IGS

SESSION 5:

GROUND-BASED GPS IONOSPHERIC ESTIMATION

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 $d = tecval(IAAC) - TOPEXtec$:

$$mean = \sum d/n \ ,$$

- $rms\text{-}diff$ ... 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: 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.

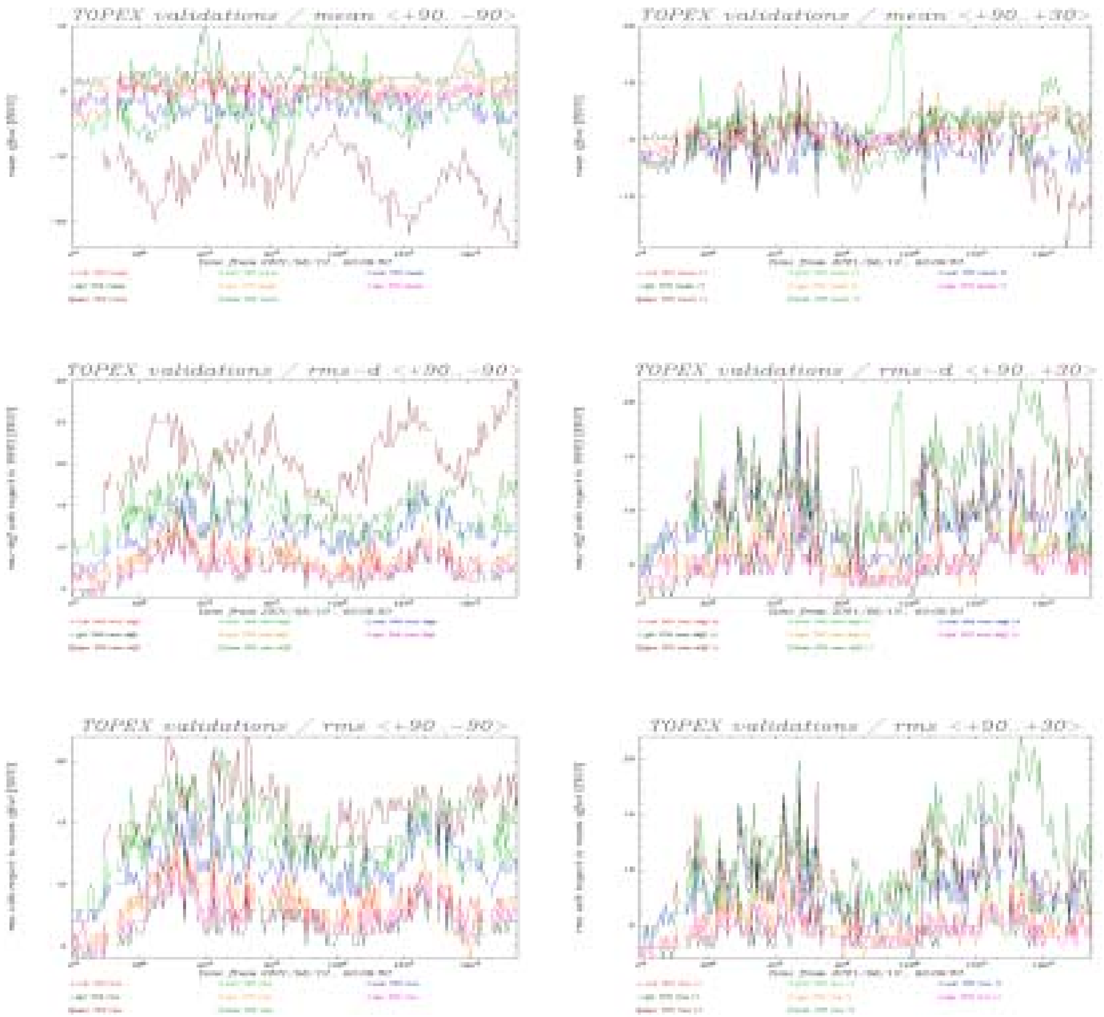
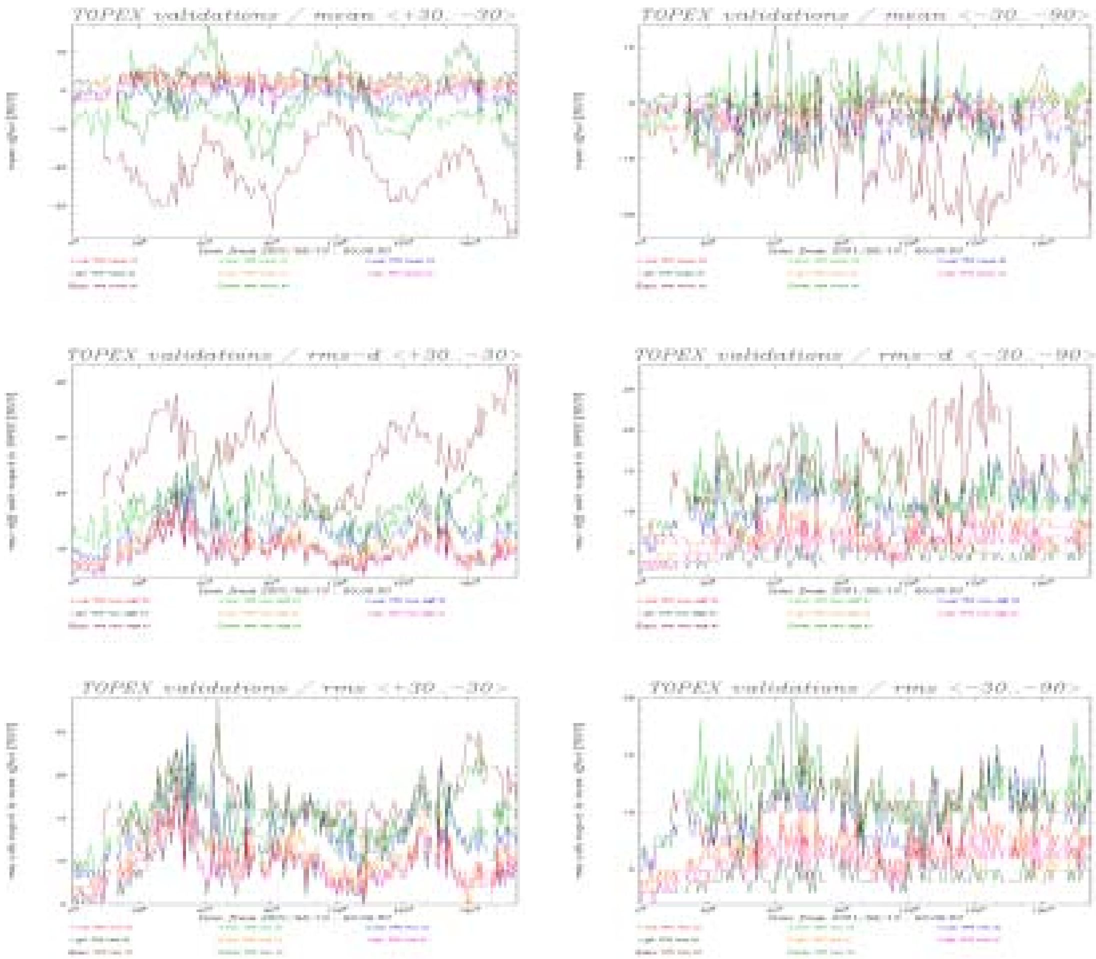


