

Further Characterization of the Time Transfer Capabilities of Precise Point Positioning (PPP)

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Abstract—In recent years, many national timing laboratories (NMIs) have installed geodetic Global Positioning System (GPS) receivers together with their traditional GPS/GLONASS Common View (CV) receivers and Two Way Satellite Time and Frequency Transfer (TWSTFT) equipment. Many of these geodetic receivers operate continuously within the International GNSS Service (IGS), and their data are regularly processed by IGS Analysis Centers. From its global network of over 350 stations and its Analysis Centers, the IGS generates precise combined GPS precise ephemerides and station and satellite clock time series referred to the IGS Time Scale. A processing method called Precise Point Positioning (PPP) is in use in the geodetic community allowing precise recovery of GPS antenna position, clock phase and tropospheric delays by taking advantage of the IGS precise products. Natural Resources Canada (NRCAN) has developed software implementing the PPP methodology. A previous assessment of PPP, as a promising time transfer method, was carried out at INRiM (formerly IEN) in 2003 [7], showing better stability over short/medium term than GPS CV and GPS P3 methods. Further analysis was carried out in 2005 [12] where, running continuously for period of up of two weeks, the NRCAN PPP software was able to reduce the day-boundary discontinuities, allowing specific time-limited campaigns (PTFs). This paper reports on follow-on work performed at INRiM and NRCAN to further characterize the PPP method for time transfer applications, involving some of the National Metrology Institutes considered in 2005. We take advantage of continuous PPP processing to develop a procedure to improve the continuity of solutions and to reduce the solution boundary discontinuities present in the daily PPP results.

I. INTRODUCTION

Time and frequency transfer using GPS code and carrier-phase is an important research activity for many institutions involved in time applications [1], [2]. This was recognized when the IGS (International GNSS Service) and BIPM (Bureau International des Poids et Mesures) formed a joint pilot study [3] to analyze the IGS Analysis Centers (ACs) clock solutions and recommend new means of combining them. That study resulted in the formation of the Final and

Rapid IGS time scales [4] as respective time references for the Final and Rapid IGS combined clock products (both station and satellites) produced since the autumn of 2000 [5].

Whereas all IGS ACs clock solutions are network-based, software and algorithms are available to use network-based products to process data from single stations. This offers a cost-effective way to integrate further solutions into global solutions, be it earth stations positions, clocks or local tropospheric parameters. This paper reports on follow-on work jointly performed at INRiM and at Natural Resources Canada (NRCAN) to assess the time transfer potential of Precise Point Positioning (PPP) [6]. PPP is a geodetic single station post-processing methodology for recovering coordinates of GPS reception antennas, GPS receiver clock offsets and local tropospheric parameters.

It has been shown that PPP clock solutions are consistent with the IGS Final clock products at the sub-nanosecond level [7], [8]. PPP solutions are also consistent at the 2 ns level with other relative measurement techniques, e.g. Two Way Satellite Time and Frequency Transfer (TWSTFT), GPS Common View (CV) and GPS P3 [9]. Finally, PPP shows a 2-times improvement in stability over GPS CV and GPS P3, providing a frequency stability (in terms of Allan deviation) of $1 \cdot 10^{-14}$ at one day [7].

The main objective of this follow-on work is to take advantage of continuous PPP solutions analyzed in [12] to develop a method to improve the continuity of solutions and attempt to reduce the solution-boundary discontinuities caused by colored-noise in pseudorange, through averaging over multi-day intervals of different duration. This procedure will be hereafter called the Sliding Batch Solution.

The following section provides background information on NRCAN's implementation of the PPP algorithm, the problem of the day boundary discontinuities and the new Sliding Batch Solution procedure.

II. PRECISE POINT POSITIONING

A. NRCan's Algorithm

NRCan's implementation of the PPP method 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 undifferenced observations coming from a single geodetic GPS receiver along with satellite orbits and clocks products, and optionally modeled ionospheric delays for single frequency users.

