IGS

ANALYSIS CENTERS

Annual Report 1998 of the CODE Analysis Center of the IGS

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Introduction

CODE, the Center for Orbit Determination in Europe, is a joint venture of

- the Federal Office of Topography (L+T), Wabern, Switzerland,
- the Federal Agency of Cartography and Geodesy (BKG), Frankfurt, Germany,
- the Institut Géographique National (IGN), Paris, France, and
- the Astronomical Institute of the University of Berne (AIUB), Berne, Switzerland.

CODE is located at the AIUB. All solutions and results are produced with the latest version of the Bernese GPS Software [Rothacher and Mervart, 1996].

This report covers the time period from July 1998 to October 1999. It focuses on the major changes in the routine processing during this period and shows the new developments and products generated at CODE. The processing strategies used till June 1998 are described in the annual reports of previous years [Rothacher et al., 1995, 1996, 1997, 1998].

The rapid solution generated at CODE are based on the extended radiation pressure model [Springer et al., 1999]. The cut-off angle for all solutions is set to 10º and the Niell mapping function [Niell, 1996] for the dry atmosphere is used. No troposphere gradients are estimated for the official global solution, gradients are determined, however, for the European as well as for some global test solutions. 1-day and 2-day predicted Global Ionosphere Maps (GIMs) are derived regularly and delivered weekly to CDDIS. The ocean loading model according to [Scherneck, 1991] together with the ocean tide maps from [Le Provost et al., 1994] is used.

For all solutions (except for the ionosphere solution) the number of stations is limited to 100. If more stations are available, those with the maximum number of observations are selected. Fig. 1 shows the number of stations used in the processing at CODE. Since spring 1998 usually more than 100 stations are available routinely.

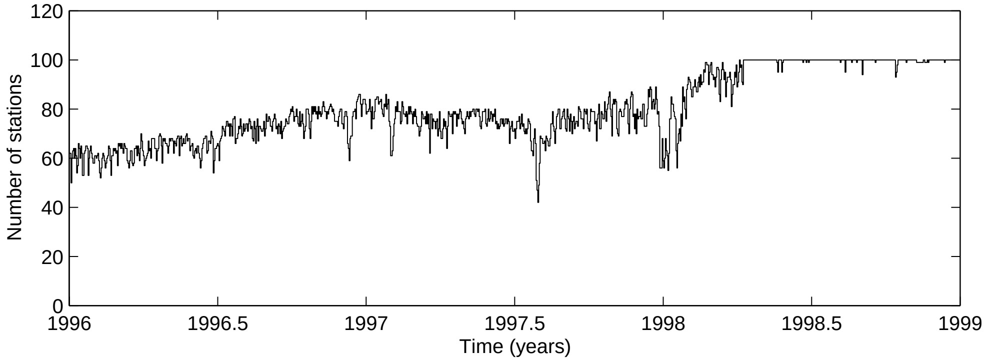
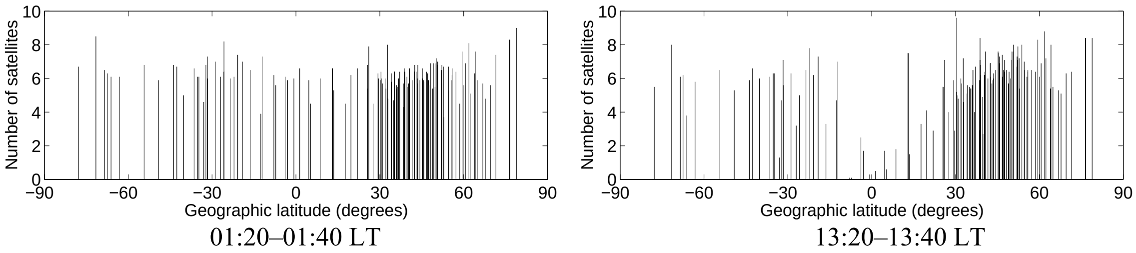


Figure 1: Number of stations used for the global 1-day solutions computed at CODE.

Numerous receivers in the IGS network, in particular those located near the geomagnetic equator, severely suffer from the increasing ionospheric activity – well before the next solar maximum comes within reach. Fig. 2 gives a summary of IGS receiver performance under aggravated ionospheric conditions.



01:20–01:40 LT

13:20–13:40 LT

Figure 2: Average number of GPS satellites tracked by IGS receivers as a function of geographic latitude for 01:30 (left) and 13:30 local time (right) in September 1998.

The two figures show the average number of GPS satellites successfully tracked by the receivers as a function of geographic latitude for time intervals of 20 minutes centered around 01:30 and 13:30 local time, respectively. 'Successfully tracked' means that at maximum one missing measurement epoch per 20 minutes is tolerated. It is alarming to see that more or less all equatorial receivers fail to keep track of the satellites during the local noon hours. This is a clear indication that the problem is related to the ionosphere. The problem should be taken serious because Fig. 2 does not address the situation for a particular day but throughout the entire month of September 1998.

Changes in the CODE Routine Processing

The major changes implemented in the CODE routine analysis since July 1998 are listed in Table 1. Modifications prior to this date have already been reported in last year's annual report of last year [Rothacher et al. 1998].

Table 1: Modification of processing scheme at the CODE Analysis Center from July 1998 to October 1999.

Date	Doy/Year	Description of Change, Impact
16-Jul-98	187/98	New IGS ERP Format activated (version 2).
20-Aug-98	232/98	Rapid solution now run using the new radiation pressure model [Springer et al., 1999].
27-Aug-98	239/98	Max degree/order of spherical harmonic expansion for TEC/differential code biases (DCB) solution increased from 3/3 to 4/4, i.e., 25 instead of 16 TEC parameters are estimated per station-day.
04-Oct-98	277/98	New normal equation stacking routine (ADDNEQ) officially used. Final orbits are now based on backsubstituted coordinates and ERP from 7-day (7 3-day) ADDNEQ combination of coordinates and ERPs.
29-Nov-98	333/98	Change of antenna offsets from 1.0259 to 1.0230 for the Block II/IIA and from 1.2053 to 0.0000 for the Block IIR.
20-Mar-99	079/99	GIM Zero-differences used as new official CODE TEC product. New TEC product submitted to CDDIS.
05-Apr-99	095/99	Rapid ionosphere product (including DCB estimates) is derived from zero differences. Station-specific TEC models based on double differences are generated to improve QIF ambiguity resolution.
11-Apr-99	101/99	All available stations are used to derive the final ionosphere product (Z1 solution). For the station-specific TEC maps and DCBs (Z1N solution), up to 100 station are used. For this reason, the maximum degree of the spherical harmonic expansion was reduced from 4 to 3.
04-Jul-99	185/99	New receiver and antenna names used.
01-Aug-99	213/99	Switch to ITRF97. The new set of reference stations consists of about 50 stations. The complete ERP time series, going back to day 200 of 1993, was recomputed using ITRF97 coordinates and velocities (see IGS Mail 2422).
24-Aug-99	236/99	Download also GZ RINEX observation files from JPL data archive if necessary.
26-Sep-99	269/99	12 new sites added: ARTU, BAKO, CORD, DAEJ, KUNM, PIMO, RIOG, RIOP, SYOG, URUM, YKRO, YSSK. For RIOP and SYOG no data is currently available.

Product Quality and Results

Ionosphere

The time series of global TEC parameters available through CODE now covers more than 4.5 years. Fig. 3 shows the evolution of the mean global TEC together with the trend function determined from the time series. The increase of ionospheric activity accompanies the solar activity reaching its maximum in about two years. A daily updated version of Fig. 3 may be found on the WWW page http://www.cx.unibe.ch/aiub/ionosphere.html.

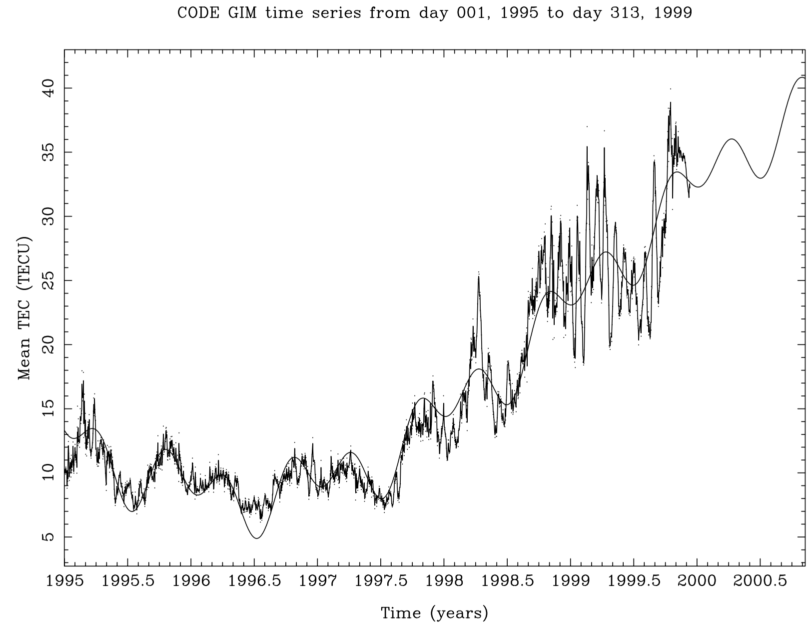


Fig. 3: Evolution of the mean global TEC computed by CODE since January 1, 1995.

Fig. 4 shows the amplitude spectrum of the sectorial coefficients C_{22} and S_{22} of the global TEC expansion into spherical harmonic functions. Very prominent is a line close to 15 days reminding us of the revolution period of the Moon. As our global TEC representation is longitude-orientated towards the Sun, the so-called synodical month, the time it takes from new moon to new moon, is the relevant lunar revolution period. A synodical month equals to approximately 29.5306 days. The time the Moon needs from one maximum elongation to the next corresponds therefore to $29.5306/2 \cong 14.77$ days. This corresponds well with the period we see in our amplitude spectra of the low-degree sectorial spherical harmonic coefficients. Computations solving for this period yield estimates which agree with the true value to within 0.01 days. We have thus demonstrated that there is a significant lunar impact on the Earth's ionosphere [Schaer, 1999].

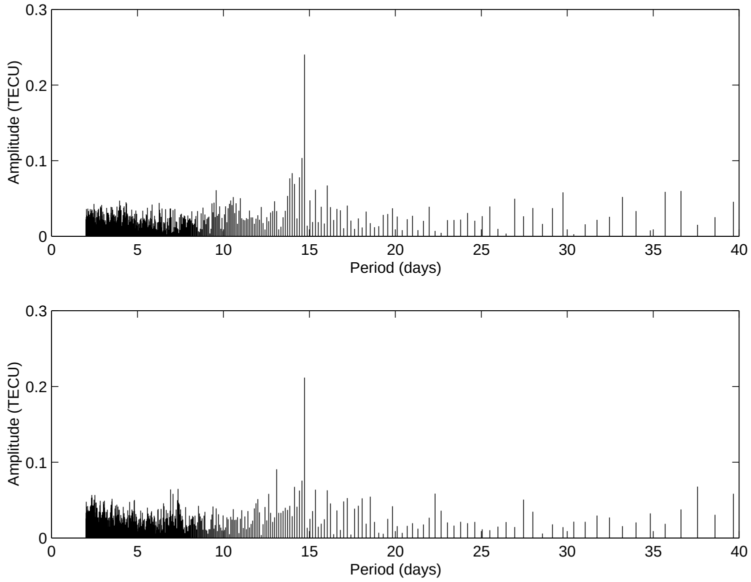


Figure 4: Amplitude spectra of the sectorial spherical harmonic coefficients C_{22} (top) and S_{22} (bottom) for periods below 40 days.

