The TAIPPP pilot experiment

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***Abstract*— Time transfer techniques using GNSS carrier phase and code signals are increasingly used in time metrology. In order to study the introduction of these techniques for TAI computation, the BIPM initiated a pilot experiment, named TAIPPP, where time laboratories contribute GPS phase and code data and where the BIPM uses the Precise Point Positioning technique to generate monthly solutions, in slightly deferred time after the regular TAI computation. This paper reports on results obtained from this experiment after one year.**

I. Introduction

The Consultative Committee for Time and Frequency, at its 17th meeting in September 2006 passed a recommendation "Concerning the use of Global Navigation Satellite System (GNSS) carrier phase techniques for time and frequency transfer in International Atomic Time (TAI)" [1] in which it asked that "the International Bureau of Weights and Measures (BIPM), in a highly cooperative manner, generate its own solutions, make them freely available to others, and add them to its time transfer comparison database," and that "the BIPM begin preparing software and techniques for introduction of the data into the computation of Circular T," (excerpts from Recommendation CCTF 4, 2006).

Among GPS processing techniques, Precise Point Positioning (PPP) appears as a natural choice for TAI computation needs because it is particularly adapted to a global, but sparse, network of stations and because its processing is flexible and easy to implement [2]. Therefore, to answer the CCTF requests, the BIPM initiated a pilot experiment, named TAIPPP, where time laboratories contribute GPS phase and code data and where the BIPM uses the PPP technique to generate monthly solutions, in slightly deferred time after the regular TAI computation.

In Section II, the TAIPPP experiment is presented. The main results are analyzed in Section III, including time links which are compared to Two Way time transfer, geodetic coordinates and discontinuities between monthly batches. Some implications of the inclusion of this technique in the TAI computation are discussed in Section IV.

II. Presentation of the TAIPPP experiment

The call for participation to the TAIPPP experiment was issued by the BIPM in January 2008, and some 30 expressions of interest were received. The experiment started in April 2008, when data from 21 laboratories were received and computed. To date (April 2009) 25 laboratories regularly participate to the experiment. Information on the experiment and results of the PPP computation are posted on a dedicated web page [3].

A. *The TAIPPP network and data*

In March 2009 (the last month in this study), 25 stations participated to the TAIPPP experiment, see the map in Fig. 1. Each station provides its data in daily Rinex files on a dedicated part of the TAI ftp server, along with information on the receiver calibration, if available. Six of these stations also participate to the network of the International GNSS Service (IGS) [4] and clock solutions for these stations are also generally available from the IGS.

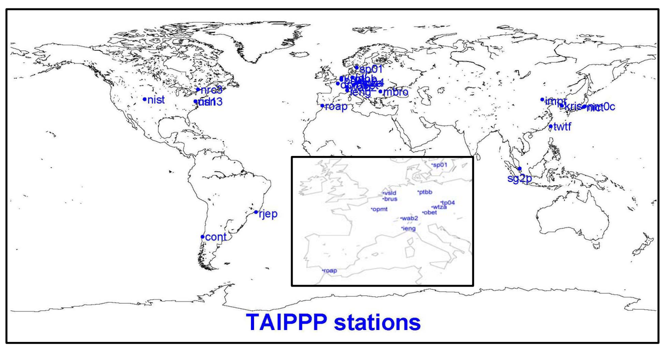

Figure 1. The network of the TAIPPP stations

B. *The TAIPPP processing and results*

In PPP, dual frequency phase and code measurements are used un-differenced and it is necessary to use precise satellite positions and precise satellite clock value with respect to IGS Time [5], obtained from the IGS, as values fixed in the processing. In the TAIPPP computation, we use the IGS Rapid products, which are available with less than 3 days of delay. The IGS Final products are expected to be slightly more accurate but they are available with a delay of 2 weeks and this would prevent their use over the whole month at the date of TAI computation.

