IGS

WORKING GROUPS/ PILOT PROJECTS/COMMITTEES

IGS/BIPM Time Transfer Pilot Project

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Introduction

The "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements" was authorized in December 1997 jointly by the International GPS Service (IGS) and the Bureau International des Poids et Mesures (BIPM). A Call for Participation was issued shortly afterwards with responses received from about 35 groups. The respondents have formed a working group, which was formally initiated on 18 March 1998.

The central goal of this Pilot Project is to investigate and develop operational strategies to exploit GPS measurements and geodetic techniques for improved availability of accurate time and frequency comparisons worldwide. This is becoming more significant for maintaining the international UTC timescale as a new generation of frequency standards emerges with accuracies of 10^{-15} or better. The objectives of the Pilot Project are described in the *IGS 1997 Technical Reports*.

The respective roles of the IGS and BIPM organizations are complementary and mutually beneficial. The IGS and its collaborating participants bring a global GPS tracking network, standards for continuously operating geodetic-quality, dual-frequency GPS receivers, an efficient data delivery system, and state-of-the-art data analysis groups, methods, and products. The BIPM and its timing laboratory partners contribute expertise in high-accuracy metrological standards and measurements, timing calibration methods, algorithms for maintaining stable timescales, and formation and dissemination of UTC. The progress of the Project and other related information is maintained at the Web site <http://maia.usno.navy.mil/gpst.html>.

Working Group Meetings

During 1998, the Pilot Project working group met twice. The first meeting was held at the BIPM (Sevres, France) on 22-23 June with representatives from about nine timing labs, BIPM, several IGS Analysis Centers (ACs), the IGS Analysis Coordinator, and the IGS Central Bureau. It was a relatively intimate, informal gathering in the rather elegant setting of the BIPM, with superb facilities and support. The forum provided a good opportunity to initiate this collaborative project. The presentations were accompanied by ample discussion which allowed the concerns and goals of the various participants to be fully voiced.

The timing community expressed their strong need for a frequency transfer method capable of comparing the new ultra-stable oscillators now under development, such as the cesium fountain and ion trap standards with stabilities of 10^{-15} over one day or better. GPS geodetic techniques should be suitable and the timing groups hope to gain from the IGS expertise in this area, particularly with data analysis. The IGS would prefer to link its clock products to the international UTC timescale rather than GPS broadcast time for improved stability and accuracy. In order to do this, calibrated links are necessary at IGS stations located at timing labs.

A brief second meeting of the working group was held on 30 November associated with the 30th Precise Time and Time Interval meeting (Reston, Virginia, USA). Representatives of 10 participating groups gave brief summaries of their recent activities or plans, including a report from the BIPM working group on two-way satellite time transfer (TWSTT). Afterwards, a general discussion of instrumental calibration issues ensued. While it was generally conceded that calibration is the central issue that must be resolved for time transfer applications, it was felt that the effects on instrumental stability are sufficiently well understood that GPS carrier phase methods can already be usefully applied for frequency transfer, at least for systems maintained under strict metrological conditions.

Areas of Activity

Deployment of GPS Receivers

The IGS network currently consists of about 200 permanent, continuously operating, geodetic stations globally distributed. Of these, external frequency standards are used at ~30 with H-masers, ~20 with cesium clocks, and ~20 with rubidium clocks. Most of the remaining sites rely on internal crystal oscillators. The 11 IGS stations listed in Table 1 are located at timing laboratories (as of late 1998). Additional installations at timing labs are expected in the near future.

