MULTI-GNSS TIME TRANSFER

P. DEFRAIGNE
Royal Observatory of Belgium
Avenue Circulaire, 3, 1180-Brussels
e-mail: p.defraigne@oma.be

ABSTRACT. Measurements from Global Navigation Satellite Systems (GNSS) are used since the eighties to perform precise and accurate Time Transfer. Only the GPS constellation was used during the last 25 years, with some experiments based on GLONASS measurements. The GLONASS constellation is presently completed, the first four GALILEO satellites are already operational, and the BEIDOU system also provides signals that can be additionally used for time transfer. Increasing the number of satellites, and hence the number of observations, will reduce the noise level of the solution. However, such a combination requires the knowledge of some inter-system biases in the receivers and the existence of satellite clock products which can be expressed with respect to a common reference. This paper will propose recent advances in these combinations, focusing on GPS, GLONASS and GALILEO.

1. INTRODUCTION

The International Atomic Time is computed by the BIPM from an ensemble time scale algorithm combining about 400 atomic clocks distributed in about 60 laboratories in the world. The data used are actually the differences between the clock readings, i.e. time intervals between the time pulses given by two clocks. It is therefore necessary to be able to compare the clocks, whatever the distance between them. One current technique for remote clock comparison (or time transfer) is based on the analysis of GNSS signals arriving in two GNSS stations where the clocks to be compared are each connected to the receiver. Measurements from GPS are used since the eighties (Allan & Weiss, 1980) to that goal. In its classical version, the GPS time transfer is performed using clock offsets collected in a fixed format, called CGGTTS (Common GPS GLONASS Time Transfer Standard), as described in (Allan &Thomas, 1994; Azoubib & Lewandowski,1998). These clock offsets represent the differences ($clock - REF$) between the local clock and the reference timescale of the GNSS. They are obtained from the pseudorange measurements, corrected for the signal travel time (satellite-station), for the troposphere and ionosphere delays, and for the relativistic effects. A smoothing is then performed over 13 minute observation tracks, and the results are then corrected for the instrumental hardware delays. These hardware delays correspond to the electric delays accumulated by the signal between the antenna phase center and the internal timing reference of the receiver (or receiver clock). They are function of the frequency so that the combination of measurements from satellites of different constellations requires taking into account the inter-system and inter-frequency biases.

Starting with C/A code receivers, the method was then upgraded to take advantage of the dual-frequency receivers measuring codes on both frequencies, which allows to remove the ionosphere delays at the first order (i.e. 99.9 percent of the effect), thanks to the ionosphere-free dual-frequency combination. This led to a factor 2 improvement in the stability of the intercontinental time links up to averaging times of 10 days (e.g. Defraigne & Petit, 2003). In the present study, all the time transfer results will be obtained with the All in View (AV hereafter) approach (Petit & Jiang, 2008), i.e. the results ($clock - REF$) for each station are first computed as a weighted average of the solutions provided by each satellite in view. The difference between the solutions obtained in the two stations gives then the time transfer solution between the two station clocks. Note that in parallel, the time-transfer technique based on Precise Point Positioning (PPP) has proven to be a very effective technique allowing the comparison of atomic clocks with a precision at the level of a hundred picoseconds, (e.g. Defraigne et al., 2008). PPP (Kouba & Héroux, 2001) is based on a consistent modeling and analysis of GPS (and possibly GLONASS) dual-frequency code and carrier-phase measurements. This technique is widely recognized for its high resolution (1 pt/30 s) and high frequency stability, reaching 10^{-15} at an averaging time of one day, thanks to the very low noise level of the carrier phases (see for instance Larson et al., 2000), enabling time transfer with a statistical uncertainty of 0.1 ns, when ignoring the uncertainty on the instrumental hardware delays. This paper however concerns only the code-only analysis as a first step in the combination of different systems for time transfer. Furthermore, the introduction of inter-system biases is requested only for code-measurements, so that the same procedure will be applied to PPP afterwards.