The parameters estimated in PPP are station positions (in static or kinematic mode), station clock states, local troposphere zenith delays and carrier phase ambiguities. The best position solution accuracies, reaching the few centimeters in horizontal coordinates and less than 10 cm in vertical coordinates (RMS), are obtained by processing GPS dual-frequency pseudorange and carrier phase observations with IGS precise high-quality satellite orbit and clock products. NRCan PPP can achieve this, using accurate models for all the physical phenomena involved. Further details on the PPP algorithms, models and specifications can be found in [6].

B. The problem of the day boundary discontinuities

The accuracy of GPS-based time and frequency transfer using combined analysis of code and carrier phase measurements greatly depends on the noise of the GPS signals. In particular, the pseudorange noise is responsible for day boundary discontinuities which can reach, for some stations, more than 1ns in the time transfer results obtained from geodetic analysis. These discontinuities are caused by the fact that the data are analyzed in daily data batches, during which the absolute datum for station clock offset and carrier-phase ambiguities is determined by the observed pseudoranges. The pseudorange noise is sometimes not white noise, for example due to near field multipath effects or variation of instrumental delays, thus inducing clock datum changes between days at the level of a few 100ps to a few ns [11].

C. Timing Specific Improvements

Prior to the current investigation [12], the NRCan PPP software was updated to address the intra-solution and solution-boundary station clock discontinuities. Concerning the solution-boundary discontinuities, the software was changed to allow processing of RINEX-format [10] observation files that span multiple-days. In this multiple-day processing, precise satellite orbit and satellite clock information from IGS are input as daily files.

However, since concatenating RINEX data files is operationally cumbersome and certainly awkward considering the current *de-facto* IGS daily file standard, this work is aimed at defining and evaluating a procedure, the

Sliding Batch Solution, that would minimize the level of day boundary clock discontinuities through multi-day PPP processing; while minimizing solution latency and ensuing availability, that is the usual consequence of processing multiple days.

III. EXPERIMENT SET-UP

A. Selected Timing laboratories

For the evaluation of the day by day Sliding Batch Solution procedure, some IGS stations operated by national timing laboratories have been selected using the following criteria:

- GPS receivers connected to an external oscillator (H-maser preferred, although not necessary).
- Availability of a large quantity of high-quality data (GPS observations).

The selected stations and related equipment are listed in Table I.

TABLE I. GEODETIC STATIONS AND ASSOCIATED EQUIPMENT FOR SELECTED TIMING LABORATORIES

Country	IGS Station	Receiver	External Frequency
USA	USN3	ASHTech Z-12T	H-maser
Germany	PTBB	ASHTech Z-12T	Laboratory Cesium
Italy	IENG	ASHTech Z-12T	H-Maser
Canada	NRC1	ASHTech Z-12T	H-maser

B. GPS data

For the current work it was not critical to define a common period of analysis for all the stations taken into account. It was more important to find meaningful periods that could effectively be used to evaluate the robustness of the Sliding Batch Solution procedure.

In particular, we want to address the behavior of such a procedure when the GPS data are affected by the intrinsic noise of the timing reference connected to the GPS receiver and by different levels and types of pseudorange noise.

C. PPP Processing Options

All PPP processing was performed using NRCan PPP Release 0246 of version 1.04 with IGS Final and Rapid 15-minute satellite orbit and 5-minute satellite clock products. The station position was estimated in static mode (i.e., one constant position per continuous processing period) with epoch station clock and local tropospheric zenith delay at 5-

minute intervals, synchronized with the satellite precise clock epochs. The tropospheric zenith delays were estimated with a process noise of $5 \text{ cm/hour}^{1/2}$.

D. Day by day Sliding Batch procedure

In order to take advantage of multiday PPP solutions [12], we devised and tested a procedure to reduce the effects of the solution-boundary discontinuities caused by colored-noise in pseudoranges, through averaging over multi-day intervals of different length, thus improving the continuity of clock solutions.

