GPS Time Transfer

Using Precise Point Positioning for Clock Comparisons

François Lahaye, Diego Orgiazzi, Patrizia Tavella, and Giancarlo Cerretto

ONE OF THE GREAT technological accomplishments on the 18th century was the solution of "the longitude problem." Although latitude could be determined to high accuracy using astronomical observations and navigation tables alone, a determination of longitude additionally required knowing the time at Greenwich (Greenwich Mean Time or GMT) at the instant of the observations. Although astronomical techniques for determining GMT or time on some reference meridian had been developed as far back as the 1500s, they didn't provide sufficient accuracy and many marine disasters occurred because of inaccurately determined longitudes.

INNOVATION INSIGHTS
with Richard Langley

The longitude problem was solved by John Harrison and his marine chronometers. He completed H4, his fourth and most portable chronometer (really a large watch) around 1760. Although not as accurate as large observatory clocks of its time, H4 was remarkably accurate for a portable clock. After a sea voyage lasting 147 days—its first real test—H4 had lost only 1 minute and 54.5 seconds, equivalent to less than 30 minutes of longitude!

Ever since the birth of the marine chronometer, improvements in positioning accuracy have been tied to improvements in clock accuracy. Today we have clocks based on atomic phenomena with extraordinary accuracies. And GPS couldn't exist without its atomic clocks — both those carried by the satellites and those used at the system's monitoring stations.

> The world's time-keeping laboratories rely on GPS for intercomparing their clocks.

While GPS relies on atomic clocks for its operation, researchers at the world's time-keeping laboratories rely on GPS for intercomparing the behavior of *their* clocks and for maintaining global time scales. Over the past 20 years or so, researchers have developed a series of GPS-based techniques for clock measurements and comparisons. The latest technique to join the arsenal is precise point positioning (PPP), a technique initially developed for determining positions with sub-decimeter accuracy from single-receiver measurements. In this month's column, we take a look at how PPP has been used to monitor the behavior of clocks and what accuracies were obtained.

"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Columnists" section on page 10.

Time and frequency transfer using GPS code and carrier phase is an important research activity for many institutions involved in time applications. This was recognized when the International GNSS Service (IGS) and the Bureau International des Poids et Mesures (BIPM) formed a joint pilot study to analyze the IGS analysis centers' clock solutions and recommend new means of combining them.

Many receivers in the IGS network use atomic frequency standards (rubidium and cesium standards and hydrogen masers) as an external frequency reference.

The IGS/BIPM study resulted in the formation of the final and rapid IGS time scales as respective time references for the final and rapid IGS combined clock products (for both stations and satellites), which have been produced since fall 2000. Whereas all IGS analysis centers' clock solutions are network-based, procedures and software are now available to process single-station receiver data. This new approach is a cost-effective way to integrate single-station solutions, be it for positions, clocks or local tropospheric parameters, into global scale solutions. Recently, the Convention of the Meter's Consultative Committee for Time and Frequency (CCTF) has recommended the operation of timing-oriented geodetic-quality GPS receivers at the national metrology laboratories for inclusion in the realization of International Atomic Time (Temps Atomique International or TAI).

Single-station techniques are quite attractive both in terms of performance and ease of use as they allow us to process data from stations that are not part of global networks while nevertheless integrating results within global solutions. This article reports on collaborative work performed at the Istituto Nazionale di Ricerca Metrologica (INRiM) in Turin, Italy, and at Natural Resources Canada (NRCan) in Ottawa to assess the time transfer potential of precise point positioning (PPP).

PPP is a single station post-processing method for recovering coordinates of GPS reception antennas, GPS receiver clock offsets and local tropospheric parameters. We show that PPP clock solutions are consistent with IGS final clock products at the subnanosecond level. PPP solutions are also consistent at the 2 nanosecond level with two-way satellite time and frequency transfer (TWSTFT) measurements, an independent relative time-transfer technique.