The software used in the analysis is the GPSPPP software developed by Natural Resources Canada [6], presently version 1.04/1087, released in May 2007 and upgraded in July 2008. The software directly uses IGS files for satellite ephemerides and clocks, as well as for the absolute antenna phase center offsets [7]. GPSPPP also includes some specific features adapted to the time transfer such as the possibility to allow for a clock process noise in solving for the station clock and the continuous processing of an "unlimited" (in principle) number of days in a single run. This feature is particularly interesting for TAI, where computations are done each month for the whole preceding month, so that the month is the natural processing interval.

The main operational parameters of the GPSPPP software for the computation of 35-day (or 40-day) batches for TAIPPP are the following: we use IGS Rapid SP3 orbits and 5-min SV clocks, ionosphere-free linear combination of code and phase measurements are taken with *a priori* weights of 1 m for code and 1 cm for phase; the elevation cut-off is set to 10°; the observation sampling and clock solution interval are both 5 minutes; the tropospheric zenith delay is modeled as 3mm/√hr random walk, with the Niell mapping function used; ocean loading coefficients are from [8]; station coordinates are estimated on each 1-month batch.

Results are made available each month is the web page of the TAIPPP experiment [3]. For each station is provided:

- The raw (uncalibrated, i.e. with respect to the reference clock of the receiver) results with a 5-min interval, [Reference – IGRT] where IGRT is the Rapid version of IGS time.
- A plot of the raw results, with a linear term and possible large jumps removed.
- The calibrated results, i.e. [UTC(Lab) – IGRT]. If no calibration is available, these results are identical to the raw results.
- The zenith tropospheric delays, with a 5-min interval.

III. Analysis of the TAIPPP Results

Each monthly computation provides the station clock results in the form [Reference – IGRT] with a 5-min interval. Station clock results provide, by simple difference between two stations, link results which can be compared to the TW link results when these are available (see sub-section A). Geodetic results, i.e. a set of geodetic coordinates for the antenna reference point of each station for each month, are studied in sub-section B for their consistency with external information. Finally sub-section C studies the discontinuities in PPP clock results between successive 1-month solutions.

A. Comparison of PPP links with TW

Since the beginning of the TAIPPP experiment, the PPP results have been included in the regular link comparisons associated with the TAI computation and the results are available in the corresponding web page [9]. They are provided as monthly plots of the difference between two techniques; specifically they are shown for all links where TW data is available. Table I shows a summary of such comparisons where the RMS of the monthly differences is shown for four months for a selection of 9 TAI links. Notes in Table I indicate local problems: (1) Outlier identified in the PPP solution; (2) Presence of a drift of unknown origin; (3) Time step identified in the TW link; (4) Poor quality of the TW link; (5) Known problem with the TW data. Overall, the agreement between the two techniques is at a level between 0.2 ns and 0.6 ns, with a significant number of results in the lower half of this interval. Because PPP results are expected to be independent of the length of the link, we can infer that PPP contributes, in general, by no more than 0.2 to 0.3 ns to the difference between the two techniques.

TABLE I. Comparison of TW and PPP links for four months and nine TAI links

Link	RMS of differences / ns			
	0811	**0812**	**0901**	**0902**
CH-PTB	0.397	0.407	0.204	0.260
IT-PTB	0.525	0.406	0.732	0.514
NICT-PTB	0.642	5	5	0.646
OP-PTB	0.356	0.350	0.860 [1]	0.295
ROA-PTB	0.638	0.687	1.517 [2]	0.725
SP-PTB	0.229	0.275	0.406	0.216
USNO-PTB	0.898 [4]	0.654	0.619	0.671
KRIS-NICT	0.658 [3]	0.380	0.320	0.209
TL-NICT	0.794 [3]	0.594	0.427	0.319

