Precise Continuous Time and Frequency Transfer Using GPS Carrier Phase

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Abstract— **The Astronomical Institute of the University of Bern (AIUB) and the Swiss Federal Office of Metrology and Accreditation (METAS) have been collaborating to investigate and apply the use of the GPS carrier phase measurements (GPS CP) for time and frequency transfer. At METAS a dedicated hardware has been developed: the so–called Geodetic Time Transfer Terminal (GeTT–Terminal) which was already presented to the community [1]. In parallel the AIUB has implemented the capability for time and frequency transfer into the Bernese GPS Software package [2].**

Within the last years several improvements of the analysis software for the time and frequency transfer have been implemented. The developments have been focused on overcoming the day boundary discontinuities. These occur in the resulting time series if the data are analyzed independently for each day. The magnitude of these artificial "clock jumps" depends on the mean noise behavior of the code observations and may typically reach a magnitude of up to one nanosecond.

An important result of the software developments is the possibility to reconnect the phase ambiguity parameters at the day boundaries which allows to generate a continuous geodetic time and frequency transfer solution for a time interval that is only limited by a loss of lock to all satellites. This allows, in addition, to generate a geodetic frequency transfer solution without using the code measurements at all. Consequences for the geodetic time transfer learned from applying the geodetic phase–only frequency transfer method in several international campaigns are discussed in this paper.

I. Introduction

For institutions operating precise clocks it is a key issue to compare them with the devices from other institutions. A low cost and easy to use possibility is to connect the clock with a geodetic GPS receiver that provides carrier phase measurements in addition to the code data from both frequencies [3], [4]. The data files can be submitted to the International GNSS Service (IGS)[1]. There are several global analysis centers — one of them is located at the Astronomical Institute of the University of Bern — that process the data to generate numerous products [5], [6]. One of them is the estimates for the receiver and satellite clocks. The contributions from the individual analysis centers are combined to an IGS product which contains the correction for each individual receiver clock to an IGS time scale realized by the ensemble of receiver clocks in the global solutions [7].

Because each IGS analysis center is free to select the stations that it includes in the solution, and the inclusion of stations with high performance clocks is not the only criteria for the station selection (global coverage for satellite orbit and clock estimation, reference frame issues, computing resources), there is no guarantee that the receiver clock of an institution submitting data to the IGS will be included in the combined IGS product. In addition the IGS has a strict schedule of deadlines for the data submission.

In this context the Swiss Federal Office of Metrology and Accreditation (METAS) and the Astronomical Institute of the to University of Bern (AIUB) established a collaboration in the field of geodetic time and frequency transfer based on the algorithms and products generated at the AIUB for the IGS [8]:

- to compute non–standard solutions in addition to the regime of the IGS including also non–IGS and non–permanent stations,
- to ensure highest consistency of the results for all stations of interest because they are computed in one single solution.

At METAS Geodetic Time Transfer Terminals (GeTT–Terminals, [1]) were developed and installed as permanent stations. The GPS station WAB1 is running since October 2003 and WAB2 has been installed in August 2004. Since June 2005 WAB2 is an IGS station [9]. For METAS the geodetic time transfer method is intended as an independent technology for the comparison of their clocks with those from other National Metrology Institutions (NMI). In addition, the method should be applied for the comparison of the Primary Frequency Standard (FOCS–1, [10]) with similar devices in other institutions during dedicated campaigns.

The AIUB has developed routines for the geodetic time and

[1]In March 2005 the acronym IGS was redefined from *International GPS Service* to *International GNSS Service* to emphasize that the activity of the IGS has been resp. will be extended from GPS to other Global Navigation Satellite Systems (GNSS), e.g., GLONASS and GALILEO.

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frequency transfer as a part of the Bernese GPS Software package [2]. The same software is used at the AIUB to generate the contributions to the IGS. Several extensions and improvements adapted to the needs of the timing community have been implemented in course of this collaboration. An important result in this context is the *ambiguity stacking* method that can be used to reconnect the phase ambiguity parameters from (e.g., daily) independent data processing batches. In this way a continuous geodetic time resp. frequency transfer solution can be generated which is adequate for the continuous measurement of the clocks with the GPS receiver [11].