The basic idea of the Sliding Batch Solution procedure is to use multi-day PPP batches and slide them, one day at a time, after selecting a specific day position inside the batch, to obtain a reconstructed sequence of daily PPP solutions, where the clock discontinuities induced by pseudorange noise are reduced. A schematic description of the procedure is given in Figure 1.

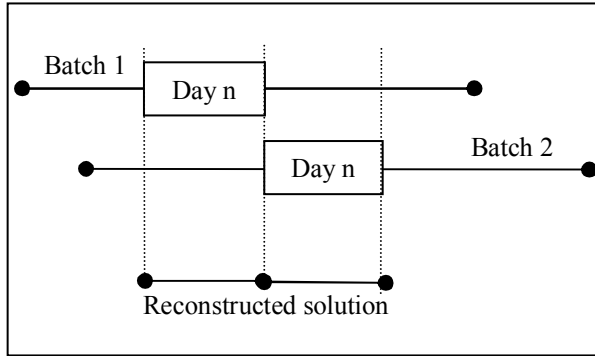


Figure 1 Schematic of the Sliding Batch Solution procedure.

We chose to slide the batches by one day because most of the known effects affecting pseudorange noise are diurnal or semi-diurnal (respectively temperature, multipath and near field effects linked to the GPS constellation repetition) and because IGS products are computed on a daily basis.

Pseudorange residuals for NRC1 during the winter of 2006 are plotted respectively for a 30-day batch (Figure 2) and for the corresponding classical daily batches over the same period (Figure 3). Pseudorange residuals (in meters) are plotted in cyan and in blue, weighted averages of the same residuals computed epoch per epoch, with weights as a function of satellite elevation above horizon. Finally in red, the NRCan clock phase solution versus the IGS time scale in meter is depicted. For sake of visualization, the PPP station clock mean value has been removed for each batch considered in this analysis.

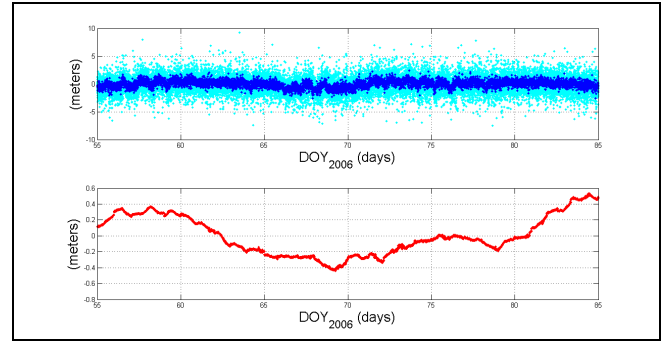


Figure 2 Pseudorange residuals for NRC1 for the 2006 winter period for 30 day batch.

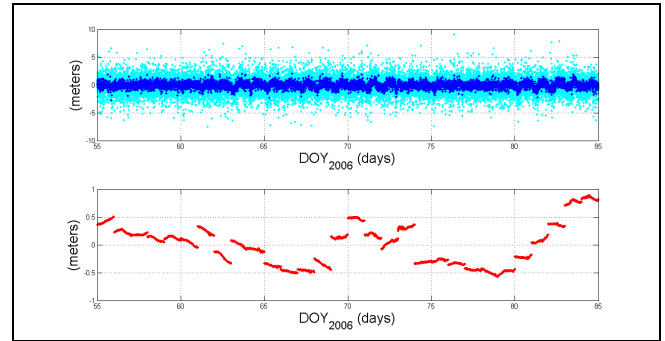


Figure 3 Pseudorange residuals for NRC1 for the 2006 winter period for 1 day batch.

Residuals from the daily batches seem to be almost white noise, because the re-initialization of phase ambiguities at beginning of each day compensates the mean colored noise of pseudoranges during the considered period. This re-initialization causes the day boundary jump in the PPP clock solution. For the 30-day batch, one can clearly see a systematic signal in the pseudorange residuals, because the clock solution keeps the phase continuity until the next batch boundary, thus revealing the colored noise of pseudorange measurements.

