IONO_WG STATUS REPORT AND OUTLOOK
- POSITION PAPER -

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ABSTRACT

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 ionosphere Total Electron Content *(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 final attempts are made to establish from the individual contributions a combined IGS Ionosphere Product and to commence with the routine delivery of that product. The implementation of near-real-time availability is then the next important task and, medium-termed, the development of more sophisticated ionosphere models. Also the inclusion of other than GPS-data might be an aspect. The final target is the establishment of an independent IGS ionosphere model.

Currently five IGS Ionosphere Associate Analysis Centers (IAACs) contribute with their ionosphere products to the Iono_WG activities. 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. 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.

During the recent IGS/IAACs Ionosphere Workshop, ESOC, Darmstadt, Germany, January 17-18, 2002, a list of final actions was decided, which shall soon lead to the routine delivery of an official IGS Ionosphere Product. Based on the outcome of the Darmstadt Workshop and on the discussions at Ottawa, five recommendations were formulated in this Position Paper, which will be the basis for the Iono_WG members on how to progress - especially to come soon into a position to start with the routine delivery of an official IGS Ionosphere Product.

It is the intent of this Position Paper to give a short history and the current status of the Iono_WG activities. The recommendations stated at the end of this paper shall then be an orientation for the IAACs on how to progress, so that the Iono_WG can soon start with the routine delivery of a combined IGS Ionosphere Product to external users through the Crustal Dynamics Data Information System (CDDIS).

1   INTRODUCTION

This Position Paper will start with a project report providing an overview over the Iono_WG activities since its establishment in 1998.

The next aspect treated will be an overview about the routine comparisons, which are done until now at the designated Ionosphere Associate Combination Center (IACC) at ESOC. Key statistics of the routine TOPEX validations will be presented.

Based on the outcome of the IGS/IAACs Ionosphere Workshop in Darmstadt, 17-18 January, 2002, and on the discussions made at Ottawa, five recommendations are then formulated defining the way on how to progress by the Iono_WG.

Finally the Position Paper will conclude with a résumé of the achievements so far reached.

2   WG-ACTIVITIES SINCE ITS ESTABLISHMENT IN MAY'98

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 the form of 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, Natural 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).

The IGS standards defining the form in which the ionosphere products must be delivered to the Crustal Dynamics Data Information System (CDDIS), are declared in the recommendations of the Darmstadt 1998 IGS Workshop Position Paper (Feltens and Schaer, 1998). In short summary the most important are: 1) *TEC* maps and GPS satellite *DCBs* must be delivered in form of daily IONEX files (Schaer et al., 1997). 2) The *TEC* maps must have a time resolution of 2 hours, they must be arranged in a fixed global grid and refer to a shell height of 450 km. 3) Ionosphere products must be made available not later than the IGS Final Orbits, i.e. 11 days after the last observations.

Once per week the IACC performs the comparisons of the ionosphere products of all 7 days of the GPS week recently delivered to CDDIS. The comparison products and a weekly report are made available at ESOC's FTP account: ftp anonymous@nng.esoc.esa.de. A short summary is e-mailed through the IONO-WG list to the Iono_WG.

Apart from the routine activities the Iono_WG organized so far two dedicated high-rate tracking campaigns with the global IGS network during events which are of special relevance for the ionosphere:

1) The Solar Eclipse campaign on 11 August 1999: About 60 IGS sites, being located along the eclipse path from the east coast of North America over Europe and the Near - and Middle East, recorded on that day dual-frequency GPS-data with 1- and 3-second sampling rates. The high rate data are archived at the CDDIS and is open to research groups to study the ionosphere's reaction on the solar eclipse (*anonymous ftp* at *cddisa.gsfc.nasa.gov* in directory */gps/99eclipse*).

2) The HIRAC/SolarMax campaign from 23 - 29 April 2001: About 100 IGS sites, being located in the northern and southern polar regions and in the low latitudes including the crest regions at both sides of the geomagnetic equator, recorded over 7 days dual-frequency GPS-data with 1- and 3-second sampling rates. This IGS/Iono_WG activity was 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 GLONASS data are archived at the CDDIS and is open to research groups to study the ionosphere's behavior under solar maximum conditions (*anonymous* ftp at *cddisa.gsfc.nasa.gov* in directory */gps/01solarmax*).

The Iono_WG is open to organize further campaigns of this type.

3   RECENT IMPROVEMENTS

3.1   *Upgraded Comparison/Combination Approach*

In short, the old comparison/combination approach (☞ see Appendix B attached) was based on unweighted and weighted mean *TEC* maps, which could be considered as something like "combined" *TEC* maps, and the individual IAACs *TEC* maps were compared with respect to the weighted mean *TEC* maps. The comparison of *DCBs* was done basically in the same way. However, it was well known from the beginning, that the different IAACs models are based on very different mathematical approaches and the weights obtained with the old approach did obviously not represent the true quality of the input IAACs *TEC* maps.

The Iono_WG thus decided to upgrade the comparison/combination algorithm with a new weighting scheme, whereby the individual IAACs-weights are derived from external validations with self-consistency tests (☞ see Appendix A attached). The weekly comparisons are done with this new approach since August 2001. The external validations needed for this method are made routinely by the Ionosphere Associate Validation Centers (IAVCs) UPC and NRCan prior to the weekly comparisons at the IACC at ESOC.

Feltens (2002a) presents results obtained with the old and with the new comparison scheme: 1) The new comparison/combination approach favors the higher quality *TEC* maps more than the old approach did. 2) Currently discrete weights are assigned to defined geographic areas, which can cause "chessboard-like" patterns in the IGS *TEC RMS* maps and might in extreme cases also become visible in the IGS *TEC* maps. At Ottawa it was thus decided to compute from these regional weights corresponding global weights, which shall then be introduced into the comparisons/combinations. 3) The satellite *DCBs* series provided by most of the IAACs are quite constant, oscillating between *0.2* and *0.4 nanoseconds* around their mean values.

3.2   TOPEX Validations

Since July 2001 JPL provides *VTEC* data derived from TOPEX altimeter observables to the working group to enable validations. Due to its orbital geometry TOPEX scans every day only a limited band of the ionosphere. Additionally, the TOPEX data may be biased by +2-5 *TECU*. These two aspects must be kept in mind when interpreting the validations with TOPEX *VTEC* data. The TOPEX validations are attached to the weekly comparisons.

Principally these TOPEX validations work as follows: JPL provides per day a so called TOPEX file containing *VTEC* values derived from TOPEX altimeter data in dependency of time, latitude and longitude. In the different IAACs IONEX files *VTEC* values for the same times/latitudes/longitudes are interpolated, and the corresponding TOPEX *VTEC* values are then subtracted. The *VTEC*-differences thus obtained are used to establish different kind of statistics, like mean daily offsets & related *RMS* values for each IAAC.

3.2.1   Results

Figure 1 below condenses the basic statistics that were obtained from the TOPEX validations since 19 August 2001. The numbers plotted are:

- *mean* ... mean IAAC *VTEC* offset with respect to the TOPEX *VTEC* values, i.e. the mean value over *n* differences *d = tecval(IAAC) - TOPEXtec*:
$$mean = \sum d / n \ ,$$

- *rms-diff* ... *RMS* of differences:
$$rms_{diff} = \sqrt{\sum d^2 / n} \ ,$$

- *rms* ... *RMS* of residuals with respect to the mean, set *v = tecval(IAAC) - mean:*
$$rms = \sqrt{\sum v^2 / (n-1)} \ .$$

From GPS week 1158 on, the following two statistics parameters are included too (not in Figure 1):

- *sf/rms* ... estimate of the scale factor of the *RMS*-values obtained from the TOPEX validation in relation to the corresponding IAAC *RMS* values, should be close to one for IAAC = IGS, i.e. for the combined *TEC* maps:
$$sf/rms = \sqrt{\sum \{d / tecrms(IAAC)\}^2 / n} \ ,$$

- *wrms* ... corresponds to a "mean" *RMS* and might be an indicator for a *TEC* map's quality:
$$wrms = \sqrt{\sum \{d / tecrms(IAAC)\}^2 / \sum \{1 / tecrms(IAAC)\}^2} \ .$$

The TOPEX validations are done globally for all latitudes ("*+90..-90*") and separately also for medium and high northern latitudes ("*+90..+30*"), equatorial latitudes ("*+30..-30*") and medium and high southern latitudes ("*-30..-90*"). Beyond the IAACs *TEC* and the IGS *TEC*, also *TEC* computed with the GPS broadcast model ("*gps*") and *TEC* computed with CODE's Klobuchar-Style Ionosphere Model ("*ckm*") enter into the daily TOPEX validations. The latter two are provided by CODE.

When inspecting the curves in Figure 1 for the different latitude bands one recognizes immediately that the best agreement of the distinct ionosphere models with the TOPEX data is achieved at medium and high northern latitudes, while the worst agreement is in the equatorial region. The agreement in the southern medium and high latitudes is more worse than in the northern ones, but as far as not as worse as in the equatorial latitude band.

The other thing that can be seen from Figure 1 is that the IAACs *TEC* and the IGS *TEC* values, which are derived from GPS dual-frequency data, are considerably closer to the TOPEX *TEC* than the Klobuchar and especially the GPS broadcast model - and what is essential for the delivery of a combined IGS Ionosphere Product: <u>The routine validations with TOPEX since July 2001 show an agreement of the "combined" IGS *TEC* maps with the TOPEX data on the same order as the best IAACs *TEC* maps.</u>
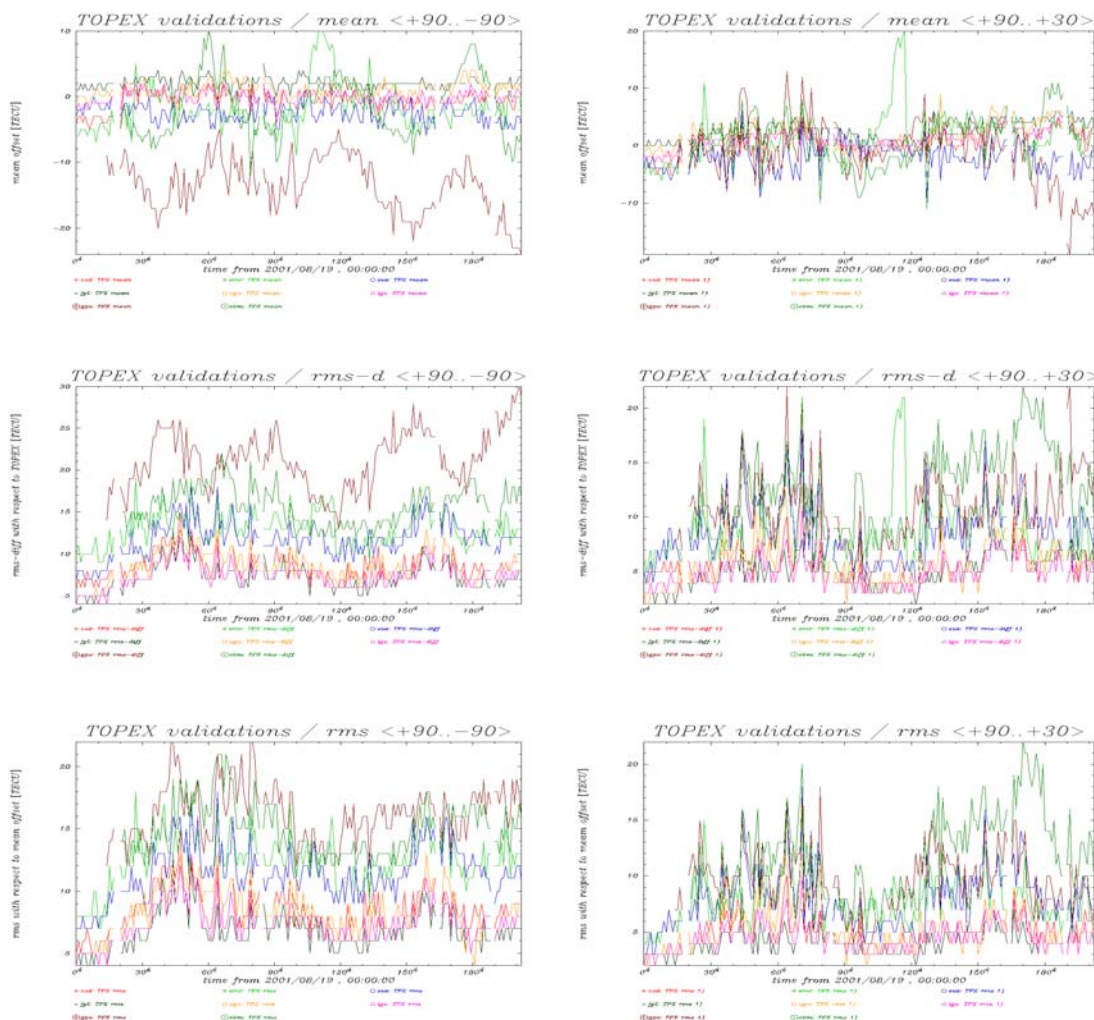

