

# Time and Frequency Transfer Using GNSS

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## *Introduction*

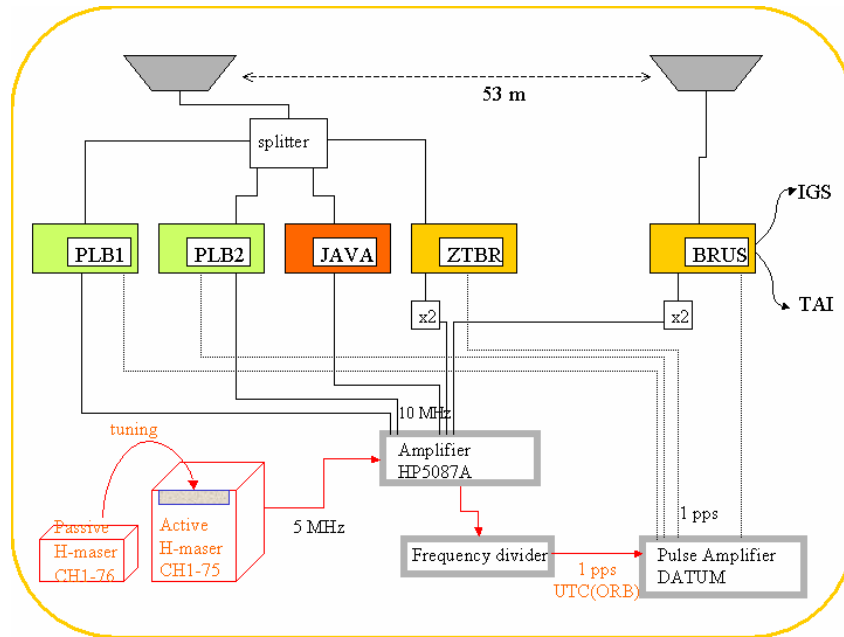
At the Royal Observatory of Belgium (ROB), we are presently computing time transfer using two Common View techniques based on geodetic receivers connected to High Frequency Standards. The first one is the standardized processing of GPS pseudoranges, following the BIPM schedule, using P3 and IGS orbits, with the RINEX-CGGTTS conversion software developed at ROB (Defraigne and Petit, 2003). The second one is a combined code-carrier phase analysis based on the Bernese software V4.2. These analysis methods were previously used to demonstrate the influence of ambient temperature variations on the time transfer results (Bruyninx et al., 1999, 2000). We are presently looking at the suitability of several kinds of geodetic receivers for very precise time/frequency transfer: the Topcon Legacy-E (Javad) and the Septentrio PolaRx2, together with the Ashtech Z-XII3T whose suitability has already been demonstrated. We then investigate the possible improvement that we can reach by adding the GLONASS P-codes and the future Galileo signals into the time transfer applications.

## *Testing different geodetic receivers*

The production of the Ashtech Z-XII3 (the core of the Ashtech Z-XII3T) will be discontinued and repair services will only be available for the Z-XII receivers for as long as replacement parts are available, with end-of-life estimated to occur in October 2004. For this reason we are presently investigating the use of a new geodetic receiver, the PolaRx2, developed by Septentrio (Belgium). This receiver provides dual-frequency tracking of the GPS signal and simultaneous tracking of up to 6 Space-Based Augmentation System (SBAS) satellites. Its raw measurements and navigation data can be converted into the RINEX format using a conversion utility provided by Septentrio. Furthermore, the receiver accepts a 10 MHz external frequency and an associated 1 pps input, which makes it suited for time transfer applications. The synchronization of the internal clock on the 1pps input signal was realized previously with an ambiguity of 8.33 ns, but this problem has now been solved by Septentrio leading to a constant offset between the 1pps input signal and the internal clock. Furthermore, the relation between the latching of observations and the external clock can also be obtained from the 1 pps output which is synchronized with the internal clock. This allows, by differential analysis of the code measurements, to determine the internal hardware delays of the receiver (see Defraigne et al., 2003).