Figure 1: The basic TOPEX validation statistics $mean$, $rms\text{-}diff$ and rms.



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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CURRENT STATUS OF ESOC IONOSPHERE MODELING AND PLANNED IMPROVEMENTS

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SUMMARY

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:

- The ionosphere is a rapidly changing medium. ➔ *The current 24 hours time resolution must be enhanced with a sequential estimate processor: Establishment of normal equation systems with a certain time resolution, say 1 hour, and estimation of the ionosphere model parameters on one hand and of the Differential Code Biases ($DCBs$) on the other hand from this basic set of normal equations in different ways*
- The current mathematical model describes the vertical electron density distribution as only one layer. ➔ *The ionosphere must mathematically be described as superimposion of different layers.*
- From pure Total Electron Content *(TEC)* observables it is difficult to estimate profile shape parameters. ➔ *Electron density profiles derived from Champ occultation data will be introduced as additional observables to allow for a better spatial resolution.*

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.

Brief summary of UPC ionospheric activities

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The authors report several ionospheric activities with GPS data, including those of IGS stations: the daily generation of global TEC maps, the development of new algorithms for real-time ionospheric corrections and for electron density retrieval. Let's describe them briefly:

The generation of **TEC Global Ionospheric Maps** (GIM's), from IGS data as an IGS Associate Analysis Center, are being done and delivered to the IGS community on a daily basis from June 1st 1998 (some details of the technique are described in *Hernández-Pajares M., J.M. Juan and J. Sanz, New approaches in global ionospheric determination using ground GPS data, Journal of Atmospheric and Solar-Terrestrial Physics, Vol 61, 1237-1247, 1999*). Moreover, since 2001, weights for the 5 different IAAC's involved in GIM's computation are being generated on a weekly basis as a function of the RMS for STEC predictions over a certain subset of IGS stations. This is done as one IGS Associate Validation Center (IAVC).