In this paper we summarize the algorithm of the ambiguity stacking method (Section II). The method was applied for the analysis of two measurement campaigns within the last year (Section III). In the description of the analysis and of the results we focus on the impact of environmental effects on the code and phase measurements (Section III-B). The results of these campaigns demonstrate the accuracy potential of the geodetic method for comparing clocks (Section III-D).

II. Theoretical Background

A. Observation Equation

The basic GPS observation equations for code and phase measurements are:

$$\begin{aligned} P_i^k &= \left|\vec{x}^{\,k} - \vec{x}_i\right| + \Delta_{trop} + \Delta_{ion} + \delta m_i^k \\ &\quad + c\delta_i - c\delta^k + \epsilon_i^k \qquad (1) \\ L_i^k &= \left|\vec{x}^{\,k} - \vec{x}_i\right| + \Delta_{trop} - \Delta_{ion} + dm_i^k \\ &\quad + c\delta_i - c\delta^k + \lambda N_i^k + e_i^k \qquad (2) \end{aligned}$$

where

P_i^k, L_i^k	Code/phase observation of station i to satellite k
$\vec{x}_i, \vec{x}^{\,k}$	Position vector of station i and satellite k, respectively
Δ_{trop}	Signal delay caused by the troposphere
Δ_{ion}	Signal delay caused by the ionosphere
$\delta m_i^k, dm_i^k$	Influence of multipath effects on the code/phase observation of station i to satellite k
δ_i, δ^k	Clock correction of the receiver at the station i, and transmitter of satellite k with respect to GPS time
c	Speed of light
N_i^k	Phase ambiguity
λ	Wavelength of the carrier phase
ϵ_i^k, e_i^k	Measurement noise for the code/phase observation of station i to satellite k

The observation equations for the code measurements (Equation 1) and the phase measurements (Equation 2) contain only the difference between receiver and satellite clocks. Therefore only the difference between clocks can be determined — all clocks that are estimated for an epoch refer to one reference clock. In the analysis the correction for this reference clock can be defined or heavily constrained to any (reasonable) value for each epoch. Otherwise one clock parameter per epoch becomes singular.

In the equation for the phase observations an additional singularity appears caused by the ambiguity term. Usually it is resolved by adding the code data to the analysis. Alternatively one reference ambiguity per station can be defined that has to be fixed or heavily constrained to an arbitrary value. Consequently a phase–only solution does not give access to the clocks difference in a network. It can only provide the change of the clock corrections with time for the stations and satellites with respect to a reference. This corresponds to a geodetic frequency transfer solution with the intrinsic high accuracy of phase measurements.

The validity interval of the ambiguity parameters of a station with respect to different satellites usually overlaps. Therefore a phase–only frequency transfer solution can not only be generated for the time interval covered by the reference ambiguity but for the entire time interval connected by overlapping ambiguity parameters. Two epochs that are not connected by overlapping ambiguity parameters (e.g., because of loss of lock to all satellites) cannot be bridged yielding two independent parts of the solution.

From the above it can be seen that the code measurements are only needed to resolve the singularity in Equation 2 and to provide access to absolute time. The estimated clock corrections can then be used for a geodetic time transfer rather than for a frequency transfer solution as long as calibration parameters are available. Code observations are, however, much more noisy than phase measurements. An important component of the code noise is multipath or related effects (e.g., as described in [12]) affecting code measurements to a much higher degree (several meters are possible) than the phase observations (limited to a few centimeters, e.g., [13]). In a common analysis of the data from both types of measurement the code observations can be down–weighted accordingly with respect to the phase observations. They will then have only a very small impact on the epoch–to–epoch difference of the estimated clock corrections. On the other hand the absolute difference between two clocks is only given by the code measurement. Thus the uncertainty of this absolute difference depends on the mean noise behaviour of the code data during the time interval connected by overlapping phase ambiguity parameters. If two epochs of a geodetic time or frequency transfer solution are not connected by overlapping phase ambiguities the corresponding epoch difference of the estimated clock corrections is computed from the difference of the absolute clock differences with higher uncertainty. It is, therefore, preferable to increase as much as possible the interval of epochs connected by overlapping phase ambiguities [14], [15].

