Precise Point Positioning for TAI computation

G. Petit, Z. Jiang
Bureau International des Poids et Mesures (BIPM)
gpetit@bipm.org

Abstract**—***We discuss the introduction of a new time transfer technique for computing time links for TAI. Precise Point Positioning uses GPS dual frequency carrier phase and code measurements to compute the link between a local clock and a reference time scale with the precision of the carrier phase and the accuracy of the code. The time link between any two stations can then be computed by simple difference. The paper presents results of link comparisons as well as a general procedure to be implemented in the regular TAI computation and shows that this technique is well adapted to this usage.*

I. Introduction

The GPS carrier phase measurements are two orders of magnitude more precise than the GPS code data, much less sensitive to multi-path and allow to better estimate the atmosphere effects. Receivers able to measure phase and code are becoming common-place in time laboratories. For this reason, the CCTF, at its 17th meeting in September 2006 [1] 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)" 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). This paper presents the first steps towards implementing this Recommendation.

Precise Point Positioning (PPP) uses dual frequency phase and code measurement from geodetic-type GPS receivers to compute [Local clock – reference time scale]. This is possible thanks to the precise satellite orbits and clocks provided by the International GNSS Service (IGS) [2], where the reference time scale is IGS Time [3]. The situation can be generalized in principle to any Global Navigation Satellite Systems (GNSS), however it should be stressed that, in order to obtain a unique PPP solution, all satellite clocks must be referenced to the same time scale. Otherwise a "system by system" approach should be used as for GPS and GLONASS [4]. For this reason, presently, only GPS can be used in practice for PPP solutions.

PPP thus allows to compute [UTC(k) – IGS Time] for any laboratory participating to TAI which is equipped with such a geodetic-type receiver. Then any link [UTC(k) –UTC(l)] can be computed by simple difference. Some basic considerations show that this approach makes sense for computing TAI time links. First it is the natural follower of the All-in-view technique [5], which has recently been introduced to compute TAI links, in which code only measurements are used to compute [UTC(k) – GPS Time]. PPP combines the precise GPS phase and the accurate code measurements, thus can provide excellent short term stability from the phase and good accuracy. Finally it is easy to put into operation at the BIPM, using one of several existing software packages.

In section 2, we present the practical implementation of PPP at the BIPM. In section 3, we show some results including those obtained during the April 2007 computation of TAI. In section 4 we discuss some topics to be considered before the full implementation in TAI.

II. Operation of PPP for TAI links

The software presently in operation at the BIPM is the GPSPPP software developed by Natural Resources Canada [6]. Its main features (version 1087 released in May 2007) are:

- A direct use of IGS products without format change;
- Adoption of the new IGS paradigm of absolute antenna phase center offsets (in usage since November 2006, see some details in next section);
- Updated models for station displacements (e.g. ocean tidal loading) and troposphere mapping function;
- Solves for, in addition to real-valued phase ambiguities, station coordinates, tropospheric delays and gradient parameters, and station clocks (at any interval larger than the data interval);
- Allows the continuous processing of an "unlimited" (in principle) number of days in a single run.

This last feature is particularly interesting for TAI where computations are done at the beginning of every month for the whole preceding month. In that case, it is not necessary to go to smaller computation interval, like e.g. in the quasi real-time IGS processing which necessitates short (daily) batches. A well-known feature of GPS phase and code solutions based on

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successive (e.g. daily) batches is the presence of so-called "boundary discontinuities" [7]. It is to be noted that, unlike what may sometimes be implied, we do not expect the "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 them if they are due to pure white noise processes. However it has been shown that other noise processes are present and sometimes dominant [8], so that discontinuities do not necessarily decrease, and may even increase, as the batch duration increases. Nevertheless long batches are preferable to daily batches because, in the latter case, the daily discontinuities greatly affect the stability estimates at averaging times of interest to clock analysis (hours to days). As long-term systematic effects in code measurements still affect results of our monthly batches, we expect to eventually evidence them by comparison to other independent time transfer techniques.

Operational parameters of the GPSPPP software for the computation of monthly batches for TAI links are the following:

- IGS Rapid SP3 orbits and 5-min SV clocks in RINEX (receiver independent exchange) format are adopted; Note that the latency of the Final IGS products (14 days) is too long for the TAI computation delay, but the quality of IGS Rapid products is expected to be sufficient;
- SV antenna offset values and station antenna phase center variations are taken from standard IGS file igs05_1421.atx;
- FES2004 ocean loading coefficients are from the Chalmers Centre for Astrophysics and Space Science: http://www.oso.chalmers.se/~loading/
- *A priori* data weights are 1 m for pseudorange, and 1 cm for phase;
- Elevation cut-off is set to 10°;
- Observation sampling and clock solutions every 5 minutes;
- Tropospheric zenithal delay estimated as 3mm/√hr random walk, and no horizontal gradient estimated;
- Station coordinates estimated on each 1-month batch.

