Time and frequency transfer by geodetic GPS: comparison of receivers and computation techniques

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***Abstract*— Geodetic GPS techniques based on dual-frequency phase and code measurements are now commonly used to perform time and frequency transfer. We present results from a dedicated experiment carried out to compare different types of geodetic GPS receivers and different processing techniques. Two time laboratories provide data from three different types of receivers as well as from Two-way time transfer and this dedicated data set is completed by data obtained from other laboratories participating to TAI. Comparisons of results between GPS analyses with two software packages and two processing techniques, and between GPS and TW are presented and discussed.**

I. Introduction

Geodetic GPS techniques based on dual-frequency phase and code measurements are now commonly used to perform time and frequency transfer [1]. Several types of receivers are available and are currently used in time laboratories. In order to improve our knowledge of techniques and equipment to be used for TAI links, an experiment has been set-up, in which three different types of geodetic-type receivers were operated in two time laboratories (the LNE-SYRTE in Paris and the METAS in Bern), allowing direct comparison of the GPS results and comparison of GPS links with Ku-band two-way time transfer (thereafter abbreviated as TW) simultaneously available. GPS time transfer links were computed with two different analysis techniques and two different analysis software packages in an attempt to estimate their relative characteristics and performance.

We present the experimental set-up of this experiment in Section II. Results obtained for GPS links with different analysis techniques are presented in Section III and the comparisons of GPS links with TW is discussed in Section IV. In those two sections, we also try to estimate whether the behaviour and performance of the three geodetic receivers can be qualitatively discriminated.

Disclaimer: Some commercial equipment or software are identified in this paper in order to describe the experimental procedure adequately. It does not imply recommendation or endorsement by the authors or their institutions.

II. Experimental set-up

A dedicated experiment was organized in the summer 2008, where three types of geodetic GPS receivers were operated in parallel at the LNE-SYRTE in Paris and at the METAS in Wabern, along with Ku-band Two-way time transfer. The three geodetic receivers are the Ashtech Z12-3T, the Septentrio PolaRx2 and the Dicom GTR50. All receivers are capable of C/A, P1 and P2 code measurements, as well as L1 and L2 phase measurements, they generate their internal reference from a user-provided frequency and they are also capable to synchronize at power-up to a 1 PPS signal derived from the input reference frequency. These features are the necessary condition for a calibration [2] and make these receivers suitable for time transfer. Note that the GTR50 directly relates its measurements to the 1 Hz input signal, which makes it particularly simple to use for calibrated time transfer.

Receivers of the first two types are owned by the two laboratories while the two units of the third type are owned by the BIPM and have temporarily been installed at the two laboratories. In addition the laboratories regularly operate Ku-band two-way time transfer. The operational set-up is presented in Figs. 1 and 2. At the LNE-SYRTE all GPS receivers are connected to the same reference clock while TW is connected to another reference. Therefore, local comparison of the GPS receivers may be carried out directly without additional transfer of the reference, while all other comparisons necessitate to transfer the reference to UTC(OP). On the other hand, at the METAS, three different references are used, so that all comparisons necessitate to transfer the reference to UTC(CH). In view of the achieved uncertainty in time transfer which is characterized, in the comparison between GPS and TW, by a noise level often as low as 200 ps (see e.g. Sect. IV), it is important to assess that the local measurements necessary to transfer the reference can be achieved with an uncertainty much lower than this figure. In

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this respect, it has been checked that the time stability of the local comparison equipment is at or below 20 ps for averaging time up to one day. Similarly, we have checked the consistency of the reference frequency with the reference 1Hz signal at the METAS and have measured time stability in the 20 ps range.

In addition to LNE-SYRTE and METAS, data from other time laboratories participating to TAI was collected and used in this study. They include geodetic GPS from PTB (Braunschweig), ORB (Brussels), and IFAG (Wettzell), which have been used in the generation of GPS network solutions, and TW data from PTB. The list of all the equipment used in this study is shown in Table 1.