Figure 1: The basic TOPEX validation statistics *mean*, *rms-diff* and *rms*.
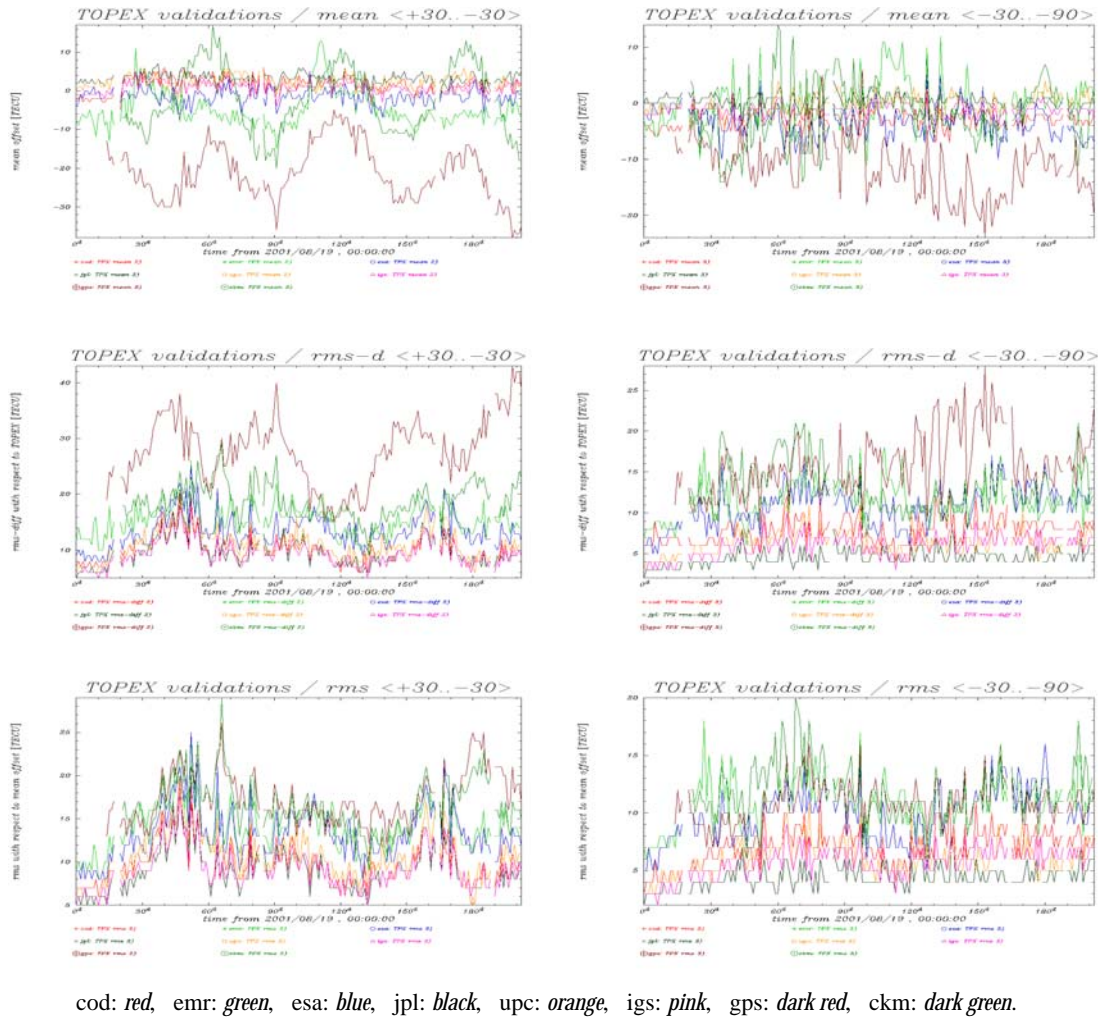
cod: *red*, emr: *green*, esa: *blue*, jpl: *black*, upc: *orange*, igs: *pink*, gps: *dark red*, ckm: *dark green*.

Figure 1 (cont.): The basic TOPEX validation statistics **mean**, **rms-diff** and **rms**.

4 OUTCOME FROM THE WORKSHOPS IN DARMSTADT AND IN OTTAWA - RECOMMENDATIONS

On 17-18 January 2002 an IGS/IAACs Ionosphere Workshop was held at ESOC, Darmstadt, Germany. The major target of this workshop was (for the complete list see Feltens, 2002b): To talk about actions still needed to be undertaken before the routine delivery of a combined IGS Ionosphere Product can be started. Apart from that, discussions were made about new research activities to be considered by the Iono_WG, discussions of points which are of vital interest for the Iono_WG within the IGS, implementation of near-real-time availability of Iono_WG products, guarantee of reliability of Iono_WG products.

Based on the conclusions of the Darmstadt workshop (Feltens, 2002b) and on the discussions at Ottawa the following five recommendations were formulated, which shall serve as orientation for

the Iono_WG on how to progress - as stated above, the major target is the start of the routine delivery of a combined IGS Ionosphere Product.

Recommendations:

(1) Start with the delivery of a combined IGS Ionosphere Product, as soon as the last required upgrades in the comparison/combination program are made in summer 2002.

(2) Combined IGS Total Electron Content *(TEC)* and **RMS** maps should be produced for the even hour numbers, i.e. 0^h, 2^h, 4^h, 6^h, ... , 24^h. In this way the 24^h maps of the previous day correspond to the 0^h maps of the current day.

(3) Global IGS Ionosphere Associate Analysis Centers (IAACs) **TEC ⁄ RMS** maps should cover all parts of the world.

(4) Explore the use of ENVISAT and JASON satellites for validation of IGS Ionosphere Products.

(5) In view of Near Real Time Monitoring of the Ionosphere the distribution of ground stations as well as the data flow (latency) has to be improved.

5 CONCLUSIONS AND OUTLOOK

The Iono_WG started working in June 1998 with the routine provision of daily IONEX files containing global **TEC** and **RMS** maps with a time resolution of 2 hours and a daily set of GPS satellite **DCB** values. Currently five IAACs contribute with their ionosphere products.

For the weekly comparison of IAACs ionosphere products a dedicated algorithm was worked out and coded from scratch at the IACC at ESOC. This "old" comparison algorithm was based on the concept of unweighted and weighted means and provided, so to say as by-product, also something like a "combination" of the IAACs individual ionosphere products. However, the IAACs use very different mathematical approaches and estimation schemes in their ionosphere processing, and this circumstance strongly reflected in the comparison results. The Iono_WG thus decided to upgrade this "old" comparison algorithm with a new weighting scheme using the results of external self-consistency test validations as input. The "new" comparison algorithm is now in operational use since August 2001. An analysis of the results obtained so far shows, that, apart from some minor weaknesses, the new approach seems to meet the demands for the computation of a combined IGS Ionosphere Product.

Additionally, since July 2001, routine validations of the IAACs **TEC** maps plus the "combined" IGS **TEC** maps with **VTEC** values derived from TOPEX altimeter data are attached to the weekly comparisons. The results of these validations show an agreement of the "combined" IGS **TEC** maps with the TOPEX data on the same order as the best IAACs **TEC** maps.

Based on the conclusions made at the IGS/IAACs Ionosphere Workshop in Darmstadt, 17 - 18 January, 2002, and on the discussions at Ottawa, five recommendations were formulated on how to

do away with remaining minor problems and to bring the Iono_WG soon into a position to start with the routine delivery of a combined IGS Ionosphere Product.

Beyond the realization of the combined IGS Ionosphere Product, goals and next steps are: enhancement of the IGS *TEC* maps time resolution, implementation of rapid products up to near-real-time availability, further validations, e.g. with ENVISAT altimeter data, and inclusion of higher order terms into ionospheric delay corrections modeling.

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APPENDIX A - COMPARISON/COMBINATION ALGORITHM - NEW

A) TEC maps

The comparison/combination is done independently for each day/reference epoch in two basic steps:

1) Validation of the IAAC TEC maps

Before the *TEC* maps of the different Ionosphere Associate Analysis Centers (IAACs) are compared/combined, validations are done with self-consistency checks using the methods proposed by UPC (Hernandez-Pajares, 2000) and NRCan (Heroux, 1999). These validation runs are made by the Ionosphere Associate Validation Centers (IAVCs) UPC resp. NRCan and delivered via FTP to the Ionosphere Associate Combination Center) IACC at ESOC early enough to be included into the weekly comparisons/combination processing, which is currently done on Tuesday (and exceptionally on Wednesday) of each week. Should the validation information not be available in time from UPC, only the validation results of NRCan will be considered and vice versa. In the case that neither validation results from UPC nor from NRCan are available, the comparison/combination will be run automatically with the old weighting scheme (☞ see Appendix B). The IACC at ESOC plans also to use the different IAAC *TEC* maps for *ERS/Envisat* orbit determinations. The *rms* values coming out from these orbital fits seem also to be a good indicator for the *TEC* maps quality and may thus enter as a third validation component into the comparison/combination at a later point of time.

UPC and NRCan make with their methods one validation run for each day and for a set of selected ground stations. In order to allow for wide-spread information in the weights computation, especially in latitude, but also in longitude, the ground stations which will be used for the validations, should be selected accordingly. Table 1 below lists possible station candidates: Considering the fact that there is somehow a station gap in the Pacific area, the global grid is first of all sub-divided into three longitudal sectors, called the American-, the European/African and the East Asian/Oceanian sector - the validity area of the latter should then also be extended for the Pacific area. With respect to latitude a subdivision is made into five zones, denoted as Northern polar cap-, Northern mid latitude-, Equatorial-, Southern mid latitude- and Southern polar cap zone. In this way 15 geographical areas are obtained, each being cut out by a sector and a zone. The table below provides now for each of these 15 areas a list of three stations with their approximate latitudes and longitudes (on the southern hemisphere some stations are lying slightly outside their area, e.g. **riog** - in such a case no alternative station is available). These stations were chosen as to be representative for their area - and the other important criterion was that these are - if possible - reliable stations providing regularly (and not sporadically) good GPS-tracking data. To each station a priority (1), (2), (3) is attached, meaning that, if station (1) is available in its area, the validation should be made with that station (1) on that day. Should station (1) not be available (e.g. because of a power breakdown), the validation should be done with station (2) in that area. Should (2) also not be available, station (3) must be used for the validation of that area and day. This priority scheme is to ensure that there

will be validation results available for the comparison/combination, also in cases of possible station outages, with high probability.

Sector	American			European/African			East Asian/Oceanian		
mean longitude	$\lambda_m = -90^o$			$\lambda_m = 15^o$			$\lambda_m = 110^o$		
longitude band	$-150^o < \lambda < -30^o$			$-30^o < \lambda < 60^o$			$60^o < \lambda < 160^o$ ➜ extend to -150°		
Northern polar cap zone $\varphi > 55^o$	(1) thu1	$\varphi = 76.5$	$\lambda = -68.8$	(1) nyal	$\varphi = 78.9$	$\lambda = 11.9$	(1) tixi	$\varphi = 71.6$	$\lambda = 128.9$
	(2) fair	$\varphi = 65.0$	$\lambda = -147.5$	(2) kiru	$\varphi = 67.9$	$\lambda = 21.0$	(2) yakz	$\varphi = 62.0$	$\lambda = 129.7$
	(3) yell	$\varphi = 62.5$	$\lambda = -114.5$	(3) trom	$\varphi = 69.7$	$\lambda = 18.9$	(3) mag0	$\varphi = 59.6$	$\lambda = 150.8$
Northern mid latit. zone $55^o > \varphi > 20^o$	(1) algo	$\varphi = 46.0$	$\lambda = -78.1$	(1) vill	$\varphi = 40.4$	$\lambda = -4.0$	(1) usud	$\varphi = 36.1$	$\lambda = 138.4$
	(2) nlib	$\varphi = 41.8$	$\lambda = -91.6$	(2) wtzr	$\varphi = 49.1$	$\lambda = 12.9$	(2) tskb	$\varphi = 36.1$	$\lambda = 140.1$
	(3) gol2	$\varphi = 35.4$	$\lambda = -116.9$	(3) pots	$\varphi = 52.4$	$\lambda = 13.1$	(3) shao	$\varphi = 31.1$	$\lambda = 121.2$
Equatoral zone $20^o > \varphi > -20$	(1) kour	$\varphi = 5.3$	$\lambda = -52.8$	(1) mali	$\varphi = -3.0$	$\lambda = 40.2$	(1) pimo	$\varphi = 14.6$	$\lambda = 121.1$
	(2) fort	$\varphi = -3.9$	$\lambda = -38.4$	(2) nklg	$\varphi = 0.4$	$\lambda = 9.7$	(2) guam	$\varphi = 13.6$	$\lambda = 144.9$
	(3) gala	$\varphi = -0.7$	$\lambda = -90.3$	(3) sey1	$\varphi = -4.7$	$\lambda = 55.5$	(3) ntus	$\varphi = 1.3$	$\lambda = 103.7$
Southern mid latit. zone $-55^o < \varphi < -20^o$	(1) sant	$\varphi = -33.2$	$\lambda = -70.7$	(1) suth	$\varphi = -32.4$	$\lambda = 20.8$	(1) pert	$\varphi = -31.8$	$\lambda = 115.9$
	(2) lpgs	$\varphi = -34.9$	$\lambda = -57.9$	(2) rbay	$\varphi = -28.8$	$\lambda = 32.1$	(2) yar1	$\varphi = -29.0$	$\lambda = 115.3$
	(3) cord	$\varphi = -31.7$	$\lambda = -64.5$	(3) hrao	$\varphi = -25.9$	$\lambda = 27.7$	(3) tid2	$\varphi = -35.4$	$\lambda = 149.0$
Southern polar cap zone $\varphi < -55^o$	(1) ohig	$\varphi = -63.3$	$\lambda = -57.9$	(1) syog	$\varphi = -69.0$	$\lambda = 39.6$	(1) cas1	$\varphi = -66.3$	$\lambda = 110.5$
	(2) palm	$\varphi = -64.8$	$\lambda = -64.1$	(2) vesl	$\varphi = -71.7$	$\lambda = -2.8$	(2) dav1	$\varphi = -68.6$	$\lambda = 78.0$
	(3) riog	$\varphi = -53.8$	$\lambda = -67.8$	(3) maw1	$\varphi = -67.6$	$\lambda = 62.9$	(3) mcm4	$\varphi = -77.8$	$\lambda = 166.7$

The IGS ground station net has some gaps in certain areas, especially on the southern hemisphere. In order to have also enough *TEC* data available in these areas, it should be allowed to the IAACs to use these validation stations in their *TEC* map processing too - additional ground station gaps in *TEC* map processing would be produced otherwise.

