IGS PRODUCTS FOR THE IONOSPHERE
- ONE YEAR OF IONO_WG ACTIVITIES -

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ABSTRACT

At the 1998 IGS Analysis Centers Workshop, 9-11 February in Darmstadt, a position paper about the ionosphere was presented by J. Feltens and S. Schaer (Feltens et al., 1998). This paper analysed the existing IGS infrastructure with regard to the establishment of an ionosphere service as new component of the IGS and pointed out the potential of future IGS activities within the area of the ionosphere for navigation, radio applications, science and other tasks. At the end of the Darmstadt workshop it was decided to establish an IGS Ionosphere Working Group (Iono_WG).

The Iono_WG was then formally established by the IGS Governing Board at its meeting of May 28, 1998 in Boston. The working group's main short-term goal is the routine provision of ionospheric TEC maps with a 2-hours resolution and of daily sets of GPS satellite differential code bias (DCB) values, based on the evaluation of GPS dual-frequency tracking data. The working group's medium- and long-term goals are the development of more sophisticated ionosphere models, also of regional and local extent, with near-real-time and real-time availability. The final target is the establishment of an independent IGS ionosphere model.

The pilot phase commenced on 1 June 1998. Four Ionosphere Associate Analysis Centers (IAACs) started with the routine delivery of their ionosphere products to the CDDIS Global Data Center. Some time later a fifth IAAC joined to these activities.

A first version of a comparison/combination algorithm was worked out and coded in form of a Fortran 77 program. Based on this algorithm a routine comparison of the IGS ionosphere products was started. However, the IAACs use very different approaches in their processing to represent the ionosphere mathematically; this reflects also in the comparison results. Consequently the Iono_WG decided that the next important step must be validations with independent non-GPS-derived ionosphere data. This step is currently under preparation.

It is the intent of this project report to present the current status of the Iono_WG activities and to give an overview over the first results obtained.

INTRODUCTION

This project report will start with an overview over the pilot phase activities, point out some IGS standards for ionosphere products, and describe the principles of ionosphere processing at the different IAACs.

The next aspect treated in the report will be some details about the routine comparisons, which are done at the designated Ionosphere Associate Combination Center (IACC) at ESOC. Some results obtained with the current comparison scheme are presented.

The results obtained so far show obvious deficiencies in the current comparison approach and demand for improvements in the comparison algorithm itself as well as in the IAAC ionosphere models. So the project report will present at this place concepts on how the Iono_WG intends to validate the ionosphere models contributed by the different IAACs in order to identify individual weaknesses, to get ideas how to improve the models and to calibrate them with respect to each other, to modify the comparison scheme, and, last not least, to achieve a better understanding.

Next the project report will then give an outlook on intended future activities of the Iono_WG.

Finally conclusions will resume the Iono_WG's achievements so far reached and relate these to the Iono_WG's initial aims and new targets.

THE PILOT PHASE

The pilot phase basic activities are the routine provision of TEC maps and GPS satellite DCBs in IONEX format files (Schaer et al., 1997) by the IAACs and the comparison of these ionosphere products by the IACC at ESOC. 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, Darmstadt, Germany.
- JPL, Jet Propulsion Laboratory, Pasadena, California, U.S.A.
- NRCan, National Resources Canada, Ottawa, Ontario, Canada.
- UPC, Polytechnical University of Catalonia, Barcelona, Spain.

The following principal approaches are used by these IAACs to model the ionosphere:

- CODE: The ionosphere's TEC is modeled as single layer with spherical harmonics of degree 12 and order 8 (see e.g. Wild et al., 1989 and Schaer et al., 1998).

- ESOC: The ionosphere's electron density is modeled with a 3-dimensional Chapman Profile approach, and the TEC is obtained from the integrated electron density along the Chapman Profile (see e.g. Feltens, 1998a).

- JPL: The ionosphere's TEC is modeled as single layer with a tessellation into spherical triangles at whose vertices TEC values are estimated (see e.g. Mannucci et al., 1998).

- NRCan: The ionosphere's TEC is modeled as single layer with a subdivision into small cells of latitude and local time in which TEC values are estimated (see e.g. Gao et al.).

- UPC: In a tomographic model the ionosphere is subdivided in 3-dimensional cells arranged in different layers in which electron content values are estimated. TEC values are then obtained by summing vertically up over the cells (see e.g. URL under http://maite152.upc.es/~manuel/manuel/manuel.html).

More details about the different IAACs modeling, e.g. the type of TEC observables used, time resolution, etc., can be found in the above stated references.

The IGS standards, defining the form in which the ionosphere products must be delivered to CDDIS, are declared in the recommendations of the Darmstadt 1998 IGS Workshop Position Paper (Feltens et al., 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, 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.

COMPARISONS

In order to put the IACC at ESOC into a position to do the routine comparison of iono-sphere products that are delivered routinely from the IAACs, the new Fortran 77 program CoMParison/CoMBination (CMPCMB) was established from scratch.

Each IAAC delivers per day a set of 12 global TEC maps plus a daily set of GPS satellite DCBs in form of an IONEX file (Schaer et al., 1997). Since already now 5 different IAACs contribute with their products to the IGS ionosphere pilot service, and further IGS Analysis Centers indicated their intention to become active as new IAACs in the future, a way had to be found how the comparison could be done efficiently. If the products of each IAAC would be compared with each other IAAC, there would be, in the case of 5 IAACs, 10 possible pairs that must be compared, and in the case of 6 contributing IAACs the number of pairs would increase to 15, and so on. To keep the extent of comparison in an acceptable frame, it was thus decided to compute per reference epoch (each of a daily IONEX file's 12 TEC maps refer to a reference epoch) from the different IAAC TEC maps a mean TEC map and to compare for that reference epoch each IAAC TEC map with that mean TEC map. Since it was well known from the beginning, that the different IAAC models are based on very different mathematical approaches, it was thought that a purely statistically comparison scheme, being based on weighted means, would be the best concept. A complete description of this comparison algorithm is attached as Appendix A to this project report.