Table 1. IGS Stations Located at BIPM Timing Laboratories

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
AMC2	AMC *	AOA TurboRogue	H-maser	Colorado Springs, CO, USA
BOR1	AOS	AOA TurboRogue	cesium	Borowiec, Poland
BRUS	ORB	AOA TurboRogue	H-maser	Brussels, Belgium
GRAZ	TUG *	AOA TurboRogue	cesium	Graz, Austria
MDVO	IMVP	Trimble 4000SSE	H-maser	Mendeleevo, Russia
NRC1	NRC *	AOA TurboRogue	H-maser	Ottawa, Canada
PENC	SGO	Trimble 4000SSE	rubidium	Penc, Hungary

Table 1. IGS Stations Located at BIPM Timing Laboratories (cont'd)

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
SFER	ROA	Trimble 4000SSI	cesium	San Fernando, Spain
TOUL	TA(F)	AOA TurboRogue	cesium	Toulouse, France
USNO	USNO*	AOA TurboRogue	H-maser	Washington, DC, USA
WTZR	IFAG	AOA TurboRogue	H-maser	Wettzell, Germany

* participates in TWSTT operations

Significant changes in the IGS network configuration are expected in coming years. Many of the factors contributing to this are discussed in the proceedings of the *IGS Network Systems Workshop*, held in November 1998. In addition to upgrades that may be required to handle the GPS Week rollover in August 1999 and the year 2000 rollover, a more serious concern is the declining performance of some older receiver models. The upturn of solar cycle 23, with its associated increase in ionospheric activity, has caused tracking to suffer, especially at lower elevation angles and for the weaker L2 frequency. These difficulties are much less for the new generation of Y-codeless, dual-frequency geodetic receivers, which are gradually being deployed. The new receivers also provide much better pseudorange tracking with far less sensitivity to multipath effects. During the current period of transition, the time-varying mix of different receiver types, which can report distinctive observables, can create other problems if care is not taken. In particular, the codeless pseudorange observables can be biased by up to ~2 ns between different receiver types and the biases are satellite-dependent. If mixed without accounting for the biases, estimates for GPS satellite clocks will be degraded, as will precise point positioning using them.

GPS Data Analysis

Of the IGS ACs, all but two already provide satellite clock estimates, which are combined and distributed with the IGS orbit products. The IGS is committed to expand its operational products to include combined clocks for the tracking receivers as well. A detailed plan for doing this was developed among the ACs and considerable progress has been made. The first step was devising an exchange format for clock-like data. This was done using as a model the RINEX standards. The initial format version was released in August 1998 and was designed to handle receiver calibration data, receiver discontinuity observations, data analysis results, or monitor data from the observations of satellite clocks at timing labs. The complete current specifications are available at the Web site <http://maia.usno.navy.mil/gpst/clock-format>.

To permit improved realignment and weighting of the clock solutions from the ACs to the same timescale, the subset of clock estimates common to all solutions must be sufficiently large, preferably including all the GPS satellites and as many stations with stable frequency standards as feasible. Thus, a set of 35 "fiducial clock" sites was identified and the ACs were encouraged to include as many of these as possible in their solutions. All but eight of the "fiducial clock" sites are equipped with H-maser frequency standards, the others having cesiums; six are located at timing laboratories.

Analysis of Instrumental Delays

In order to relate clock estimates derived from GPS data analysis to external timing standards it is necessary to understand the instrumental electronic delays introduced by the associated hardware. There are, as yet, no geodetic receiver systems for which the timing calibration bias is known. This situation is a fundamental challenge to exploiting GPS geodetic techniques for time transfer. Two types of instrumental calibration approaches are being pursued by various groups. One method characterizes the delay through individual components of the receiver system. A second method attempts the end-to-end calibration of a complete (or near-complete) system by injecting simulated GPS signals. Both methods involve significant technological feats. Generally, the first method is more accessible, at least for certain components, and has the advantage of permitting the most sensitive system elements to be identified. An overall accurate system calibration determination, which is ultimately required for time transfer applications, can be difficult to obtain, however. The end-to-end methods are clearly desirable for practical uses but they require unique, expensive test equipment and may not be suitable for routine operational settings.

An alternative to direct instrumental calibration, which should be feasible and simpler, is to calibrate a geodetic receiver system differentially against a previously calibrated timing receiver by collocated common viewing of satellite clocks. The two receiver systems must be close to one another and all cable delays must be accurately known.

