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 1999, the Pilot Project working group did not hold any specific dedicated meetings. However, the Project was represented at the 14th meeting of the Consultative Committee for Time and Frequency (CCTF), which met at the BIPM (S_vres, France) on 20-22 April 1999. Professor Sigfrido Leschiutta (Istituto Elettrotecnico Nazionale, Turin, Italy) presided as the delegates of the various national timing laboratories presented their reports and considered a number of recommendations. The report submitted from the Pilot Project (Ray and Petit, 1999) is available in postscript format at <http://maia.usno.navy.mil/gpst/refs/cctf.ps>. Among the recommendations adopted by the CCTF and submitted for consideration by the Comité International des Poids et Mesures

(CIPM) was the following:

CCTF RecommendationS5 (1999): Time and frequency comparisons using GPS phase and code measurements

"The Consultative Committee for Time and Frequency

considering that

· the International GPS Service (IGS) has established an infrastructure of a global observing network, a data distribution system, a robust analysis methodology and high-quality GPS products,
· a joint IGS/BIPM Pilot Project has been established to study time and frequency comparisons using GPS phase and code measurements,
· calibration methods are still lacking to exploit fully the capabilities of these techniques for time comparisons,

fully supports

· the joint IGS/BIPM Pilot Project,

and recommends that

· timing laboratories consider participation in the IGS by installing appropriate GPS receivers and following the IGS procedures and standards to the greatest extent possible,
· appropriate methods be developed to calibrate the instrumental delays relating the receiver internal reference to the external clock,
· the IGS reference for clock products be aligned as closely as possible with UTC and TAI,
· the timing laboratories and the BIPM take the necessary steps to allow the IGS to realize this goal."

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 IGS stations listed in Table 1 are located at timing laboratories (as of 1999). Additional installations at timing laboratories are under development.

Significant changes in the IGS network configuration are underway. 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 have been 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 approaching maximum 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. At the IGS Analysis Center Workshop, held in La Jolla, California in June 1999, this subject was discussed and a convention recommended to reference pseudorange biases to those of the cross-correlation style of receivers, at least for the time being. Methods for doing so and further information were distributed in IGS Mail #2320 (24 June 1999).

Table 1. IGS stations located at BIPM timing laboratories (in 1999).

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
AMC2	AMC *	AOA SNR-12 ACT	H-maser	Colorado Springs, CO, USA
BOR1	AOS	AOA TurboRogue	cesium	Borowiec, Poland
BRUS	ORB	AOA SNR-12 ACT	H-maser	Brussels, Belgium
GRAZ	TUG *	AOA TurboRogue	cesium	Graz, Austria
MDVO	IMVP	Trimble 4000SSE	H-maser	Mendeleevo, Russia
NRC1	NRC *	AOA SNR-12 ACT	H-maser	Ottawa, Canada
OBER	DLR	AOA SNR-8000 ACT	rubidium	Oberpfaffenhofen, Germany
PENC	SGO	Trimble 4000SSE	rubidium	Penc, Hungary
ROAH	ROA	AOA TTR4-P	cesium	San Fernando, Spain
SFER	ROA	Trimble 4000SSI	cesium	San Fernando, Spain
TOUL	TA(F)	AOA TurboRogue	cesium	Toulouse, France
USNO	USNO*	AOA SNR-12 ACT	H-maser	Washington, DC, USA
WTZR	IFAG	AOA SNR-8000 ACT	H-maser	Wettzell, Germany

* participates in two-way satellite time transfer operations

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 in the process of expanding 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. Some changes and clarifications have continued to be made; the current specifications are available at <http://maia.usno.navy.mil/gpst/clock-format>.

Analysis of Instrumental Delays

In order to relate receiver 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. 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 care is taken to minimize environmentally induced variations (*e.g.*, Bruyninx *et al.*, 1999; Petit *et al.*, 1999).

Time Transfer Comparisons

So far, only a few controlled experiments have been conducted to compare geodetic timing results with simultaneous, independent techniques. Larson and Levine (1999) have compared their geodetic results with conventional common-view and two-way satellite techniques over a 60-day period for a 2400-km baseline. They demonstrated a time transfer stability of 100 ps and a frequency uncertainty of two parts in 10^{15} for an averaging time of one day. Dudle *et al.* (1999) are conducting a similar longer term experiment spanning the Atlantic Ocean. Preliminary results indicate possible seasonal differences between geodetic and two-way satellite results.

References

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Petit, G., C. Thomas, Z. Jiang, P. Uhrich, and F. Taris, Use of GPS Ashtech Z12T receivers for accurate time and frequency comparisons, *IEEE Trans. on Ultrasonics, Ferroelectrics, and Freq. Control*, **46**(4), 941-949, 1999.

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IGS Reference Frame Pilot Project

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The need to generate unique IGS station coordinates and velocities, Earth Rotation Parameters (ERP) and geocenter products was recognized as early as 1994 by the IGS members and described in a position paper (Kouba et. al., 1998). The Reference Frame Working Group (RFWG) was organized to address this need. These products have a direct impact on the GPS satellite ephemerides and and clock products. Starting with GPS week 1000 (March 7, 1999), the first weekly preliminary SINEX combinations were produced. The Analysis Centers (AC) weekly SINEX solutions are used in the combinations. The Global Network Associate Analysis Centers (GNAAC) weekly combinations are used to control the quality of the results. Following several improvements proposed by the RFWG members and with the IGS Governing Board approval, the SINEX products became official starting with GPS week 1050 (February 20, 2000). As of February 27, 2000, the orbit products are aligned by the Associate Analysis Center to the weekly SINEX cumulative combinations, to ensure products consistency. This requires that the SINEX combination be available for the final orbit combinations, which is now produced within 12-13 days after the end of each week.

The IGS realization of ITRF97 (IGS (ITRF97)) has been implemented starting with GPS week 1021 (August 1, 1999). It consists of 51 high quality, well-distributed,global Reference Frame (RF) stations. It replaces the IGS realization of ITRF96 (IGS (ITRF96)), which utilized 47 RF stations. Based on the 45 common stations between the two IGS (ITRF96-7) realizations, the estimated transformation parameters from IGS (ITRF96) to IGS (ITRF97) at the August 1, 1999 epoch are given in Table 1 below.

Table 1. Transformation Parameters from IGS (ITRF96) to IGS (ITRF97) at August 1,1999

At Aug. 1,99	Translations			Rotations			Scale
	TX (mm)	TY (mm)	TZ (mm)	RX (mas)	RY (mas)	RZ (mas)	S (ppb)
 (1 sigma)	0.3 (2.1)	0.5 (2.1)	-14.7 (2.1)	0.159 (0.090)	-0.263 (0.098)	-0.060 (0.088)	1.43 (0.31)
Rate (/y) (1 sigma)	-0.7 (0.3)	0.1 (0.3)	-1.9 (0.3)	0.013 (0.011)	-0.015 (0.012)	0.003 (0.011)	0.19 (0.04)

The translation in Z, the scale and their rates are the significant (at 3 sigmas) transformation parameters. With the IGS (ITRF97) realization, additional stations in the South Pacific/Antarctic (AUCK, BAHR, CAS1, CHAT, and MCM4) regions have improved the RF stations global coverage. Station MADR was removed due to some inconsistencies in its estimated coordinates time series. The RMS of the RF station coordinates and velocity residuals after aligning the two IGS realizations of ITRF, at the reference epoch (January 1, 1997) are 1.7mm, 2.0mm, 4.3 mm and 1.4mm/y, 2.3mm/y and 3.2mm/y in the north, east and up directions. The comparison of the ITRF97 RF stations with NUVEL-1A plate motion model shows a RMS of 3.1mm/y, 4.1 mm/y and 3.8mm/y in north, east and up respectively. These results indicate some improvement in the horizontal velocity with the adoption of the IGS (ITRF97).

