GALILEO COMMON VIEW: FORMAT, PROCESSING, AND TESTS WITH GIOVE

Pascale Defraigne
Royal Observatory of Belgium (ROB)
Avenue Circulaire, 3, B-1180 Brussels, Belgium
e-mail: ***p.defraigne@oma.be***

M. C. Martínez-Belda
Dept. Matemática Aplicada, Escuela Politécnica Superior,
Alicante University, P. O. Box 99, Alicante 03080, Spain

Abstract

R2CGGTTS is a software program dedicated to provide clock solutions for GNSS time transfer in the standard CGGTTS (Common GPS GLONASS Time Transfer Standard) from RINEX observation files. This paper presents the upgrade of the R2CGGTTS to include observations of the future Galileo satellites; the approach is validated using the GIOVE data. A second part of the paper presents the possibilities of the future Galileo E5 signal, of which the very small noise level promises a large improvement to the GNSS time transfer accuracy.

INTRODUCTION

Precise time transfer between ground clocks by GPS Common View has been tested already by the 1980s **[1]**. In the early 1990s, the processing and data format for this time transfer method was standardized by the Consultative Committee for Time and Frequency **[2]**. The data processing of GPS Common View was originally defined for single-channel GPS user equipment receiving the GPS Standard Positioning Service signal (based on the C/A-code) when the Selective Availability (SA) mode was active. After it was extended to GLONASS, the format and the corresponding processing were referred as CGGTTS (Common GPS GLONASS Time Transfer Standard) **[3]**.

Following the discontinuation of SA mode and the progress of GPS user equipment with multi-channel receivers processing not only L1 C/A, but also decoded Precise Positioning Service signals in L1 and L2 bands (P1 and P2 respectively), the GPS Common View procedure was updated **[4]**. The revised procedure is based on GPS dual-frequency measurements, using the so-called ionosphere-free P3 combination, and uses 30-second measurements, while the original CGGTTS was based on 1-second data.

Galileo signal has been on the air since December 2005, when the first experimental Galileo satellite GIOVE-A was launched. Presently, there are two experimental Galileo satellites in operation, GIOVE-A and GIOVE-B, and the first four operational Galileo satellites (building the Galileo In-Orbit Validation [IOV] constellation) are due for launch in 2011. It is, thus, time now to investigate the use of these new GNSS data for time transfer. GIOVE satellites transmit the ranging signals using all the code modulations currently foreseen for the future Galileo, and provides, therefore, a foretaste of their performance in real-life applications.

In the first section of the paper, we propose Galileo Common View processing based on the GPS P3 procedure defined in **[4]** and making use of the dual-frequency Galileo Open Service signals (E1 and E5). Initial tests with GIOVE observations from the GIOVE ground network will be presented. In a second part of the paper, we investigate the use of the very precise Galileo E5 code for time transfer applications, and demonstrate the possible improvements using the experimental GIOVE satellites observations.

CGGTTS WITH GALILEO

The procedure used to compute the CGGTTS results from RINEX files, as proposed in **[4]**, can be summarized as follows. At each epoch defined by the BIPM schedule, and for each individual GPS satellite, the ionosphere-free combinations P3 of raw pseudoranges P1 and P2 at 30-second sampling rate are collected during 13 minutes (leading to 26 data points). These 26 points are then corrected for: geometric delay (computed with antenna coordinates and broadcast ephemerides), tropospheric delay (computed with Hopfield's model with standard atmosphere values), the Sagnac effect, the periodic relativistic effect associated with the satellite orbit, receiver hardware delay, and antenna and local clock cable delays. The final CCTF results for each satellite track are obtained after performing two linear fits. A first one is applied on the 26 corrected data points, and the value of this fit at the midpoint of the track is given as "UTC (k) - Tsat" (column REFSV in the CGGTTS files). A second linear fit is applied on the 26 points additionally corrected for the satellite clock offset using the broadcast polynomial parameters. The final result of the track for "UTC (k) - SYS time" (column REFSYS in the CGGTTS files) is the value of this second linear fit at the midpoint of the track. In a post-processing, the BIPM then corrects these results for the difference between the broadcast satellite orbits and clocks, and precise orbits and clocks provided by the IGS.