B. Ambiguity Stacking for Continuous Geodetic Solution

Due to the processing schedule of the IGS the GPS data and products are provided in daily files. Adopting this daily processing scheme is most convenient and efficient for the analysis of GPS data. However, computing daily independent solutions limits the intervals connected by overlapping ambiguity parameters to $\leq$24 hours. In daily independent time transfer solutions using code and phase data in a common analysis the results of each day are connected by the phase ambiguities, and the estimated clock corrections within each day have the corresponding small epoch–to–epoch uncertainty. Because the individual daily solutions are not connected by phase ambiguities through the midnight epoch, the epoch–to–epoch uncertainty between different days is higher because the epoch difference is computed as a difference between two independently computed absolute clock differences. Consequently, discontinuities at the day boundaries may occur that usually can reach a magnitude of up to 1 ns.

Since clocks and GPS receivers work continuously over midnight there is no physical reason to have a day boundary discontinuity in the geodetic time transfer solution. To connect the daily independent solutions over many days, the following algorithm — widely used in space geodesy (see, e.g., [16], [17]) — has been adapted at AIUB: The data of day n are preprocessed to detect outliers and cycle slips. The contribution of each observation of day n to the unknown parameters is computed and added to a normal equation system (NEQ) of the day. The NEQs from several days can be combined to generate a multiple day solution. For parameters with contributions in more than one NEQ only one common estimate is computed. This algorithm is usually applied to station coordinates, satellite orbits, and other parameters. At AIUB the same algorithm has been applied to the phase ambiguity parameters in order to connect daily independent solutions and to transform them into multi–day continuous solutions [18].

This extension of the analysis reads simple but requires extensive software developments. A large number of parameters, that are usually pre–eliminated, have to be kept active. Finding the pairs of ambiguity parameters that can be connected requires an elaborated bookkeeping. Additional checks for potential cycle slips at the NEQ boundaries have to be performed at the NEQ boundaries before the ambiguity parameters of two consecutive NEQs are connected. Last but not least the independent initialization of the ambiguity parameters in the individual NEQs (e.g., for phase–windup, [19]) must be unified before stacking the parameters.

The benefit of all this supplementary processing is a continuous time series of clock corrections that is independent of the processing scheme. Daily independent solutions concatenated by means of the ambiguity stacking method does not show any peculiar statistical behaviour at the day boundaries. The advantage of the ambiguity stacking method, with respect to other algorithms used to generate continuous geodetic time or frequency transfer solutions is that it reflects the physical measurement setup. The receiver generates a continuous flow of measurements that is artificially cut into daily files. It is actually the daily independent analysis approach that causes the discontinuities at midnight. The ambiguity stacking method reconnects the interrupted ambiguity parameters at the day boundaries and generates a continuous solution. Moreover this method may shorten the time interval that has to be processed together from 24 hours to one hour or even less.

III. Campaigns

A. Description

The ambiguity stacking method was implemented in August 2004. Since then it was successfully applied to two campaigns. The first campaign, noted PFS2004, took place between in 2004 October, 26th and November, 15th with four participating stations in Europe (IEN, NPL, PTB, OP — see Table 1) and one in America (NIST — see Table 1). These five institutions agreed to run their caesium fountain clocks simultaneously and to compare them by means of multiple remote comparison methods:

- Two–way satellite time and frequency transfer (TWSTFT, [20], [21]),
- GPS common–view analysis using the ionosphere–free linear combinations of code measurements from geodetic GPS receivers (GPS P3, [22], [23]), and
- GPS CP with ambiguity stacking [18]

The results of these three time transfer methods are analyzed and compared in [24].

Another campaign, noted TW2005, was planned by the TWSTFT community to monitor the impact of a change of satellite on the calibration of the stations. A continuous GPS CP analysis was performed across the satellite switch–over period to provide an independent clock comparison as a means to compute and cross–check the calibration of the

Tab. 1. Station location and equipment during the campaigns.

