Precise Point Positioning: implementation of the constrained clock model and analysis of its effects in T/F transfer

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ABSTRACT

In recent years, many national timing laboratories have collocated geodetic Global Positioning System receivers together with their traditional GPS/GLONASS Common View receivers and Two Way Satellite Time and Frequency Transfer 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 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 by taking advantage of these IGS precise products. Previous assessments, carried out at INRIM with a PPP implementation developed at NRCan, showed PPP clock solutions have better stability over short/medium term than GPS CV and GPS P3 methods and significantly reduce the day boundary discontinuities when used in multi-day continuous processing, allowing time-limited, campaign-style time-transfer experiments. This paper reports on follow-on work performed at INRIM and NRCan, to further investigate the effects of applying statistical constraints on station clock parameter in the PPP estimation process, specifically its impact on clock solution short term noise.

INTRODUCTION

In most geodetic processing, including PPP, clocks are treated as white noise with near-infinite uncertainty. With such a large uncertainty, it is possible the solved-for clock errors can absorb noise and systematic signals from other components of the overall system. The primary objective of this work is to modify the PPP algorithm to take into account known behaviour and noise characteristics of the frequency standard driving the GNSS receiver, with the objective to mitigate unwanted contributions to the clock solutions and possibly view the real behaviour of the underlying frequency standard. This is what is meant by applying clock constraints within the PPP algorithm. Previous work on this subject has been done jointly by NRCan and INRiM [1,2]. Constraints were applied within the NRCan-PPP software in the case of GNSS receivers connected to physical UTC(k) realizations, e.g. at national UTC providers facilities. It was demonstrated the short-term noise could be reduced by 1 to 2 orders of magnitude, up to one half day time intervals, for stations connected to Hydrogen-Masers (HM). For stations connected to Cs standards, the internal Cs noise dominates in the system and therefore no constraints can be effective: the underlying Cs frequency standard is already visible in the PPP results.

The objectives of this work are to further improve the knowledges on the best way constrain the PPP algorithm, trying to understand where the noise removed from the clock solutions in the PPP overall solution system goes.

NEW CLOCK CONSTRAINT MODEL

With respect to previous work [2], PPP being mechanised as a least-squares filter, the new clock constraints are implemented as follows. The user inputs are the frequency offset and drift of the station frequency standard, the deterministic model, and the Allan deviation at 1s, the noise model. There are two important considerations about these user inputs, both pertaining to the deterministic model: 1) the frequency parameters must be with respect to the reference implied in the satellite clock products to be used; and 2) since there is a frequency drift involved, the frequency offset must be tied to an epoch and that epoch must be the first epoch processed in PPP. The later limitation could be alleviated by adding an epoch of reference as part of the user inputs.

At the first epoch processed the station clock phase error is estimated as white noise with quasi infinite a priori uncertainty. In the subsequent epochs, the a priori value of the clock error is function of the previous estimate and input frequency offset and drift, i.e. :

$$x(t_{i+1}) = \hat{x}(t_i) + \left(y_0 + \frac{1}{2} d_0 \cdot (t_{i+1} - t_{ref}) \right) \cdot (t_{i+1} - t_i) \tag{1}$$

where x are the clock phase errors, t_i and t_{i+1} estimate epochs, and y_0, d_0 and t_{ref} the deterministic model parameters. Note this is a change on the model used in **[5]**, which was erroneous in not properly propagating the frequency offset to current time. This error was responsible for the small divergence of clock phase error estimates between the unconstrained and constrained solutions.

The a priori uncertainty of the clock phase error is function of the previous epoch uncertainty, the appropriate diagonal member of the inverted least-squares normal equations, and user input Allan deviation:

$$\sigma^2(t_{i+1}) = \hat{\sigma}^2(t_i) + (\mathrm{ADev(1s)})^2 * (t_{i+1} - t_i) \tag{2}$$

where ADev(1s) is the user input Allan deviation at 1s and σ^2 is the uncertainty of clock phase error estimates.

These are equivalent to the respective propagation of deterministic and stochastic models, prior to the data update, in Kalman filtering.

Frequency offset and drift estimation

The NRCan-PPP software already estimates a model of the processed station clock from the epoch clock errors estimates. This model is a linear polynomial in clock phase, i.e. a clock phase error at the initial epoch of the processed period and mean clock phase drift – or mean clock frequency – over the processed period. This was modified to estimate a second order polynomial in clock phase, now yielding the clock phase error and clock frequency offset at initial epoch, and mean clock frequency drift, i.e.:

$$x(t) = \hat{x}(t_{ref}) + \hat{y}(t_{ref}) \cdot (t - t_{ref}) + \frac{1}{2} \hat{d}(t_{ref}) \cdot (t - t_{ref})^2 \tag{3}$$

This new feature will be used to accurately determine the deterministic model parameters of the clock with respect to the reference implied in the input satellite clock phase errors.