The present version of the R2CGGTTS software only applies for RINEX 2.xx observation and navigation files. In order to upgrade it to Galileo, we first modified the software to allow processing with RINEX 3.xx files. Then, some first processing of GIOVE data was done with the ionosphere-free combination of E1 and E5b signals. With that aim, the observations of two stations of the Galileo Experimental Sensor Stations (GESS) network were used: GNOR (ESTEC, The Netherlands), and GUSN (USNO), both equipped with an H-maser. In order to be independent of the reference time scale of the system, and to be able to compare the results with GPS results, we present here the time link between these two stations obtained via Common View. The reference time scale, which is different for GIOVE clocks and for GPS satellite clocks, indeed disappears in Common View. Figure 1 presents the results obtained with broadcast satellite orbits and clocks, while Figure 2 was obtained with the post-processed CONGO orbits and clocks **[5]**. Only GIOVE-B was used, as the broadcast orbits of GIOVE-A were not of sufficient quality at the epochs tested. Note that the epochs chosen for the two figures are different due to the availability of the orbits. This, however, does not impact the conclusions.

We can conclude from these preliminary results that the ionosphere-free combination based on E1 and E5b produces clock solutions with a similar noise level as the GPS ionosphere-free combination of P1 and P2. We also looked at the comparison of the noise obtained by different GPS satellites and the GIOVE-B satellite. This provides the same conclusion as seen in Figure 3. This also confirms some previous results **[6]** where GIOVE data were used in a code-only analysis to provide clock solutions which were then compared to the results of a similar analysis of GPS data. Note that the comparison proposed in Figure 3 corresponds to the specific time link GNOR-GUSN. As the major component of the noise level of the clock solution is the code multipath, it is of course station-dependent. A clear illustration of this multipath is given by the PRN 25 (Block IIF), for which one point appears each day at the same time at more than 5 ns from the other points. This daily repetition comes from the schedule used for the tracks in the CGGTTS: the schedule repeats with an exact 1-sidereal-day period, i.e. the repeat cycle of the GPS constellations with respect to the ground.

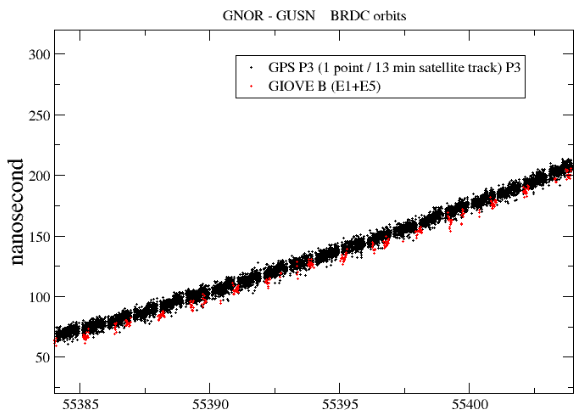

Figure 1. Time transfer between GNOR (ESTEC, the Netherlands) and GUSN (USNO) obtained via Common View from CGGTTS results with broadcast satellite orbits and clocks.

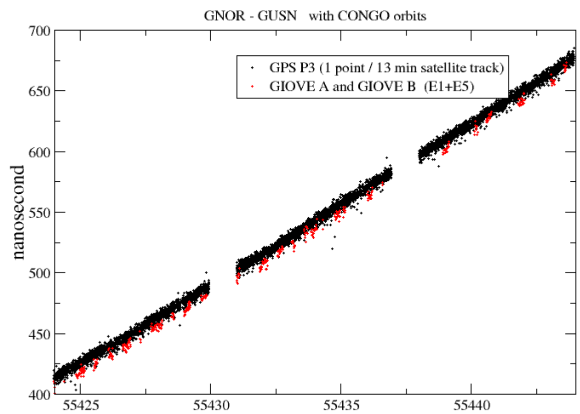

Figure 2. Same as Figure 1, but with the CONGO reprocessed orbits and clocks.

