Hindawi Publishing Corporation
International Journal of Navigation and Observation
Volume 2008, Article ID 562878, 8 pages
doi:10.1155/2008/562878

Research Article

Precise Point Positioning for TAI Computation

Gérard Petit and Zhiheng Jiang

Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France

Correspondence should be addressed to Gérard Petit, gpetit@bipm.org

Received 27 July 2007; Revised 19 October 2007; Accepted 27 November 2007

Recommended by Demetrios Matsakis

We discuss the use of some new time transfer techniques for computing TAI time links. Precise point positioning (PPP) 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 a simple difference. We show that this technique is well adapted and has better short-term stability than other techniques used in TAI. We present a method of combining PPP and two-way time transfer that takes advantage of the qualities of each technique, and shows that it would bring significant improvement to TAI links.

1. INTRODUCTION

GPS carrier phase measurements are two orders of magnitude more precise than the GPS code data, much less sensitive to propagation multipaths, and allow a better estimate of the atmosphere effects. Receivers able to measure phase and code are becoming commonplace 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).

One GPS carrier phase analysis technique is precise point positioning (PPP), in which dual frequency phase and code measurement are used to compare the reference clock of a single receiver to a 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]. In recent years, the time community has shown a growing interest in this technique and a number of time transfer experiments have been carried out (see, e.g., [4–6]).

PPP allows one to compute UTC(k)-IGS Time, where UTC(k) is the local reference of any laboratory participating in TAI, which is equipped with such a geodetic-type receiver. Then any link [UTC(k)-UTC(l)] can be computed by simple difference. This approach makes sense for computing TAI time links because it can be applied for any individual laboratory, properly equipped, without the need to participate in an organized network such as the IGS. Although participation in the IGS has other practical advantages such as improved experience return and reliability, it is unlikely that all laboratories in the TAI network will participate, so that the PPP approach is particularly adequate. In addition, it is easy to be put into operation using one of the several existing software packages. PPP is the natural follower of the all-in-view technique [7], 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.

In Section 2, we recall the basis of the PPP technique and in Section 3, we present the practical implementation of PPP used at the BIPM. In Section 4, we present a combination method that allow a merging of the independent techniques PPP and two-way time transfer (TW). In Section 5, we present results of time link comparisons between PPP, TW, and the PPP+TW combination that allow an estimation of the stability of each technique and a determination of an optimal processing of TAI time links.

2. BASIC PRINCIPLES OF PRECISE POINT POSITIONING

The observation equations for the carrier phases L_j at each the two GPS frequencies (f_j, $j = 1,2$) and the pseudoranges (P_j), here both expressed in meters, can be written as

$$\begin{aligned}\frac{L_j}{c} &= T_p + \tau_t - \tau_{i,j} - \tau_s + \tau_r + N_j \frac{\lambda_j}{c} + \tau_{\phi,j} + \varepsilon_{\phi,j},\\ \frac{P_j}{c} &= T_p + \tau_t + \tau_{i,j} - \tau_s + \tau_r + \tau_{C,j} + \varepsilon_{C,j},\end{aligned} \tag{1}$$

where c is the velocity of light, T_p is the coordinate time of propagation of the signal from the satellite to the receiver in empty space (between the instantaneous positions of the antenna phase centers), and τ_t and τ_i are the propagation delays due to the troposphere and the ionosphere, respectively. τ_s is the satellite clock error, τ_r is the receiver clock error, λ_j is the carrier wavelength, N_j is the phase ambiguity, τ_C is the instrumental code delay, τ_ϕ is the instrumental phase shift on the carrier, and ε_ϕ and ε_C represent the phase and code errors, respectively. In the PPP processing, the measurements (1) are processed without differencing and it is necessary to use precise satellite position (from the IGS) and precise satellite clock value with respect to a given time reference (IGS time). In this case, T_p is a function of the receiver's position X_r only, and τ_s disappears from (1), where $\tau_r(t)$ is now referenced to IGS time. Note that errors in the IGS precise orbits and clocks will then contribute to the measurement errors in (2) and (3) below. In addition, the ionosphere-free linear combinations, $L_3 = (f_1^2 L_1 - f_2^2 L_2)/(f_1^2 - f_2^2)$, $P_3 = (f_1^2 P_1 - f_2^2 P_2)/(f_1^2 - f_2^2)$, are used, so that τ_i disappears. Note that ionospheric effects of higher orders, which are not removed by the linear combination, also end up in the measurement errors. The unknown code delay corresponding to the linear combination, $\tau_{C,3}$, is included in the receiver clock term $\tau_r(t)$ if we consider that PPP is used only to provide a stable link. However, calibration can provide an estimate of τ_C (see some discussion on the achievable accuracy of PPP in Section 4). The tropospheric delay τ_t (t, direction) is expressed as $\tau_z(t)M_f$, where τ_z is the delay at zenith and M_f is a given mapping function. Note that the actual tropospheric model distinguishes a hydrostatic and a wet component, but this distinction is not necessary in this short presentation. After the ionosphere-free linear combination, the phase ambiguities together with the unknown carrier phase shift are considered as a real-valued phase ambiguity for each satellite pass, here noted X_3. Equation (1) is then rewritten as