The level of understanding and control of environmental factors that affect frequency comparisons is much more advanced than time calibration (Petit and Thomas, 1996). Standards of metrological control are well known in the timing community and have been implemented to varying extent at several IGS stations. Frequency comparisons at the level of 10^{-15} over one day, or better, appear entirely feasible already provided that reasonable care is taken to minimize environmentally induced variations. Indeed, Bruyninx *et al.* (1998) found the GPS instrumental limitations to be below 10^{-15} if temperature stabilization is strictly enforced. Petit *et al.* (1998) showed that when using temperature-stabilized antennas, cables with low temperature coefficients, and receiver units in a temperature-controlled laboratory, frequency comparison of the same clock by two different systems in the same lab may be performed with a stability below 10^{-16} over one day. For the less ideal situation using the USNO station with strong diurnal variations (at that time), Larson *et al.* (1998) reported an observed frequency stability of 2.5×10^{-15} in one day over a 2360-km baseline.

Time Transfer Comparisons

So far, only a few controlled experiments have been conducted to compare geodetic timing results with simultaneous, independent techniques. Tests are being organized and data collection is getting underway.

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Densification of ITRF Reference Frame Working Group

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Objectives

One objective of the Reference Frame Working Group is to generate IGS station coordinates and velocities, Earth Rotation Parameters (ERP) and geocenter estimates along with the appropriate covariance information. A cumulative solution, which contains at least a set of estimated coordinates and velocities at a reference epoch for each station is updated weekly. The weekly submissions started with GPS week 999. Work is continuing to improve on the quality and timeliness of the submissions. The cumulative solution includes GNAAC solutions dating back to GPS week 837. Starting with GPS week 978 the ACs were included in the combination while the GNAAC were included to quality control the combination. Although the combination was only made available starting with GPS week 0999, the procedure was tested on weekly solutions dating back to GPS week 0978.

Procedure

To meet the working group objectives a procedure was put in place. The procedure in place does for each AC and GNAAC solution: 1) validate the format; 2) check (and correct) site names and parameters; 3) rescale, condition and unconstrain the matrices; 4) align to ITRF; 5) compare to ITRF, to other solutions, to the previous and current weekly solution and to the cumulative solution; 6) reject outliers; 7) combine weekly and cumulative solutions; 8) iterate if required; 9) correct inconsistencies with igs.snx; 9) prepare the report.

The format validation ensures that all the files used respect the SINEX V 1.0. During the validation process, changes are also made such that all the SINEX files use a consistent interpretation of the SINEX format. This imply that minor differences may exist between the information provided and the reported information.

The site names and point are changed to be consistent with the igs.snx file. Corrections to the parameters may also be applied only if they can be justified (e.g.: igs.snx/station log/communication with the owner). Corrections such as pole tide, LODR to LOD are also applied when appropriate. The LOD bias estimated as part of the orbit combination process is also applied. The ERPs are always referred to the origin.

Occasional problems with unconstraining or inverting matrices are usually resolved by rescaling the estimated and/or apriori diagonal matrix. The rescaling required is usually below the part per billion. All the weekly matrices are also rescaled by a variance factor (chi**2/dof) determined by a comparison with the combined cumulative solution.

Some solutions do contain multiple estimates for a given point at a site. The coordinate differences between those multiple solutions are usually a few mm. In the situation when significant differences existed, the outlier one is rejected. In all other cases, the multiple solutions are recombined to produce one estimate per point. The AC & GNAAC SINEX files coordinates system origin is assumed to correspond to the “apparent” geocenter. An explicit geocenter is added to the parameters for each SINEX file. The ERPs are always referred to the solution origin, regardless of the position of the apparent geocenter during the transformation/combination process.

The alignment of all the weekly solutions is done with a 7-parameters similarity transformation. MADR is currently not used in the similarity transformation estimation. All the other common points between each weekly solution and ITRF96 Reference Frame are used to estimate the transformation. Unit weight on the coordinates is assumed during the transformation parameter estimation. The use of the matrices usually leads to very similar results. Occasionally, the transformation has shown to be sensitive to abnormalities in some matrices.