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

As already pointed out above, the IAACs use very different approaches to establish their TEC maps, resulting in very different temporal and spatial resolutions, and the RMS maps provided in the IONEX files represent only the internal accuracy of the respective approach. These circumstances reflected also in the comparison results, and it became clear quite soon, that the comparison scheme has to be improved on one side, and that the different IAAC models must be validated and calibrated on the other side. These two tasks are essential for the achievement of a common combined IGS product! So, under the impression of these comparison results the Iono_WG decided:

- not to evaluate all the data accumulated since 1 June 1998 at CDDIS and
- not to deliver any "combined" products to CDDIS for public use

and to start instead with an intense validation and calibration of the different ionosphere models in order to assess the quality of the TEC maps originating from the different modeling approaches.

Before coming closer to the validations aspect, some comparison results shall show the necessity of validations and models calibration and improvements. The comparison program CMPCMB is called by a Tcl which runs a loop over all requested days to process one week. Within this loop CMPCMB is called for each day. After the CMPCMB call, plots of different kind of maps are created for that day. It is the task of these maps to illustrate the comparison results. All in all the comparison output per day is:

- "igsg*DDD*0.*YY*s" daily comparison summary;
  '*YY*' 2-digit year number, e.g. '99' for 1999, '00' for 2000,
  '*DDD*' 3-digit day-of-the year number, e.g. '365' for 31 Dec,

- "igsg*DDD*0.*YY*i" IONEX file containing the "mean" (or "combined") TEC maps & GPS satellite DCBs,

- "*III*g*DDD*0.*YY*d" per IAAC an IONEX file containing the TEC & DCB differences with respect to "mean"; '*III*' 3-character IAAC identifier, e.g. 'esa' for ESA/ESOC,

- GIF animation files showing in a film-like manner for each IAAC its TEC + RMS + DTEC maps, DTEC with respect to the IGS "mean" TEC. For IGS "mean" TEC + RMS animation files are given too. These GIF files can be viewed via netscape.

All these comparison products are made available to the Iono_WG through ESOC's FTP account: ftp anonymous@nng.esoc.esa.de ; a short summary is e-mailed to all Iono_WG members. Because of limited space capacity, comparison products older than 3 weeks must be archived and deleted thereafter. In the following an extract of comparison products will be presented for 25 April 1999 (doy 99115). First of all some parts of the daily comparison summary "igsg1150.99s" (see Feltens, 1998b) are shown (each day's summary provides in its header a comprehensive description about its content):

```
Condensed overview:

Table 1   1st level general statistics on all 12 daily TEC maps from
          all IAACs in [TECU] / 25 Apr 1999 (99115):

          "o" = general offset (bias) with respect weighted mean IGS
                TEC map
          "S" = 1st level sigma
```

Epoch	cod "o"	cod "S"	emr "o"	emr "S"	esa "o"	esa "S"	jpl "o"	jpl "S"	upc "o"	upc "S"	"o"	"S"
01:00	-1.2	1.9	0.0	3.0	0.3	3.8	2.0	3.3	-0.6	5.3		
03:00	-1.1	1.8	-0.3	2.5	0.3	3.4	2.5	3.2	-0.2	4.9		
05:00	-1.1	2.0	-0.6	2.0	0.0	2.8	3.0	2.7	0.1	4.8		
07:00	-1.2	2.0	-0.5	1.7	-0.1	2.5	3.4	2.8	0.4	4.5		
09:00	-1.4	2.0	-0.3	1.7	-0.3	2.7	3.5	3.0	0.7	4.1		
11:00	-1.6	2.0	0.1	2.0	-0.5	2.6	3.1	2.9	0.5	3.9		
13:00	-1.8	2.1	0.7	2.9	-0.5	2.8	2.5	3.1	0.1	3.5		
15:00	-1.8	2.4	1.3	3.6	-0.5	2.7	2.6	3.5	-0.1	4.0		
17:00	-1.6	2.7	1.5	4.0	-0.5	2.8	2.5	4.2	-0.1	4.5		
19:00	-1.5	2.9	1.2	3.7	-0.4	2.8	2.3	4.7	0.2	5.3		
21:00	-1.4	3.1	0.8	3.5	-0.2	3.0	2.1	4.9	0.1	6.0		
23:00	-1.3	3.4	0.4	3.3	0.0	3.2	2.3	5.1	-0.1	6.7		

```
Information per epoch:

>>> Reference epoch:   01 hours          at 25 Apr 1999 (99115)

    :
    :
    :

>>> Reference epoch:   07 hours          at 25 Apr 1999 (99115)

Table 2.04 General combination statistics / 25 Apr 1999 (99115):

           np1   = no. of grid points where all IAACs provided non-9999 values
           np2   = no. of grid points where one IAAC  provided non-9999 values
           n9999 = no. of grid points where one IAAC  provided 9999 values
           rms1  = overall RMS for one IAAC computed from np1 (unweighted mean)
           wgt1  = 1/rms1^2   IAAC weight for weighted mean
```

```
           rms2  = overall RMS for one IAAC computed from np2 (unweighted mean)
           wgt2  = 1/rms2^2   IAAC weight, only printed out for information
           wrms  = weighted mean overall RMS for one IAAC computed from np1

IAAC         ||   cod    |   emr    |   esa    |   jpl    |   upc    |
============++=========+=========+=========+=========+=========+=========
np1      5039|          |          |          |          |          |
np2          ||     5112|     5112|     5112|     5112|     5039|
n9999        ||        0|        0|        0|        0|       73|
rms1         ||   2.9    |   2.3    |   2.7    |   3.8    |   4.3    |
wgt1         ||  0.12    |  0.19    |  0.14    |  0.68E-01|  0.54E-01|
rms2         ||   2.9    |   2.3    |   2.7    |   3.8    |   4.3    |
wgt2         ||  0.12    |  0.19    |  0.14    |  0.68E-01|  0.54E-01|
wrms         ||   2.6    |   1.8    |   2.3    |   4.3    |   4.8    |

Table 3.04 bias and rms-matrices for each IAAC with respect to weighted mean
           in [TECU] / 25 Apr 1999 (99115).

IAAC    || 1st level | 2nd level sig      | 3rd level sig
=======++==========+===================+=======================================
        ||           |                    |
cod     ||  overall  |  1.9    |  2.0     |  1.3    |  1.6    |  1.4    |  1.8
        ||  bias =   |---------+--------- |---------+---------+---------+---------
        ||   -1.2    |  1.5    |  2.6     |  2.8    |  2.0    |  1.4    |  2.9
        ||           |                    |---------+---------+---------+---------
        ||  sig =    |                    |  1.6    |  1.3    |  1.8    |  3.5
        ||    2.0    |                    |---------+---------+---------+---------
        ||           |                    |  1.8    |  1.4    |  2.5    |  2.2

IAAC    || 1st level | 2nd level sig      | 3rd level sig
=======++==========+===================+=======================================
        ||           |                    |
emr     ||  overall  |  1.2    |  1.8     | 0.99    |  1.1    |  1.2    |  1.3
        ||  bias =   |---------+--------- |---------+---------+---------+---------
        ||  -0.52    |  1.5    |  2.2     |  1.3    |  1.4    |  2.7    |  1.6
        ||           |                    |---------+---------+---------+---------
        ||  sig =    |                    |  1.5    |  1.4    |  1.4    |  2.0
        ||    1.7    |                    |---------+---------+---------+---------
        ||           |                    |  1.9    |  1.2    |  2.6    |  2.5

IAAC    || 1st level | 2nd level sig      | 3rd level sig
=======++==========+===================+=======================================
        ||           |                    |
esa     ||  overall  |  2.4    |  2.7     |  1.9    |  2.9    |  3.1    |  2.3
        ||  bias =   |---------+--------- |---------+---------+---------+---------
        ||  -0.93E-01|  2.4    |  2.6     |  2.9    |  1.5    |  2.5    |  3.0
        ||           |                    |---------+---------+---------+---------
        ||  sig =    |                    |  1.9    | 0.99    |  1.8    |  2.8
        ||    2.5    |                    |---------+---------+---------+---------
        ||           |                    |  4.1    |  1.1    |  1.7    |  3.6

IAAC    || 1st level | 2nd level sig      | 3rd level sig
=======++==========+===================+=======================================
        ||           |                    |
jpl     ||  overall  |  2.1    |  3.1     |  1.8    |  1.5    |  2.5    |  1.7
        ||  bias =   |---------+--------- |---------+---------+---------+---------
        ||    3.4    |  2.3    |  3.4     |  3.0    |  1.6    |  3.6    |  4.1
        ||           |                    |---------+---------+---------+---------
        ||  sig =    |                    |  2.8    |  1.9    |  3.3    |  2.6
        ||    2.8    |                    |---------+---------+---------+---------
        ||           |                    |  1.9    |  2.3    |  4.2    |  3.6

IAAC    || 1st level | 2nd level sig      | 3rd level sig
=======++==========+===================+=======================================
        ||           |                    |
upc     ||  overall  |  2.8    |  4.4     |  3.0    |  1.6    |  2.5    |  3.7
        ||  bias =   |---------+--------- |---------+---------+---------+---------
        ||   0.40    |  4.3    |  6.1     |  3.6    |  2.5    |  3.5    |  6.8
        ||           |                    |---------+---------+---------+---------
        ||  sig =    |                    |  5.3    |  3.4    |  4.3    |  9.9
        ||    4.5    |                    |---------+---------+---------+---------
        ||           |                    |  4.7    |  3.5    |  4.3    |  3.7

    .
    .
    .
```