III. TESTS ON TIME LINKS

We present time transfer results obtained for the April 2007 TAI computation. For simplicity of data collection and time link comparisons, the data set has been restricted to those stations for which RINEX observation data are available through the IGS database, which provide Two-way time transfer (TW) data for TAI, and for which the time reference of the geodetic receiver can directly be compared to that of TW. PPP time link results for some of these stations (OP in Parsi, IT in Torino, PTB in Braunschweig, USNO in Washington DC) are presented below, first to try to estimate the influence of the new IGS Antenna phase center treatment, then to perform some comparisons with TW. In the figures 1 to 4, the top plot show the time link values (unit ns) computed with two techniques as indicated, the middle plot shows the difference between the two computations (unit ns) and the two bottom plots show the modified Allan deviation MDev and the time deviation TDev computed for the difference (data in the middle plot) over different averaging times, presented in log-log coordinates.

A. The new IGS treatment of antenna phase centers

On November 5, 2006 (GPS week 1400), the IGS introduced a major change in its computation procedure by choosing a model for antenna phase center based on Absolute Phase Center (APC) calibrations [9], instead of Relative Phase Center (RPC). The change is designed to provide a more realistic representation of the effects of antenna phase center patterns. On the geodetic side, this change mostly affects the scale of the network (a global effect) and the vertical coordinate of each station as well as the zenith tropospheric delay, all at the level of a few mm [10]. The effect of this change on the PPP clock solution have been estimated to be at the level of a few tens ps RMS [11], after removing a global shift in the solution. This does not directly provide an estimate of the effect on a time link (the difference of two PPP clock solutions), therefore we have carried out a few tests in this aim. However, a rigorous test would require using IGS products in the two versions (APC and RPC) for the same period; but the RPC products are not available any more. Therefore we warn that the results presented here may not be fully realistic and should be interpreted as providing, at best, an order of magnitude of the effects.

Two PPP solutions have been computed with the same RINEX observation data and IGS satellite ephemerides and clock products (obtained by IGS with the new APC computation), using either the APC model or the RPC model. Then two solutions (APC and RPC) are obtained for a given link and compared. An example is presented in Figure 1 for the link OP-PTB in April 2007. We see that the RMS of the difference of the two solutions is of order a few tens ps, in line with the effect on clock solutions in [11].

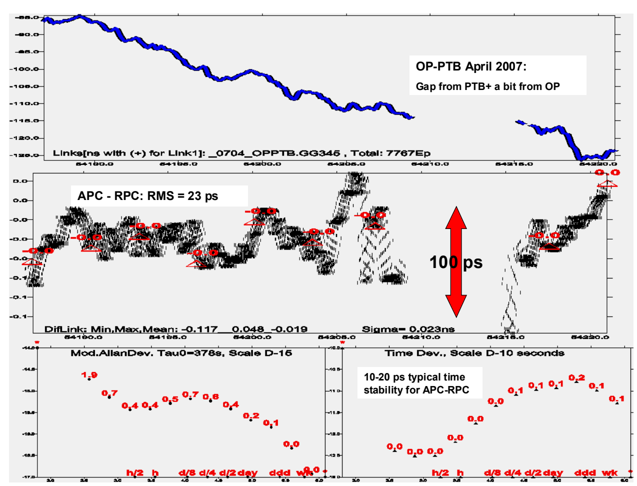

Fig. 1: Comparison of two different treatments of Antenna phase centers APC vs. RPC: effect on the link OP-PTB over April 2007.

B. *Comparisons for some TAI time links*

Previous analysis [12, 13] has shown that PPP links are more stable than TW links for the short term. For what concerns the long term, the RMS of differences (PPP-TW) over several months has been shown to be of order 0.4 ns to 1 ns. In the same study, three-corner hat analysis of the link (USNO-PTB) with two other independent TW techniques, one in Ku band and one in X band, showed that PPP is the most stable for averaging time until 3 days and then has similar stability until 10 days. Compared to the code-only P3 time links, presently used in TAI, PPP is obviously at an advantage because it has the better short term stability due to the phase measurements and similar long term stability.