The first section of the paper describes a method presented in (Defraigne et al., 2013) to combine GPS and GLONASS measurements for time transfer in All-in-View, using calibration data for both GPS and GLONASS. This method is based on a least square approach where the clock solutions for both stations are computed in the same process, and constrained by the difference between the calibration data of the two stations. The method was tested on the link Brussels-Paris for which a calibration was performed for GPS and GLONASS. After describing the methodology, the paper will present an estimation of the impact of using or not the GLONASS calibration results for that link using 6 weeks of data. The second section of the paper will provide some first results of the Galileo time transfer using a link between Brussels (Belgium) and Torino (Italy).

2. COMBINED GPS+GLONASS TIME TRANSFER

2.1. Theory

The AV clock solutions determined from GNSS signals refer to the receiver clock; these must be combined with the measurements of station hardware delays to get the de-synchronization of the clock with respect to the reference time scale REF of the GNSS:

$$clock - REF = < (t_{rec} - REF)_{sat} - \delta_a - \delta_c - \delta_r > + (clock - t_{rec}) \tag{1}$$

where $< >$ means averaging, $(t_{rec} - REF)_{sat}$ is the clock solution obtained from measurements on a given satellite, δ_a, δ_c and δ_r are the GNSS signal delays inside the antenna, cable and receiver, and $(clock - t_{rec})$ is the synchronization difference between the receiver clock and the external clock, which contains the cable delay between the clock and the receiver, and the delay between the connector and the receiver clock. This delay or the way to measure it is given by the manufacturer, while δ_a, δ_c and δ_r must be determined by experimental calibration.

The antenna and the receiver delay depend on the frequency of the GNSS signal. As all the GPS satellites emit the same frequencies L1 and L2, the hardware delays are the same for all the satellites and can be easily corrected for after the averaging procedure. Equation (1) for GPS can be simplified as:

$$clock - REF = < (t_{rec} - REF)_{sat} > - \Delta(rec) + (clock - t_{rec}) \tag{2}$$

It is however not the case with GLONASS as different satellites transmit on a different frequency pair, so that the antenna and receiver delays are different for each satellite, with inter-frequency biases (ISB) up to 25 ns in the code measurements. Equation (1) then becomes for GLONASS:

$$clock - REF = < (t_{rec} - REF)_{sat} - ISB(rec, sat, day) > + (clock - t_{rec}) \tag{3}$$

These ISBs must therefore be corrected for before the averaging when GLONASS data are used for time transfer. To get a time transfer solution from combined GPS and GLONASS measurements, we use the ESOC products in which the satellite clocks from both constellations are given with respect to the same reference time scale (Springer, 2009). However, due to the existence of the station-satellite biases, some ISBs are also present in the satellite clock products. As these are determined on a daily basis, it is necessary to determine also daily ISBs for time transfer, while physically these ISBs should be constant (if the temperature around the receiver is constant). One solution is to determine the ISBs present in the GLONASS measurements, with respect to the calibrated GPS solution, as proposed in (Harmegnies et al., 2013). However, the final solution is then based only on GPS calibration. We propose therefore an alternative which is to introduce the GLONASS calibration data for a link between two stations. This requires determining the ISBs of both stations at the same time in the time transfer computation.

Indeed, the ISBs can be separated into two components: $D(rec, sat)$ the physical station (receiver+antenna) hardware delay for the frequencies of the GLONASS satellite, which is constant over time, and $B(day, sat)$ a satellite bias which varies from day to day, associated with the GLONASS satellite clocks, and which is the same for all the GNSS stations. This reads:

$$ISB(rec, sat, day) = B(day, sat) + D(rec, f_{sat}) \tag{4}$$

where f_{sat} is the satellite frequency. Therefore, the difference between the ISBs of two stations is equal to

$$\begin{aligned} ISB(rec_1, sat, day) - ISB(rec_2, sat, day) &= D(rec_1, f_{sat}) - D(rec_2, f_{sat}) \quad (5) \\ &= \Delta_{12}(f_{sat}) \quad (6) \end{aligned}$$

and should be constant over time. The difference $\Delta_{12}(f_{sat})$ can be determined by relative calibration of the two stations, for each GLONASS frequency.

