GPS TIME AND FREQUENCY TRANSFER: STATE OF THE ART

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ABSTRACT. The comparison of clocks located in different laboratories, called Time and Frequency Transfer, can be obtained from the common view of GPS satellites. This method consists in determining the clock offsets between the laboratory clocks and a common time scale associated with the GPS system; this can be either the satellite clocks, or the GPS time scale, or the IGS time scale. The last developments in GPS data analysis for time transfer, in collaboration with the geodetic community associated with the IGS, have improved significantly the capabilities of the technique. The paper presents the state of the art of the performances and limitations of the GPS time and frequency transfer.

1. USING GEODETIC RECEIVERS FOR TIME TRANSFER

The GPS signal is presently composed of two carriers (L1 and L2) modulated by two pseudo-random noise codes. Geodetic GPS receivers measure in addition to the C/A-code also the precise P1 and P2 codes as well as the carrier phases on the L1 and L2 frequencies. Time transfer benefits from geodetic-like GPS receivers because their dual frequency measurements allow eliminating the first order ionospheric delay. As the ionospheric perturbation on an electromagnetic wave is frequency-dependent, a combination of two signals with different frequencies can be used to cancel the first order ionospheric delays. Rather than using the C/A code, which is the only available information on the classical time receivers, the geodetic receivers allow to use the so-called 'ionospheric-free' code observable P3, corresponding to a combination of the two GPS precise codes P1 and P2 (Defraigne and Petit, 2003). Users limited to the C/A code observable correct the ionospheric delay using the ionospheric maps issued by the International GNSS Service (IGS). These IGS IONEX maps only correct for the long wavelength and long term variations (above 2 hours), while the ionospheric-free combination eliminates both the short and long wavelength behavior of the ionosphere as well as short and long term variations.

Figure 1 shows the time transfer between two Hydrogen masers, the first one located NPLD (UK) and the second one located at USNO (Washington), when using on one hand the C/A code and correcting for the ionospheric delays using the IGS IONEX maps and when using on the other hand the P3 code. In both cases the precise satellite ephemeredes provided by the IGS have been used for the determination of the geometric distances satellites-station and for the satellite clock synchronization errors. This use of P3 improves the Allan deviation by a factor of 2 on a transatlantic baseline.

Next to the availability of dual frequency observations, the geodetic GPS receiver also provide carrier phase observables (L1, L2) which have a noise about 100 times smaller than the code measurements. For this reason, the carrier phases have been used since '80 for different geodetic applications requiring very high precision. During the last years, the potential of GPS carrier

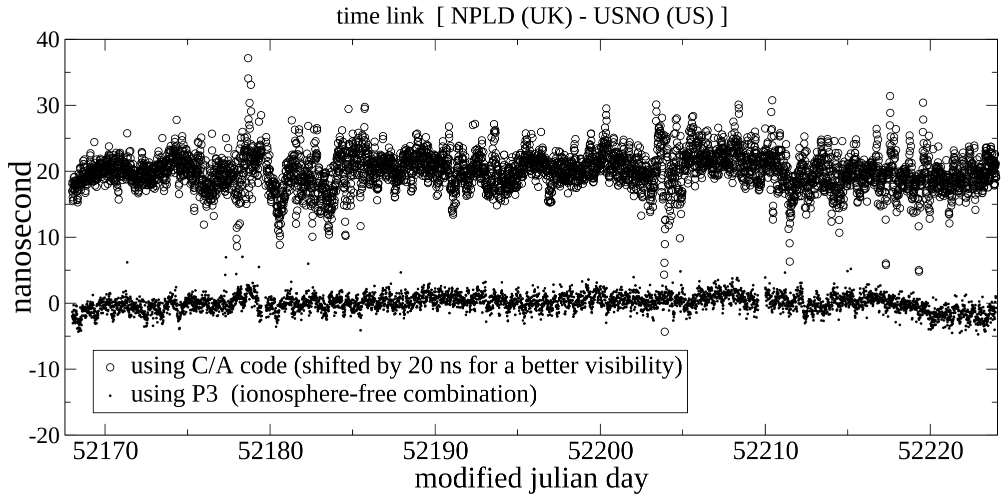

Figure 1: Time transfer between two Hydrogen Masers located in stations NPLD and USNO, using either the C/A code corrected for the ionosphere with the IONEX maps, or the P3 code.