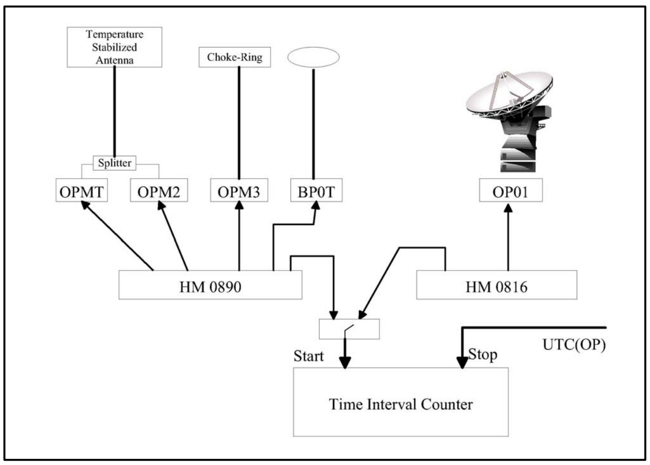

Figure 1. Set-up at the LNE-SYRTE.

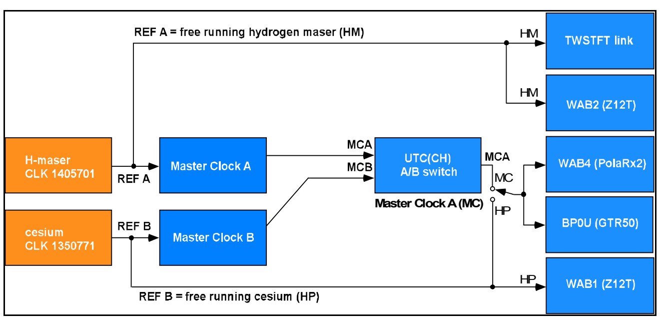

Figure 2. Set-up at the METAS.

TABLE I. LIST OF EQUIPMENT USED IN THIS STUDY

Laboratory	TW	GPS equipment by type		
		Z123T	*PolaRx2*	*GTR50*
LNE-SYRTE	Yes	**OPMT** OPM2	OPM3	BP0T
METAS	Yes	WAB1 **WAB2**	WAB4	BP0U
PTB	Yes	**PTBB**		
ORB	No	**BRUS**		
IFAG	No	**WTZA**		

The comparisons were carried out over the period extending from MJD 54672 to 54720 when all equipments were expected to be operational. However a number of events prevented to obtain a complete data set, the major one being a power failure at the LNE-SYRTE on MJD 54707 that affected all the equipments there. Note also that the TW link LNE-SYRTE to METAS had a special schedule providing 24 points per day after MJD 54492.6, but followed the regular schedule with 12 points per day until that date.

III. TESTS OF DIFFERENT GEODETIC GPS PROCESSING STRATEGIES

GNSS processing techniques can be divided in two main types: In a network computation, measurements of all participating stations are processed in a single analysis and the clock of all stations can be determined with respect to one of them chosen as a reference. In the precise point positioning (PPP) technique, data from one station is considered and the reference clock is obtained with respect to a reference time scale. This is possible thanks to the precise satellite orbits and clocks provided by the International GNSS Service (IGS) [3].

In general both phase and code measurements are used in both types of processing. However, some analysis software also provide the option to use phase measurements only, in which case time transfer solutions have an arbitrary offset over each interval of continuous data and comparisons are possible only over such continuous intervals, which is a severe limitation in practice. In the following, only solutions using both code and phase measurements are considered. Presently, it is estimated that GPS techniques using phase and code measurements allow clock comparisons with a noise level of 100 ps or below (see e.g. [1, 4]), so that we here consider a level of significance of order tens of ps (e.g. 50 ps).

PPP solutions have been computed with two different software packages: GPSPPP developed by Natural Resources Canada [5] and Bernese developed by the Astronomical Institute of the University of Bern [6]. Although both allow similar processing, they differ in some aspects:

- IGS products are directly used in GPSPPP while they are translated to an internal format in Bernese. This might cause small differences that should not be significant with respect to the level considered.
- GPSPPP is based on a Kalman filter while Bernese uses standard least squares analysis; the main consequence of this difference concerns the zenith tropospheric delay which is solved for differently in each software. In GPSPPP it is considered as a random process with a constraint between each 5-min point, while Bernese considers a piece-wise linear model over an interval of (typically) 2 hours. Because the zenith tropospheric delay is strongly correlated to the clock solution and may vary by up to 100 ps over a typical 2-hour interval, this difference is expected to be important and to cause significant differences in the clock solutions. Comparisons of tropospheric delay solutions obtained in this analysis have shown that they typically differ by some 50 ps RMS, with possible systematic differences of the same magnitude.

- Data edition is (obviously) done differently in two independent programs. The effect of this difference cannot be estimated for this study.
- Both programs allow the continuous processing of a number of days in a single run. However practical considerations (dimensions of arrays, run-time) limit this feature to e.g. 10 days for Bernese, a limit which has been chosen for the comparisons reported below.