In order to use these differential delays in All in View (AV) and similarly in the future for PPP, the determination of the AV (or PPP) solution must be done at the same time for both stations. The reason is that for each station the biases $ISB(rec, sat, day)$ must be determined with respect to the GPS AV solution of the station, while verifying the relation

$$ISB(rec_1, sat, day) - ISB(rec_2, sat, day) = \Delta_{12}(f_{sat}) \quad (7)$$

We propose therefore, to first determine a GPS-only AV solution, and then to use a constrained least square approach to determine the ISBs of both stations (see Defraigne et al., 2013, for a full description).

2.2 Validation with the link ORB-OP

An experimental GLONASS+GPS calibration has been realized in June 2013, between two time laboratories: OP (Paris Observatory) and ORB (Royal Observatory of Belgium). Both stations are equipped with a Septentrio PolaRx4TR-PRO receiver connected to a H-maser, while a cesium is used in the second part at ORB. The corresponding station names are OPM8 and BRUX. The link calibration was realized using a traveling GNSS station, containing a Septentrio PolaRx4TR-PRO receiver, a 30 m antenna cable, and a Choke Ring Trimble Antenna. The scheme of the calibration follows the procedure proposed in (Esteban et al., 2010). The differential hardware delays in the GLONASS P3 band for the link OMP8-BRUX are shown in Figure 1.

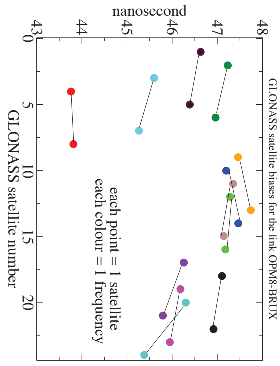

Figure 1: Differential GLONASS hardware delays of the P3 link OPM8-BRUX, computed for each satellite separately; two satellites transmitting the same frequencies are joined by a segment.

We can observe that except for satellites 20 and 24, which are on the frequency channel +2, i.e. on the border of the frequency band, the satellite pairs corresponding to a given frequency channel have differential hardware delays with a difference smaller than half a nanosecond.

Figure 2 presents the difference between the combined GPS+GLONASS solutions using or not the GLONASS calibration constraint to determine the ISBs of BRUX and OPM8. The global impact of using or not the GLONASS calibration constraint on the combined AV solution is, for this six week period and this particular baseline, between -1.2 and +1.2 nanosecond. Finally, Figure 3 shows the smoothed time transfer solution (median of a 1 day sliding window) over six weeks for BRUX-OPM8, based on the AV solution using GPS-only, and using GPS+GLONASS with and without taking the GLONASS calibration into account. We clearly see the impact of using the GLONASS calibration, while using only the GPS Calibration provides a solution very similar to the GPS-only solution.

The differences between the ISBs obtained with and without GLONASS calibration constraint are depicted in Figure 4 for BRUX and OPM8. These differences range between -2 and +2 nanosecond, and

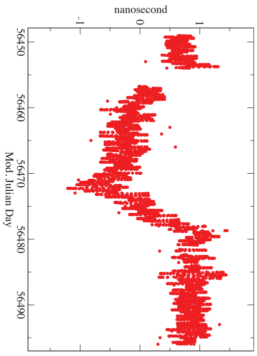

Figure 2: Differences between the time transfer solution OPM8-BRUX computed with AV in both stations with ISBs determined with and without the calibration constraint.

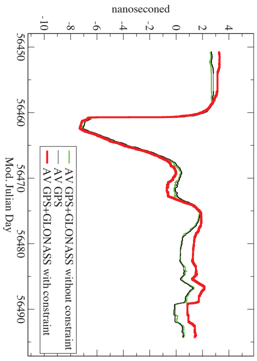

Figure 3: Comparisons between the time transfer solution for OPM8-BRUX computed with AV in both stations using GPS-only (black), GPS+GLONASS with (green) and without (red) the GLONASS calibration data.

are not constant over the one month period analyzed. The large peaks for OPM8 at mjd 56456 are due to an incomplete daily RINEX file, reducing the number of observations used to determine the ISBs; in that case the constraint is very useful to keep the correct calibration in the analysis.