Finally, PPP results show a two-times improvement in stability over two traditional GPS time synchronization methods (single and dual-frequency common view GPS), providing a frequency stability (in terms of Allan deviation) of $1 \cdot 10^{-14}$ over an averaging period of one day. In this article, we also address the issue of the clock series discontinuities caused either artificially by the batch nature of PPP processing or by actual receiver loss-of-lock on satellite signals.

Precise Point Positioning

NRCan's implementation of the PPP method (NRCan-PPP) was originally developed as a geodetic tool to provide station-positioning capability within geodetic reference frames. The PPP method is a post-processing approach using un-differenced observations from a single geodetic GPS receiver along with IGS precise satellite orbits and clocks, and modeled ionospheric delays for single frequency receivers.

The parameters estimated in NRCan-PPP are station positions (in static or kinematic mode), station-clock states, local troposphere zenith delays, and carrier-phase ambiguities. The best root-mean-square (rms) position solution accuracies — reaching a few centimeters in horizontal coordinates and less than 10 centimeters in vertical coordinates — are obtained by processing dual-frequency pseudorange and carrier-phase observations together with high-quality GPS orbit and clock products, such as those provided by the IGS. NRCan-PPP can achieve this using accurate models for all the physical phenomena involved.

For our experiment, the NRCan-PPP software was updated to address station-clock solution discontinuities either arising from receiver loss-of-lock (the intra-solution discontinuities) or at solution boundaries, arising from the limited time span of the observation period processed with NRCan-PPP or used in the computation of the external IGS products. With respect to the artificial solution-boundary discontinuities, we changed the software to allow processing of RINEX-format observation files that span multiple-days (currently up to a maximum of 14). For intra-solution discontinuities, we attempted to use *a priori* knowledge of the clock state and to propagate its value, taking into account the noise characteristics of the reference frequency standards (cesium or hydrogen maser) to help in the estimation process of newly introduced ambiguities.

Specifically, the user can set a station-clock process-noise value that will be used as *a priori* weight to constrain the *a priori* epoch clock value, computed from an internal station-clock model. Currently, this internal model is a one-state model — essentially the estimate of the station clock for the previous epoch — suitable only for steered frequency standards affected by white frequency noise. Also, the clock model does not relax the station-clock offset process noise to accommodate real receiver clock resets, when the station-clock offset process noise should be relaxed. These two timing-specific improvements were implemented in release 1365 of NRCan-PPP version 1.04, which we used for the analysis discussed here. In addition, the most recent release (0246) allows one to append daily files to process an observation period of indefinite length — at least theoretically.

Experiment Set-up

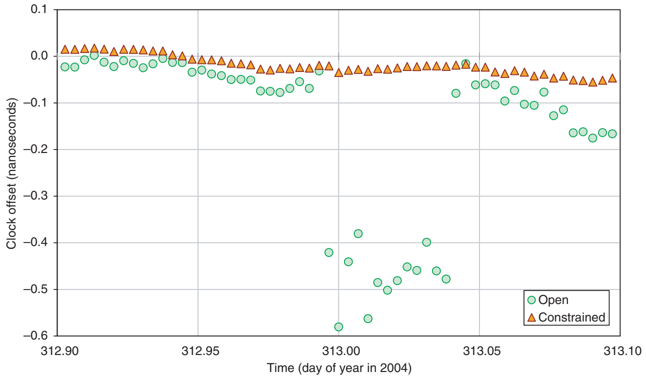
We selected nine national timing laboratories from around the globe to participate in the experiment (see **TABLE 1**). These laboratories regularly contribute to the BIPM realization of TAI; operate at least one TWSTFT station, regularly performing measurement sessions with other laboratories; and operate a dual-frequency geodetic GPS receiver, which is preferably part of the IGS network, allowing for a direct comparison with IGS clock products.