Table 4 DCBs combination summary / 25 Apr 1999 (99115):

wDCB = IAAC weights used for IGS DCB combination
dDCB = differences IAAC DCB values minus IGS DCB values [ns]
Y/N = a DCB value was provided/not provided by the IAAC

IAAC	cod	emr	esa	jpl	upc	
wDCB	95.	34.	13.	40.	27.	
PRN	Y/N dDCB	Y/N dDCB	Y/N dDCB	Y/N dDCB	Y/N dDCB	Y/N dDCB
01	Y-0.17E-01	Y 0.11	Y 0.55E-01	Y-0.16	Y 0.13	
02	Y-0.92E-02	Y-0.47E-01	Y-0.10	Y 0.16	Y-0.91E-01	
03	Y 0.10	Y-0.28	Y-0.35	Y 0.17E-01	Y 0.14	
04	Y-0.85E-01	Y 0.21	Y-0.16	Y 0.35E-01	Y 0.51E-01	
05	Y 0.41E-01	Y-0.45E-01	Y 0.40	Y 0.14E-01	Y-0.30	
06	Y 0.16E-01	Y-0.10	Y 0.29	Y-0.57E-01	Y 0.24E-01	
07	Y-0.21E-01	Y 0.13	Y-0.24E-02	Y 0.40E-01	Y-0.16	
08	Y-0.91E-01	Y 0.26	Y 0.51	Y-0.89E-01	Y-0.13	
09	Y-0.50E-01	Y 0.11	Y 0.49	Y 0.11	Y-0.36	
10	Y-0.11	Y 0.19	Y 0.49E-03	Y 0.20	Y-0.16	
13	Y-0.46E-01	Y 0.97E-01	Y-0.25	Y 0.20	Y-0.14	
14	Y 0.95E-01	Y-0.24	Y-0.26	Y-0.24E-02	Y 0.96E-01	
15	Y 0.73E-01	Y 0.28E-01	Y-0.21	Y-0.83E-01	Y-0.64E-01	
16	Y 0.42E-01	Y-0.20	Y-0.39	Y-0.31E-01	Y 0.34	
17	Y 0.33E-01	Y-0.15	Y 0.53E-01	Y 0.30E-01	Y 0.77E-02	
18	Y 0.71E-01	Y 0.93E-01	Y-0.59	Y 0.39E-01	Y-0.14	
19	Y 0.39E-01	Y 0.13	Y-0.74	Y 0.96E-02	Y 0.47E-01	
21	Y 0.52E-02	Y-0.33	Y 0.11	Y-0.31E-01	Y 0.39	
22	Y 0.84E-02	Y-0.94E-01	Y 0.16	Y-0.12	Y 0.19	
23	Y 0.48E-01	Y-0.28	Y 0.19	Y 0.30E-01	Y 0.48E-01	
24	Y-0.11	Y 0.67E-01	Y 0.12	Y 0.15	Y 0.12E-02	
25	Y-0.13E-01	Y 0.25	Y 0.28	Y-0.32	Y 0.75E-01	
26	Y-0.50E-01	Y 0.92E-01	Y-0.12	Y 0.23	Y-0.23	
27	Y-0.10	Y 0.74	Y-0.13	N	Y-0.52	
29	Y-0.65E-01	Y 0.26	Y 0.29	Y-0.25	Y 0.14	
30	Y 0.44E-01	Y-0.90E-01	Y 0.43	Y-0.12	Y-0.68E-01	
31	Y 0.46E-01	Y-0.17	Y-0.22	Y 0.26E-02	Y 0.16	

Table 1 of this summary provides a condensed overview over the comparisons of the TEC maps of all 12 reference epochs for that day. For all 12 epochs each IAAC's general offset (bias) and its overall sigma with respect to the IGS "mean" TEC map are listed. One can see very clearly that each IAAC has its individual offset with respect to the "mean". The Tables 1 of all summaries of one GPS week are copied into a short summary and then e-mailed to all Iono_WG members.