In an effort to get the best possible solution, several comparisons are made to reject all outliers. The outlier detection threshold is currently set at 5 sigmas. In this process, it is assumed that the ITRF RF stations in ITRF96_IGS_RF47.SNX, the previous week “weekly solution” and the cumulative solution are correct. During the alignment process to ITRF, any outlier is rejected in the input weekly solution. All the weekly solutions pairs are also checked. Detected outliers in the weekly pairs are currently rejected in both files. This reveals station coordinates with inconsistent estimates. The weekly solutions are also compared with the previous week combined solution to detect significant station coordinates variations between consecutive weeks. The outlier stations are rejected from the offending solutions in the current weekly solutions. The weekly solutions are finally compared with the cumulative solution to detect significant station coordinates discrepancy. Again, when this happens, the outlier stations are rejected from the offending current weekly solutions.

The weekly solutions are then combined to produce the weekly combination. Although, no rejection is expected from the combination, the outlier detection/rejection process is repeated. The cumulative solution is then updated with one last outlier detection/rejection exercise.

The results are analyzed and appropriate action is taken. The process is repeated if necessary. Otherwise a summary is prepared, the SINEX files consistency with igs.snx is checked.

The report is divided in 5 sections: 1) Contacts, 2) Products, 3) Combination Strategy, 4) Remarks and 5) Results.

The contact section gives information on the person to be contacted for questions, comments, suggestions, concerns, etc.

There are 7 product files generated each week. They are available from cddisa.gsfc.nasa.gov. There are three residual files (igsyyPwwww.itr, igsyyPwwww.res, IGSyyPww.res), two SINEX files (igsyyPwwww.snx, IGSyyPww.snx), one ERP file (igsyyPwwww.erp) and one summary file (igsyyPwwww.sum); with yy being the last two digits of the year, ww is it week of the year and wwww is the GPS week. The three residual files (igsyyPwwww.itr, igsyyPwwww.res, IGSyyPww.res) list the station residuals with respect to 1) the ITRF Reference Frame stations, 2) the weekly combined solution, 3) the combined cumulative solution at the current epoch . In the case of the weekly combined solution, the residuals are also given for the ERPs. The combination strategy is also briefly described. Some remarks are also included to clarify some specifics.

The last section presents a summary of the results. It is divided in 7 sub-sections: 1) the variance factor, 2) the stations residuals weighted average and RMS; 3) the 7-parameters transformation to the reference frame; 4) the geocenter; 5) the ERP residuals weighted average and RMS; 6) the outliers; 7) the conflicts.

The solution is presently generated on average 2 days after the last GNAAC is available.

Results

The results presented in this section are taken from the weekly summary files from GPS weeks 0978 to 1009. Even if the solutions are publicly available only since GPS week 0999, the procedure was tested with data going back to GPS week 0978. The cumulative solution includes the GNAAC solutions between weeks 837 and 977. Since week 978, the AC have been used in the combination.

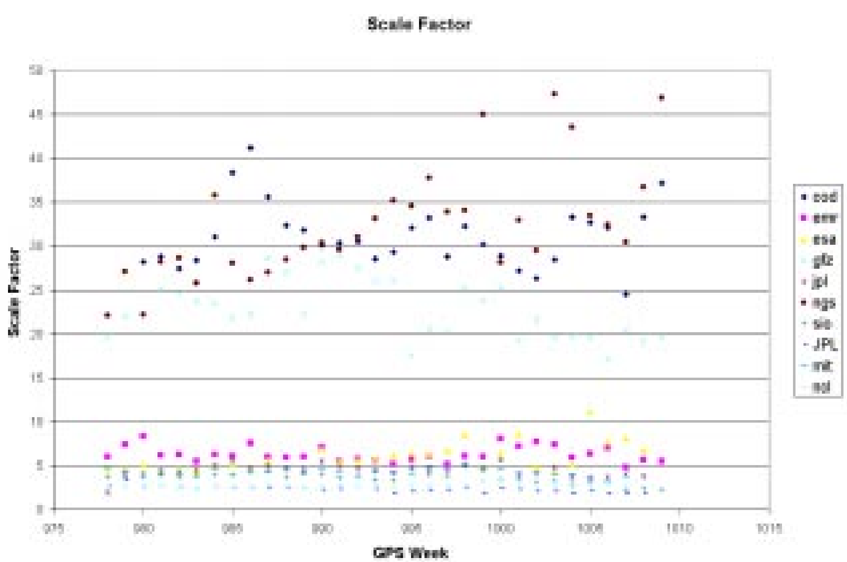

Figure 1. - Estimated Scale Factor (variance factor)**.5 for the ACs and the GNAACs between GPS weeks 978 and 1009.