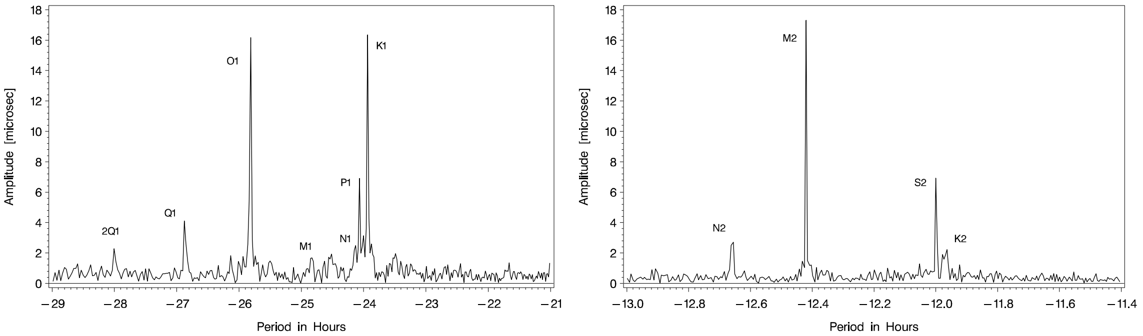
These perturbations are probably indirectly caused by atmospheric pressure variations associated with lunar gravitational tides as postulated by [Rishbeth and Garriott, 1969]. These tidal waves, considered in an Earth-fixed frame, respond to the well-known tidal cycle of about 12 hours 25 minutes. Another piece of evidence has to be seen in the fact that the influence of the Moon on the ionosphere is not only confirmed by the particular period of 14.77 days but also by the coefficient-specific phases themselves, which are in agreement with the lunation cycle. Small phase shifts offer a basis for further investigations.

Earth Rotation Parameters

In April 1994 CODE started to estimate nutation rate corrections in longitude and obliquity relative to the IAU 1980 theory of nutation (which is used as a priori model in our processing). The series of nutation rate estimates covers by now a time interval of more than 5 years. Results of a detailed analysis of the time series was presented at the IGS Analysis Workshop in Darmstadt, 1998 [Rothacher and Beutler, 1998]. They show that GPS may give a significant contribution to nutation in the high frequency range of the spetrum (periods below 20 days). The nutation coefficients estimated from GPS rate series show an overall agreement of about 10 µas with the most recent nutation models by Souchay and Kinoshita [Rothacher et al., 1999].

Internally, CODE uses a 2-hour resolution since January 1995 to account for polar motion and LOD. Each component of this high-resolution polar motion series (and the corresponding integrated LOD series) is approximated by a linear function within each 2-hour sub-interval and continuity is enforced at the interval boundaries. The sub-daily variations of polar motion and UT correspond very well to models derived from oceanography using altimetry data.

Fig. 5 shows the amplitude spectrum of the diurnal and semi-diurnal tidal frequency bands for UT1 generated from the sub-daily ERP series. The noise level is of the order of 0.5-1.0 µs which enables us to clearly see all the major tidal terms. The spectra of these GPS series demonstrate the potential of the technique. The series is still far too short, however, to give insight into the sidebands of the major tides. For more details we refer to [Rothacher, 1998].



Diurnal UT1

Semi-diurnal UT1

Figure 5: Amplitude spectra of the diurnal and semi-diurnal tidal frequency bands generated from the entire sub-daily ERP series. The major tidal terms are labeled. The spectra were computed from the UT1 rate estimates and subsequently converted to spectra in UT1.

Orbit Validation Using SLR

The SLR observations of the GPS (and GLONASS) satellites provide a unique opportunity to validate the quality of the IGS (and IGEX) orbit determination using an independent method. For a comparison all observations acquired by 25 SLR stations to the two GPS satellites PRN 5 and PRN 6, that are equipped with retroreflectors were used [Springer, 1999]. The SLR station positions were taken from the ITRF realization, the satellite orbits from the CODE analysis center. The tropospheric delays are modeled using the Marini-Murray model [Marini et al., 1973].

Figure 6 shows the differences between the observed and computed ranges using all SLR observations of the GPS satellites over the time span from January 1995 to July 1999. Outliers were removed using a 5σ outlier criterium.

Two interesting results emerge from Fig. 6: First, we see an average bias of –55 mm between the observed and computed ranges. The negative sign indicates that the observed SLR ranges are shorter than the computed ranges. A range bias of similar magnitude and the same sign is observed also for GLONASS satellites [Springer, 1999]. The occurrence of this bias is unexpected and asks for explanations.

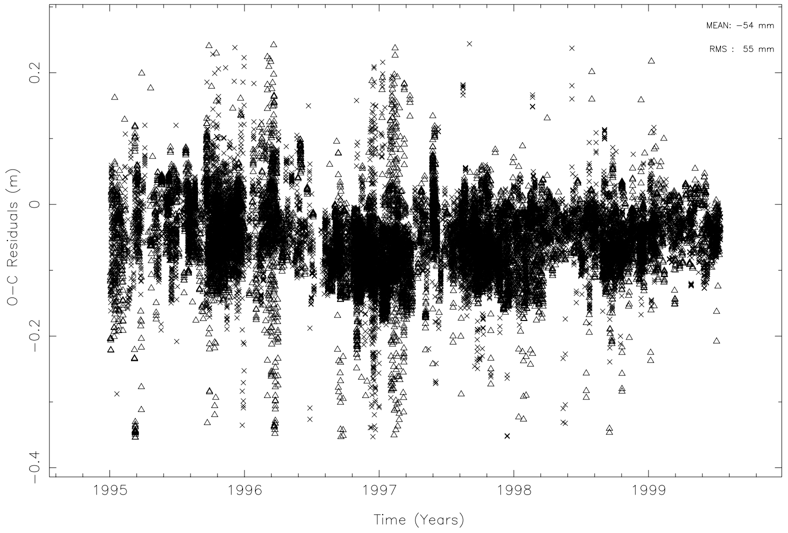


Figure 6: Range residuals of the SLR observations from GPS satellites PRN 5 (crosses) and PRN 6 (triangles).

Secondly, the RMS of the residuals, around the mean, is as low as 55 mm. This result implies that the two independent techniques, microwave and SLR, agree at the level of a few centimeters. Most importantly it also shows that the (radial) orbit error of the IGS orbits is at maximum as small as 55 mm. This corresponds quite well to the RMS statistics of the weekly IGS orbit combinations. On the other hand, the 55 mm RMS is well above the noise level of the SLR normal point observations.

Intensive tests to routinely combine GPS and SLR observations for the generation of the CODE products were carried out. The impact on the GPS-only results is small, however, because of the sparseness of SLR data. No obvious improvements could be observed. For more details we refer to [Springer, 1999].

GLONASS Processing

On October 19, 1998, at the beginning of the International GLONASS Experiment (IGEX-98) [Slater et al., 1999], CODE started to compute precise orbits for all active GLONASS satellites. The processing of the IGEX network is done on a routine basis and precise ephemerides are made available through the global IGEX Data Centers. For the combined processing of GLONASS and GPS data the enhanced Version 4.1 of the Bernese GPS Software is used [Rothacher and Mervart, 1996, Habrich 1999].

The analysis is done by fixing both, the GPS orbits and Earth rotation parameters to CODE's final IGS solution. The number of available sites within the IGEX network (about 35 sites) would not allow to estimate these parameters with an accuracy comparable to the IGS solutions. The orbital parameters of the GLONASS satellites are estimated using double difference phase observations (including double differences between GLONASS and GPS satellites). The processing of the IGEX network is done without fixing the ambiguities to their integer values.

Six initial conditions and nine radiation pressure parameters are determined for each satellite and arc. So far only receivers providing dual-frequency GPS and GLONASS data or dual frequency GLONASS data are included in the processing procedure. The final precise orbits stem from the middle day of a 5-day arc. In order to align the IGEX network to the terrestial reference frame the coordinates of seven sites are constrained to their ITRF 96 coordinates [Ineichen et al., 1999].

In order to check the internal consistency of our GLONASS orbits, we perform a long-arc fit for each processed week. For each satellite, one orbital arc is fitted through the seven consecutive daily solutions of the week. The RMS values lie in general between 5 and 20 cm. These small values indicate that the adopted orbit model is well suited to describe the motion of the GLONASS satellites over a time period of several days. An independent check of the orbit accuracy is given by the range residuals of SLR observations showing a RMS of 13 cm [Springer, 1999].

The difference between the GLONASS and GPS system times was set up as one additional parameter for each station and session. The results show that this time system difference is receiver dependent. Fig. 7 shows the estimated system time difference for the Z18 (upper band) and the JPS receivers (lower two bands). The time differences for other receivers are of the order of one microsecond.

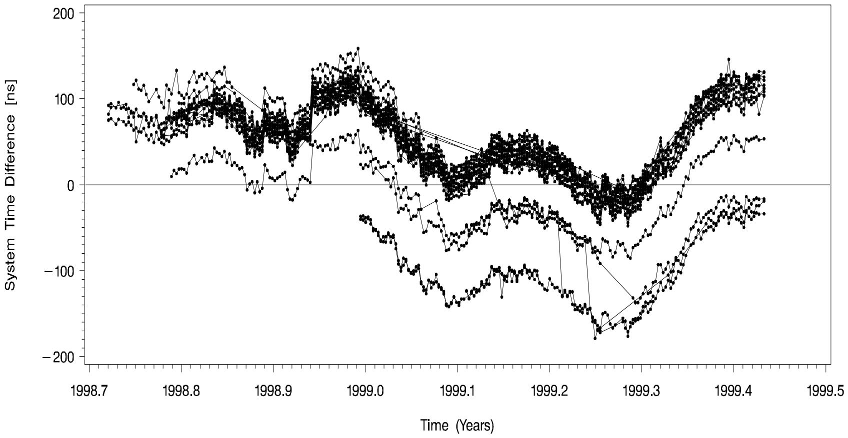


Figure 7: Differences between GPS and GLONASS system times for Z18 (upper band) and JPS receivers (lower two bands).

GPS and GLONASS broadcast orbits are given in different reference systems. The seven parameters of a Helmert transformation were determined using precise GLONASS orbits in the ITRF 96 reference frame and the broadcast GLONASS orbits in the PZ-90 reference frame. For each day one set of parameters (three translations, three rotations, and one scale factor) was established. The accuracy of the daily Helmert transformations (RMS between 3 m and 6 m) indicate the GLONASS broadcast orbit quality.

Fig. 8 shows the time series of the rotation parameters. A rotation of –350 mas around the z-axis is found to be highly significant and has to be taken into account when processing combined GLONASS and GPS data using broadcast orbits. The values of the other rotation parameters as well as the translation and scale parameters are limited by the broadcast orbit accuracy.

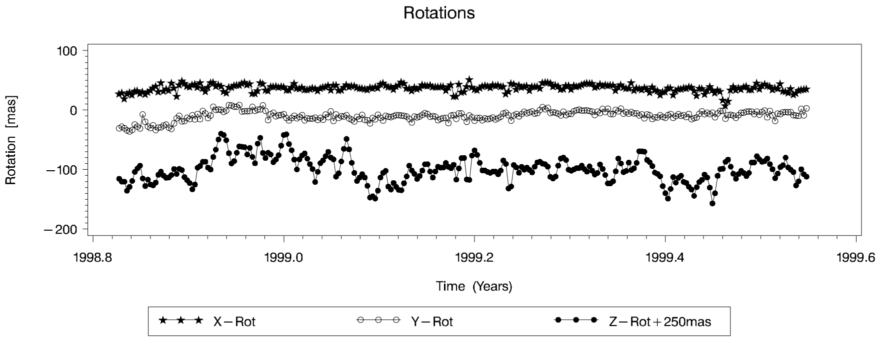


Figure 8: Daily rotation parameters of the Helmert transformation between broadcast orbits in the PZ-90 system and CODE's precise orbits in the ITRF 96 system.

Time and Frequency Transfer using GPS

In 1991 a common project of the Federal Office of Metrology (EAM) and CODE/AIUB was initiated to develop time transfer terminals based on geodetic GPS receivers. The goal is the comparison of time scales with sub-nanosecond accuracy and frequencies with an accuracy of 10^{-15} over one day for two or more (GPS-external) clocks.

Three prototype Geodetic Time Transfer terminals (GeTT terminals) were developed. They are based on modified Ashtech Z-12 receivers installed in a temperature controlled container. More information about the time transfer project and the GeTT terminals may be found in [Schildknecht et al., 1990, Overney et al., 1998, Dudle et al., 1999].

After careful calibration of delays in cables, temperature-dependent delays, etc., two GeTT terminals were deployed on two European baselines (EAM-NPL, PTB-NPL(UK)). Since July 1998 two terminals are located in the time laboratories of PTB in Braunschweig, Germany, and USNO in Washington, USA, on an intercontinental baseline with a length of 6'275 km. In both laboratories other time transfer equipment is available, such as GPS Common View (GPS-CV) or Two Way Satellite Time and Frequency Transfer (TWSTFT) allowing a comparison with the geodetic time transfer method on the sub-nanosecond level.