3. FIRST RESULTS WITH GALILEO

Some first data analysis has been done using Galileo code measurements collected in two time laboratories equipped with a H-maser: the Royal Observatory of Belgium (Brussels), where two GNSS stations are equipped with a PolaRx4 receiver, and one in Torino, Italy, at the INRIM. While the existence of new signals could lead to new analysis strategies (see e.g. Martinez et al., 2013, or Panek, 2012), the present results are based on the same approach as used with GPS data, i.e. the ionosphere-free combination of Galileo codes E1 and E5 (E5a or E5b or E5-AltBoc) in a CGGTTS-like computation of the receiver clock solutions. The satellite tracks were however limited to 5 minutes rather than the conventional 13 minutes of the CGGTTS. The satellite positions and clocks were deduced from the IGS-MGEX products delivered by the Munich analysis center TUM. A first picture (Figure 5) shows the results of a 100 meter baseline, using the two stations in Brussels, BRUX and ZTB3, and compares them with the corresponding results obtained with GPS satellites and the ionosphere-free combination P3. Note that not the same clock is connected to BRUX and ZTB3; one is the free maser, while the second one is the steered maser. A linear drift was removed from the results.

From this first result, it can be concluded that the quality of the time transfer based on the ionosphere-free combination, directly related to the noise of the pseudoranges, is at least as good for Galileo as for GPS. A more precise comparison of the statistics of both solutions will be possible only when a larger

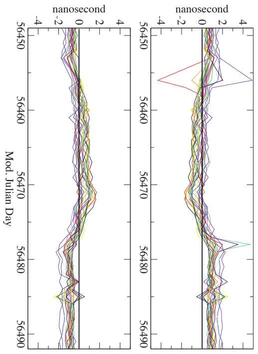

Figure 4: Differences between the GLONASS ISBs determined with and without GLONASS calibration data for OPM8 (top) and BRUX (bottom); each colour is for one given satellite

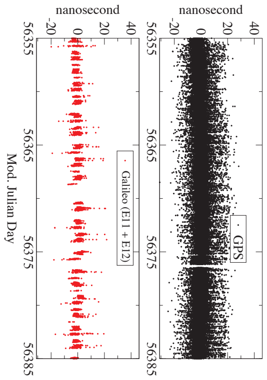

Figure 5: First results of time transfer on a zero-baseline using the ionosphere-free combination of Galileo E1 and E5.

number of Galileo satellites will be available. In order to determine if there is an optimal choice of signal in the E5 band, the time transfer link between Brussels and Torino was computed using the ionosphere-free combinations E1,E5A / E1,E5b / E1,E5. We could expect a smaller noise when using the combination E5, i.e. the AltBOC signal, as this one is characterized by a significantly reduced multipath (Simsky et al., 2008), but as seen in Figure 6, this is not the case, due to the combination with E1, and the considerable increase of the noise and multipath from the coefficient 2.26 appearing before E1 in the ionosphere-free combination with E5. The main conclusion from these preliminary results of Galileo time transfer is that using the ionosphere-free combination of E1 with one other code in the E5 frequency band provides a solution with a noise level at least similar to the one of GPS.