The cumulative solution, updated weekly as part of the RFWG products, contains 4 years of weekly solutions. Between GPS week 0837 and 0977 (January 21, 1996 —October 3, 1998) the GNAAC solutions were used. Since then, the AC SINEX solutions are used to update the cumulative SINEX combined solution. Using the cumulative solution for the GPS week 1046 (January 23, 2000), a new set of the IGS coordinates and velocities for the RF stations was proposed for the IGS (ITRF97). This proposed realization should be internally more consistent, because it is based on GPS information only. The cumulative solution is aligned to ITRF97 by applying a 14 parameters transformation estimated with the RF stations. Some stations show periodic variations mainly in the height component. Figure 1 shows the AC/GNAAC/IGS weekly solution height residuals with respect to the IGS cumulative solution since GPS week 0978 for station Penticton (DRAO). The time series clearly show an annual period. Since this cumulative solution contains almost exactly 4 years of uninterrupted weekly solutions at most of the RF stations, the effect of annual and potentially semi-annual periodic signal on velocity estimation do to a large extent cancel out.

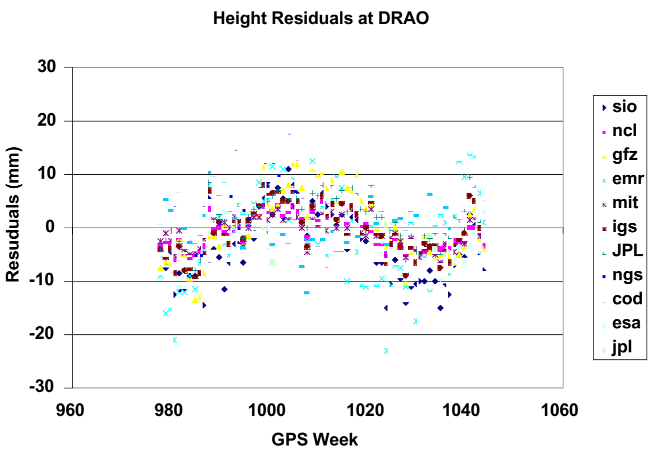

Figure 1

Comparisons between the cumulative solution and ITRF97, at the reference epoch of the cumulative solution (January 1, 1998), shows RMS of the position and velocity differences at 0.9mm, 0.8mm and 3.6 mm, 1.0mm/y, 1.2mm/y and 4.3mm/y in north, east and up components. When both solutions are propagated to a more recent epoch such as January 1, 2000, the RMS of the position differences becomes 2.8mm, 3.5mm and 11.2mm. The comparison between the cumulative IGS and the ITRF97 solutions is expected to have optimistic statistics, since they have significant data in common. ITRF97 is also at some disadvantage because the solution is extrapolated beyond the observation period. A more independent quality check can be obtained by comparing the cumulative IGS solution velocities with the NUVEL-1A plate motion model. After removal of the RF stations AREQ, BAHR, GUAM, MAC1, SANT, and TSKB which are affected by large local crustal deformation, the RMS of the velocity differences is 2.3mm/y, 2.5mm/y and 3.7mm/y in north, east and up. Small, but real local deformations may still be present in the other station velocity estimates as well. These RMS are probably a fairly good indication of the accuracy of the estimated velocity of the stations. The standard deviations derived from the rigorous propagation of the AC/GNAAC rescaled variance-covariance information are in horizontal position and velocity about 3-4 mm and 1.5-2.0mm/y respectively, and in vertical position and velocity 4-5mm and 2-3mm/y respectively. This indicates that the propagated formal error may still be optimistic by a factor 1-1.5. The uncertainty in origin, orientation and scale (and rates) of the combined cumulative solution is constrained to 0.003mas (0.03mas/y), 0.1mm (0.1mm/y) and 0.02ppb (0.02 ppb/y), thus do not contribute significantly to the estimated position and velocity standard deviations.

The daily ERP (X, Y, X rate, Y rate, LOD) parameters estimated by the AC were simultaneously and rigorously combined with the station coordinates to ensure products consistency. The AC LOD bias corrections were also applied (Mireault et. al., 1999) prior

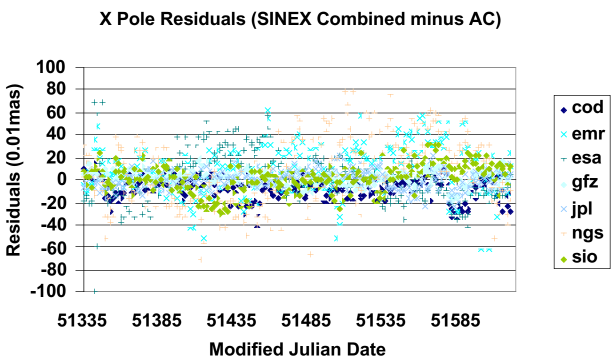

Figure 2-a

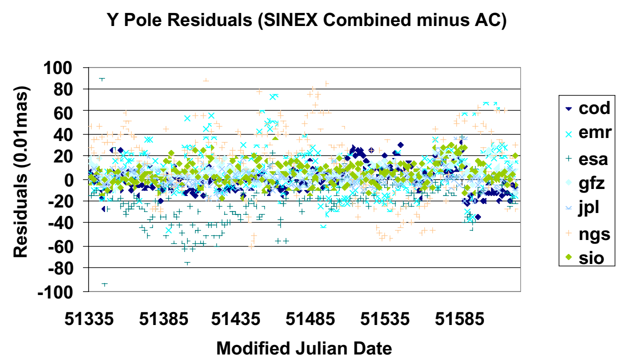

Figure 2-b

to the combination. Figures 2-a and 2-b show the AC X and Y pole residuals with respect to the IGS SINEX weekly combined solution. The combined pole position is referenced to the origin of the RF realization. The results shown are for GPS weeks 1013-1053. GPS week 1013 coincides with the first week when all the AC had included the ERP estimates in their SINEX solution. The overall pole position (and rate) residuals have a standard deviation of 0.18mas (0.5mas/d) and 0.22mas (0.6mas/d). Most centers have average pole position residuals well below 0.1mas with standard deviation also at or below the 0.1mas level. The AC X and Y pole rate average residuals is also well below 0.1mas/d in most cases, with the best centers residuals having a standard deviation approaching 0.1mas/d. The AC LOD average residuals are insignificant due to the calibration being applied. Most centers have LOD residual standard deviation between 20-40 us.

