HIGH PRECISION TIME AND FREQUENCY TRANSFER USING GPS PHASE MEASUREMENTS

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Abstract

The use of GPS C/A code measurements for time transfer by means of the so-called common view method is a widely accepted technique. The full potential of the GPS system for time and frequency transfer is, however, only exploited by using all phase and code observables from all satellites in view. Geodetic processing techniques, adapted to the specific requirements to process data from specially modified geodetic receivers, will be presented. We will also discuss the requirements for the receivers, and the control as well as the calibration of instrumental delays. The potential of the technique will be illustrated by laboratory experiments and measurement campaigns on continental and intercontinental baselines.

INTRODUCTION

The GPS has been used for many years by the time and frequency community to compare clocks over long baselines. The predominant technique in this field is the so-called common-view method. This technique uses C/A code pseudorange measurements in order to estimate the receiver clock offset with respect to GPS time at each station. To compare clocks of two timing laboratories the corresponding clock offsets registered at the two stations are then simply differenced a posteriori. The term "common-view" reflects the fact that the observation scenarios are arranged in a way that the two stations of a baseline observe the same satellite simultaneously. In this configuration the predominant errors, namely the satellite orbit and the satellite clock error, are to a great extend "common" to both stations and thus reduced considerably.

Results from single frequency, single channel receivers show routinely an accuracy of several nanoseconds over a 13 minute pass and a frequency stability of a few parts in 10^{-14} over one day [1].

Many extensions of the common-view technique have been conceived over the past years. They all try to overcome one or several basic limitations of the classical common-view approach by using:

- multi channel receivers to observe several satellites simultaneously,
- P-code receivers to reduce the intrinsic measurement noise,
- dual frequency receivers to measure the ionospheric delays.

In the early days of GPS, the geodetic community recognized that the system offers a much more precise observable than the code pseudoranges, namely the reconstructed carrier phases. Geodetic GPS receiver therefore record C/A-, and P-code on both frequencies as well as the carrier phases on both frequencies. In contrast to the common-view technique the raw data is stored at each station, and then collected and processed in a central processing center. The position uncertainties obtained for global networks of stations are of the order of 1 cm [2]. Since receiver clock errors are closely related to position errors, the use of geodetic GPS techniques for precise frequency and time transfer has been suggested a long time ago [3]. During the last years several groups started to publish results (see e.g. [4], [5]).

Recent progress in the field stipulated the setup of the IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons in December 1997 [6]. This joint project of the International GPS Service (IGS) and the Bureau International de Poids et Mesures (BIPM) wants to exploit the potential of the IGS network and analysis centers by a) using the precise orbit and position information from the IGS and by b) including geodetic-type GPS receivers at timing laboratories into the IGS processing schemes.

In this paper we describe the principles of the geodetic GPS processing for time and frequency transfer. We also discuss the problem of tying the receiver internal clock to the external clock, and emphasize the necessity to monitor and control all types of delays. Finally, for time transfer results on long baselines we refer to a separate communication of these proceedings [7].

GEODETIC GPS PROCESSING FOR TIME AND FREQUENCY TRANSFER

The C/A- and/or the P- or Y-code, as registered by receiver i at time t_i from satellite j, is defined as follows:

$$p_i^j = c \cdot (t_i - \tau^j)$$

where

t_i is the arrival time, or observation time, of a signal as measured by the clock of receiver i.

τ^j is the transmission time of the same signal, measured in the time frame of satellite j.

The pseudorange p_i^j may be related to the slant range ρ_i^j at time t_i and to the delays due to the Earth's atmosphere. The slant range is the geometrical distance between receiver at observation time t_i and the position of the satellite at time τ^j:

$$p_i^j = \rho_i^j - c \cdot \Delta\tau^j + c \cdot \Delta t_i + \Delta\rho_{i,ion}^j + \Delta\rho_{i,trop}^j \tag{1}$$

where

c is the speed of light,

$\rho_i^j \doteq |\vec{r}(\tau^j) - \vec{R}(t_i)|$, $\vec{r}(\tau^j)$ being the satellite position at transmission time, $\vec{R}(t_i)$ being the position of receiver i at time t_i,

$\Delta\tau^j$ is the error of the satellite clock w.r.t. a theoretical GPS-time,

Δt_i is the error of the receiver clock w.r.t. GPS-time.

$\Delta\rho_{i,trop}^j$ is the delay of the signal due to the neutral atmosphere (tropospheric refraction), and

$\Delta\rho_{i,ion}^j$ is the delay of the signal due to the ionosphere (ionospheric refraction).