In the next section, we report on the results of the Sliding Batch Solution procedure for different batch lengths and day positions within the batch, which form the reconstructed continuous clock solution. Hereafter, these two parameters will be respectively indicated as x and n , and the nomenclature to specify each Sliding Batch procedure will be:

SBxDn

for Sliding Batch of x days and position n . Note that parameter n is counted from the end of the multiday batch, and thus is equivalent to the latency of the results.

IV. PROCESSING RESULTS

In order to evaluate the robustness of the day by day Sliding Batch Solution procedure, data from different stations have been processed in batches of 7, 14 and 30 days. Using the above mentioned nomenclature, we generated SB7Dx, SB14Dx, and SB30Dx day by day sliding batch solutions. The mean absolute value of day-boundary clock discontinuities has been computed for all positions in the batch. Different combinations of batch length were analyzed with respect to computation time and solution latency. Comparisons with IGS Final clock solution, together with the classic daily PPP solution, were also performed.

Figures 4 and 5 show the clock phase respectively for NRC1 and USN3 stations versus the IGS time scale. For both figures, the daily IGS final products is plotted in black, the associated day by day PPP solution in red and the SB7D2 solution in green.

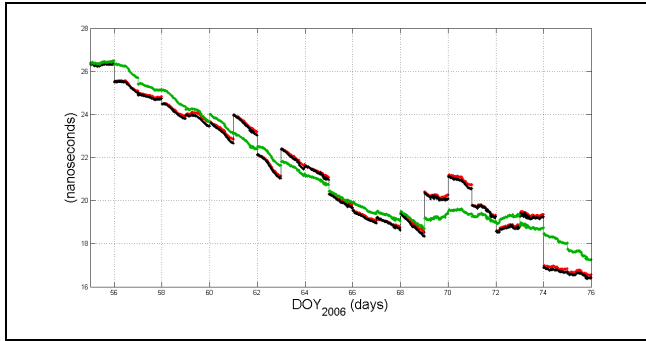


Figure 4 Clock phase solution for NRC1 station.

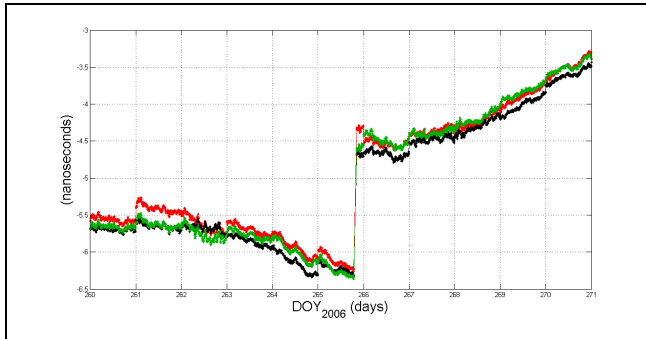


Figure 5 Clock phase solution for USN3 station.

Figure 4 shows a good improvement in day-boundary discontinuities due to the averaging effect of the multi-day batches versus both the IGS and the classic PPP solution for a period usually critical for the NRC1 station (winter season).

Figure 5 shows the behavior of the day by day sliding batch solution when a clock jump is present in the data. The clock jump is correctly treated by the SB7D2 solution and an improvement is still apparent even though the IGS and classical PPP solution show minimal day-boundary clock discontinuities for this station. Statistics of the different quality parameters for selected cases of sliding batch solutions are summarized in Table II.

TABLE II. STATISTICS OF QUALITY PARAMETRES FOR SLIDING BATCH SOLUTIONS.