UPC and NRCan provide with their validation runs for each of the above defined 15 areas - normally by using station (1) - a *rms* value for each IAAC, which will then be used as representative IAAC *TEC* map weight for this area and day.

Example output for an UPC validation run for 7 days of a week (extract).

```
vill 356 40
          codg  emrg  esag  jplg  upcg
20011223  0.31  0.56  0.83  0.36  0.47
20011224  0.42  0.92  0.92  0.35  0.43
20011225  0.38  0.64  0.98  0.33  0.51
20011226  0.31  0.68  0.91  0.36  0.52
20011227  0.32  0.63  0.84  0.37  0.44
20011228  0.26  0.65  0.92  0.25  0.39
20011229  0.35  0.74  1.03  0.27  0.59
```

Example output for a NRCan validation run (extract).

	COD		EMR		ESA		JPL		UPC	
	DCB	S.D.	DCB	S.D.	DCB	S.D.	DCB	S.D.	DCB	S.D.
NYAL	-224.9	76.2	-280.7	142.0	-259.8	120.7	-256.0	71.2	-251.2	106.0
THU1	-28.4	86.4	-76.8	106.8	-23.8	95.2	-75.5	83.8	-27.6	96.5
TROM	-138.7	68.9	-206.0	127.6	-205.4	111.9	-174.8	68.3	-164.9	89.5
KIRU	-15.7	56.3	-78.0	112.9	-81.8	105.0	-49.9	59.0	-36.0	76.0
FAIR	-164.7	56.1	-195.7	114.7	-209.0	175.1	-175.8	59.5	-116.1	59.9
YELL	87.0	73.0	71.8	108.4	87.5	186.2	50.9	75.1	76.2	89.0

From the NRCan tables the numbers listed under S.D. (Standard Deviation) will be read by the comparison/combination program and used as *rms* values for weighting.

2) Weighted mean

The *TEC* maps of all IAACs are read from the IONEX files, 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 IAAC weights are taken from the above daily validations. The result of this step is a weighted mean *TEC* map which can be understood as the **combined IGS *TEC* map**.

Comparisons are then made with respect to that combined IGS *TEC* map, i.e. at each grid point the "residual" of each IAAC *TEC* map with respect to the combined *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) and a global weighted *rms* are computed and presented in the daily comparison summary.

B) DCBs

Sets of satellite (and station) *DCB* values are provided by the IAACs.

First of all the *DCB* set of each IAAC (stations & satellites) is referred to its mean value over *all satellites* for which *all IAACs* did provide *DCB* estimates, in order to achieve a common reference for the comparison/combination.

The comparison/combination of *DCBs* is then basically done in the following two steps as: 1) *Unweighted mean* over all IAACs for each spacecraft/station for which *all* IAACs did provide a *DCB*

value and establishment of weights from the differences with respect to that unweighted mean. 2) *Weighted mean* over all IAACs for each spacecraft/station. Comparison of the individual IAAC *DCB* values with the *DCB* values of the weighted mean. The weighted mean is thereafter again referred to $\Sigma_{DCBsat} = 0$, which will then be the **combined IGS satellite/station *DCBs*** set.

NEW COMPARISON/COMBINATION ALGORITHM IN DETAIL

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

A) TEC maps

1) Validation of the IAAC TEC maps

UPC and NRCan provide with their validation methods per day a ***rms*** value $rms(IAAC, area)$ for each IAAC and each of the 15 above defined geographic areas. These ***rms*** values are provided in ***TEC***-units *[TECU]* and are used to compute a comparison/combination weight for a certain IAAC in a certain geographic area. Since the ***rms***-sets provided by the UPC- and NRCan-method are of different magnitude, they must be re-scaled to a common level, before being put into the weights computation. To achieve this re-scaling, per area a mean $\overline{rms}$ value is computed from the UPC- and NRCan ***rms***-sets as follows:

$$\overline{rms}(area)_{UPC} = \sqrt{\frac{\sum_i \{rms(IAAC, area)_{UPC}\}^2}{n_{IAACs}}}$$

and

$$\overline{rms}(area)_{NRCan} = \sqrt{\frac{\sum_i \{rms(IAAC, area)_{NRCan}\}^2}{n_{IAACs}}} \quad (A.1)$$

where $\quad i = $ sum over all IAACs

The total weight for an IAAC/area is then computed from the ***rms*** values provided by UPC and NRCan by means of standard error propagation as follows:

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

$$(A.2a)$$

Should, for some reason, only UPC or only NRCan provide **rms** values for a certain day/area, the weights for that day in that area will be computed for all IAACs as:

$$weight(IAAC, area) = \frac{1}{\left\{\dfrac{rms(IAAC, area)_{UPC}}{\overline{rms(area)}_{UPC}}\right\}^2}$$

resp.   (A.2b)

$$weight(IAAC, area) = \frac{1}{\left\{\dfrac{rms(IAAC, area)_{NRCan}}{\overline{rms(area)}_{NRCan}}\right\}^2}$$

This approach thus enables also a weighting for the comparison/combination in cases that only UPC or only NRCan provide **rms** values for a certain day/area. - However, if UPC/NRCan provide **rms** values for a certain day/area, they must provide them <u>for all IAACs that have delivered **TEC** maps for that day/area</u>, because either the weighting (A.2a) or the weighting (A.2b) must be applied commonly to all IAACs for that day/area in order to be objective!

However, tests have shown, that introducing these discrete weights per geographic area into the comparison/combination causes discontinuities at the borders between the areas and thus "chessboard-like" patterns in the combined IGS **TEC rms** maps and in very extreme cases also in the combined IGS **TEC** maps. - On the other hand these tests did also show that the ratios between the IAACs weights are very similar in all areas, i.e. mean global weights derived from the area weights should thus show also similar ratios between the IAACs. Therefore for each IAAC a global mean weight value is computed from all area weights for that IAAC: This is done in two steps:
i) Per area the weights of all IAACs are normed to one:

$$\overline{weight}(IAAC, area) = \frac{weight(IAAC, area)}{\sum\limits_{i} weight(IAAC, area)}$$

where   (A.3a)

$$i = \text{sum over the weights of all IAACs in that area}$$

ii) Build per IAAC the mean over all normed weights over all areas. The sum over the mean global weights of all IAACs is again equal to one, as can be very easily mathematically demonstrated:

$$Weight(IAAC) = \frac{\sum\limits_{j} \overline{weight}(IAAC, area)}{n_{areas}}$$

where   (A.3b)

$$j = \text{sum over all areas in the geographic grid}$$
$$n_{areas} = \text{number of all areas in the geographic grid, i.e. 15}$$

These global weights are then introduced into the comparison/combination.

2) Weighted mean

Run in 4 nested loops over all grid points and over all 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 from corresponding IONEX file.

- Build with the associated global weights the weighted mean over all IAACs providing non-**9999** values; if all IAACs did provide a **9999**, set weighted mean equal to **9999**.

$$combTEC(GP) = \frac{\sum\limits_i Weight(IAAC) \cdot TEC(IAAC, GP)}{\sum\limits_i Weight(IAAC)}$$

(A.4)

where

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

- Compute differences **TEC(IAAC,GP) - combTEC(GP)** and store them in an IAAC's **TEC** difference IONEX file.

- Compute at current GP the weighted **rms** of combined **TEC** as:

$$m_0 = \sqrt{\frac{\sum\limits_i Weight(IAAC) \cdot \{TEC(IAAC, GP) - combTEC(GP)\}^2}{n_{IAACs} - 1}}$$

$$combTECrms(GP) = m_0 \cdot \frac{1}{\sqrt{\sum\limits_i Weight(IAAC)}}$$

(A.5)

where

m_0 = mean error of unit weight

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

The benefit of using Equation (A.5) for the combined IGS **rms** maps computation is that no individual **rms** values from the IAAC **rms** maps enter into that formula, thus giving objective **rms** numbers. - The **rms** maps currently delivered by the distinct IAACs look very different in magnitude as well as in pattern, representing only the internal accuracy of each individual IAAC estimation method. An inclusion of these individual IAAC **rms** maps might thus result in distorted combined IGS **rms** maps and should be avoided.

- Compute global **rms** for each IAAC only over those GPs where all IAACs did provide non-**9999** values. 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**] repre-

sents directly a squared **rms**):

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

(A.6)

where

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

The global **rms** is finally calculated as follows for each IAAC:

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

(A.7)

End of 4 nested loops to establish weighted mean.

B) DCBs

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

2) Refer independently for each IAAC its station and satellite **DCB** values to the reference $\Sigma_{DCBsat} = 0$ for those satellites for which all IAACs did provide a **DCB** value in order to achieve a common reference for comparison/combination. All station **DCBs** and all satellite **DCB** values are referred to this new reference, also the **DCBs** of those satellites for which not all IAACs did provide a **DCB** value.

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

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

where

k = sum over all IAACs per satellite/station

n_{IAACs} = number of all IAACs

(A.8)

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

where

sat/sta = summation over all n_d satellites/stations per IAAC

(A.9)

$$unweightedRMS(IAAC) = \frac{1}{\sqrt{n_d}} \cdot m_0 = \frac{1}{\sqrt{n_d}} \cdot \sqrt{\frac{[dd](IAAC)}{n_d - 1}}$$

$$Weight(IAAC) = \frac{1}{\{unweightedRMS(IAAC)\}^2} \tag{A.10}$$

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

$$combDCB_{sat/sta} = \frac{\sum\limits_{j} Weight(IAAC) \cdot DCB(IAAC)}{\sum\limits_{j} Weight(IAAC)}$$

where   (A.11)

$j = $ sum over all IAACs that provide a DCB value

for that satellite/station

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

6) Compute for each satellite/station the weighted **rms** of the combined *DCB* as:

$$m_0 = \sqrt{\frac{\sum\limits_{j} Weight(IAAC) \cdot \{DCB(IAAC)_{sat/sta} - combDCB_{sat/sta}\}^2}{n_{IAACs} - 1}}$$

$$combDCBrms_{sat/sta} = m_0 \cdot \frac{1}{\sqrt{\sum\limits_{j} Weight(IAAC)}} \tag{A.12}$$

where

$j = $ sum over all IAACs that provide a DCB value

for that satellite/station

$n_{IAACs} = $ number of all IAACs that provide a DCB value

at that satellite/station

Like Equation (A.5) for the combined **TEC rms**, Equation (A.12) does not consider individual **DCB rms** values of the different IAACs, since these again represent the internal accuracy of the respective estimation method, and their usage might result in distorted combined **DCB rms** values.

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

REFERENCES (for Appendix A)

Feltens, J., (1998): 'IGS Compared/Combined Ionosphere Products - Summary DD MMM YYYY (YYDOY)', daily comparison summary of IGS ionosphere products, igsgDDD0.YYs, available under *ftp anonymous@nng.esoc.esa.de*.

Hernandez-Pajares, M. (2000): 'Self-Consistency of the IONEX TEC Maps', *IONO-WG mails of 24.05.2000 and of 31.05.2000*.

Heroux, P. (1999): 'NRCan Global Ionospheric Grid', *Proceedings of the 1999 IGS Analysis Centers Workshop*, SIO, La Jolla, CA, U.S.A., June 8-10, 1999, in preparation.

APPENDIX B - COMPARISON ALGORITHM - OLD

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. Feltens, 1998).

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.

Comparisons 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 agree-

ment. 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. Feltens, 1998).

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.

