Combination of GPS and TWSTFT data for time and frequency transfer

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Abstract— **Combining GPS and TWSTFT considerably increases the robustness of the accurate time transfer result due to the complete independence between these two spatial techniques. In this paper we present the last improvements of a time and frequency transfer method based on a least-square analysis of GPS code and carrier phase measurements in common view, constrained by TWSTFT data. The combined method developed here provides a time transfer solution which benefits from the high short-term stability and high resolution of the GPS data and the high accuracy of the TWSTFT data. It allows to solve the large day boundary discontinuities that exist in some clock solutions obtained with geodetic time transfer, but some discontinuities appear occasionally in the CV+TW solution, due to the noise and diurnal perturbation in the TWSTFT data.**

I. INTRODUCTION

The two main techniques presently used for time transfer are GPS common view (or all in view) and, for about 12 years, the «Two-Way Satellite Time and Frequency Transfer» (TWSTFT, TW heareafter), which is playing an increasing role [1]. The GPS-based tecnhique, known as «Geodetic time transfer» is based on the joint analysis of GPS code and carrier phase measurements. It is widely recognized for its high frequency stability (see for instance [2-4]) and its high resolution (1 point/30 second), although limited by the colored signature of the code noise, affecting the medium-term stability of the solution and inducing possible discontinuities at the day boundaries [5]. Furthermore, the calibration of the GPS equipment is presently limited to 5 ns, as set in the uB uncertainty in the BIPM Circular T. The carrier phases themselves allow to give a precise signal evolution, but as these measurements contain an unknown initial ambiguity (integer number of cycles), the code measurements are necessary to determine the absolute offset between the clocks.

TW, on the other hand, is a time transfer method completely independent of GPS, currently used by the BIPM (Bureau International des Poids et Mesures) as an alternative technique to generate the International Atomic Time (TAI). Due to its principle, it allows to cancel important sources of error such as the atmospheric delay effect. TW is calibrated and the measurements may be performed with sub-nanosecond uncertainty and reproducibility [6] as set in the uB uncertainty in the BIPM Circular T. The long-term performance of TW has already been shown to be equivalent to those of geodetic time transfer (see for instance [7]). However, TW measurements may be disturbed by a diurnal oscillation of 1 to 3 ns peak to peak [8] of unknown origin and its resolution its poor, with 1 point every 2 hours in general.

Due to the redundancy of the TAI time transfer network it is possible to combine the GPS and TW time links. A post-combination of the time transfer solutions obtained with both of them was proposed in [9], based on the Vondrak-Cepek combined smoothing algorithm [10]. An alternative method was presented by the authors in [11], which directly combines the TW data and GPS data (code and carrier phase measurements in common view) of such redundant links in a common least-square analysis. This combined solution, named as CV+TW, keeps the advantages of both systems, i.e., an accuracy corresponding to the accuracy of the TW and a high resolution and a high-frequency stability assigned by the GPS carrier-phase measurements.

The purpose of this article is to explain the method that combines GPS and TW in a direct common-view analysis, focusing on the most recent advances of the algorithm. The first section of this paper will focus on the algorithm and methodology used for the combination, and the second section will discuss the results obtained with this approach.

II. METODOLOGY

In order to combine TW with GPS data in a common analysis, we must process the GPS data in common-view mode (or single differences), due to the fact that TW directly provides the time link between two stations, and not individually as for GPS. The methodology of the CV+TW combination consists in inserting the TW data as additional observation equations in a least-square analysis of GPS code and carrier-phase measurements in common view. This algorithm was implemented inside the Atomium software

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[12], initially developed for providing clock solutions in GPS Precise Point Positioning (PPP or zero differences). In order to deal with some disadvantages of the single-difference mode, two approaches of the combination of TW and GPS have been performed, which were already described in [13], and will be then here only summarized.