The data from a permanent time and frequency comparison network is processed routinely at CODE using the zero differencing capability of the Bernese GPS Software and using the IGS final products such as precise orbits, troposphere and ionosphere parameters. In Fig. 9 the time difference between PTB and USNO is shown as measured by GeTT, TWSTFT, and Circular T, the official difference determined by the Bureau International des Poids et Mesures (BIPM) based on GPS-CV which relies on pure GPS code measurements. Fig. 10 shows the difference between the GeTT and the TWSTFT measurements. The reason for the systematic variations of the difference between the two methods is not yet understood and is discussed within the time transfer community. It has to be pointed out that accuracy-wise, geodetic time transfer with GPS is the only method competing with TWSTFT on intercontinental baselines.

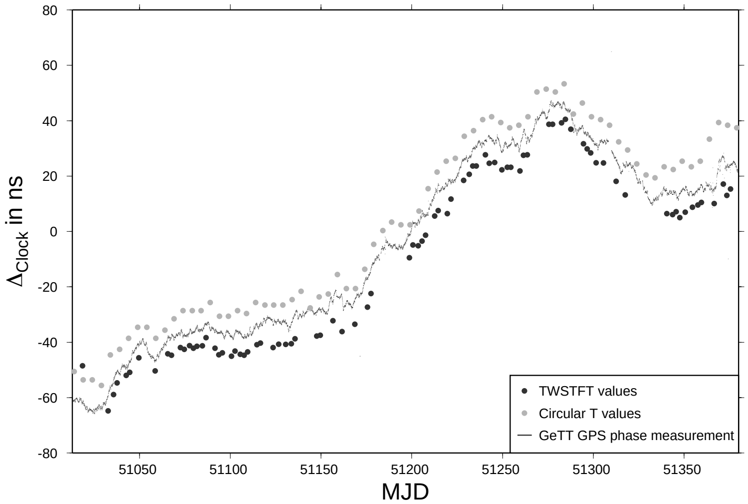


Figure 9: Time difference between reference clocks at PTB, Braunschweig, Germany, and USNO, Washington, USA, as measured by geodetic GPS (GeTT) and Two Way Satellite Time and Frequency Transfer (TWSFTF), together with the values from Circular T published by the Bureau International des Poids et Mesures (BIPM). The offsets between the different measurements are arbitrary.

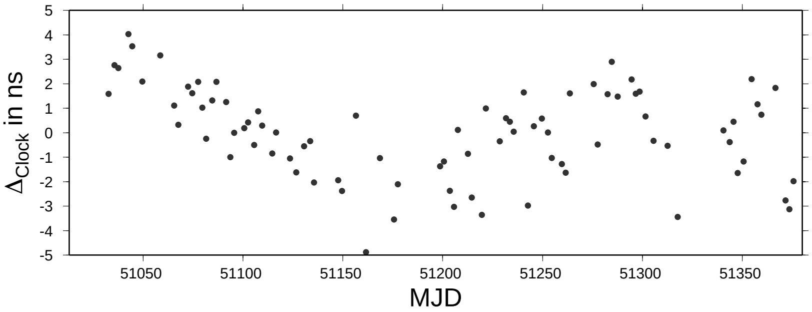


Figure 10: Difference between the clock differences between PTB and USNO as measured by geodetic GPS (GeTT) and TWSTFT. The systematic variation of the difference between the two methods is not yet understood.

Outlook

A number of questions have to be studied in more detail in the near future such as the correlation between satellite antenna phase centers, troposphere, and GPS scale; and the ‘y-shift’ of the geocenter observed when introducing stochastic parameters for the orbit modeling [Springer, 1999]. For the European solutions the cut-off angle is set to 5° and troposphere gradients are estimated. The corresponding time series cover already several years. The goal is to implement these changes for the global solutions. We are aiming at integrating the routine IGEX solution into our IGS solution. Following the trend to generate ultra-rapid solutions we intend to replace the rapid solution by an ultra-rapid solution at some point in the future.

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Summary

In 1998 the ESOC IGS contributions have been continued. It can be defined as a transition year in which most of the development was concentrated in the extension of the software to process GLONASS undifferenced data. The IGEX campaign started on October 1998. The ESOC IGS processing benefited from this developments since from the beginning of 1999 the undifferenced processing was also adopted for IGS.

The year has been characterized by the following:

- Development of undifferenced processing. More observations can be used. Orbits are consistent with clocks. The final implementation was materialized in April 1999.

- In February 9-11, ESOC hosted the 1998 Analysis Centre Workshop. Proceedings were issued and they contain the main events and recommendations.

- The use of our IGS products for the data processing of satellites carrying GPS receivers was resumed with the analysis of the Automated Rendezvous Pre-development (ARP). The analysis of the second Flight Demonstration was issued in February 1998 and the third in March.

- Several tests were done in the field of empirical solar radiation presure models.

ESOC GPS Web Pages

Information on our activities can be found at our web pages:

http://nng.esoc.esa.de

ESOC IGS Analysis

Information on the models and estimated/used parameters in our routine processing is located at:

http://igscb.jpl.nasa.gov/igscb/center/analysis/esa.acn

The following products have been made available during 1998:

- Final Orbits
- Rapid orbits
- Daily rapid EOP file
- Weekly final EOP file
- Weekly final processing summaries
- Weekly free network solution in SINEX format
- Daily final tropospheric files

ESOC Analysis Centre Major Changes in 1998

- 1st March 1998. Use of ITRF96 coordinates as recommended in the Darmstadt workshop. The set of core stations was increased from 13 to 47.

- 28th June 1998. Minimum transformation parameter constraints in SINEX file.

Empirical Force Models for Solar Radiation Pressure

Empirical models had already been tried in previous years to compare to the a priori ROCK model. Following the discussions in the Darmstadt workshop the tests comparing the different estimation possibilities were resumed.

The parametrization of the model describes the forces on each of the reference frame axes as a function of the selected argument A as:

$$Fi = K (a_{i0} + a_{ic} \cos(A) + a_{is} \sin(A) + a_{ic2} \cos(2A) + a_{is2} \sin(2A))$$

where K is a factor that can be 1 or a scaling including the variation in solar radiation pressure with satellite-sun distance and an estimable global scale factor.

Several arguments (mainly solar angle and solar anomaly) and reference frames (mainly ROCK model frame and Solar frame) were tested.

The ESOC IGS set-up uses ROCK as a priori model with the estimation of CR and y-bias. One cycle per revolution sine and cosine empirical accelerations are estimated in the radial component.

After the tests the conclusion was that other four parameter set-ups produce similar or worse results to the parametrization used in the ESOC IGS processing.

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GFZ Analysis Center of IGS — Annual Report 1998

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Summary

The GeoForschungsZentrum (GFZ) continued the contribution to the IGS in 1998. During this year the main achievements are:

- Accuracy of the final orbits at 3-cm level
- Weekly station coordinate repeatability at 2-mm level
- Ambiguity fixing in the global network
- Generation of the new station clock product
- Compatibility between SINEX, SP3 and ERP products

Changes in the Routine Analysis

The changes introduced during 1998 are summarized in Table 1; the changes in the upper part of the table were already reported in (Gendt et al., 1998). The recent distribution of sites used for the final analysis is given in Figure 1.

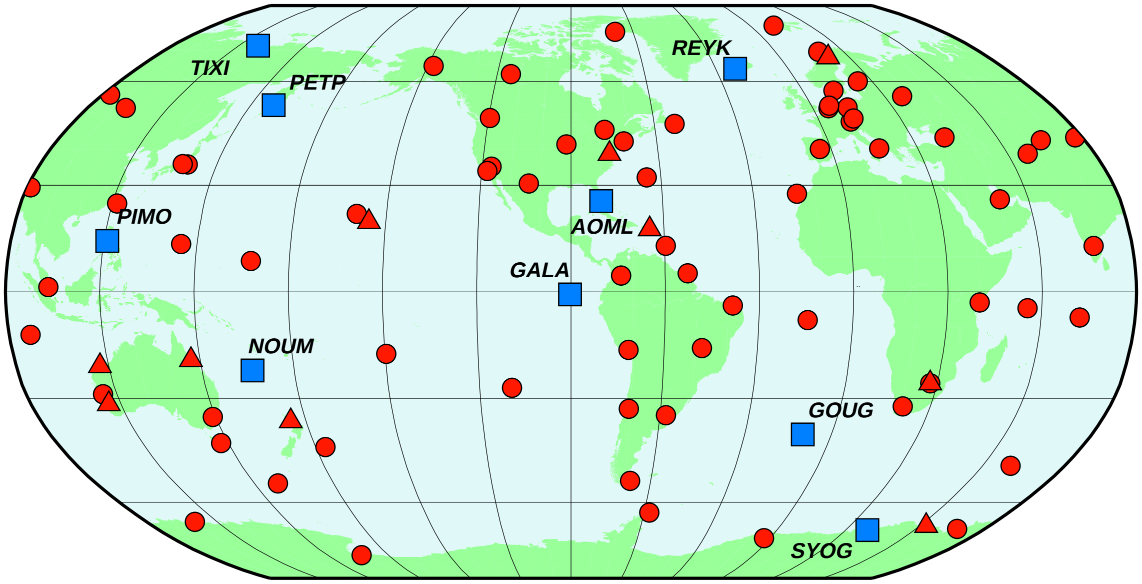

Fig.1. Distribution of stations used in the IGS analysis
(■ sites added during 1998; ▲ sites used for IGR only)

Table 1. Modification in software and technology

Week	Date	Description
944	1998-02-08	5-min sampling rate, 15-degree elevation cutoff angle
945	1998-02-15	Introduction of tropospheric gradients
947	1998-03-01	Introduction of ITRF96 with 47 core sites
949	1998-03-15	SINEX using 3-day orbits (compatible to SP3 orbits)
951	1998-03-28	Error for PRN8 corrected (IIR to IIA)
958	1998-05-17	PRN13: antenna phase center offset changed from 1.6746 m to 1.0229 m
960	1998-05-31	Radiation model of JPL implemented (Bar-Sever, 1998)
971	1998-08-18	Introduction of ambiguity fixing
983	1998-11-08	Generation of station clock product
984	1998-11-15	Generation of compatible SINEX, SP3 and ERP products
986	1998-11-29	PRN13: antenna phase center offset set to 0.0 m

Table 2. Technology for the generation of consistent products

STEP 1:

Daily analysis using 24 hours of data.
RESULT: - 1-day normal equations (NEQ)
(containing: station coordinates, ERP, orbit parameters)

STEP 2:

Generation of 3-day orbital arcs by combining three 1-day NEQ.
RESULT: - Orbital parameters, the middle day is extracted as the product
- 3-day NEQs
(containing: station coordinates, ERP;
orbit parameters preeliminated, i.e. implicitly contained, not fixed)

STEP 3:

Generation of weekly SINEX product by stacking seven 3-day NEQs (spanning nine days in total).
RESULT: - ERP solution (**gfz*wwwwd*.erp**)
- SINEX file (**gfz*wwww*7.snx**)

STEP 4:

Repetition of STEP 2. However, introducing and fixing the station coordinates and ERP from gfz*wwww*7.snx (STEP3).
RESULT: - orbit solution compatible with SINEX (**gfz*wwwwd*.sp3**)

STEP 5:

Repetion of STEP 1. However, introducing and fixing the orbits from gfz*wwwwd.sp3* (STEP 4). The coordinates of the core stations are stabilized according to the official ITRF (e.g. ITRF96), all other sites are free and can vary from day to day (not fixed to the weekly coordinate solution; this way problems with sites can partly be absorbed).
RESULT: - clock solution (***gfzwwwwd.clk***) compatible with gfz*wwwwd*.sp3

Generation of Compatible Products

Our Rapid Product is based on daily solutions, where within one adjustment all parameters (satellite orbits, ERPs, satellite clocks) are solved fixing the coordinates of the core sites to the standard values (ITRF96). Consequently the various products are compatible.

The situation is different for our Final Product which is based on 3-day arcs and where the product is extracted from the middle day. To fulfill the recommendation on compatibility from the 1998 workshop (Kouba et al., 1998), changes in the technology had to be implemented. The procedure is not a straightforward one, some kind of repetition is necessary. It can be described by the five steps summarized in Table 2.

As a result of this procedure compatible SINEX, ERP and SP3 products are generated. The clock solutions are not fully compatible, here the compatibility is only to the SP3 products.