$$\frac{L_3}{c} = T_p(X_r) + \tau_z(t)M_f + \tau_r(t) + X_3 + \varepsilon_{\phi,3}, \tag{2}$$

$$\frac{P_3}{c} = T_p(X_r) + \tau_z(t)M_f + \tau_r(t) + \varepsilon_{C,3}, \tag{3}$$

which show explicitly the parameters which have to be determined by PPP, that is, the receiver position X_r, the receiver clock $\tau_r(t)$, the zenith tropospheric delay $\tau_z(t)$, and the real-valued ambiguities. These parameters are obtained in a global adjustment, where a priori uncertainties are assigned to the observations, of order, a few nanoseconds for the codes (3) and, of order, tens of picoseconds for the phase observations (2). For a more complete presentation of PPP (see the geodetic literature, e.g., [8, 9]).

3. OPERATION OF PPP FOR TAI LINK COMPUTATION

The software presently in operation at the BIPM is the GPSPPP software developed by Natural Resources Canada [8]. Until early 2007 data processing (such as those presented in Section 5) were performed with the version 1365, released in June 2005, while more recent treatments use version 1087, and released in May 2007. GPSPPP follows the lines presented in Section 2, and also includes some specific features adapted to the time transfer such as the possibility to allow for a clock process noise in solving $\tau_r(t)$ and the continuous processing of an "unlimited" (in principle) number of days in a single run. In addition, the recent (1087) release adopts the new IGS paradigm of absolute antenna phase center offsets [10, 11], in usage since November 2006, and uses updated models for station displacements (e.g., ocean tidal loading) and troposphere mapping function.

The feature which allows long continuous runs is particularly interesting for TAI, where computations are done at the beginning of each month for the whole preceding month, so that one month is the natural processing interval. In this case, it is not necessary to go to smaller computation intervals, like in the quasi-real-time IGS processing, which necessitates short (daily) batches. A well-known feature of GPS phase and code solutions based on successive (e.g., daily) batches is the presence of the so-called "boundary discontinuities" [12]. 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 them if they are due to pure white noise processes. However, it has been shown that other noise processes are present and sometimes dominant [13], 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 (of order 100 picoseconds or more) greatly affect the stability estimates at averaging times of interest to clock analysis (hours to days). As long-term systematic effects in code measurements may still affect results of our monthly batches, we expect to eventually see them by comparison to other independent time transfer techniques.

The main operational parameters of the GPSPPP software for the computation of 1-month batches for TAI links are the following: we use IGS final SP3 orbits and 5-minute SV clocks (note that, for a real TAI computation carried out at the beginning of each month, the latency of the final IGS products (14 days) is too long so that the IGS rapid products must be used); a priori data weights are taken as 1 m for pseudorange, and 1 cm for phase; the elevation cutoff is set to 10°; the observation sampling and clock solution interval are both 5 minutes; the tropospheric zenith delay is modeled as $3\,\mathrm{mm}/\sqrt{\mathrm{hr}}$ random walk, with the Niell mapping function [14] used; ocean loading coefficients are from the Chalmers Centre for Astrophysics and Space Science (http://www.oso.chalmers.se/~loading); station coordinates are estimated on each 1-month batch.

With the recent 1087 release, additional operational parameters include the use of the IGS file igs05.atx for satellite antenna offset values and station antenna phase center variations [10, 11], and the use of the VMF1 mapping function [15], without horizontal gradient estimated and updated models for ocean loading coefficients.

4. COMBINATION OF PPP WITH TWO-WAY TIME TRANSFER

PPP or any technique including code and carrier phase (CP) provides time transfer results with high sampling rates due to the automatic acquisition and analysis procedures, and very good short-term stability, due to the low noise of the CP measurements. However, the long-term stability and accuracy depend on the code measurements which are subject to variations in the multipath environment, in the hardware of the receiving equipment, or to residual propagation effects (although these should be at a much lower level). It is estimated that the accuracy of a GPS dual-frequency link is limited to a few nanoseconds by the calibration techniques used [16], but the long-term stability may be at a lower level. On the other hand, TW techniques generally have relatively low sampling rates due to the cost and complexity of the observation procedures. It may have a better long-term stability than GPS because of the low level of multipaths and of the cancellation of several effects in the two-way operation but no clear evidence is yet available. However, it seems that the calibration of TW links can be performed with higher accuracy than for GPS links; for TW calibration, the uncertainty is at or below 1 nanosecond [17], although the calibration exercise is difficult and expensive. Considering that TW presently provides the most accurate link, we expect to develop a combination technique that would allow obtaining the short-term stability of PPP or any CP-based link with the accuracy of the TW link.