Station abbrev. BIPM	IGS	Station location	Receiver type
CH	WAB2	Wabern (Switzerland)	ASHTECH Z–XII3T
IEN	IENG	Torino (Italy)	ASHTECH Z–XII3T
NIST	NISU	Boulder, Co. (U.S.A.)	NOV EURO4–1.00–222
NPL	NPLD	Teddington (U.K.)	ASHTECH Z–XII3T
OP	OPMT	Paris (France)	ASHTECH Z–XII3T
PTB	PTBB	Braunschweig (Germany)	ASHTECH Z–XII3T
ROA	SFER	San Fernando (Spain)	TRIMBLE 4000SSE
SP	SPT0	Borås (Sweden)	JPS LEGACY
USNO	USN3	Washington, DC (U.S.A.)	ASHTECH Z–XII3T

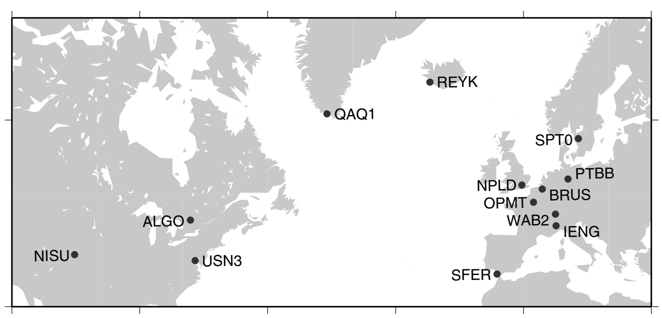


Fig. 1. Location of the stations participating in at least one of the campaigns.

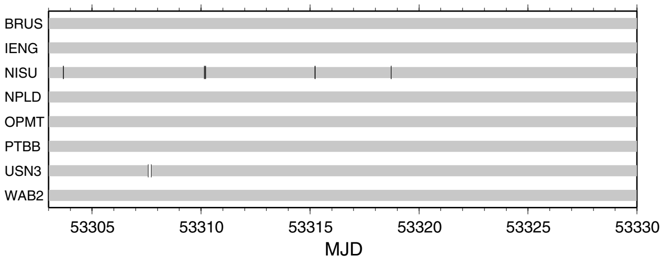


Fig. 2. Time intervals continuously connected by phase ambiguity parameters for the geodetic frequency transfer solution.

equipment before and after the event. The participating stations are listed in Table 1. The campaign was scheduled from April, 27th to May, 10th in 2005 — one week before and one after the switch of the satellite. At some stations the data from alternative receivers are used for the analysis.

In both campaigns the relevant information is not the absolute time difference but the increment of the time difference over the bridge interval. To that purpose it is only necessary to know the time series of the external reference clock of each receiver but not the absolute value of the clock corrections. In that case, as discussed in Section II, a phase–only solution is sufficient as long as the daily solutions are connected using the ambiguity stacking method to a solution with continuously overlapping ambiguities. In Figure 2 these time intervals are shown for the PFS2004 campaign. If the ambiguity parameters are continuous over the entire campaign, one offset per receiver clock remains undetermined corresponding to the freely chosen reference ambiguity. In the case of NISU, short interrupts in satellite tracking (about 5 minutes or more) have occurred that could not be bridged by ambiguities. At USN3 there were no observations made for several hours on MJD 53307. Consequently, for those two stations the phase–only solution contains more than one independent part with one unknown offset each.

B. Environmental Effects

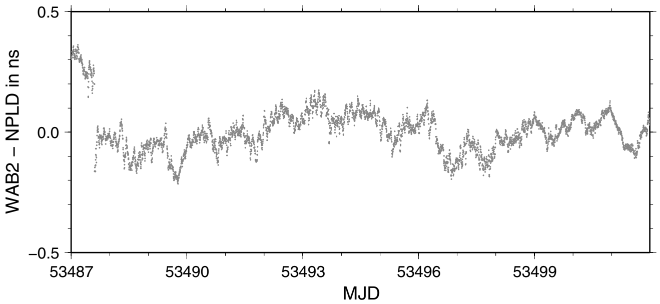
Multipath and related effects have a different impact on code and phase observations. Whereas the classical multipath — the interference between a direct and a reflected signal — is limited to a fourth of a wavelength (5 cm) for the phase data it can typically reach a magnitude up to 5 m for the code measurements [25]. Because the simultaneous observations of multiple satellites contribute to the estimated receiver clock value for a single epoch a "mean" multipath from all these observations will affect the estimated clock correction for a particular station and epoch, and further on the noise of the resulting solution. Consequently it can be expected that the main effects of multipath is an increase of the post–fit residuals, i.e., the noise of the parameter adjustment.