Table 1 is then followed by a Table 2.*i* and a Table 3.*i* for each epoch *i*, which provide more detailed information. Table 2.*i* condenses the *rms* values and the *weights* that came out of the unweighted and of the weighted mean for each IAAC. Table 3.*i* presents, in form of sigma-matrices, the order of agreement between the IAACs TEC maps and the IGS "mean" map at different geographic regions. 4 levels of resolution are provided for each IAAC (for a closer description of these matrices take a look into the daily summary file's header). In principle these sigma-matrices can the viewed like geographic maps. Zones with good agreement will show a low sigma-value, while areas of worse agreement have large sigmas. Especially around the equator large sigma-values can often be observed, then indicating that an IAAC has problems to represent the ionosphere in that region.

To the of the daily summary file Table 4 is attached. This table condenses the results of the DCBs comparison.

As already mentioned above, the IAACs use very different approaches to represent the ionosphere mathematically. This reflects also in the comparison results and can be seen in form of large sigma values in the Tables 3.*i*. These differences can of course also be seen when directly comparing the TEC maps of the different IAACs. To make them more transparent, for each IAAC TEC- and DCB-differences with respect to the IGS "mean" are put into files in IONEX format files "*III*g*DDD*0.*YY*d", so that each IAAC can see in which geographic regions it has the biggest problems. Figure 1 presents an example of such a TEC difference map:

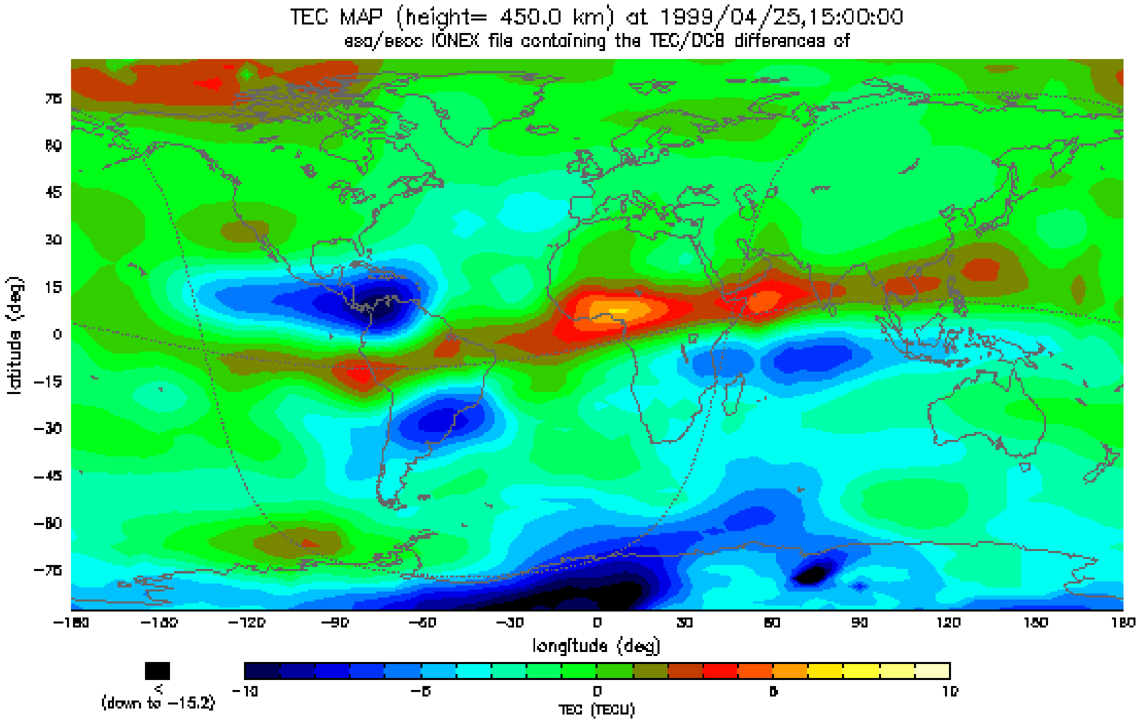

Figure 1: TEC difference map containing values of IAAC TEC minus IGS "mean" TEC.

Figure 1 shows typically high values along the geomagnetic equator, but also at the high northern polar regions. Reasons for that can be a bad station coverage in these areas and, at the equator, adaption problems of the model to fit the observables. Sometimes even systematic tilts of the overall niveau can be observed at some models, concretely systematically higher TEC values on the northern than on the southern hemisphere.

The other important topic of comparisons are the DCBs. Figure 2 presents a comparison between DCB values of the IAACs, the IGS “mean” and values from DLR Fernerkundungsstation Neustrelitz for the timespan 25 April to 15 May 1999 (doys 99115 - 99135):