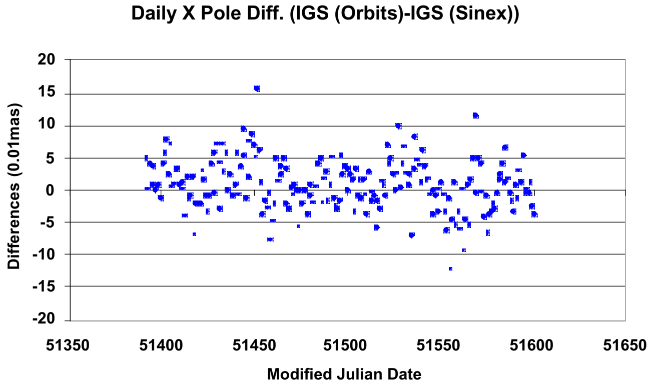

Figure 3-a

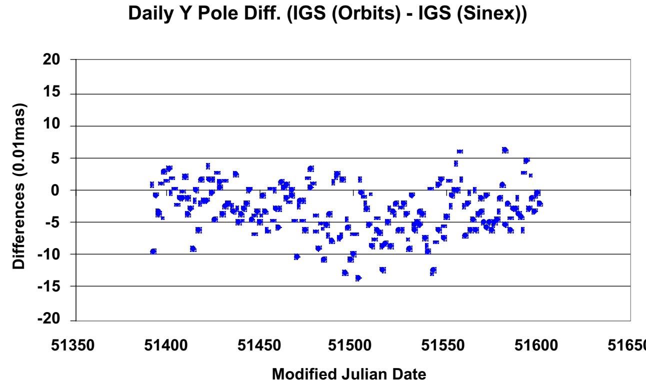

Figure 3-b

Between August 1, 1999 and February 26, 2000 (GPS weeks 1021-1050); the mean difference between the daily pole position combination produced by the official orbit combination and the SINEX combination were consistent at the 0.009mas and 0.030 mas level in the X and Y components, with a standard deviation of the mean of about 0.003 mas. As already mentioned GPS week 1021 correspond to the start of the use of the IGS (ITRF97). The daily variations of the differences in the X and Y pole are shown in Figures 3-a and 3-b. They have a standard deviation of about 0.04 mas.

Comparisons of the X and Y pole with Bulletin A between the same period, shown in Figures 4-a and 4-b, have a mean differences of respectively —0.026 mas and —0.255 mas in the X and Y components, with a standard deviation of the mean differences of about 0.004 mas. The standard deviation of the daily variations is at the 0.06mas level. Those differences have been reported before and are again confirmed here.

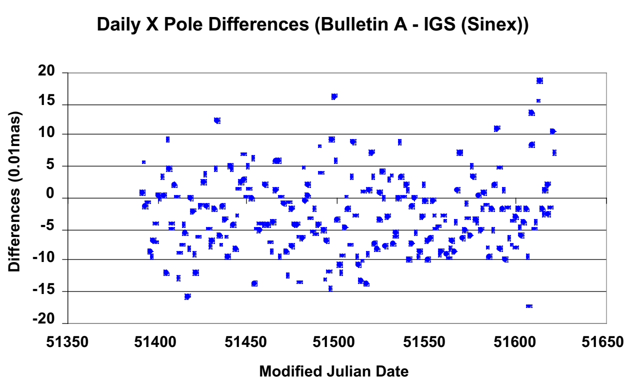

Figure 4-a

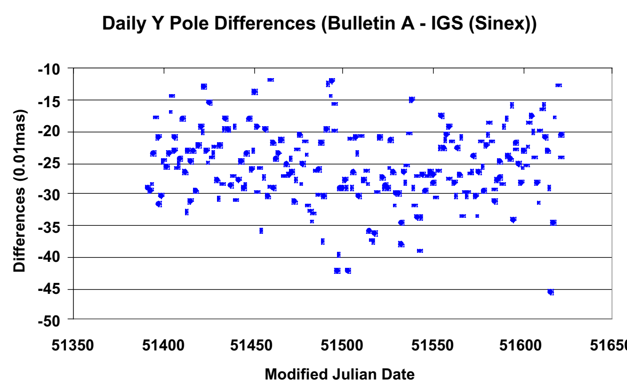

Figure 4-b

The weekly apparent geocenter position is also combined from the AC weekly combinations. Since GPS week 0978, the average weekly apparent geocenter estimates are 2.3mm, 4.8mm and —15.2mm with respective standard deviation of 6.8 mm, 9.2 mm and 14.4 mm. As shown in Figure 5, there is some obvious non-random behavior in the time series, especially on the

Y and Z-axis components. From this short time series a periodic, probably annual period, appears to be present.

Apparent Geocenter Position w.r.t ITRF97

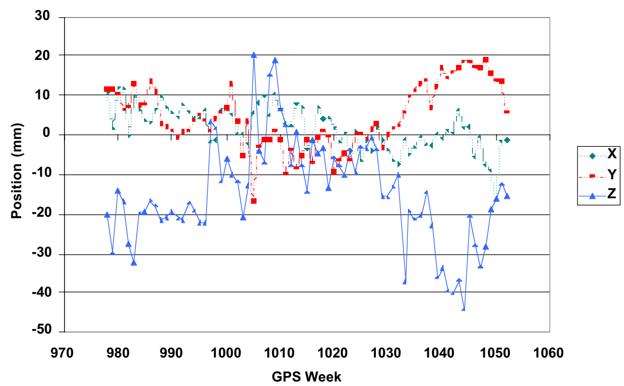

Figure 5

The ongoing active participation from the group members is instrumental in the continuous improvements of the station coordinates and velocities, Earth Rotation Parameters (ERP) and geocenter products. Thanks to Y. Mireault and P. Heroux for their constructive comments and suggestions.

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1999 IGS Activities in the Area of the Ionosphere

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Introduction

The IGS Ionosphere Working Group (Iono_WG) is active since June 1998. The working group s most important short-term goal is the routine provision of global ionosphere TEC maps plus GPS spacecraft differential code biases (DCBs) with a delay of some days.

Medium- and long-termed, the development of more sophisticated ionosphere models and the establishment of a near-real-time service are the major tasks. The final target is the establishment of an independent IGS ionosphere model.

Five Ionosphere Associate Analysis Centers (IAACs) contribute with their products to the Iono_WG activities:

a. CODE, Center for Orbit Determinationin Europe, AstronomicalInstitute, University of Berne, Switzerland.
b. ESOC, European Space Operations Centre, Darmstadt, Germany.
c. JPL, Jet Propulsion Laboratory, Pasadena, California, U.S.A.
d. NRCan, National Resources Canada, Ottawa, Ontario, Canada.
e. UPC, Polytechnical University of Catalonia, Barcelona, Spain.

It is the intent of this Technical Report to give an overview over the Iono_WG activities in 1999.

Routine Activities

Daily Ionospheric Total Electron Content (TEC) Information

Each IAAC delivers per 24 hours an IONEX file (Schaer et al., 1997) with 12 TEC maps containing global TEC information with a 2-hours time resolution and a daily set of GPS satellite DCBs in its header.