Moreover investigations of the impact of temperature dependency of the receiver components on the estimated receiver clock corrections have given different results for code and phase measurements. Once more in this case the code observations are more sensitive to the temperature effects than the phase observations [26], [27]. The impact of a temperature change of the receiver and of the antenna cable can be assumed to be identical for all tracked satellites. Consequently this influence is reflected in the estimated receiver clock corrections with full magnitude. The electrical characteristics of the antenna is represented by an elevation dependent phase center variation model in the analysis. One may imagine that an environmental temperature change slightly modifies this antenna characteristic. As far as we know there are no detailed studies of this effect due to the uncertainty on the antenna calibration itself [28]–[30]. Nevertheless, the main part of the temperature dependency of the antenna can be expected to be equal for all tracked satellites of a station and consequently also affects the estimated receiver clock corrections.

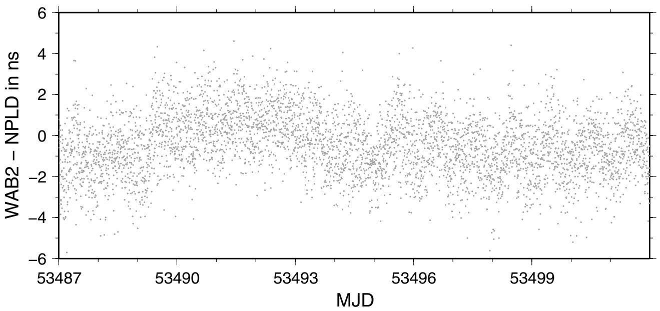
In conclusion, environmental effects acting on the GPS receiver equipment affect the code measurements much more than the phase observations. This is confirmed by Figure 3 where a continuous solution using only phase data (Figure 3(a)) and the epoch–wise solution using only code data (Figure 3(b) — note the different scales of the plots) are compared. Both solutions show a clear daily pattern that is very likely caused by environmental effects acting on the geodetic GPS equipment since the external reference clock and its connection to the GPS receiver are common for code and phase measurements. While the magnitude of the variation of the clock corrections estimated from phase data is about a tenth of a nanosecond it reaches 4 to 5 nanoseconds for code data. Even in the noisy solution displayed in Figure 3(b) and generated from code measurements a clear daily pattern can be observed indicating the impact of environmental effects.

Code and phase observations must be combined with proper weighting for geodetic time transfer. Even for geodetic frequency transfer this is necessary when no ambiguity stacking — or an adequate method to generate a continuous solution (e.g., [15], [31]) — is applied. As a consequence of the environmental effects affecting mainly the code measurements, the day boundary discontinuities may increase depending on the characteristics of the noise in the code data. As Figure 3(c) shows, the time series generated as daily independent solution (black line) approximately fits the daily mean value of the epoch–wise code–only solution (gray dots). According to the change of the variation in the code–only solution the magnitude of the day boundary discontinuities will increase or decrease.

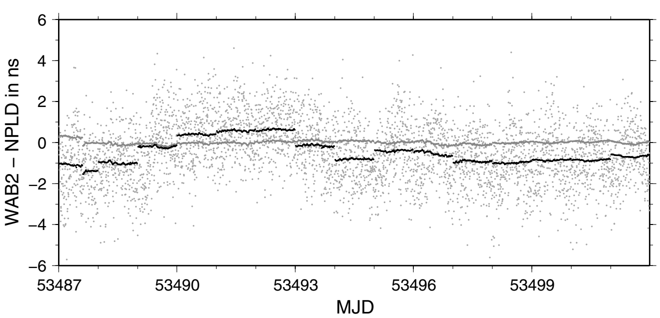
The difference between the daily independent solution and the continuous phase–only solution is expected to be a constant for each day because the code data are only necessary to resolve the singularity for one reference ambiguity per day. However, in practise a small trend of about 0.1 ns per day can be found for some of the days — again — depending on the characteristics of the pattern in the code data. This shows that code measurements have still a small influence on the estimated time series of clock corrections. This influence can be reduced by adapting the weight between code and phase data which can, however, only be changed within a given



