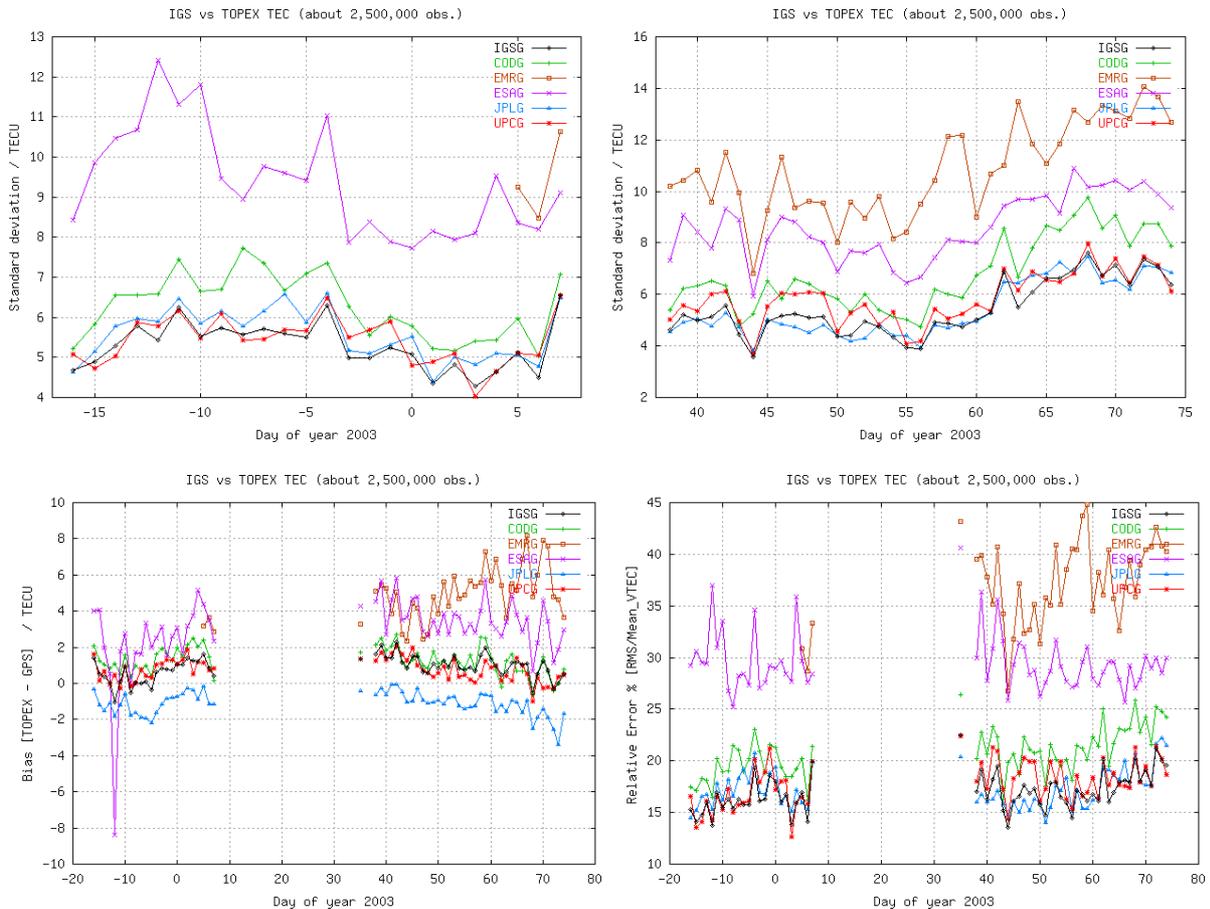


Figure 6: Evolution of the Ionosphere GPS Standard Deviation regarding to the available TOPEX data (top upper plots), and the corresponding biases (TOPEX-GPS) and “relative errors” (bottom left and right plots, respectively).

On the other hand the daily evolution of the discrepancies with TOPEX TEC in the studied period is shown in the plots included in Figure 6. In the two top plots, the Standard Deviation values for the days with available TOPEX data show again, now in terms of time, the good performance of the combined IGS products, which typically present a similar performance to the best daily IAACs. In the two bottom

plots, the bias and relative error are shown, confirming the IGS bias trend of 0-2 TECU (compatible with the TOPEX error), and a daily error around 17% (from 13 to 22%).

### 3. Effect of the distance to the GPS sites in the performance.

In order to study the performance of the IGS TEC maps, regarding the increase of distance between the considered Ionosphere Pierce Points (IPPs) and the nearest used GPS sites, three areas at the same geomagnetic latitude (+43 degrees) have been selected with increasing distances:

1. “Close” area to IGS GPS receivers, corresponding to the Mediterranean Sea (green rectangle in Figure 7), which is surrounded by several IGS sites.
2. “Medium” distance region in the Atlantic Ocean close to the South of Portugal. It presents few GPS sites around.
3. “Far” region, in the center of the Atlantic Ocean (black region), quite isolated.