Weekly Comparisons

On Tuesday of each week the TEC maps from the different IAACs are compared for all days of the week before. These comparisons are done at ESA/ESOC. A weekly compari-son summary is e-mailed to the "Iono_WG members" via IONO-WG mail. Furthermore, the daily summaries, the daily IONEX files with the "mean" TEC maps & GPS satellite DCBs and daily TEC & DCB difference files with respect to the "mean" for each IAAC, and also plots of these maps, are made available to the "Iono_WG members" on ESOC s FTP account. The algorithm used in the comparison program is described in (Feltens, 1999 — Appendix A).

On the northern hemisphere the deviations of the different IAAC TEC maps from the IGS "mean" are under normal conditions 5 TECU or less. At the equator and on the southern hemisphere the situation is more problematic, because of gaps in the station coverage at these latitudes. The agreement of the different IAAC DCB sets is normally better than 0.3 nanoseconds, sometimes 0.5 nanoseconds. IAAC DCB sets showing differences of one 1 nanosecond and more with respect to the IGS "mean" are excluded from the comparison. Figure 1 below was computed by Stefan Schaer at CODE and shows the development of the Mean TEC since the beginning of 1995. A clear increase of the TEC, closely related to increasing solar activity, can be seen in this figure.

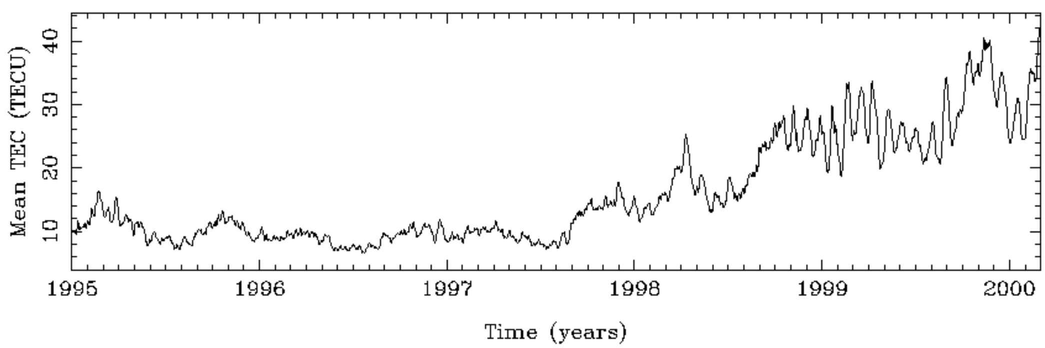

Figure 1. Development of Mean TEC since 1995 (computed at CODE).

Improvement of the Comparison Scheme / Validations

The current comparison/combination algorithm is based on a pure statistical approach using weighted means. On the other hand, the methods used by the IAACs to model the ionosphere are very different. In order to achieve an objective combination scheme the existing comparison/combination algorithm must be improved. The Iono_WG thus decided to make validations of the different IAAC models in order to define an objective weighting and an optimal comparison/combination scheme with which the individual IAAC TEC maps can be combined to one common IGS solution. At the moment the comparison results are thus only circulated to the Ionosphere Working Group members and not to the outside world.

Several types of validation were proposed by the Iono_WG members (Feltens, 1999). In the meantime validations were started with a method that was proposed by Pierre Heroux (Heroux, 1999) and which is based on the computation of ground station DCB series by subtracting from observed TEC values corresponding model TEC values and GPS satellite DCBs read from the IONEX files. The output is then given in form of some statistics made with these ground stations DCBs series.

The software to run the validations with measured vertical TEC obtained from TOPEX altimeter data is ready. However, there are still problems with the routine access to the TOPEX data, which could not be solved yet. The method to use TOPEX data for valida-tion was proposed by Brian Wilson from JPL. The software to run these validations was written by Joachim Feltens at ESA/ESOC.

Special Activities

Initiated by a proposal from Norbert Jakowski from DLR Neustrelitz, Germany, a special GPS tracking campaign was organized by the Iono_WG during the total solar eclipse event on 11 August 1999. About 60 ground stations from the global IGS tracking network contributed with high sampling rate tracking data (1 sec resp. 3 sec) to this campaign. These stations were located along the eclipse path from the east coast of North America over Europe to the Middle East. The high-rate data have been archived in form of RINEX files at the CDDIS and can be used for ionosphere analysis efforts (Feltens and Noll, 1999); they can be accessed via anonymous ftp to the host cddisa.gsfc.nasa.gov in the directory /gps/99eclipse. First results obtained with GPS data from the eclipse day were published in (Jakowski et al., 1999a) and in (Jakowski et al., 1999b).

Figure 2 below shows the sequence of 2-hourly TEC maps that were obtained from the comparison as mean IGS TEC maps for the 11 August 1999. In this sequence of TEC maps one can clearly recognize a decrease in the TEC level from the 9^{h} TEC map onwards, until the ionosphere starts to recover again in the evening hours.