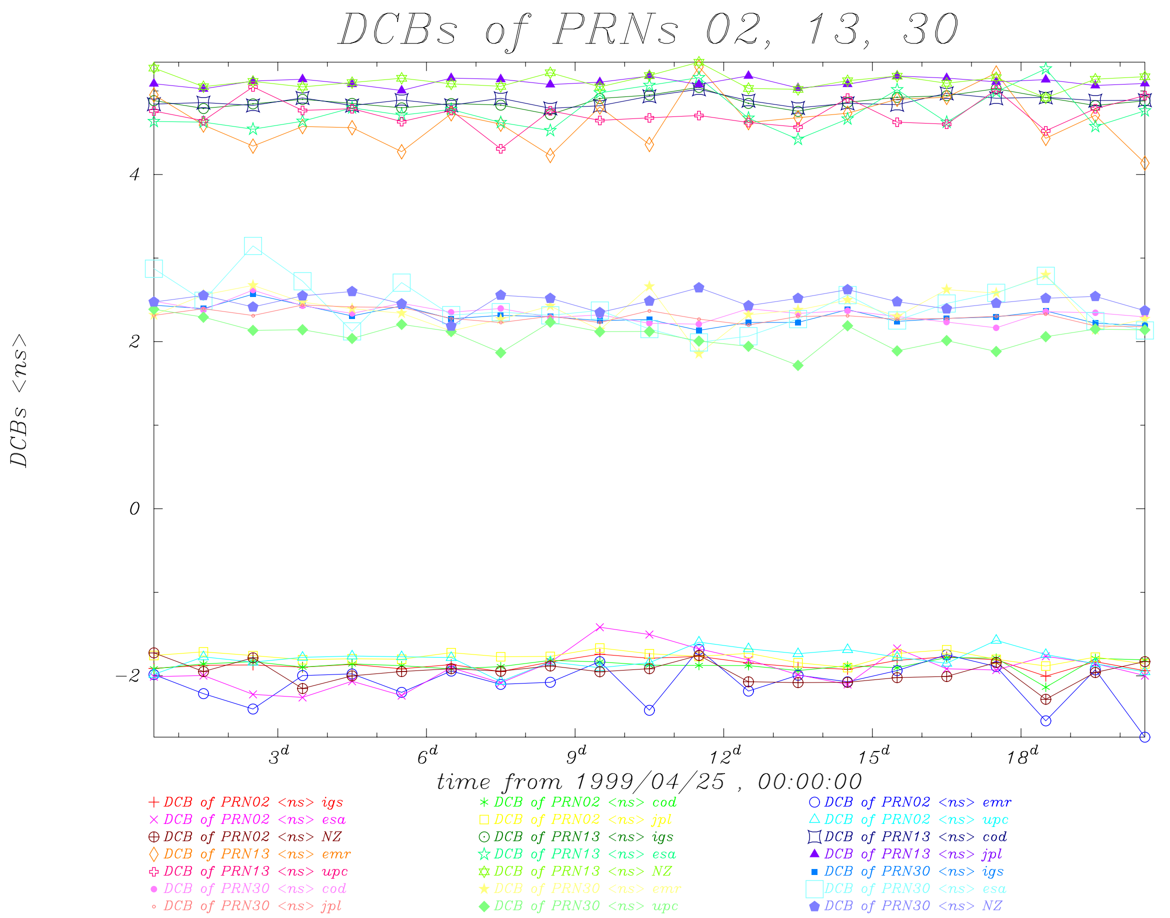

Figure 2: DCBs from IAACs, IGS “mean” and DLR Neustrelitz for PRNs 02, 13 and 30.

The overall agreement between the different DCB series seems to be around $0.3\ ns$, while peaks up to $0.5\ ns$ can be reached.

VALIDATIONS

The major tasks of the anticipated validations are: 1) to find out the capability of the individual IAAC ionosphere models to represent the “true” ionosphere in/at different geographical regions/times, 2) to calibrate the different IAAC models with respect to each other and with the “true” ionosphere, and to remove systematic discrepancies, like constant offsets or systematic tilts of some models, 3) to find out objective accuracy parameters for each IAAC model which can be used to define optimal weights for a comparison and combination to a common IGS ionosphere product, 4) to get ideas how to improve, based on the findings of the prior points, the comparison algorithm and to a achieve a reliable combination scheme.

In order to validate the IAAC ionosphere models, several proposals were made by different Iono_WG members:

1) JPL has offered to provide VTEC data derived from TOPEX altimeter observables to the working group to enable validations, and at ESOC a new program "TOPEXobs" has already been coded for that task and is in principle ready to be attached to the routine weekly comparison processing. However, because of its orbital geometry TOPEX can scan 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! As an example Figure 3 shows the VTEC curves of all IAACs, the IGS “mean”, VTEC derived from TOPEX altimeter data, and VTEC from the Bent ionosphere model for TOPEX pass 09 of 30 August 1998 (doy 98242). The TOPEX data were kindly provided by JPL:

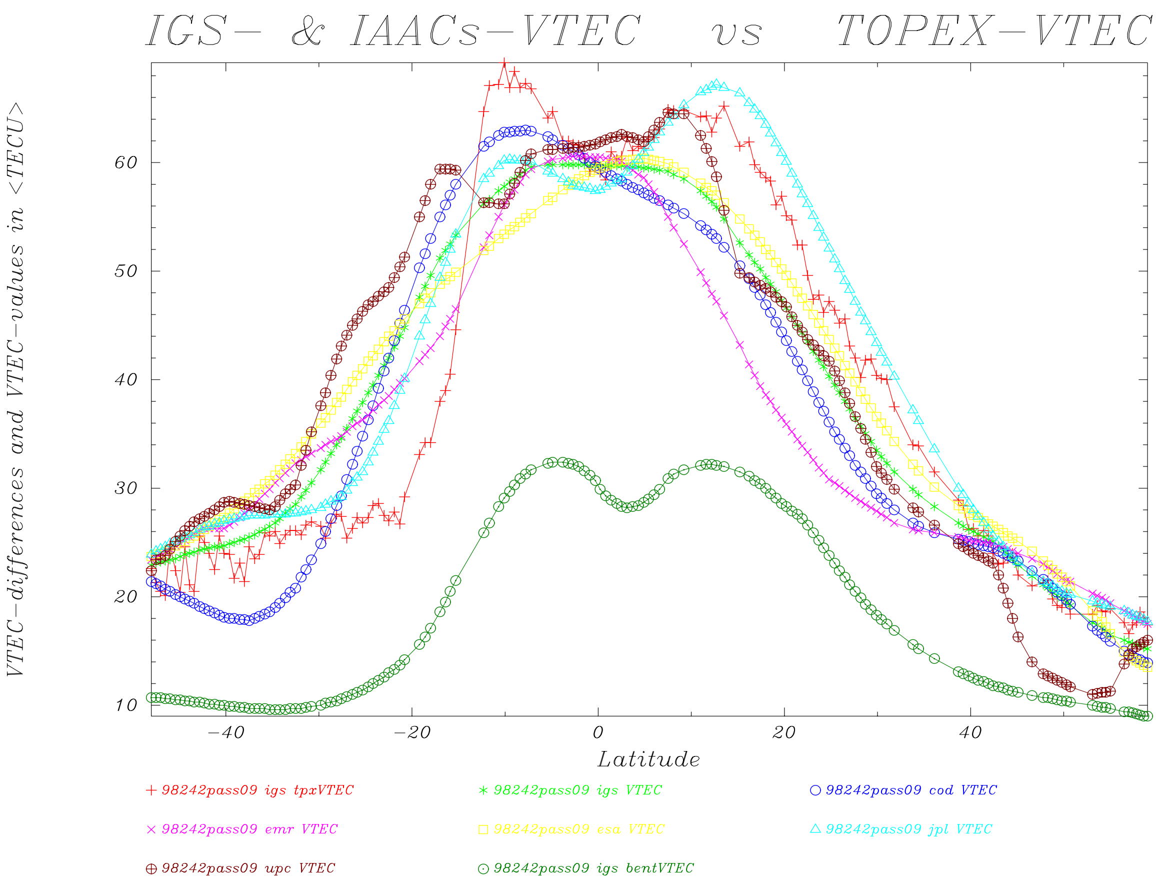

Figure 3: VTEC from TOPEX, the IGS “mean”, the IAACs and Bent.

2) Another interesting proposal came from DLR Fernerkundungsstation Neustrelitz/ Germany for making validations with ionosonde data. Together with the IZMIRAN at Moscow such validations could be done: IZMIRAN has access to the world data center in

Moscow and would be ready make systematic comparisons with ionosonde data from 60 globally distributed ionosonde stations and also give support in the analysis of results. The procedure is basically as follows: The ionosondes provide information of the critical frequency f_0F_2 of the ionosphere's F_2-layer. Since for the electron density N_mF_2 at F_2 the relation holds: $N_mF_2 \sim (f_0F_2)^2$, the comparison with GPS-derived TEC could be based on the computation of the equivalent slab thickness of the electron density profile which is defined by the ratio TEC/N_mF_2. The slab thickness acts as a rather sensitive indicator for the reliability of the derived TEC values, in particular at low TEC levels (low solar activity) and has typical values in the order of 200 - 400 km at day-time. Systematic studies should provide typical diurnal and seasonal variations of this parameter, e.g. higher day-time values in summer than in winter. Figure 4 presents a global map of the ionosonde stations:

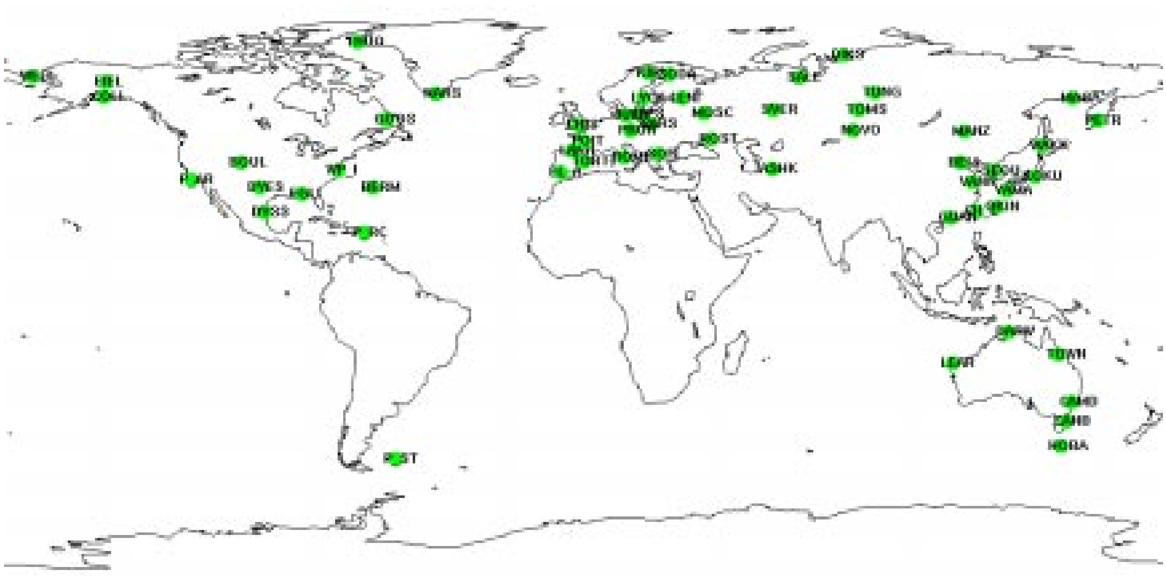

Figure 4: Global distribution of ionosonde stations.

3) UPC has proposed to make validations with the International Reference Ionosphere (IRI): Using slant ranges calculated from the actual GPS-satellites and ground stations geometry, synthetic "TEC-observables" could be computed with IRI model to these ranges and then be fed into the different IAAC models. The ionosphere models thus produced with the different IAAC methods, could then be compared with the IRI. The IRI serves in this way as a mathematical surface, and it is looked, how good each IAAC model can adapt to this surface.

4) NRCan offers a validation procedure which is based on the estimation of station receiver DCBs. The algorithm does the following for selected stations: 1) It reads RINEX dual-frequency observations every 30 seconds and computes carrier-phase filtered ionospheric group delays, corresponding to $observedTEC_{along\_path} + DCB_{sat} + DCB_{sta}$. 2) Satellite and station coordinates at epoch are used to compute the position of the ionospheric pierce point; the vertical TEC is interpolated from the IONEX file at that point, i.e. $modeledVTEC$. 3) With the standard mapping function the modeled vertical TEC is mapped along the satellite $\leftrightarrow$ station path, i.e. $modeledTEC_{along\_path}$. 4) The satellite

DCB from the IONEX file is added to the $modeledTEC_{along\_path}$ term, the result is $modeledTEC_{along\_path}$ + DCB_{sat}. 5) Then the difference between the terms $observedTEC_{along\_path}$ + DCB_{sat} + DCB_{sta} and $modeledTEC_{along\_path}$ + DCB_{sat} is computed. Result of this differencing is a station receiver DCB estimate. Assuming that DCB_{sta} is constant, one can compute the standard deviation of the estimates from the observations of the RINEX file with respect to the mean over a selected time interval for each IAAC. The IAAC with the smallest standard deviation tells us the modeled grid that best matches the observations over a chosen time period for a particular station.