The combination of TW and a CP-based technique can be considered as a typical estimation problem, where a function $y(\mathrm{t})$ must be determined from two estimates Y and Y': Y is an estimate of y, provided by TW; and Y' is an estimate of the time derivative y', provided by the CP-based technique. Note that PPP also provides an estimate of y due to the use of the codes, but we will not make use of this fact in the following.

There are several existing methods to estimate a function using an estimate of its derivative. One of the successful methods is that of Vondrak-Cepek [18], which is based on the Whittaker-Robinson smoothing that removes the high-frequency noise present in a series of unequally spaced observations. The goal is to find a compromise between the smoothness of the searched function, on the one hand, and the fidelity of this function to the observed values, on the other hand. The original Vondrak smoothing [19, 20] considered only the fidelity to an estimate of the function itself. It has largely been used in astrometry and in TAI production. The Vondrak-Cepek smoothing also takes into account the fidelity to an estimate of the function's derivative by minimizing the quantity $Q = S + \varepsilon F + \varepsilon^0 F^0$, where S measures the smoothness of the searched function y, F its fidelity to the observed function Y, and F^0 the fidelity of y' to the observed function Y'. The coefficient $\varepsilon \geq 0$ quantifies the fidelity F, and $\varepsilon^0 \geq 0$ quantifies the fidelity F^0. The coefficients can be considered as defining the response of a filter with transfer functions $T(f)$ and $T^0(f)$, respectively, where $T(f) = 1/(1 + (1/\varepsilon)(2\pi f)^6)$ and $T^0(f) = 1/(1 + (1/\varepsilon^0)(2\pi f)^4)$. The dimensions of ε and ε^0 are time^{-6} and time^{-4}, respectively. The transfer functions $T(f)$ and $T^0(f)$ represent the ratio between the amplitude after smoothing to the amplitude before smoothing for a periodic function of frequency f.

5. TESTS ON TAI TIME LINKS

We present time transfer results obtained on the link between the USNO (Washington DC, USA) and the PTB (Braunschweig, Germany). This link is particularly suited for comparisons because three independent techniques are operated on a regular basis in these two laboratories. One (TW-Ku) is the typical Intelsat-based two-way link regularly used for TAI, one (TW-X) is a special link operated by the USNO in the X-band, and one (PPP) is from the PPP analysis of the data from geodetic GPS receivers. In addition, time transfer based on single-frequency GPS receivers is also available, but is not considered here because of the higher noise level due to the single-frequency operation.

Results of several technique comparisons are presented below for this particular link. In such a case (several independent techniques available), it is possible to determine which of the techniques is more advantageous; however, our main goal here is to test analysis strategies that may be applied to a number of TAI links, particularly those where two techniques (TW-Ku and geodetic GPS) are available. Indeed, considering that some 10 laboratories accounting for some 60% of the total clock weight in TAI are already in this case, it is of utmost importance to devise a technique that provides the best stability and robustness to TAI computation.

It is the analyst's choice to determine the transfer function coefficients best adapted to the problem at hand. In our case, the goal is to give predominance to the CP-based technique for short-term and to remove most of the possible diurnal disturbances in TW signals (see Section 5). This leads to choosing $\varepsilon = 26400\,\mathrm{d}^{-6}$ and $\varepsilon^0 = 154000\,\mathrm{d}^{-4}$ (see [21] for details).

5.1. *Estimation of the stability of PPP and of two independent TW techniques by three-corner hat analysis*

Four consecutive months from the link USNO-PTB for the three independent techniques (PPP, TW-Ku, and TW-X) have been analyzed and compared. The data cover October