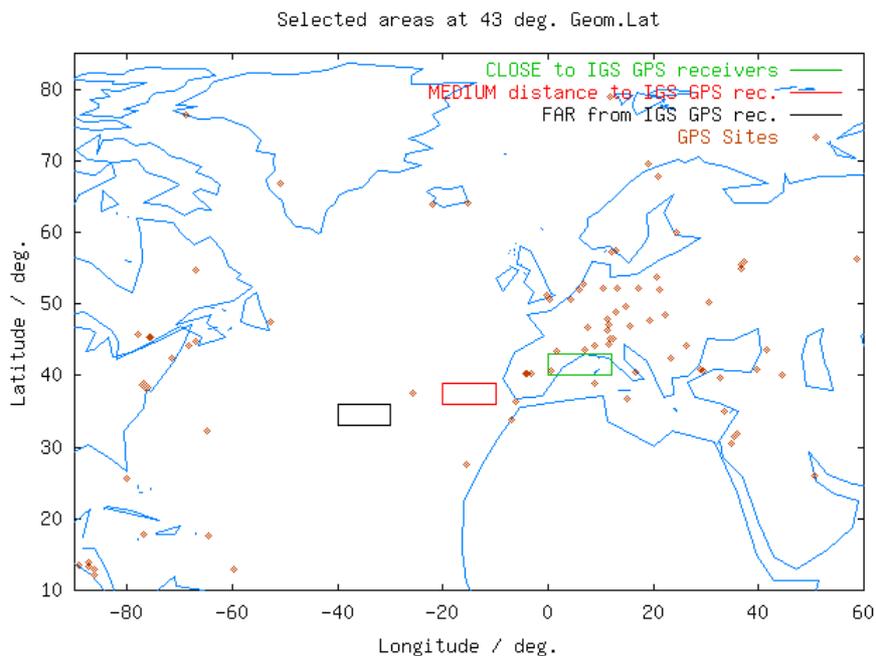


Figure 7: Map representing the three regions considered to illustrate the IGS performance versus the distance to the GPS sites used in the computations.

In Figure 8 (and, with more detail, in Figure 9) the three corresponding histograms (“close”, “medium” and “far”) of the differences between IGS and TOPEX TEC are presented. It can be seen that the performance degradation (from 10 to 12% of relative error) is significantly smaller than that corresponding to the IAACs (Figure 8).

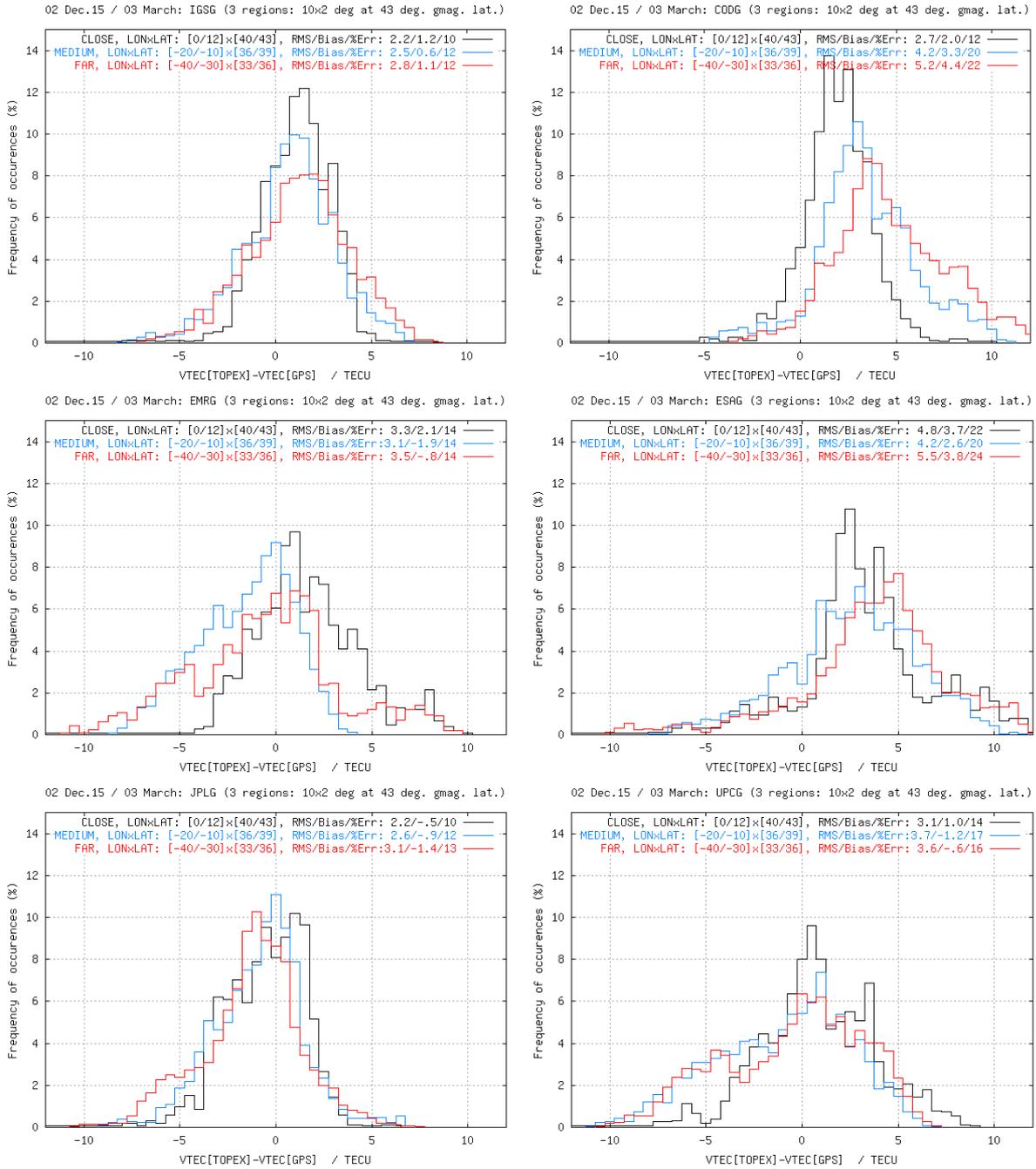


Figure 8: Histograms representing the discrepancies between the GPS and TOPEX TEC in the three considered regions (“Close”, “Medium” and “Far”) for IGS, CODE (first row), EMR, ESA (second row), JPL and UPC (last row).