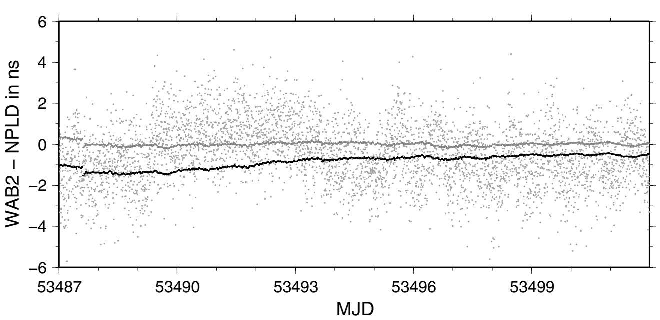
(a) Continuous solution using only phase data.



(b) Epoch–wise solution using only code data



(c) Epoch–wise solution using only code data (gray dots), continuous solution using only phase data (gray line), and daily independent solution using code and phase data (black line).



(d) Epoch–wise solution using only code data (gray dots), continuous solution using only phase data (gray line), and continuous solution using code and phase data (black line).

Fig. 3. Receiver clock corrections for the baseline NPLD→WAB2 during the TW2005 campaign. A common second order polynomial was subtracted for plotting.

range for numerical reasons in a common analysis of both observation types.

For a geodetic time transfer solution the code data are indispensable, even if the ambiguity stacking method is applied to generate a continuous time series of clock corrections. In Figure 3(d) a continuous solution using code and phase data in a common analysis and generated with the ambiguity stacking method is shown. Because the daily solutions are connected, the continuous solution does not follow the code–only solution as closely as the daily independent solution in Figure 3(c). Nevertheless, it tries to fit the mean value of the clock corrections defined by the code data. The weighting between code and phase measurements in the common analysis defines how much influence the code gets on the estimated frequency.

Unfortunately, there are no TWSTFT measurements available for the analyzed baseline for the considered time interval. The "truth" can thus not be identified with an independent method. The experience that environmental effects have more impact on code than on phase measurements makes the phase–only solution in Figure 3(a) the preferable solution.

C. Further Discussion of the Carrier–Phase Solutions

Nevertheless, Figure 3(a) shows two additional interesting details. First, there is a subdaily pattern with a magnitude of the order of 50 ps (corresponding to 15 mm) that seems to coincide with the two–hourly parameterization of the troposphere delay. The studies in [32], [33] have investigated the high correlation between troposphere and receiver clock parameters in the GPS carrier–phase data analysis. With a further improvement of the analysis models this subdaily noise might be reduced.

Another noticeable feature in Figure 3(a) is the discontinuity at MJD 53487 of about 0.35 ns that can be assigned to NPLD when comparing with the results from other baselines. A cycle slip of one cycle in the carrier phase observations on both GPS frequencies ($\lambda_1 = 19$ cm, $\lambda_2 = 24$ cm) at the same epoch corresponds in the ionosphere–free linear combination used for the data analysis to 10.7 cm (corresponding to 0.36 ns). If cycle slips with the same size affect the observations of all satellites in view, the preprocessing algorithm has no choice but to assume a discontinuity in the receiver clock time series since it cannot single out the cycle slip as the cause of the step. In fact, it is not possible to find out from the GPS CP data alone whether a discontinuity is caused by the clock or whether it is introduced by the receiver wrongly counting the cycles of the phase measurement. An independent measurement of the clock is necessary to remove the ambiguity. A similar event was also found during the PFS2004 campaign in the GPS CP solution of station OPMT at MJD 53304.

It should be added that these two phenomena occur in all three solutions in Figure 3 where the carrier–phase data are used but it can only be seen in the Figure 3(a) because of its different scale.