B. Geodetic positions of TAIPPP stations

Each monthly computation provides the geodetic position of the antenna reference point with a typical standard uncertainty of about 1 mm in horizontal directions and a few mm in the vertical. As these coordinates are not related to a reference marker, they cannot be directly compared with those obtained from ITRF2005, the latest realization of the terrestrial reference frame [10], but their variation with time can be compared if the set-up of the antenna does not change over the whole period. Over the 11 months of the TAIPPP experiment, we have determined the horizontal velocity of the TAIPPP stations with respect to the terrestrial frame implicitly realized by the IGS Rapid ephemerides used in our analysis, i.e. one that is aligned to ITRF2005. The corresponding vectors are shown in Fig. 2 and it can be checked that they, in general, closely match the velocity vectors of the ITRF2005 (see the corresponding map in [10]). Even though ITRF2005 velocities are determined with many years of data up to 2005 while our solution corresponds to 2008, such a match is expected because the plate motions are globally stable. This analysis confirms that our solutions provide valid results.

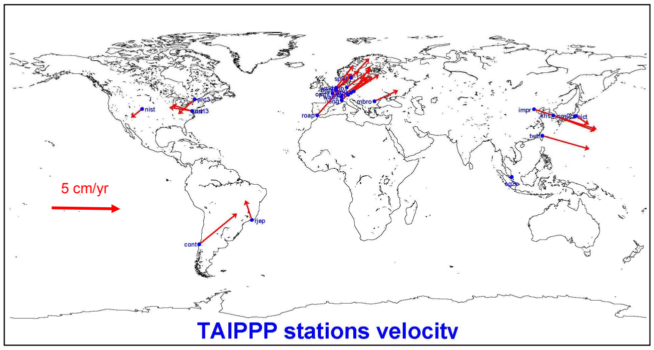

Figure 2. Velocity vectors of the TAIPPP stations computed from 11 months of TAIPPP data

C. *Analysis of discontinuities*

A well-known feature of GPS phase and code solutions based on successive (e.g. daily) batches is the presence of so-called "boundary discontinuities" [11]. It is to be noted that we do not expect our "long batch" solution to remove boundary discontinuities, as if they were somehow an artifact of an analysis procedure. The discontinuities originate in the noise of the GPS code measurements and long batches would decrease the discontinuities only if they are due to pure white noise processes. However, it has been shown that other noise processes are present and sometimes dominant [12], so that discontinuities do not necessarily decrease, and may eventually increase, as the batch duration increases.

We here examine the 1-month discontinuities observed over 11 months of TAIPPP analysis, i.e. from an ensemble of (at most) 10 discontinuities for 24 stations. Because each monthly batch has a 5-day common period with the preceding, we estimate an average value of the discontinuity over the 5-day period and we also estimate an average rate of the difference between the two results over this period. Table II shows the statistical information computed from the TAIPPP discontinuity results. We see that the typical discontinuity is about 150 ps in phase and about 3×10^{-16} in rate. Values marked with * in the Table have been found to correspond to cases when one of the monthly processing had been affected by an undetected error. The resulting error in station clock amounts to several ns so that the corresponding discontinuity results are not significant.

The IGS computes its network solutions in daily batches, so that it can provide information on daily discontinuities. Such information is regularly computed by the IGS clock products Working Group and made available on its web site [13]. In Table III, we report the values obtained by the IGS and by TAIPPP for the 6 stations common to both analyses. It seems that there is more variability on the daily discontinuities, which may depend more on local conditions. However it is to be noted that the IGS values represent a much longer analysis period than the TAIPPP and local conditions of the equipment may vary over time. This may be the case for OPMT for which the larger value in the IGS analysis seems dominated by values with a large scatter several years ago. Overall we may conclude that the daily and monthly discontinuities have a similar magnitude, which would mean that no significant gain is obtained on the accuracy of code data by averaging more than a day.