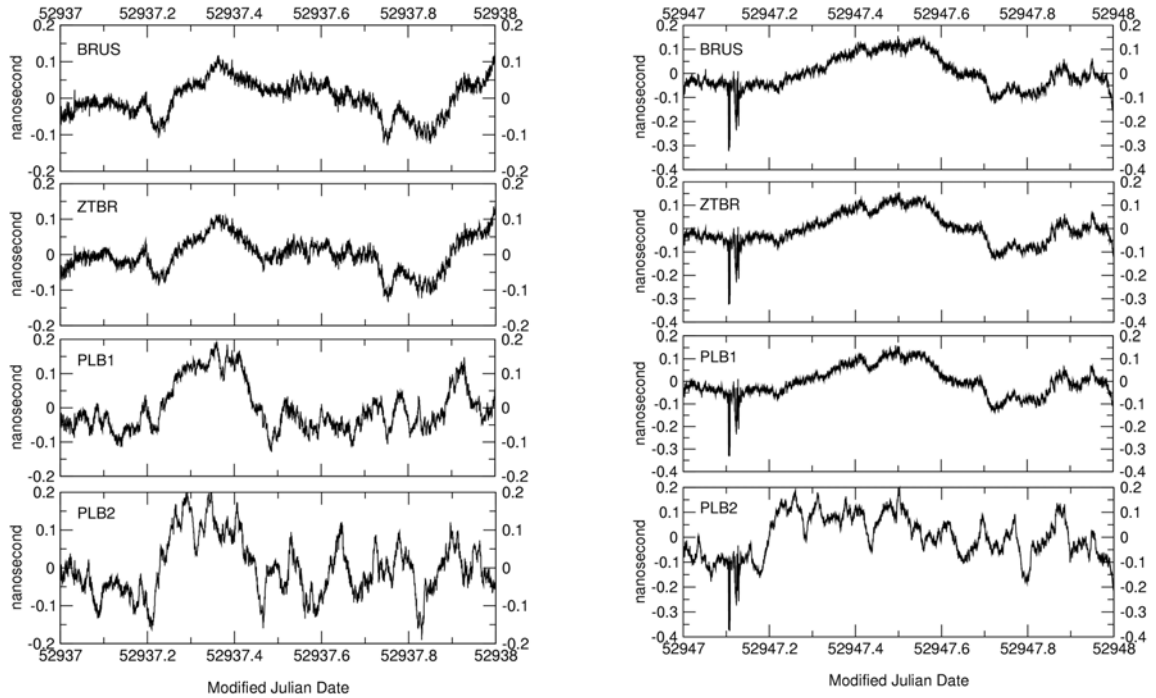
In order to investigate their ability to participate to time transfer studies, two PolaRx2 receivers (named PLB1 and PLB2) were installed at the Royal Observatory of Belgium, in addition to the two Ashtech Z-XII3T receivers (named ZTBR and BRUS). Finally a Javad receiver (named JAVA) was installed during one month. Four receivers (PLB1, PLB2, JAVA and ZTBR) were connected to the same Ashtech antenna (type Dorne Margolin, ASH701945B\_M) with a one input, four output GPS splitter (type S14, from GPS Source Inc.); the RGB233 antenna cable is about 50 m long. The BRUS receiver is connected to a similar Ashtech antenna (using the low-loss 85 m heliax LDF250A cable from Andrew Cooperation), but located on the IGS reference marker about 53 m from the other antenna. This receiver is used for the participation to the IGS as well as to the TAI. All receivers are located in the same laboratory where temperature

variations are limited to  $0.1^{\circ}\text{C}$ , and are driven by a multiple (x2 or x4) of the 5 MHz frequency provided by ROB's active Hydrogen Maser CH1-75 (KVARZ). The 1 pps is obtained from the same 5 MHz frequency using a frequency divider developed in-house, and amplified with a distribution amplifier DATUM (see Figure 1). This signal corresponds to our local realization of UTC as time laboratory: UTC(ORB).



**Figure 1.** setup

Using a combined code and carrier phase analysis with the Bernese V4.2 analysis software, we computed the time link between BRUS and USNO for all of our four receivers. Our first results showed significant discrepancies (below the 1 ns level) between the signals obtained with the Z-XII3T or the PolaRx2 receivers, as well as between the signals obtained with the two PolaRx2, while there was a very good agreement between the signals obtained with the two Z-XII3T, although they were tracking on separate antennae (see figure 2, left). From discussions with Septentrio, and from the observed daily repeatability of the variations obtained with PLB1 and PLB2, emerged the hypothesis that the variations obtained with the PolaRx2 could be due to temperature variations associated with the variable load on the receiver's channels when tracking different amounts of satellites. These temperature changes induce variations of the internal hardware delays and hence of the determination of the time signal. We then tested with PLB1 an option of the receiver, which consists in fixing the number of channels used, and we got results in good agreement between the PLB1 and Ashtech results (see figure 2, right). Also now, a new firmware has been proposed by Septentrio, forcing a constant use of the processor, and the tests made with this new firmware show that the problem is solved.