A. Single-baseline approach of CV+TW

The Atomium software [12] is based on a weighted least-square analysis of ionosphere-free combinations of dual-frequency GPS code (named P_3) and carrier-phase (named ϕ_3) observations, with a consistent analysis of all the non-clock contributions in the signal. This software, in PPP mode, determines the station position for the whole period processed, the receiver clock at each epoch, and tropospheric delays at a given rate (2 hour in our case). The analysis is performed in daily data batches.

The single differences in GPS are performed by subtracting the observation equations of two different stations with the same satellite in view at the same time. This technique allows canceling the satellite clock bias, assuming that the nominal times of observation of the satellite by the two stations are the same. Denoting the stations by p and q and the satellite by i, the single-difference code and carrier-phase equations are:

$$\begin{aligned} (P_3)_p^i - (P_3)_q^i &= \rho_{pq}^i + c\Delta t_{pq}^{GPS} + (\tau_p - \tau_q) + \varepsilon_P, \\ (\phi_3)_p^i - (\phi_3)_q^i &= \rho_{pq}^i + c\Delta t_{pq}^{GPS} + (\tau_p - \tau_q) + N_{pq}^i \lambda + \varepsilon_\phi, \end{aligned} \quad (1)$$

where ρ_{pq}^i is the difference between the geometric ranges between stations p and q and the satellite, Δt_{pq}^{GPS} is the synchronization error between the receiver clocks in stations p and q, c is the vacuum speed of light, N_{pq}^i is the total phase ambiguity of the phase difference $(\phi_3)_p^i - (\phi_3)_q^i$, λ is the wavelength of the carrier-phase combination ϕ_3, τ_p and τ_p are the tropospheric delays, and ε_P and ε_ϕ are the noise terms for the code and carrier-phase combinations.

The observation equations (1) are completed by adding the TW measurements. In order to do it, we must take into account the relation between the clock difference appearing in the GPS single-difference equations and the TW data: as the hardware delay of the TW and GPS equipments (total delay between the clock and the measurement point) are different, it is necessary to estimate an additional parameter, k, which is the offset between the TW and GPS data, and is considered constant for each day processed. Note that this parameter also contains the long-term variations of the GPS code data, which are due to some site effect [5], so that it can vary with time. The TW hardware delay is considered as constant with time and this parameter contains therefore the sum of the offset between the TW hardware delay and the GPS hardware delay plus the average GPS code error during the day analyzed. Under these assumptions, the additional TW observation equations are written as:

$$c\Delta t_{t_k pq}^{TW} = c\Delta t_{t_k pq}^{GPS} + k\,, \quad (2)$$

for each observation epoch t_k where a TW measurement exists.

As the single-difference method does not allow to estimate both positions of the receivers in the same analysis, one receiver position is fixed (its approximate value is taken from the IGS weekly products <ftp://cddis.gsfc.nasa.gov>), and then, the CV+TW approach will finally determine: one station position, the synchronization error between the two station clocks, tropospheric delays for both stations, the total ambiguities of the phase differences and the daily offset between GPS and TW.

The weights for the GPS code and carrier-phase observations are computed as a function of the elevation angle of the satellite in view and the noise of each type of observable, and the weight of the TW measurements is determined in function of the GPS code weights. As the noise level of the phase measurements is about 100 times smaller than the corresponding noise level of the code observable, we set their weights to keep the relation $w_{L_3}/w_{P_3} = 10^4$; and the weight for all the TW equations is fixed to be 9 times the average weight given to the code data (due to the fact that the level of noise of the TW measurements (in Ku-band) is approximately 3 times smaller than the GPS code measurements noise).

Thanks to this weight repartition, the clock solution keeps the high stability given by GPS carrier phases, but the mean absolute clock synchronization error over one day is determined by the TW data rather than by the P-code data. Therefore, the long-term instability due to the P-code noise in the GPS-only time and frequency transfer solution is mitigated.

B. Network approach of CV+TW

For long baselines, the number of GPS satellites in common visibility at each epoch from both stations is reduced, and they are also at low elevations. Then, the quality of their data may be lower, being more affected by the atmosphere and multipath. The CV+TW combined solution is therefore degradated because of the reduced quality of the GPS single differences [11, 13]. In order to overcome that problem, we add intermediary GPS stations in the analysis, which do not participate to any TW measurements, but allow reducing the GPS baselines and improving the clock solution based on GPS single differences. In this new approach, which keeps the principle of the weight repartition explained above, one station position is fixed and all other positions are determined together with the clock solutions.