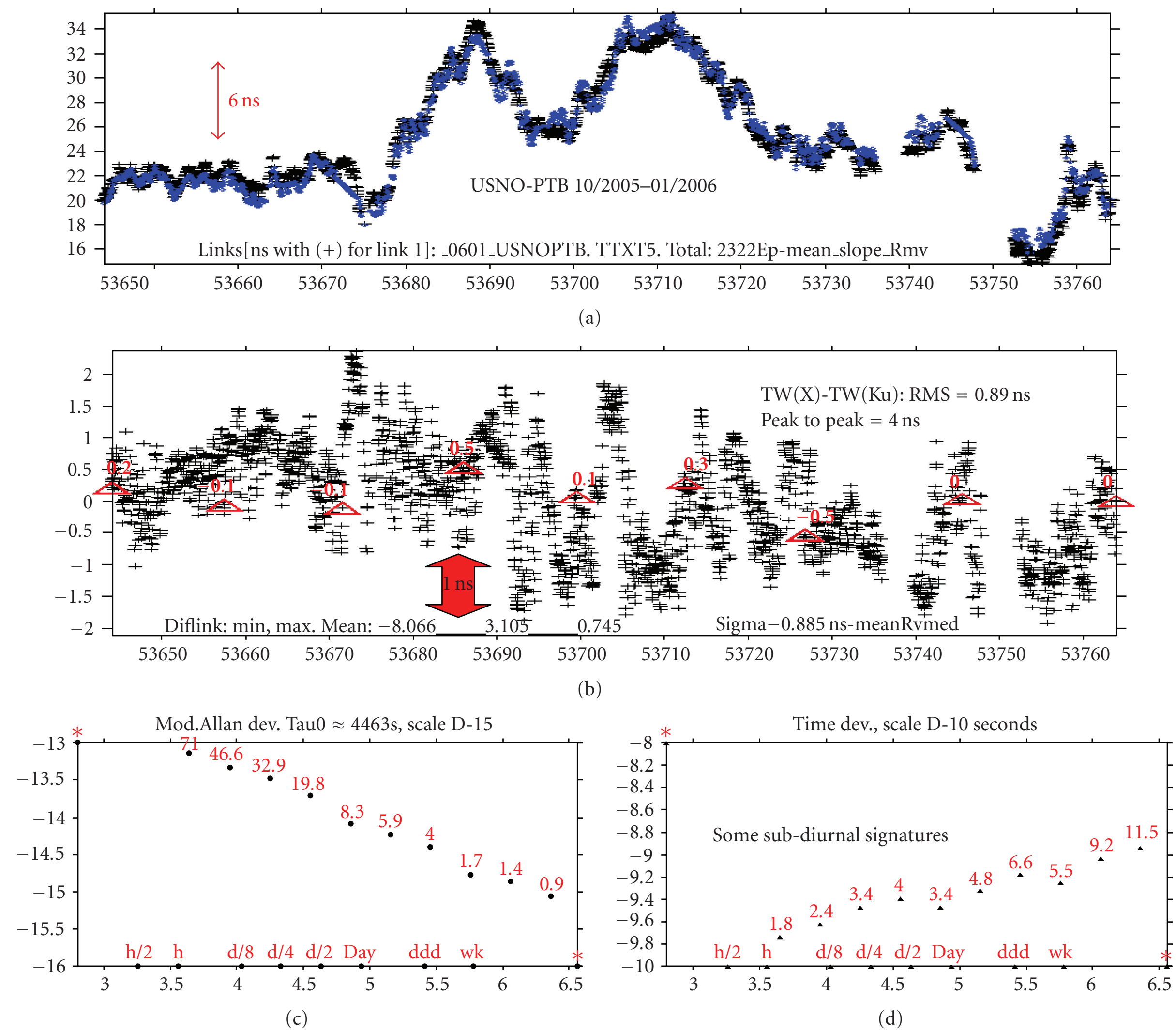

Figure 1: Comparison of TW-X and TW-Ku for the link USNO-PTB over 4 months. Top plot shows the two results, middle plot shows the difference, and bottom plots show the modified Allan deviation (left) and the time deviation (right) of the difference.

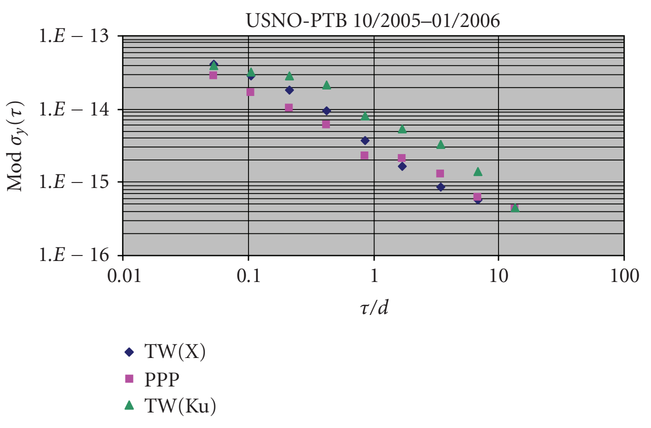

Figure 2: Modified Allan deviation for the link USNO-PTB estimated by three-corner hat analysis for TW-X (diamonds), PPP (squares), and TW-Ku (triangles).