Geodetic receivers also record the reconstructed carrier phase ϕ_i^j of the received signal. The essential difference of phase vs. code is (a) a much higher precision (rms error of about one millimeter compared to an rms of about one centimeter for the P-code), and (b) an unknown number N_i^j of entire cycles of carrier phase.

As the receiver keeps track of the integer number of cycles as a function of time, only one initial phase ambiguity number N_i^j is needed per satellite pass. An additional difference between code and phase concerns the sign of ionospheric refraction: a signal delay corresponds to a phase advance. This leads us to the following phase observation equation:

$$\lambda \cdot \phi_i^j = \rho_i^j - \Delta\rho_{i,ion}^j + \Delta\rho_{i,trop}^j - c \cdot \Delta\tau^j + c \cdot \Delta t_i + \lambda \cdot N_i^j \tag{2}$$

where N_i^j is the initial phase ambiguity parameter for satellite j and receiver i.

Eqns.(2) and (1) immediately reveal that the receiver clock errors (w.r.t. to GPS-time) can be determined under the provision that all remaining terms can either be accurately determined from the data or may be inferred from an independent source. In order to compare two receiver clocks the difference of two quasi-simultaneous observations of the same satellite by two receivers i and k may be formed. This difference will no longer contain the satellite clock error.

It is essential that each receiver makes measurements to several satellites (ideally to all in view) quasi-simultaneously (“quasi” says that simultaneity can only be achieved apart from (small) receiver and satellite clock errors).

Given the much higher precision of the phase observable we would like to directly use Eqn. (2) to derive the receiver clock error Δt_i. It is, however, impossible to solve for the initial phase ambiguities N_i^j at this point. The phase measurements alone thus provide information about the behaviour of the receiver clock (w.r.t. to GPS-time or in the case of single differences w.r.t. to a second receiver clock) but there remains an unknown “calibration” constant. However, the phase measurements provide all information we need to perform frequency transfer!

For time transfer the code observations are mandatory in order to determine the phase ambiguity. We note, however, that the low precision code measurements are used to determine a few parameters only. In other words we could also say that all code observations of an uninterrupted measurement series (which may last weeks) are used to estimate a single clock offset parameter for the beginning of the series.

In the actual processing we take advantage of the IGS network by taking all the geometrical information from the IGS products.

Figure (1) shows a short interval of a clock comparison between two hydrogen masers at USNO as estimated from P-code measurements (P3) and from carrier phase measurements (L3). The Figure illustrates the dramatic difference in the intrinsic precision of the two observables. This is also reflected in the Allan deviation for the same data given in Figure (2).

ACCESSING THE RECEIVER CLOCK

There is one fundamental question common to all GPS techniques trying to compare clocks:

How can we relate the receiver internal time tags to the external signals of the clock to be compared?

It is important to notice that the epochs used in the GPS data processing are receiver internal epochs which are related (via software) to a receiver internal hardware clock. This hardware clock is not directly accessible in most geodetic GPS receivers! Clock estimates from geodetic GPS receivers are therefore first of all estimates of (virtual) internal clocks only!

There are in principle two possibilities to tie this internal clock to the laboratory clock to be compared: a) by forcing the receiver clock to operate synchronously with the laboratory clock, or b) by measuring clock signals from the internal clock with respect to the external clock.

Many geodetic GPS receivers possess an option to syntonise their internal time base with an external time base by means of a frequency input. Technically this syntonization has to be performed very carefully in order not to compromise the phase stability of the external time base (e.g by the phase noise of phase locked loops). The use of this external frequency input thus allows to compare frequencies of laboratory clocks.

In order to compare time we must, in addition to the syntonization, either synchronize the receiver internal clock and the laboratory clock, or measure the phase of the receiver clock with respect to the external clock. Currently geodetic receivers are generally not fitted with either a 1 PPS synchronization input or a 1 PPS output. (The steered 1 PPS 'GPS time' output of some receivers should not be confused with a 1 PPS output of the internal clock!)

For our experiments we decided to fully synchronize the receiver clock with the external clock. This approach eliminates the necessity of an external time interval counter and the associated data logging hard- and software. We built two geodetic time transfer terminals (GeTT terminals) around custom modified Ashtech Z12 receivers. The receivers have a 20 MHz and a 1 PPS input allowing to completely replace the internal clock by the external laboratory clock. For details see [8]. The modified receivers were marketed as Ashtech Z12-T and an upgraded version will soon be available under the name Z12-Metronom.

CONTROLLING LOCAL RECEIVER DELAYS

When using zero or single difference GPS observations for time transfer each single delay from the receiver antenna phase center to the point where the observables are measured has to be taken into account. This is different for the standard geodetic techniques where the so-called double-differencing eliminates all receiver internal delays in the processing.