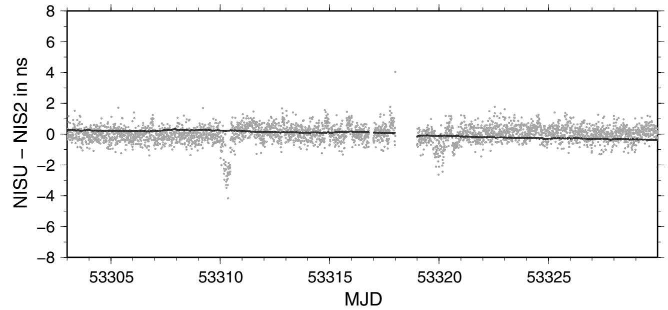
D. Results for a local network at NIST

In [24] the GPS CP solution was compared with the results from other independent time transfer techniques during the PFS2004 campaign. On one hand a very high short term stability of the GPS CP solution was outlined. On the other hand a drift of about 2 ns during the four weeks of the campaign between the TWSTFT and the GPS CP results for all baselines from Europe to NIST was noted as an open issue for further investigations.

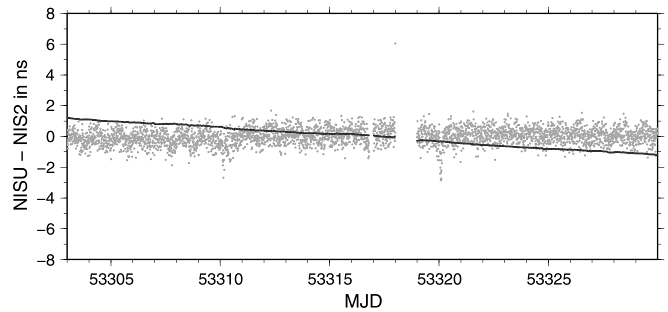
To exclude any impact from error sources possibly affecting the GPS analysis on large scale networks (e.g., satellite orbits, troposphere modeling) a local baseline at NIST including the IGS receiver and an alternative receiver (NIS2 is equipped with another receiver type than the IGS receiver NISU) was processed. Both receivers at NIST are driven by the same external clock and therefore only an offset in the resulting time series of clock corrections is expected. Because of the very short baseline no troposphere parameters have been estimated. The impact from the ionosphere can be assumed to be identical for both sites and thus separate solutions for each of the four observables (code and phase from both frequencies) can be computed. The results are compiled in Figure 4.

The results displayed in Figure 4(a) are as expected: the clock corrections obtained from the code as well as from the phase data of the first frequency (P1 resp. L1) are identical apart from the different noise levels and an offset that was subtracted for plotting. Figure 4(b) shows a surprising result because only the P2 solution follows the expectation. The L2 phase solution shows a drift. If the ionosphere–free linear combination is analyzed — as in the case of the large scale network solution — the drift in L2 can be found with opposite sign and a slightly different magnitude. This is consistent with the way the ionosphere–free linear combination is formed. It can be concluded that the drift in the clock corrections between NIS2 and NISU correspond to the drift that was detected between the GPS CP solution and the TWSTFT results for the baselines from Europe to NIST. From this it follows that the drift was not introduced by the analysis of the long baseline data but that it is already in the data. Because the analysis started with RINEX observation files either the phase signal hardware measurement of the second frequency is faulty in one of the receivers (or possibly in both) or one of the RINEX converter software did introduce this drift.

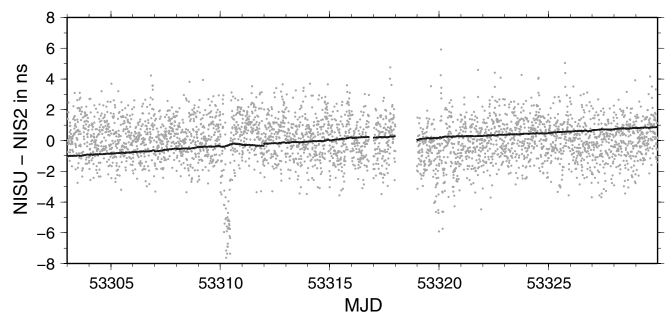
Because an apparent drift in a four weeks experiment can also be a part of a long–term periodic function (e.g., yearly introduced by a temperature or satellite geometry dependent effect like, e.g., multipath) the investigation was repeated during the TW2005 campaign. During this campaign data from a local network at NIST — consisting of three receivers of the same type as NISU and two receivers from two other manufacturers that were all connected to the same clock at NIST — was analyzed in the same way as the local baseline during the PFS2004 campaign. Again six independent solutions for each of the four available measurement types and the ionosphere–free linear combinations for the code and phase



(a) Solutions using only L1 resp. P1/CA data.



