Annual Report 1998 of the CODE Analysis Center of the IGS

M. Rothacher, T. Springer, G. Beutler, R. Dach, U. Hugentobler, D. Ineichen, S. Schaer
Astronomical Institute, University of Bern

U. Wild, A. Wiget, E. Brockmann
Federal Office of Topography, Wabern

C. Boucher
Institut Géographique National, Paris

E. Reinhart, H. Habrich
Bundesamt für Kartographie und Geodäsie, Frankfurt

1. 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.

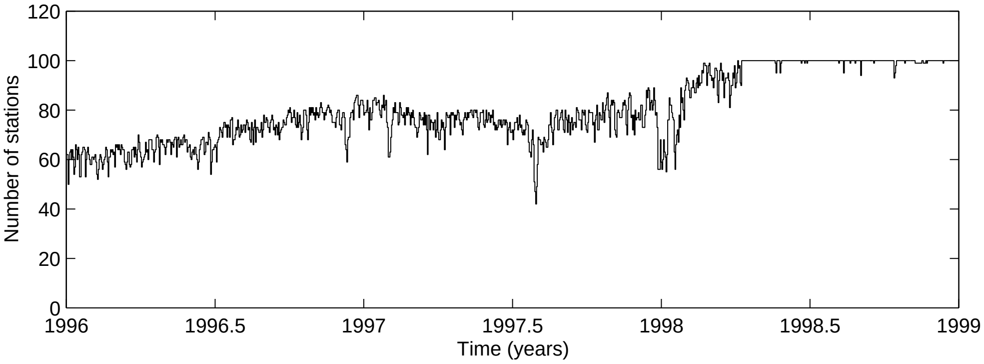
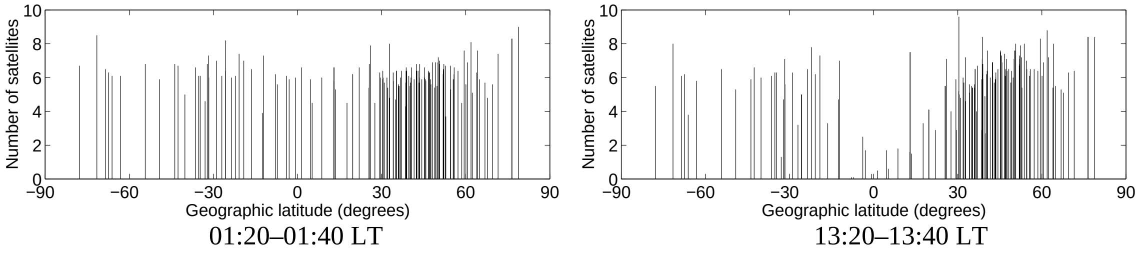


Figure 1: Number of stations used for the global 1-day solutions computed at CODE.

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.

2 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.

3. Product Quality and Results

3.1 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`.

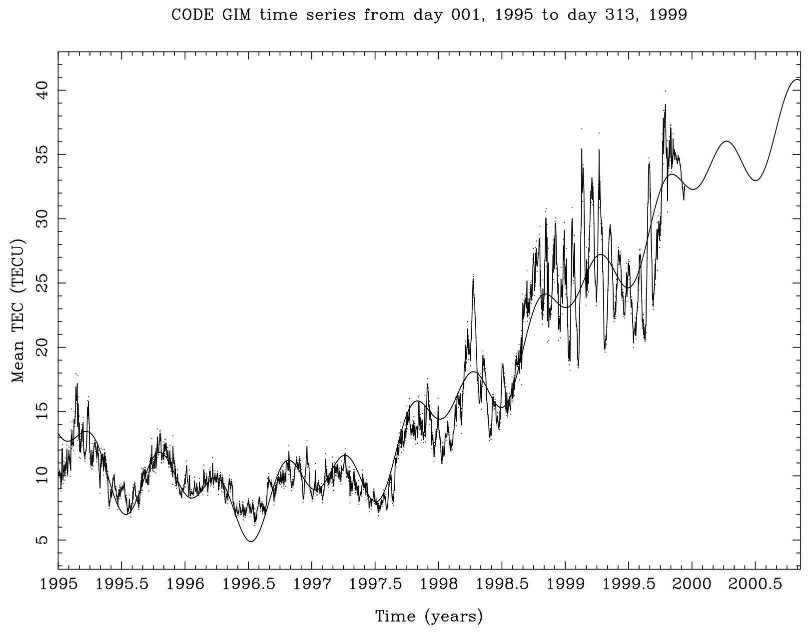


Fig. 3: Evolution of the mean global TEC computed by CODE since January 1, 1995.

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].