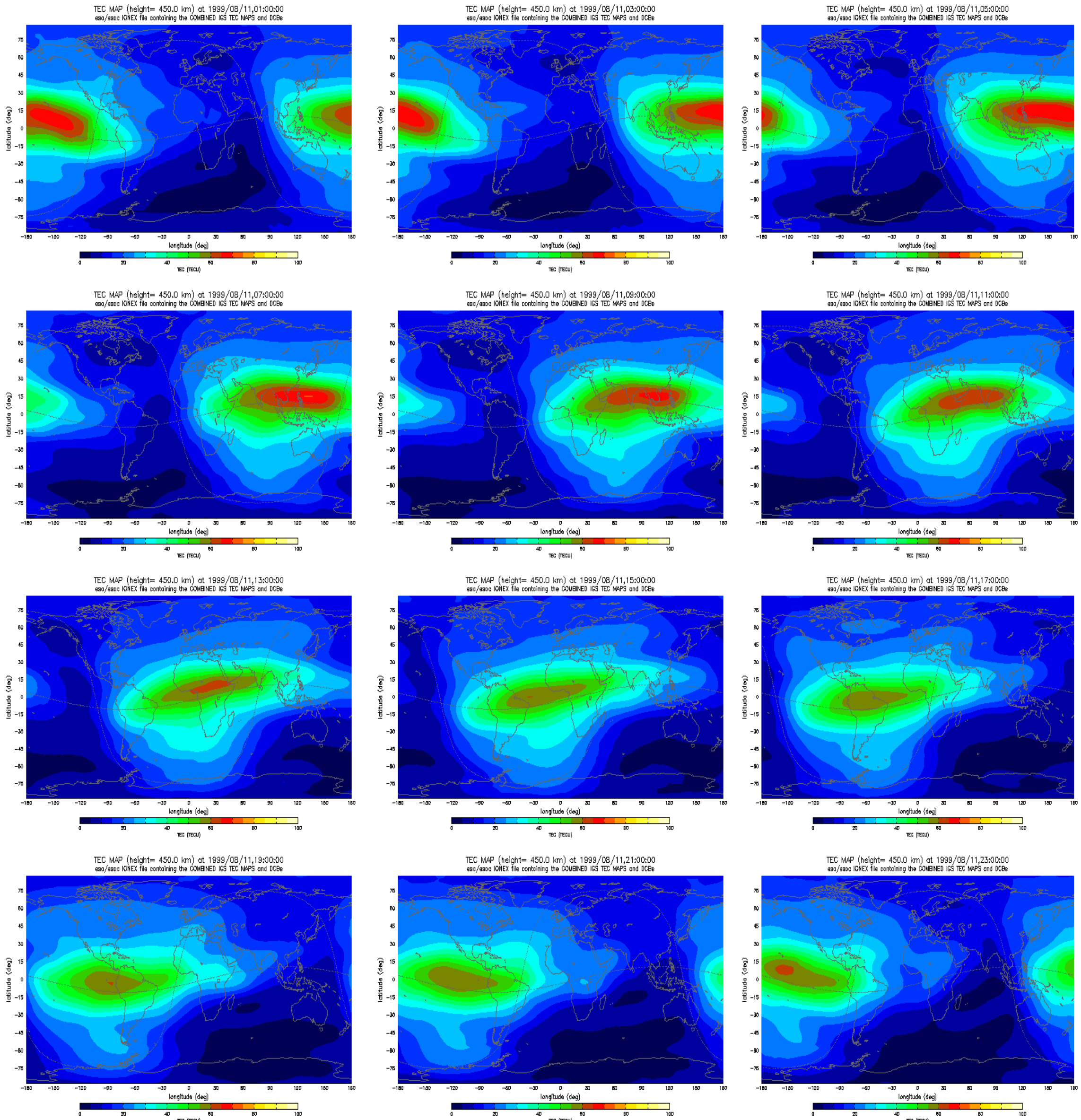

Figure 2. The IGS mean TEC maps of 11 August 1999 (Total Solar Eclipse).

The below Figure 3 was taken from (Jakowski et al., 1999b) and shows the TEC development at 11 August 1999 along the 10¡ E Meridian in the picture at the top. The Moon s shadow is indicated with the black dot. For comparison the monthly mean of daily progress of TEC is illustrated in the picture below. When comparing both TEC pictures, one can clearly see how the ionosphere reacts to the abrupt switch off of the Sun s radiation: the reduction in TEC level seems to follow the solar eclipse with a delay of up to 40 minutes at low latitudes.

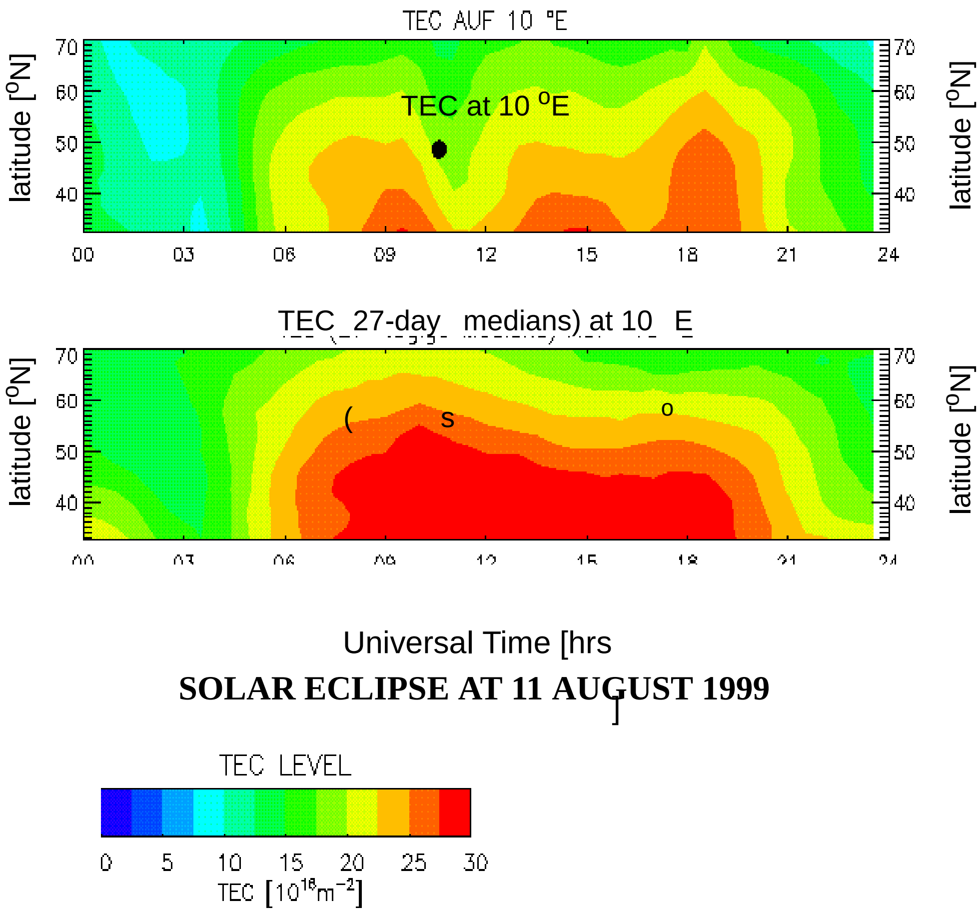

Figure 3. Diurnal progress of TEC along the 10¡ E Meridian (top) in comparison with the monthly mean TEC (below); this figure was taken from (Jakowski et al., 1999b).

Under the point "special activities" attention shall also be drawn to the JASTP —special issue "GPS Applications to the Structure and Dynamics of the Earth s Oceans and Ionosphere: Measurement, Analysis, Instrument Calibration, and Related Technologies" (JASTP, 1999). This issue includes several papers (co-)authored by members of the Iono_WG.

Future Tasks

It is intended to continue with the validation activities so that the Iono_WG will soon be in a position to provide an IGS ionosphere to users outside the IGS. The comparison/combination algorithm has to be improved accordingly.

Another important aspect 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 intention to provide actual ionosphere models in short time frames - this is of special importance with regard to the solar maximum, which is approaching.

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International GLONASS Experiment (IGEX-98)

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Introduction

The International GLONASS Experiment (IGEX-98) which began in October 1998 ended as scheduled on April 19, 1999. Its purpose was to exploit the Russian GLONASS satellite system primarily as an enhancement to GPS for both scientific and navigation applications. Accordingly, the four sponsors of the experiment were the IGS, the Institute of Navigation (ION), the International Association of Geodesy (IAG), and the International Earth Rotation Service (IERS). Participants represented 25 countries and approximately 80 organizations.

The objectives of the experiment included (1) establishment of a global network of GLONASS tracking stations collocated with GPS stations, (2) precise orbit determination, (3) evaluation of GLONASS receivers, (4) development of GLONASS applications software, (5) definition of reference frame relationships between the GPS WGS 84 frame, the GLONASS PZ-90 frame, and the International Terrestrial Reference Frame (ITRF), and (6) time and time transfer applications. A workshop, co-sponsored by IGS, ION and NASA, was held in Nashville, Tennessee on September 13-14, 1999 for the presentation and discussion of IGEX-98 results. Over 80 people attended.

Although IGEX-98 officially ended in April 1999, the success of the experiment prompted almost half of the tracking stations to continue their data collection efforts, while three organizations continued to produce precise orbits during the remainder of 1999.