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**):

$$[dd]_2(IAAC) = \frac{\sum\limits_{j} \cos\varphi \cdot d_{IAAC}^2}{\sum\limits_{j} \cos\varphi} \qquad \text{(B.1a)}$$

where

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

$$[dd]_1(IAAC) = \frac{\sum\limits_{i} \cos\varphi \cdot d_{IAAC}^2}{\sum\limits_{i} \cos\varphi} \qquad \text{(B.1b)}$$

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:

$$weight_1(IAAC) = \frac{1}{[dd]_1(IAAC)} \qquad \text{(B.2a)}$$

$$weight_2(IAAC) = \frac{1}{[dd]_2(IAAC)} \qquad \text{(B.2b)}$$

weight₁*(IAAC)* will be used for the weighted mean, **weight₂*(IAAC)*** is only for information and comparison (with **weight₁**) 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**.

$$combTEC(GP) \; = \; \frac{\sum\limits_{i} weight_1(IAAC) \cdot TEC(IAAC)}{\sum\limits_{i} weight_1(IAAC)} \tag{B.3}$$

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:

$$combTECrms(GP) \; = \; \sqrt{\frac{\sum\limits_{i} \dfrac{\{TEC(IAAC, GP) - combTEC(GP)\}^2}{\{TECrms(IAAC, GP)\}^2}}{\sum\limits_{i} \dfrac{1}{\{TECrms(IAAC, GP)\}^2}}} \tag{B.4a}$$

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 (B.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 (B.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.

$$combTECrms(GP) \; =$$

$$\sqrt{\frac{\sum\limits_{i} weight_1(IAAC) \cdot \{TEC(IAAC, GP) - combTEC(GP)\}^2}{n_{IAACs} - 1}}$$

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

$$\tag{B.4b}$$

- 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**):

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

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:

$$rms(IAAC) = \sqrt{[dd](IAAC)} \qquad \text{(B.6)}$$

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:

$$uwmean_{sat} = \frac{\sum_k DCB(IAAC)_{sat}}{n_{IAACs}} \qquad \text{(B.7)}$$

where

k = sum over all IAACs per satellite

n_{IAACs} = number of all IAACs

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

where

sat = summation over all n_d satellites per IAAC

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

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

$$combDCB_{sat} = \frac{\sum_j weight(IAAC) \cdot DCB(IAAC)}{\sum_j weight(IAAC)}$$ (B.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:

$$combDCBrms_{sat} = \sqrt{\frac{\sum_j \dfrac{\{DCB(IAAC)_{sat} - combDCB_{sat}\}^2}{\{DCBrms(IAAC)_{sat}\}^2}}{\sum_j \dfrac{1}{\{DCBrms(IAAC)_{sat}\}^2}}}$$ (B.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 (B.4b) might thus provide more objective **DCB rms** values as Equation (B.11) may do.

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

REFERENCES (for Appendix B)

Feltens, J., (1998): 'IGS Compared/Combined Ionosphere Products - Summary DD MMM YYYY (YYDOY)', daily comparison summary of IGS ionosphere products, igsgDDD0.YYs, available under *ftp anonymous@nng.esoc.esa.de*.

IONO_WG STATUS REPORT AND OUTLOOK
- POSITION PAPER -

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1. Introduction

2. WG-Activities since its Establishment in May'98

3. Recent Improvements

3.1 Upgraded Comparison/Combination Approach

3.2 TOPEX Validations

4. IGS/IAACs Workshop in Darmstadt, Last Steps for a Combined IGS Ionosphere Product

- Recommendations / Goals and Next Steps -

5. Conclusions and Outlook

1 INTRODUCTION

The IGS Iono_WG was established on 28 May 1998,

start of activities in June 1998.

- Main task: routine provision of
  - ✯ ionosphere *TEC* maps with a 2-hours time resolution   and of
  - ✯ daily sets of GPS satellite (and also soon receiver) hardware differential code bias (*DCB*) values,
  - ✯ weekly comparison of these products.

Currently, final attempts are made to start with the routine delivery of a combined IGS Ionosphere Product.

- Further important goals: 1)   Implementation of near-real-time availability,
  - 2)   inclusion of other than GPS-data,
  - 3)   development of more sophisticated IONO models,
  - 4)   final target: independent IGS IONO model.

- Other activities:
  - ✯ Solar Eclipse Campaign on 11 August 1999,
  - ✯ HIRAC/SolarMax campaign on 23 - 29 April 2001.

2 WG-ACTIVITIES SINCE ITS ESTABLISHMENT IN MAY'98

5 IAACs contribute with their ionosphere products, these are:

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

Standards:

- Each IAAC: Daily IONEX files with 12 global *TEC* maps (2^h-time resolution, fixed global grid, *450 km* shell height), one set of GPS satellite *DCBs*.

- Delivery with the Final Orbits, i.e. with a delay of 11-days.

- Weekly comparisons at the IACC at ESOC.

- The comparison products are made available at ftp anonymous@nng.esoc.esa.de .

3   RECENT IMPROVEMENTS

3.1 *Upgraded Comparison/Combination Approach*

The old comparison program:

- The old comparison algorithm was a pure statistical approach based on unweighted and weighted means ☞ Appendix B of the paper.

  - *Comparisons were made with respect to the "weighted mean" TEC map.*

  - *This "weighted mean" TEC map could be something like a "combination".*

  - *For the DCBs principally the same approach was used.*

- The IAACs use very different approaches to model the ionosphere.

  - *This circumstance clearly reflected in the comparison results.*

The new comparison program:

- Upgrade with a geographic-dependent weighting derived from external validations using self-consistency tests ☞ Appendix A of the paper.

- The external validations are made at the Ionosphere Associate Validation Centers (IAVCs) UPC and NRCan prior to the weekly comparisons.

- The weekly comparisons are done with this new approach since August 2001.

Status in short summary:

1) *The new comparison/combination approach favors the higher quality* **TEC** *maps more than the old approach did.*

2) *The discrete weights being assigned to defined geographic areas, can cause "chessboard-like" patterns in the IGS maps. The discrete weights must thus be fitted to some smooth surface function - or global weights must be used.*

3) *The satellite* **DCBs** *series provided by most of the IAACs are quite constant, oscillating between* **0.2** *and* **0.4 nanoseconds** *around their mean values.*

3.2 TOPEX Validations

Since July 2001 JPL provides VTEC data derived from TOPEX altimeter observables to enable validations.

The TOPEX validations are attached to the weekly comparisons:

- JPL provides per day a so called TOPEX file containing *VTEC* values derived from TOPEX altimeter data in dependency of time, latitude and longitude.

- In the different IAACs IONEX files and in the "combined" IGS IONEX file *VTEC* values are interpolated for the same times/latitudes/longitudes, of which the corresponding TOPEX *VTEC* values are then subtracted.

- The *VTEC*-differences thus obtained are used to establish different kind of statistics, like mean daily offsets & related *rms* values for each IAAC.

- The TOPEX validation results are made available at

ftp anonymous@nng.esoc.esa.de .

The TOPEX data may be biased by +2-5 TECU. A limited ionosphere band is scanned per day.

Results

The TOPEX validations are attached to the weekly comparisons since 8 July 2001 (doy 01189).

- The TOPEX validations are done globally for all latitudes ("*+90..-90*"),
  for the medium and high northern latitudes ("*+90..+30*"),
  for the equatorial latitudes ("*+30..-30*"),
  for the medium and high southern latitudes ("*-30..-90*").

- Beyond the IAACs *TEC* and the IGS *TEC*,   also *TEC* computed at CODE with
  the GPS broadcast model ("*gps*")   and *TEC* computed with
  CODE's Klobuchar-Style Ionosphere Model ("*ckm*")
  ➜ enter into the daily TOPEX validations.

The figures below show the basic statistics that were obtained from the TOPEX validations since 19 August 2001:

- **mean** ... mean IAAC **VTEC** offset with respect to the TOPEX **VTEC** values, i.e. the mean value over **n** differences **d = tecval(IAAC) - TOPEXtec**:

$$mean = \sum d/n \text{ ,}$$

- **rms-diff** ... **RMS** of differences:

$$rms_{diff} = \sqrt{\sum d^2/n} \text{ ,}$$

- **rms** ... **RMS** of residuals with respect to the mean, set **v = tecval(IAAC) - mean:**

$$rms = \sqrt{\sum v^2/(n-1)} \text{ ,}$$

In near future the following two statistics parameters will be included too:

- **sf/rms** ... estimate of the scale factor of the **RMS**-values obtained from the TOPEX validation in relation to the corresponding IAAC **RMS** values, should be close to one for IAAC = IGS, i.e. for the combined **TEC** maps:
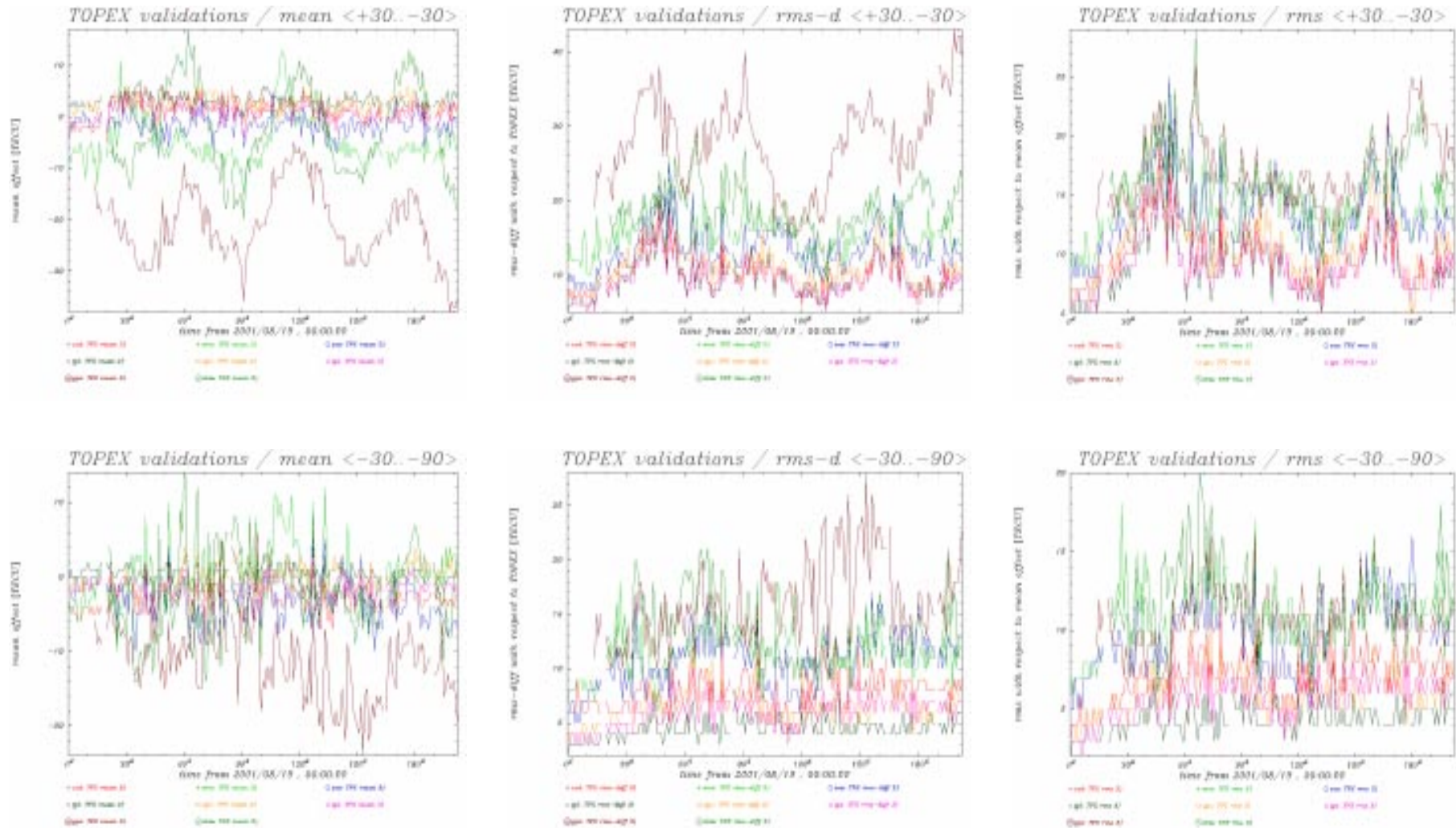
$$sf/rms = \sqrt{\sum \{d/tecrms(IAAC)\}^2/n} \text{ ,}$$