Network solutions were computed with Bernese only.

A. Comparisons of PPP solutions

The PPP solutions considered here are 10-day batches in which the 30-s Rinex data and the IGS Rapid products are used to obtain the following parameters:

- One set of station coordinates for the whole batch.
- The station clock with a 5-min sampling interval.
- The zenith tropospheric delay: with a 5-min sampling interval for GPSPPP, as a linear piecewise model over 2-hour intervals for Bernese.
- One real-valued ambiguity per satellite pass.

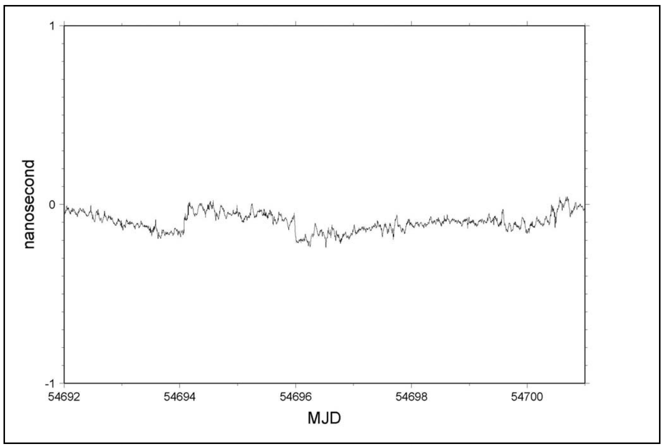

Figure 3. Comparison of the PPP link OPMT-WAB2 computed with GPSPPP and Bernese.

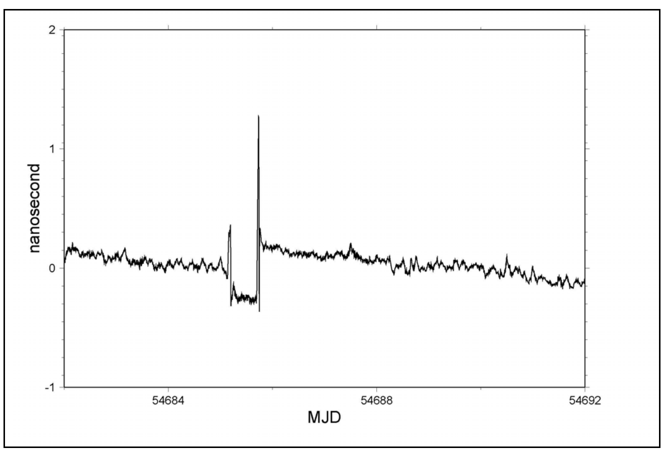

Figure 4. Comparison of the PPP link PTBB-OPMT computed with GPSPPP and Bernese.

Because the time reference used by GPSPPP and Bernese differ, it is not possible to directly compare the PPP solutions but link results can be compared. For the period 54692-54701 the RMS of the differences between the links computed with the two packages range from 51 ps for OPM2-WAB2 (LNE-SYRTE to METAS, see Fig. 3) to 108 ps for PTBB-OPMT (PTB to LNE-SYRTE, see Fig. 4). These results are in line with, or better than past comparisons of PPP packages which have shown differences of order 100-ps [7].

B. Comparisons of PPP and network solutions

Links obtained from GPSPPP solutions, computed as specified in the previous subsection, were compared to those obtained from a network 10-day continuous solution obtained with Bernese. In the latter solution, Rinex data from the five laboratories in Table I are used to solve for the following parameters: satellite positions and clocks for the passes considered, station positions with constraints to ITRF positions, station clocks with a 5-min sampling interval, station zenith tropospheric delays as a linear piecewise model over 2-hour intervals, real-valued ambiguities. Clock solutions are expressed with one of the station clocks chosen as a reference from which link results are derived by differenciation and are compared to PPP link results when the continuity of data is maintained over the 10-day interval. The RMS of the differences between such link results range from 65 ps for OPM2-WTZA (LNE-SYRTE to IFAG for the period 54692-54701, see Fig. 5) to 92 ps for PTBB-WTZA (PTB to IFAG for the period 54682-54691, see Fig. 6).