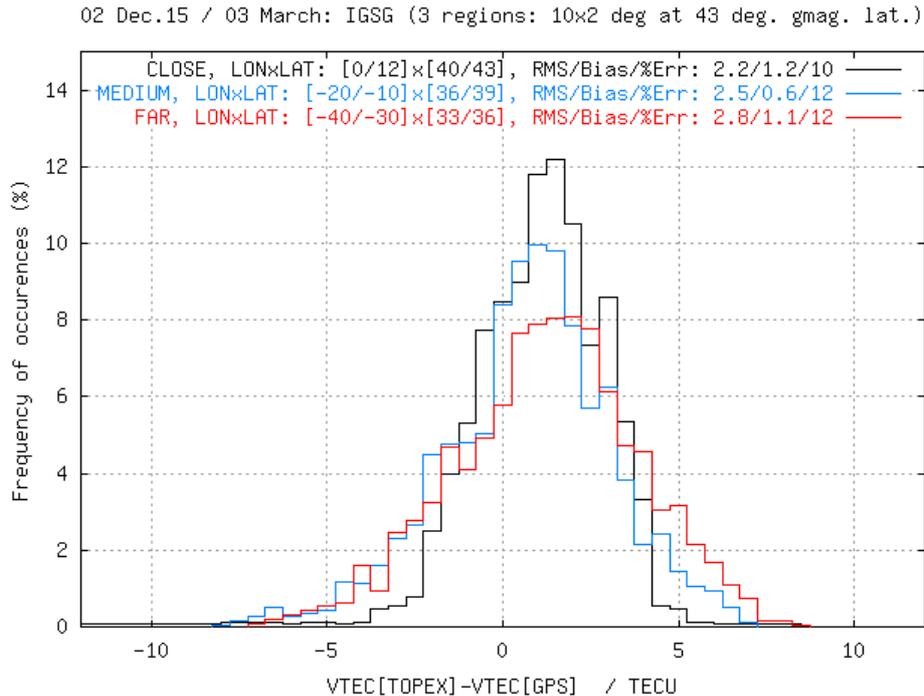


Figure 9: Figure representing a zoom of the IGS histogram of previous Figure 8.

#### 4. Slant TEC performance by comparing with GPS observations.

In the previous section, a detailed study of the Vertical TEC performance of the combined IGS maps have been presented, by comparing with external TEC data coming from the TOPEX altimeter, gathered over the oceans. In this section we are going to illustrate the performance of the IGS maps reproducing STEC variations at the same elevation, for several IGS receivers distributed worldwide. These reference values are very accurately observed by using the geometric-free carrier phase combination. Although part of these reference GPS data have been used by some IAACs to build their maps, the comparison provides information about how the combined maps respond to this “Self-Consistency” Test. This same “residual” test is used to compute the IAACs weights for the combination of the IAAC maps into the IGS product, but applied on a different set of stations.

In the plots of Figure 10, the RMS of the differences between the observed and modeled STEC variations are shown for 6 representative IGS stations, at different geomagnetic latitudes in both hemispheres, and during the three consecutive months of the studied period. It can be seen that in the STEC domain, the IGS maps show good performance as well, typically at the level of the best IAAC.