- **wrms** ... corresponds to a "mean" **RMS** and might be an indicator for a **TEC** map's quality:

$$wrms = \sqrt{\sum \{d/tecrms(IAAC)\}^2 / \sum \{1/tecrms(IAAC)\}^2} \text{ .}$$
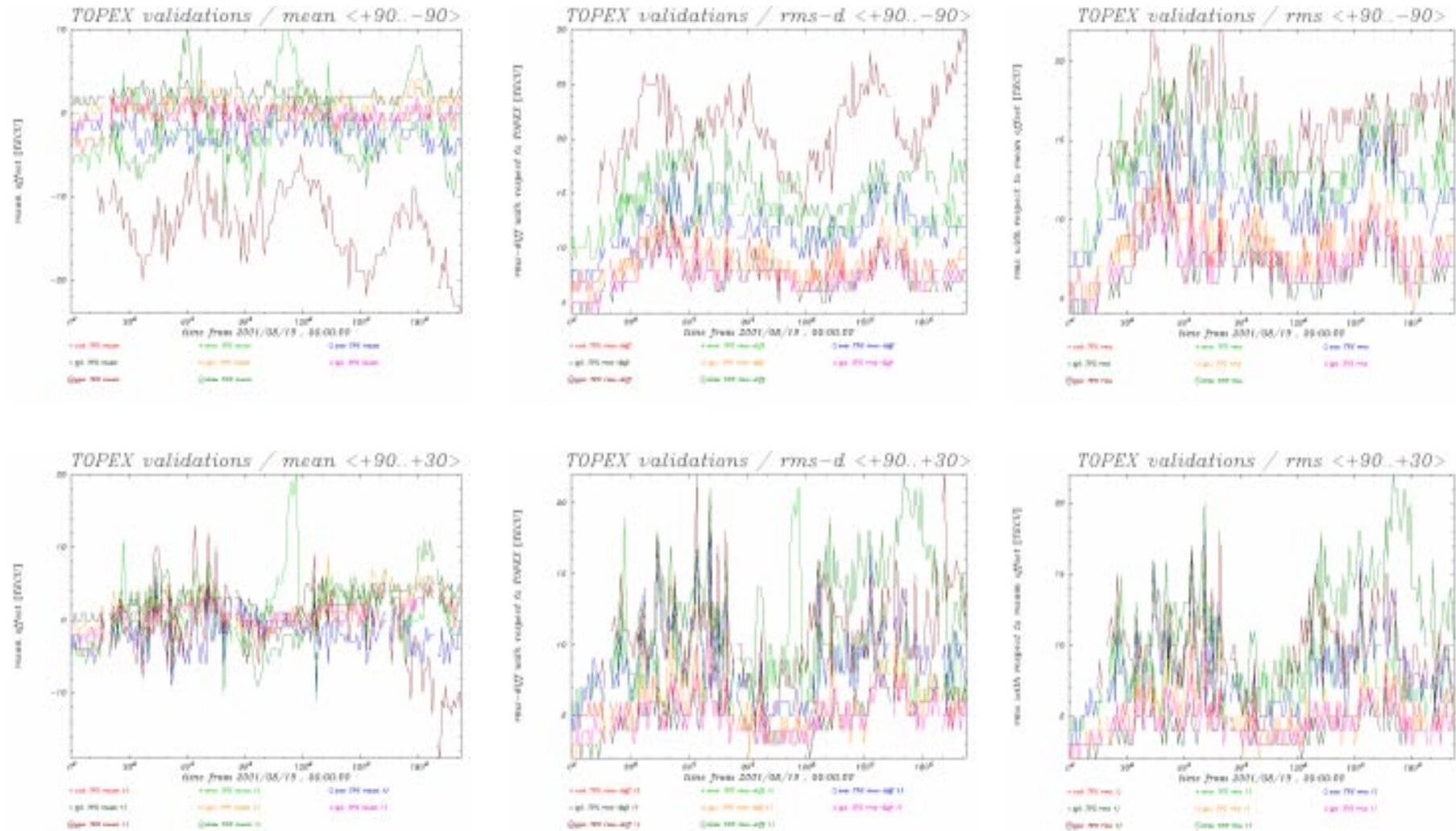
The basic TOPEX validation statistics *mean*, *rms*-*diff* and *rms*
("*+90..-90*") and ("*+90..+30*").

The basic TOPEX validation statistics *mean*, *rms-diff* and *rms*
("*+30..-30*") and ("*-30..-90*").

✵ *The best agreement of the distinct ionosphere models with the TOPEX data is achieved at medium and high northern latitudes.*

✵ *The worst agreement is in the equatorial region.*

✵ *The agreement in the southern medium and high latitudes is more worse than in the northern ones, but as far as not as worse as in the equatorial latitude band.*

✵ *The GPS-derived IAACs **TEC** and the IGS **TEC** values are considerably closer to the TOPEX **TEC** than the Klobuchar - and especially the GPS broadcast model.*

❀ ❀ ***The routine validations with TOPEX since July 2001 show an agreement of the "combined" IGS TEC maps with the TOPEX data on the same order as the best IAACs TEC maps.***

4 IGS/IAACs WORKSHOP IN DARMSTADT, LAST STEPS FOR A COMBINED IGS IONOSPHERE PRODUCT

Recommendations:

(1) Start with the routine delivery of a combined IGS Ionosphere Product:

- Global ↔ regional weights? ➜ see questionnaire in Table 1 below.
- Stations *DCB* values should be included.
- To the 4-characters station identifiers the DOMES numbers might be attached.
- A simple measure of the quality should be available.

(2) The combined IGS *TEC* maps should be produced with an overlap of one *TEC* map before the current day and one *TEC* map after the current day.

(3) Global IAAC *TEC* maps should cover all parts of the world.

(4) The interpolation algorithm for the IAACs *TEC* values interpolation in the TOPEX validations should be referred to the geomagnetic reference frame.

(5) In the IONEX files the geographic latitude should be replaced by the geocentric latitude as reference. ➜ see questionnaire in Table 1 below.

(6) Improvement of the weekly comparisons report and daily short summary:

- should be in ASCII format,
- should be restricted to essential parameters,
- should provide information about the points of best and of worst *RMS*-level and the *RMS*-values for different areas with GPS-data.

(7) Further Iono_WG products validations which could run on routine basis:

- validation with Envisat altimeter data (available after SODAP phase),
- validation with Jason altimeter data (to be cleared up).

(8) An Iono_WG Web page should be implemented soon.

(9) The available ground stations distribution and data latency should be improved as far as possible.

(10) Clear agreements should be made on how to derive from 3-d Iono models the 2-d *TEC*-values and on how to refer these *TEC*-values to the "single-layer shell height" required for the IONEX files.

(11) Inclusion of external ionosphere models data:

- External Iono models (e.g. IRI) are helpful in assisting to improve GPS-derived Iono models.
- Should be avoided whenever GPS *TEC* data are available in the considered areas.
- An inclusion should be declared accordingly as comment in the IONEX file header.

Goals and Next Steps:

(1) The time resolution in the IONEX files should be reduced from 2 hours to 1 hour.

- A corresponding pilot project should be organized.

(2) Reduction of products delivery time lines, near-real-time & real-time service:

- a corresponding pilot project should be organized,
- critical is the availability of a sufficient number of ground stations for short-term GPS observation data delivery,
- a new "rapid" pilot project should be introduced.

Each IAAC shall fill out its column in the below questionnaire table at/after the Ottawa IGS Workshop:

IAAC	COD	EMR	ESA	JPL	UPC
rapid	y		y		
ultra-rapid	asap		?		
predictions	y		asap		
near-real-time	n		asap		
geocentric latitude in IONEX	y		y		y
global or regional weights	glo.		?	reg.	

"**y**" ... yes,   "**n**" ... no,   "**asap**" ... as soon as possible,   "**?**" ... to be tried out, "**glo.**" ... global,   "**reg.**" ... regional.

Table 1: Questionnaire to be filled out by the IAACs during/after the Ottawa IGS Workshop.

(3) Further types of validation:

    - with external Iono models (e.g. IRI), not much effort,
    - COST 271 starts *TEC* evaluation studies at 5 - 10 selected european reference
      sites for the HIRAC/SolarMax campaign (23 - 29 April 2001). These sites are
      equipped with ionosondes or incoherent scatter radar. A validation of
      Iono_WG *TEC* maps with independent non-GPS-data is possible.

(4) Extended IONEX version for 3-d models, should be considered.

(5) Inclusion of higher order terms into *TEC* modeling, should be considered.

(6) Extension to the usage of other than GPS-data (e.g. Champ-occultations), should
be considered. - The pure GPS-based product should be maintained.

(7) Identification of possible new working areas & products (e.g. occultation, scintil-
lation), might be considered.

(8) Possibilities of cooperation with the SCAR/WG-GGI project, will be discussed at
the next COST 271 meeting in October 2002.

5 CONCLUSIONS AND OUTLOOK

The IGS Ionosphere Working Group started working in June 1998.

- 5 IAACs contribute with daily IONEX files containing 2^h *TEC* maps & daily sets of GPS satellite (and soon receiver) *DCBs*.

- The comparison/combination algorithm was recently upgraded with a new weighting scheme using external self-consistency test validations ➜ *in operational use since August 2001*.

- Validations with *VTEC* from TOPEX altimeter data were attached to the weekly comparisons ➜ *in operational use since July 2001*.

*The validation results show an agreement of the "combined" IGS **TEC** maps with the TOPEX data on the same order as the best IAACs **TEC** maps.*

- The above stated recommendations shall help to solve remaining minor problems and to start soon with the routine delivery of a combined IGS Ionosphere Product.

- Beyond that, goals and next steps were defined, to give the Iono_WG an orientation for further progress and activities in the future.

Global Ionosphere Maps Produced by CODE

CURRENT STATUS OF ESOC IONOSPHERE MODELING
AND
PLANNED IMPROVEMENTS

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ABSTRACT

Since the beginning of the year 1998 ESOC employs a 3-dimensional ionosphere model, based on a Chapman Profile approach, for its routine IGS ionosphere processing (Feltens, 1998 and Feltens et al., 1998). However, three years of routine application show certain weaknesses and limitations of this algorithm. New mathematical formulae have been worked out to overcome these problems and to improve performance. Before being implemented into the ESOC Ionosphere Monitoring Facility (IONMON) software, these new mathematical models must be validated - which is the current stage of activity. In this paper it is intended to give, starting with a short summary of the current approaches, an overview over the different kinds of modification which shall lead to an improved routine ionosphere processing at ESOC.

1   INTRODUCTION

This paper is a strongly reduced version of the paper presented at the IGS/IAACs Ionosphere Workshop in Darmstadt, 17-18 January 2002 (Feltens, 2002), and is restricted to the presentation of some of new the mathematical algorithms that were worked out to improve the current ESOC ionosphere modeling. Currently these new algorithms are implemented into the IONMON software. - Numerical results will thus be presented at a later time.

A complete presentation of all new mathematical algorithms would be far beyond the scope of this paper; only the basics of some major parts of the new algorithms can be described here. A complete and detailed mathematical description will be written down in the form of a technical note, as soon as the new algorithms are implemented into the IONMON software and tested.

At its beginning, this paper will give a condensed overview on how the routine ionosphere processing is currently done at ESOC and point out its weaknesses that were identified during three years of routine application. Based on that, the modifications will be described which shall improve the IONMON software performance. These modifications go into three basic directions: 1) enhancement of time resolution, 2) option to predict the ionosphere's state, 3) improved and extended mathematical modeling and inclusion of new observation types, namely electron density profiles derived from Champ occulation data.

Finally this paper will conclude with an outlook into the future.

2   CURRENT PROCESSING

2.1   TEC

In short overview, the current IONMON processing uses so called "leveled Total Electron Content (*TEC*) observables", being derived from dual-frequency GPS tracking data. These data are collected with the global IGS tracking network. The *TEC* observables are then fitted to a 3-dimensional *TEC* model, which represents the ionosphere's vertical electron density distribution by a simple Chapman Profile, whereby the layer of Maximum Electron Density N_0 acts as scaling factor for the Chapman Profile function and the Height of Maximum Electron Density h_0 as profile shape parameter. N_0 and h_0 in turn are modeled as global surface functions, of which the coefficients are estimated. 24 hours of *TEC* data enter into one daily batch least squares fit. A description of the model can be found in (Feltens, 1998).

The following weaknesses were identified during the routine IONMON processing with this approach:

1) The ionosphere is a rapidly changing medium - especially under the current solar maximum conditions, and due to the 24 hours fits, a lot of these variations are smoothed out, resulting in high *RMS* values and a loss of information. ➜ *The time resolution must be enhanced with a sequential estimate processor.*

2) The current mathematical model describes the vertical electron density distribution with one Chapman Profile. However, in reality the ionosphere is composed of different layers. Some of these layers (E and F_1) depend on the solar zenith angle χ and behave like Chapman layers, while others do not (F_2). ➜ *Describe the ionosphere mathematically as a superimposion of different Chapman Profiles, or more generally of profiles, one for each layer, being dependent on the so called* $\sec\chi$*-term or not.*

3) It was already pointed out in (Feltens, 1998) that it is difficult to estimate the profile shape parameter h_0 from pure *TEC* observables, since the *TEC* is the integral over the electron density and thus represents the area enclosed by the profile, and this area does not give any information about the profile's shape. An extraction of profile shape parameters is thus only possible with slant range *TEC* data incoming from a lot of different directions - with limited spatial resolution. ➜ *Electron density profiles derived from Champ occultation data are introduced as additional observables to allow for a better spatial resolution.*

2.2   DCBs

GPS satellite and ground station receiver Differential Code Biases (*DCBs*) are currently estimated in separate daily, so called "nighttime data fits": All nighttime *TEC* data of one day, i.e. 24 hours, are taken and fitted to a global spherical harmonic shell model for the nighttime *TEC* plus the *DCBs*, which are assumed to be constants. The idea behind this is that during the nighttime hours the *TEC* is low and the *DCBs* can thus be extracted with higher significance; the spherical harmonic shall absorb the nighttime *TEC*. The *DCB* values estimated in this way are then introduced with certain constraints into all the other ionosphere fits of that day.