phases for time transfer was recognized and demonstrated by different authors (Larson et al., 1999, Bruyninx et al., 1999). Carrier phases have been shown to be extremely interesting for averaging times smaller than 5 days. However, due to the presence of the initial ambiguities, the carrier phases are ambiguous and are not able to determine the absolute offset between the remote clocks. It is therefore necessary to process the code observations together with the phase observables. The absolute offset between the remote clocks is then only determined by the code information, while the carrier phases allow to give a precise signal evolution. Due to the use of daily data batches for the data processing, day boundary jumps appear in the clock solution obtained with the combined code/carrier phase data analysis. For each data batch (each day in our case) the evolution obtained from carrier phases has to be "calibrated" with the absolute offset obtained with the code data, and this within the noise level of the code measurements, i.e. about 1 ns. This leads to day boundary jumps up to 500 ps in the solution. In order to avoid these jumps, several ideas have been tested: either an overlap of the data files (Bruyninx and Defraigne, 1999), or the use of a longer data batch (Orregazzi et al., 2005) in order to have less jumps (one jump between 2 data batches); or the use ambiguities obtained from the previous data batch (Dach et al., 2004). The concatenation of the results is probably the worse solution as it can introduce some trend in the result (Ray and Senior, 2005).

2. LIMITATIONS OF CARRIER PHASE RESULTS

Environmental effects

Among the hardware considerations, one has to account for the hardware delays of the GPS equipment, which have to be determined by calibration. These hardware delays are sensitive to the ambient temperature variations; this is the reason why it is important to have temperature stabilization in the laboratories. Some experiments have been performed to test the sensitivity of the equipment (receiver, amplifiers, ...) to the temperature variations and the results showed the importance to keep the temperature constant within 0.1°C. Concerning the GPS antenna, the experiments show maximum diurnal variations (for diurnal variations of 20°C) of 40 ps for the carrier phases (Ray and Senior, 2001), while up to 2 ns for the code measurements (Smolarski et

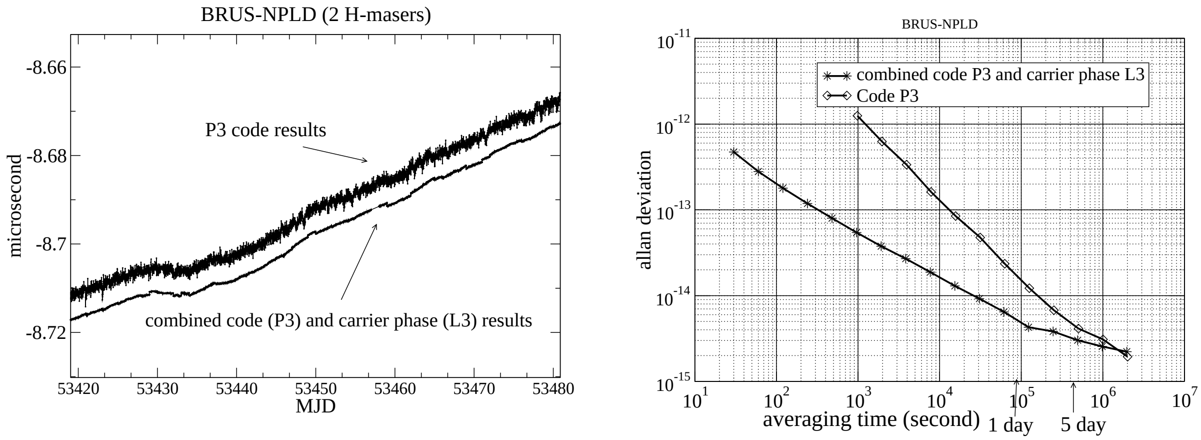

Figure 2: left : Comparison between the time transfer results obtained with precise codes (ionosphere free combination P3) or combined code-carrier phases (ionosphere free combination L3) analysis; the two curves have been separated by 5 nanoseconds in order to improve the visibility. right: allan deviation of the two curves.

al., 2002); some GPS antenna cables exist with very small sensitivity to temperature variations and should be used for precise time and frequency transfer.

Troposphere (zenith total delay)

As the troposphere activity varies rapidly, the troposheric delay must be corrected using either Water Vapor Radiometer (WVR) measurements or by an estimation of the parameters of a given tropospheric model. In that case, there will be a correlation between the tropospheric parameters determined and the clock solution, because both appear in the equation to be solved. As shown by Hackman and Levine (2004), this can lead to differences up to 300 ps in the clock solution between the solutions obtained either using WVR data for the troposphere delay or using an estimation of the tropospheric parameters. This is illustrated in Figure 3.

Reaction of the receiver to frequency changes

We recently tested the fidelity of GPS receivers to the external frequency standard used to drive them (Defraigne and Bruyninx, 2005). For this, we connected two GPS receivers to the same antenna and to two separate atomic frequency standards. The time and frequency transfer results obtained from the GPS code and carrier phase data analysis were then compared with the measurements of a phase comparator connected to the two frequency standards. The numerical differences obtained in this study were of course related to the receiver type. On the short term, we measured differences of tens of picoseconds between the GPS results and the phase comparator. On the long term, 3 weeks in our case, the maximum differences reached 180 picoseconds peak-to-peak, after correction for the day boundary jumps. These differences between the GPS timing results and the phase comparator seemed to be caused by a smoothing of the phase measurements within the GPS receiver.