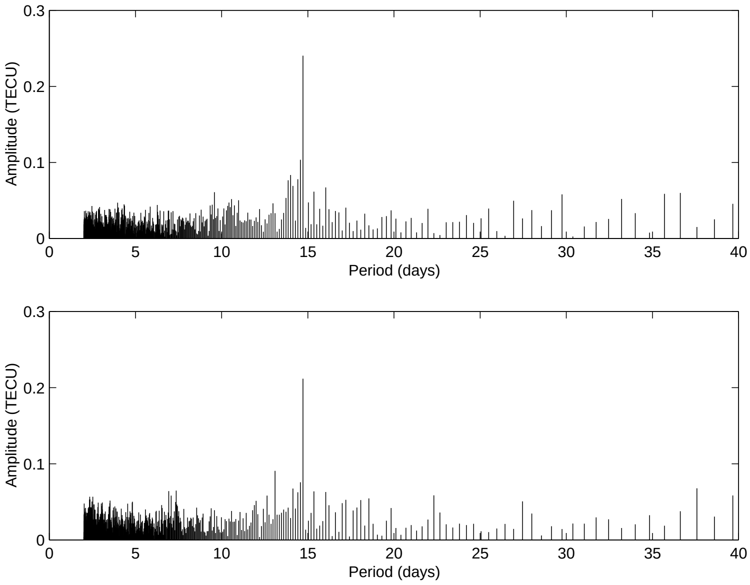


Figure 4: Amplitude spectra of the sectorial spherical harmonic coefficients C_{22} (top) and S_{22} (bottom) for periods below 40 days.

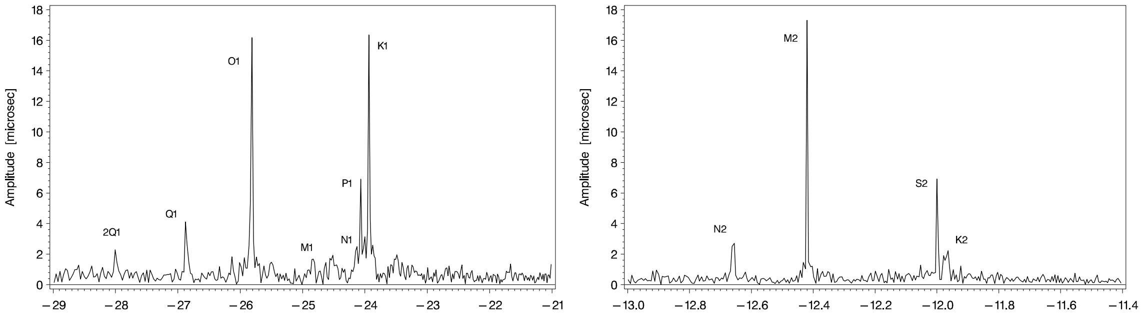
These perturbations are probably indirectly caused by atmospheric pressure variations associated with lunar gravitational tides as postulated by [Rishbeth and Garriott, 1969]. These tidal waves, considered in an Earth-fixed frame, respond to the well-known tidal cycle of about 12 hours 25 minutes. Another 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.

3.2 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.

3.3 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.

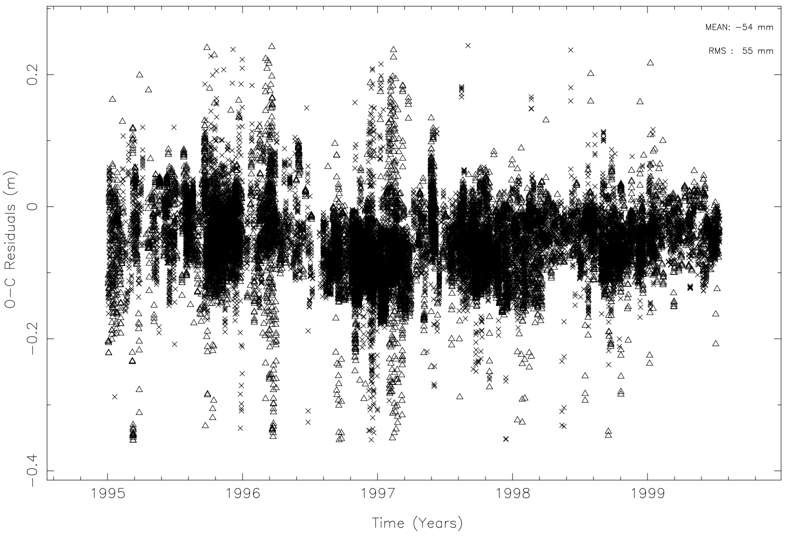


Figure 6: Range residuals of the SLR observations from GPS satellites PRN 5 (crosses) and PRN 6 (triangles).