A dataset of dual-frequency GPS pseudorange and carrier-phase observations, collected from October 3, 2004 (modified Julian date (MJD) 53281), to January 1, 2005 (MJD 53371), was assembled from the daily RINEX files with 30-second data sampling, available from the IGS data centers. The period covered by the GPS dataset fully overlaps a 20-day comparison campaign of cesium (Cs) fountain primary frequency

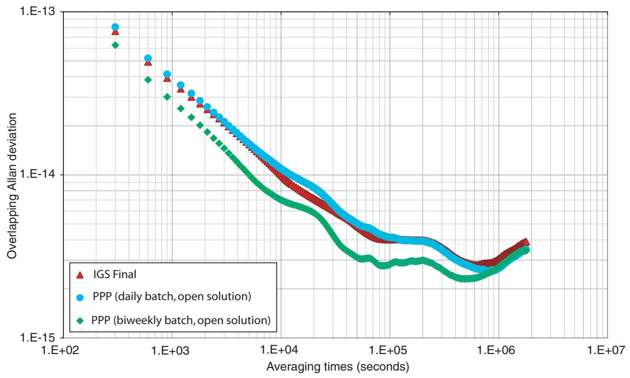
TABLE 1 Geodetic Stations and Associated Equipment for Selected Timing Laboratories

Laboratory (TAI acronym)	Country	IGS Station	Receiver	External Frequency	Time Links	Allan Deviation @ 300s (units of 10^{-14})	Resulting Process Noise Variance (10^{-3} ns^2)
USNO	USA	USN3	Ashtech Z-12T	H-maser	TWSTFT, GPS P3	-	-
NIST	USA	NISU	NovAtel	H-maser	TWSTFT	-	-
PTB	Germany	PTBB	Ashtech Z-12T	Laboratory Cesium	TWSTFT, GPS P3	34.2	10.50
NPL	UK	NPLD	Ashtech Z-12T	H-maser	TWSTFT, GPS P3	4.4	0.17
OP	France	OPMT	Ashtech Z-12T	H-maser	TWSTFT, GPS P3	-	-
IEN	Italy	IENG	Ashtech Z-12T	Industrial Cesium	TWSTFT, GPS P3	53.8	26.00
NICT	Japan	KGN0	Ashtech Z-12T	Industrial Cesium	TWSTFT, GPS P3	37.2	12.40
NRC	Canada	NRC3 [a]	Ashtech Z-12T	H-maser	GPS P3	4.1	0.15
ORB	Belgium	BRUS	Ashtech Z-12T	H-maser	GPS P3	4.4	0.17

[a] "NRC3" is actually collocated at the National Research Council of Canada (NRC) facilities with the "NRC1" IGS station.



▲ **FIGURE 1** PPP estimate of NRC3 station-clock offset (1-week PPP solution), with two ambiguity resets affecting "open" solution



▲ **FIGURE 2** Frequency stability comparison (in terms of Allan deviation) between PPP 1-day solution, PPP 2-week solution, and IGS final clock products for the BRUS-NPLD link between ORB and NPL timing laboratories

standards (PFS). Five of the nine selected timing laboratories (NIST, PTB, NPL, OP, and IEN) participated in the PFS campaign that analyzed multiple synchronization techniques in detail. After our initial processing of the data, some station-days were rejected due to tracking problems causing code-phase inconsistencies.

Seven of the nine timing laboratories (USNO, NIST, PTB, NPL, OP, IEN, and NICT) use the TWSTFT technique. These laboratories perform TWSTFT measurements following the standard procedures issued by the CCTF working group on TWSTFT. Specifically, a nominal schedule with four measurement sessions per day (at 0h, 8h, 14h and 16h UTC) has been regularly followed since January 2004. Each two-minute session at each pair of stations consists of 120 measurements (one per second), which are then processed following recommendations provided by the International Telecommunication Union radiocommunication sector. For our experiment, the laboratories involved in the Cs PFS comparison used an intensified schedule with up to 12 sessions per day (nominally one every two hours).