In addition, for some of the receivers under study, other network solutions are available from the IGS or from some IGS analysis centers, e.g. CODE [8] which also uses the Bernese software. Therefore the above comparisons can also be carried out with respect to the CODE results, some of which (those with a corresponding TW link) may be found in Tables IV and V. These comparisons confirm that the RMS of the difference between GPSPPP and the CODE results are at the level of 100 ps (the comparisons including OPMT In Table IV are affected by an unidentified problem in the CODE solution). It is to be mentioned that the CODE analysis is based on 1-day batches, therefore its results are expected to differ somewhat from a 10-day continuous solution.

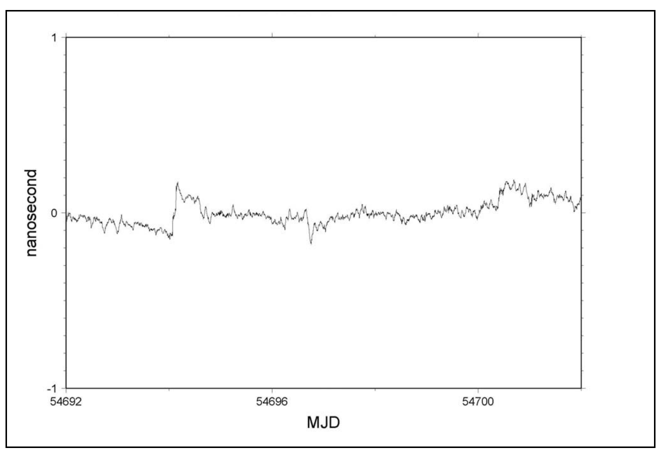

Figure 5. Comparison of the link OPMT-WTZA computed with GPSPPP and Bernese network solution.

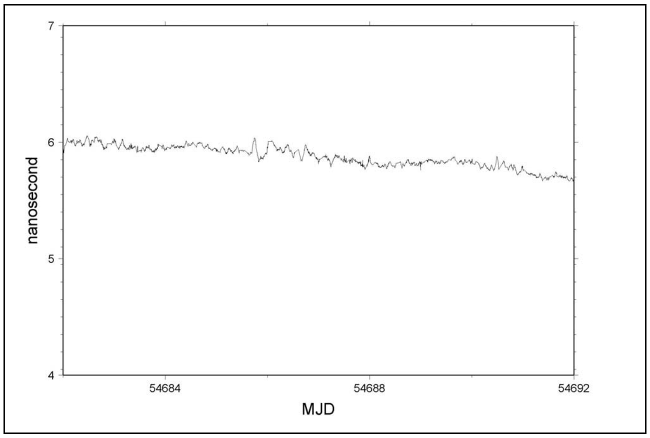

Figure 6. Comparison of the link PTBB-WTZA computed with GPSPPP and Bernese network solution.

Combining these results with those of the previous section, we conclude that the different processing techniques and different software packages considered here provide time link results which are consistent down to a level of 100 ps or better, which can be considered as the upper level for “analysis noise”.

C. Statistical analysis of GPSPPP solutions

We have investigated whether the statistics of the measurements residuals for GPSPPP solutions may be related to some characteristics of the set-up.

First in Table II, we list the RMS of residuals for phase and code measurements vs the equipment type. These results suggest that the variability is more related to the receiver than to the type, as there is a larger variability between receivers of the same type than between receivers of different types. However, the number of receivers of the same type is very small (2 units) for PolaRx2 and GTR50.

TABLE II. STATISTICS OF THE GPSPPP SOLUTIONS FOR THE RECEIVERS CONSIDERED IN THIS STUDY

Receiver	Type	Period.	# obs/ day	RMS value of	
				Code/m	Phase/cm
BRUS	Z12T	54672-54706	2270	1.28	0.85
OPMT	Z12T	54672-54706	2100	1.30	1.10
OPM2	Z12T	54672-54706	2150	1.30	1.10
PTBB	Z12T	54672-54706	2100	1.40	0.95
WAB1	Z12T	54672-54706	2250	0.69	0.86
WAB2	Z12T	54672-54706	2350	0.93	0.87
WTZA	Z12T	54672-54706	2350	0.89	0.85
OPM3	PolaRx	54672-54706	2200	0.77	0.92
WAB4	PolaRx	54682-54706	2300	0.58	0.85
BP0T	GTR50	54672-54706	2030	1.07	1.04
BP0U	GTR50	54682-54706	1800	0.82	1.05

This is consistent with the observation [1] that the dominant sources of noise are the multipath and the troposphere propagations; hence the RMS of the residuals probably reflects the level of multipath and of troposphere fluctuations.