However, with regard to the current solar maximum conditions, the assumption of low *TEC* at nighttime is somehow limited. ➜ *Establish normal equation systems with all* ***TEC*** *data - nighttime and daytime - with a certain time resolution, say 1 hour, and estimate the ionosphere model parameters on one hand and the* ***DCBs*** *on the other hand from this basic set of normal equations in different ways (for details see "Planned Improvements - Enhancement of Time Resolution" below).*

2.3   External User Interface

To the IONMON belongs also a so called "External User Interface (EUI)". This EUI is basically a collection of subroutines that allow external users to have access to the IONMON ionosphere models in the form of model coefficients (restricted to the ESOC models), or to the IGS ionosphere models which are accessed through IONEX files. In this way it shall be possible to external users to compute ionosphere corrections for their own tracking data with IONMON and/or IGS models. A preliminary version of this EUI has just been made available to the Interplanetary Mission Support Section people at ESOC to be used as part of the system tests for the "***Rosetta***" mission. This preliminary version accesses the IGS/Ionosphere Working Group (Iono_WG) 2-hours resolution IONEX files and interpolates then for given epochs and ground station ↔ and spacecraft positions corresponding slant range *TEC* values. Test runs with this EUI-version were also made for *ERS* tracking data some time ago.

As already stated above, the current EUI version is considered as "preliminary". ➜ *In future it must be adapted to the improved IONMON processing, and surely also to more complex IONEX versions.*

2.4   Higher Order Terms

For the refractive index of the ionosphere normally a power series expansion in $1/f^n$ (f = signal frequency) is used, see e.g. Brunner and Gu (1991), where the first term $1/f^2$ is only TEC-dependent and covers about *98%* of the total ionospheric delay experienced by GPS signals. The higher terms are at least three orders of magnitude less, some of them depend also on the Earth magnetic field. However, under worse conditions it can be expected that also these higher order terms may contribute to centimeter level to the total ionospheric delay of GPS-signals. ➜ *In spite of that the higher order terms have no significant effect on the* ***TEC*** *models estimation, they should be included into the computation of ionospheric delays. Apart from the* ***TEC***, *which is obtained from the IONMON fits, the geomagnetic field must be incorporated into the higher order terms modeling. Tests must show to which extent this must be done, e.g. is a simple dipole approach sufficient, or more sophisticated modeling necessary - or will it even be possible to estimate geomagnetic field parameters with a known* ***TEC***.

3   PLANNED IMPROVEMENTS

3.1   Enhancement of Time Resolution

In order to enhance the time resolution of the IONMON software, the current batch least squares fit shall be replaced by a sequential estimate, which will work according to the following principle:

With a certain time resolution, e.g. 1 hour or less, normal equation systems will be established for time intervals *i*. This archive of normal equation systems is then used in two different ways for *TEC* estimation and for *DCBs* estimation:

1) TEC:

To make an update for the time interval *i+1*, to the normal equation system for *i+1* pseudo-observation equations are added. To these pseudo-observation equations a weight matrix is assigned which is put together from the normal equations of the previous time intervals. The normal equations are multiplied with a scaling function decreasing exponentially with time to reduce the influence of the older data when computing the weight matrix. The resulting normal equation system for time interval *i+1* is then solved to estimate the unknowns for update *i+1*.

The normal equations of update *i+1* enter then in turn into the establishment of weight matrix $\underline{W}_{i+2}$ to constrain update *i+2*, and so on ... *TEC* parameters as well as *DCB* values will be updated during this fit - but only the *TEC* parameters are of interest here.

2) DCBs:

DCBs (for satellites and receivers) fits will be done in daily batch estimates, now using nightime and daytime data. For *DCB* estimates, the normal equations of all time intervals *i* of a day will be put together to one big normal equation system. The solution of this normal equation system provides the *DCB* values for the satellites and the ground stations as well as the *TEC* parameters - but only the *DCB* values are of interest in this fit.

3.2   RMS maps

The IONMON software will also be extended for the option to compute *TEC*-*RMS* maps, which will then be included into the ESA-IONEX files too.

3.3   Predictions of the Ionosphere's State

For the support of interplanetary missions it is essential to have the information of the ionosphere's actual state available in very short times - and predicted ionosphere information is of great benefit too. With regard to several NASA/ESA interplanetary missions which will be launched in 2003, it was thus decided to include also an ionosphere prediction tool into the IONMON software. This prediction tool will in principle work according to the approach developed by Stefan Schaer (Schaer et al., 1998 and Schaer, 1999).

3.4 Mathematical Modeling

3.4.1 Describing the Ionosphere as being composed of several layers

The basic assumption made in the current mathematical model to describe the vertical electron density distribution with only one Chapman Profile does represent the reality only within certain limits; in reality the ionosphere is composed of several layers. Furthermore, some of the ionospheric layers (E and F_1) depend on the solar zenith angle χ and behave like Chapman layers, while others do not (F_2). To take into account these circumstances, the IONMON software will be modified such that the ionosphere can mathematically be modeled as a superimposion of different layers, maximal five (D_1, D_2, E, F_1, F_2). To account for the plasmasphere, an exponential correction function with a very large scale height will be added to the topside of the highest layer, namely F_2. The electron density at a certain altitude is then the sum of the electron densities of the profile functions of all layers at that altitude plus the plasmasphere exponential function:

$$
\begin{aligned}
N_e(h) &= N_{D_1}(h) + N_{D_2}(h) + N_E(h) + N_{F_1}(h) + N_{F_2}(h) + plasmasphere(h \geq h_{0_{F_2}}) \\
&= N_{0D_1} \cdot p_{D_1}(h) + N_{0D_2} \cdot p_{D_2}(h) + N_{0E} \cdot p_E(h) + N_{0F_1} \cdot p_{F_1}(h) + N_{0F_2} \cdot p_{F_2}(h) + plasmasphere(h \geq h_{0_{F_2}})
\end{aligned}
$$

$$(3.1)$$

where:

$N_e(h)$ ... total ionospheric electron density at altitude h,

$N_i(h)$ ... electron densities of the layers $i = D_1, D_2, E, F_1, F_2$ at altitude h,

N_{0i} ... maximum electron density of layer $i = D_1, D_2, E, F_1, F_2$ (scales the layer's profile function),

$p_i(h)$ ... profile function describing the layer i's electron density as function of altitude h,

$plasmasphere(h \geq h_{0F2})$ ... exponential correction to the topside part of the highest layer profile function for the plasmasphere, for $h \geq h_{0F2}$.

This approach follows basically the concept of Ching and Chiu, 1973, Chiu 1975, and Zhang et al. 1999.

The *TEC* is thus the sum of the integrals of the profile functions of all layers along the signal path (how the slant range integration *ds* is expressed in terms of a corresponding vertical integration *dh* can be found in (Feltens, 1998)):

$$
\begin{aligned}
TEC &= \int_s N_e(h)ds = N_{0D_1} \cdot \int_s p_{D_1}(h)ds + N_{0D_2} \cdot \int_s p_{D_2}(h)ds + N_{0E} \cdot \int_s p_E(h)ds + N_{0F_1} \cdot \int_s p_{F_1}(h)ds + N_{0F_2} \cdot \int_s p_{F_2}(h)ds \\
&\quad + \int_s plasmasphere(h \geq h_{0_{F_2}})ds \\
&= N_{0D_1} \cdot P_{D_1}(h)\Big|_s + N_{0D_2} \cdot P_{D_2}(h)\Big|_s + N_{0E} \cdot P_E(h)\Big|_s + N_{0F_1} \cdot P_{F_1}(h)\Big|_s + N_{0F_2} \cdot P_{F_2}(h)\Big|_s \\
&\quad + \int_s plasmasphere(h \geq h_{0_{F_2}})ds
\end{aligned}
$$

$$(3.2)$$

where:

   $P_i(h)$ ... integral over profile function of layer i along the slant range pass s.

Figure 1 below was taken from (Zhang et al., 1999) and shows a composition of three ionospheric layers.

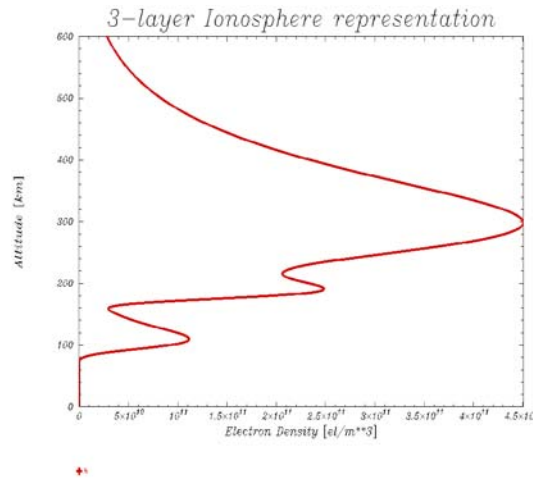

Figure 1: Representation of the ionospheric electron distribution by a composition of three layers.

3.4.2   Inclusion of Further Observation Types

Since the observed *TEC* represents the integral over the electron density along the signal path, i.e. mathematically the area below the electron density profile, it is difficult to extract profile shape parameters, like the Height of Maximum Electron Density h_0, from pure *TEC* observables. An estimation of profile shape parameters is only possible with slant range *TEC* data incoming from a lot of different directions, and the spatial resolution remains limited. The estimability of profile shape parameters can be improved by supplementing the *TEC* observables with observed electron densities. The IONMON software will thus be extended to process electron density profiles derived from Champ occultation data as additional observables together with observed *TEC* data. The inclusion of digisonde data (Galkin et al., 1999) might be in future an option too.

3.4.3   Mathematical Models

Concerning the mathematical modeling, improvements into several directions are currently prepared for implementation into the IONMON software:

1) Profile functions:

Beyond the Chapman Profile, which is currently used in the IONMON software, additional empirical profile functions were worked out, as well as modifications of the classical Chapman Profile. Some of the profile functions that will be used by the IONMON software after its modification are presented below. To become a profile function the candidates had to fulfill the following criteria:

- The candidate functions have to be "bell curves", either asymmetric (like the Chapman Profile), or symmetric (like e.g. the Hyperbolic Secant, see below).

- The candidate functions shall have one maximum at $\chi = 0$ (with $f(0) = 1$, if possible) and converge to *zero* for $\chi \to \pm \infty$. The candidate functions must not have negative values anywhere on χ. - These are basically the conditions for a "bell curve".

- With regard to the fact that the IONMON is primarily used for *TEC* observables processing, also the existence of the analytical integral of a candidate function was a criterion.

The relation between an ionospheric layer *i*'s electron density N_i and the profile function p_i was generally defined as follows:

$$N_i(z, \chi) = N_{0_i} \cdot \{ p_i(z, \chi) \}^{\alpha_i} \qquad , \qquad z = \frac{h - h_{0_i}}{H_i}$$

example: Chapman α-layer (3.3)

$$N_i(z, \chi) = N_{0_i} \cdot e^{\alpha_i(1 - z - \sec\chi \cdot e^{-z})} = N_{0_i} \cdot \left\{ e^{(1 - z - \sec\chi \cdot e^{-z})} \right\}^{\alpha_i} \qquad \rightarrow \qquad p_i(z, \chi) = e^{(1 - z - \sec\chi \cdot e^{-z})}$$

where:

N_i ... is the electron density at altitude h,

N_{0i} ... is the Maximum Electron Density,

h_{0i} ... is the Height of Maximum Electron Density,

H_i ... is the Scale Height,

α_i ... is the recombination coefficient,

χ ... is the solar zenith angle,

$p_i(z,\chi)$ ... is the profile function.

By this definition, $p_i(z,\chi)$ itself is not a function of the recombination coefficient; α_i is applied "externally" as power to $p_i(z,\chi)$ in the electron density computation. The summation formula, which is used to compute the *TEC* integral (Feltens, 1998), has been modified in such a way, that it will account for the power of α_i during the summation.

In the following, some of the profile functions, which can be employed by the extended IONMON software, are listed:

a) *Chapman Profile:*

Basic function:

$$Cp(x) = e^{(1 - x - e^{-x})} \qquad \rightarrow \qquad \int Cp(x)dx = e^{(1 - e^{-x})}$$

Final formula for IONMON application:

$$\rightarrowtail \quad N_i(z, \chi) = N_{0_i} \cdot \left\{ e^{(1 - z - \sec\chi \cdot e^{-z})} \right\}^{\alpha_i}$$

(3.4)

$$\twoheadrightarrow \quad p_i(z, \chi) = e^{(1 - z - \sec\chi \cdot e^{-z})} \quad , \quad P_i(z, \chi) = \int p_i(z, \chi)dz = \cos\chi \cdot e^{(1 - \sec\chi \cdot e^{-z})}$$

b.1) Versiera der Agnesi-like:

Basic function:

$$A_1(x) = \frac{1}{1 + (a \cdot x)^2} \quad \rightarrow \quad \int A_1(x)dx = \frac{1}{a} \cdot arc\tan(a \cdot x)$$

Final formula for IONMON application:

$$\rightarrowtail \quad N_i(z, \chi) = N_{0_i} \cdot \left\{ \frac{\cos\chi}{1 + \{z - \ln\{\sec\chi\}\}^2} \right\}^{\alpha_i}$$

(3.5)

$$\twoheadrightarrow \quad p_i(z, \chi) = \frac{\cos\chi}{1 + \{z - \ln\{\sec\chi\}\}^2} \quad , \quad P_i(z, \chi) = \int p_i(z, \chi)dz = \cos\chi \cdot arc\tan\{z - \ln\{\sec\chi\}\}$$

For the square root form of the Versiera der Agnesi a profile function was worked out too.

c) Hyperbolic Secant-like:

Basic function:

$$\operatorname{sech}(a \cdot x) = \frac{1}{\cosh(a \cdot x)} = \frac{2}{e^{a \cdot x} + e^{-a \cdot x}} \quad \rightarrow \quad \int \operatorname{sech}(a \cdot x)dx = \frac{2}{a} \cdot arc\tan\{e^{a \cdot x}\}$$

Final formula for IONMON application:

$$\rightarrowtail \quad N_i(z, \chi) = N_{0_i} \cdot \left\{ \frac{2 \cdot \cos\chi}{\cos\chi \cdot e^z + \sec\chi \cdot e^{-z}} \right\}^{\alpha_i}$$

(3.6)

$$\twoheadrightarrow \quad p_i(z, \chi) = \frac{2 \cdot \cos\chi}{\cos\chi \cdot e^z + \sec\chi \cdot e^{-z}} \quad , \quad P_i(z, \chi) = \int p_i(z, \chi)dz = 2 \cdot \cos\chi \cdot arc\tan\{\cos\chi \cdot e^z\}$$

d) Modified Versions of the Chapman Profile:

Additionally, two modified versions of the Chapman Profile formula were worked out. The first version combines the Chapman Profile with its mirrored counterpart. Depending on the degree of combination, varying ratios between topside and bottomside electron densities can be achieved. The second version is a MacLaurin Series expansion of the Chapman Profile formula. By fitting the series expansion coefficients to observed profiles, modified Chapman Profiles can thus be achieved. - The mathematical background of these formulae is quite comprehensive and out of scope of this paper, for more details see (Feltens, 2002).