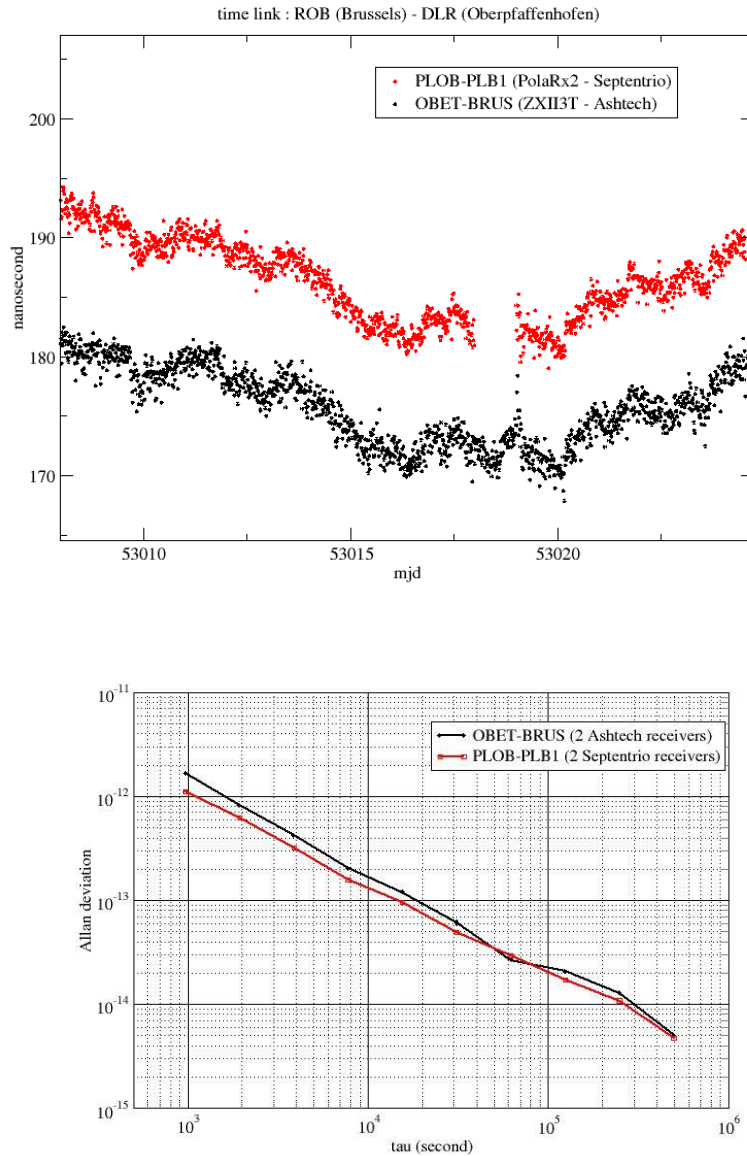


**Figure 2.** Time link (detrended) between USNO and each of the four receivers installed at ROB, based on a combined code and carrier phase analysis. (left) both PLB1 and PLB2 are tracking on variable numbers of channels; (right) PLB1 is using the fixed 8-channel option while PLB2 tracks variable number of satellites.

The noise level specifications on the pseudoranges for the Septentrio receiver are smaller than the corresponding values for the Ashtech receiver. This was confirmed by an analysis of the difference of pseudoranges between our two PolaRx2 receivers, in comparison with the differences of pseudoranges of two Ashtech receivers set up on a same antenna during a calibration campaign (not shown here). An advantage of this reduced code noise level will be the reduction of the day boundary jumps that are inherent in the combined code and carrier phase analysis for time transfer. Indeed, these jumps are due to the unknown phase ambiguities so that the absolute time differences can only be determined using the code information, and this with the limitation of the code noise level. This induces a jump at the boundaries of the data blocks analysed, i.e. at the day boundaries in our case. We applied the Bernese time transfer analysis on a zero baseline between the two Septentrio receivers (PLB1 and PLB2) and between one Septentrio and one Ashtech receiver (PLB1 and ZTBR). The results show a clear improvement in the jumps at the day boundaries: the mean jump is 0.6 ns (with a rms of  $1.3 \times 10^{-4}$ ) for the link PLB1 - ZTBR and 0.3 ns (with a rms of  $6.6 \times 10^{-3}$ ) for the link PLB1 - PLB2.