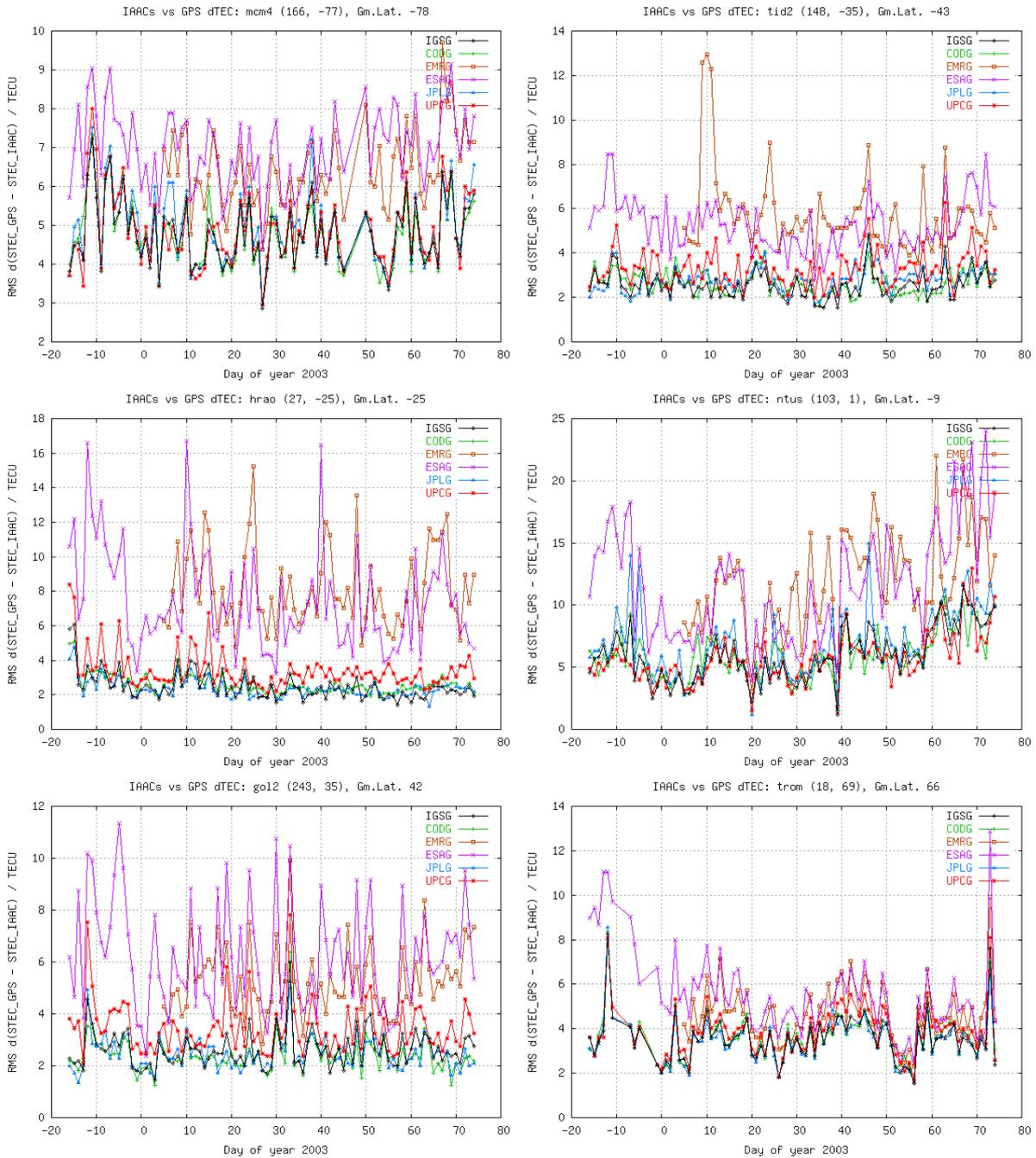


Figure 10: Plots showing the evolution of the IGS and IAAC map error reproducing STEC variations between two points of the same GPS carrier phase (“Self-Consistency” test), for a set of representative IGS stations. From left to right, from top to bottom: mcm4, tid2, hrao, ntus, go12 and trom, at geomagnetic latitudes of  $-78$ ,  $-43$ ,  $-25$ ,  $-9$ ,  $42$  and  $66$  degrees, respectively). The GPS maps are: IGS in black, CODE in green, EMR in brown, ESA in magenta, JPL in blue and UPC in red.

## 5. Measured vs. Formal Standard Deviations.

Another aspect that has been inspected is the relationship between the formal Standard Deviation estimates in the IGS Ionosphere Maps and the corresponding RMS of the corresponding predictions relative to TOPEX TEC observations. This study is summarized in Figure 11, where the IGS measured and formal errors show an approximately linear relationship, about 150% greater for the most part of the observations, and about 75% greater for the outliers.

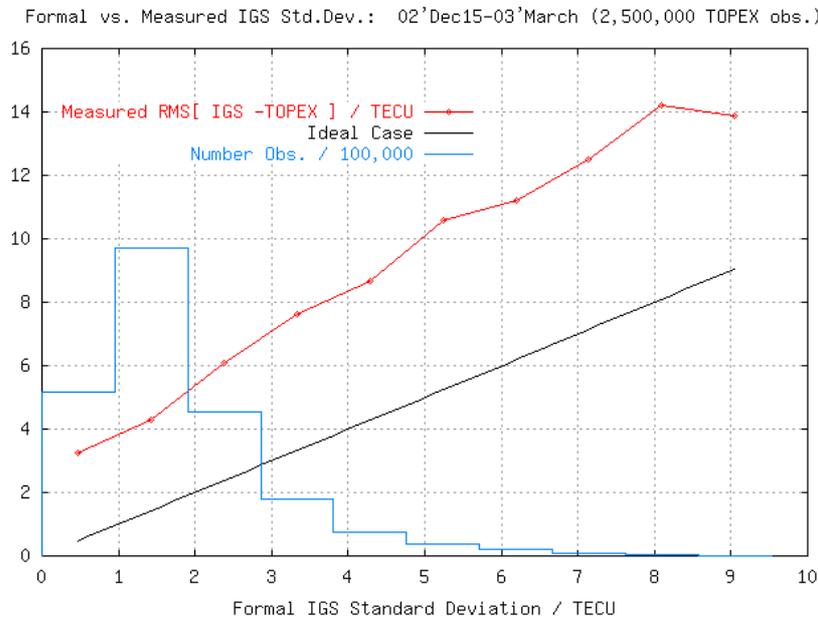


Figure 11: Plots showing for the IGS Ionosphere maps, the measured RMS regarding to TOPEX versus the formal errors, during the period 2002 December 15 to 2003 March 15.

## 6. Satellite Delay Code Biases estimation.

The mean Satellite Delay Code Biases, and the Standard Deviation of its variation during the 3 month period, are shown in Figure 12 for the IGS Ionosphere product and the five IAACs. It can be seen that both the mean values and small variability (at the level of 0.1 ns) are in agreement with the most stable values provided by the IAACs. This is also fulfilled in the particular case of the new satellite PRN16.

## 7. Delay Code Bias estimation of available IGS Receivers.

Even though the satellite DCB estimates are stable, this does not necessarily imply that the estimates of the total DCB, including the receiver DCB, will also be good. This is due to the fact that the different strategies adopted by the IAACs range from practically “freezing” the satellite DCBs as unknowns that vary slowly, to estimating them, along with the TEC, as a white noise process. In this context, the DCBs for the IGS stations estimated for 4 IAACs (ESA does not provide such values for now) are shown for the IGS product and the IAACs in Figure 13. Again, this time for the receivers, the IGS DCBs are quite stable, below 1 ns, with the exception of the CHUR receiver, as a result of the corresponding lack of stability of all the IAACs during this day. This abnormal case corresponds to a sudden change of the DCB of this receiver during the day 035 of 2003, as can be seen in Figure 14.