4. CONCLUSIONS

This paper summarized a method to combine GPS and GLONASS measurements for time transfer in All-in-View, using calibration data for both GPS and GLONASS. A more detailed presentation of the method can be found in (Defraigne et al EFTF 2013). GLONASS calibration data can only be introduced in the computation of a LINK, i.e. a difference of 2 AV solutions. Our proposed method introduces the calibration as constraints in the determination of inter-satellite biases and request that the AV solutions for both stations are computed together. The same method can also be applied to combined GPS+GLONASS PPP. This method was validated on a time transfer experiment between Brussels and Paris. The difference during six weeks between the time transfer solutions based on a combined GPS+GLONASS AV, obtained with and without GLONASS calibration results is in this case smaller than 2.5 ns peak to peak. This study will be extended to more baselines, and the uncertainty budget will be further evaluated. It will then be applied to Precise Point Positioning. The second part of the paper presented some first results of time transfer using Galileo measurements, using the ionosphere-

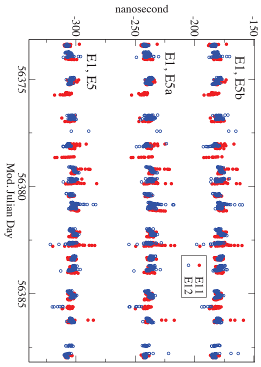

Figure 6: Comparison between the 3 iono-free combinations: E1+E5 / E1+E5a / E1+E5b; CGGTTS-like results, over 5 minutes tracks.

free combination of E1 with one other code in the E5 frequency band. It was shown that the noise level of the solutions is at the same level as when using GPS measurements.

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5. REFERENCES

Allan, D.W., Weiss, M., 1980, Accurate time and frequency transfer during common-view of a GPS satellite, Proc. IEEE Freq. Contr. Symp., Philadelphia, PA, pp. 334-356.

Allan, D.W., Thomas, C., 1994, Technical directives for standardization of GPS time receiver software, Metrologia 31, pp. 69-79.

Azoubib, J., Lewandowski, W., 1998, CGGTTS GPS/GLONASS data format Version 02, 7th CGGTTS meeting.

Defraigne, P., Petit, G., 2003, Time transfer to TAI using geodetic receivers, Metrologia, 40, pp. 184-188.

Defraigne, P., Guyennon, N., Bruyninx, C., 2008, GPS Time and Frequency Transfer: PPP and Phase-Only Analysis, Int. J. of Nav. and Obs., vol. 2008, Article ID 175468, 7 pages, doi: 10.1155/2008/175468.

Defraigne, P., Aerts, W., Harmegnies, A. Petit, G., Rovera, D., Uhrich, P., 2013, "'Advances in multi-GNSS time transfer"', in Proc. EFTF-IFCS, Prague.

Esteban, H., Palacio, . J. , Galindo, F.J., Feldmann, T., . Bauch, A. , Piester, D., 2010, "'Improved GPS based time link calibration involving ROA and PTB"', IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, UFFC-57, pp. 714-720.

Harmegnies, A., Defraigne, P., Petit, G., 2013, Combining GPS and GLONASS in all in view for time transfer, Metrologia 50, pp. 111.

Kouba, J., Heroux, P., 2001, GPS Precise Point Positioning using GPS orbit products, GPS solutions, vol. 5, pp. 12-28.

Larson, K., Levine, J., Nelson, L., Parker, T., 2000, Assessment of GPS carrier-phase stability for time-transfer applications, IEEE Trans. Ultrason., Ferroelect., Freq. Contr., vol. 47(2), pp. 484-494.

Martinez, M.C., Defraigne, P. Bruyninx, C., 2013, On the Potential of Galileo E5 for Time Transfer, IEEE Trans. Ultrason., Ferroelect., Freq. Contr., 60(1), pp. 121-131.

Panek, P., 2012, Time scales comparisons using simultaneous measurements in three frequency channels, Proc. of the 44th PTTI, Reston.

Petit G., Jiang, Z., 2008, GPS All in view time transfer for TAI computation, Metrologia 45, pp. 35-45.

Simsky, A., Sleewaegen, J.-M., Hollreise, M., Crisci, M., 2008, Experimental results for the multipath performance of Galileo signals transmitted by GIOVE-A satellite, Int. J. of Nav. and Obs., vol. 2008, Article ID 416380, 13 pages, doi: 10.1155/2008/416380.

Springer, T., 2009, NAPEOS mathematical models and algorithms, DOPSSYS-TN-0100-OPS-GN, 1.0.