Figure 1 shows the time series for the scale factor applied to the AC and GNAAC solutions. It is interesting to note the consistency of the scale factor. In average the scale factor from week to week varies by about 15%. In the best case (NCL) it is down to 7%. Such stability permits the use of the previous week scale factor for the first iteration of the weekly combination. Under normal situations, 2 to 3 iterations are sufficient for the scale factor to converge.

The LOD are corrected for biases with respect to Bulletin A; the best LOD have weekly RMS of about 10 to 15 us. The best X and Y pole position have weekly RMS at about 0.05–0.10 mas and 0.10–0.15 mas level respectively, while their rates have RMS at the 0.10-0.15 mas/d level. The estimated daily ERP were also compared to Bulletin A and to the current IGS final ERPs. All LOD solutions are unbiased with respect to Bulletin A and IGS Final. They have a standard deviation on the differences of up to 22 us. The X and Y pole position have a standard deviation on the differences of less than 0.10 mas with bias reaching 0.31 mas in one case. The pole rates are compared to the Bulletin A "derived" rates. They have standard deviations on the differences of about 0.2 mas/d.

A preliminary analysis of the station coordinates residuals between the weekly GNAAC (MIT, JPL, and NCL) solutions and the cumulative solution was done to detect potential periodicity. Some nearly annual periods had been noticed in the past and were expected. A spectral analysis was done on all the station time series residuals (North, East, Height) containing at least 150 weeks. Trends and discontinuities were removed from the residuals whenever appropriate. The correlations within and between residual time series are ignored. Potential significant periods were then estimated. Significant periods were found at most stations. The amplitudes are the largest for the vertical axis where they may reach about 10 mm. The horizontal components rarely exceed 5 mm. No systematic pattern has been detected in the initial phase. Small groups of stations with similar initial phase/amplitude/period could be detected, but no systematic behavior or pattern can be found at this time. More stations with significant periods can be found in North America and Europe where denser networks with at least 150 weekly solutions are available. A more refined cumulative combination and longer time series would help to eliminate some small systematic effects and potentially improve the spectral results.

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1998 IGS Activities in the Area of the Ionosphere

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Introduction

The IGS Ionosphere Working Group (Iono_WG) was 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 global ionospheric Total Electron Content (TEC) maps with a 2-hours time 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 (Feltens and Schaer, 1998).

The pilot phase commenced then 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. Based on this algorithm a routine comparison of the IGS ionosphere products was started in October 1998.

It is the intent of this Technical Report to give an overview over the Iono_WG activities in 1998. This Technical Report is in principle a short-version of the Project Report presented at the 1999 IGS Analysis Centers Workshop in La Jolla, CA, U.S.A. (Feltens, 1999).

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 Ionosphere Associate Combination Center (IACC) at ESOC once per week. Such an IONEX file is valid for one day and contains a set of 12 global TEC maps, i.e. 2-hours time resolution, plus a daily set of GPS satellite DCBs. 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.

Comparisons

Before the IACC at ESOC could start in October 1998 with the routine comparison of ionosphere products that are delivered routinely from the IAACs, dedicated software had to be established from scratch. The comparison algorithm and the output of a comparison run are described in detail in (Feltens, 1999). This algorithm is purely statistically based, being based on unweighted and weighted means; the individual IAAC TEC maps are compared with respect to "mean" TEC maps. In this way the "mean" TEC maps can be considered as something like a "combination" of the input IAAC TEC maps. The same approach is principally also used for the comparison of the daily DCB values.