Local delays are not critical as long as they are stable over time. In the case of frequency comparison constant delays are of no influence at all. For time comparison between laboratory clocks the receiver internal as well as the external delays (e.g. cable delays) have to be calibrated. The simplest approach is to calibrate an ensemble of GeTT terminals by mutually comparing them with their 1 PPS input connectors as reference points. This is performed by driving two or more terminals by the same clock on a short baseline of a few meters.

The crucial point, especially for time transfers, is the long term stability of the local delays. For most delays it is very difficult to measure them in a direct way during the observations. We may therefore try to either stabilize them by some means, or correct for the variations in the processing by means of a calibrated model of their dependency on environmental parameters. We use a mixture of both approaches, depending on the type of delay.

Three major delays may be distinguished: a) the delay through the antenna and the associated preamplifier, b) the delay through the cable from the antenna to the receiver, and c) the receiver internal delays. The variation of these delays depends, to the first order, on the variation of the ambient temperature only. Figure (3) shows the measured temperature dependency of two antennas of the same type (Dorne Margolin) for code and phase observations. Measurements for the standard RG213 antenna cables have shown variations of up to 1.44 ps/°C/m. For the Z12 receiver internal delays we measured variations of up to 165 ps/°C. For details see [8], extensive measurements may also be found in [9].

Antenna delay variations may be minimized by thermally stabilizing the preamplifier. Commercial versions of stabilized antennas are available e.g. from 3S Navigation. We decided to measure the antenna temperature continuously and to apply corresponding corrections in the processing on the basis of a calibrated model.

In many cases the antenna cable is the most critical element. This may be surprising, but unprotected cables on roof-tops can easily exhibit seasonal delay variations of up to 0.1 ns per meter of cable! There are simple remedies like using so-called "phase stabilized" cables, minimizing the length of cable submitted to the outside environment, and protecting the cables from direct sunlight.

The variations of the receiver internal delays may be very different for different types of receivers. In the case of the Ashtech Z12 we simply stabilize the temperature of the receiver to about 0.1°C by means of a small thermal chamber. The same chamber also serves to stabilize all clock signal distribution electronics.

RESULTS

There are two types of results to report on: a) results from a time transfer experiment on an intercontinental baseline, and b) results from clock comparisons within the existing global IGS network.

Since July 1998 two GeTT terminals have been continuously operating on a transatlantic baseline between the US Naval Observatory (USNO), Washington, and the Physikalisch Technische Bundesanstalt (PTB) in Germany. The hydrogen masers driving the terminals at both sites are simultaneously compared via GPS common-view, and TWSTFT. The campaign is a collaboration between the Astronomical Institute of the University of Bern (AIUB) and the Swiss Federal Office of Metrology (OFMET). First results are reported in a separate communication of these proceedings [7].

The Center for Orbit Determination in Europe (CODE), an IGS analysis center located at the AIUB, has been routinely determining precise satellite and receiver clocks in the IGS network. Since July 1998 a dedicated time and frequency comparison subnet is processed separately. It contains sites of the IGS net as well as a series of stations of dedicated campaigns (e.g. the USNO-PTB campaign). Figure (4) indicates the locations of the stations of this subnet. The processing scheme is arranged in a way that only station clock parameters are estimated while using CODE final IGS products for all remaining parameters. The results are accessible on the CODE anonymous FTP, and shall soon be available as official products in the framework of the IGS/BIPM Pilot Project.

Figure (5) shows Allan deviations for a set of clocks in the mentioned subnet. The Maser at PTB was (arbitrarily) chosen as a reference. The results clearly demonstrate that a frequency comparison at the 10^{-14} level on global baselines is achievable after a few hours. On the other hand the slopes of the Allan deviations show that the frequency transfer process is not dominated by pure phase noise (the slopes are roughly -0.5 instead of -1.0). This may indicate correlations between the clock estimates and other parameters like tropospheric delays. Although the slopes for very short baselines are close to -1 (see Figure 2) there is no obvious dependency from the baseline length on long baselines. Further investigations are necessary to identify the potential correlations, and to improve the models.

CONCLUSIONS

A dedicated time and frequency comparison subnet is processed at the IGS CODE analysis center. Carrier phase and pseudorange observations are processed with geodetic techniques using the precise orbit and position information from the IGS. Frequency comparisons of h-masers on global baselines at the level of 10^{-14} over a few hours are routinely achieved.