	NRC1 DOY 2006 [055-075]	
IGS	0.44 ns +/- 0.32 ns	
PPP Day by day	0.48 ns +/- 0.34 ns	
SBxDn	SB7	SB14
END (D1)	0.36 ns +/- 0.24 ns	0.32 ns +/- 0.22 ns
END-1 (D2)	0.20 ns +/- 0.15 ns	0.16 ns +/- 0.14 ns
1/3 x	0.12 ns +/- 0.11 ns	0.08 ns +/- 0.05 ns
MIDDLE (Dx/2)	0.11 ns +/- 0.10 ns	0.10 ns +/- 0.08 ns
2/3 x	0.15 ns +/- 0.09 ns	0.17 ns +/- 0.15 ns
START+1 (Dx-1)	0.24 ns +/- 0.18 ns	0.28 ns +/- 0.18 ns
START (Dx)	0.35 ns +/- 0.24 ns	0.38 ns +/- 0.25 ns

	IENG DOY 2006 [210-228]		
IGS	0.13 ns +/- 0.17 ns		
PPP Day by day	0.12 ns +/- 0.09 ns		
SBxDn	SB7	SB14	SB30
END (D1)	0.08 ns +/- 0.04 ns	0.08 ns +/- 0.04 ns	0.07 ns +/- 0.04 ns
END-1 (D2)	0.06 ns +/- 0.03 ns	0.06 ns +/- 0.04 ns	0.06 ns +/- 0.04 ns
1/3 x	0.06 ns +/- 0.04 ns	0.06 ns +/- 0.05 ns	0.05 ns +/- 0.03 ns
MIDDLE (Dx/2)	0.06 ns +/- 0.04 ns	0.05 ns +/- 0.04 ns	0.05 ns +/- 0.03 ns
2/3 x	0.06 ns +/- 0.05 ns	0.04 ns +/- 0.03 ns	0.05 ns +/- 0.03 ns
START+1 (Dx-1)	0.08 ns +/- 0.04 ns	0.05 ns +/- 0.04 ns	0.05 ns +/- 0.03 ns
START (Dx)	0.06 ns +/- 0.06 ns	0.07 ns +/- 0.06 ns	0.06 ns +/- 0.03 ns

	USN3 DOY 2006 [240-300]		
IGS	0.07 ns +/- 0.05 ns		
PPP Day by day	0.10 ns +/- 0.07 ns		
SBxDn	SB7	SB14	SB30
END (D1)	0.06 ns +/- 0.05 ns	0.06 ns +/- 0.05 ns	0.06 ns +/- 0.04 ns
END-1 (D2)	0.04 ns +/- 0.03 ns	0.04 ns +/- 0.04 ns	0.04 ns +/- 0.04 ns
1/3 x	0.05 ns +/- 0.04 ns	0.04 ns +/- 0.04 ns	0.04 ns +/- 0.04 ns
MIDDLE (Dx/2)	0.04 ns +/- 0.03 ns	0.04 ns +/- 0.03 ns	0.04 ns +/- 0.04 ns
2/3 x	0.05 ns +/- 0.03 ns	0.04 ns +/- 0.04 ns	0.05 ns +/- 0.04 ns
START+1 (Dx-1)	0.05 ns +/- 0.04 ns	0.05 ns +/- 0.04 ns	0.05 ns +/- 0.04 ns
START (Dx)	0.06 ns +/- 0.05 ns	0.06 ns +/- 0.05 ns	0.08 ns +/- 0.09 ns

	PTBB DOY 2006 [240-300]		
IGS	0.08 ns +/- 0.08 ns		
PPP Day by day	0.22 ns +/- 0.13 ns		
SBxDn	SB7	SB14	SB30
END (D1)	0.13 ns +/- 0.08 ns	0.10 ns +/- 0.07 ns	0.09 ns +/- 0.07 ns
END-1 (D2)	0.11 ns +/- 0.07 ns	0.08 ns +/- 0.05 ns	0.07 ns +/- 0.06 ns
1/3 x	0.11 ns +/- 0.07 ns	0.07 ns +/- 0.06 ns	0.07 ns +/- 0.06 ns
MIDDLE (Dx/2)	0.11 ns +/- 0.07 ns	0.08 ns +/- 0.07 ns	0.07 ns +/- 0.06 ns
2/3 x	0.11 ns +/- 0.06 ns	0.08 ns +/- 0.06 ns	0.07 ns +/- 0.07 ns
START+1 (Dx-1)	0.12 ns +/- 0.08 ns	0.09 ns +/- 0.07 ns	0.09 ns +/- 0.07 ns
START (Dx)	0.13 ns +/- 0.08 ns	0.11 ns +/- 0.07 ns	0.12 ns +/- 0.09 ns