The GPS datasets from all stations were processed as one-day, one-week, and two-week continuous solutions, without applying constraints to the station-clock process noise (hereafter called "open" solutions). Also, the one-week and two-week continuous solutions were also produced with constraints on the station-clock process noise (hereafter called "constrained" solutions), which considered the previous clock-state estimate as an initial value for the next epoch and applied a specified level of white frequency noise.

The process noise values were derived from a stability assessment of the one-day "open" clock time series (Table 1). Station OPMT was excluded from these constrained solutions, because the PPP internal one-state clock model could not handle its free-running hydrogen (H) maser. Also, stations NISU and USN3 were excluded due the number of receiver clock resets, as well as a few days from other stations that also exhibited receiver clock resets.

All PPP processing was performed using IGS final 15-minute satellite orbit and 5-minute satellite clock products referred to the IGS timescale. The station (antenna) position was estimated in static mode (one constant position per continuous processing period) with epoch station-clock and local tropospheric zenith delay estimated at 5-minute intervals, synchronized with the satellite precise clock epochs. The tropospheric zenith delays were estimated with a random walk process noise of 5 millimeter/hour$^{1/2}$. To be consistent with the IGS clock products that are generated based on the ionosphere-free combination of (semi-codeless) P-code pseudoranges on the L1 and L2 frequencies (P1 and P2) — called P3, all stations were processed using P1 and P2 pseudoranges, except for station NISU that observed only the C/A-code on L1 (C1) and P2. In that case, the C/A-code observations were corrected with the C1-P1 satellite biases published by the IGS.

PPP Processing Results

In this section, we will look at the results of the constrained and multi-day solutions including the effect of solution discontinuities and compare the results with IGS products.

Constrained Solutions. Whereas the objective of constraining a station-clock estimate is to reduce the impact of real phase discontinuities on the clock solution, it must not artificially improve its quality by enforcing too tight a constraint. Over-constraining the station-clock parameter would mean that part of the natural clock noise is considered as external noise and filtered out instead of being included in the clock estimate.

Differencing constrained and open one-week clock solutions, it is apparent that for most stations the clock constraint did not significantly affect the solutions, particularly for Cs frequency standard stations (IENG, KGN0, and PTBB), whereas H-maser equipped stations (BRUS, NPLD, and NRC3) seem slightly over-constrained. Over all of the processed station-days, we found only three clear-cut cases of ambiguity resets due to loss of lock. The clock discontinuities introduced by loss of lock were significantly reduced when the constraint was applied, as clearly depicted in **FIGURE 1** for station NRC3. All other ambiguity resets resulted from significant gaps in the tracking data (over which a more suitable constraint on the station-clock parameter should be introduced), or cases of code-phase inconsistencies or receiver clock resets.

These preliminary results of the clock constraint are encouraging. Further work is needed to implement internal clock models that accommodate a larger class of frequency standards as well as real receiver clock resets. Tuning of the input constraint value also needs better defining principles, especially for H-maser stations.

Multi-Day Solutions. In order to evaluate clock discontinuities at solution boundaries (day-boundaries, week-boundaries, etc.), all PPP-derived station-clock series were fitted to a linear model over 15-day intervals, with intervals overlapping each other by one day. The clock series differences with respect to the fitted models and the change in these clock differences between 5-minute epochs over solution boundaries were then computed, yielding estimates of boundary discontinuities.

Day-boundary clock discontinuities, which were effectively solution boundaries in one-day solutions, are considerably reduced in one-week and two-week solutions, more so for H-maser than for the Cs-equipped stations, but significantly for both. However, residual day-boundary discontinuities can still be noticed in both one-week and two-week solutions, at the level of less than 100 picoseconds for H-maser equipped stations.