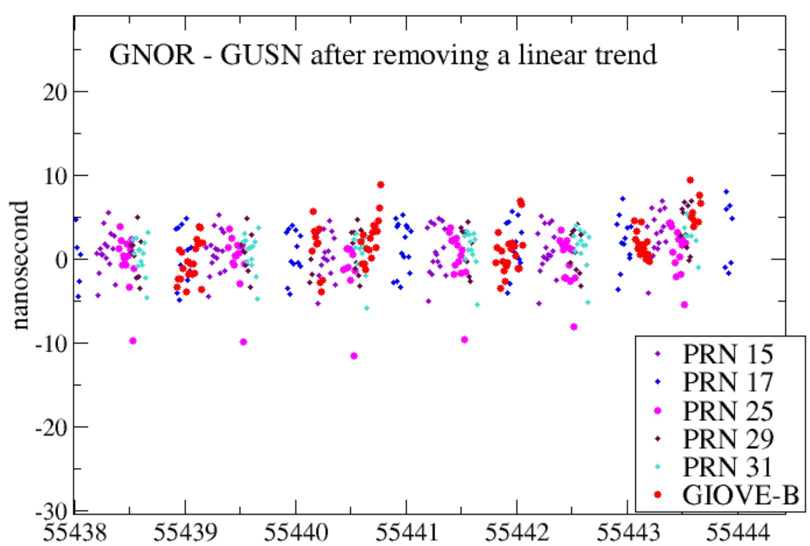

Figure 3. Time transfer obtained via Common View from CGGTTS results with the CONGO reprocessed orbits and clocks; comparison between the results obtained with GIOVE-B and some GPS satellites.

In order to test the sensitivity of the results to the choice of the signal used in the ionosphere-free combination, we plotted in Figure 4 the Common-View results obtained with GIOVE-B using E1 with either E5a, E5b, or the full E5 signal E5(a+b) (or E5AltBOC). No significant differences were found between the three sets of results.