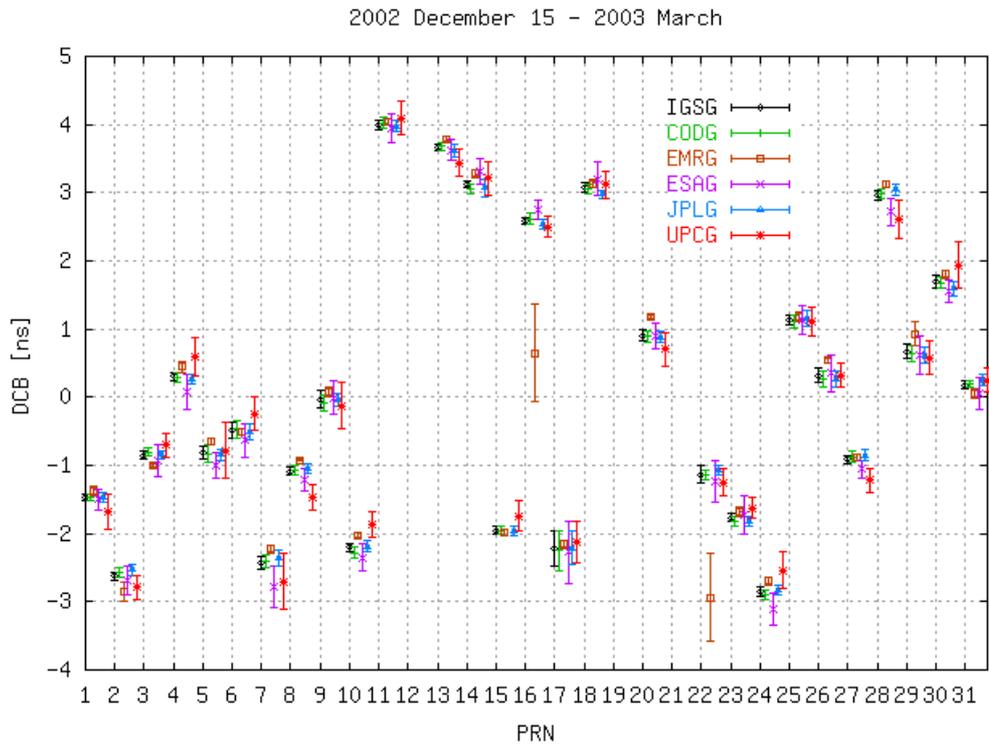


Figure 12: Inter-frequency Delay Code Biases (ns) for the GPS satellites: IGS in black, CODE in green, EMR in brown, ESA in magenta, JPL in blue and UPC in red.

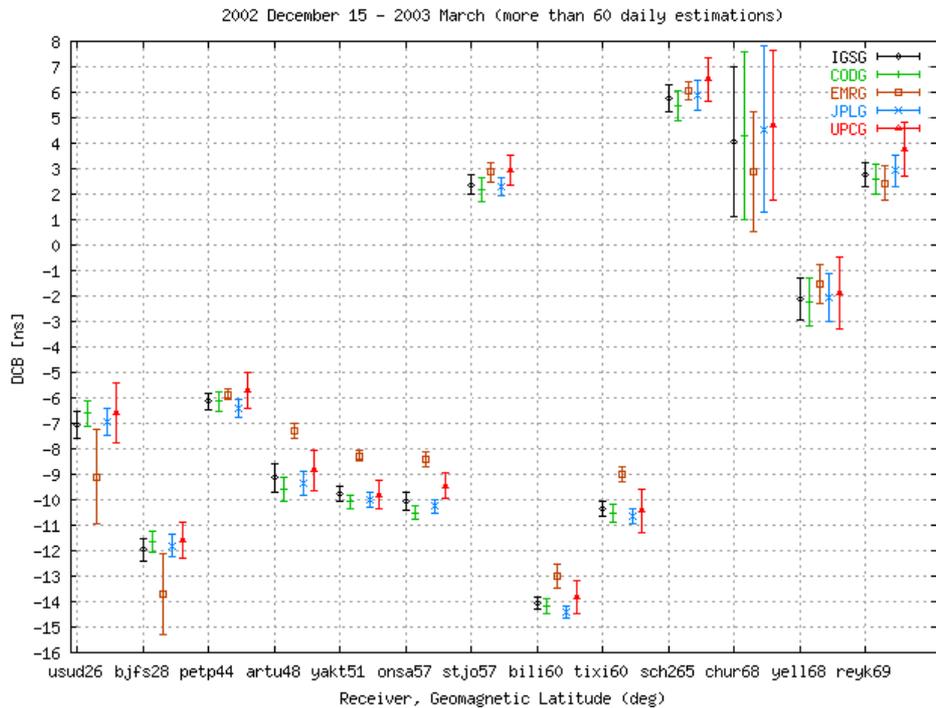


Figure 13: Inter-frequency Delay Code Biases (ns) for the IGS receivers estimated in common by the IAACs providing such values during 60 days or more of the three months period: IGS in black, CODE in green, EMR in brown, JPL in blue and UPC in red.

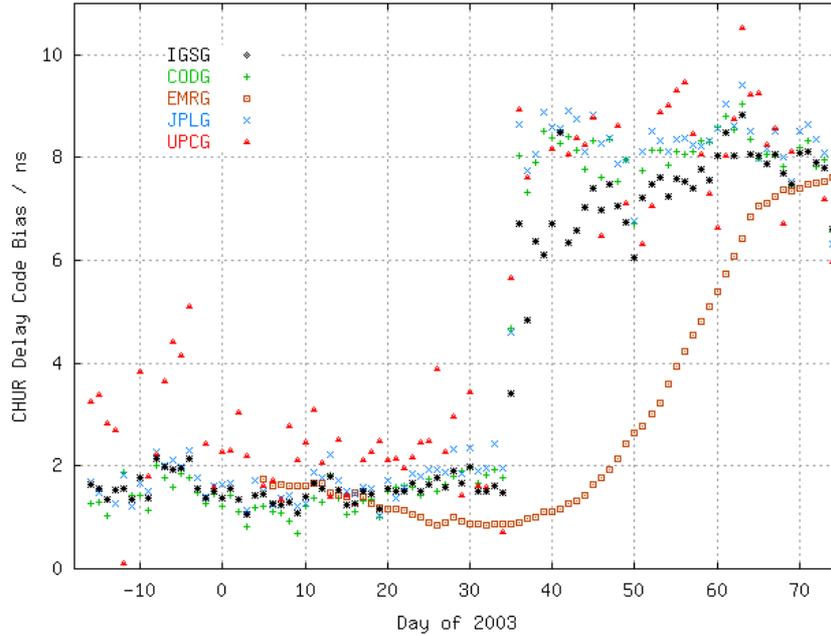


Figure 14: Inter-frequency Delay Code Bias evolution for receiver CHUR.