However, as being pointed out in (Feltens, 1999), the IAACs use very different approaches to establish their TEC maps, resulting in very different temporal and spatial resolutions, and these circumstances reflect also in the comparison results. It became clear quite soon, that the weighting procedure in the comparison scheme must be improved on one side

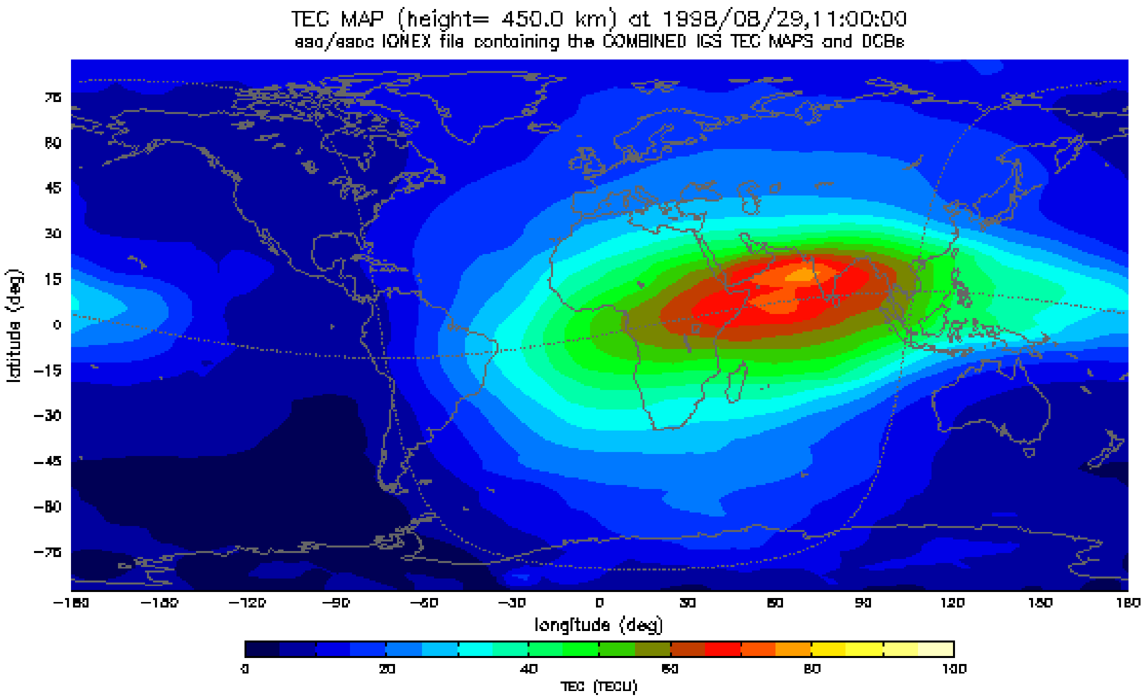

Figure 1: "mean" TEC map for reference epoch 1998/08/29 11:00:00 UT.

and that the different IAAC models must be validated and calibrated on the other, before an IGS ionosphere product can be opened for public use. Figure 1 shows an example of a "mean" TEC map obtained as weighted mean of all IAAC TEC maps for the reference epoch 1998/08/29 11:00:00 UT.

Figure 2 compares for three selected GPS satellites the DCB values of the IAACs with the IGS "mean" DCB values for the timespan of 28 August to 4 September 1998 (doys 98240 - 98247). UPC did not deliver DCB values at that time.