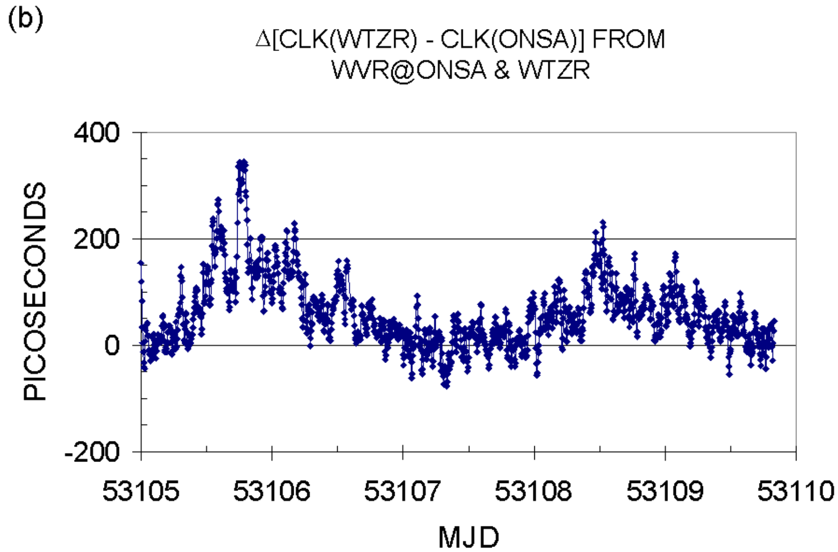

Figure 3: (from Hackman and Levine, 2004) Difference between the time transfer results obtained with estimated tropospheric delay and those obtained using Water Vapor Radiometer data. The stwo stations used are in Wettzel (Germany) and Onsala (Sweden).

GPS analysis strategy

The clock solutions can be obtained either through a network analysis or in a PPP (Precise Point Positioning) process. In the first case, all the station clocks are determined in a global solution, and these clock solutions correspond to the clock synchronization errors with respect to a reference time scale which can be either one clock in the network, or a combination of the network clocks. In the PPP analysis, the clock solutions of one single station are determined with respect to a reference time scale (GPS time or IGS time scale). In that case, the satellite orbits and clocks are taken from some external source, as for example the IGS products.

To compare the PPP and network results we express them both with respect to the IGS time scale. This time scale is provide by the IGS with a 1-day delay. IGST (or IGRT for the rapid version) is realized from the IGS clock combinations, i.e. satellite and receiver clock offsets (Kouba and Springer, 2001; Senior et al., 2003, Ray and Senior, 2003), and is based on code/phase time transfer between IGS receiver and/or satellite clocks.

Figure 4 shows the differences between the PPP and network solutions. The differences obtained between both kinds of analysis can be up to 400 picosecond peak-to-peak in the clock solutions, depending on the analysis software used among the existing tools. For longer data batches, the differences can reach 800 ps due to the day boundary jumps mentioned above. Also the final IGS clock solution which gives the clock synchronization errors of all the station clocks with respect to the IGST or IGRT is shown in this Figure. This IGS clock solution can be used by the IGS stations for a short term monitoring of their clocks.