Ambiguity Affixing in the Global Network

Starting with GPS week 971 (1998, day 228) the ambiguity fixing in the global network was implemented. Our software uses the ionospheric linear combination (L3) of undifferenced data and therefore no true ambiguity fixing is possible, i.e. ambiguities be eliminated from the normal equation system. Only constraints are put onto the adjustment of undifferenced ambiguities which force selected double-differences of the ambiguities to fulfill given conditions.

The algorithm is (following Mervart, 1998):

STEP 1: Adjustment of undifferenced real-valued L3-ambiguities (as before)
STEP 2: Additional software components:

- Formation of baselines and single differences
- Adjustment of double-difference wide-lane ambiguities in baseline mode
- Double-difference L3-ambiguities are formed from the undifferenced L3-ambiguities derived in STEP 1. They are used to determine the double-difference narrow-lane (L1) ambiguities by introducing the known wide-lane ambiguities.

STEP 3: Derivation of constraints on double-differences from undifferenced L3-ambiguities and restart with STEP 1 introducing these constraints.

The quality of the real-valued ambiguities is crucial for this procedure. Having the daily final products with high quality station coordinates, ERPs and orbits, the accuracy for the ambiguities is sufficient to fix the narrow-lane ambiguities for baseline lengths of several thousand kilometers. The fixing is an iterative process which starts with baselines up to 2000 km and ends with the longest baselines of 4000 km. As an example some statistics for one day are given in Table 3.

Table 3. Statistics on ambiguity fixing for a 24-hour session.

Length [km]	No.	No. Amb.	Percentage of ambiguities fixed		
			Wide lane	N1 of fixed WL	Total
0 - 1000	13	550	87	96	83
1000 - 2000	21	1000	84	93	78
2000 - 3000	15	600	71	76	54
3000 - 4000	9	250	68	74	50
All	58	2400	80	88	70

Clock Products for Stations

Besides the satellite clocks, which have been part of the regular IGS product (included in the SP3 file) for a long time, the clock solutions for the IGS stations should also be delivered to the Analysis Center Coordinator to combine them into a new product. For this reason a new product format was prepared by Jim Ray. This RINEX-like format is valid for both types of GPS clocks. Due to the use of undifferenced measurements in the GFZ software the derivation of the station clocks needed only small additional effort. The station clocks are aligned to GPS time the same way as the satellite clocks; this procedure was already described in (Gendt et al., 1998). The regular output of the new product which includes the station as well as the satellite clocks in a 5-minute sampling rate started in November 1998 (GPS week 0983). Since there are only two analysis centers sending station clocks so far there is no quality assessment for the new product at the moment.

Quality of the Products

Orbits

The changes introduced led to a significant improvement of the final orbits which is now at the 3-cm level (cmp. Fig. 2).

Reference Frame

Up to GPS week 948 the weekly SINEX products were based on the daily normal equations using all data only once. Starting with week 949 we changed our strategy and switched to the stacking of 3-day normal equations. This way the data were not any longer used only once, however, the quality of the results could be improved.

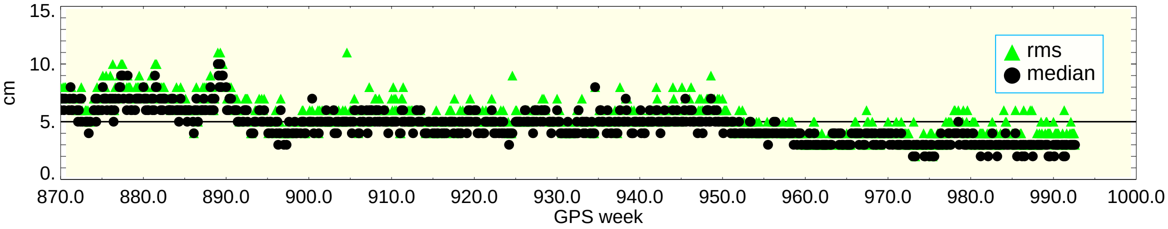

Fig. 2. Development in the orbit quality of the final orbits (Differences to IGS Final)

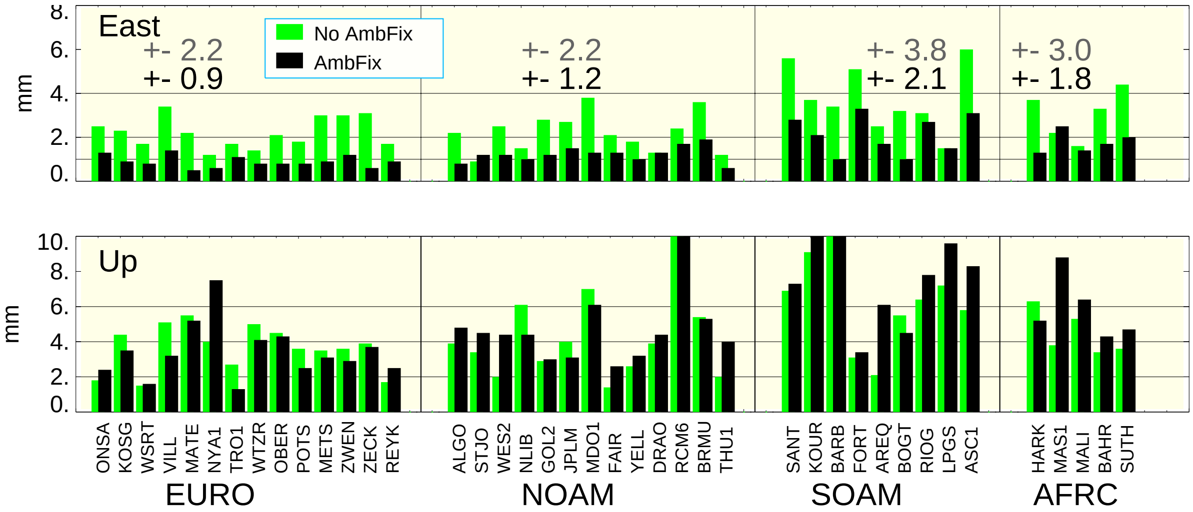

Fig. 3. Improvement of station coordinate determination by ambiguity fixing. Daily repeatability for selected sites (GPS weeks 971 and 972). (No improvement by ambiguity fixing for north component; same quality as the east component (~1 mm)).

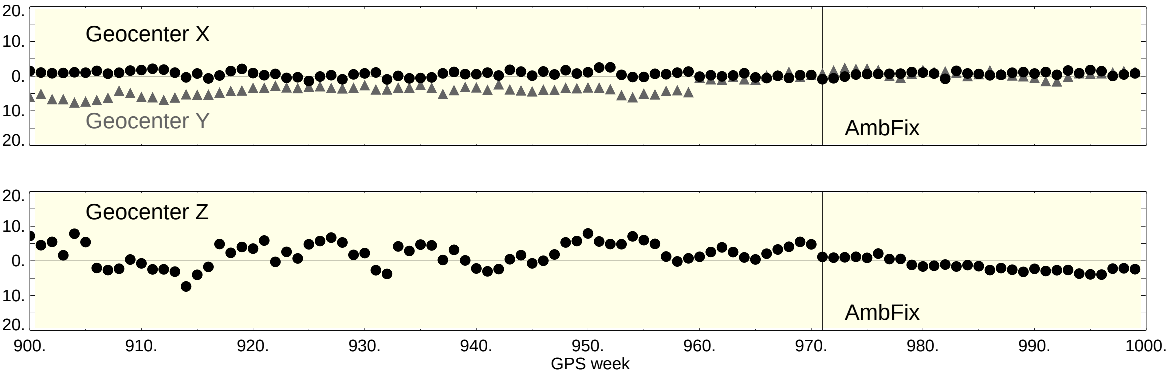

Fig. 4. Weekly GFZ geocenter estimates. At week 971 (1998/228) the ambiguity fixing was introduced.

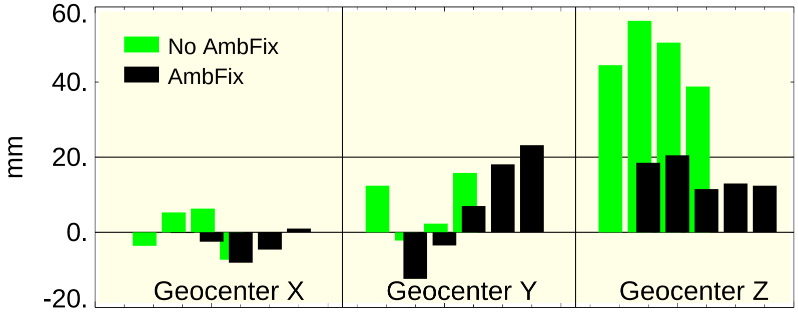

Fig. 5. GFZ geocenter solution for week 970 to 975 with and without ambiguity fixing. Differences to MIT GNAAC solutions.

The introduction of the ambiguity fixing was an important further step in increasing the quality of the solution of station coordinates and the definition of the geocenter. To test the influence of the ambiguity fixing some weeks were analyzed in both variants, with and without fixing. A significant improvement was gained for the east-component, so that now for both horizontal components a level of 1 to 2 mm is reached (Fig. 3). The fixing stabilized also the definition of the geocenter in the z-component by a factor of two (Figs. 4, 5). The overall consistency of our weekly SINEX-solution with the GNAAC solution of JPL and MIT has reached the level of 2 mm, or even better, for the horizontal components (cp. Fig. 6).

ERP Quality and Consistency

In the past the quality of the ERPs was to a high degree depending on the realization of the Terrestrial Reference Frame (TRF). This can be seen by re-computing the ERP fixing the TRF to the latest GFZ solution (SSC_GFZ_99P01, Gendt et al., 1999). Figure 7 shows the differences between the new, re-analyzed and the originally submitted ERP solutions. The introduction of ITRF94 provided a good quality in the ERPs until the number of core sites had to be reduced dramatically (from 13 to 8-9 sites). The situation has been improved significantly switching to ITRF96 (1998/060, week 947) and using an enlarged set of 47 core sites to realize the TRF.

Starting with SINEX-compatible products at GFZ the ERPs are consistent with the weekly station coordinate solution. The coordinates of the core sites were not fixed any longer, instead of this no-net-rotation constraints were introduced. To reduce systematic effects in the pole position by fluctuations in the geocenter variations (3 mm in geocenter corresponds to 0.1 mas in pole position), small constraints on geocenter position were also applied.

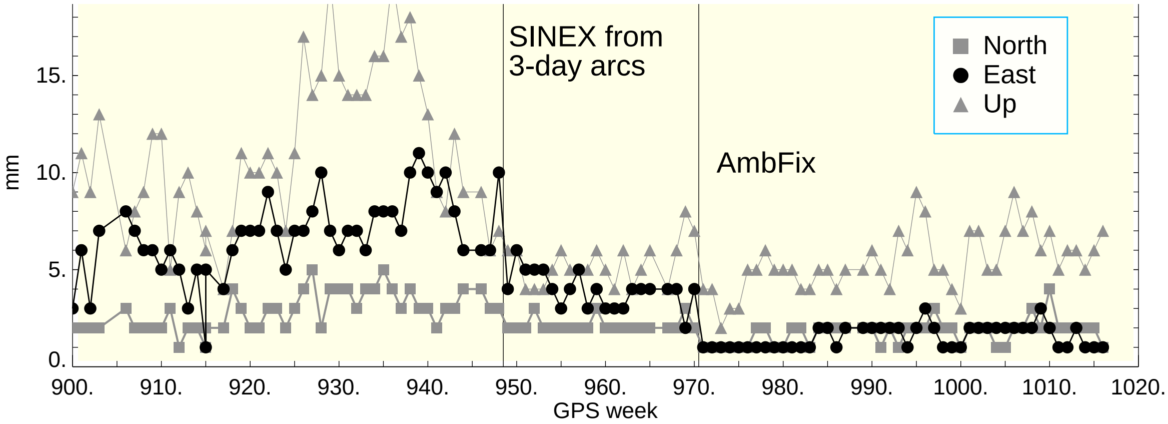

Fig. 6. Helmert-transformation residuals between GFZ weekly station coordinates (SINEX) and JPL GNAAC solution. At week 949 (1998/074) the 3-day arcs were used for generation of the SINEX products, and at week 971 (1998/228) the ambiguity fixing was introduced.