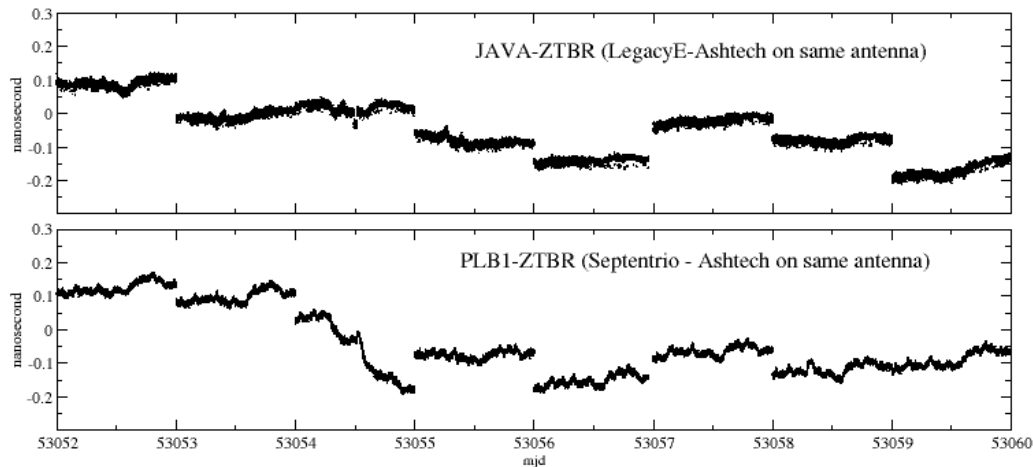
Furthermore, we investigated the use of the Septentrio receiver for time transfer with code only using the BIPM standardized processing on a regional baseline. We computed the time link between the ROB and the DLR (Germany). In each station, two receivers (one Ashtech and one Septentrio) are driven by a same clock: the active H-maser at the ORB and a HP5071A at the DLR. At the ROB these are named respectively BRUS and PLB1 and at the DLR, OBET and PLOB. The time link between the two clocks can therefore be obtained using either two

Septentrio receivers or two Ashtech receivers. The improvement obtained when using the Septentrio receivers is shown in Figure 3.



**Figure 3.** (upper part) Time link between the ROB and the DLR using either Ashtech receivers or Septentrio receivers. (lower part) Allan deviation of the time link for both cases.

We also tested a Topcon receiver LegacyE. Some preliminary results obtained with the Bernese analysis software are shown in Figure 4. They correspond to a zero baseline between the receivers connected to the same antenna (PLB1-ZTBR and JAVA-ZTBR) or a very short baseline (BRUS-ZTBR). The noise level of the link (which comes from the carrier phase data) is clearly smaller with the Septentrio than what we got with the Topcon, but this should be confirmed in further analyses.