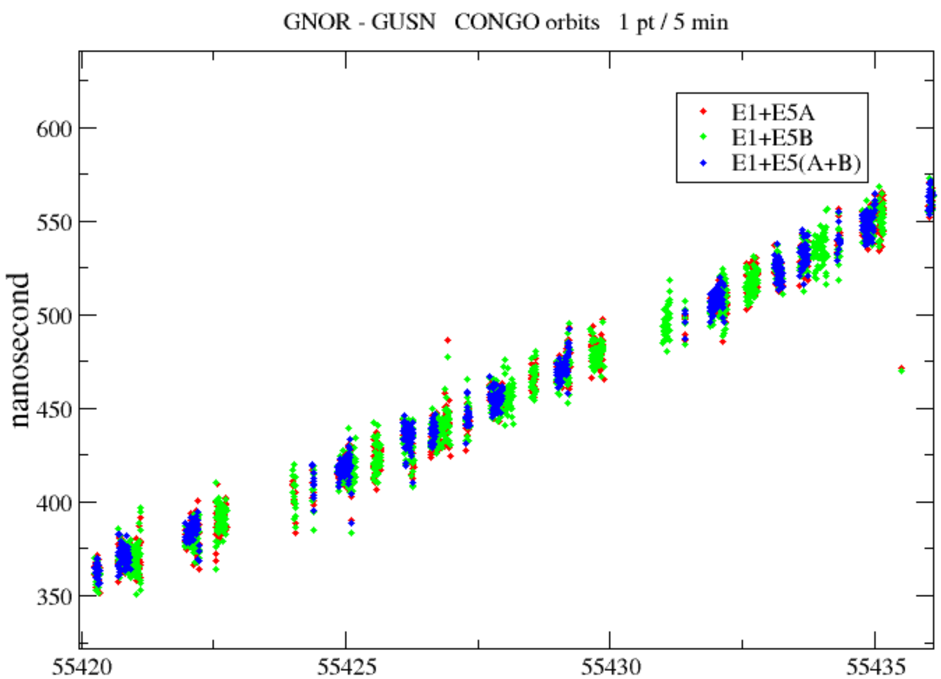

Figure 4. Time transfer obtained between GNOR (ESTEC, the Netherlands) and GUSN (USNO) obtained by Common View from CGGTTS results computed with the CONGO reprocessed satellite orbits and clocks; comparison between different ionosphere-free combinations.

From this experience using GIOVE data for generating CGGTTS results, we can conclude that the ionosphere-free combinations of the future E1 and E5 Galileo signals will provide similar performances as the present combinations of GPS P1 and P2. We, however, noticed the difficulty using the GIOVE broadcast orbits in post-processing, due to the fact that several sets of parameters (IOE) appear with the same reference epoch, but with a different message, while only the message transmitted at the epoch of observation can be used. It was, therefore, necessary to use the hourly navigation files. One solution to this difficulty could be to compute directly the CGGTTS results with some reprocessed orbits rather than with the broadcast orbits with later a correction for the difference between broadcast and precise IGS orbits. That could be done also for GPS data, using directly the IGS products in the R2CGGTTS software. Of course, the alternative is to perform a PPP computation rather than a classical R2CGGTTS, if the RINEX observation file is available with dual-frequency code and carrier-phase data.

POSSIBLE EVOLUTIONS OF THE CGGTTS FORMAT

The CGGTTS, or even before the CCTF standard, was originally dedicated to GPS. Some adaptations would, therefore, be required to include the Galileo results. One column specifying the constellation was already proposed by the CCTF in 2006, with one letter similar as what is used in the RINEX 3.xx, i.e. G for GPS, R for GLONASS and E for Galileo. Furthermore, the acronyms of the possible frequency

combinations used for the different constellations should be defined. Presently, L1C and L3P are used for either the C/A code or the ionosphere-free combination of P1 and P2 for GPS and GLONASS. We also suggest changing the name of the standard, which presently explicitly points to GPS and GLONASS.
The use of a given observation schedule and the 13-minute track duration were also fixed by the GPS system: the schedule has been designed in agreement with the revolution period of the GPS satellite, and the track duration was fixed correspondingly to the time required to get a full navigation message. Of course the schedule can be used for GLONASS and Galileo (and the future COMPASS system) even if we do not have a same repeatability of the satellite visibilities for these systems. This daily repeatability is currently no more necessary: it allowed retrieving the same visibilities of common satellites for the intercontinental links, but as the CGGTTS is presently mainly used for All in View rather than Common View, the daily repeatability of the visibility is not needed any more. Concerning the duration of the tracks, no study has been done up to know for some optimal duration, but the 13 minutes are still working well, reducing the noise level of the pseudoranges. This duration could, therefore, be kept up to a complete move from CGGTTS to another standard (like PPP, for example).

USING GALILEO E5 PSEUDORANGES FOR TIME TRANSFER

Due to the use of advanced code modulations, the ranging signals of Galileo provide significant improvement of the multipath performance as compared to current GPS. E5AltBOC demonstrates the highest multipath suppression as compared to other signals and very low magnitude of average multipath errors, down to the values about 20 cm **[7]**. Thanks to this very precise GNSS pseudorange, we can find a large improvement in time transfer accuracy. We should, however, use it without any combination with another code signal in order to avoid an increase of the noise level. The idea proposed here is to use the Code-plus-Phase (CPC) ionosphere-free combination. Indeed, the pseudorange and carrier-phase observation equations read:

$$E5 = \| x_{rec} - x_{sat} \| - c\Delta t_{rec} + c\Delta t_{sat} + Iono_5 + Trop + \delta_5^P + \varepsilon_5{}^P \quad (1)$$

$$L5 = \| x_{rec} - x_{sat} \| - c\Delta t_{rec} + c\Delta t_{sat} - Iono_5 + Trop + \lambda_5 N_5 + \delta_5^\phi + \varepsilon_5^\phi \quad (2)$$

where x_{rec} is the receiver position, x_{sat} is the satellite position, Δt_{rec} is the receiver clock error, Δt_{sat} is the satellite clock error, $Iono_5$ is the ionospheric delay for the frequency E5, *Trop* is the tropospheric delay, δ_5^P is the receiver hardware delay for the frequency E5, $\varepsilon_5{}^P$ is the pseudorange noise and multipath, N_5 is the carrier phase ambiguity, $\delta_5{}^\phi$ is the initial phase delay, and $\varepsilon_5{}^\phi$ is the carrier phase noise. Adding the first equation to the second one provides the CPC combination, which is ionosphere-free:

$$\frac{E5 + L5}{2} = \| x_{rec} - x_{sat} \| - c\Delta t_{rec} + c\Delta t_{sat} + Trop + \frac{1}{2}\delta_5^P + \frac{1}{2}(\lambda_5 N_5 + \delta_5^\phi) + \varepsilon. \quad (3)$$

The noise and multipath ε of this combination are mainly the noise of the pseudoranges, as the carrier phase noise is significantly lower. Of course, the CPC combination is ambiguous, and a first part of the work will consist in solving the carrier-phase ambiguities. Different approaches can be used for that; one first option will based on the Code-minus-Carrier (CMC) combination:

$$\frac{E5 - L5}{2} = Iono_5 + \frac{1}{2}\delta_5^P - \frac{1}{2}(\lambda_5 N_5 + \delta_5^\phi) + \varepsilon'. \quad (4)$$

Determining the ionosphere at the same time as the ambiguities from the CMC combination should provide the ambiguities required to put in equation (3), which then can be solved as in a classical PPP approach, i.e. determining the receiver position, clock, and either determining or fixing the wet troposphere path delays. That will be studied in the near future. The following results show what we can obtain once the ambiguities are solved.

Figure 5 presents, for the time link GNOR-GUSN, the clock solutions obtained with either the CPC, or the ionosphere-free codes using the combination of E1 and E5(a+b) for GIOVE, and P1 and P2 for GPS. The results are shown for one satellite track of GIOVE-B and of GPS PRN 19, these two satellites appearing visible at the same time for both stations. The clock solutions have been computed using pseudorange observations at a 30-second sampling rate, and correcting them for the geometric distance satellite-receiver, the satellite clock, and the relativistic effect due to the satellite orbit eccentricity, using the IGS orbits for GPS and the CONGO orbits for the GIOVE-B. The troposphere delays were taken from the IGS products (*ftp://cddis.nasa.gov/gps/products/troposphere/zpd*) for USNO and for DLFT (25 km far from GNOR). The station positions were fixed to *a priori* known coordinates. As before, the results are presented in Common View in order to get rid of the reference time scale, which is different for GPS and for GIOVE satellites clock products.