2) Correction for the Plasmasphere:

At its top, the ionosphere passes over into the plasmasphere which extends several tenthausand kilometers into space. The plasmaspheric electron density from the top of the ionosphere up to the GPS satellites altitude at about 20200 km can also be in the order of several TEC-units and must thus be included into the ionosphere modeling. In the IONMON the correction for the plasmasphere will be done by adding an exponential correction function with a very large Scale Height to the topside part of the profile function used to model the highest ionosphere layer, i.e. F_2.

3) Height-Dependent Scale Height modeling:

The current IONMON version uses an empirical formula to calculate the Scale Height only in dependency of the Height of Maximum Electron Density h_0 (Feltens, 1998), i.e. the Scale Height is thus not assumed to vary with height. However, the Scale Height varies considerably with height (see e.g. Kelley, 1989). For the IONMON software upgrade, empirical curves in combination with 2-dimensional Gauss-Type-Exponential (GE)-functions were thus worked out, which shall be used for the computation of height-dependent Scale Height profiles. The other option foreseen in the IONMON software is to use per profile function either one or two constant Scale Heights; in the case of two constant Scale Heights one for the bottomside and the other one for the topside.

4) Inclusion of Higher Order Terms:

In the medium term, the higher order terms of the ionospheric refraction coefficient series expansion shall be included into the ionospheric delays computation, since these terms can also contribute to the centimeter level to ionospheric delays experienced by GPS-signals. The inclusion of higher order terms also requires the geomagnetic field to be incorporated. Tests must show to which extent the treatment of the geomagnetic field is necessary - simple dipole approach, or more complex modeling, or even possibility to estimate geomagnetic field parameters with a known *TEC*.

Current implementation status:

All the mathematical modeling described above (apart from the higher order terms stuff) is completely worked out, coded and compiled. During a next step it must be unit-tested and validated. First results can be presented then. Thereafter the new subroutines will be implemented into the IONMON software. Before going into operational use, further tests and validations will be performed. After all this work is done, the complete mathematical models will be put together into a technical note, and the IONMON External User Interface will be extended and adapted accordingly.

4   CONCLUSIONS AND OUTLOOK

The ESOC Ionosphere Monitoring Facility (IONMON) software is in operational use since the beginning of the year 1998 for routine IGS ionosphere processing. It employs a 3-dimensional ionosphere model, based on a Chapman Profile approach. However, three years of routine application show certain weaknesses and limitations of this algorithm. To improve performance, modifications are currently ongoing into the following directions:

- Enhancement of the time resolution for ionosphere fits.
- Modified **TEC/DCBs** estimation scheme plus computation of **TEC RMS** maps.
- Software tool to predict the ionosphere's state.
- Inclusion of other observation types than **TEC** data, namely Champ occultation profiles.
- Improvement of mathematical modeling into several directions (composition of several layers, alternative profile functions, α-layer handling, correction for the plasmasphere, height-dependent Scale Height).
- Availability of the improved ionosphere models through an upgraded external user interface.
- Inclusion of higher order terms (in the medium-term).

At the current stage of work the new algorithms are completely worked out, coded and compiled. In the next step they must be unit-tested and validated and then be implemented into the operational IONMON software. It is hoped that these different kinds of modification will lead to an improved routine ionosphere processing at ESOC.

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UPC ionospheric activities

TEC maps, Real-Time corrections and Electron Density retrieval

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Outline

- TEC maps from International GPS Service data:
  - Generation.
  - Validation of the IAAC's TEC maps:
    - Absolute performance: vs. TOPEX TEC
    - Relative performance: vs. observed GPS δSTEC
- Improving vertical electron density profiles:
  - Mixing radio-occultation and ground GPS data.
  - Mixing ionosonde and ground GPS data.

- Improving real-time ionospheric determination

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TEC maps: Generation and validation

Goal: The generation of TEC Global Ionospheric Maps (GIM's) from IGS data (as a IAAC), and helping on the validation of the differents centers (as a IAVC):

- The UPC GIM are being computed on a daily basis since June 1st 1998, and delivered to the IGS community.

- Weights for the different centers are being computed on a weekly basis in function of the STEC GPS prediction RMS. The bias and RMS regarding to TOPEX TEC observations have been computed for the full database of IAAC TEC maps.

Some details: Hernandez-Pajares M., J.M. Juan and J. Sanz, New approaches in global ionospheric determination using ground GPS data, JASTP, Vol 61, 1237-1247, 1999a.

Electron dens.: Improving mixing data

Goal: To improve the electron density estimations mixing ionospheric data with horizontal (ground GPS) and vertical information (GPS radio-occultation and ionosonde data).

Experiments:

- LEO GPS-MET / CHAMP + ground GPS IGS data, at mid and low latitudes during Solar Minimum and Maximum conditions. The results are compared with ionosonde data

- European and USA ionosondes + ground GPS IGS data. The results are compared with LEO GPS-MET data.

Details: Hernández-Pajares M., J.M. Juan, J. Sanz, Improving the Abel inversion by adding ground data LEO radio occultations in the ionospheric sounding. GRL, 27, 2743-2746, 2000b

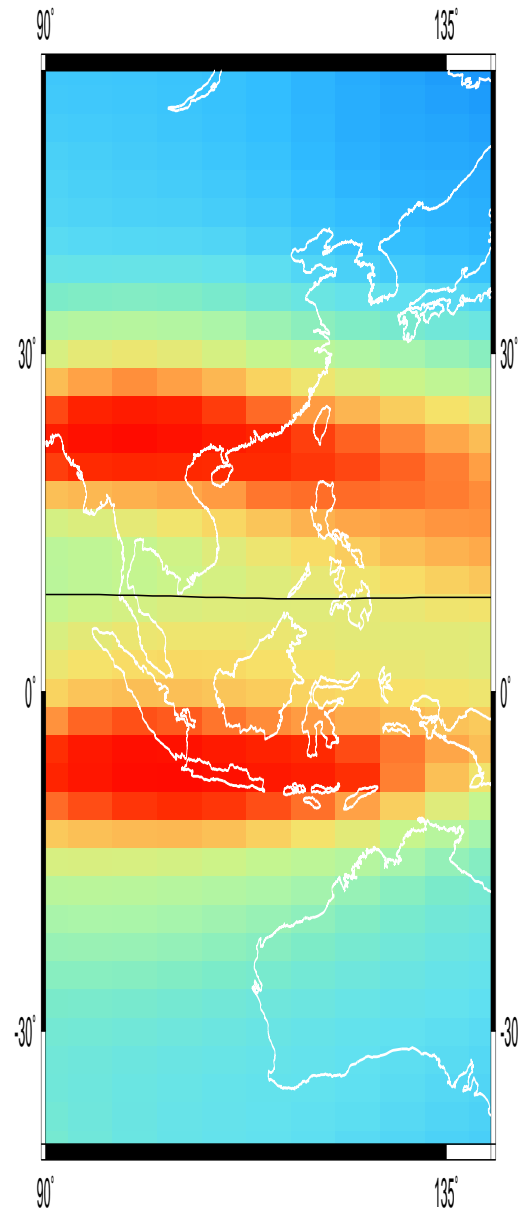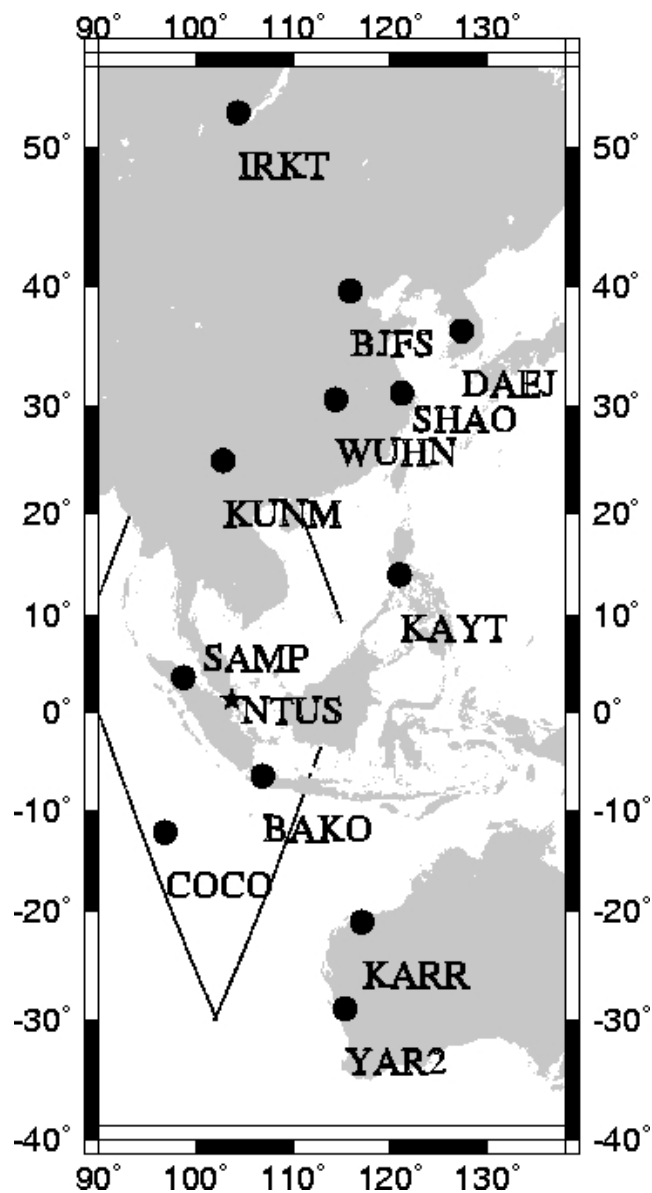# R-T ionos.: Improving at Very Long Dist.

Goal: To improve the real-time TEC determinations from GPS sites at very long distances (1000-3000 km), combining both ionospheric and geodetic computation, resolving and fixing the integer ambiguities common unknowns.

Experiment:

- 4 consecutive weeks in March-April 2001: days 65 - 92 (Solar Max. conditions, noon TEC seasonal maximum).

- 12 IGS GPS sites (-40 < latitude < +40 deg.), part of them affected by the equatorial anomalies.

