Precise Point Positioning for timing

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Abstract

In recent years, many national timing laboratories have installed geodetic Global Positioning System receivers together with their traditional GPS/GLONASS Common View receivers and Two Way Satellite Time and Frequency Transfer equipments. 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 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 atmospheric delays for GPS geodetic receivers which are not part of the IGS network, by taking advantage of IGS precise products without ensuring the effort of a formal belonging to the IGS federation. This article reports on the results of a collaborative work performed at the Istituto Nazionale di Ricerca Metrologica (INRiM) in Turin, Italy, and at the Natural Resources Canada (NRCan) in Ottawa to assess the time transfer potential of Precise Point Positioning.

1. Introduction

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 de 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 studies 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 Meters' Consultative Committee for Time and frequency (CCTF) has recommended the operation of timing-oriented geodetic 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 processing data from stations that are not part of global networks while nevertheless integrating results within global solutions. Precise Point Positioning (PPP) is a single station post-processing method for recovering coordinates of GPS reception antennas, GPS receiver clock offset and local tropospheric parameters. We showed that PPP clock solutions are consistent with IGS final clock products at the sub-nanosecond level [2]. 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 [2]. PPP results showed a two-fold 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. The issue of discontinuities in the clock series caused by the batch nature of PPP processing has also been addressed [4] developing a procedure (Sliding Batch Procedure) that takes advantage of the improved stability of the phase-connected multiday PPP solutions, while allowing the generation of continuous clock time series, more applicable to continuous operation/monitoring of timing equipments.

2. Precise Point Positioning for Timing

2.1 NRCan's Algorithm

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

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 centimetres 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 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 [1].

2.2 Comparison with IGS products and with TWSTFT

In this section are reported some of the results of a jointly NRCan and INRiM experiment [2] performed using 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) and related to nine national timing laboratories selected around the globe (USNO, NIST, PTB, NPL, OP, INRiM, NICT, NRC, ORB). This period fully overlaps a 20 day-comparison campaign of caesium (Cs) fountain primary frequency standards (PFS) performed in five of the nine selected timing laboratories (NIST, PTB, NPL, OP, INRiM).

PPP autonomously allows recovery of the IGS combined clock solution at sub-nanosecond level (130 picoseconds rms for the analyzed stations), without the requirement to be part of a network solution. In terms of frequency stability, the Allan deviation 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, as plotted in Figure 1. This means that no additional noise is introduced by the single-station estimation method performed by PPP. Moreover, a clear improvement using a longer period of continuous processing (two weeks) is achieved. It's worth mentioning that both one-day and two week PPP solution stabilities showed in plot, 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 modelled ocean loading effects in the PPP algorithm.

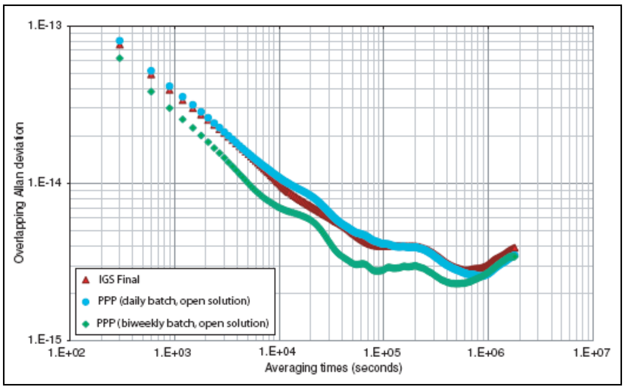

Figure 1 Frequency stability comparison (in terms of Allan deviation) between PPP 1-day solution, PPP 2-week solution, and IGS final clock products for the BRUS-NPLD link between ORB and NPL timing laboratories.

PPP comparison with TWSTFTF, an independent synchronization technique, shows very good agreement, with maximum differences of less than 1 nanosecond after removing mean offset to account for any hardware calibration issued between different pieces of equipment. In Figure 2, the stability of the comparison data between PPP and TWSTFT for selected baselines is shown in terms of overlapping Allan deviation. The measurement noise introduced by PPP is a factor of 1.5 lower than TWSTFT (at least for the short baseline) for intervals varying from two hours up to one day and even longer. For longer intervals, the two methods converge approaching the nominal behaviour of H-masers of the stations, with a flicker floor of $4 \cdot 10^{-15}$ for an averaging period up to about three days.