Major Accomplishments

A globally-distributed GLONASS tracking network was established for the first time. Over 60 GLONASS tracking stations and 30 Satellite Laser Ranging (SLR) observatories participated in the campaign. Data collected by these stations during the 6-month campaign were archived at NASA s Goddard Space Flight Center (GSFC) in the U.S. and at the Institut Geographique National (IGN) in France, and are available for use by anyone.

Three commercial manufacturers and one university produced dual-frequency GLONASS receivers, which were operated and given their most thorough testing and evaluation as a result of IGEX-98. The Ashtech Z-18 and Javad Positioning System receivers were deployed extensively for the first time; other stations used 3S Navigation receivers. The University of Leeds tested a new receiver built for the European Space Agency. All of these receivers were designed to track both GLONASS and GPS satellites simultaneously, in a variety of configurations.

Precise orbits were computed by 11 Analysis Centers using both the SLR and GLONASS receiver data, with resulting accuracies of 20-50 cm. A combined orbit was computed at the University of Technology, Vienna from the individual solutions provided on a regular basis by a subset of the Analysis Centers. (See the report in this volume by R. Weber and E. Fragner on the IGEX Analysis for more information.) The precise orbits from all the Analysis Centers are archived at NASA GSFC and IGN. A number of different software packages that were designed for GPS observations were successfully modified to process GLONASS data as well and to compute precise orbits. A list of the Analysis Centers and their software (where known) are shown in Table 1. In order to accommodate the new GLONASS observations and orbits, the RINEX and SP3 data exchange formats were expanded for the experiment.

Table 1. Analysis Centers that Produced Precise GLONASS Orbits During IGEX-98

Analysis Center	Software	Data Type
Bundesamt fuer Kartographie und Geodaesie (BKG)	Bernese	Phase
Center for Orbit Determination in Europe (CODE)	Bernese	Phase
European Space Agency/ European Space Operations Center (ESA/ESOC)	BAHN	Phase/Code
GeoForschungsZentrum (GFZ)	EPOS.P	Phase
Jet Propulsion Laboratory (JPL)	GIPSY/OASIS	Phase/Code
University of Olsztyn, Poland	TOP	Phase/Code
University of Texas, Center for Space Research (CSR)	GIPSY/OASIS;UTOPIA	Phase; SLR
Australian Surveying and Land Information Group (AUSLIG)	MICROCOSM	SLR
United Kingdom SLR Facility (NERC)	SATAN	SLR
Russian Mission Control Center (MCC)/GEO-ZUP		SLR
University of Technology, Vienna		Combined

The availability of independently-computed orbits derived from the laser observations provided a measure of truth for orbit evaluations. Orbits computed from the SLR data by NERC, for example, had post-fit residual RMS values of about 6-10 cm. The University of Texas CSR similarly computed RMS values of 3 cm for SLR normal point residuals over the campaign, although there was considerable week-to-week variation. The CSR noted RMS orbit differences in the radial, along-track and cross-track directions of approximately 10 cm, 40 cm and 45 cm when comparing their laser-based orbits with the receiver-based orbits of the other Analysis Centers. Comparisons of AUSLIG s SLR orbits and CODE precise orbits produced similar values — 14 cm, 75 cm and 51 cm.

The availability of precise GLONASS orbits in the ITRF reference frame provided the means for several of the groups to compute transformations between the Russian PZ-90 reference frame and ITRF. CODE, BKG and JPL all computed 7-parameter transformations between the broadcast PZ-90 orbits and their respective precise ITRF orbits. All found the rotation about the z-axis to be the most significant parameter. BKG also noted a time-dependence to the transformation parameters for x-, y- and z-rotations and y-translation. An extensive study done by GEO-ZUP and the Mission Control Center in Russia shows this time dependence with longer term fluctuations that exceed one year, and attributes this to the way Earth Orientation Parameters are introduced into the operational GLONASS orbit determination process by the GLONASS System Control Center (SCC). The GEO-ZUP work is based on comparisons of laser-based orbits with averaged post-processed GLONASS SCC ephemeris data and with broadcast orbits. The reported results show z-translation and z-rotation to be the most significant parameters.

Workshop Resolutions

At the September 1999 IGEX-98 Workshop in Nashville, a number of resolutions were introduced by the IGEX Steering Committee for discussion and a vote. There was strong support for continuing the effort begun with the 6-month campaign. The resolutions approved during the meeting were as follows:

1. Global, internationally coordinated GLONASS tracking and orbit determination should continue in the time interval 1999-2003.

2. The International Association of Geodesy s Committee for the Coordination of Space Techniques for Geodesy and Geodynamics (CSTG) and the IGS should continue to collaborate in an International GLONASS Pilot Service.

3. The International GLONASS Pilot Service should be proposed as an IGS Pilot Project, initially for the period 1999-2003. A new committee should be formed to organize the new project.

International GLONASS Service Pilot Project (IGLOS-PP)

After the IGEX Workshop, due to the continued interest of the IGEX participants, a new pilot project was initiated under the auspices of the IGS. A Pilot Project Committee was formed with the following membership: James Slater (Chair, NIMA), Vladimir Glotov (Russian Space Agency), Ramesh Govind (AUSLIG), Werner Gurtner (International Laser Ranging Service Liaison, University of Berne), Arne Jungstand (DLR), Angelyn Moore (IGS Central Bureau), Carey Noll (Data Center Coordinator, NASA/GSFC), Robert Weber (GLONASS Analysis Center Coordinator, University of Technology, Vienna), and Pascal Willis (IGN). Ruth Neilan (Director, IGS Central Bureau) and Tim Springer (GPS Analysis Center Coordinator, University of Berne) are ex officio members.

A Charter was prepared by the Project Committee and approved provisionally by the IGS Governing Board in December 1999. The general intent of the service is to facilitate the use of combined GLONASS and GPS observations for scientific and engineering applications, and to allow users to combine the systems as a prototype Global Navigation Satellite System. The goals and objectives of the pilot service are:

1. Establish and maintain a global GLONASS tracking network
    a. Collocate dual-frequency, combined GPS/GLONASS receivers with dual-frequency GPS receivers or upgrade existing dual-frequency GPS receivers to dual-frequency, combined GPS/GLONASS receivers at existing IGS sites and at new sites
    b. Apply International GPS Service (IGS) network operations standard.
    c. Calibrate and evaluate combined GPS/GLONASS receivers and antennas

2. Produce precise (10-cm level) orbits, satellite clock estimates, and station coordinates
    a. Evaluate microwave-derived orbits using SLR observations and orbits
    b. Incorporate SLR observations in routine orbit processing
    c. Obtain initial operational capability of 20-50 cm orbits at Analysis Centers
    d. Receive independent orbit/clock/station solutions from Analysis Centers within three weeks of observations

3. Monitor and assess GLONASS system performance

4. Investigate the use of GLONASS to improve Earth Orientation Parameters

5. Improve atmospheric products of the IGS

6. Fully integrate GLONASS into IGS products, operations and programs.

A Call for Participation will be issued to enlist the participation of stations, analysis centers, and data centers. The plan calls for a pilot service to operate for a period of up to four years from 2000-2003.