ANALYSIS SET UP

The same data sets used in [2] were taken into account for this work. Results related with IENG station (Ashtech ZXII-3T receiver connected to a steered Active Hydrogen Maser, namely UTC(IT)) installed at the INRIM RadioNavigation Laboratory are presented here as a significant test case.

In particular, a ten days period since 2008 DOY 120 to 129 has been considered and three PPP solutions obtained:

1. an unconstrained solution labelled **open** whereby the station clock phase errors are estimated with quasi infinite a priori uncertainty;

2. a constrained solution labelled **const1** whereby the clock deterministic parameters (frequency offset and drift) are taken from the **open** solution and the clock stochastic model ADev(1s) is based on specifications of typical hydrogen-masers (2E-13), with a priori uncertainties of pseudorange and carrier-phase observations respectively set at 1m and 1cm; and

3. a similarly constrained solution labelled **const2** with a priori pseudorange and carrier-phase observations uncertainties respectively set at 5m and 3cm.

RESULTS

IENG, a significant test case

The IENG station is part of the IGS network. Operated by INRIM, Italy, it is an Ashtech Z XII-3T receiver connected to a HM steered to UTC(IT). A 10 days period of analysis is here presented, when the systems was affected by diurnal signals caused by temperature variations surrounding a component of the frequency distribution chain [2].

The diurnal variations in the 10day IENG clock solutions can be readily seen in Fig.1 and Fig.2. The amplitude however depends on the a priori uncertainty of the station clock parameter relative to that of the observations, i.e. the lower the ratio the less the amplitude. As expected the more these oscillations are damped in the clock solution the more they appear in the carrier-phase observations residuals, up to 1-2 cm in amplitude. Some of the signal is also transferred to the tropospheric delay parameter, at the level of a 1cm. From the 100ps amplitude sinusoid removed from the clock, about .5cm goes in the troposphere parameter and 1cm goes to carrier-phase residuals, accounting for only half the total.

Also noticeable is the slight drift of the **const1** and **const2** solutions with respect to the **open** solution. A linear regression yields 3E-17 and 8E-18 frequency difference respectively for the **const1** and **const2**, indicative of the accuracy with which the frequency offset and drift were obtained from the **open** solution.

The Allan deviation plots show the relative improvement of the different solutions. Constrained solutions improve the noise over all the span of intervals. The stronger we constrain the clock with respect to observables, the larger the improvement. Conversely, the Allan deviation computed on the carrier-phase residuals, averaged epoch by epoch and weighted according to the corresponding satellite elevation, show an increase in noise. The same can not be said for the epoch weighted average pseudorange residuals, which is dominated by the level of measurement noise (larger by 2 orders of magnitude than that of carrier-phases).

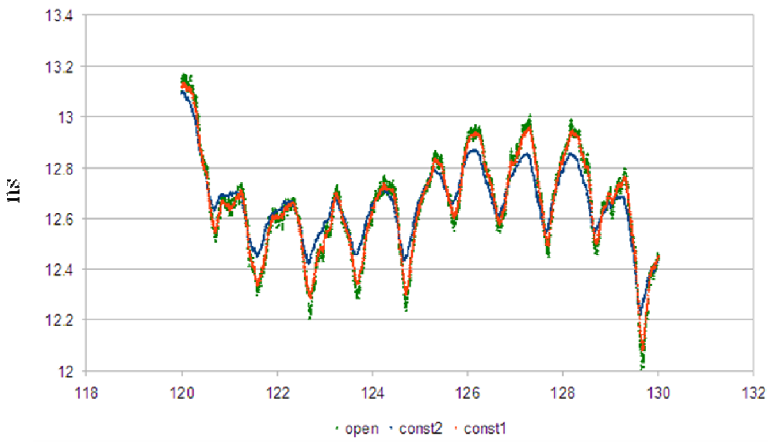

Fig. 1. IENG clock phase errors in ns with frequency offset and drift removed.

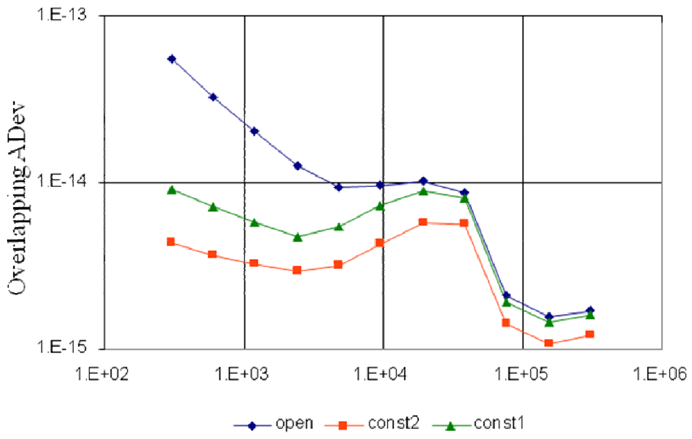

Fig. 2. IENG (10 days) Allan Deviation of the clock phase errors with frequency drift removed.