TABLE II. STATISTICAL DATA ON THE MONTHLY DISCONTINUITIES IN THE TAIPPP EXPERIMENT

Station	# disc.	Average value of		
		# points	*Phase disc. / ns*	*Rate disc. /ns/d*
brus	10	1438	0.154	0.028
cont	7	1440	0.291	0.056
ieng	10	1345	0.195	0.029
impr	10	1385	0.985 *	0.306
kris	6	1344	0.093	0.035
mbro	9	1284	0.974 *	0.094
nict	10	1411	0.109	0.029
nist	10	1394	0.400	0.035
nm0c	10	1435	0.131	0.038
nrc3	2	1440	0.268	0.027
nrl1	9	1440	0.104	0.024
obet	9	1227	0.163	0.055
opmt	10	1263	0.187	0.05
ptbb	10	1439	0.142	0.029
rjep	9	1437	0.207	0.04
roap	8	1396	0.335	0.039
sp01	9	1440	0.179	0.05
tp04	10	1355	0.047	0.024
twtf	10	1436	0.141	0.055
usn3	10	1439	0.152	0.032
vsld	10	1306	0.18	0.034
wab2	10	1440	0.132	0.028
wtza	9	1408	0.099	0.033

TABLE III. COMPARISON OF MONTHLY DISCONTINUITIES FROM TAIPPP AND DAILY DISCONTINUITIES FROM THE IGS

Station	Daily disc /ns	Monthly disc /ns
brus	0.138	0.154
ieng	0.116	0.195
opmt	0.331	0.187
twtf	0.149	0.141
usn3	0.142	0.152
wab2	0.067	0.132

IV. USE OF PPP FOR TAI COMPUTATION

In considering the use of PPP for TAI computation, we first have to consider the issues of data transfer, computation procedures, and validation of results; these are explicit goals of the TAIPPP experiment. Then we have to consider which statistical uncertainties should be used when introducing such links. From Circular T section 6, we read that two types of uncertainty are considered: The type A uncertainty, u_A, is the statistical uncertainty evaluated by taking into account the level of phase noise in the raw data, the interpolation interval between data points and the effects with typical duration between 5 and 30 days. The type B uncertainty, u_B, is the estimated uncertainty on the calibration.

We expect that the monthly discontinuities provide a good estimate of the instability in PPP time transfer for averaging time of up to one month. Therefore the analysis of discontinuities may be used to set the type A uncertainty for each link because the other two components of u_A are negligible: the noise in each PPP result is typically of order a few tens of ps and the interpolation noise is close to zero as the results are provided with a 5-min interval. In typical cases when the monthly discontinuities are of order 150 ps, the value u_A can then be taken as 0.3 ns.

Longer-term systematic effects in code measurements may still affect results of our monthly batches but they are not to be used in estimating u_A. They should be revealed by comparison to other independent time transfer techniques, mostly TW: From the comparisons in Section IIIA, we conclude that they are not expected to be larger than those associated to TW links.

Finally the calibration of PPP links is to be considered. As the PPP results use the same P1/P2 code observations as the regular dual-frequency "P3" results regularly used in TAI computation, calibration issues are the same for both. Presently, many of the dual-frequency equipment providing P3 or PPP data have been calibrated by comparison to the travelling BIPM receiver [14]. In such a case, the type B uncertainty of a link between any two such laboratories is presently conservatively estimated to be 5 ns. In the future, it will be useful to consider cases when a traveling equipment is used to specifically calibrate one given link in a given set-up, in which case a significantly lower value could be taken for u_B (see e.g. [15]).

V. CONCLUSIONS

Precise Point Positioning using dual-frequency phase and code measurements with a continuous batch covering the whole month of TAI computation seems a good solution for TAI links. The TAIPPP experiment, after nearly one year of operation at the BIPM, has shown that the PPP technique can easily be applied routinely in the computation of TAI. The GPSPPP package, routinely used so far at the BIPM, is found reliable although it may be refined for data screening. The PPP link results are superior to code-only P3 links and have a short-term (below one month) stability comparable to or sometimes lower than TW.

The quality of PPP time links is such that TAI would already benefit from its introduction (PPP would then replace the presently used code-only P3 links). Because PPP and TW have different features the situation is not as straightforward to choose among them. It has been shown [16] that one solution is to combine PPP with TW in order to obtain the short- and medium-term stability of PPP and the accuracy of TW. This would make better usage of the high redundancy of the TAI worldwide network without significantly complicating the computation procedures.

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