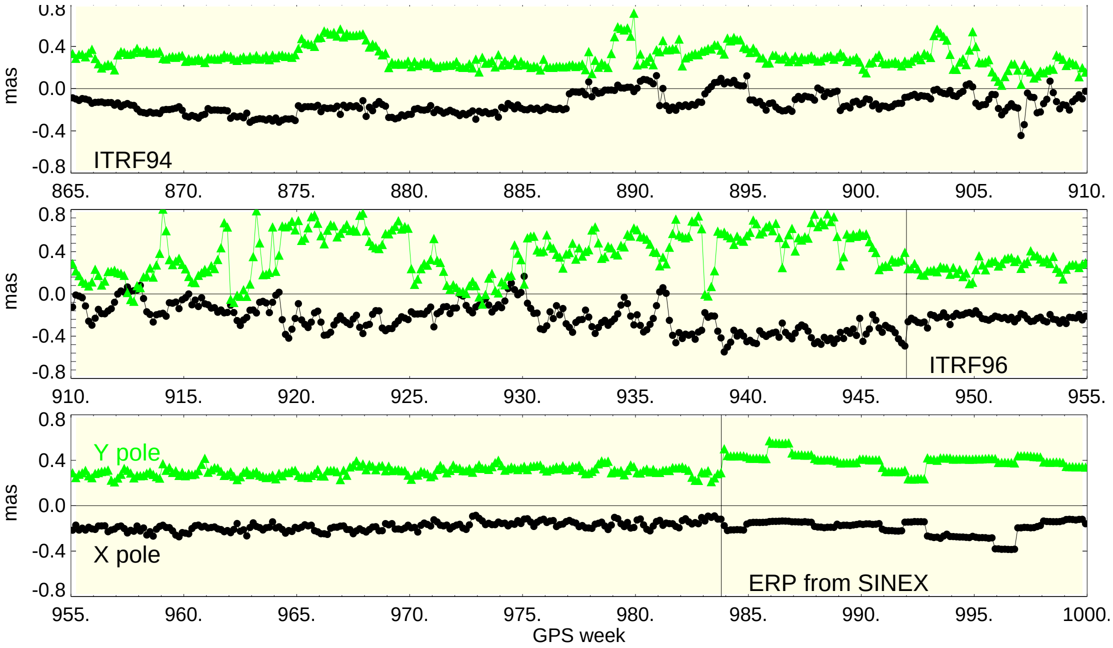

Fig. 7. Differences between GFZ final ERP submissions and GFZ ERP re-analysis fixing the multi-year station coordinate solution SSC(GFZ)99P01.

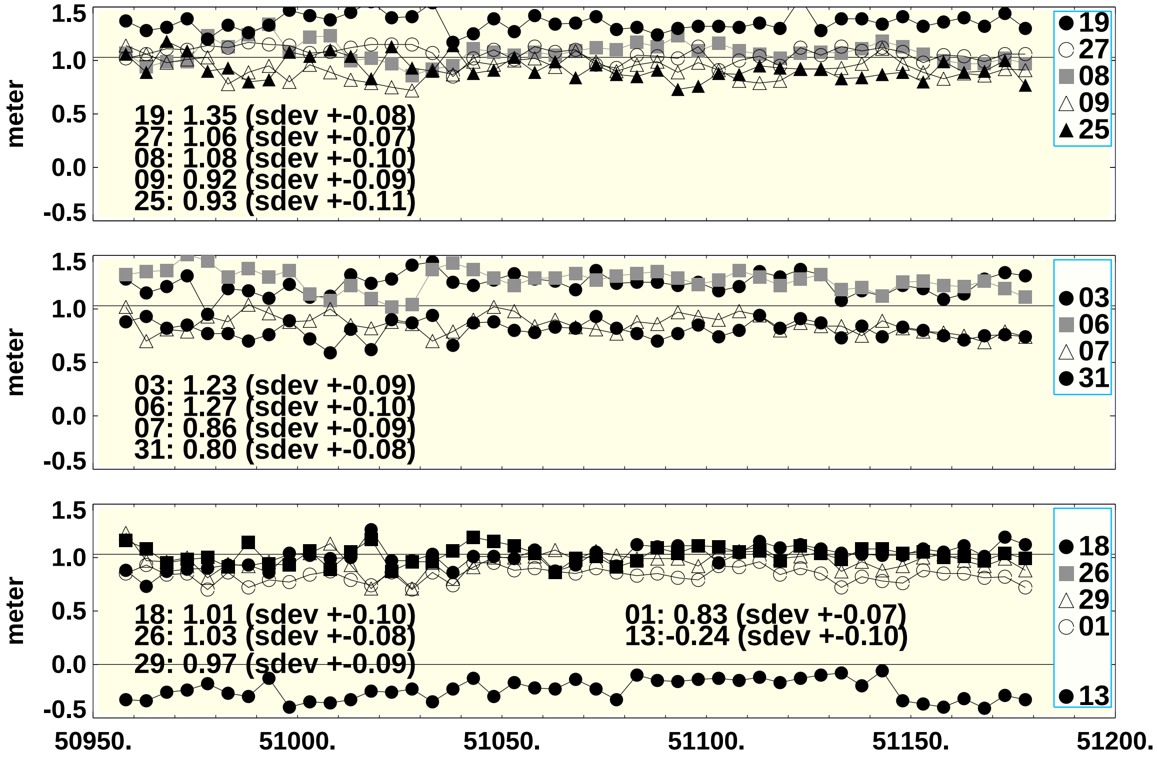

Fig. 8. Estimates of satellite antenna offsets for three selected orbital planes. The estimates and the standard deviations are given for all satellites in each plane (estimates for 5-day intervals)

Satellite Antenna Offsets

During 1998 a few ACs investigated the GPS antenna phase center offsets. Because the antenna is oriented to the center of the earth the elevation angle for the observation varies between ±14° only. Therefore the determination of the offsets is rather weak. If the observation noise is at 2-3 mm level the offset estimates have an accuracy level of about 10 cm. This is reflected by the obtained standard deviation of the estimates (Fig. 8). The nominal values are 1.0259 m for block II/IIA satellites and 1.6764 m for block IIR (PRN 13) (for L1, igsmail #1653). The offsets were estimated simultaneously for all satellites in 5-day intervals from 1998/145 to 1998/365. Examples for three orbital planes are given in Figure 8. The estimates show a significant deviation for the offset of PRN13, which is in agreement with the results from CODE and JPL. The deviation of the other satellites are smaller, however, an indication of systematic effects from satellite to satellite can be observed. For PRN13 the offset 0.0 m was adopted as the new standard for IGS.

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JPL IGS Analysis Center Report, 1998

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Summary

JPL activities as an IGS Analysis Center continued throughout 1998; regular deliveries of rapid, precise, and high-rate GPS orbits and clocks, Earth orientation parameters, and free-network ground station coordinates were maintained. Early in the year a larger subset of the augmented group of 47 IGS fiducial stations was put in use, and all fixed-network solutions were made to align with ITRF96. Starting June 28, only free-network products aligned with ITRF96 are submitted. A new product was made available in 1999: daily satellite and station clock estimates in RINEX format.

Evolution in 1998

Material relating to JPL participation as an IGS analysis center, beginning in 1992, can be found in [1] and references therein. [2] describes JPL activities as a GNAAC (Global Network Associate Analysis Center). Table 1 indicates the evolution of our activities during 1998 and into 1999. A major event was the incorporation of ITRF96 along with the expansion of all free-network product submissions.

Table 1: Analysis Evolution, 1998 through Mid 1999

Action	Date
Use 32-hour nominal orbit interval, map final orbits for 30 hours	Feb 1
Use ITRF96 coordinates and velocities for 22+ subset of 47 IGS fid	Mar 1
Use free-network estimates in troposphere products	Mar 15
Lower threshold of global site RMS isolation from 2000 to 1800 km	Mar 18
Use USNO as default reference clock (previously NRC1)	Apr 26
Increase a priori sigma for pole rates from 0.18 to 0.50 mas/day	May 6
Use all free-network solutions for products and analysis report statis	Jun 28
Remove all data during eclipse from PRN02	Dec 1
Use IGS-sanctioned satellite antenna phase center offsets	Dec 27
Exclude stations within 25 degrees of equator	Feb 14, 1999
Align satellite and station clocks to GPS time	Feb 21
Stop exclusion of equatorial sites	Mar 14
Create and submit RINEX-formatted clock files	May 16
Increase global analysis station set from 37 to 39 sites	May 23

Table 1: Analysis Evolution, 1998 through Mid 1999

Exclude MAD2 as a fiducial site	Jun 15
Exclude non-Dorne-Margolin antenna stations	Jun 27

Product Summary

Tables 2 and 3 summarize the regular products that result from JPL IGS AC activities. Newly added products are the daily GPS satellite and station clock solutions in RINEX format. These are described in section 6 of this report. Table 4 contains addresses of World Wide Web pages with related information.

Table 2: Regular Products from the JPL IGS Analysis Center, at ftp://sideshow.jpl.nasa.gov/pub/jpligsac

Example File	Contents
1010/jpl1010.sum.Z	narrative summary for GPS week 1010
1010/jpl1010[0-6].sp3.Z	precise orbits for days 0-6 (Sun through Sat) of GPS week 1010
1010/jpl1010[0-6].yaw.Z	yaw-rate data for eclipsing satellites, days 0-6, GPS week 1010
1010/jpl10107.erp.Z	free-network Earth orientation parameters for GPS week 1010 (fixed-network prior to week 947)
1010/jpl10107.snx.Z	free-network station coordinates for GPS week 1010 (7-parameter transformation to ITRF beginning wk 947) (3-parameter rotation to ITRF beginning wk 964)
1010/jpl1010[0-6].tro.Z	free-network troposphere solutions, days 0-6, for GPS week 1010 (fixed-network prior to week 949)
1010/jpl1010[0-6].clk.Z	30-sec GPS and 5-min station clocks, days 0-6, GPS week 1010, in RINEX clock format
hirate/JPL1010[0-6].sp3.Z	30-s GPS orbits and clocks, days 0-6, GPS week 1010
1998.eng.Z	engineering data for 1998, sites in global solution
1998_p.eng.Z	engineering data for 1998, point-positioned sites
ytd.eng	year-to-date engineering data, sites in global solution
ytd_p.eng	year-to-date engineering data, point-positioned sites

Table 3: Other products at ftp://sideshow.jpl.nasa.gov/pub/gipsy_products

Example File	Contents
RapidService/orbits/jpl1010[0-6].sp3.Z	quick-look fixed-network precise orbits for days 0-6 (Sun through Sat) of GPS week 1010
RapidService/orbits/jpl1010[0-6]_pred.sp3.Z	quick-look fixed-network 3-day predicted orbits for days 0-6, GPS week 1010
RapidService/orbits/1998-01-01.*	daily quick-look and predicted fixed-network files for use in GIPSY
1998/clocks/1998-01-01.*	1998 daily free- and fixed-network clocks and yaw-rates for use in GIPSY
1998/orbits/1998-01-01.*	1998 daily free- and fixed-network precise orbits, polar motion, shadow-events data for use in GIPSY
hrclocks/1998-12-21.*	high-rate free- and fixed-network clocks (in TDP format) for use in GIPSY
IERSB/*	IERS Bulletin-B information

Table 4: Addresses of relevant web pages

Address	Contents
http://sideshow.jpl.nasa.gov/mbh/series.html	graphical time-series of site coordinates
http://sideshow.jpl.nasa.gov/mbh/all/table.txt	table of site coordinates and velocities
http://milhouse.jpl.nasa.gov/eng/jpl_hp2.html	summaries and plots of station and satellite performance

Use of ITRF96 and Site Selection Update

At the outset of the year, fixed-network station coordinates and GPS orbits were aligned with ITRF94. Beginning with GPS week 947 (March 1, 1998), JPL adopted IGS procedures set forth at the IGS Analysis Center Workshop in Darmstadt, Germany, February 9-11, 1998 regarding the use of an augmented set of fiducial ground stations and their respective ITRF96 positions. Monument coordinates and velocities were taken from ftp://igscb.jpl.nasa.gov/igscb/station/coord/ITRF96_IGS_RS47.SNX.Z, and antenna heights from ftp://igscb/igscb/station/general/igs.snx. (Antenna reference point to L1 and L2 phase centers are from ftp://igscb/igscb/station/general/igs_01.pcv.) Because fewer than 47 stations are used in the daily analyses, a subset of the sites included in these files is selected as described later in this section.

