RECENT RESULTS WITH TRANSATLANTIC GeTT CAMPAIGN

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Abstract

A dedicated time and frequency transfer experiment over the Atlantic by GPS Carrier Phase (GPS CP) has now been running for more than one year. For this experiment a geodetic time-transfer terminal (GeTT) was installed at the PTB and another at the USNO. The data are processed in the framework of a small network of IGS stations, most of which are driven by H-masers. Frequent comparisons between GPS CP and TWSTFT throughout the campaign allow a comparison of the long-term stability of the two entirely independent techniques. Small discrepancies between the time transfer by GPS CP and the time transfer by TWSTFT have been observed.

INTRODUCTION

The Astronomical Institute of the University of Bern (AIUB) is operating the Center of Orbit Determination in Europe (CODE), which is one of the analysis centers of the International GPS Service (IGS). CODE routinely analyzes a global network of GPS stations to produce improved orbits, Earth orientation parameters, ionosphere models, station coordinates, and their velocities, as well as additional results for geodetic and other purposes. Since spring 1998 a small subnetwork of stations is processed separately in the framework of a time-transfer experiment (see Figure 1). The procedures used in this experiment are focusing on the estimation of receiver clocks using all available code and phase observations. The network has currently produced a time series of time transfer data of more than 450 days.

The network includes two special Geodetic Time Transfer terminals (GeTT) developed at the Swiss Federal Office of Metrology (OFMET) - see [1] for more details. They are located at the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany (PTB) and at the U.S. Naval Observatory, Washington, DC (USNO; the GPS station is named USNB). These terminals are based on the geodetic Ashtech Z-XII receiver. These receivers provide not only the code measurements on both frequencies, but also the carrier phase. For the time-transfer purpose the receiver is driven directly by an external clock. All electronic equipment is installed in a thermostatic box together with the receiver itself. This design should minimize the influence of temperature changes on the time transfer. [2]

OBSERVATION EQUATION AND ANALYSIS STRATEGY

The observation equation for GPS phase observations of a station i to a satellite k may be written as (see e.g. [3]):

$$\phi_i^k = \left|\vec{r}^k(t-\tau_i^k) - \vec{r}_i(t)\right| - c\cdot\delta^k - I_i^k + T_i^k + c\cdot\delta_i + \lambda N_i^k + \epsilon_i^k \tag{1}$$

ϕ_i^k	Phase observation in m
$\vec{r}^k(t-\tau_i^k)$	Position of the satellite k at transmission time $t-\tau_i^k$
$\vec{r}_i(t)$	Position of the station i at receiving time t
δ^k	Error of the satellite clock w.r.t. the GPS time
I_i^k	Delay of the signal due to the ionosphere (ionospheric refraction)
T_i^k	Delay of the signal due to the neutral atmosphere (tropospheric refraction)
δ_i	Error of the receiver clock w.r.t. the GPS time
N_i^k	Initial phase ambiguity parameter
ϵ_i^k	Term of observation errors

The influence of multipath is neglected here. The position of the satellite $\vec{r}^k(t-\tau_i^k)$ can be assumed to be known, because of the high quality of the orbits provided by the IGS [4]. The ionospheric refraction I_i^k is taken into account by forming a linear combination of the phase observations on the two frequencies transmitted by the GPS satellite. All other terms in Equation (1) – except the error term – have to be estimated. Some of them are highly correlated, like model parameters of the tropospheric refraction and the station height (see, e.g., [5]), the phase-ambiguity parameters and the receiver clock error, as well as the station height and the receiver clock error.