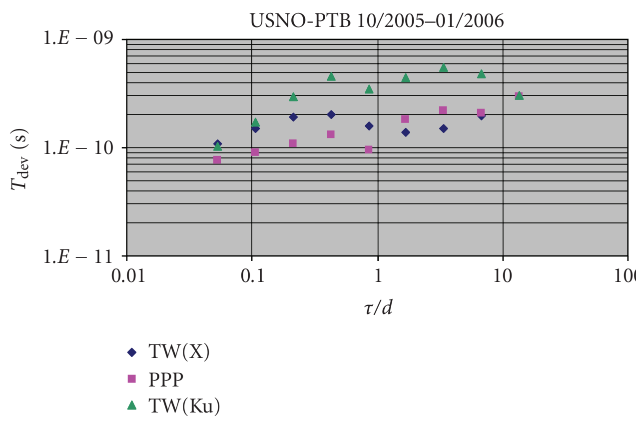

Figure 3: Time deviation for the link USNO-PTB estimated by three-corner hat analysis for TW-X (diamonds), PPP (squares), and TW-Ku (triangles).

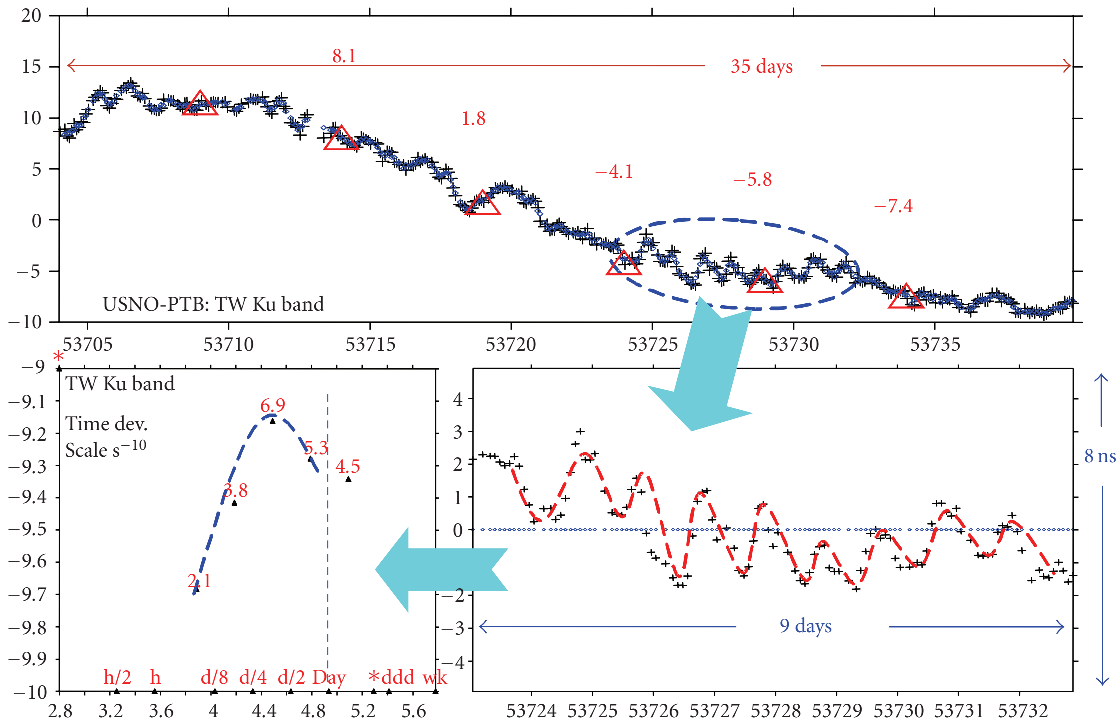

Figure 4: Link USNO-PTB computed with TW-Ku over December 2005. Top and bottom right plots: link values in ns. Bottom left: time deviation (unit is 0.1 ns).

2005 to January 2006 and are nearly complete except for three gaps, each a few days long, one in TW-Ku end October 2005, and two in TW-X in January 2006. The TW-Ku data are generally available every 2 hours and the total number of data points is 1230 (average interval 2.4 hours), while the TW-X are generally available every hour with a total number of points of 2360 (average interval 1.2 hours). The PPP results are computed every 5 minutes and are interpolated at the exact dates of the TW observations for comparisons. Direct comparisons of the three pairs of techniques yield the root-mean square (RMS) of the results over the whole period, as follows:

$$\begin{aligned}
&\mathrm{RMS}\left[(\text{USNO-PTB})_{\text{TW-Ku}} - (\text{USNO-PTB})_{\text{PPP}}\right] = 1.2\ \text{ns},\\
&\mathrm{RMS}\left[(\text{USNO-PTB})_{\text{TW-X}} - (\text{USNO-PTB})_{\text{PPP}}\right] = 0.7\ \text{ns},\\
&\mathrm{RMS}\left[(\text{USNO-PTB})_{\text{TW-Ku}} - (\text{USNO-PTB})_{\text{TW-X}}\right] = 0.9\ \text{ns}.
\end{aligned} \tag{4}$$