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].

3.4 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.

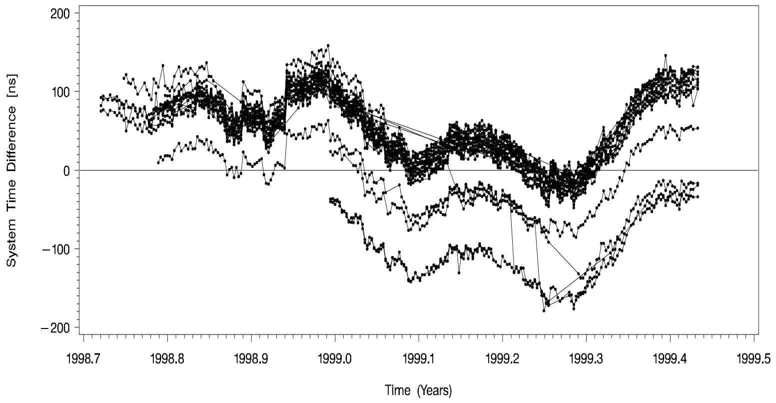


Figure 7: Differences between GPS and GLONASS system times for Z18 (upper band) and JPS receivers (lower two bands).

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.

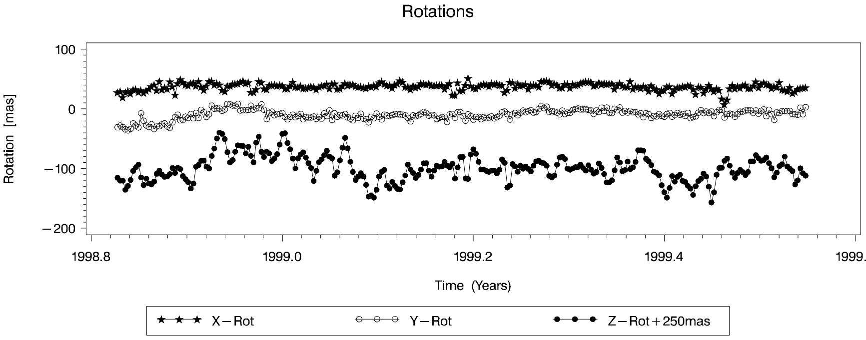


Figure 8: Daily rotation parameters of the Helmert transformation between broadcast orbits in the PZ-90 system and CODE's precise orbits in the ITRF 96 system.

3.5 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.

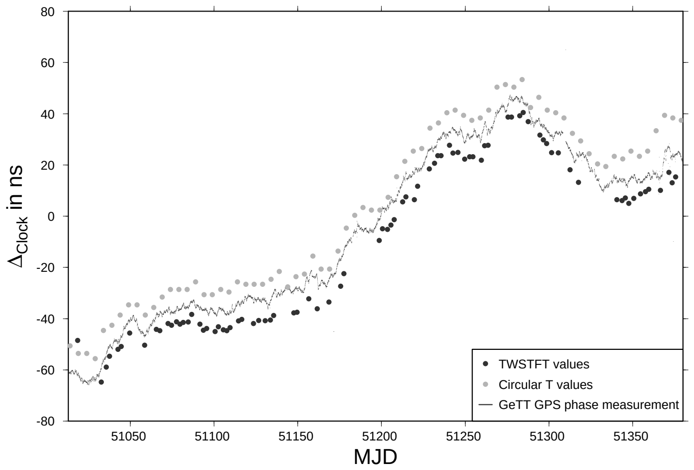


Figure 9: Time difference between reference clocks at PTB, Braunschweig, Germany, and USNO, Washington, USA, as measured by geodetic GPS (GeTT) and Two Way Satellite Time and Frequency Transfer (TWSFTF), together with the values from Circular T published by the Bureau International des Poids et Mesures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

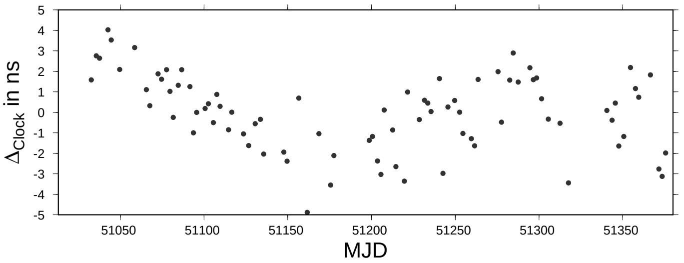


Figure 10: Difference between the clock differences between PTB and USNO as measured by geodetic GPS (GeTT) and TWSTFT. The systematic variation of the difference between the two methods is not yet understood.

4 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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