- Quiet geomagnetic conditions during the weeks 1-2 (Kp < 4), and geomagnetic activity during the weeks 2-4 (day 90: Kp reached 8.5).
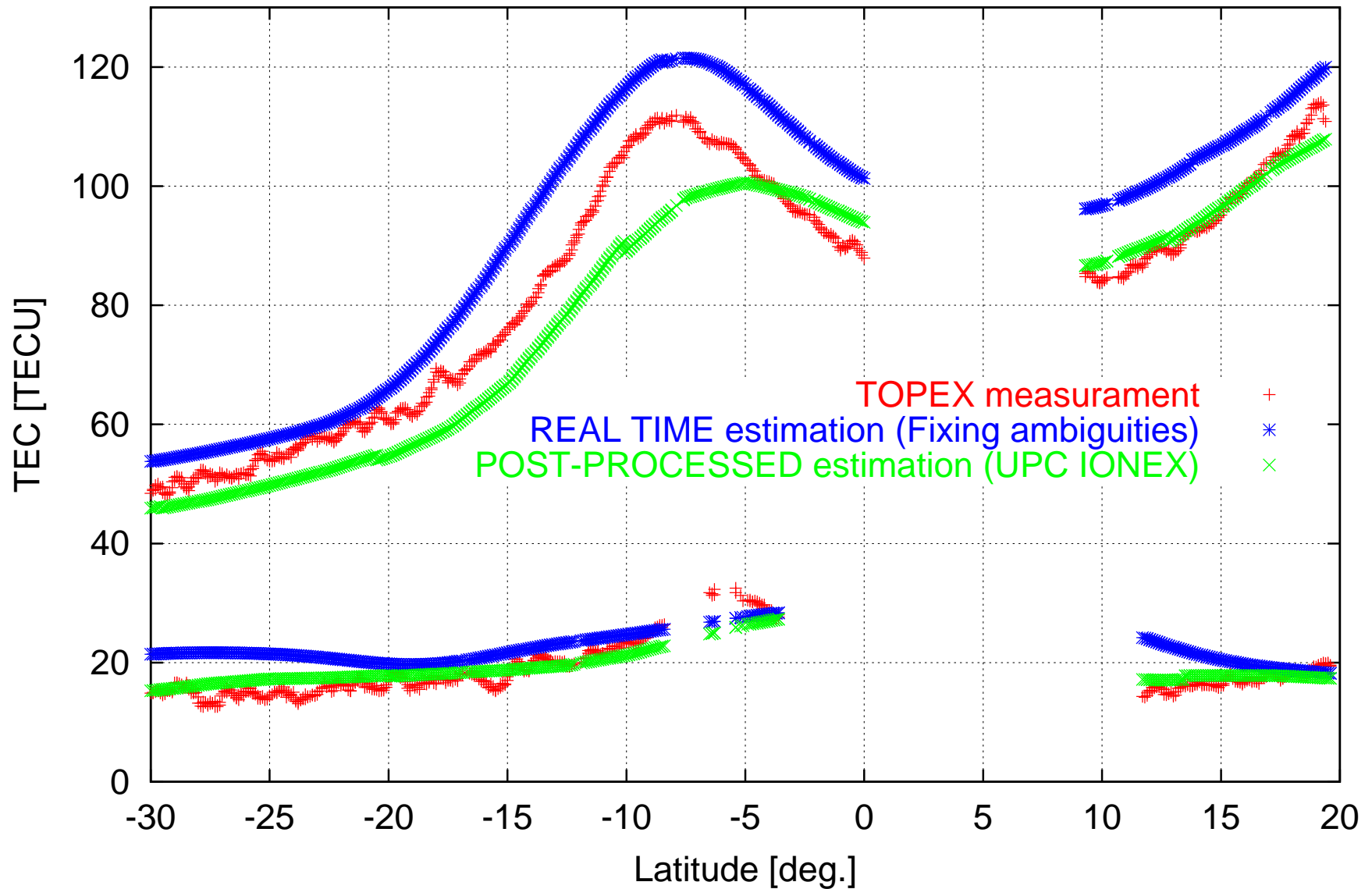
Details: Hernández-Pajares M., J.M. Juan, J. Sanz and O. Colombo, Improving the real-time ionospheric determination from GPS sites at Very Long Distances over the Equator, Journal of Geophysical Research - Space Physics, In Press, 2002.
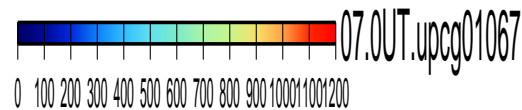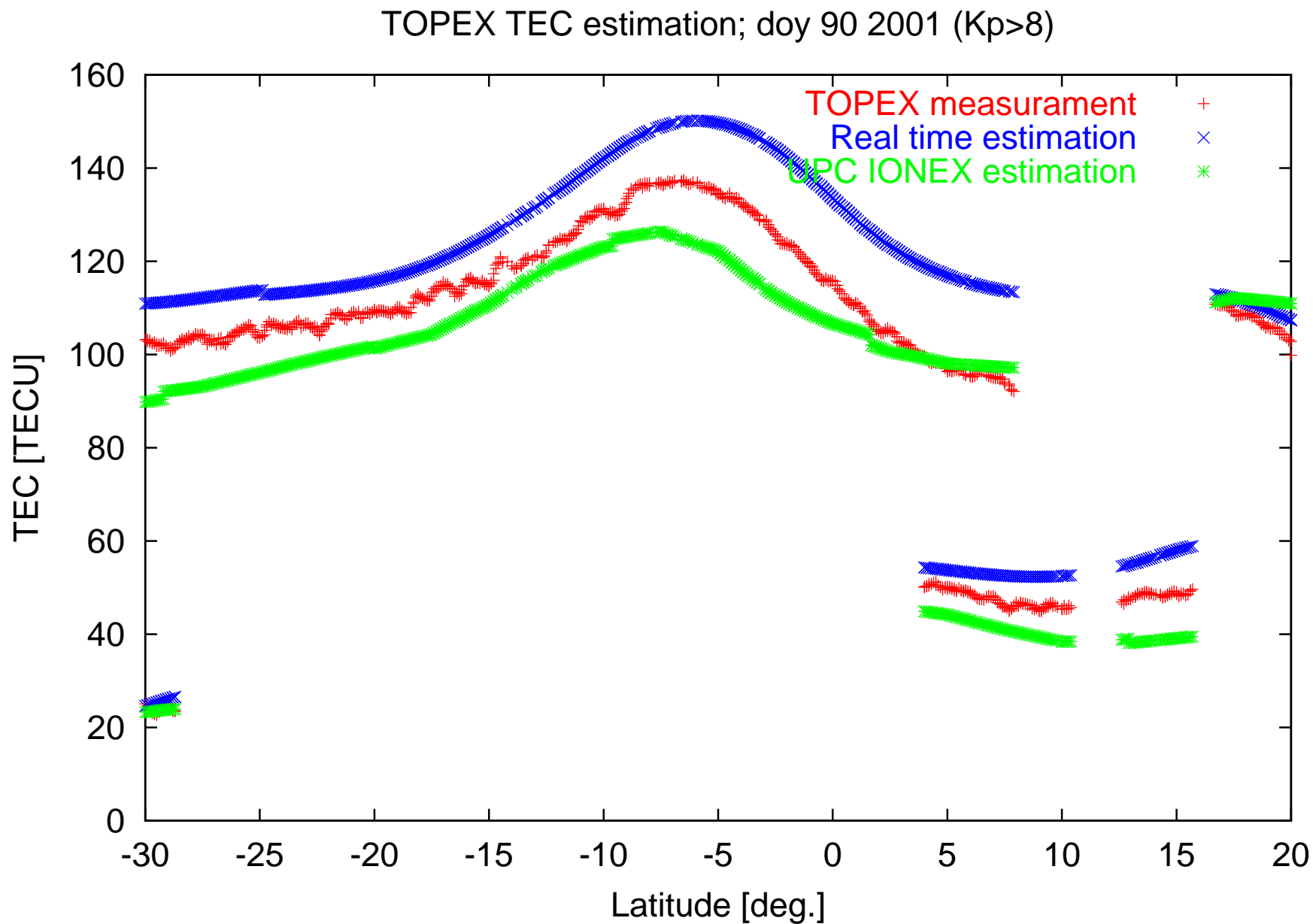
R-T ionos.: GPS / TOPEX TEC (Kp < 3)

TOPEX TEC estimation; doy 67 2001 (Kp<3)

TOPEX measurament +
REAL TIME estimation (Fixing ambiguities) *
POST-PROCESSED estimation (UPC IONEX) ×

TEC [TECU] vs Latitude [deg.]

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R-T ionos.: GPS / TOPEX TEC (Kp ≃ 8)

TOPEX TEC estimation; doy 90 2001 (Kp>8)

Legend:
- TOPEX measurament +
- Real time estimation ×
- UPC IONEX estimation ∗

Y-axis: TEC [TECU]
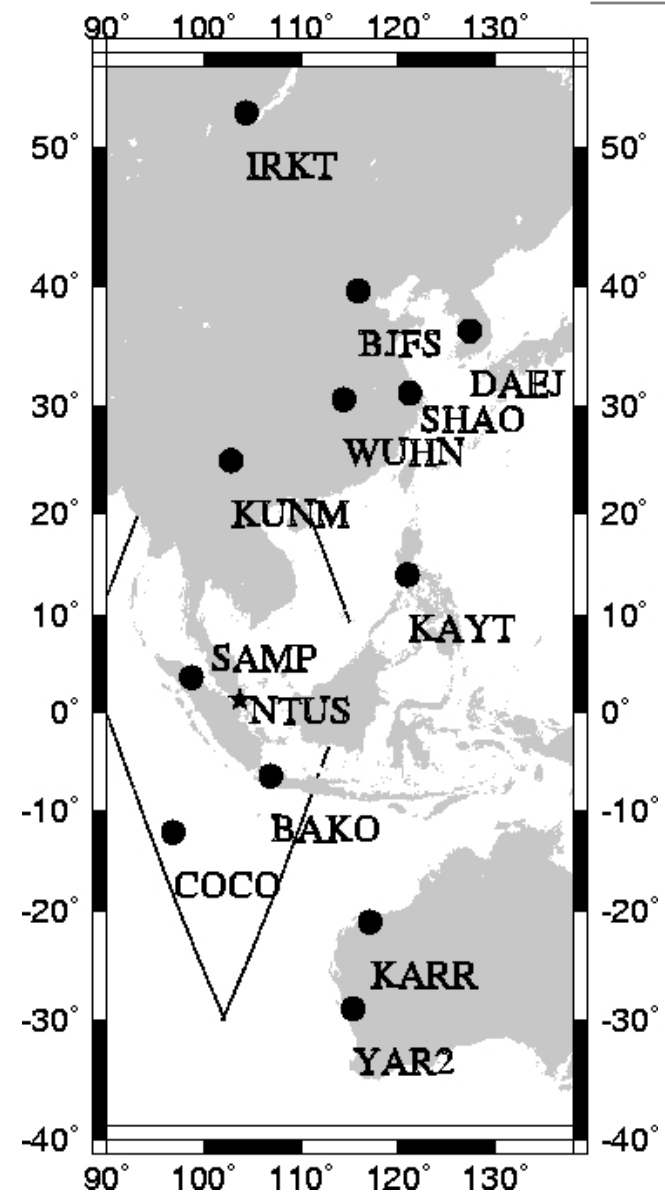X-axis: Latitude [deg.]

R-T ionos.: $\nabla\triangle STEC$ assesment

DD(STEC) RMS and Success in ambiguity resolution coco_karr (2354 km)
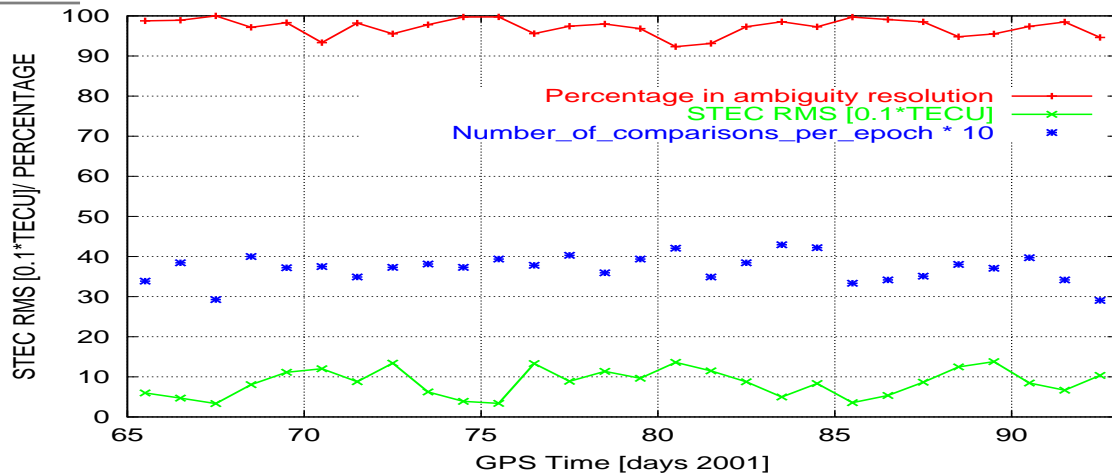
Sta.	Ref.	Dist. (km)	% Succ.	RMS [TECU]	# Obs.
IRKT	DAEJ	2507	93	1.2	8329
BJFS	DAEJ	1067	91	1.4	8131
KUNM	DAEJ	2640	95	1.0	3900
WUHN	DAEJ	1369	92	1.4	6358
SAMP	KARR	3341	95	1.1	6441
COCO	KARR	2354	97	0.9	9963
BAKO	KARR	1939	90	1.5	6121
YAR2	KARR	909	97	0.8	12630

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R-T ionos.: Comments

- The technique has been improved to get precise real-time STEC's from reference GPS sites in a difficult scenario: long distances (1000-3000 km) at low latitudes and Solar Maximum conditions, including periods of high geomagnetic activity.

- The real-time TEC obtained with the new strategy is more compatible with the TOPEX TEC + plasmaspheric component than the postprocessed solutions (each 2 hours).

- $RMS(\Delta\nabla STEC) \simeq 1$ TECU, regarding the truth $\Delta\nabla STEC$ obtained in postprocess after fixing the ambiguities.

- Equiv. success rate of $\simeq 95\%$ in real-time ambiguity resolution: potential applications such as precise (subdecimeter) navigation, and real-time meteorology.

- **This real-time approach is being implemented in different phases during 2002 to improve the gAGE/UPC TEC maps delivered to IGS.**

More details in:

- Hernández-Pajares M., J.M. Juan, J. Sanz and O. Colombo, Improving the real-time ionospheric determination from GPS sites at Very Long Distances over the Equator, Journal of Geophysical Research - Space Physics, In Press, 2002.

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