### 8. Latency of the combined IGS product distribution

Finally, we consider the latency of the combined IGS product that has been unofficially distributed (one whole week each time), defined as the elapsed days since the last day processed of the distributed GPS week. In Figure 15 a histogram depicts the frequency for 162 weeks between the end of 1999 to March 2003. In more than 80% of the cases, the latency has been 12 or less days.

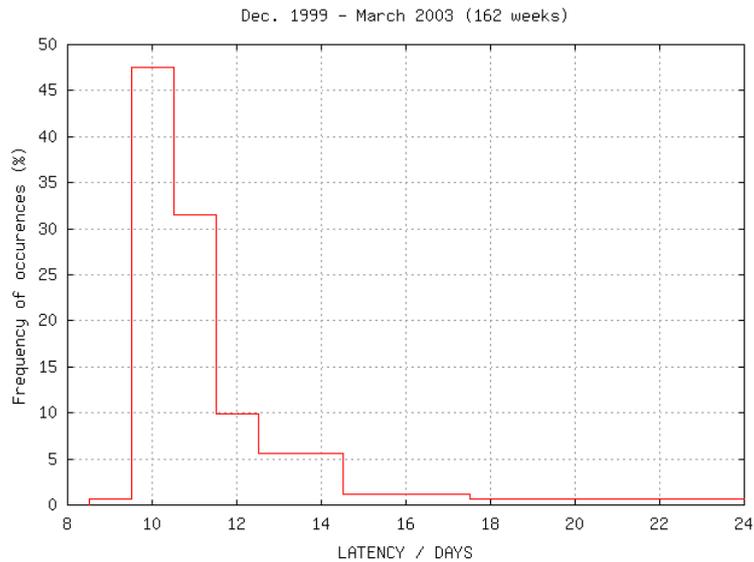


Figure 15: Latency of the distribution of the unofficial IGS combination product, performed weekly since end 1999. This latency has been defined such as the number of elapsed days from the end of the distributed GPS week.

## 9. Conclusions

The last 3 available months of IGS Ionosphere TEC maps have been deeply analyzed from many aspects. Vertical TEC performance, effect of the distance to GPS sites, Slant TEC performance, Formal Error relationship with the Measured ones, Delay Code Biases stability and agreement for both GPS satellites and several representative IGS receivers, and product distribution Latency, have been studied. In all points the IGS Ionosphere product shows good performance, and we therefore recommend migration to an official status.

## Acknowledgments

The author acknowledges the IAACs responsables for their help in reviewing this manuscript. In special he thanks to Brian Wilson, from JPL, his detailed review and suggestions.

## References

- Feltens, J., 1998, Chapman Profile Approach for 3-d Global TEC Representation, IGS Presentation, in proceedings of the 1998 IGS Analysis Centers Workshop, ESOC, Darmstadt, Germany, February 9-11, 1998, pp 285-297.
- Feltens, J., IONO-WG Status Report and Outlook, position paper at the IGS meeting, Ottawa, Canada, 2002.
- Feltens, J. and M. Hernández-Pajares, 2002 IGS Activities in the Area of the Ionosphere, IGS Annual report, 2003.
- Gao, Y., Heroux, P., and Kouba, J., Estimation of GPS Receiver and Satellite L1/L2 Signal Delay Biases Using Data from CACS, Proceedings of KIS-94, Banff, Canada, August 30 - September 2, 1994, pp. 109-117.
- Hernández-Pajares M., J.M. Juan und J. Sanz, New approaches in global ionospheric determination using ground GPS data, Journal of Atmospheric and Solar Terrestrial Physics, Vol 61, pp 1237-1247, 1999.
- Ho, C.M., Wilson, B.D., Mannucci, A.J., Lindqwister, U.J., Yuan, D.N., 1995. A comparative study of ionospheric total electron content measurements using global ionospheric maps of GPS, TOPEX radar, and the Bent model. Radio Science 32, 1499–1512.
- Mannucci, A. J., B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqwister and T. F. Runge, 1998, A global mapping technique for GPS-derived ionospheric total electron content measurements, in Radio Science, Vol. 33, pp. 565-582, 1998.
- Orús R., M.Hernández-Pajares, J.M.Juan, J.Sanz and M.García-Fernández, Performance of different TEC models to provide GPS ionospheric corrections, Journal of Atmospheric and Solar-Terrestrial Physics, Vol.64, pp. 2055– 2062, 2002
- Schaer, S. (1999): ‘Mapping and Predicting the Earth’s Ionosphere Using the Global Positioning System’, *Dissertation*, Astronomical Institute, University of Berne, Berne, Switzerland, 25 March 1999.

# IGS Tropospheric Products and Services at a Crossroad

Position paper for the March 2004 IGS Analysis Center Workshop  
Yoaz Bar-Sever, JPL

This position paper addresses two issues that are facing the IGS tropospheric community. These are: changes to the IGS Combined trop products, and the challenges of calibrating the many met packages in the IGS network.

## Issue #1: Needed changes to the IGS Combined trop products

The IGS currently produces two trop products: Final, with latency of several weeks, and UltraRapid (UR), with latency of 5-6 hours (relative to the oldest data point). The quality of both products is good, quoted at 4 mm for the Final product, and 6 mm for the UR product (based on inter-comparison among the contributing solutions). Both these products are derived through a complex procedure that combines individual solutions from several Analysis Centers (ACs).

Both products have been available in their present form and quality for several years.

The problem I see with these products is lack of users. Yes, there are occasional visitors who sample the products, but I know of no regular scientific or operational usage of these products. The contributing ACs are not using the products either, which indicates their disinterest not only in the Combined products, but also the combination process and its derived relative quality metrics for their contributions.

I do not think that the IGS should produce products that are not widely used, especially in light of the cumbersome and costly production process. As the new Tropospheric Product Coordinator I quickly realized the significant costs associated with the transfer, monitoring, and maintenance of the present combination process from GFZ, where it was developed over several years by Gerd Gendt.