The present study is based on a smaller dataset, so that only a few additional results can be provided for time link comparisons between PPP and TW. Nevertheless, they fully agree with the previous findings: Over one month, the RMS of the difference between PPP and TW(Ku), after removing the mean value, is of order 0.4 ns (Figure 3) to 0.6 ns (Figure 2). Moreover, PPP and TW(X) are in significantly better agreement (RMS=0.25 ns, Figure 4) than PPP and TW(Ku) (RMS=0.42 ns, Figure 3).

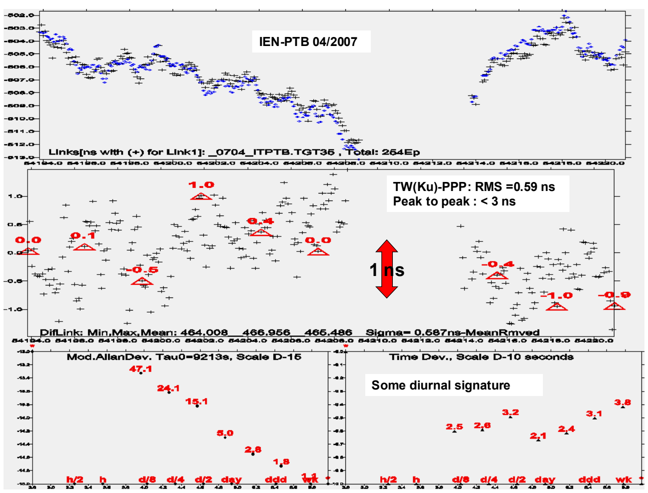

Fig. 2: Comparison of PPP with TW(Ku) for the TAI link IT-PTB over April 2007

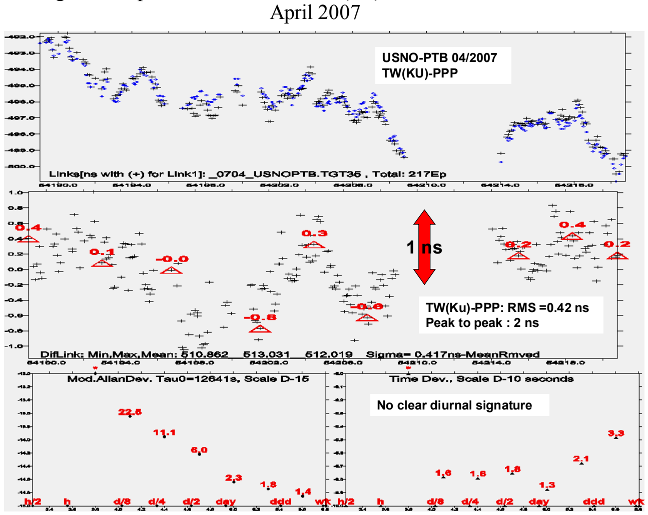

Fig. 3: Comparison of PPP with TW(Ku) for the TAI link USNO-PTB over April 2007

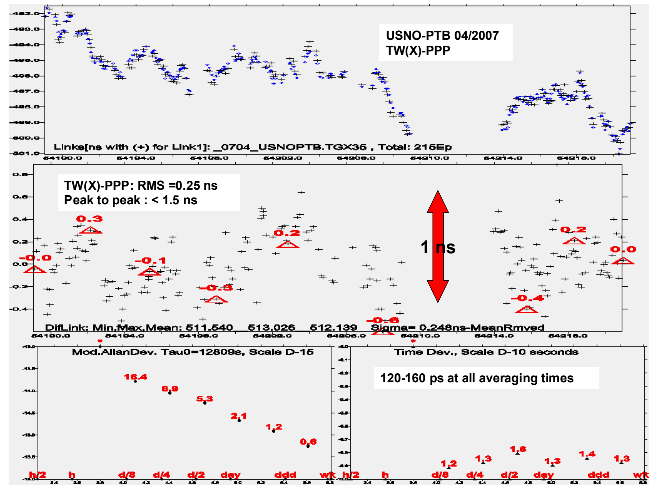

Fig. 4: Comparison of PPP with TW(X) for the TAI link USNO-PTB over April 2007

After implementation into TAI computation, such comparisons will be added to the existing database of time link comparisons at ftp://tai.bipm.org/TimeLink/LkC.