Hence, for a set of four stations (p,r,s,q), i.e. using two intermediary stations r and s for the TW link pq, the new observation equations are, firstly equation (1) applied to receiver pairs p-r, r-s and s-q, and secondly equation (2), which now have the form:

$$c\Delta t_{t_k pq}^{TW} = c\Delta t_{t_k pr}^{GPS} + c\Delta t_{t_k rs}^{GPS} + c\Delta t_{t_k sq}^{GPS} + k\,, \quad (3)$$

for each observation epoch t_k where a TW measurement exists.

The long baseline pq is then reduced to 3 shorter baselines, which provide more data per epoch in each of the three single differences of the analysis and lead to a better determination of the tropospheric parameters and hence, the clock solution is not deformed. Fig. 1 shows a comparison between the clock solutions obtained with a single differences analysis of stations USNO and PTB using the single-baseline (SD(2), in red) and network approaches (SD(4), in green). These are depicted together with a reference classical geodetic time transfer solution (in black) deduced from the IGS final clock products [14], (USNO-IGST) - (PTB-IGST), for a 3-day sample time period in April 2008. A clear deformation of the SD(2) solution within each daily data batch is observed, which is not the case of the network solution, with STJO and OPMT used as intermediary stations. Indeed, the standard deviation of the differences with the IGS time transfer solution is 285 ps, with a maximum of 1 ns reached in the middle of mjd 54566, while the differences of IGS and SD(4) have a standard deviation of 170 ps, i.e., a reduction of 40% with respect to SD(2), and the maximum difference is 0.52 ns.

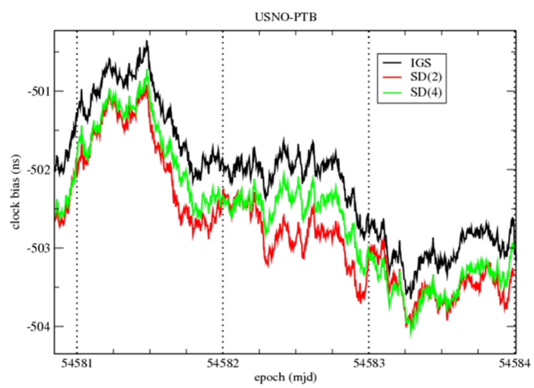

Figure 1. Comparison between the clock solutions obtained for USNO-PTB using the single-difference analysis with or without intermediary stations.

III. RESULTS

The CV+TW combined method has been tested on data from 2008 for several time links of the TAI time transfer network. The links investigated are (see Fig. 2): (a) short and medium (intra-continental) baselines: IT-PTB (using IGS stations IENG for InRim and PTBB for PTB) and TL-NICT (using IGS station TWTF for TL and using station KGN0 for NICT); (b) long (inter-continental) baselines: USNO-PTB (using IGS station USN3 for USNO), and NIST-PTB (using IGS station NISU for NIST).

The single-baseline approach has been used for the intra-continental time links whereas for the intercontinental time link, a network approach has been used, with STJO and OPMT stations as the GPS intermediary stations. The results are presented in Figs. 3 to 8. Each plot shows the combined CV+TW solution (in green), the isolated TW data (in blue) and a GPS-only solution corresponding to the IGS combined solution deduced from the IGS final clock products [14], or to a PPP-derived solution (computed with the Atomium software, in black), in case of links including station KGN0, which is not in the IGS network. This reference curve has been shifted in order to improve the visibility of the graphics.

Figure 2. Distribution of the stations used for the analysis.