IMPACT OF NOISE REDUCTION ON THE CLOCKS ON OTHER PARAMETERS

We have analyzed the carrier-phase and pseudorange residuals, station position and tropospheric delay estimates of the solutions to understand how these are impacted by the noise reduction in the clock phase estimates. Since we have no truth to compare to for all but one of these parameters, we have examined how they changed in the **const2** solutions with respect to the **open** solution.

Our metric is the reduction/increase in RMS. For the estimated parameters however we do not have access to solution-specific RMS but to the RMS of the difference between solutions. For these cases, we have computed our metric as follows:

$$dRMS = RMS_{diff} * sign \qquad (5)$$

where RMS_{diff} is the RMS of the differences and sign is assigned based on the generally observed increase/decrease of the noise, with respect to the **open** solution, on the parameter plotted over time. For the clock estimates, the noise decreases so the sign is negative, for the tropospheric delay estimates the noise increases so the sign is positive. In the case of the stations, having one fixed estimate per solution does not allow to compute an RMS per dataset. Although there are truth coordinates for most of the stations we used, for consistency of the measures we have chosen to look at the RMS of position differences with respect to the **open** solution over all datasets we processed using Eq. 5.

For the pseudorange and carrier-phase observation residuals, it is simply computed as the difference of the RMS values from the **const2** and **open** solutions.

Results for IENG station are reported in Table 1, where it is possible to depict a decrease of about 100ps on the clock solution RMS. The troposphere shows about 2mm increase and the noise on carrier-phase observation residuals are increased by about 1-2 mm. The change in pseudorange residuals is not consistent through all test cases.

Table 1. Noise transfer budget in ns. Negative values mean noise loss and positive noise gain.

Dataset	Clock	Tropo.	Position	CP	Total Gain	Vanished
IENG	-0.0764	0.0208	0.0222	0.0077	0.0314	-0.0257

SOLUTION-BOUNDARY DISCONTINUITIES

All datasets were reprocessed in smaller batches of 5-7 days, dividing the 10days datasets in 2 parts. Both an **open** and **const2** solution were performed, the **const2** using the frequency offset and drift values obtained in the corresponding **open** solution.

Results for IENG station are reported in the Fig.3, where it is readily apparent that applying constraints to the NRCan-PPP clock estimation process generally increases the size of solution boundary discontinuities.

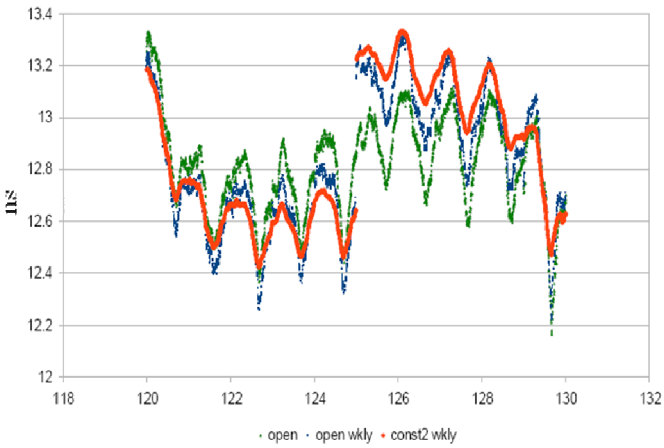

Fig. 3. IENG station boundary discontinuities.

CONCLUSIONS

In general the clock constraint works quite well, reducing the noise by nearly an order of magnitude at short-term (5min), from a few parts in 10^{-14} to a few parts in 10^{-15}. To achieve this level of improvement, it was necessary to increase the a priori uncertainty of the carrier-phase observations, from 1cm to 3cm, to allow some of the noise to transfer to carrier-phase residuals. In least-squares, much like a water balloon, noise that is removed from one side must reappear on another. Since the station position is estimated as a constant over the processed period and the tropospheric delay estimation is also constrained to some 5mm/√hr, relaxing the carrier-phase uncertainty allowed further improvement. The solution boundary discontinuities seem to be enlarged when constraining the clock estimation to a deterministic model. More tests are however required to find out, operationally, how the deterministic model parameters estimation/usage combination can be best articulated to minimize this effect.

REFERENCES

[1] D. Orgiazzi, P. Tavella, F. Lahaye, "Experimental Assessment of the Time Transfer Capability of Precise Point Positioning (PPP)", *Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Vancouver, B.C., August 29-31, 2005.

[2] G.Cerretto, P. Tavella, F. Lahaye, "Statistical constraints on station clock parameters in the NRCan PPP estimation process", *Proceedings of the 2008 Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Reston, VA, December 2-4, 2008.