To reduce the number of parameters to be estimated in one program run we use the standard geodetic approach in our software by forming double differences of the original observations. This means: at first, differences between two simultaneous measurements to the same satellite from two different stations will be computed (the so-called single differences). In a second step the differences between two simultaneous single-difference observations to two different satellites are formed. In this way the influence of some error sources (e.g., orbit error) on the results can be reduced or eliminated. The observation equation for double differences corresponding to Equation (1) reads as follows:

$$
\begin{aligned}
\phi_{ij}^{kl} &= (\phi_i^k - \phi_j^k) - (\phi_i^l - \phi_j^l) \\
&= \left|\vec{r}^k(t-\tau_i^k) - \vec{r}_i(t)\right| - \left|\vec{r}^k(t-\tau_j^k) - \vec{r}_j(t)\right| - \left|\vec{r}^l(t-\tau_i^l) - \vec{r}_i(t)\right| + \left|\vec{r}^l(t-\tau_j^l) - \vec{r}_j(t)\right| \\
&\quad -(I_i^k - I_j^k - I_i^l + I_j^l) + (T_i^k - T_j^k - T_i^l + T_j^l) + \lambda N_{ij}^{kl} + \epsilon_{ij}^{kl} \qquad (2)
\end{aligned}
$$

A solution for the global network using these double differences of the original observations is performed routinely. The results from this computation can be introduced into Equation (1) for the clock estimation. The only remaining parameters are the ambiguity parameters and the clock errors for the satellites and the stations. (Note that there is one clock error parameter per epoch for each station and each satellite.)

Because GPS is an interferometric method, one of the clocks has to be defined to be the reference clock. For all results shown in the next sections, PTB was selected as the reference clock. If there are no data from this station over one day, the solution is not included in the time series.

The code measurements of GPS are less accurate than the phase observations by a factor of about 100. Nevertheless, they can help to solve for the ambiguity parameters and the clock errors, because they are strongly correlated. Therefore, both observation types will be introduced into a common parameter estimation.

RESULTS

In the discussion of the results we will focus on the baseline between PTB and USNB, which is equipped with the two GeTT terminals described above. The time series of the time-transfer experiment is shown in Figure 2. This figure demonstrates the high density for the GeTT values in comparison to the other time-transfer methods: two-way satellite time and frequency transfer (TWSTFT) and Circular T (derived from GPS common-view observations). The results of the GeTT may be available about 20 hours after the measurement, which is much faster than for the other two methods.

Due to the high rate of values obtained from the GeTT, some of the "noise" of the TWSTFT can be explained as real signal. This is difficult to do between TWSTFT and the Circular T values, because of the different epochs for these data.

In Figure 3 the difference between the GeTT – from the corresponding epoch only, no smoothing was applied – and the TWSTFT measurements is shown. The question of the characteristics of these data points can be explained only with a long time series (negative linear trend up to MJD 51150, a one-year periodic function, or noise only?). All differences before MJD 51389 have a standard deviation of 2 ns. Assuming any systematics in this difference, this value will decrease. The correlation (Four-Field-Correlation[1] see [6]) between the time series of GeTT results and TWSTFT measurements becomes 0.98.

An other interesting phenomenon in this figure is the jump in the difference with a size of about 20 ns at MJD 51389. The reason for this could not be explained at present. Both original curves in

[1] The *Four-Field-Correlation* is independent from the distribution characteristics of the two data series; equidistant values are not necessary – like for the computation of the usual cross-correlation.

Figure 2 – the time series of GeTT as well as the time series of TWSTFT – look each to be normal. Due to the comparison of the two independent measurement techniques with an equivalent accuracy, it is possible to detect such a phenomenon.

Figure 4 shows the difference between the Circular T values and the GeTT solution. It shows similar characteristics as Figure 3, but it is more noisy. The jump is smaller and at a different epoch. The standard deviation of the differences – assuming no systematics – becomes 3 ns.

If one assumes an annual periodic function as a possible systematic in the two diagrams of the Figures 3 resp. 4, it comes probably from the GeTT solution. An annual periodic function in GPS time series can also be found in the coordinate solution with an amplitude of less than 2 cm in the vertical component. However, in Figure 3 the amplitude of an annual term would be about 1 ns, which corresponds to 30 cm. In a next step we will have to focus on these discrepancies and carefully analyze all potential correlations between the different parameters estimated in the GPS CP technique.

CONCLUSIONS

Two dedicated geodetic time-transfer terminals have been built by the OFMET and set up on an intercontinental baseline between PTB, Braunschweig, Germany, and USNO, Washington, D.C. The terminals continuously acquire data since July 1998.