SINEX files submitted from JPL have always been based on free-network station coordinates rigorously transformed into ITRF. It was decided at the aforementioned AC workshop to eventually discontinue the use of the non-minimal fiducial constraints for all products. Therefore, as of GPS week 964 (June 28, 1998), all orbits, clocks, EOP, station coordinates, and relevant statistics reported in our weekly AC summary reports are representative of free-network solutions that are minimally aligned with ITRF96. Only 3 rotations are applied so that geocenter and scale changes can continue to be observed. Also as of this time, JPL SINEX files were made to contain weekly Earth orientation parameters which are consistent with the corresponding sp3-formatted orbits and clocks. More details of the transformation applications are provided in table 5.

Table 5: Product-specific ITRF Alignment

GPS orbits	daily translation to weekly mean geocenter, daily rotation to ITRF
Station coordinates	weekly rotation to ITRF
Satellite and station clocks	no transformation necessary
Troposphere	no transformation necessary
World-Wide-Web time series	daily translation, rotation, and scale to ITRF

Due to the continuous growth of the global network and the impracticality (with current computer resources) of simultaneously analyzing data from all stations, an algorithm for selecting a well-distributed subset of sites along with required sites such as the IGS fiducials was implemented in late 1994 (see [1]). This scheme chooses N ground stations on the basis of isolation. That is, the Nth site is chosen so as to maximize its distance from the nearest of the N-1 already chosen sites. The RMS isolation _ (further described in [3]) is used to assess the distribution after all sites have been selected.

As described in [4], we determine “processing readiness” primarily by periodically calculating the RMS isolation, a measure of the global distribution of available ground sites. As more stations have become a part of the IGS network, in mid-March 1998, we lowered the threshold of this value from 2000 km to 1800 km. While this meant a longer delay in some instances, the four-day maximum wait time was still enforced.

The site selection process has evolved since its first implementation. While 37 sites were routinely used for the global analyses in 1998, this figure was increased to 39 in late May, 1999, and they are selected as follows:

- Choose a reference clock station (usually USNO as of week 955).
- Use 24-hour rapid-service processing results to make a separate list of stations with highly stable clocks. Although these are usually sites with H-masers, in general, these are any stations for which there are at least 250 5-minute clock solutions (out of a maximum of 288) that are smooth at the 4-cm level on timescales of 5 minutes.
- Based on isolation, choose the next 8 most isolated sites from the list of stable clock sites. These will aid in post-processed high-rate clock production.
- Add any sites not yet selected that are fiducial sites and use pseudorange observations. Note that as of GPS week 947, the list of fiducials to choose from is a predetermined, well-distributed 22 station subset of the 47 sites designated as IGS fiducials (see IGS Mail Message No. 1794).
- Again based on isolation, choose a number of well-distributed stations using pseudorange, accounting for other fiducials and desired isolated stations not using pseudorange (i.e., sites with older Rogue receivers).
- Choose the remaining most isolated stations to complete the 39 total. Ensure that any of these that are of the 47-site IGS fiducial set will be constrained during the fixed-network portion of the processing.

The site selection algorithm was modified a bit in early 1999 in an initial effort to circumvent the effects of the TurboRogue L2 Tracking anomaly. IGS Mail Message Nos. 2071, 2190, and others describe the problem encountered at ground stations employing TurboRogue receivers during periods of increased ionospheric activity. This effect is most pronounced at sites in the equatorial region of the Earth. After a preliminary positive study, it was decided to exclude stations at low latitudes, specifically those within +/- 25 degrees of the equator. Implemented over a period of four weeks (mid-Feb to mid-Mar '99), this strategy change actually had an adverse effect on JPL's solutions (primarily due to degraded global coverage), and we subsequently reverted to our previous methods, removing equatorial proximity as a criterion for exclusion from global processing. (Further discussion of the progress in resolving this tracking issue can be found in IGS Mail Message Nos. 2240, 2336, etc.)

Application of GPS Antenna Phase Center Offsets

Towards the end of 1998, it was recommended by the IGS that analysis center GPS clock estimates should be consistent with agreed upon satellite antenna phase center locations. These values are satellite dependent, and are currently accepted as:

	X	Y	Z	
Block II and IIA:	0.279	0.000	1.023	(m)
Block IIR:	0.000	0.000	0.000	(m)

Only the radial (Z) component is applied. JPL began adjusting its clock solutions as of GPS week 989. For this week only, erroneous adjustments were inadvertently made. This was corrected and clock solutions as of the following week, 990, are consistent with the phase center offsets listed above.

New in 1999

Starting with products for GPS week 998, all of our reported GPS satellite and station clocks are synchronized with GPS time. This is accomplished by using the JPL Rapid solution (which uses broadcast clocks to align itself with GPS time) to initialize the clock offset and drift of the clock at the chosen reference station at an epoch of 00:00 UTC each day.

Also, beginning with GPS week 1010 (May 16, 1999), JPL began to submit a contribution to the IGS combined clock product. These files contain our daily high-rate (30-sec) estimates of the GPS clocks and 5-min estimates of ground station clocks (5-min) for each satellite and station used in the free-network global solution (the free-network station position estimates are also included in the file headers). The file format is the RINEX clock format as described at http://maia.usno.navy.mil/gpst/clock-format. We acknowledge Rob Liu of Raytheon Systems Company for providing the conversion software which produces these files, and also the software which creates SINEX files based on information from the igs.snx database file at the IGS Central Bureau.

Results and Performance

Figure 1 chronicles the progression of orbit quality since 1995. As in the past, our metric for orbit quality is the day-to-day consistency of the solutions, i.e., the degree to which estimates from adjacent days agree near the midnight boundaries. Contributing factors to improvement are the continuing expansion of the global network, the use of global phase ambiguity resolution (implemented in April 1996), and the estimation of tropospheric gradients (implemented in August 1997). In recent weeks, internal orbit repeatabilities are typically at the 9- to 12-cm level.

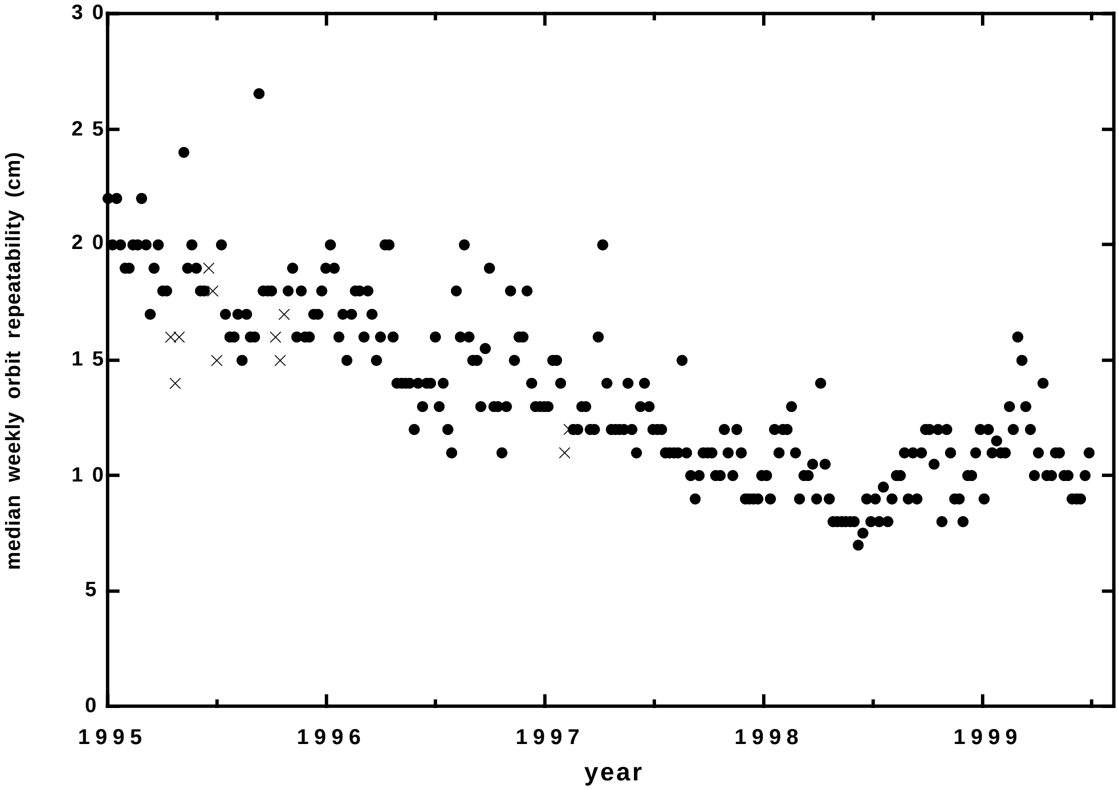

Figure 1: JPL Orbit Repeatability (3drms) Since 1995. Each data point indicates the median over all satellites and days for a particular GPS week. (The daily number for a given satellite indicates the degree to which the precise orbit agrees with those of adjacent days near the midnight boundary.) Weeks during which AS was off are marked with an 'X'.

Another measure of performance is how well the JPL GPS solutions for station coordinates and velocities compare with other those from other geodetic techniques. Table 6a below shows the level of agreement between JPL derived station velocities and those independently realized from Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). Table 6b displays a similar comparison, but for dependent GPS data sets.

Table 6a: Independent Geodetic Velocity Comparisons

	GPS-VLBI	GPS-SLR	SLR-VLBI
N (mm/yr)	1.3	1.6	1.1
E (mm/yr)	1.0	2.1	1.4
V (mm/yr)	2.7	2.8	2.2
No. common sites	33	17	9
GPS years	5.5	4.7	-

Table 6b: Dependent GPS Velocity Comparisons

	GPS-ITRF96	GPS-ITRF97
N (mm/yr)	1.2	1.3
E (mm/yr)	1.7	1.2
V (mm/yr)	2.8	2.6
No. common sites	44	44
GPS years	5.0	5.1

Finally, an overall measure of IGS analysis center performance is presented below in Table 7. The values indicate typical agreement between the analysis centers and the various combined products produced by the IGS analysis center coordinator.

Table 7: IGS Comparison Results

Orbits (daily)	3 cm
Clocks (daily)	0.2 ns
Polar Motion (daily)	0.1 mas
Length of Day (daily)	0.02 ms/day
Tropospheric Delay (daily)	4 mm
Station Coordinates (weekly)	2 , 2, 5-7 mm (N,E,V)
Station Velocities (approx. 5 years)	1, 1, 3 mm/yr (N, E, V)
Geocenter (daily)	1, 1, 2 cm (X,Y,Z)
Scale (daily)	1 ppb

Acknowledgment

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                    INTERNATIONAL GPS SERVICES