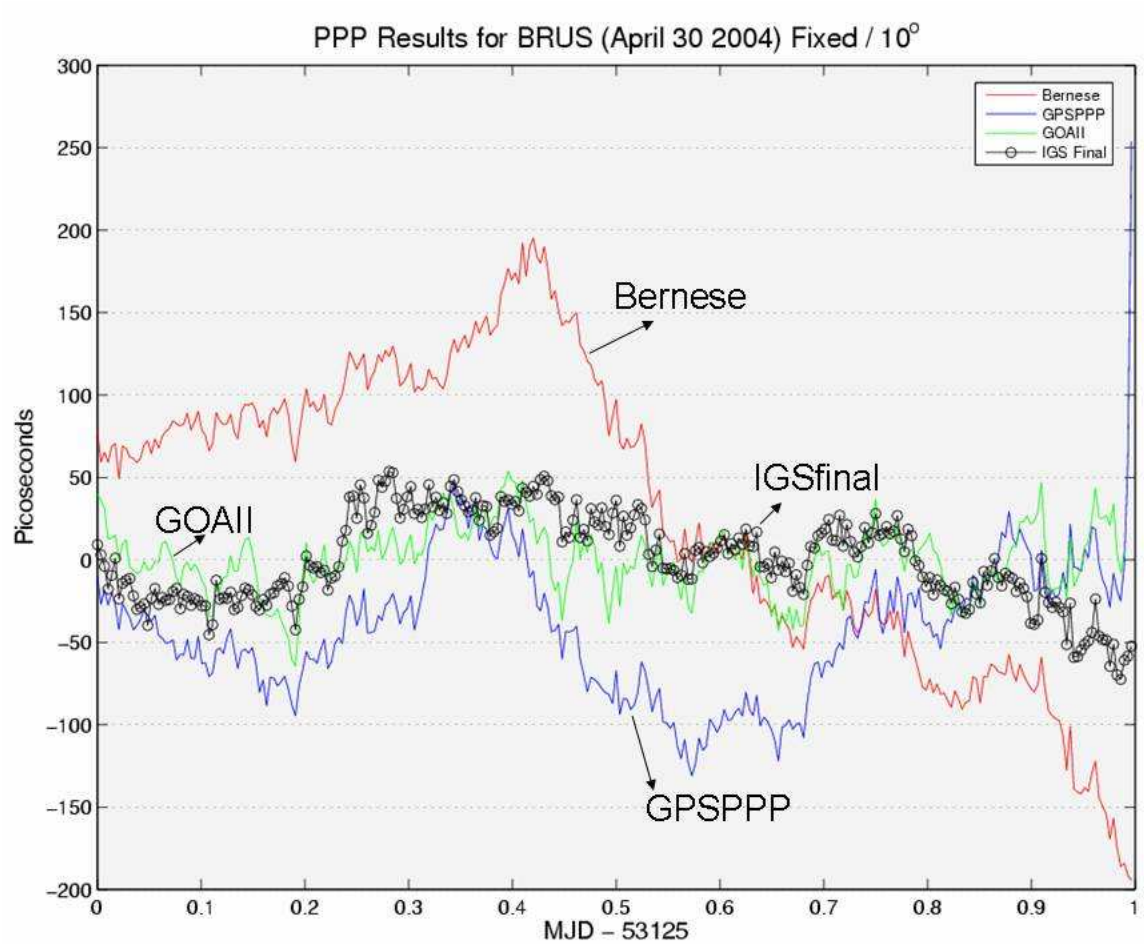

Figure 4: Results obtained for the clock solution BRUS-IGST with either a PPP solution, using different software tools, or the network solution computed by IGS (final).

3. CONCLUSIONS

This paper presented a summary of the capabilities and limitations of the present GPS data analysis for time and frequency transfer. The carrier phases are a very efficient tool for short term clock comparisons. The major factor limiting their use is the day boundary jumps, as illustrated by the Figure 5 which presents the different uncertainty sources in the combined GPS code-carrier phase data analysis for time and frequency transfer. These jumps can reach 500 ps or even more for some receivers. One parameter not yet tested in detail is the network geometry, and should be the subject of a further study. Furthermore, the accuracy of the calibration was not mentioned in this study. This calibration presently limits the determination of the absolute offset between the remote clocks to an uncertainty of 2.5 ns. However the hardware delay should not deteriorate the frequency comparisons as it is constant with time (for instruments in temperature stabilized rooms).

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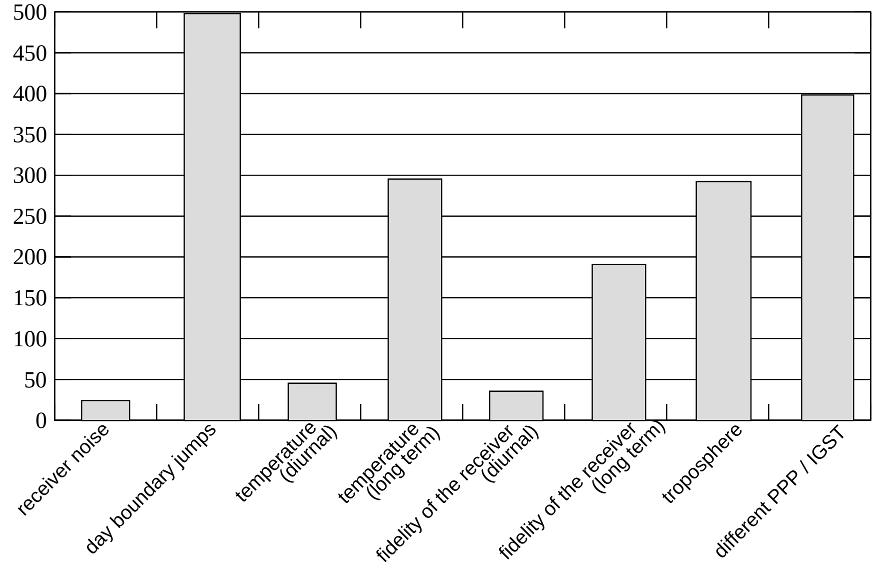

Figure 5: Summary of the uncertainty sources on combined GPS code-carrier phase data analysis for time and frequency transfer.

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