In the same line of thought, we present in Table III the RMS of residuals for one receiver for three different locations of the antenna at METAS. We estimated *a priori* the quality of the antenna location (noted as good/fair/bad) according to the quantity of reflecting surfaces in the vicinity. It is clearly seen that the RMS of the residuals is well correlated to the *a priori* estimation of the quality.

TABLE III. STATISTICS OF THE GPSPPP SOLUTIONS FOR THE RECEIVER BP0U IN METAS FOR 3 LOCATIONS OF THE ANTENNA

Solution	Period.	# obs/ day	RMS value of	
			Code / m	Phase / cm
Fair	54687-54796	1970	0.82	1.03
Good	54715-54720	1940	0.68	0.87
Bad	54722-54731	1800	1.09	1.32

IV. COMPARISONS OF GPS RESULTS WITH TW

For the links between the LNE-SYRTE, METAS and PTB, we can compare TW to all GPS solutions, i.e. those derived in this study as well as those from the IGS analyses which generally include one receiver from each of these laboratories. In order to present results for as long a period as possible (30 days), we below show only the comparisons between TW, GPSPPP continuous and CODE 1-day solutions. Our Bernese continuous solutions could not be generated in a practical way for such a long interval, although there is in principle no such limitation. Results are shown in Table IV for a 30-day period and in Table V for a 24-day period. In the latter, data from the LNE-SYRTE cannot be included because of the power failure reported earlier.

TABLE IV. COMPARISON OF TW AND GPS SOLUTIONS OVER THE PERIOD 54677-54706 (N/A = NOT AVAILABLE)

Link	RMS of comparisons / ns		
	TW - GPSPPP	*TW - CODE*	*GPSPPP - CODE*
PTBB-OPMT	0.348	0.449	0.271
PTBB-OPM2	0.326	N/A	N/A
PTBB-BP0T	0.319	N/A	N/A
PTBB-WAB2	0.166	0.170	0.101
OPMT-WAB2	0.352	0.448	0.248
OPM2-WAB2	0.335	N/A	N/A
BO0T-WAB2	0.303	N/A	N/A

TABLE V. COMPARISON OF TW AND GPS SOLUTIONS OVER THE PERIOD 54697-54720 (N/A = NOT AVAILABLE)

Link	RMS of comparisons / ns		
	TW - GPSPPP	*TW - CODE*	*GPSPPP - CODE*
PTBB-WAB2	0.289	0.303	0.098
PTBB-WAB4	0.283	N/A	N/A

We see that the difference between TW and GPSPPP shows a typical RMS of about 300 ps (from 166 ps for PTBB-WAB2 to 352 ps for OPMT-WAB2). This is comparable to the level found in the best cases in a larger study [9].. The comparison to the CODE results is at a similar level (except for the links to OPMT for which the CODE solution is affected by an unidentified problem): This is expected because it has been shown that all GPS solutions agree at a level at or below 100 ps (see previous section).

It is worth mentioning that there is a marginally significant correlation between the RMS of the comparison to TW and the receiver type for a given link. This can be seen in Table IV where RMS(BP0T) < RMS(OPM2) < RMS(OPMT) and, more anecdotally, also in Table V where RMS(WAB4) < RMS(WAB2). Further study would be necessary to determine the significance of this result.

V. CONCLUSIONS

The comparison of GPS analyses indicates that PPP solutions (obtained from GPSPPP and Bernese) and network solutions (from Bernese) typically show a difference with a RMS between 50 ps and 100 ps for a 10-day computation. Network continuous solutions seem slightly better than PPP continuous solutions but they are much more resource consuming. Similarly, in PPP solutions, the Bernese package seems slightly better at detecting problems in the data, again at a large cost in computational resources and operation time.

Therefore PPP (phase+code) with a continuous batch covering the whole period under study seems to be a good compromise for computing a geodetic GPS time link as it provides results of overall similar quality as other techniques and is much simpler to operate than network computations. The GPSPPP package, routinely used so far at the BIPM, is found reliable but could be refined for data screening. Although network computations may be less affected by local problems such as loss of phase continuity or data gaps, they are much more difficult to operate and cannot easily be extended to a global but sparse network such as that of the TAI laboratories [9].

The comparison of GPS geodetic receivers indicates that the three receiver types considered provide consistent results, but there are hints for some small systematic differences between links that may be related to the type of receiver used. Further study is necessary on this issue. It is also important to consider all aspects of the system set-up: link of the reference, antenna location, cable length, etc…

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