In contrast, solution-boundary clock discontinuities for the one-week and two-week solutions show a slight increase with increasing length of processing interval. Although not very conclusive due to the small number of one-week (12) and two-week (6) solution boundary data, this phenomenon could be caused by un-modeled signals in the GPS observables. This hypothesis is currently under investigation at NRCan.

Any station-clock datum issue also affects ambiguities and consequently introduces biases in the pseudorange residuals (observed pseudoranges minus modeled ranges). We verified this by analyzing the effect of a reduction in day-boundary clock discontinuities on the PPP pseudorange residuals. The pseudorange residuals were averaged over one-day intervals. These daily averages of pseudorange residuals were then differenced between adjacent days, leading to an estimate of the day-to-day variation of the datum change on the pseudorange.

It follows that such residuals significantly increase in multi-day continuous processing (especially between one-day and one-week solutions), which would be consistent with the hypothesis that solution-boundary discontinuities are a result of averaging properties of the PPP code-observation residuals.

Comparison with IGS Products. All one-day, one-week, and two-week PPP position solutions of IGS stations were compared to the IGS final weekly combination. For the stations NRC3 and NISU — not included in IGS solutions at the time of the experiment — PPP position solutions were compared with an average value over all PPP solutions. The solutions agree with the IGS values (or the mean) at better than 1 centimeter in horizontal components and better than 2 centimeters in vertical, consistent with typical PPP positioning quality. Moreover, as far as the position solution is concerned, the clock-constrained solutions provided the same quality as the open solutions and processing longer datasets slightly reduced the variability of position solutions.

The differences between station-clock estimates from PPP and IGS final products show an rms of less than 130 picoseconds for all stations and even better in some cases (better than 80 picoseconds for NPLD and OPMT, both equipped with H-masers).

In terms of frequency stability, the Allan deviation plotted in **FIGURE 2** for a baseline between BRUS and NPLD shows that the PPP one-day solution performs as well as IGS final clock products for all averaging times. This means that no additional measurement noise is introduced by the single-station estimation method performed by PPP. Moreover, Figure 2 shows a clear improvement with a longer period of continuous processing (two weeks in this case). Nevertheless, it is worth mentioning that both one-day and two-week PPP solution stabilities differ from those of IGS clock products by a significant increase of the Allan deviation for intervals close to $2 \cdot 10^4$ seconds (about 5.6 hours). This matter was later investigated at NRCan and lead to an improvement in the modeled ocean loading effects in the PPP algorithm.