(b) Solutions using only L2 resp. P2 data.



(c) Solutions using the ionosphere–free linear combination of the data.

Fig. 4. Receiver clock corrections for the baseline NISU→NIS2 during the PFS2004 campaign. (dark line: continuous solution using only phase data, gray dots: epoch–wise solution using only code data.) An offset was subtracted for plotting.

data were generated. In addition to the satellite and receiver clock corrections only the station positions (apart from NISU) and the ambiguity parameters for the phase measurements are estimated.

The difference of the clock corrections between NISU and NIS2 confirmed the graphs displayed in Figure 4: the results from the PFS2004 campaign could be repeated about half a year later. Nevertheless the difference in behaviour between both campaigns can not be inferred from this experiment. Even if both results imply an accumulating drift any other behaviour is also possible.

Because more receivers at NIST are included in the analysis during the TW2005 campaign it can be concluded that the results for all three receivers of the type as NISU (the same RINEX converter was used for all these receivers) are consistent and that on the other hand the results obtained from the data of the two receivers from two different manufacturers (another RINEX converter was used for these two receivers) are consistent, too. Further investigations including more receiver types should be carried out to identify the source of this inconsistency.

It should be noted that the inconsistency detected in this experiment causes a very small frequency offset of about 1×10^{-15}. Many geodetic GPS receivers can be connected to external clocks but most of them are not explicitly designed as timing receivers. In conventional daily independent solutions this inconsistency in the L2 phase observations (as provided in the RINEX files) cannot be identified because it is too small. On the other hand these findings underline the sensitivity of the analysis method itself. The geodetic time and frequency transfer method is capable to identify clock effects at this order of magnitude.

IV. Summary

The ambiguity stacking method has been developed and implemented in the Bernese GPS Software package to reconnect the ambiguity parameters at the boundaries of independently processed intervals of data. In consequence the discontinuities at the day boundaries that the conventional geodetic time transfer solutions usually contain are prevented and a continuous time transfer solution is generated.

This software implementation allows two extensions of the usual daily combined processing of code and phase for geodetic time and frequency transfer:

- The time intervals of data that have to be processed together may be shortened to get the results closer to real–time.
- A geodetic frequency transfer can be computed without using the code measurements — only analyzing the phase data.

The second extension was successfully applied to two campaigns during the last year. The comparison of the solution with results from other time transfer methods are encouraging.

The code measurements are more sensitive to environmental effects than the phase observations. This is known from the theory for multipath and related effects. In several experiments investigating the temperature dependence of geodetic time transfer series similar results were published. Comparisons of the phase–only solution from both campaigns with the epoch–wise estimations of the receiver clock parameters have confirmed this. For daily independent geodetic time solutions the influence of environmental effects is reflected in the size of the day boundary discontinuities (e.g., in [7] detailed investigations were presented) whereas their impact on a continuous geodetic time transfer solution using the ambiguity stacking method is smaller. Therefore, it is preferable to generate a continuous geodetic frequency transfer solution using only the phase measurements whenever possible. It should be investigated in the future whether a continuous geodetic frequency transfer solution densifying, e.g., TWSTFT measurements gives better results than a continuous geodetic time transfer solution generated in a combined analysis of code and phase observations of the geodetic GPS receivers.

When analyzing the data from several GPS receivers from different manufacturers at NIST, all connected to the same clock in a local network solution, an inconsistency of the phase measurements at the second frequency (L2 phase observations in the RINEX files) has been detected. It has a magnitude of 1×10^{-15} ($\approx$60 ps per day). This observation confirms the sensitivity of the geodetic method which proves to be capable of discriminating extremely small effects in the clocks that are compared.

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