In all the time links and epochs investigated, the major differences between the combined CV+TW and the reference GPS-only solutions appear as expected at the day boundaries. The constraint provided by the TW data in the least-square analysis eliminates the day boundary jumps appearing in the GPS-only solution, as for the time links NICT-TL (Fig. 3) in mjds 54567 and 54570, and NIST-PTB (Fig. 4 (up)) in mjds 54559 and 54573, where the combined solution is continuous while the GPS-only solution is not, probably due to some variations of the pseudorange measurements at some of the stations at those epochs.

The combined CV+TW method also eliminates the discontinuities caused by GPS hardware delay changes. For instance, we show in Figure 4 (down) a large jump for NIST-PTB, inside mjd 54579, which is due to a jump of about 50 ns in the GPS clock bias of NIST. This jump is not clearly due to any clock variation as the TW data are continuous at this epoch, but it is rather due to a sudden change in the hardware delay of the GPS equipment at NIST. The combined solution, still showing the clock signal given by the GPS carrier phases, is continuous at that epoch thanks to the calibration with TW data which are continuous.

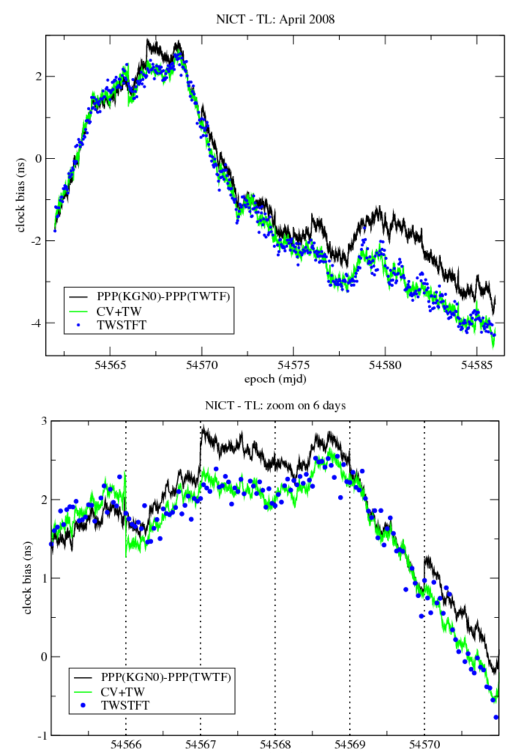

Figure 3. Continuity of the CV+TW solution across the day boundaries for the link NICT-TL in April 2008.

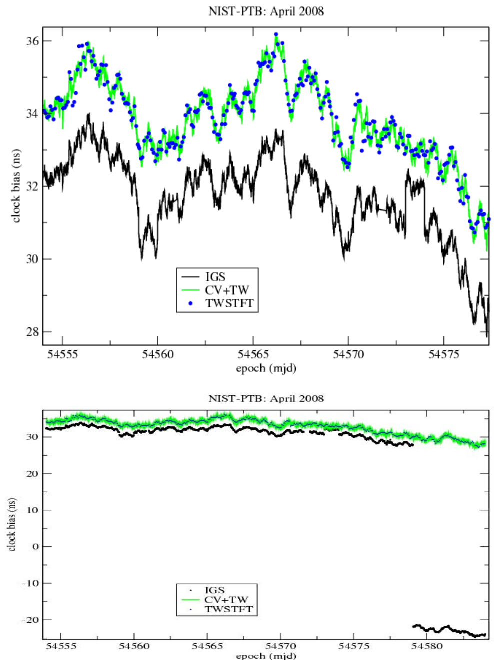

Figure 4. Comparison between the CV+TW solution and the GPS-only solution for NIST-PTB (up) and continuity of the combined solution CV+TW in case of GPS hardware delay changes as observed for this time link, in April 2008.

Another intraday jump of about 7.5 ns has been detected in IT-PTB, at the near end of mjd 54556 (see Fig. 5). We see again that the CV+TW combination ignores this GPS hardware problem, as the clock solution deduced from the carrier phases is calibrated by the TW data.