We should figure out why our trop products are not used, and make the necessary adjustments. At the same time we should strive for an efficient, portable production, so as to optimize the cost-benefit ratio.

So why are the products not used, despite their fairly high accuracy?

The following are my speculations:

1. The scientific value of the Final product is in climatology, as there are no direct operational usage for this low latency product. Here the product is hurt by lack of consistency over time. As contributing ACs change their estimation strategy from time to time (e.g., different elevation angle cutoff, antenna phase maps), the combined product develops spurious 'climatological' signals. The product availability extends only a few years back, and there is no way to backfill without major coordinated effort from all ACs.

Required adjustment: the IGS Final trop product must be consistent in time, and must be easily regenerated, and backfilled when a better estimation strategy is available.

2. The Final and UR products may not be sufficiently accurate, as they depend on a rather uneven set of solutions. Indeed, the distribution of the internal quality control metric, the standard deviation among the contributing solution, is quite broad (Fig 1,2).

Required adjustment: the IGS Final and UR trop products should be more consistently of higher quality.

3. The integrity of the Final and UR products is compromised because the only quality control metric is based on inter-comparisons among the contributing solutions, which may have common error sources. Too often there are not enough contributed solutions for a given site, resulting in unrealistically low, or effectively non-existent (zero) sigma. (See Figs. 1,2)

Required adjustment: develop a product for which formal errors can be rigorously derived from input. Periodic campaign will validate performance through intercomparisons with other solutions and techniques.

4. Too few sites in either the Final or the UR products due to relatively small subset of common sites in all AC's contributions. This diminishes the scientific and operational benefits from these products.

Required adjustment: The IGS trop product must be available for nearly every site in the IGS network.

5. The UR product is too late for weather forecasting operations.

Required adjustment: to be useful in operational weather forecasting the product must be at most 3 hours late.

6. Reluctance of operational weather services to rely on external voluntary organization for critical operations. This common attitude is enhanced by the (correct) perception that it is not particularly challenging to generate good trop solutions.

Required adjustment: None.

In response to these perceived problems I am proposing a new type of IGS combined tropospheric product that, in my opinion, offers significant quality and operational advantages compare to the present products. I am proposing to replace the existing products with these new products for a specific period of time, nominally two years. At the end of this period we should assess the success of these new products, and consider whether to continue productions, make adjustments to the products, or cease to production altogether.

The proposed new product is completely independent of individual contributions by the ACs. However, it rightly earns its 'IGS Combined' designation because it is derived from the IGS Combined GPS orbit and dock solution, which together with Rinex files from each site, form the input to a point-positioning-based trop estimation process. The key to its quality and robustness is the use of the extremely accurate and reliable IGS combined GPS orbit and dock solutions.

The process to derive the new product has been operational since September. For the time being only the new 'Final' products, derived from the IGS Final Combined GPS orbit and dock

solutions are produced. These can be retrieved from [ftp://sideshow.jpl.nasa.gov/pub/igs\\_trop](ftp://sideshow.jpl.nasa.gov/pub/igs_trop). In a poster presented at the December AGU meeting in San Francisco (attached) we compared this new product to the current product, and discussed its many advantages. Here is a short summary of these advantages:

1. Highly efficient point-positioning-based approach enables massive production of solutions to practically all IGS stations. We plan on processing effectively every site in the IGS network (more than 300 sites per day).
2. Uniform estimation strategy insures long-term stability of the product, which is of critical value to climatology studies. Reanalysis is also easy, and years of products can be regenerated if

better estimation strategy emerges. Reanalysis can start right away to establish a long and consistent time series.

3. More accurate and more robust than the legacy product (Fig. 3).
4. Better quality control and high integrity through many rigorous metrics, such as formal errors, post-fit residuals, and site position repeatabilities.
5. Arbitrary temporal resolution (up to the resolution of the Rinex file). The nominal resolution of the new product is 5 minute (the resolution of the legacy product is 2 hours).

Since the ACs have never shown interest in using the IGS combined trop combination process to assess the quality of their own solutions (indeed, it is not a very informative comparison), the elimination of the inter-comparison statistics would not be noticed. Moreover, since it is more consistently accurate, the new product is far more suitable for quality comparison by the AC' s (or anybody else), and I expect to see increased usage of the new product for this purpose.

External quality assessment is essential for any operational product. In this case I propose frequent inter-comparisons with similarly derived solutions from other software packages. Most important are periodic campaigns (nominally annually) to compare the solutions with collocated WVRs and Radiosondes. Of course, if they are so inclined, ACs can inter-compare their own point-positioning-based solutions to the Combined solution, or submit their solutions to the coordinator for comparisons.

To similarly derive a new UR product would require reduced latency for the IGS Combined UR orbit and dock product. This will be discussed separately at this workshop. Until this product is in place I recommend discontinuing the formal production of the current UR trop product.

### **Summary of recommendations**

1. Replace the current IGS Final trop product with a higher quality, higher efficiency Final product based on the IGS Combined orbit and dock solutions
2. Discontinue the current IGS UR trop product for lack of use
3. Reduce the latency of the IGS UR orbit and dock product to 2 hours
4. Produce new IGS UR trop product based on the 2-hour latency IGS UR orbit and dock solutions

### **Issue #2. How to manage the many met packages around the world.**

There are roughly 70 meteorological sensors in the vast IGS network. These precision instruments emerge from the factory calibrated to better than half a mbar, and are certified to remain calibrated for three years, typically. Left uncalibrated for more than three years, a met package becomes less than useful, as its data can contaminate precipitable water vapor measurements derived by combining surface pressure with GPS data.

Ensuring calibration of the various met packages in the IGS network is a logistical and financial challenge for all the responsible agencies. I have looked into several options to pool our resources together in order to realize efficiencies in managing the met sensors, and increase the meteorological and climatological value of the network.