In the interim period between the end of the IGEX campaign and the beginning of the new pilot service, about 30 stations have continued to track GLONASS and three groups (BKG, CODE, and ESA) have continued to generate precise orbits. The data and orbits are archived at NASA/ GSFC and at the IGN. Nine GLONASS satellites remained operational at the end of 1999. Every six months an assessment will be made as to the viability of the GLONASS constellation and whether or not the pilot service should be continued.

IGEX Analysis

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Introduction

In October 1998 the IGEX field campaign, the first coordinated international effort to monitor GLONASS satellites on a global basis, has been launched. Besides more than 60 institutions contributing to the station network, 6 Analysis groups comprising the BKG (Federal Bureau for Cartography and Geodesy), CODE (University of Berne), ESOC (European Space Operations Center), GFZ (Geoforschungszentrum Potsdam, Wks 980-1002), JPL (Jet Propulsion Laboratory, Wks 991-1006) and MCC (Mission Control Moscow) were willing to calculate regularly precise satellite orbits (at least over a limited number of weeks).

This paper reflects the continuing improvements in modelling GLONASS orbits obtained by these centers in 1999. Moreover the combination of the ephemeris performed by the IGEX-AC Coordinator in order to generate a robust, reliable and complete IGEX orbits product will be discussed.

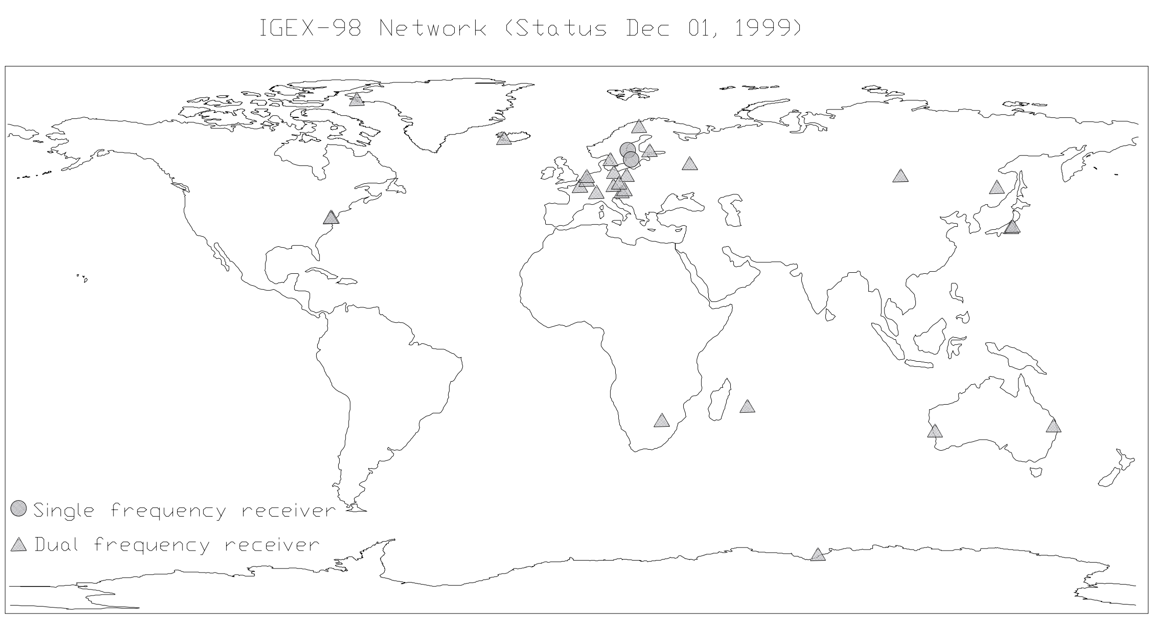

Figure 1.

Over the period of the main campaign the station network consists of about 30 dual frequency and 15 single frequency receivers (Figure1). Frequently expressed fears, that the status of the operational network would become an element of uncertainty after April 1999, finally turned out to be baseless. Thus, about 20 dual frequency and 10 single frequency receivers are still operational today. On the other hand the irregular distribution of the sites, centered in the European region, is of course not satisfying and by no means comparable to the current IGS/GPS network.

Data Analysis and Orbit Combination

Although the AC s base their computation on different data types (microwave phase and code data, laser ranges), different basic variables (zero and double differences), a varying parametrization of the force field (2, 5 or 9 parameters to characterize radiation pressure; in addition stochastic pulses/ rev.) and different arc-lengths (3 days up to 8 days) all of them were able to estimate GLONASS orbits well below the 1 meter accuracy level and consistent at about 30cm from the start. In this context it has to be mentioned, that the MCC-solution is solely based on Laser distance measurements. Therefore the delivered ephemerides are restricted to the number of satellites tracked by the ILRS (9 satellites from October 98 till April 99 and 3 satellites afterwards).

Usually GPS orbits and the Earth Rotation Parameters were fixed to the values given in the centers IGS submission, respectively to the IGS-GPS combined solution. Coordinates of few tracking sites were constrained to the ITRF96 (from Aug.1,1999 onwards to the ITRF97 respectively).

Figure 2 shows the delay of the center submissions in weeks relative to the time of observation. The plot covers the period Oct. 1998- Mar. 2000 and highlights the fact that soon after the Nashville workshop (Sept. 1999) the situation improved considerably.

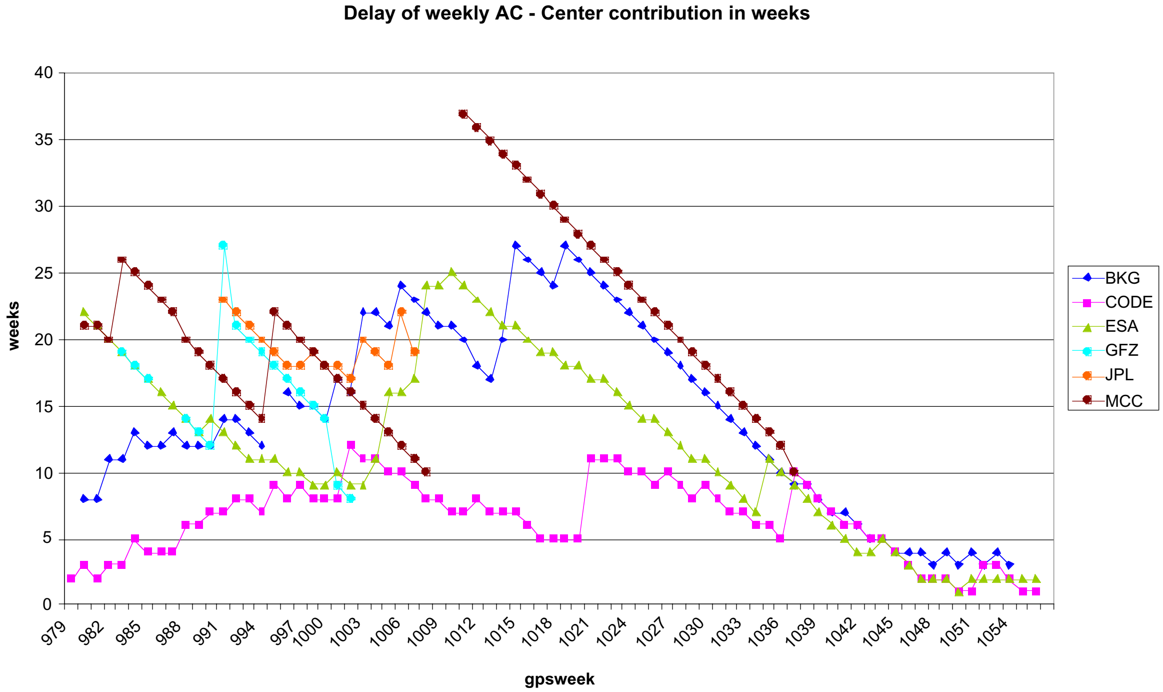

Figure 2.