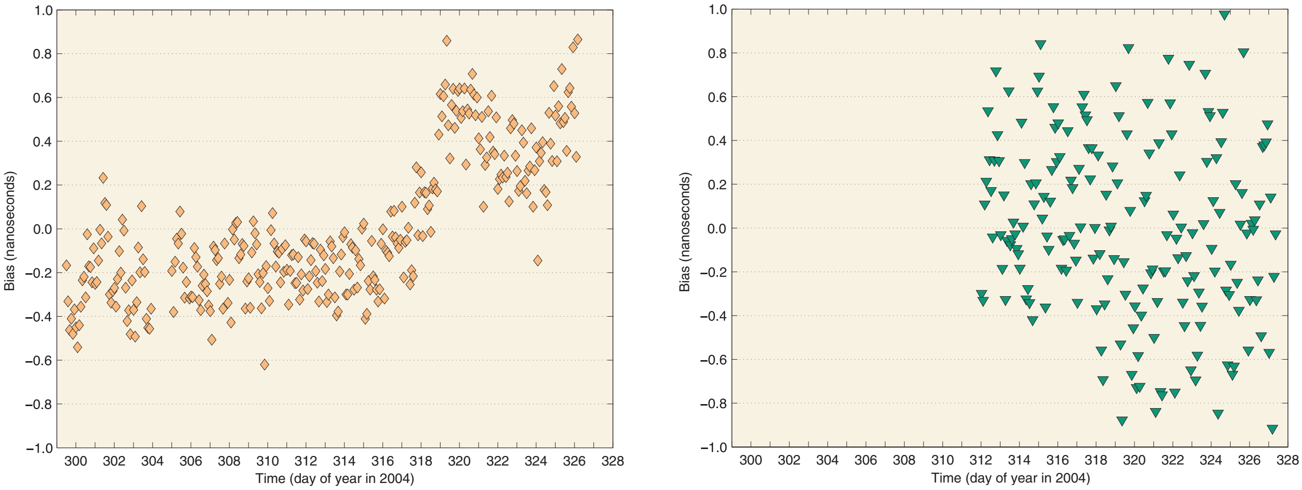
Comparison with TWSTFT

We evaluated the capabilities of the PPP method, in terms of time and frequency transfer, versus TWSTFT data for three baselines NPL-OP, OP-NIST, and NIST-NPL, involving three timing laboratories with receivers connected to H-masers. Of course, a more complete comparison between the two methods involving an extended set of baselines and a longer observation period is an important consideration for future work. To avoid injection of any artificial effects by over-constraining the station-clock estimates, the two-week open PPP solutions have been considered here. Also, only the TWSTFT intensive measurement schedule campaign (12 two-hour sessions per day) was used, in order to get a larger set of comparison data.

Individual station PPP clock solutions were differenced between stations and then differenced with the associated baseline TWSTFT data, yielding double differences free of possible IGS timescale reference effects (see **FIGURE 3** for double differences for NPL-OP and OP-NIST baselines). The discontinuity occurring in the second half of the NPL-OP graph is a reflection of the two-week solution-boundary discontinuity in PPP results. Residual biases in the double differences fall within ±1.0 nanoseconds with smaller than 500 picosecond standard deviation, indicative of the level of agreement between these two completely independent synchronization techniques. It is worth mentioning that in this experiment the comparison between PPP and TWSTFT seems to be highly driven by the short-term noise affecting TWSTFT, especially for transatlantic baselines involving the NIST laboratory, as confirmed by the following frequency stability analysis.

The stability of the comparison data between PPP and TWSTFT for the selected baselines was assessed in terms of overlapping Allan deviation (**FIGURE 4**). The measurement noise introduced by PPP is a factor of 1.5 lower than TWSTFT (at least for the short baseline) for observation periods varying from two hours up to one day and even longer. For intervals beyond one day, the two methods come together approaching the nominal behavior of H-masers of the two stations with a flicker floor of $4 \cdot 10^{-15}$ for an averaging period up to about three days.

Looking at stability results for the double differences between TWSTFT and PPP, it can be noticed that, since measurement noise



▲ **FIGURE 3** Double differences between PPP estimates and TWSTFT data for the NPL to OP European link (27 days, left plot) and for the OP to NIST transatlantic link (16 days, right plot)

is dominant, the noise exhibited represents a contribution of the noisier of the two measurement systems. For longer averaging times (one day and longer), the double differences go down with a τ^{-1} slope (where τ is the averaging time) resulting in decreasing measurement uncertainty when longer observation times are considered. Moreover, a significant improvement using PPP is clearly noticed for the very long OP-NIST baseline, showing that PPP performance seems to be independent of the distance between stations. The results obtained here for the TWSTFT links with NIST may not represent its typical quality, as it could be due to poor performance of the dedicated transponder on the Intelsat geostationary satellite at that time.