                NOAA/NGS Analysis Strategy Summary


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ANALYSIS CENTER     | National Oceanic and Atmospheric Administration (NOAA)
                    | National Geodetic Survey (NGS)
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                    |   Gerald Mader      e-mail: gerry@mozart.grdl.noaa.gov
                    |                     phone : 301-713-2854 ext.-201
----------------------------------------------------------------------------
SOFTWARE USED       | pages developed at NOAA
----------------------------------------------------------------------------
NGS PRECISE         | NGSwwwwn.SP3   GPS ephemeris/clock files in 7 daily
PRODUCTS GENERATED  |                files at 15 min intervals in SP3 format,
FOR GPS WEEK 'wwww' |                including accuracy codes computed from
DAY OF WEEK 'n'     |                the formal orbit errors of the solution
(n=0,1,...,6)       | NGSwwww7.ERP   EOP (pole and LOD estimates; a priori
7 weekly files      |                UT1-UTC) in 1 weekly file.
                    | NGSwwww7.SUM   Processing summary in 1 weekly file.
                    | NGSwwww7.SNX   Processing Sinex weekly file.
                    | NGSwwwwn.TRO   Processing Tropo 7 daily files.
----------------------------------------------------------------------------
NGS RAPID PRODUCTS  | NGSwwwwn.SP3   GPS ephemeris/clock files at 15 min
                    |                intervals in SP3 format. Produced
                    |                within 16 hours of the preceeding day.
                    | NGSwwwwn.ERP   EOP (pole and LOD estimates; a priori
                    |                UT1-UTC) in 7 daily files.
----------------------------------------------------------------------------
PREPARATION DATE    | Nov. 12, 1999
----------------------------------------------------------------------------
EFFECTIVE DATE FOR  | Jul. 26, 1998
DATA ANALYSIS       |
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MEASUREMENT MODELS	
Preprocessing	Phase preprocessing in a baseline by baseline mode using double-differences. In most cases cycle slips are fixed automatically looking simultaneously at different linear combinations of L1 and L2. Manual re-editing is done if any baseline shows larger than normal post-fit RMS statistics in the all baseline combined solution. At that time, bad data points are
Basic observable	Carrier phase, code only used for receiver clock sync. Elevation angle cutoff : 15 degrees Sampling rate : 30 seconds Weighting : Aug. 6, 1995 - Jun. 29, 1996 1 m uniform Jun. 30, 1996 - 0.10 m uniform Rejection criteria : No rejection during parameter estimation. Outliers marked during preprocessing step; manual re-edit done for any baseline with high RMS fit.
Modelled observable	Double-differences, ionosphere-free linear combination.
RHC phase rotation corr.	applied (Wu et al., 1993)
Ground antenna phase centre	Elevation-dependent phase center corrections are applied to all antenna types (Mader & MacKay, 1995)
Troposphere	A priori zenith delay : Saastamoinen (1972) "dry" + "wet" zenith delays Mapping function: NMF dry and wet mapping functions (Niell, 1995) Met. data input : latitude, height, DOY model Estimation : wet zenith delay adjusted in 2-hour intervals for all sites
Ionosphere	Not modelled (ionosphere eliminated by forming the ionosphere-free linear combination of L1 and L2)
Plate motions	ITRF97 station velocities fixed
Tidal displacements	Solid earth tidal displacement : Cartwright & Taylor (1971) tidal potential complete thru degree 3 with newest Shida and Love numbers (Mathews et al., unpublished) Correction applied: to remove zero-frequency contribution not removed

	permanent tide Nominal Love nos. : h2 = 0.6067; el2 = 0.0844 h3 = 0.2900 el3 = 0.0152 dh resonance corrections : applied for 6 largest tides
	Pole tide : not applied
	Ocean loading : not applied
Earth orientation models	Tidal UT1 (>5day) : not modelled Sub-daily EOP : Herring & Dong (1994) model applied
Atmospheric load.	not applied
Satellite center of mass correction	Block I x,y,z: 0.2110, 0.0000, 0.8540 m
	Block II/IIA x,y,z: 0.2790, 0.0000, 1.0230 m
	Block IIR x,y,z: 0.2790, 0.0000, 1.0230 m
Satellite phase centre calibrat.	not applied
Relativity	periodic corrections applied
GPS attitude model	not applied

ORBIT MODELS	
Geopotential	GEM-T3 model up to degree and order 8; C21, S21 as recommended by IERS (1992)
	GM = 398600.4418 km**3/sec**2
	AE = 6378.1363 km
Third-body	Sun and Moon as point masses
	Ephemeris: Generated from the MIT PEP program
	GMsun = 132712440000 km**3/sec**2
	GMmoon = 4902.7989 km**3/sec**2
Solar radiation pressure	Direct radiation: ROCK4 and ROCK42 models (T10 and T20) for Block I and II satellites, resp. (Fliegel et al., 1992) Satellite masses: PRN 01 972.9 kg PRN 15 885.9 kg PRN 02 878.2 kg PRN 16-19 883.2 kg PRN 03-07 972.9 kg PRN 20 887.4 kg PRN 09 972.9 kg PRN 21-22 883.9 kg

	PRN 12 519.8 kg PRN 23-29 972.9 kg PRN 14 887.4 kg PRN 31 972.9 kg
	x,y, and z scale plus once-per-revolution perturbation terms adjusted for each 1-day arc.
	Earth shadow model includes: umbra and penumbra
	Reflection radiation: not included
	New GPS satellite attitude model: not applied Geometrical effects : not applied Orbit dynamic effects : not applied Yaw rates : --
Tidal forces	Solid earth tides: C20, C21, S21, C22, and S22 as in IERS (1992); n=2 order-dependent Love numbers and frequency-dependent corrections for 6 (2,1) tides from Richard Eanes (private comm., 1995)
	Ocean tides : Schwiderski Model
Numerical Integration	11th order Adams-Moulton Predictor-corrector
	Integration step : variable
	Starter procedure: Initial conditions taken from the rapid day at 12:00
	Arc length : 24 hours

ESTIMATED PARAMETERS (APRIORI VALUES & SIGMAS)	
Adjustment	Least-squares algorithms using 24 hours of double-differenced phase observations from the global network.
Station coordinates	Aug. 6, 1995 - Jun. 27, 1998 Standard 13 stations fixed to the ITRF93 positions as given in IGSMAIL#819, plus MDO1 and MATE also fixed. The ITRF93 velocities are used for coordinate updates. All remaining stations estimated. Rapid: Jun. 28, 1998 - Jul. 31, 1999 Standard 47 stations fixed, minus fiducial site GODE, to the ITRF96 epoch 1997.0 positions as given in the Kouba 1998 IGS Mail message. The ITRF96 velocities are used for coordinate updates. All remaining stations estimated. Precise: Jun. 28,1998 - Jul. 31, 1999 Final precise orbits are minimally constrained and adjusted over 1 week to be consistent with the weekly combination. Rapid: Aug. 1, 1999 – Present

	Standard 53 stations fixed, minus GODE, to the ITRF97 epoch 1997.0 positions as given by IGS mail (R. Ferland). The ITRF97 velocities are used for coordinate updates. All remaining stations estimated. Precise: Aug. 1, 1999 - Present Final precise orbits are minimally constrained and adjusted over 1 week to be consistent with the weekly combinations.
Satellite clock bias	Satellite clock biases are not estimated but eliminated by forming double-differences.
Receiver clock bias	Receiver clock corrections are estimated during the pre-processing using code measurements.
Orbital parameters	Geocentric position and velocity, solar radiation pressure scales and once-per-revolution perturbation terms along the satellites - sun, body centered Y, and orthogonal third directions estimated as constant offsets for each one-day arc.
GPS attitude parameters	none estimated
Troposphere	Jun. 28, 1998 Wet zenith delay estimated as constant offset for 2-hr intervals at each station.
Ionospheric correction	Not estimated; L1 & L2 used for 1st order corrections
Ambiguity	Estimated as real values with no a priori constraints
EOP	Aug. 6, 1995 - Jun. 29, 1996 x and y pole and LOD estimated as constant offsets for each one-day arc. A priori values taken from IERS Rapid Service Bulletin A. Jun. 30, 1996 - x and y pole estimated in a piece-wise, linear (endpoints of a straight line) with no a priori constraints for each one-day arc. LOD estimated as constant offset for each one-day arc. A priori values continue to be taken from IERS Rapid Service Bulletin A. Jun. 28, 1998 - This product is modified in a weekly combination consistant with orbits, EOP, and troposphere.
Other parameters	None

REFERENCE FRAMES	
Inertial	Geocentric; mean equator and equinox of Besselian year 1950 (B1950.0)
Terrestrial	Aug. 6, 1995 - Jun. 29, 1996 ITRF93 reference frame realized through a set of 15 station coordinates and velocities as given in IGSMAIL #819 as well as the antenna offsets for the above stations given in /igscb/station/tie/localtie.tab (available from IGS at igscb.jpl.nasa.gov). Jun. 30, 1996 - Feb. 28, 1998 ITRF94 reference frame realized through a set of 15 station coordinates and velocities as given in Kouba (1996) as well as the antenna offsets for the above stations given in /igscb/station/tie/localtie.tab. Mar. 1, 1998 - Jul. 31, 1999 ITRF96, epoch 1997.0 reference frame realized through a set of 46 station coordinates and velocities as given in the Kouba 1998 Mail message, as well as the antenna offsets for the above stations given in /igscb/station/tie/localtie.tab. Aug. 1, 1999 - Present ITRF97, epoch 1997.0 reference frame realized through a set of 53 station coordinates and velocities as given by IGS (R. Ferland 1999), as well as the antenna offsets for the above stations given in /igscb/station/tie/localtie. tab. Jun. 28, 1998 - Present Minimally constrained combination using all available station coordinates; Product is modified to be consistent with the weekly combination.
Interconnection	Precession: IAU 1976 Precession Theory Nutation: IAU 1980 Nutation Theory Relationship between UT1 and GMST: USNO Circular No. 163 (IAU Res.) A priori EOP values: from IERS Rapid Service Bull. A Tidal UT1 (>5day) : not modelled Sub-daily EOP : not modelled

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NRCan IGS Analysis Centre Report for 1998

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Summary

In 1998 NRCan initiated estimation and submission to the IGS of two new products, an ionospheric grid and a station and satellite clock rinex file, and implemented the IGS recommended fiducial-free estimation strategy in its final solutions. New standardized satellite antenna phase centers and the ITRF96 station coordinates and velocities were also adopted by NRCan during 1998.

Estimation Strategy

For 1998 NRCan continued the estimation and submission of satellite orbits and clock corrections in the sp3 format, Earth Rotation Parameters (ERP), including Polar Motion (PM) x,y and their rates, UT1-UTC and LOD, station coordinates in the SINEX format and zenith tropospheric delays. The NRCan final products estimation strategy was modified on July 5th (GPS Week 965) in order to implement the fiducial-free approach as recommended by IGS. For a description of NRCan's estimation strategy prior to the modification see (Tétreault et al., 1996, 1997). Since GPS Week 965, only loose constraints (10m) for 47 IGS Reference Frame stations are used in NRCan's daily final estimation. Rotations are also applied a-posteriori to the solutions to align them to ITRF96. This is accomplished by computing a weekly combination of station coordinates and ERP's which are rotationally aligned to ITRF96. Each daily orbit solution is then rotated by an amount equal to the difference between the daily and weekly ERP estimates.

Before adopting the fiducial-free estimation strategy, it was necessary to mitigate the translations in NRCan's orbit solution with respect to ITRF. This was done by extending the 24-hour data arc (0h UT to 23h 45m UT) used in the NRCan strategy to a 30-hour data arc (21h UT on day n-1 to 2h 45m UT on day n+1, where day n is the day for which products are estimated). Figure 1 depicts the Y and Z translations of various NRCan products with respect to ITRF94 and ITRF96. Note that three of the solutions (daily, weekly and weekly corr.) refer to the IGS orbit combinations whereas one solution (MIT) is based on a station combination. Figure 1 also shows that the Y and Z translations of the unconstrained station solution (MIT) were greatly reduced by using a longer data arc after week 965. However, the Y and Z orbit translations increased slightly after removal of orbit constraints (GPS Week 965).

In 1998, NRCan implemented two estimation modifications recommended by IGS. Firstly, on March 1st (GPS Week 947), a-priori station coordinates and velocities were changed from ITRF94 to ITRF96. Table 1 contains the effects of the change of reference frame on various NRCan final products for GPS Week 947 using both ITRF94 and ITRF96. Secondly, on November 29th (GPS Week 986) standardized antenna phase offsets were adopted (Table 2).

Table 1: Discontinuities[(1)] in NRCan Final Products.

ITRF94 to ITRF96 Transformations

	RX (PMy) mas	RY (PMx) mas	RZ Mas	SC ppb	TX cm	TY cm	TZ cm
ORBITS	-0.36	0.19	-0.42	0.1	-0.5	0.3	0.1
SIGMAS	0.2	0.2	0.2	0.01	0.05	0.05	0.05
STATIONS	-0.38	0.16	-0.4	0.8	0.1	-0.1	-0.7
SIGMAS	0.02	0.02	0.04	0.1	0.1	0.1	0.1
EOP	-0.33	0.27					
SIGMAS	0.05	0.07					

(1) Estimated by processing GPS Week 947 with both ITRF94 and ITRF96.

Table 2: Satellite antenna phase center offsets.

	Dx (m)	Dy (m)	Dz (m)
Block II & IIA	0.279	0.000	1.023
Block IIR	0.000	0.000	0.000

The existing NRCan orbit prediction (EMP) processing strategy, with the exception of the a- priori ERP strategy, was maintained during 1998 (Tétreault et al., 1998; Huot et al, 1998). Following the announcement of the new IERS Bulletin A ERP daily updates (Ray, 1998), the prediction procedure was modified (GPS Wk 966/4) to automatically select the most recent IERS Bulletin A updates amongst the available daily and bi-weekly updates. The reader is reminded that four IGR orbits are used as a-priori data for the prediction and that the ERP strategy consists of using IGR PM x and y together with the IERS Bulletin A UT1 series.