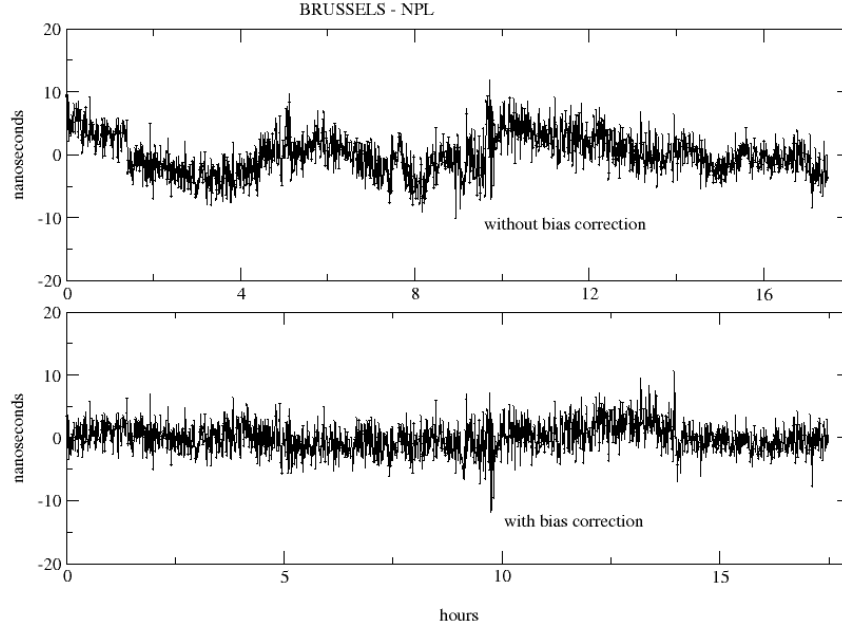


**Figure 4.** Comparison between three types of receivers: preliminary results

### ***Time transfer with GLONASS P-code***

We have also used GLONASS P1-code measurements from different geodetic GPS/GLONASS receivers (Roosbeek et al., 2000, 2001a and b), to perform frequency/time transfer between remote clocks. Because the frequencies used by GLONASS satellites are different, the receiver hardware delays are different for each satellite frequency. In consequence, the time transfer results are affected by a variable 'mean' hardware delay, corresponding to the mean of the delays of the observed satellites at each time. For GPS, the hardware delay is the same for each of the satellites, inducing a constant offset, but which does not affect the shape of the curve. For GLONASS, the obtained time transfer signal presents some small jumps or curvatures not attributable to the clocks, but to the hardware delays. This is illustrated in Figure 5 where we present the time transfer between the ROB and NPL (Teddington) using the GLONASS P1-code; both stations were equipped with 3S Navigation receivers R100-30T.

Presently, there are no calibration values available for the GPS/GLONASS receivers. In order to remedy to this lack of calibration values, we made an attempt to estimate, directly from the common view code residuals, the differential calibration values for a specific baseline and relative to a reference satellite. Our experiments showed that the noise of common view code residuals is of the same order of magnitude (some *ns*) as the hardware delays that we have to determine. However, we could determine some differential satellite biases and introduce them in the time transfer results, to get a new solution, where a good proportion of the jumps or fluctuations are mitigated (see Figure 5, lower part).



**Figure 5.** Time transfer between the ROB and NPL (Teddington) using the GLONASS P1-code;

Because of this calibration problem, we did not continue to use the GLONASS P-code for time transfer applications. This could be reinvestigated if the evolution of the GLONASS system is in favor of a larger constellation of satellites

### ***Time transfer with GALILEO***

Similar to GPS, Galileo users will be able to make pseudorange measurements (on two or more frequencies) and to receive broadcast navigation messages (satellite orbits and clock parameters). Therefore, the basic scheme of the GPS Common View processing can be also applied for Galileo. Furthermore, due to the service guarantees that Galileo will provide to its users, Galileo-based time transfer has a chance to become a primary tool for applications which require not only high accuracy, but also high continuity and integrity. Here we discuss accuracy improvements in time transfer based on a combined usage of GPS and Galileo. A more detailed study of potential utilization of Galileo for timing applications is presented in Moudrak et al., 2004 or Furthner et al., 2003.

Common View time transfer can be easily implemented with combined GPS/Galileo measurements (calibration problems will be not considered here). The GPS Common View pre-processing procedure (see Defraigne and Petit 2003) provides estimates  $\Delta t_{i,GPS}^k$  of the offset between the clock reading of i-th user  $t_i$  and the GPS Time obtained from measurements of k-th GPS satellite. This estimate contains also an error due to the uncertainty of the satellite clock parameters  $\Delta t_{GPSsat}^k$ , and a cumulative error  $\varepsilon_{i,GPS}^k$  due to uncertainties of the satellite ephemeris, uncompensated tropospheric errors, multipath effects and errors of the hardware calibration. Similar components will be obtained when the Common View pre-processing is applied to Galileo observations, but in that case the reference time scale will be Galileo System Time (GST):

$$\begin{aligned}\hat{\Delta t}_{i,GPS}^k &= t_i - GPStime + \Delta t_{GPSsat}^k + \varepsilon_{i,GPS}^k \\ \hat{\Delta t}_{i,Gal}^l &= t_i - GST + \Delta t_{Galsat}^l + \varepsilon_{i,Gal}^l\end{aligned}$$

The difference of the estimates  $\hat{\Delta t}_i^k$ , calculated at two remote sites (provided that they are obtained from simultaneous observations of satellites visible from both locations), gives the offset  $\hat{\Delta t}_{12}^k$  between the user clocks at these sites for the observation epoch:

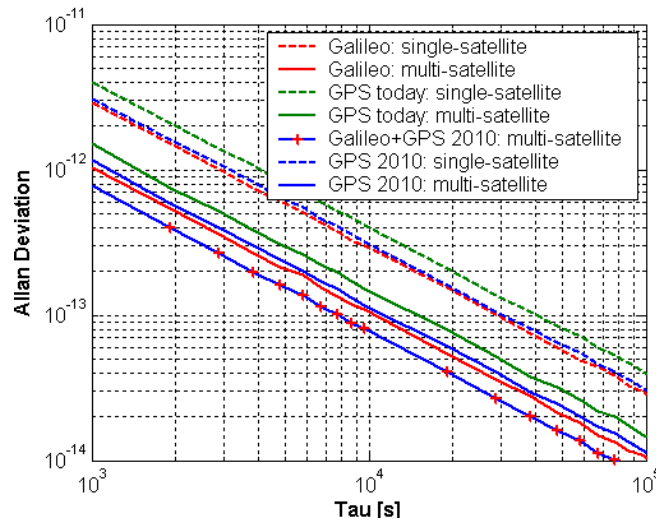
$$\begin{aligned}\hat{\Delta t}_{12,GPS}^k &= \hat{\Delta t}_{1,GPS}^k - \hat{\Delta t}_{2,GPS}^k = t_1 - t_2 + \Delta \varepsilon_{12,GPS}^k \\ \hat{\Delta t}_{12,Gal}^l &= \hat{\Delta t}_{1,Gal}^l - \hat{\Delta t}_{2,Gal}^l = t_1 - t_2 + \Delta \varepsilon_{12,Gal}^l\end{aligned}$$

The equations above contain no terms related to the offset between GPS Time and GST. The straight-forward way to combined GPS and Galileo data is to average estimates  $\hat{\Delta t}_{12}^k$  (see above) over all simultaneously visible GPS and Galileo satellites (M and N respectively) since the error budget of modernized GPS and Galileo will be similar:

$$\hat{\Delta t}_{12,GPS+Gal} = \frac{\sum_{k=1}^M \hat{\Delta t}_{12,GPS}^k + \sum_{l=1}^N \hat{\Delta t}_{12,Gal}^l}{M + N}$$

Obviously, users of combined GPS/Galileo equipment will have more simultaneously visible satellites than users of only GPS or Galileo. Our simulations showed that

- for two stations located in Germany (DLR and PTB) the average number of simultaneously visible satellites increases from 7.6 (GPS only) to 15.6 (GPS+Galileo),
- for an intercontinental link (DLR and the US Naval Observatory) the average number of simultaneously visible satellites increases from 3.6 (GPS only) to 7.3 (GPS+Galileo).



**Figure 6.** Allan deviation of simulated common view results

To assess the improvement of GPS+Galileo Common View precision, we simulated GPS and Galileo observations for two sites (DLR and PTB) and processed them following the procedure described in Defraigne and Petit, 2003. Both single-channel and multi-channel (all

simultaneously visible satellites) Common View was considered. User clocks were not simulated since we were interested in assessing the noise of the Common View procedure itself. Figure 6 presents the Allan Deviation of Common View time transfer with Galileo, GPS and their combination (present and modernized with better ephemeris data, ionosphere and troposphere models). The results indicate that we may expect that the Allan Deviations of the combined GPS+Galileo Common View to be about a factor of 2 better than the results presently obtained with GPS.

## ***Conclusion***

In this paper we have shown that the Septentrio receiver PolaRx2 is suitable for precise time and frequency transfer and is a very good candidate to replace the Ashtech Z-XII3T. The Topcon receiver LegacyE was also tested, and the preliminary results obtained here show also a good suitability for frequency transfer. However, to see exactly how a receiver reproduces the frequency changes, two separate clocks should be used for both receivers used in the time transfer analysis, and these same clocks should be monitored by an independent technique. This will be the next step in our studies. We have also shown the main limitation of the GLONASS-P code for time transfer, coming from the differential biases between the satellite results, which are due to the different receiver hardware delays associated with the different frequencies. We have then investigated the improvements that we can get from using a combination of the future Galileo with the GPS for time transfer with code only. The results of simulations indicate an improvement of about a factor of 2 with respect to the results obtained presently with GPS.

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