Taking a preliminary look at the frequency comparison potential of PPP, the relative frequency difference between pairs of H-masers for the three selected baselines have been computed. The frequency values have been simply calculated as

$$y(t) = [\delta_{ck}(t) - \delta_{ck}(t - T)] / T$$

where $\delta_{ck}(t)$ is the time difference at epoch t between the PPP clock offset estimates of the two stations involved in the baseline, and T is the measurement interval (300 seconds). These values have been then compared with those coming from TWSTFT data, for the period of intensified schedule operated by some timing laboratories during the Cs fountain clock comparison campaign. Results are given in **FIGURE 5**, where a significant reduction of noise achieved by PPP is clearly noticed, especially for transatlantic baselines. Comparing the mean frequencies, the TWSTFT and PPP methods match very well, at the level of $1.2 \cdot 10^{-15}$. Moreover, an expected zero closure is achieved by PPP, because PPP estimates are site-based. In contrast, TWSTFT results show a $-0.6 \cdot 10^{-15}$ departure from zero, mainly due to the fact that TWSTFT measurements are not simultaneously performed and the clock rates have to be considered.

Conclusions

These experimental results show PPP as a promising alternate synchronization technique offering high-level performance comparable with state-of-the-art methods, such as TWSTFT. PPP autonomously allows recovery of the IGS combined clock solution at sub-nanosecond level (130 picoseconds rms for all selected stations), without the requirement to be part of a network solution.

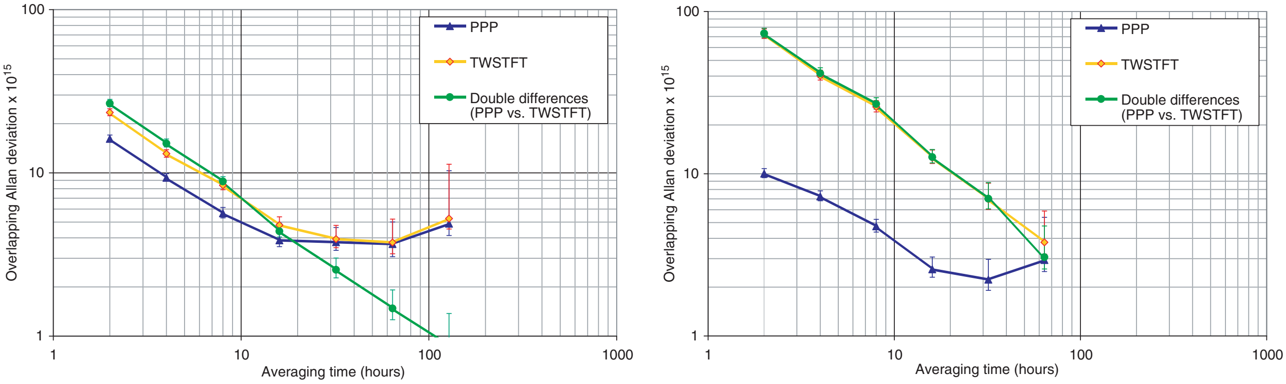
Also, continuous solutions for periods of up to two weeks (and potentially longer) reduce the artificial solution-boundary discontinuities, thus allowing a specific time-limited campaign (such as the PFS comparison). In addition, comparison with TWSTFT, an independent synchronization technique, shows very good agreement with maximum differences of less than 1 nanosecond after removing a mean offset to account for any hardware calibration issues between different pieces of equipment. We observed that the measurement noise introduced by PPP seems to be a factor of 1.5 lower than TWSTFT (for observation times up to one day) over a European baseline and potentially more on transatlantic baselines, PPP performance being independent of the geographical separation of the time link.

In terms of logistics, possible re-use of existing geodetic GPS receivers and the relatively small investment required for the procurement of new GPS equipment, are valuable advantages of PPP for timing laboratories. Additionally, no bureaucratic procedures are required with PPP, unlike TWSTFT where authorization to transmit Ku-band signals is a mandatory requirement of the satellite-transponder provider.