First results provided with this method by NRCan show that the TEC grids from COD, EMR and ESA have about the same average standard deviation, JPL is lower and UPC is higher. This differs from what the CMPCMB comparisons show. Also the "combined" IGS TEC maps do not have the smallest standard deviation (because they are pulled towards the IAACs that are in agreement with each other). Additionally, this method can provide information on at which stations the grids have problems (often equatorial stations).

FUTURE TASKS

Once the IAAC ionosphere models have been validated and a reliable combination scheme has been found, the next important task will be the reduction of the time deadline for ionosphere products delivery. The ionosphere is a very rapidly changing medium, and it must be the working group's intent to provide actual information about the ionosphere's state in short time frames.

Medium- and long-termed, also the provision of regional and local ionosphere models will be an important task for the Iono_WG, as well as the development of more sophisticated ionosphere models. The final target is the establishment of an independent IGS ionosphere model - and another very important task will be the implementation of near-real-time and real-time capability in order to be able to provide ionosphere information on-line.

On the occasion of the solar eclipse on 11 August 1999 the WG intends to organize and coordinate a special observation campaign. This event is a unique opportunity to demonstrate the power of the GPS technique in monitoring the ionospheric ionization. As the zone of totality crosses Europe, the rather dense portion of the IGS network provides excellent conditions for monitoring the eclipse. Nevertheless, non-IGS stations should also be activated and included in the data analysis.

CONCLUSIONS

The IGS Ionosphere Working Group was established by the IGS Governing Board on 28 May 1998. The Iono_WG started its pilot phase on 1 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 5 IAACs contribute with their ionosphere products to that pilot phase activities.

A first version of a comparison algorithm was worked out and coded. Based on that comparison scheme, comparisons are done weekly by the IACC at ESOC. Products and a weekly summary are made available to all Iono_WG members via e-mail and through FTP.

The comparison algorithm provides, so to say as by-product, also something like a “combination” of the IAACs individual ionosphere products. However, this comparison/combination algorithm is based on the concept of weighted means and must be considered as *preliminary*. The IAACs use very different mathematical approaches and estimation schemes in their ionosphere processing. This circumstance reflects in the comparison results: Significant offsets between the different IAAC TEC maps can be seen. So the Iono_WG decided to make as next step intense validations of the different IAAC ionosphere models and to calibrate them with respect to each other. Another important task of these validations is the assessment of the quality of the different IAAC models and to assign appropriate weights to them to be in a position to make objective comparisons and combinations. It is the working group’s intent that these validations will lead to a final scheme to combine the IAACs individual ionosphere maps and DCBs to a new common IGS ionosphere product.

With regard to medium- and long-term time planning, significantly reduced delivery time deadlines for ionosphere products, up to near-real-time and real-time processing, and the development of independent IGS ionosphere models, also of regional and local extent, will be important aspects.

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APPENDIX A - COMPARISON ALGORITHM

COMPARISON STRATEGY

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

<u>A) TEC maps</u>

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, 1998b).

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 agreement. Furthermore from these "residual"-TEC maps a constant offset (bias), an overall rms, and rms-values in sub-parts of the geographic grid are computed and presented in the daily comparison summary in the Tables 3. for each IAAC (see e.g. Feltens, 1998b).

<u>B) DCBs</u>

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:

<u>A) TEC maps</u>

1) Unweighted mean

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

- get the TEC value for each IAAC.
- build unweighted mean over all IAACs providing non-9999 values; if all IAACs provide a 9999, set unweighted mean equal to 9999.
- update for each IAAC the squared sum $[dd]_2$ of differences with respect to the unweighted mean, if this IAAC does not provide a 9999 at this GP ($[dd]_2$ is needed for

the computation of parameter $weight_2$). Find out at the same time, whether all IAACs provide non-9999 values at the current GP.

- if all IAACs provide non-9999 values at current GP, update for each IAAC the squared sum $[dd]_1$ of differences with respect to the unweighted mean over those GPs where all IAACs provide non-9999 values ($[dd]_1$ is needed for the computation of parameter $weight_1$).

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

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

where

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

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

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:

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

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

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

End of 4 nested loops to establish unweighted mean.

2) Weighted mean

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

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

$$combTEC(GP) = \frac{\sum_i weight_1(IAAC) \cdot TEC(IAAC)}{\sum_i weight_1(IAAC)} \quad \text{(A.3)}$$

where

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

- compute differences *TEC(IAAC)* - $combTEC$ and store them in an IAAC's TEC difference IONEX file.
- compute at current GP weighted rms of combined TEC as:

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

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 (A.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 (A.4b) would be an alternative to calculate an rms of the combined TEC at each grid point, since no individual rms values enter into that formula.

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

where (A.4b)

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

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

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

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

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:

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

End of 4 nested loops to establish weighted mean.

B) DCBs

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

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

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

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

where

k = sum over all IAACs per satellite

n_{IAACs} = number of all IAACs

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

where

sat = summation over all n_d satellites per IAAC

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

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

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

where

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

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

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

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

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 (A.4b) might thus provide more objective $DCB\ rms$ values as Equation (A.11) may do.

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

APPENDIX B - CHARTER

Terms of Reference for the IGS Ionosphere Working Group

- Stefan Schaer and Joachim Feltens on behalf of the GPS-IONO Group -

June 5, 1998

General Goals

The IGS Ionosphere Working Group is a long-term working group (WG). It should be active at least till the end of the next solar maximum. It exploits the permanent IGS network of stations and the IGS infrastructure to derive global IGS ionosphere maps and IGS ionosphere models.

The most important short-term goal (to be accomplished by an IGS Pilot Project of two years, see below) consists of the development of IGS Global Ionosphere Maps based on a combination of ionosphere maps regularly produced by IGS Ionosphere Associate Analysis Centers (IAACs) on which more information is provided below.

One of the important long-term goals consists of the validation of the IGS Ionosphere Maps. This validation may lead, in the collaboration with the ionosphere community, to an IGS Ionosphere Model.

This charter is based on first considerations provided by Gerhard Beutler and John Dow (e-mail from April 6, 1998).

Working Plan 1998-2000

The following goals should be achieved in the time period mid 1998 to mid 2000 (these goals were stated in the ionosphere position paper at the Darmstadt workshop):

- Global ionosphere maps (TEC maps) including satellite-specific differential code biases (DCBs) from contributing Analysis Centers are made available in IONEX format through the IGS Global Data Centers.