I have received cost estimates from Paroscientific for calibration services as well as reference met sensors, which I will be happy to share with any interested party. At this stage I would like to receive expressions of interest from the relevant networks, and assess the scope of the challenge so we can begin a discussion of the possible solutions.

Please refer to [ftp://sideshow.ipl.nasa.gov/pub/yeb/met\\_sites](ftp://sideshow.ipl.nasa.gov/pub/yeb/met_sites) for a table that I extracted from the site log files, describing the sites, the type of met sensors, and the calibration status. It is dear the vast majority of met sensors have never been calibrated in the field.

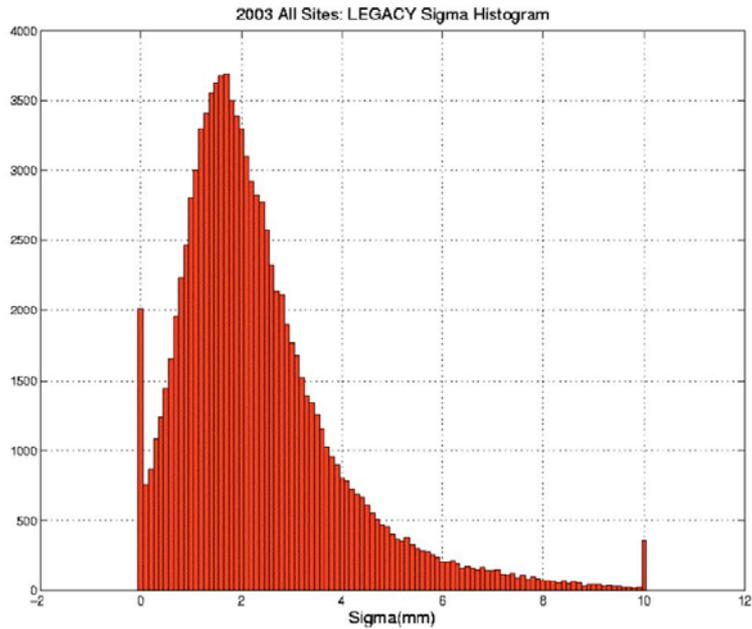


Figure 1: Histogram of the formal errors reported for the current Combined Final trop solutions. The histogram was generated using all site solutions for 2003. Zero sigma is reported when only one solution is contributed for a given site.

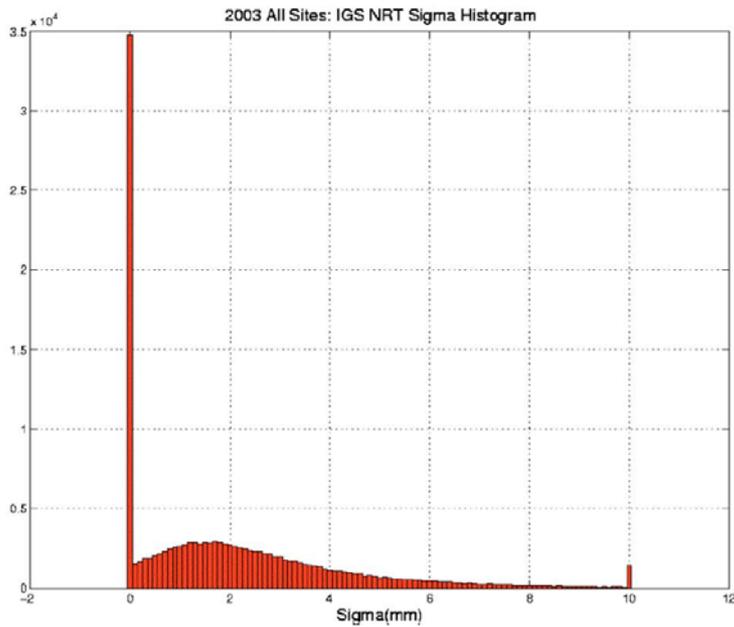


Figure 2: Histogram of the formal errors reported for the current Combined Ultra Rapid trop solutions. The histogram was generated using all site solutions for 2003. Zero sigma is reported when only one solution is contributed for a given site.

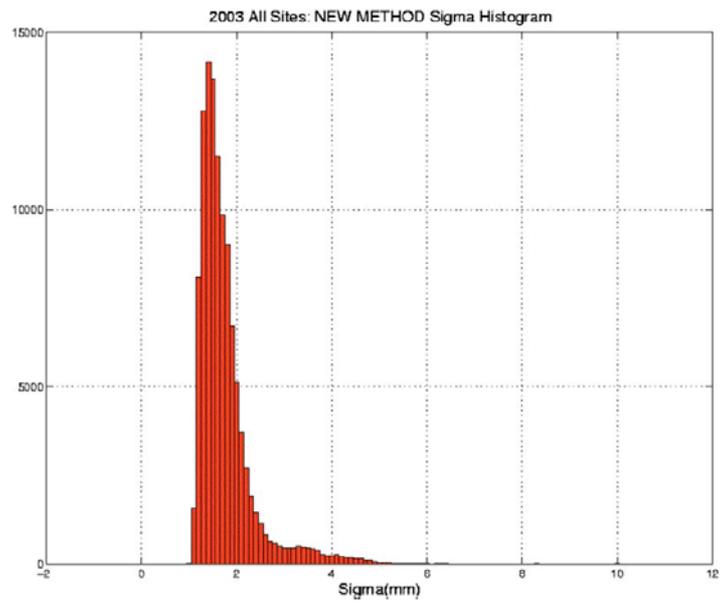


Figure 3: Histogram of the formal errors reported for the proposed new Combined Final trop solutions (using IGS combined Final GPS orbits and clocks, 7 deg elevation angle cutoff, estimation zenith delay and gradients as random walk processed, with 5 minute temporal resolution). The histogram was generated from daily point-positioning for a set of ~30 globally distributed sites during 2003.