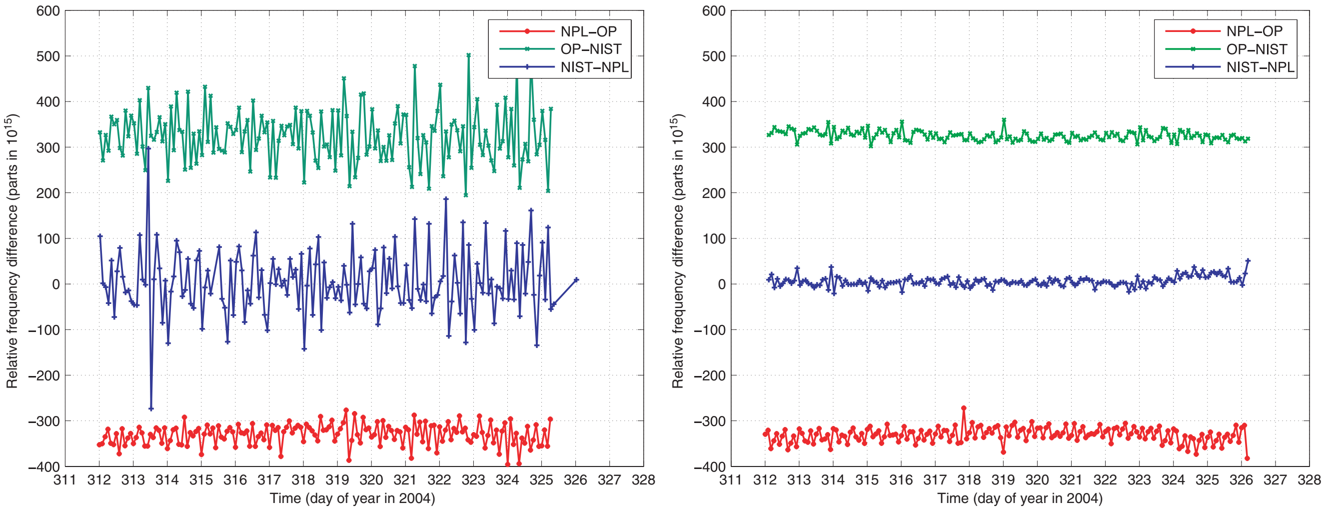
Further assessment of the PPP geodetic time transfer method is planned, as well as improvements to NRCan-PPP software to increase the continuity of the PPP clock-estimate time series. Possible improvements include more robust data editing, discrimination between carrier-phase resets and clock jumps, and generalization of the software's internal clock model.

Acknowledgments

The authors wish to thank all the people in the timing laboratories involved in this experiment for granting the use of their GPS and TWSTFT data and acknowledge the many individuals and institutions forming the IGS for the high quality GNSS prod-



▲ **FIGURE 4** Frequency stability comparison (in terms of Allan deviation) between PPP and TWSTFT for the NPL to OP European link (left plot) and for the OP to NIST transatlantic link (right plot). Residuals between the two techniques are also depicted.



▲ **FIGURE 5** Relative frequency difference between pairs of H-masers located at NIST, OP and NPL laboratories (see legend for details) using TWSTFT (left plot) and PPP (right plot) estimates, for the period from days of year 312 to 326 in 2004 (15 days inclusive).

ucts and data without which the PPP timing application reported herein would not be possible. This article is based on the paper "Experimental Assessment of the Time Transfer Capability of Precise Point Positioning (PPP)" presented at the Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting held in Vancouver, Canada, August 29–31, 2005. ⊕

Manufacturers

The GPS receivers used at the time-keeping laboratories for the results presented in this article are **Ashtech** *Z-12T Metronome* receivers, formerly manufactured by **Magellan Navigation's** Professional Products Division *(professional.magellangps.com)*, and the **NovAtel Inc.** *(www.novatel.ca) Euro 4* receiver. The stations use a variety of atomic frequency standards including products manufactured by **Symmetricom Inc.** *(www.symmetricom.com)*; **Sigma Tau Standards Corp.** (now part of Symmetricom); **IEM Kvarz**; and **Quartzlock (UK) Ltd.** *(www.quartzlock.com)*.

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