For time transfer two terminals were developed, and their internal delay variations carefully analyzed. Since July 1998 these terminals are continuously operating on a transatlantic baseline between USNO, Washington, and the PTB in Germany. The comparison with TWSTFT is very promising.

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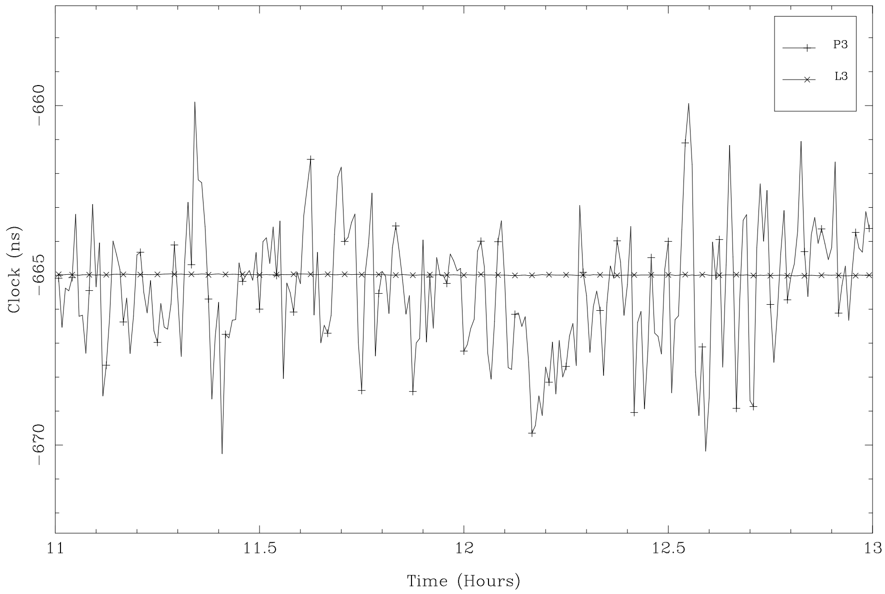

Figure 1: Comparison between 2 hydrogen masers at USNO, as estimated from P-code (P3) and carrier phase (L3) measurements.

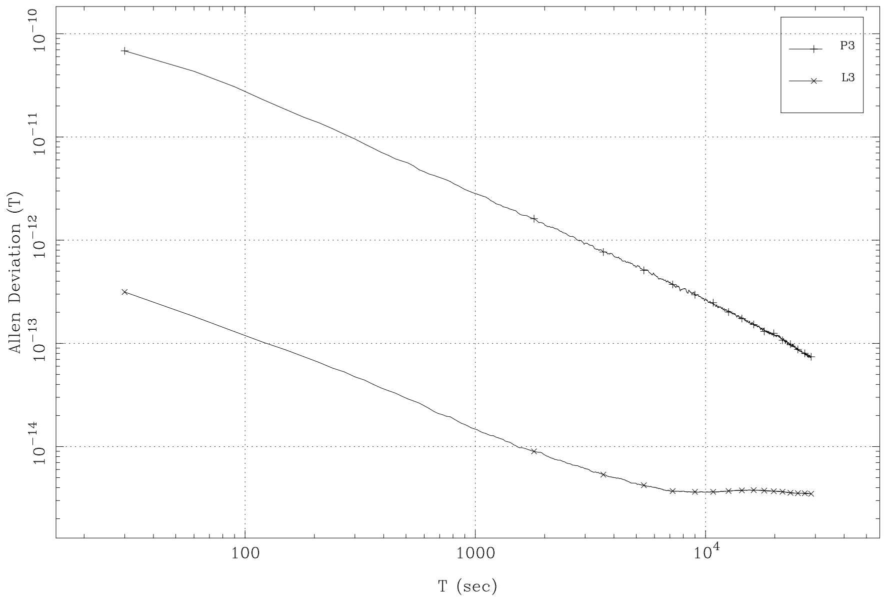

Figure 2: Allan deviation for the data given in Figure (1) using 24 hrs of data. Both Figures (1) and (2) reflect the difference in the intrinsic precision of the two observables.