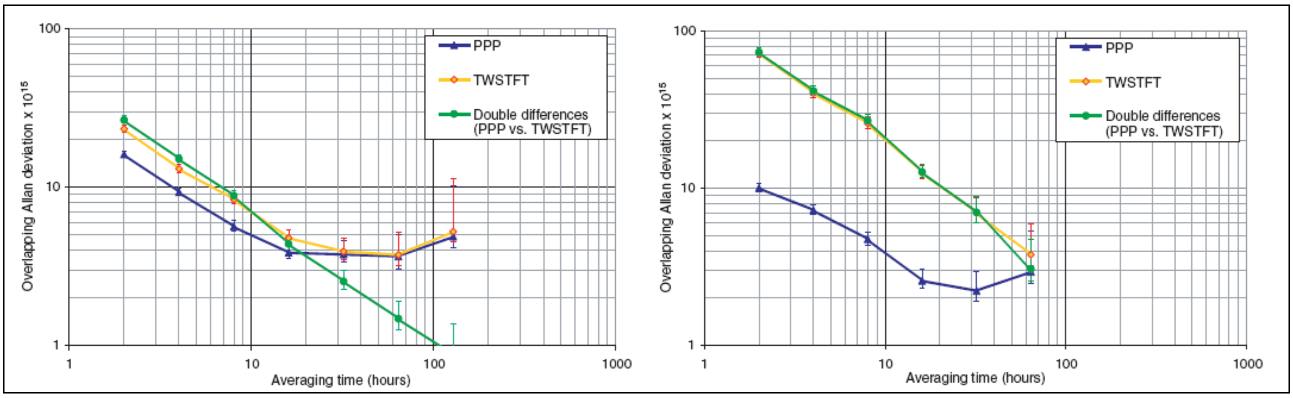

Figure 2 Frequency stability comparison (in terms of Allan deviation) between PPP and TWSTFT for the NPL to OP European link (left plot) and for the OP to NIST transatlantic link (right plot). Residuals between the two techniques are also plotted.

2.2 Day boundary discontinuities and Sliding Batch Procedure

PPP 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 [3]. Computation in batches of data, e.g. single day as is the standard in IGS products, induces batch boundary clock discontinuities that limit the quality of time-transfer. In order to reduce this effect of pseudorange colored noise, a new PPP post-processing procedure has been developed, namely Sliding Batch Procedure [4]. Through averaging pseudorange data on multi-day periods and overlapping solutions, the Sliding Batch Procedure avoids batch boundary discontinuities and reduces the level of day boundary discontinuities down to a level of less than 100ps on average for most stations, thus improving the PPP time transfer quality. The procedure was carefully designed to constrain the additional cost in computer time when processing multi-day batches and the added latency in availability of the results.

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

In Figure 3 clock phase results using data from the NRC1 and USN3 GPS receivers both connected to atomic external oscillators (H-masers), are shown. For both figures, the daily IGS Final solutions are plotted in black, the associated daily PPP solutions in red and the Sliding Batch Procedure solutions in green. In the left, good improvement in day boundary discontinuities is clear, due to the averaging effect of the multi-day batches versus both the IGS and the daily PPP solutions for a period usually critical for the NRC1 station (winter season). Classic day by day solutions give a mean solution boundary discontinuities of 0.723 ns (+/- 0.629 ns) similar to the IGS one (0.723 +/- 0.643 ns), where Sliding Batch Procedure shows better performances at 0.208 ns (+/- 0.152 ns). The USN3 results show the behaviour of the Sliding Batch solution when a real clock discontinuity is present in the data. The clock discontinuity is correctly reflected by the Sliding Batch Procedure and an improvement is still apparent even though the IGS and daily PPP solution show minimal day boundary clock discontinuities for this station (IGS : 0.066 +/- 0.067 ns, daily PPP : 0.096 +/- 0.075 ns, Sliding Batch Procedure : 0.035 +/- 0.029 ns).

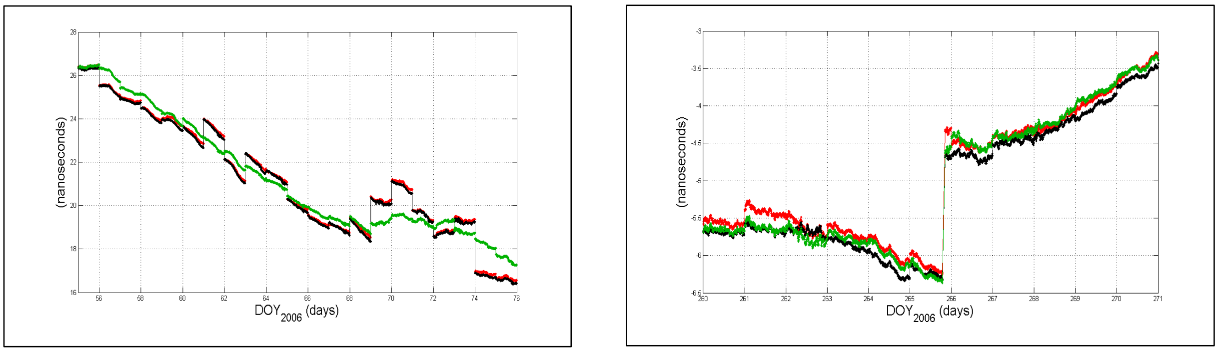

Figure 3 Clock phase solution for NRC1 station (left) and for USN3 station (right).

3. Conclusion

Experimental results show PPP as a promising alternate synchronization technique, offering high-level performance comparable with state-of-the-art methods, such as TWSTFT. In terms of logistic, possible re-use of existing geodetic GPS receivers and the relative small investment required for the procurement of new GPS equipment, are valued advantages of PPP for timing laboratories. Additional, 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. This led the BIPM to start with a pilot experiment which aim is to regularly compute some TAI links with Precise Point Positioning technique that should provide a much improved statistical uncertainty, compared to the code-only techniques presently used, expecting that the pilot experiment will result in the future use of the PPP technique for TAI computation.

4. Acknowledgments

The authors wish to thank all the people in timing laboratories involved in the experiments that lead to the results presented in this paper, for granting the use of their GPS and TWSTFT data. Their contribution is highly appreciated. The authors also wish to acknowledge the many individuals and institutions forming the IGS for the high quality GNSS products.

5. References

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