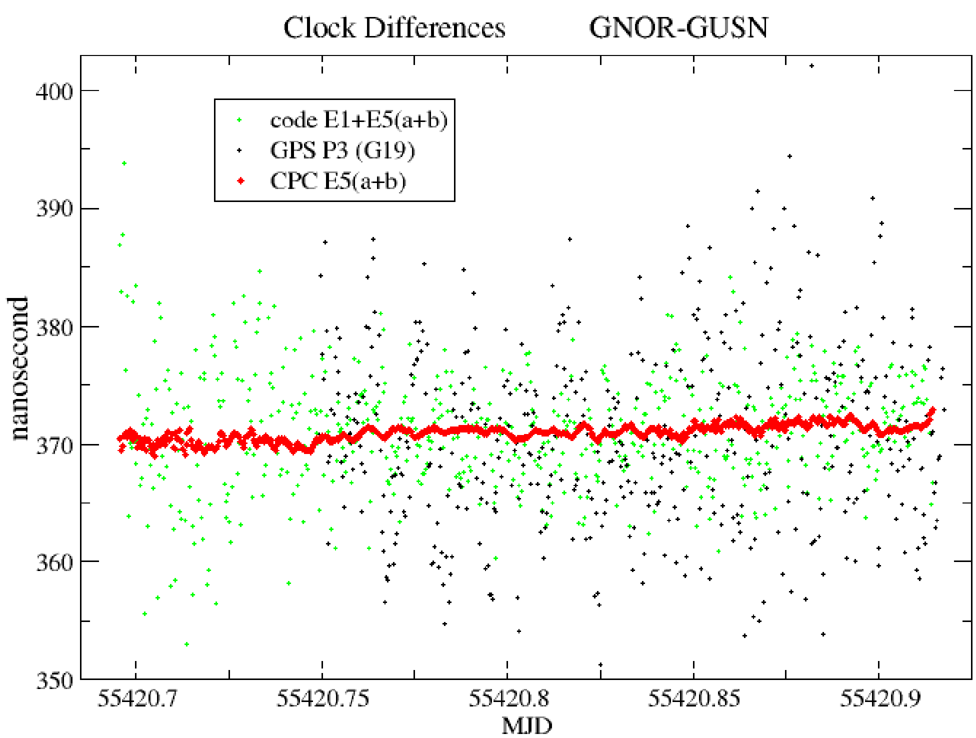

Figure 5. Comparison between the clock solutions obtained with either dual-frequency ionosphere-free combination of pseudoranges, or the CPC combination.

The improvement in terms of noise level obtained with the CPC with respect to the classical dual-frequency ionosphere-free codes appears clearly. The rms of the GPS P3 and of the GIOVE E1+E5AltBOC combinations are about 7.8 and 4.8 ns, respectively, whereas the rms of the CPC E5AltBOC falls down to 0.4 ns. That means that the latter has a noise level about 10 times lower than the ionosphere-free E1+E5 and more than 15 times lower than GPS P3. The small variations of the CPC curve correspond to E5 multipath.

If we do not consider the instrumental calibration issues, the clock solutions so-obtained correspond to the quantity that determines the accuracy of the time transfer solutions. The advantage of the CPC will be, therefore, to improve the accuracy of time transfer with respect to the dual-frequency ionosphere-free combination, i.e. with CGGTTS or PPP, provided that the ambiguities of the CPC are precisely determined.

When using the CPC, there exists a real advantage to use the E5AltBOC signal rather than the isolated E5a and E5b signals. This can be seen from the comparison between the clock solutions obtained from CPC data corresponding to these three signals. This comparison is presented in Figure 6 for the station GNOR, during one track of GIOVE-B. The curves this time correspond to the synchronization error between the station clock and the reference clock of the CONGO products. After removing the linear drift, the rms of the residuals is about 0.26 ns for the E5AltBOC, while it is about 0.60 ns for both E5b and E5a. These rms were computed with all observations above an elevation of 5 degrees. Reducing this to 30 degrees makes the rms fall down to 0.28 ns for E5a and E5b and to 0.12 ns for E5(a+b). In view of this significant difference, the scientific community will have to encourage the manufacturers of receivers for timing applications to give us the ability to measure the E5AltBOC signals.