The data are routinely processed at the AIUB on a daily basis in the framework of a small subnet of IGS stations taking full advantage of the official IGS products (orbits, Earth rotation parameters, etc.). The results for the experimental time transfer between these two stations using the GeTT method have been compared with results from the TWSTFT technique and Circular T values.

A good long-term stability has been achieved. The standard deviation of the differences between the GeTT results and TWSTFT measurements is of the order of 2 ns. It becomes less if one assumes an annual term in this time series of differences. At the epoch of MJD 51389 a jump in this differences of the order of 20 ns has been detected. There is no obvious problems with the original data series from each technique. The GPS CP has clearly proven to be competitive with the most accurate currently available time-transfer techniques in the field. At the same time the GPS CP results have a higher resolution (up to 30 sec.) and are available much more rapidly (within 20 hours).

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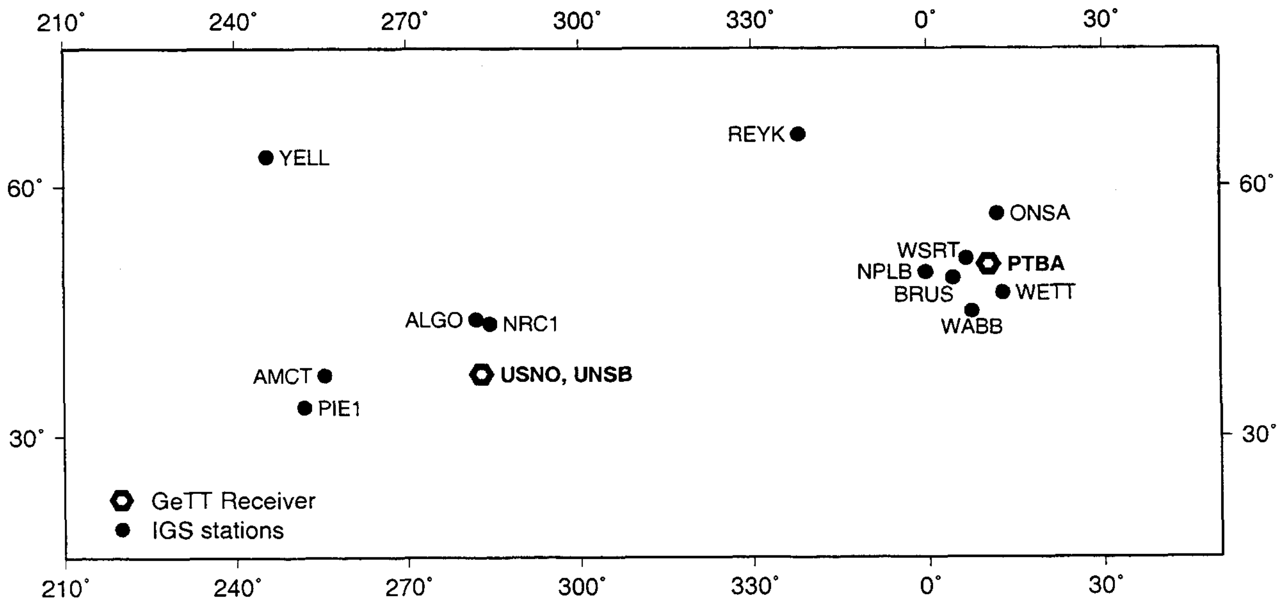
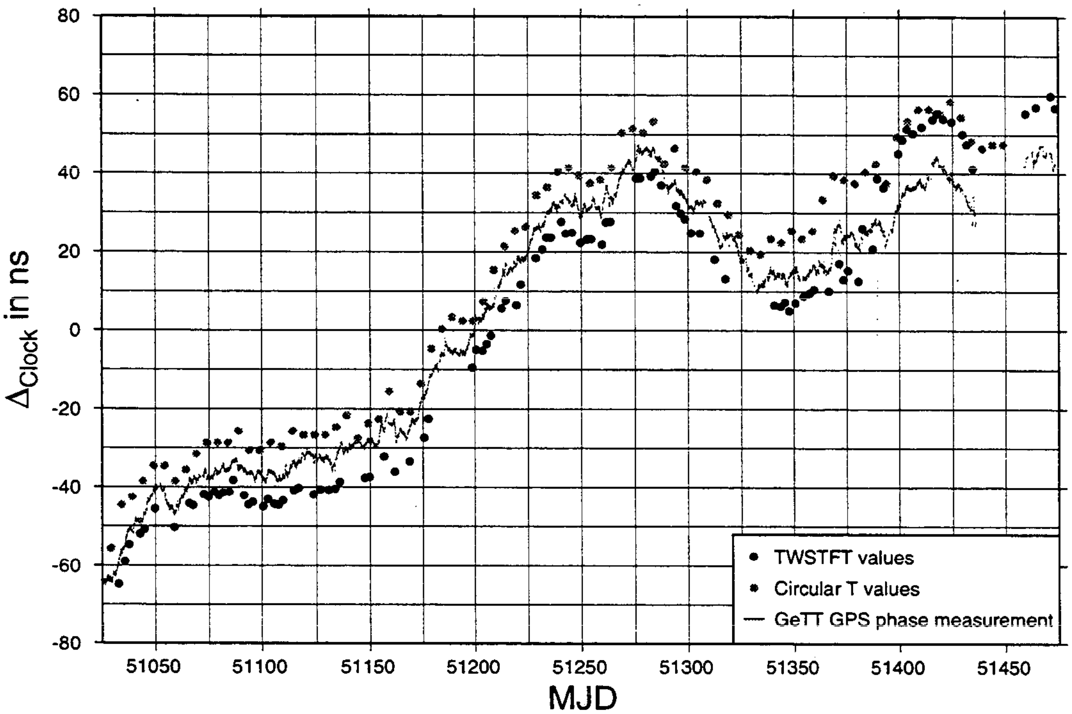
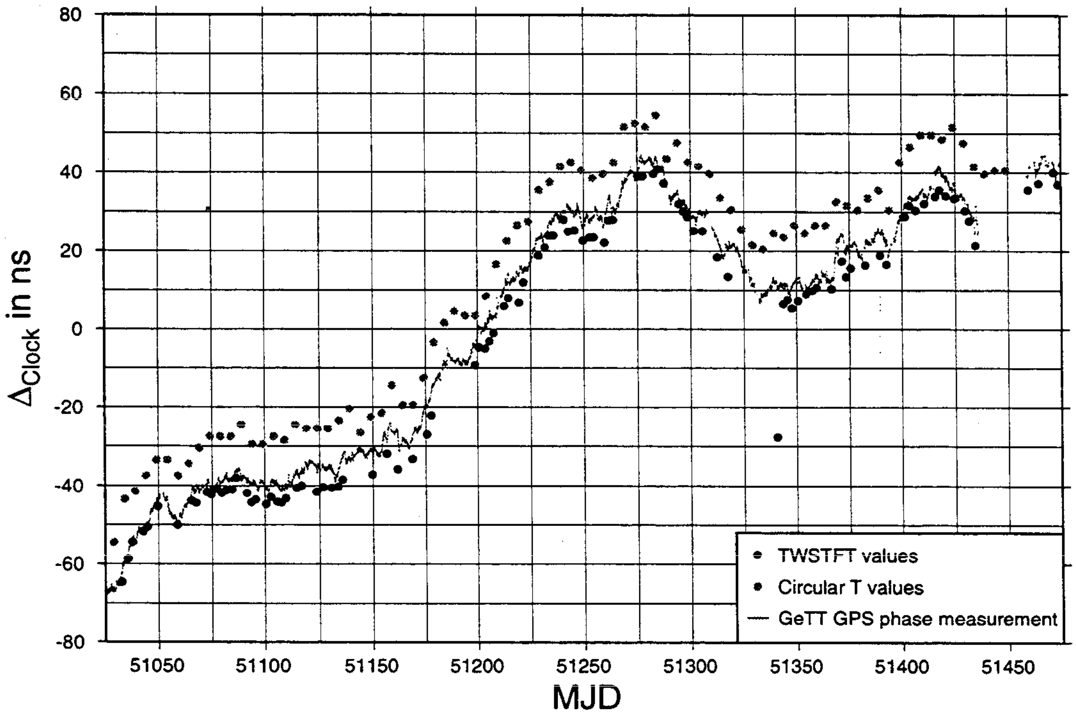


Figure 1: Geographical distribution of the stations in the network for the clock solution.