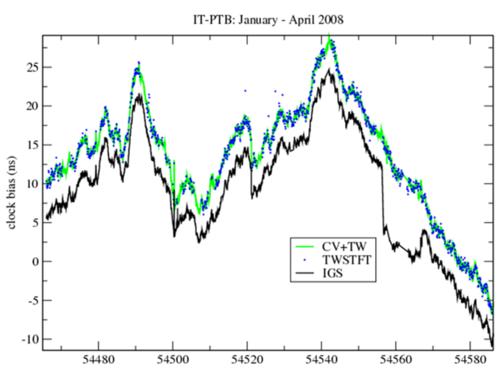

Figure 5. Comparison between the combined CV+TW solution and the GPS-only solution for the link IT-PTB beween January and April 2008.

The CV+TW combination provides a medium and long-term stability similar to the TW and GPS-only stability, while its short-term behaviour shows a slight improvement with respect to the one of the GPS-only solution, thanks to the removing of large jumps present in the GPS-only solution. These conclusions are illustrated with the time link NICT-TL in Fig. 6, where a 10-day-data period has been analyzed.

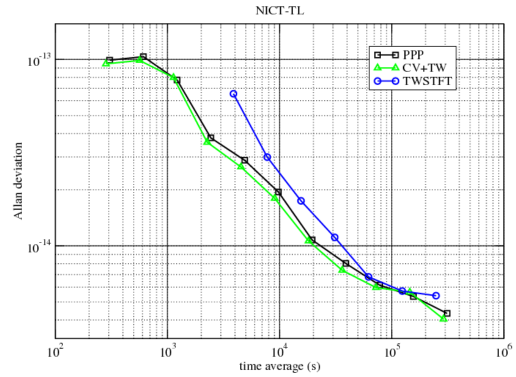

Figure 6. Allan deviation of TW, CV+TW and the reference GPS-only solution for 10 days starting at mjd 54556 for the link TL-NICT(see Fig. 3).

As we have exposed in previous paragraphs, the CV+TW combination eliminates the day boundary jumps present in some classical geodetic solutions, as the carrier phases are calibrated by the TW data rather than the GPS codes, which have a colored noise. However, due to the fact that the solution is calibrated on the TW data daily, some new discontinuitites can appear in CV+TW if the TW data are very noisy or they have a diurnal signal, reaching up to 1 ns as for NICT-TL in mjd 54566 (Fig. 3 (down)) for very noisy TW data. Nevertheless, these jumps are below 600 ps in general (see Fig. 7 where the absolute day boundary jumps of CV+TW and of the geodetic solution of NICT-TL are depicted).

As a summary, Table 1 shows some statistics of the differences between the results obtained with the CV+TW combination method and the TW data, for all the links investigated over a period of 25 days.The average of the differences between the CV+TW method and TW is very close to zero for TL-NICT, NIST-PTB and USNO-PTB and their standard deviations are below 260 ps. However, for the time link IT-PTB, the non-zero mean and higher standard deviation (nearly 500 ps) are a consequence of the very high level of noise of the TW data in this link, as it could already be stressed in Fig. 5 around mjds 54515-54530.

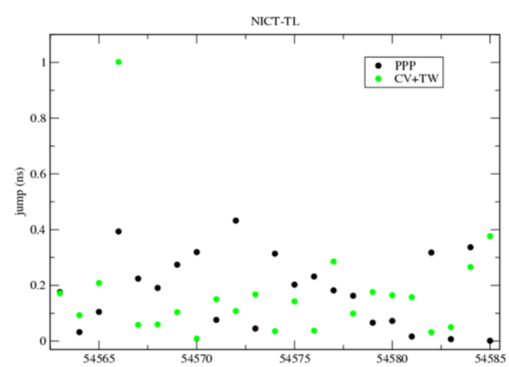

Figure 7. Comparison between the day boundary amplitudes of the CV+TW combination and the geodetic reference solution computed using PPP version of Atomium, for the time link NICT-TL.

TABLE I. STATISTICS SUMMARY OF THE DIFFERENCES BETWEEN TWSTFT AND THE GPS CV CONSTRAINED BY THE TW DATA, FOR THE TIME LINKS NICT-TL, NIST-PTB, USNO-PTB AND IT-PTB (ANALYZED FOR 25 DAYS IN APRIL 2008).