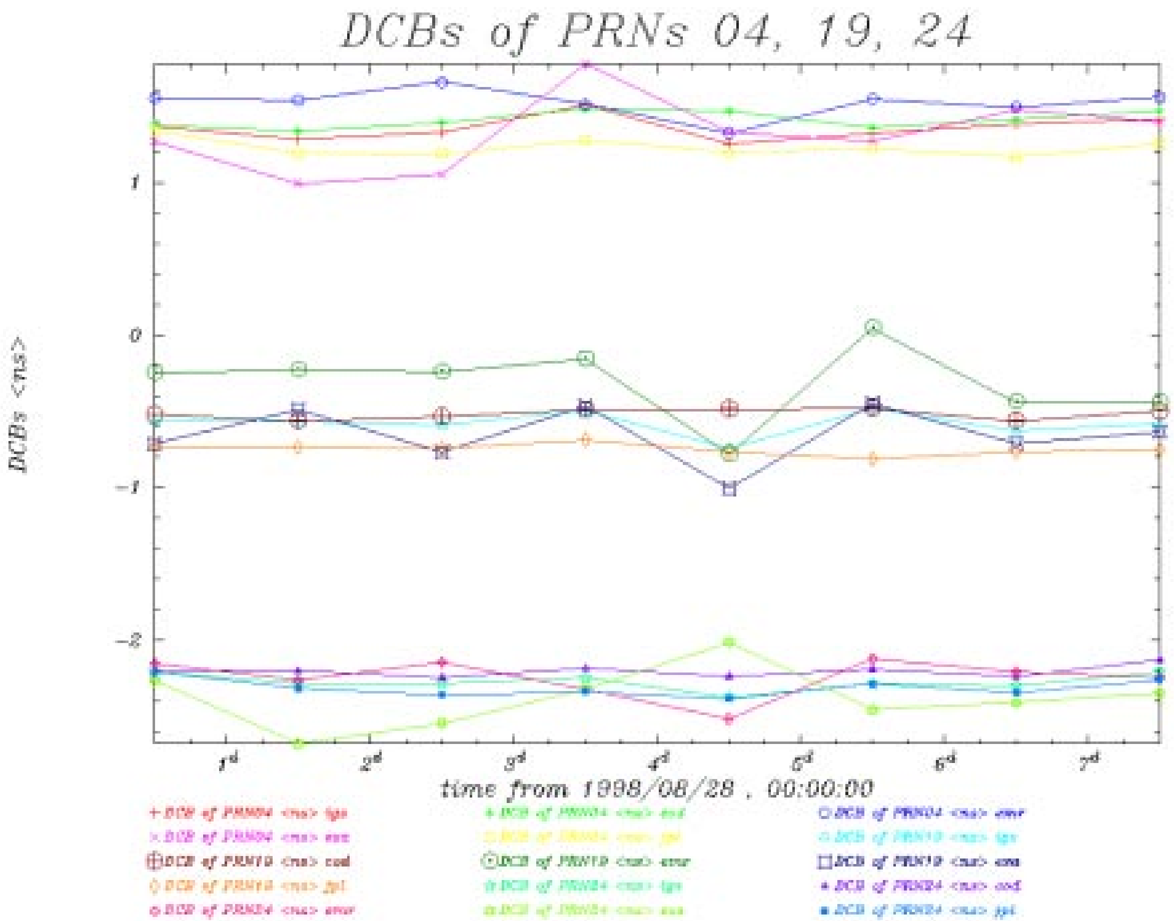

Figure 2: DCBs from four IAACs and the IGS "mean" for PRNs 04, 19 and 24.

Next Steps

Before a combined IGS ionosphere product can be made available to the public, intense validations must be made with respect to the following aspects: 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. Four different methods of validation were identified by the Iono_WG. A detailed description of these four methods is given in (Feltens, 1999). In short summary the four methods are: 1) Validation with VTEC data derived from TOPEX altimeter observables. 2) Validation with ionosonde data. 3) Using the International Reference Ionosphere (IRI) as mathematical surface and see how good the IAAC models can adapt to this surface. 4) Establishment of ground station DCB time series from TEC observables (obtained from RINEX files containing dual-frequency GPS data) and VTEC model values plus satellite DCBs (obtained from the IONEX files) and making some statistical analyses on the stability of these time series. UPC did already make internally calibrations with IRI, comparisons with TOPEX altimeter data and combined GPS ionosonde data evaluations (Hernández-Pajares, 1999).

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 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 since October 1998. However, the IAACs use very different mathematical approaches and estimation schemes in their ionosphere processing. This circumstance reflects in the comparison results and indicates that the current comparison/combination scheme needs to be improved. The Iono_WG has thus decided to perform as next step intense validations of the different IAAC ionosphere models and to calibrate them with respect to each other in order to achieve an improved weighting scheme and an improved combination algorithm. After the conclusion of these activities a combined IGS ionosphere product can be made available to public users.

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