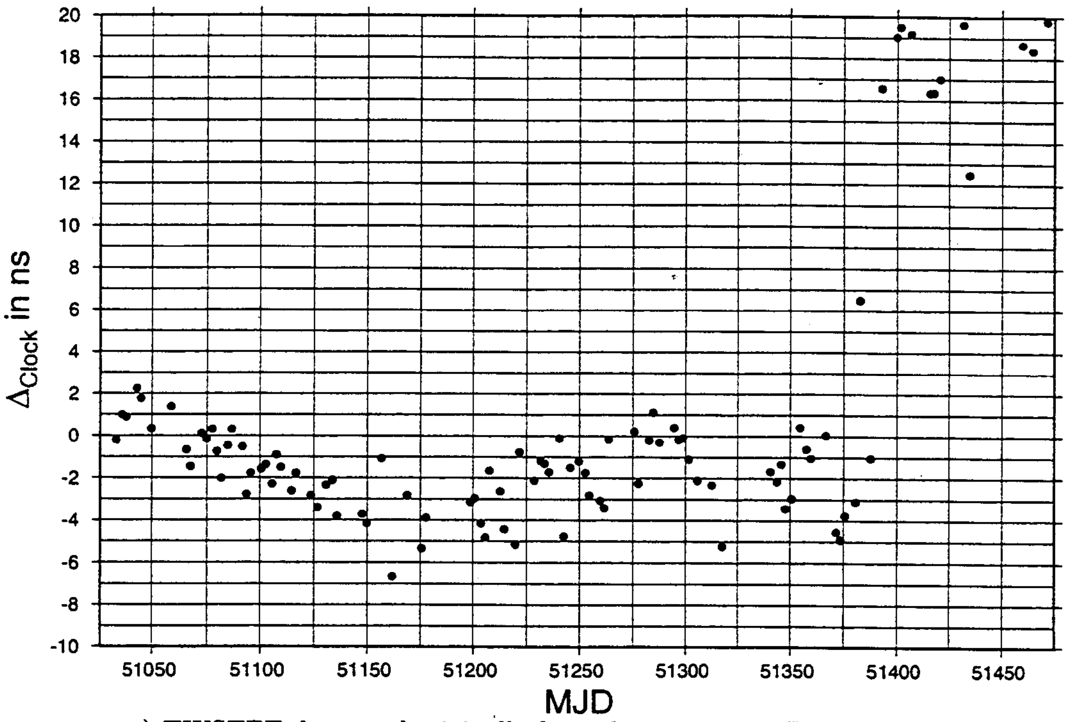


a) original Circular T resp. TWSTFT data are used without any corrections

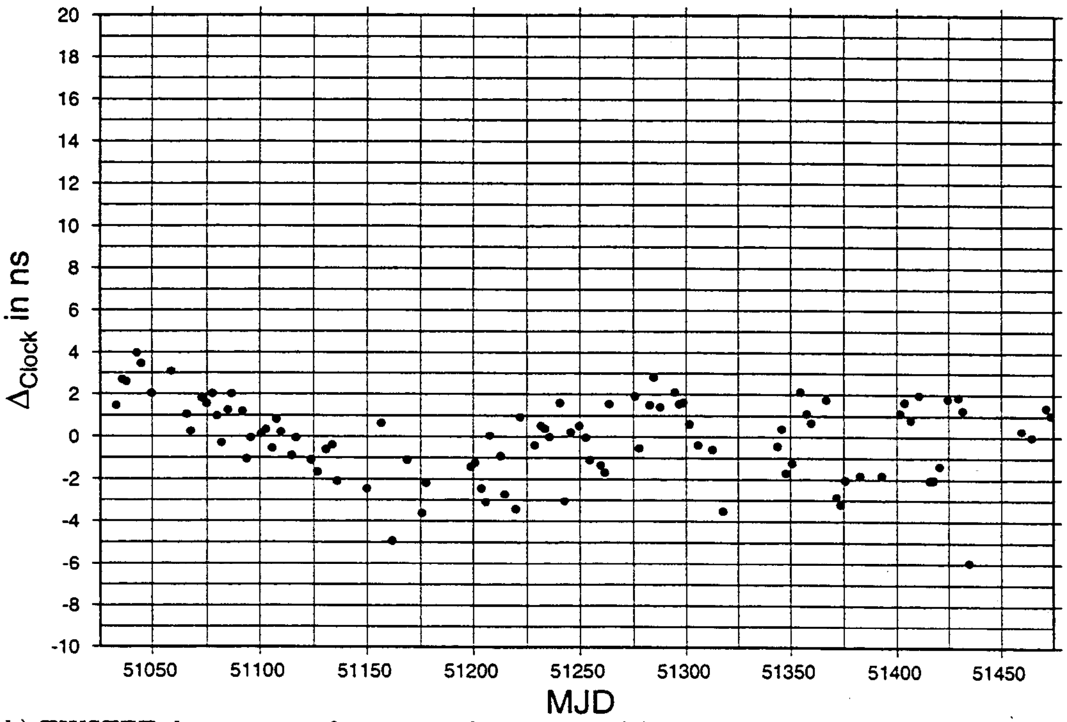


b) TWSTFT data and Circular T are corrected corresponding
to e-mail from J. DeYoung from 05.Jan.2000 resp. p.c. G. Petit at PTTI'99 meeting

Figure 2: Experimental time transfer between PTB and USNB using the GeTT terminals in comparison to the TWSTFT results and the Circular T values. (The values of the different techniques haven been shifted arbitrary.)