As explained above, the troposphere delays have been corrected using IGS products. When using a code-only analysis of GPS signal for timing applications like the CGGTTS, only the hydrostatic part of the troposphere delay is usually considered; the wet delay is lower than 1 ns, i.e. in the noise of the GPS codes. When using the Galileo E5 signal for timing applications, it will be necessary to either determine the wet troposphere delay as presently done in PPP (because the wet delay is larger than the GPS carrier phase noise), or to use some external product as we have done here. Using a model of the troposphere for a standard atmosphere is no more sufficient with respect to the precision of the E5 code. Figure 7 illustrates that point: when using the Hopfield model as it is done classically in code-only analysis (e.g. for CGGTTS Common View), some remaining elevation-dependent signal remains in the clock solution. This remaining signal disappears when both the wet and dry components of the troposphere delay are used for the correction.

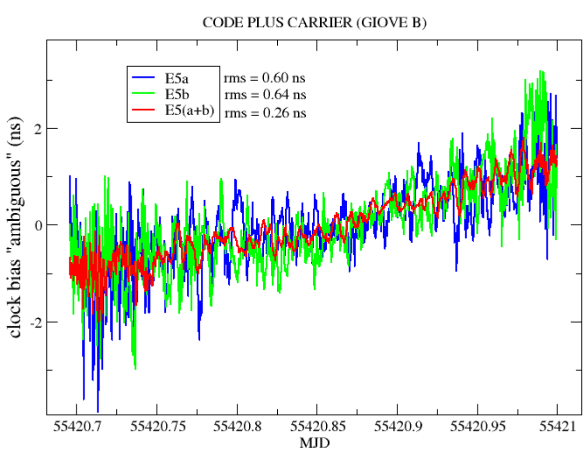

Figure 6. Comparison between the CPC clock solutions for station GNOR, obtained with 30-second data and with E5a, E5b or E5(a+b).

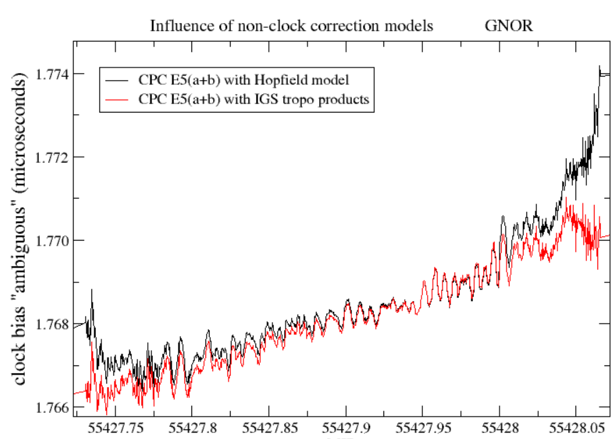

Figure 7. Comparison between the CPC clock solutions obtained with tropospheric corrections from the Hopfield model or with the IGS troposphere products.

The CPC combination can also be carried out with GPS data. This was done using the L1 signal of PRN 19. The associated clock solution is plotted in blue in Figure 8, and shows a noise level about three times larger than the CPC obtained with GIOVE-B. In parallel, the ionosphere-free combination of dual-frequency carrier-phases is shown in orange for the GIOVE-B combination of E1 and E5(a+b) and in violet for the GPS PRN19 combination of L1 and L2. From this comparison, we see that, for the very short term, the ionosphere-free combination of dual-frequency carrier-phases is still more precise than the E5 CPC, as it does not suffer from multipath as the E5 codes. Note that in PPP the ambiguities of these carrier-phase results are determined thanks to the dual-frequency ionosphere-free codes (black dots), while in the CPC approach, the ambiguities of CPC should be determined in a separate way, for example using the determination of both the ionosphere and the ambiguities from the CMC combinations.

CONCLUSIONS

The first part of this paper presented the upgrade of the R2CGGTTS software allowing its use with the future Galileo observations. As the first Galileo satellites should be launched during the next year, it is urgent to consider also how to upgrade the CGGTTS format to include these new observations. The present study did not investigate all aspects of this upgrade, but mentioned already some points to consider. Concerning the CGGTTS results, we have shown that the dual-frequency ionosphere-free combinations of the GIOVE E1 and E5 codes provide the same level of precision as the GPS combination of P1 and P2. We, however, noticed the difficulty of using the current navigation files from GIOVE satellites. This leads us to propose to use directly some reprocessed orbits and clocks (like the IGS rapid or precise products) when generating the CGGTTS files from RINEX observation files. This would simplify the computations and avoid the BIPM correction of the CGGTTS results afterwards for the difference between broadcast and precise orbits. This could also be done for all the constellations.