As the comparison covers four months, the RMS values are probably mostly driven by the long-term stability of the techniques compared. It seems therefore that, over this period, TW-Ku would be the less stable over the long term. As an example, the TW-X to TW-Ku comparison is shown in Figure 1. In order to obtain more rigorous estimates of the stability of each of the techniques, we apply the three-corner hat analysis [22] to the three pairs of comparisons. The results are shown in Figure 2 for the modified Allan deviation and in Figure 3 for the time deviation. We see that PPP appears as the most stable technique at all averaging times until 3-4 days, with TW-X a close second and TW-Ku a bit more unstable (note that the data points for this comparison have been chosen to be those of TW-X, so that the TW-Ku data had to be interpolated from a larger data interval; this must explain the bending of the TW-Ku curve for the left-most point). Above 10-day averaging time, no valid result can be obtained from this study, as the three-corner hat analysis provides negative variances for most of the techniques and averaging times.

From the modified Allan deviation results, we estimate that PPP and TW-X provide 1×10^{-15} uncertainty in frequency comparison for averaging time at 3-4 days, while TW-Ku reaches this performance for averaging time close to 10 days. The time deviation results are directly derived from those in Figure 2, but reveal more clearly the level of diurnal signatures (of order 100 picoseconds for PPP, 200 picoseconds for TW-X, and more than 400 picoseconds for TW-Ku). They also show that PPP and TW-X provide time stability below 200 picoseconds at all averaging times.

We conclude that PPP has very good short-term stability and is, at least, as stable as TW-X (with 1 point every hour) for averaging time up to a few days. PPP is typically more stable than TW-Ku (with 1 point every two hours) for averaging time up to 10 days. The long-term stability (averaging time > 10 days) is more difficult to estimate, but the results presented here indicate long-term instability typically similar to those of the TW techniques. Nevertheless, systematic variations at a level of 1-2 nanoseconds over durations of months are visible in PPP-TW comparisons, although their origin cannot be readily determined.