IV. DISCUSSION AND FUTURE NEEDS

The computation of PPP links for TAI is under implementation at the BIPM. In this paper we have focused on the procedures for computation and on the validation of the results by comparison to the TW technique. In view of its regular use for TAI computation, we have to address two practical problems: First the data flow from the participating laboratories to the BIPM must be organized in order to gather RINEX observation files and, if necessary, auxiliary files to relate the time reference of the geodetic receiver to the local realization of UTC, with a sufficient time sampling. Second, the information on the calibration of the receiver must be transmitted. Two possible solutions can be envisioned (see figure 5): one is to transmit the information as in the CGGTTS format in a special file; another one is to use an existing RINEX clock format, however details on the composition of the total delay cannot be provided in that case.

```
INT DLY =  304.5 ns (GPS P1),  318.9 ns (GPS P2)
CAB DLY =  301.7 ns (GPS)
REF DLY =   65.5 ns

REF = UTC(PTB)
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```
     2.00           CLOCK DATA                                  RINEX VERSION / TYPE
TORINEXC V9.9       USNO                3-APR-96 00:10          PGM / RUN BY / DATE
EXAMPLE OF A CLOCK DATA FILE                                    COMMENT
IN THIS CASE CALIBRATION/DISCONTINUITY DATA GIVEN               COMMENT
    10                                                          LEAP SECONDS
     2    CR    DR                                              # / TYPES OF DATA
USNO 40451S003                                                  STATION NAME / NUM
UTC(USNO) MASTER CLOCK VIA CONTINUOUS CABLE MONITOR             STATION CLK REF
                                                                END OF HEADER
CR USNO 1994 07 14 20 59 50.000000  2    .123456789012E+00   .123456789012E-01
CR USNO 1994 07 14 22 19 30.000000  2   -.123456789012E+00   .123456789012E-02
DR USNO 1994 07 14 22 23 14.500000  2   -.123456789012E+01   .123456789012E+00
CR USNO 1994 07 14 23 44 50.000000  2   -.123456789012E+02   .123456789012E+00
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Fig. 5: Description of two formats to transmit calibration information Top: CGGTTS format; Bottom RINEX clock format.

As we have shown, the quality of PPP time links is such that its introduction to replace code-only P3 time links would improve the TAI network. The comparison with TW links is not as straightforward because PPP has a clear advantage at short term, but may be subject to more instability in the long term. On the other hand, the calibration uncertainty should be lower for TW links which are therefore expected to be more accurate. One solution would be to combine PPP with TW to obtain the short and medium term stability of PPP and the accuracy of TW. Methods for such combination have been proposed [14] and are readily usable. This would make better usage of the high redundancy of the TAI worldwide network without significantly complicating the computation procedures.

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REFERENCES

[1] Consultative Committee for Time and Frequency, Report of the 17th meeting, 2006, http://www.bipm.org/utils/common/pdf/CCTF17.pdf.

[2] J.M. Dow, R.E. Neilan, G. Gendt, "The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade," Adv. Space Res. 36 vol. 36, no. 3, pp. 320-326, 2005. doi:10.1016/j.asr.2005.05.125

[3] K. Senior, P. Koppang, J. Ray, Developing an IGS time scale, Proc. IEEE Trans. UFFC 50, 585-593, 2003.

[4] Q. Baire, P. Defraigne, N. Guyennon, Time and frequency transfer from PPP using GLONASS and GPS data, Proc. EFTF 2007.

[5] G. Petit and Z. Jiang, GPS All-in-view time transfer for TAI computation, Metrologia, 2007, submitted.

[6] J. Kouba, P. Héroux: Precise Point Positioning using IGS orbits and clock products, GPS Solutions, 4, p.31, 2001.

[7] J. Ray and K. Senior: Geodetic Techniques for Time and Frequency Comparisons Using GPS Phase and Code Measurements, Metrologica, vol. 42, pp. 215-232, 2005.

[8] P. Defraigne, C. Bruyninx, On the link between GPS pseudorange noise and day-boundary discontinuities in geodetic time transfer solutions, GPS Solutions, 2007, in press.

[9] http://igscb.jpl.nasa.gov/mail/igsmail/2006/msg00184.html

[10] http://igscb.jpl.nasa.gov/mail/igsmail/2006/msg00163.html

[11] G. Gendt, Th. Nischan, First validation of new IGS products generated with absolute antenna models, IGS Workshop, 2006.

[12] G. Petit and Z. Jiang,, Comparison of Precise point positioning and Two way time transfer techniques for TAI links, CPEM 2006. available at ftp://tai.bipm.org/TimeLink/PPP.

[13] Z. Jiang, R. Dach, G. Petit, T. Schildknecht, U. Hugentobler: Comparison and combination of TAI time links with continuous GPS carrier phase results, Proc. EFTF 2006.

[14] Z. Jiang, G. Petit, P. Defraigne, Combination of GPS carrier phase solution with a calibrated time transfer link, Proc. EFTF 2007.