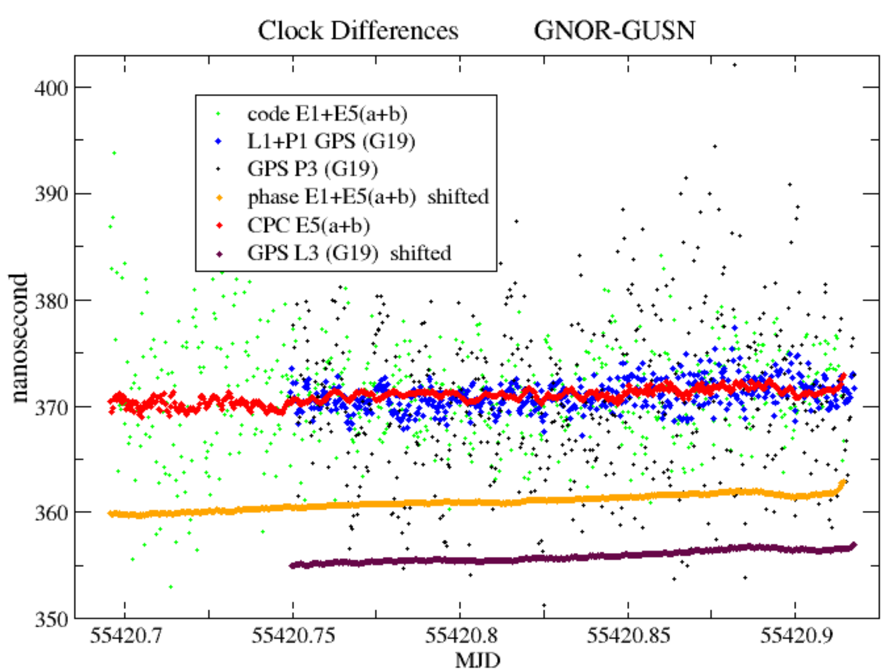

Figure 8. Comparison between the clock solutions obtained with either dual-frequency ionosphere-free combination of pseudoranges, either dual-frequency ionosphere-free combination of carrier phases, or the CPC combination using either GIOVE-B or GPS PRN 19.

The second part of the paper showed the future possibilities of the Galileo E5 code. Thanks to its high precision and low multipath, this code can offer large improvement to the time transfer accuracy. In order to remove the ionosphere delay, a combination of the code and carrier can be done, called CPC for Code plus Carrier. A parallel combination CMC (Code minus Phase) should serve to solve for the ambiguities. We have shown that the ionosphere-free CPC combination is about 10 times less noisy than the ionosphere-free E1/E5 and more than 15 times less noisy than the GPS P3. Using the CPC should, therefore, require precise modeling of the signal as it is done currently for Precise Point Positioning, in regard to the precision of the carrier phases. These carrier phases, even in a dual-frequency ionosphere-free combination, have still a noise level about three times smaller than the E5 CPC noise and should, therefore, still be used for short-term frequency transfer.

ACKNOWLEDGMENTS

We acknowledge the ESA for making their GIOVE data available, and the CONGO team for the GIOVE orbits.

DISCLAIMER

The datasets used for (part/all) of the work presented in this paper have been provided by the European Space Agency. The views presented in the paper represent solely the opinion of the authors and should be considered as research results not strictly related to Galileo or EGNOS Project design.

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Journal of Navigation and Observation, Vol. 2008, Article ID 416380, 13 pp., doi:10.1155/2008/416380.