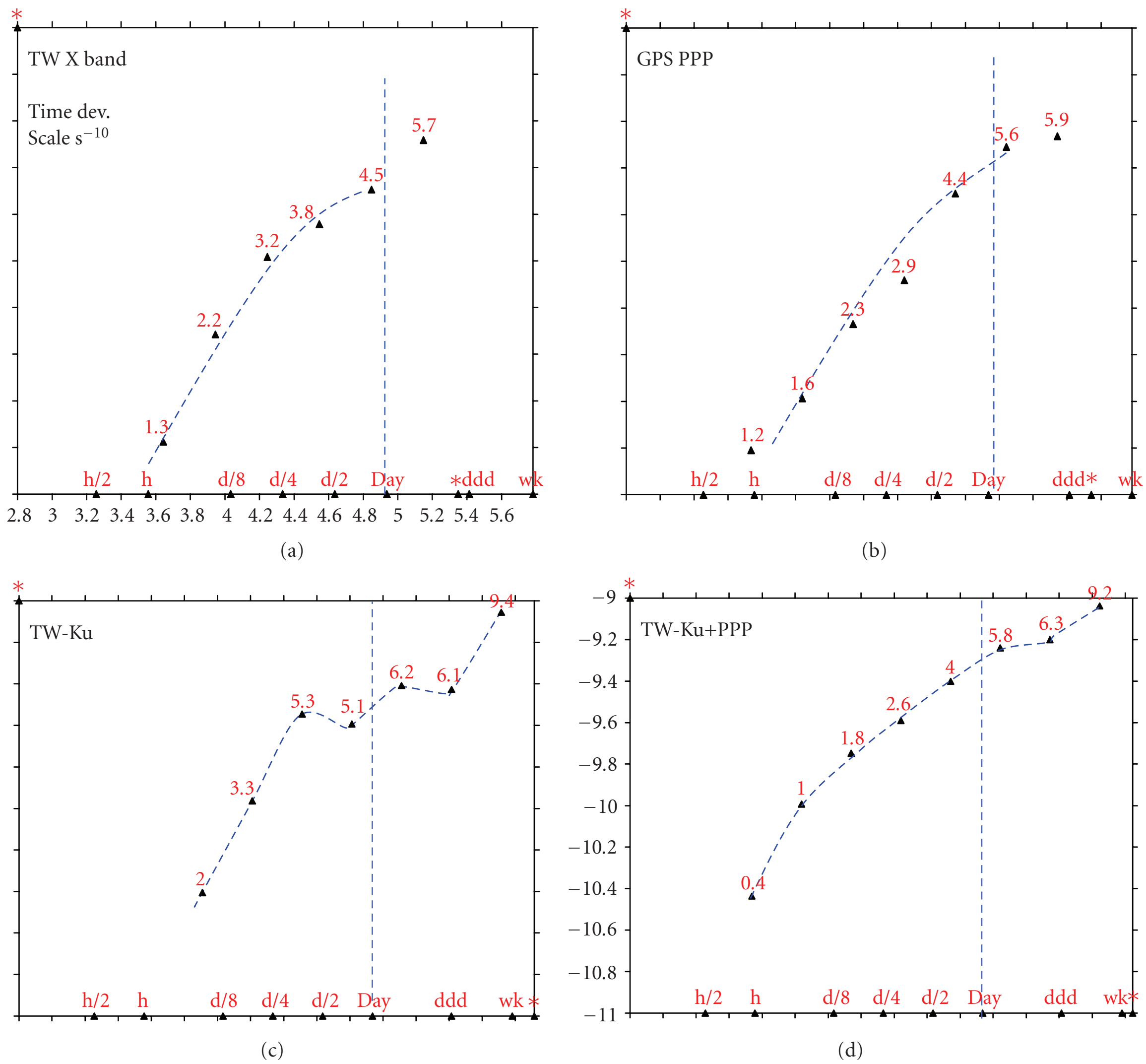

FIGURE 5: Time deviation versus averaging time for the link USNO-PTB for various techniques: TW-X (a); PPP (b); TW-Ku (c); combination PPP+TW-Ku (d). Unit is 0.1 nanosecond. Note that TW-Ku has a time interval of 2 hours hence the first point is for that averaging time.

5.2. *Comparisons of PPP, TW, and PPP-TW combination*

Recent studies have already considered such combinations of TW with a GPS CP-based technique [21, 23]. It has been shown that it may alleviate problems due to diurnal disturbances in the TW-Ku band links (which is the major TW observation in TAI). Figure 4 is a typical example where such diurnal signals, of 1–2.5 nanoseconds peak to peak, are visible in the TW-Ku link. The time deviation (Figure 5(c)) obviously confirms the 1-day periodic term. Comparisons with PPP and TW-X (Figures 5(a) and 5(b)) indicate that the diurnal signal originates indeed in the TW-Ku technique. By combining the TW-Ku link with the PPP result, which is not subject to such disturbance, we expect that the combined result will benefit both from the short-term stability of the second technique and the accuracy of the first technique. It can be shown (Figure 5(d)) that the combination indeed provides the expected short-term stability. Comparing Figure 6 with Figure 4, one can see that the combination has removed some fluctuations and one gap associated with TW-Ku while preserving the link accuracy from TW-Ku.

Comparisons between TW-X, on one hand, TW-Ku, PPP, and the combination PPP+TW-Ku, on the other hand, have been carried out for several months starting October 2005. In all cases, it can be shown that the combination provides performances which are equivalent or better than each of the techniques. As an example, Table 1 summarizes 4 months of comparisons by showing the RMS of the results of each comparison over each month, and over the whole period. It can be seen that if we consider TW-X to be the reference, the combination PPP+TW-Ku has equivalent or slightly better performance than PPP only, and provides about 30% improvement with respect to TW-Ku only. As already mentioned, it is worth performing the combination in order to obtain the accuracy of the TW link and the robustness, for example, with respect to gaps in either of the two techniques.

Table 1: Comparison of several time transfer techniques for the link USNO-PTB over 4 months. Values of the RMS of the comparison results in nanoseconds.

YYMM/points	TW-X−TW-Ku	TW-X−PPP	TW-X−PPP+TW-Ku
0510/661	0.598	0.422	0.439
0511/678	0.872	0.503	0.449
0512/666	0.704	0.343	0.306
0601/478	0.834	0.812	0.791
4 months/2369	0.902	0.693	0.688

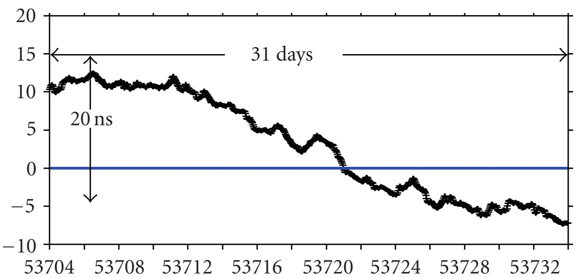

Figure 6: Link USNO-PTB computed with the combination PPP+TW-Ku over December 2005. Unit is 1 nanosecond.

6. CONCLUSIONS

The computation of PPP links for TAI is under implementation at the BIPM. In this paper, we have described the procedures for computation and the validation of the results in comparison to the TW technique. As we have shown, 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). The comparison with TW-Ku 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 and the calibration uncertainty should be lower for TW links. We have shown that one solution is to combine PPP with TW-Ku in order to obtain the short- and medium-term stability of PPP and the accuracy of TW, and we have described such a combination method that is readily usable. This would make better usage of the high redundancy of the TAI worldwide network without significantly complicating the computation procedures.