As asked by the timing and frequency community, the Analysis Centers were able to deliver precise GLONASS orbits within 2-4 weeks of observation.

Besides the 'Center solutions' a combined Glonass Orbit (IGX) has been madeavailable to the user community with the background to foster the reliability of the orbit product and to include all satellites which are given in at least one center solution. At the start (Wks 980-1005) the combination process was based on long-arc fits of the individual center submissions. Satellite positions were used as pseudo observations to establish seven-day arcs and afterwards the center weights were calculated from the post fit residuals. Unfortunately this scheme does not allow for a proper daily valuation of the incoming ephemerides. Thus, since GPS week 1006 (after the period of the official IGEX-98 campaign) a combination strategy more similar to the IGS-GPS combination has been applied. The basic principles are outlined very briefly below:

Again, the orbits are combined in the ITRF system. The effect of less precise orbit estimates can be reduced by applying center specific weights which have to be determined every day for all processing centers. Therefore an unweighted mean for each satellite position $\vec{x}_s^{(1)}$ has to be computed and center (Center i , Center Weight / Day p_i) and satellite specific (Satellite s , Satellite Weight / Center / Day p_{si}) weights are calculated from the rms. errors of a Helmert transformation between $\vec{x}_s^{(1)}$ and the individual center solutions $\vec{x}_{si}$.

$$\vec{x}_s^{(1)} = \frac{\sum_{i=1}^{n} \vec{x}_{si}}{n} \qquad T_7(\vec{x}_s^{(1)} \Leftrightarrow \vec{x}_{si}) \Rightarrow p_i = \frac{1}{\sigma_i^2},\ p_{si} = \frac{1}{\sigma_{si}^2}$$

The center specific weights are used to compute a weighted mean for each satellite position and another Helmert transformation is performed between $\vec{x}_s^{(2)}$ and the center solutions (this time weighted, using the satellite specific weights).

$$\vec{x}_s^{(2)} = \frac{\sum_{i=1}^{n} p_i \vec{x}_{si}}{\sum_{i=1}^{n} p_i} \qquad T_7(\vec{x}_s^{(2)} \Leftrightarrow p_{si}\vec{x}_{si}) \Rightarrow \Delta\vec{x}_i,\ R_i,\ m_i$$

This step results in a shift vector, a scale factor and 3 rotations (per center) used to calculate the weighted (p_i) IGX orbit $\vec{x}_s^{(3)}$.

$$\vec{x}_s^{(3)} = \frac{\sum_{i=1}^{n} p_i\, m_i R_i (\vec{x}_{si} + \Delta\vec{x}_i)}{\sum_{i=1}^{n} p_i}$$

The IGX precise ephemerides as well as a weekly report can be retrieved from the global data centers (e.g. CDDIS; igex - products directory). The summary file contains comprehensive information on the quality and consistency of the individual center solutions. For example, the seven parameters of a daily performed spatial Helmert transformation with respect to the combined orbit and the center specific rms. of this transformation are listed. Figure 3 gives time series of these rms. values starting in the late 1998 till end of 1999. We want to emphasize that starting at about 40cm the consistency of the orbit submissions achieved the 20cm level within a year.

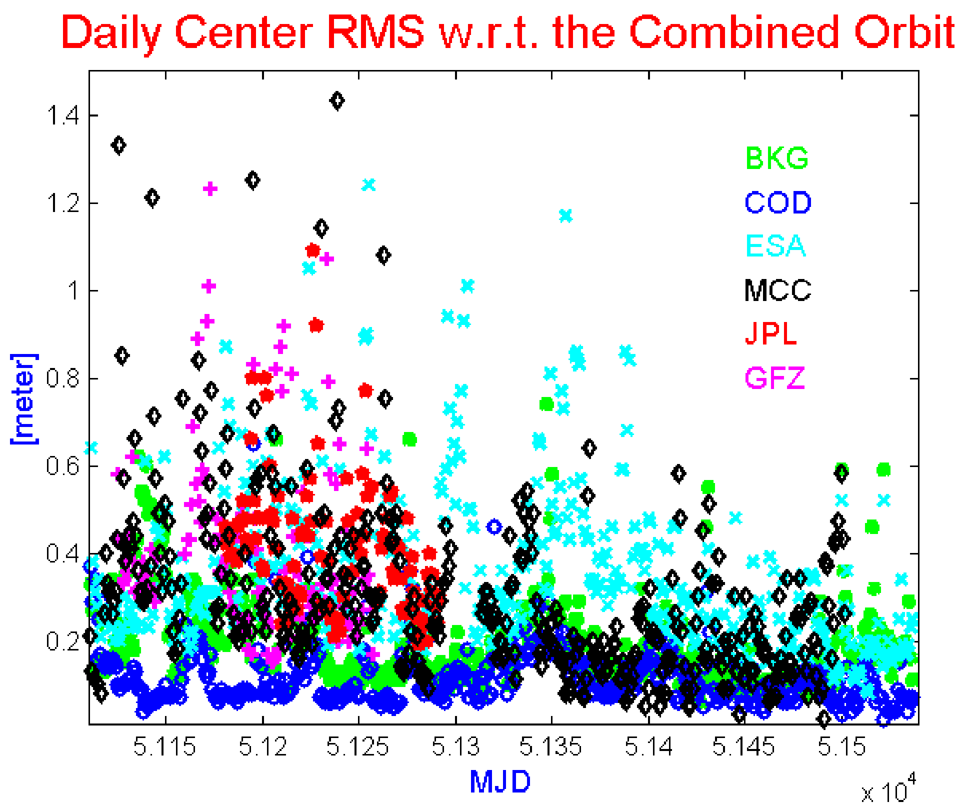

Figure 3.

Conclusions

We may conclude, that the various Analysis-Centers managed to calculate precise GLONASS orbits with an internal consistency of about 20 cm. Despite of this success, further improvements are inseparable linked to an increasing number of tracking sites and to a more regular global distribution of these sites. Combined precise GLONASS Orbits are available for the entire duration of the IGEXperiment-98 as well as for 1999 (GPS Wks 980 - 1042). The combination strategy has been changed slightly to allow for a more convenient daily valuation of the incoming ephemerides.

Finally we want to refer to the upcoming IGLOS Pilot Project, which is designed as a formal continuation of IGEX-98 with very ambitious goals concerning the accuracy, availability and number of its products. This service should start in mid 2000 and will operate for a period of up to four years.

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