In order to improve the capability of computing **accurate ionospheric corrections in real-time**, we have developed a new technique combining a tomographic modeling of the Ionosphere with an accurate geodetic computation, which allows to improve the performance of both ionospheric and navigation software (*Hernández-Pajares M., J.M. Juan, J. Sanz, O.L. Colombo, Application of ionospheric tomography to real-time GPS carrier-phase ambiguities resolution at scales of 400-1000 km and with high geomagnetic activity, Geophysical Research Letters, Vol 27, No 13, 2009-2012, 2000*). The performance of this approach for fixed GPS sites separated several thousands of kilometers has been tested over four consecutive weeks in hard ionospheric conditions and over a wide range of latitudes crossing the equator (*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*).

The last but not the least, in the context of the existing and incoming GPS receivers on board Low Earth Orbiters with antennas pointing to the Earth limb (CHAMP, SAC-C,...), the authors have developed **algorithms to improve the electron density estimations**. They are based on modeling the horizontal gradients of the electron content with a TEC model, that can be computed from IGS fixed sites. The new technique also takes into account the topside electron content, specially in very low satellites such as CHAMP (*Hernández-Pajares M., J.M. Juan, J. Sanz, Improving the Abel inversion by adding ground data LEO radio occultations in the ionospheric sounding. Geophysical Research Letters, 27, 2743-2746, 2000*). Moreover, we have applied new schemes combining complementary kind of data in the common framework of a tomographic voxel model, such as ground GPS and ionosonde which can provide a similar performance as the use of LEO GPS occultation data.

CODE Ionosphere Products

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Abstract

The list of ionosphere products as regularly generated at CODE includes final, rapid, as well as predicted products. The vertical total electron content (VTEC) is modeled in a solar-geomagnetic reference frame primarily using a spherical harmonics (SH) expansion up to degree and order 15. To convert line-of-sight TEC into vertical TEC, a modified single-layer model mapping function approximating the JPL extended slab model mapping function is adopted (to retrieve VTEC consistent to TOPEX-derived TEC). No external ionosphere model is used.

The global ionosphere map (GIM) information is made available generally in three different forms: (1) Bernese ionosphere files containing the originally estimated SH coefficients, (2) IONEX (IONosphere map EXchange) files containing VTEC grid maps at 2-hour intervals, and (3) content-reduced RINEX navigation data files containing daily Klobuchar-style ionospheric (alpha and beta) coefficients best fitting the (corresponding) IONEX information. In the CODE data archive, time series of all these products are accessible without any gaps back to 1995 (see www.aiub.unibe.ch/ionosphere.html for details). Solely the final product in IONEX format is delivered to the IGS. For comparison purposes, also our final Klobuchar-style model and the ionospheric model broadcast by the GPS system are supplied by CODE in form of IGS-compatible IONEX files. It is worth mentioning that, starting with GPS week 1158, our final ionosphere results are no longer results from a 24-hour analysis but results for the middle day of a 72-hour combination analysis done on the normal equation level. In this way, discontinuities at day boundaries can be minimized and a time-invariant quality level is achieved.

The new possibility to stack and manipulate GIM-related normal equations takes us a lot further towards producing a GPS/TOPEX-combined ionosphere product. The IGS policy with respect to "combined" products, specifically combinations with non-GPS/GLONASS data, has to be reviewed.

IGS IONEX files contain 12 VTEC maps for times 01:00, 03:00, 05:00, ..., 23:00 UT. This circumstance makes the interpolation between 23:00 and 01:00 UT difficult, especially for users interested in TEC information without discontinuities at day boundaries. Consequently, we propose to start to include 13 maps in IONEX files, referring to epochs 00:00, 02:00, 04:00, ..., 24:00 UT.

Instrumental biases, so-called differential P1–P2 code biases (DCB), for all GPS satellites and ground stations are an important by-product of the ionospheric analysis. They are estimated at CODE as constant values for each day, simultaneously with the parameters used to represent the global VTEC distribution. The DCB datum is defined by a zero-mean condition imposed on the satellite bias estimates. P1–C1 bias corrections are taken into account if needed. Latter corrections are routinely generated at CODE in the global satellite and station clock estimation procedure and newly as part of the final widelane ambiguity resolution step (on the basis of ambiguity-fixed double differences related to the Melbourne-Wübbena linear combination of code and phase measurements). Sliding 30-day averages of both P1–P2 and P1–C1 DCB retrievals are computed every day. At the end of each month, month-specific averages are produced and stored in our DCB data base. P1–C1 DCB files specific to the CC2NONCC utility program are offered.

For global ionosphere mapping in particular, a good GPS tracking station coverage is indispensable. Against this background, we could show that there is still much potential in improving the IGS data availability and latency, respectively. These problems actually concern final and principally rapid and ultra-rapid applications. Moreover, data from very remote stations (typically tide gauge stations) not yet meeting the few-day delay requirement might be utmost useful, not only for IGS ionosphere mapping but also for global orbit and clock determination.