ACKNOWLEDGMENTS

The authors would like to thank the Natural Resources Canada for providing the GPSPPP software, particularly F. Lahaye for continuous support and maintenance of the software. The authors acknowledge the data contributed by time laboratories participating in TAI. This work is based partly on two papers presented by the authors at the joint IEEE-FCS'07/EFTF'07 conference.

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, and G. Gendt, "The international GPS Service: celebrating the 10th anniversary and looking to the next decade," *Advances in Space Research*, vol. 36, no. 3, pp. 320–326, 2005.

[3] K. Senior, P. Koppang, and J. Ray, "Developing an IGS time scale," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 50, no. 6, pp. 585–593, 2003.

[4] D. Orgiazzi, P. Tavella, and F. Lahaye, "Experimental assessment of the time transfer capability of precise point positioning (PPP)," in *Proceedings of the IEEE International Frequency Control Symposium and Exposition (FCS '05)*, vol. 2005, pp. 337–345, Vancouver, BC, Canada, August 2005.

[5] P. Defraigne, C. Bruyninx, and N. Guyennon, "PPP and phase only GPS frequency transfer," in *Proceedings of the IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum (EFTF '07)*, pp. 904–908, Geneva, Switzerland, May-June 2007.

[6] P. Defraigne, Q. Baire, and N. Guyennon, "GLONASS and GPS PPP for time and frequency transfer," in *Proceedings of the IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum (EFTF '07)*, pp. 909–913, Geneva, Switzerland, May-June 2007.

[7] G. Petit and Z. Jiang, "GPS all-in-view time transfer for TAI computation," *Metrologia*, vol. 45, no. 1, pp. 35–45.

[8] J. Kouba and P. Héroux, "Precise point positioning using IGS orbits and clock products," *GPS Solutions*, vol. 5, no. 2, pp. 12–28, 2001.

[9] J. Kouba, "A guide to using International GPS Service (IGS) products," 2003, http://igscb.jpl.nasa.gov/igscb/resource/pubs/.

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

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

[12] J. Ray and K. Senior, "Geodetic techniques for time and frequency comparisons using GPS phase and code measurements," *Metrologia*, vol. 42, no. 4, pp. 215–232, 2005.

[13] P. Defraigne and C. Bruyninx, "On the link between GPS pseudorange noise and day-boundary discontinuities in geodetic time transfer solutions," *GPS Solutions*, vol. 11, no. 4, pp. 239–249, 2007.

[14] A. E. Niell, "Global mapping functions for the atmospheric delay at radio wavelengths," *Journal of Geophysical Research*, vol. 101, no. B2, pp. 3227–3246, 1996.

[15] J. Boehm, B. Werl, and H. Schuh, "Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts

operational analysis data," *Journal of Geophysical Research*, vol. 111, Article ID B02406, 2006.

[16] G. Petit, P. Defraigne, B. Warrington, and P. Uhrich, "Calibration of dual frequency GPS receivers for TAI," in *Proceedings of the 20th European Frequency and Time Forum (EFTF '06)*, pp. 455–459, Braunschweig, Germany, March 2006.

[17] D. Piester, J. Achkar, J. Becker, et al., "Calibration of six european TXSTFT earth stations using a portable station," in *Proceedings of the 20th European Frequency and Time Forum (EFTF '06)*, pp. 460–467, Braunschweig, Germany, March 2006.

[18] J. Vondrak and A. Cepek, "Combined smoothing method and its use in combining earth orientation parameters measured by space techniques," *Astronomy & Astrophysics. Supplement Series*, vol. 147, no. 2, pp. 347–359, 2000.

[19] J. Vondrak, "A contribution to the problem of smoothing observational data," *Bulletin of the Astronomical Institutes of Czechoslovakia*, vol. 20, pp. 349–355, 1969.

[20] J. Vondrak, " Problem of smoothing observational data II," *Bulletin of the Astronomical Institutes of Czechoslovakia*, vol. 28, no. 2, pp. 84–86, 1977.

[21] Z. Jiang, G. Petit, and P. Defraigne, "Combination of GPS carrier phase solution with a calibrated time transfer link," in *Proceedings of the IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum (EFTF '07)*, pp. 1182–1187, Geneva, Switzerland, May-June 2007.

[22] J. E. Gray and D. W. Allan, "A method for estimating the frequency stability of an individual oscillator," in *Proceedings of the 28th Annual Symposium on Frequency Control Symposium (FCS '74)*, pp. 243–246, Atlantic City, NJ, USA, May 1974.

[23] T. Gotoh, M. Fujieda, and J. Amagai, "Comparison study of GPS carrier phase and two-way satellite time and frequency transfer," in *Proceedings of the IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum (EFTF '07)*, pp. 1188–1193, Geneva, Switzerland, May-June 2007.