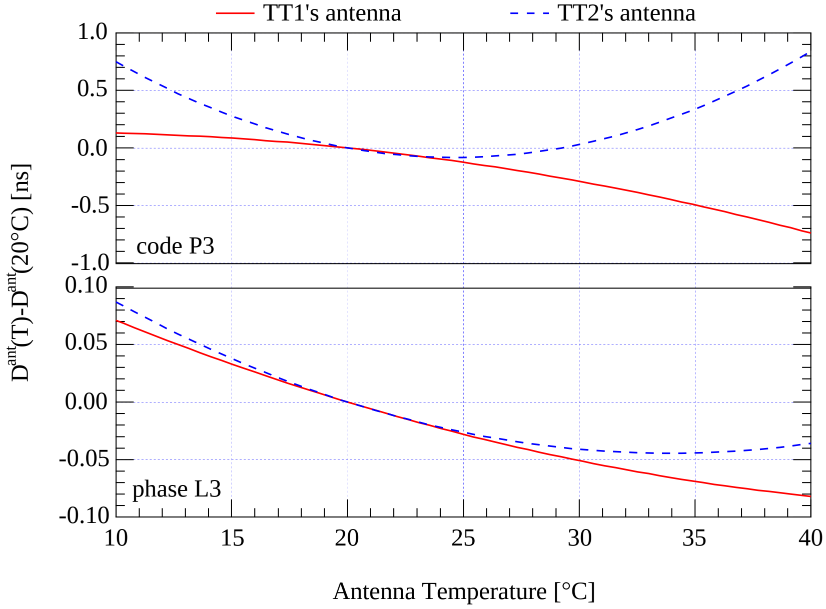

Figure 3: Measured temperature dependency of two antennas of the same type (Dorne Margolin) for code (P3) and phase (L3) observations.

Figure 4: Locations of stations used in the time and frequency comparison subnet since July 1998, comprising IGS sites and stations from dedicated campaigns.

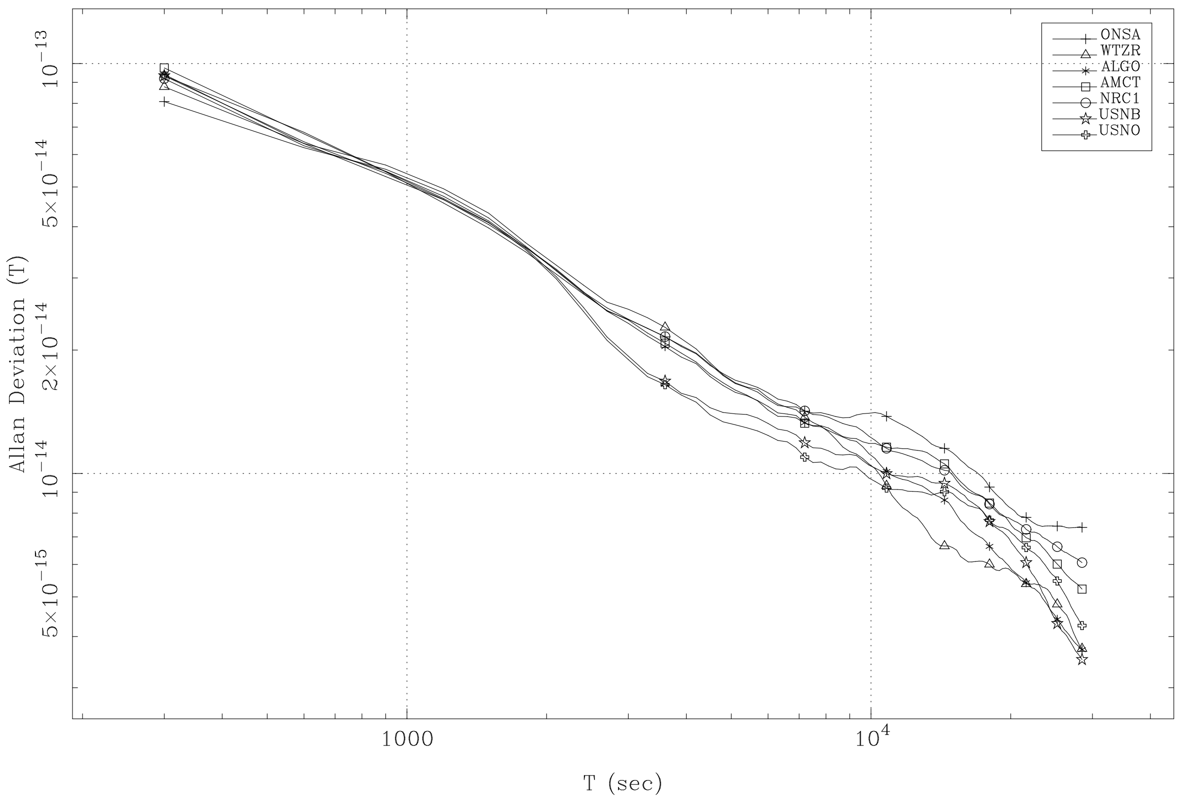

Figure 5: Allan deviations for a set of clocks in the mentioned subnet. The Maser at PTB was (arbitrarily) chosen as a reference.