- Definition of minimum analysis and performance standards for IAACs:

    - minimum analysis standards, see recommendations of Darmstadt position paper,

    - ionosphere products are made available not later than the IGS final orbits and EOPs, i.e., 11 days after the observations.

- TEC maps and DCB values as produced by individual analysis centers are compared by the IGS Ionosphere Coordinating Center. A weekly report has to be produced.

- Individual TEC maps and DCB sets are combined into a preliminary IGS Combined Ionosphere Product. The weekly report contains also "rms-values" relative to the combined product.

- Validation of IGS Ionosphere Products using independent data and methods (ionosondes, TOPEX, future satellite missions, etc.). The WG has to define criteria and guidelines for the validation of TEC maps (absolute accuracy in comparison with independent ionospheric data, consistency between equivalent TEC maps).

- A comparison of TEC maps with TEC data derived from well-known models such as IRI will be useful to check both, the IONEX data as well as the model considered.

- Deadlines for ionosphere product delivery will be reviewed after at least one year of pilot service. Possibly, an IGS Rapid Ionosphere Product may be defined.

- Principles for the definition of an IGS Ionosphere Model are developed.

On the occasion of the solar eclipse on 11 August 1999 the WG will organize and coordinate a special observation campaign. This event is a unique opportunity to demonstrate the power of the GPS technique in monitoring the ionospheric ionization. As the zone of totality crosses Europe, the rather dense portion of the IGS network provides excellent conditions for monitoring the eclipse. Nevertheless, non-IGS stations should also be activated and included in the data analysis.

Structure of the Working Group and Initial membership list

Representatives of those Analysis Centers which confirmed their willingness to contribute to an Pilot IGS Ionosphere Service, namely

Mihail Codrescu (SEC),
Joachim Feltens (ESOC),
Mariusz Figurski (WUT),
Manuel Hernandez-Pajares (UPC),
Pierre Heroux (NRCan),
Attila Komjathy (CCAR),
Steven Musman (NOAA),
Stefan Schaer (CODE),
Peter Stewart (UNB),
Rene Warnant (ROB),
Brian Wilson (JPL),

representatives from the ionosphere research community,

Dieter Bilitza (GSFC),
Norbert Jakowski (DLR),
John A. Klobuchar (AOL),
Reinhard Leitinger (TU Graz, not confirmed),

as IGS Analysis Center Coordinator,

Jan Kouba (NRCan),

and as representative from the IGS CB,

Ruth Neilan (JPL).

Further participation will be called for through an IGS-mail message.

The IGS Ionosphere Working Group consists of

- Chairperson: Joachim Feltens (ESOC).
- IGS Ionosphere Associate Analysis Centers (IAACs) generating ionosphere maps in the IONEX format with the defined time resolution, namely

CODE,

ESOC,

JPL,

NOAA (not yet ready),

NRCan,

UPC.

All these centers confirmed their participation.

- IGS Ionosphere Associate Combination Center(s) (IACC); interest indicated by ESOC.
- IGS Ionosphere Associate Validation Center(s) (IAVC).

Further participation for all categories of IAACs, IACCs, and IAVCs is fostered through IGS-Mail message.

The chairperson should be the representative of a TEC map producing center (IAAC/IACC). The IACC(s) must be associated with one of the IAACs. The IAVC(s) should have experience in the analysis of alternative (non-GPS) data. IAVC candidates are:

ESOC, using ERS data,

ROB, using ionosonde data,

UPC, making comparisons with IRI.

Schedule for Pilot Project

- Establishment of IGS Ionosphere Working Group (May 1998)
- Make IONEX files of IAACs available through IGS Global Data Centers (June 1998)
- Start of pilot project in August 1998 including comparisons (not yet combinations)
- Start of combinations, based on proposal from IACC(s)
- Start of validation, based on proposal from IAVC(s)
- First report to IGS GB (December 1998)
- Review of first year of operations (August 1999)

Acronyms

CB	…	Central Bureau
CCAR	…	Colorado Center for Astrodynamics Research, Boulder, Colorado, U.S.A.
CODE	…	Center for Orbit Determination in Europe, Astronomical Institute, University of Berne, Switzerland
DCB	…	Differential Code Bias
DLR	…	Deutsche Forschungsanstalt fuer Luft- und Raumfahrt, Fernerkundungsstation Neustrelitz, Germany
ESOC	…	European Space Operations Centre, Darmstadt, Germany
GB	…	Governing Board
GPS	…	Global Positioning System
GSFC	…	Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
IAAC	…	Ionosphere Associate Analysis Center
IACC	…	Ionosphere Associate Combination Center
IAVC	…	Ionosphere Associate Validation Center
IGS	…	International GPS Service
IONEX	…	IONosphere Map EXchange Format
IRI	…	International Reference Ionosphere
JPL	…	Jet Propulsion Laboratory, Pasadena, California, U.S.A.
NOAA	…	National Oceanic and Atmospheric Administration, Silver Spring, Maryland, U.S.A.
NRCan	…	National Resources Canada, Ottawa, Ontario, Canada
ROB	…	Royal Observatory of Belgium, Brussels, Belgium
SEC	…	Space Environment Center, Boulder, Colorado, U.S.A.
TEC	…	Total Electron Content
TU Graz	…	Technical University Graz, Graz, Austria
UNB	…	University of New Brunswick, Fredericton, New Brunswick, Canada
UPC	…	Polytechnical University of Catalonia, Barcelona, Spain
WUT	…	Warsaw University of Technology, Warsaw, Poland

APPENDIX C - MEMBER LIST (JUNE 1999)

The Iono_WG's common e-mail address: GPS-IONO@listserv.unb.ca

The Iono_WG's common e-mail address: IONO-WG@listserv.unb.ca
(the IONO_WG list is for "WG members" only, not for "observers", see Status)

Beutler, Gerhard Status: Observer

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Gurtner, Werner Status: Observer

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Hernandez-Pajares, Manuel Status: Iono_WG member

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Horvath, Ildy Status: Observer

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Jakowski, Norbert Status: Iono_WG member

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Jungstand, Arne Status: Observer

Deutsches Zentrum fuer Luft- und Raumfahrt e.V. (DLR), Deutsches Fernerkundungsdatenzentrum (DFD), Fernerkundungsstation Neustrelitz, D-17235 Neustrelitz, GERMANY

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