	(CV+TW) – TWSTFT	
	Average	***Std. deviation***
NICT-TL	<0.001 ps	179 ps
NIST-PTB	<0.001 ps	238 ps
USNO-PTB	<0.001 ps	250 ps
IT-PTB	10 ps	485 ps

Focusing on April for IT-PTB, one can observe that the noise in the TW data induces a large dispersion of the TW data points around the combined solution. A further consequence of the noisy TW data used for the CV+TW combination is thus the possible presence of important discontinuities at the day batch boundaries. This is illustrated in Fig. 8 (down), where the jump in mjd 54568 reaches a magnitude of 1 ns, while the GPS-only was perfectly continuous at that epoch.

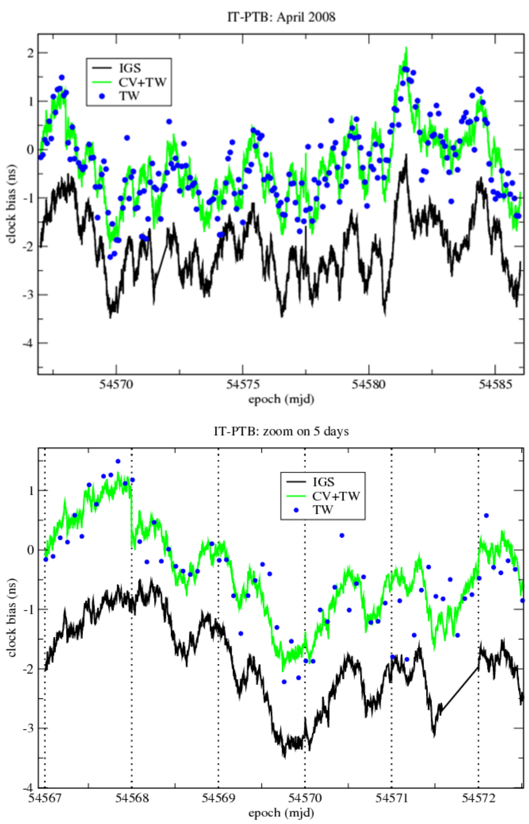

Figure 8. Comparison between the reference IGS solution and the GPS CV constarined by the TW data for IT-PTB in April 2008, where the TW data available have a very high level of noise. A linear drift has been removed to all curves (y=37629-0.68945x) so as to improve the visibility.

IV. CONCLUSIONS

This paper investigated a direct combination of GPS and TWSTFT data, by means of a least-square analysis of GPS code and carrier phase measurements constrained by TWSTFT data. It was shown that the time transfer solutions obtained with this procedure, named as CV+TW, benefit from the best characteristics of the two techniques, i.e., the high short-term frequency stability and high resolution of the GPS data, and the high accuracy of the TWSTFT data, which is indeed 5 times higher than the accuracy of the GPS code data. As the TW data express the synchronization error between two station clocks, it was necessary to use single differences of GPS code and carrier phase measurements rather than zero differences as in PPP. The method was validated on different time links, and was shown successful for all of them. Due to the degradation of the clock solution obtained with GPS single differences in the case of long baselines, a new version of the CV+TW combination was developed (labelled as “network approach”), which consists in adding two GPS intermediary stations in the analysis. This approach overcomed the problems of the single-difference mode when the stations of the link are very far away, allowing to produce a clock solution with a quality similar to the classical GPS-only solutions. The method developed here is successful in solving the large day boundary discontinuities, either due to GPS hardware delay changes, or due to the coloured signature of the noise of GPS codes, that exist in some clock solutions obtained with geodetic time transfer, although it was illustrated that a very-high level of noise of the TW data used can introduce new discontinuities in the combined solution, with a magnitude not greater than 1 ns.

TW and GPS are two completely independent spatial techniques. Combination of the both increases the robustness of the accurate time transfer, which would be not reachable using only one technique. This is also a good solution for the high redundancy in the worldwide TAI time transfer network and creates a possibility towards a multi-technique time and frequency transfer.

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