EMP statistics for 1998 are given in (Kouba et al., 1999) but are augmented with the addition of 29 weeks in 1999. The additional data confirms the results obtained after having implemented the new strategy. Figure 2 shows the daily translations, rotations and scale factors of the satellite coordinates with respect to IGS Rapid orbits (IGR). Table 3 lists the scale factor and orbit median RMS for time periods both before and after the change in strategy. The use of IERS Bulletin A daily updates significantly decreased the noise level on the scale factor from ~1.0 ppb to ~0.5 ppb. Also, the orbit combination RMS median went down from ~45 cm to ~40 cm. The improvement to EMP could not be related to better IGR orbits since no real change has been reported for IGR orbit quality and consistency before nor after GPS Week 966 (Kouba et al., 1999). We conclude that the use of IERS Bulletin A daily updates for the UT1 series is responsible for the improvements to EMP. The Bulletin A UT1 values used in the EMP 2-day predictions prior GPS Week 966 were sometimes up to 5 days old. Daily updates used after week 966 reduced this latency to about 2 days. Finally, it also appears that the annual trend in the EMP Z-translation, see Figure 2, decreased in amplitude after the implementation of ITRF96 (GPS week 947).

Table 3: EMP 1998-1999 scale factors and orbit median RMS with respect to IGR.

Period GPS Wks From-To		Scale factor (ppb)	Orbit median RMS (cm)
938-965	μ	-0.1	45
	σ	1.0	
966-990	μ	0.0	40
	σ	0.5	
966-1020	μ	0.0	39
	σ	0.5	
991-1020	μ	0.0	39
	σ	0.4	

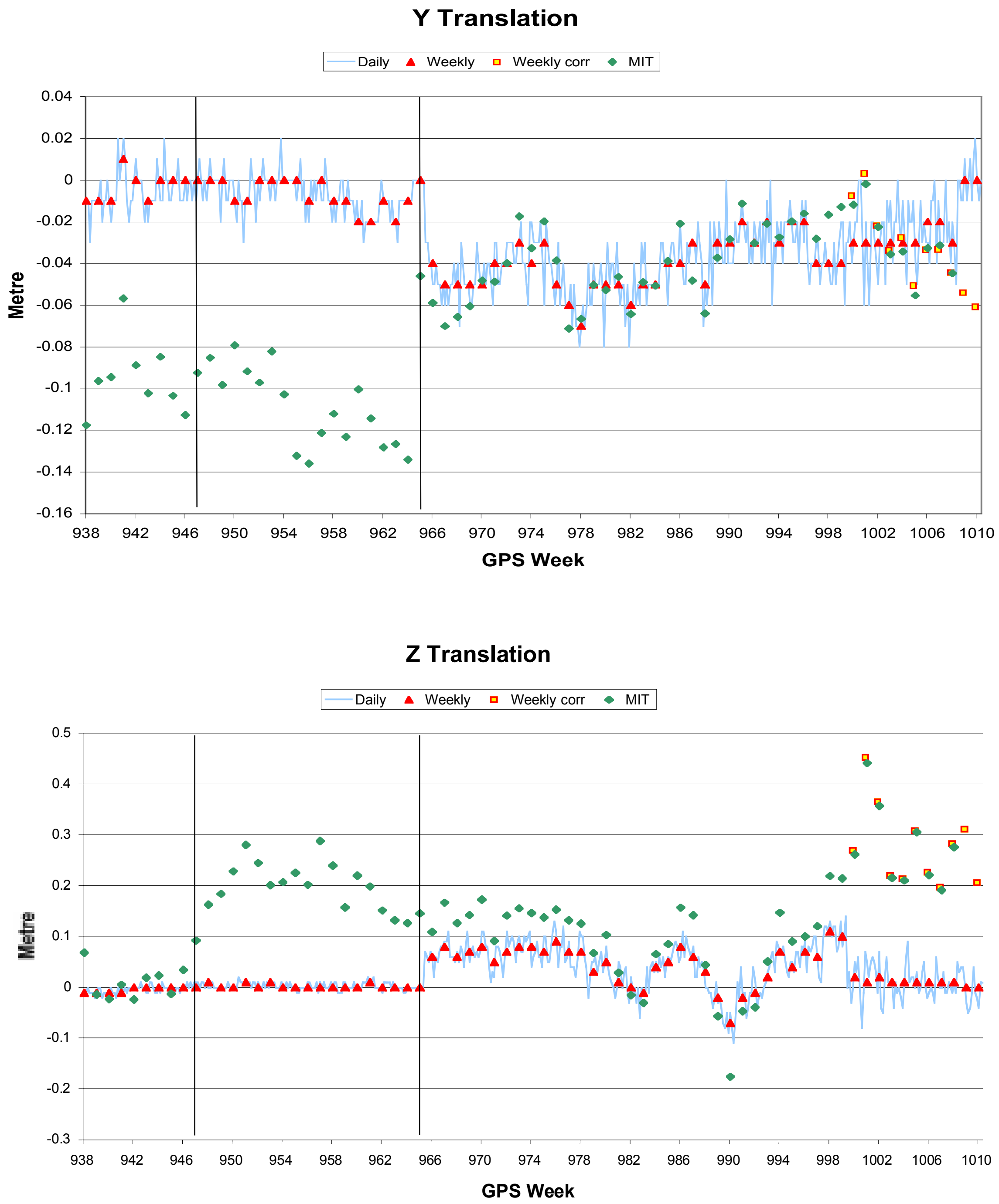

Figure 1: NRCan final products transformations to ITRF.
ITRF94 (Wk0938 to Wk0946) and ITRF96 (Wk0947 to Wk1010)

Daily: Transformations from daily IGS orbit combinations
Weekly: Transformations from IGS weekly orbit combinations
Weekly corr : Transformations from weekly IGS orbit combinations alignment corrections
MIT: Transformations from MIT weekly station combinations

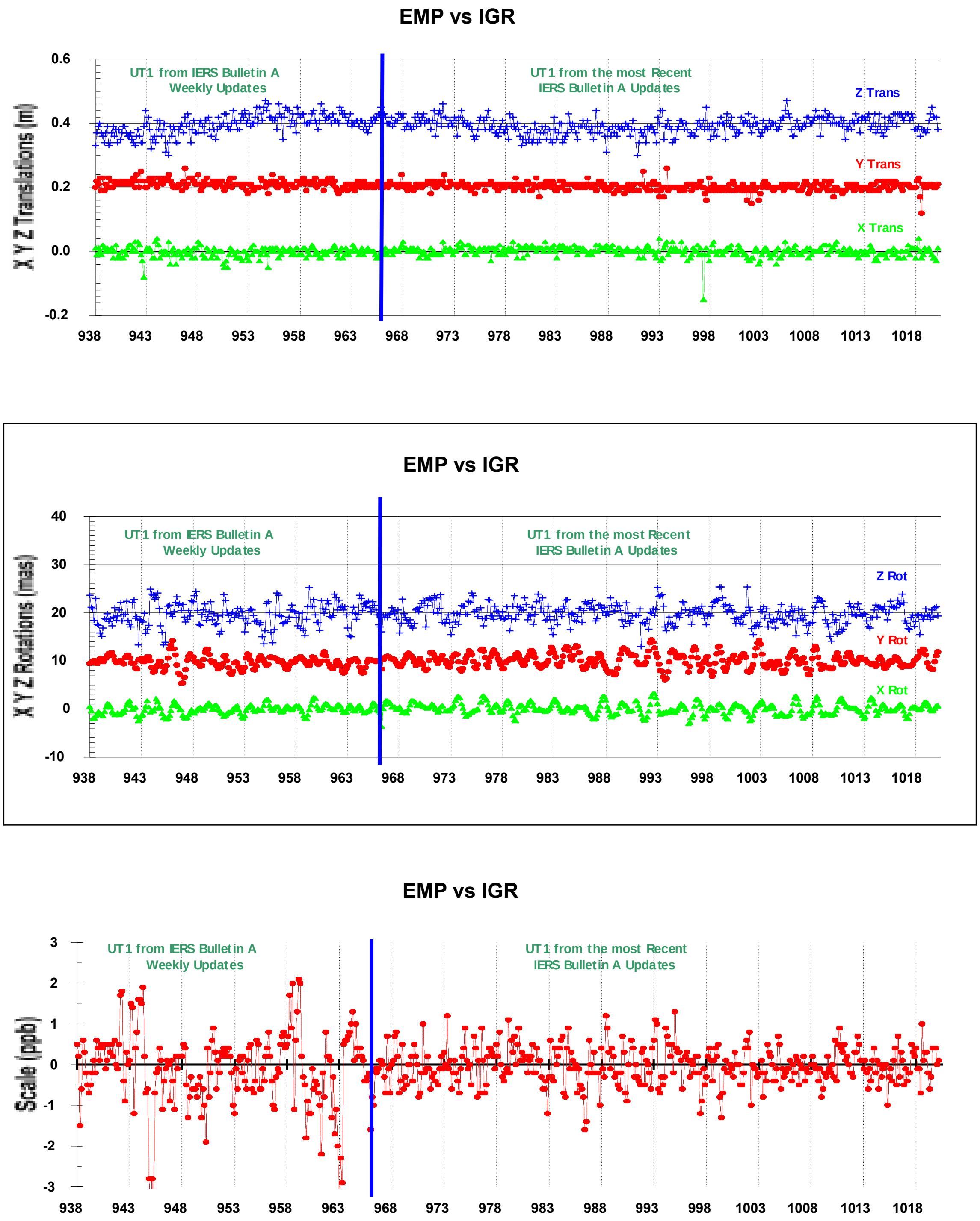

Figure 2: EMP 1998-1999: Prediction daily seven-parameter Helmert Transformation

Notes: (1) X, Y and Z Translations are each offset by 0.2 metre;
(2) X, Y and Z Rotations are each offset by 10 mas

New Products

During the first quarter of 1998, the IGS invited the scientific community to participate in the ionosphere pilot project. Following this call for participation, the Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) decided to prepare its submission of a daily global ionospheric grid following IGS specifications. Daily submissions started on July 1, 1998 (GPS Week 1016/4).

NRCan uses up to 60 global IGS tracking stations for the production of daily global ionospheric maps (GIMs). Production is fully automated and is executed within 5 days of data collection. Resulting ionospheric maps are forwarded to the Crustal Dynamics Data Information System (CDDIS) global IGS data center. They are subsequently inter-compared with submissions from other ionospheric associate analysis centers (IAACs). NRCan has developed a three-step process for the computation of daily GIMs. The first step is the computation of the GPS carrier phase smoothed ionospheric delays and their respective ionospheric pierce point location (latitude, hour angle and zenith angle) on a single layer shell (450 km). The IGS specified shell height is currently 450 km. The second step is a sequential least squares estimation process that estimates GPS receiver and satellite differential code biases (DCBs). Finally, the last step removes station and satellite DCBs from the observed GPS inter-frequency delays and creates a GIM with specified temporal and spatial resolution in IONEX format.

In order to assess the quality of DCBs and GIMs, NRCan has put in place a procedure that estimates at the station level, the RMS of differences between GPS observed and modeled ionospheric path delays. Globally, the RMS of the along-path ionospheric differences is at the 5-7 TECU level, with significant degradation in the equatorial region due to poor GPS receiver tracking. Additionally, a procedure to perform precise point positioning in post-processing by using IGS precise satellite orbits, clocks and GIMs was implemented. This approach is useful to analyse the impact of different observables on GPS point-position estimates. For example, by processing L1 pseudo-ranges, L1 pseudo-ranges corrected using GIM delays and ionospheric free pseudoranges and computing the RMS of the position differences, it is estimated that approximately 85% of the position error is removed when applying GIM delays to L1 observations.

In response to the IGS Timing Pilot Project clock solution initiative (Ray and Kouba, 1998), NRCan initiated, on December 13th (GPS Week 988), submission of 15-minute interval station and satellite clock corrections. The modified RINEX format developed by the Timing Project Working Group is used for the submission. NRCan clock corrections are estimated simultaneously with the other orbital and station parameters using the JPL GIPSY's software. Undifferenced ionospheric free combinations of phase and of pseudo-range observations are used for the estimation of station and satellite clocks using a whitenoise stochastic model. One station clock, usually Algonquin Park (ALGO), is held fixed for the estimation and thus provides the reference for all other clock correction estimates.

Acknowledgment

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