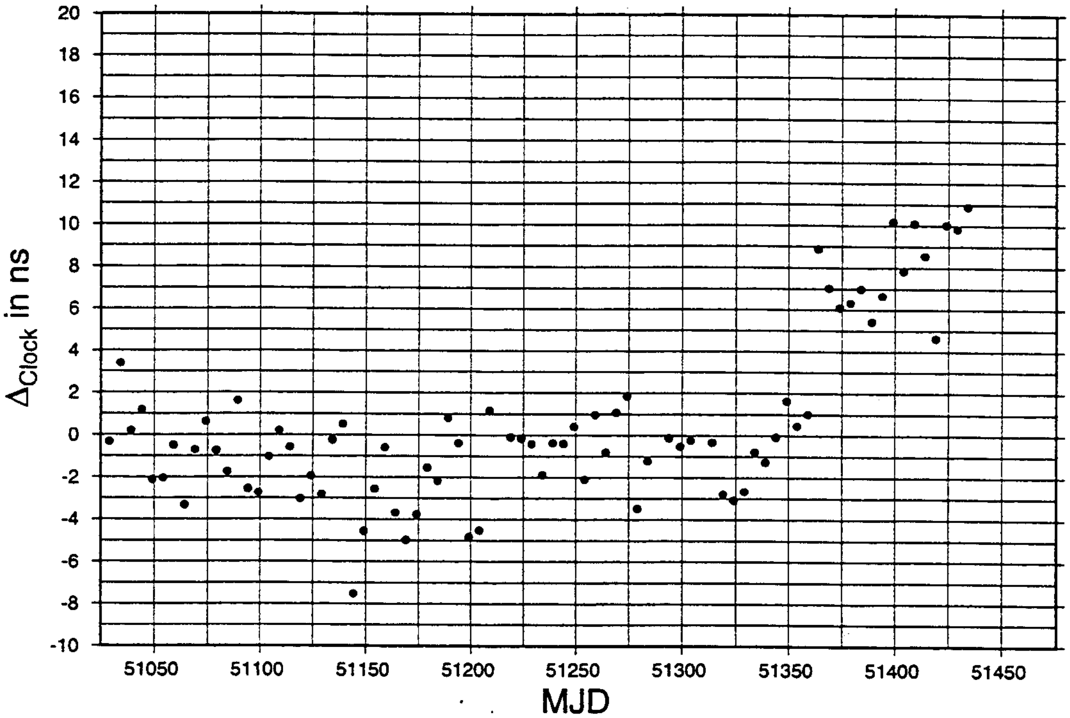


a) TWSTFT data used originally from the anonymous FTP server

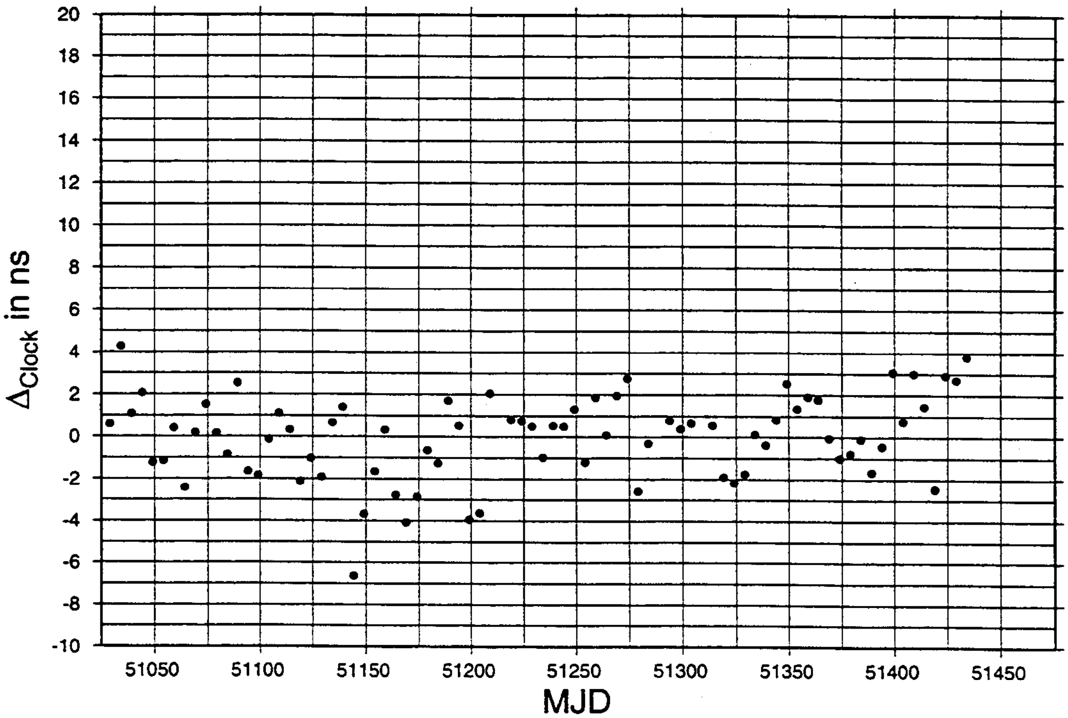


b) TWSTFT data corrected corresponding to e-mail from J. DeYoung from 05.Jan.2000

Figure 3: Differences of the time series of the experimental time transfer results for the baseline PTB – USNB using the GeTT terminals and the TWSTFT.



a) original Cricular T values are used



b) Circular T values are corrected for the change in the modelling of the ionosphere (p.c. G. Petit at PTTI'99 meeting)

Figure 4: Differences of the time series of the experimental time transfer results for the baseline PTB – USNB using the GeTT terminals and the Circular T values.

Questions and Answers

GERARD PETIT (BIPM): Your comparison with Circular T, there is a small jump of a few nanoseconds. I think it's maybe explained by the fact that in early July we changed the computation with USNO to using ionospheric maps from IGS. So if you take this into account, probably the agreement is okay over the whole period.

ROLF DACH (University of Bern): Thank you. Then that's one jump explained already.

DEMETRIOS MATSAKIS (USNO): The jump that you saw in our two-way, which I think was more like 30 nanoseconds than 20, was due to an instrumental problem. You were automating our system and it didn't automate that well. We've told people not to use those data for that 2-month period. I guess they didn't communicate that well enough.

I think if you allow for it, then your data come together. But a seasonal term still seems to go away. It seems to be a 1-year seasonal term in this season is not going back, which I think is very interesting.