V. COMPARISON WITH TWSTFT

The capabilities of the PPP Sliding Batch procedure, in terms of time and frequency transfer, were compared against TWSTFT data for the two baselines involving three timing laboratories equipped with both Cesium and H-maser, namely UTC(PTB) versus UTC(IT), and UTC (USNO) versus UTC(IT). Results are shown in Figure 6 as Allan deviation plots. We also show the behavior of the commercial cesium, PTB primary cesium (1996 IEEE) and INRIM Hydrogen maser (versus the INRIM cesium primary standard fountain) involved at the respective stations. White frequency noise and white phase noise are shown as blue lines on the same graphs.

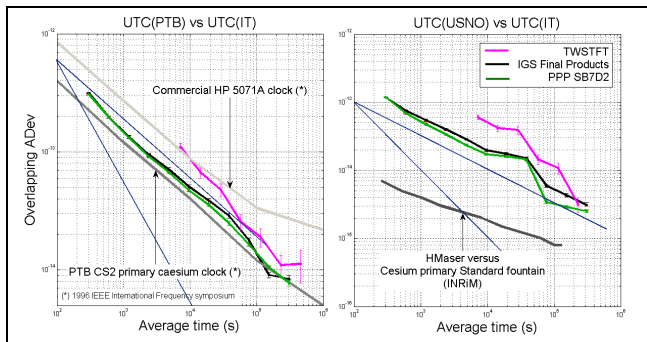


Figure 6 PPP Sliding Batch Solution and TWSTFT techniques comparison.

The short term noise improvement using PPP over TWSTFT is apparent. The sliding batch solution, minimizing day-boundary discontinuities, extends this stability improvement. For intervals beyond about 2 days, both TWSTFT and SB7D2 techniques show similar performances.

VI. DISCUSSION AND CONCLUSION

Using GNSS code and carrier-phase data and precise ephemeris, classical daily Precise Point Positioning solutions presently show better stability performance at short term than the classical two way method for frequency time transfer.

The Precise Point Positioning needs pseudorange data for absolute time scale transfer purposes. However the pseudorange noise is sometimes and for some stations not white and thus affects precise point positioning results. Computation of short batches of data, e.g. single day, induces batch boundary clock discontinuities that are not acceptable for time scale transfer purposes. The day by day Sliding Batch Solution procedure reduces the level of discontinuities through averaging pseudorange data on multi-day periods and improves the Precise Point Positioning time transfer quality.

Using batches of more than seven days does not improve, in the current tests, the mean level of day-boundary discontinuities. The implied increase in computation time

and availability delay also reduces the usefulness of longer batches.

One has to compromise between latency and size of remaining discontinuities. Best results are obtained in the middle of the batch (P4 for SB7), but these induce a few days of additional latency with respect to the classical PPP solution. The end of the batch position has the same latency than the classical PPP solution (1 day after IGS products availability) but it is affected by larger solution boundary discontinuities, a significant degradation in the results with respect to the best performance that can be obtained. For all these reasons, the D2 position appears to be the best compromise, yielding a latency of 3 days when using IGS Rapid products and 20 days using IGS Final products.

The Sliding Batch Solution procedure offers the possibility to easily transfer time scales using a low cost installation reaching the short term precision of the GNSS phase data, minimizing the effects induced by the pseudorange colored noise and providing a solution independent of the TWSTFT technique.

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