First investigations on using Galileo E5AltBOC for time transfer

Mari Carmen Martínez-Belda

Applied Mathematics Dept.,
University of Alicante, Spain
Carmen.Martinez@ua.es

Pascale Defraigne

Royal Observatory of Belgium, Belgium
P.Defraigne@oma.be

Summary

Measurements from Global Navigation Satellite Systems (GNSS) are used since the eighties to perform precise and accurate time and frequency transfer (i.e., remote atomic clock comparisons). Using GPS measurements, the time transfer accuracy and precision are limited by the coloured signature of the codes noise, mainly due to near-field multipath. This signature affects the medium-term (from some hours to some days) stability of the solution and induces possible discontinuities at the day boundaries, which can reach the nanosecond level for some stations, mitigating the quality of the results obtained by this technique.

The **European Galileo system** is under development, with currently two experimental satellites and two operational satellites launched in October 2011. Galileo transmits a new civil signal in the E5 frequency band, named the **E5AltBOC code** (E5 hereafter), which has shown to provide **significant improvement of the noise and long-term multipath** performance as **compared to** current **GPS/GLONASS codes**, down to the values about 20 cm. **E5** is then **very promising for** improving the medium-term stability of **time transfer**. This paper presents **new analysis procedures to take benefit of** the very precise **E5 code for time transfer** applications.

1. State Of The Art

PRESENTLY: GNSS geodetic time transfer is used, based on the dual-frequency ionosphere-free combination of both code (P_3) and carrier-phase (L_3) measurements:

$$\begin{Bmatrix} P_3 \\ L_3 \end{Bmatrix} = 2.545 \cdot \begin{Bmatrix} P_1 \\ L_1 \end{Bmatrix} - 1.545 \cdot \begin{Bmatrix} P_2 \\ L_2 \end{Bmatrix}$$

with a consistent modeling of all non-clock contributions to the signals (geometric distance, tides, ocean loading, phase windup, antennas' PCVs, etc.)

• Precision: 0.1 ns (thanks to the very high-frequency stability of the L_3 measurements)
➔ pseudorange noise and multipath are amplified

• Accuracy: given by the codes and the calibration
➔ Noise of P_3: $\sigma_{P_3} = \sqrt{2.54^2 \cdot \sigma_{P_1}^2 + 1.54^2 \cdot \sigma_{P_2}^2} \approx 3 \cdot \sigma_{P_1}$
➔ Pseudorange noise and multipath are amplified

Accuracy of the time transfer solution determined by this technique can only reach the level of a couple of nanoseconds in the best cases

VERY NEAR FUTURE: New code signal in the E5 frequency band, named E5AltBOC (E5 here), offered by Galileo, with very low range noise & great suppression of (long-term) multipath effect [e.g., Simsky et al., ION GNSSS, 2006, Simsky et al., *Int J Obs Nav*, 2008].

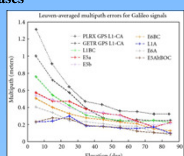

Fig. 1. [Simsky et al., *Int J Obs Nav*, 2008]: standard deviation of code multipath for Galileo signals in comparison to GPS-C/A for some tests in Leuven, Belgium (E5 code in brown).

* * * * *

3. Using The E5 Code-plus-carrier Combination For Time Transfer

$$E_5 = \| x_{rec} - x^{sat} \| + c\Delta t^{sat} - c\Delta t_{rec} + \cancel{Iono_5} + Trop + \delta_5^E + \varepsilon_5^E$$

$$+ \quad L_5 = \| x_{rec} - x^{sat} \| + c\Delta t^{sat} - c\Delta t_{rec} - \cancel{Iono_5} + Trop + \lambda_5 \hat{N}_5 + \varepsilon_5^L$$

$$E5CPC = \frac{E_5 + L_5}{2} = \| x_{rec} - x^{sat} \| - c\Delta t_{rec} + c\Delta t^{sat} + Trop + \frac{\delta_5^E}{2} + \frac{\lambda_5}{2}\hat{N}_5 + \varepsilon_{CPC}$$

- **Ionosphere-free observable**
- **Noise and multipath reduced by about a factor 2 with respect to to E5**

ambiguity (float) that must be solved

Clock differences between GNOR and GUSN stations (from GESS network) obtained with different approaches

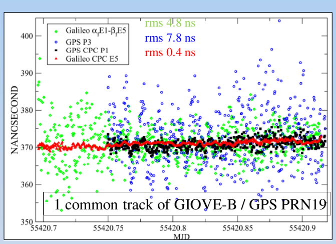

Fig. 2. Clock solutions obtained with either code-plus-carrier applied to E5 (**red**) and GPS L1 (**black**) or dual-frequency ionosphere-free codes using the combination of E1 and E5 (**green**) for GIOVE-B, and P1 and P2 (**blue**) for GPS PRN 19.

- Pseudorange observations corrected for: geometric distance satellite-receiver, satellite clock, and the relativistic effect due to the satellite orbit eccentricity, using the IGS orbits for GPS and the CONGO [Montenbruck et al., *GPS World*, 2009] orbits for GIOVE-B.
- Tropospheric delays taken from the IGS products for USNO and for DLFT (25 km far from GNOR). Stations' positions fixed to *a priori* known coordinates.

N.B.: E5CPC clock solution ambiguous (vertically shifted to artificially solve for the ambiguities)

E5CPC noise level: reduction by a factor about 20 with respect to GPS P_3

How to determine the E5CPC ambiguities?

<u>**Strategy:**</u> use the code-minus-carrier combination : $E5CMC = \frac{E_5 - L_5}{2} = Iono_5 + \frac{\delta_5^E}{2} - \frac{\lambda_5}{2}\hat{N}_5 + \varepsilon_{CMC}$

same ambiguity as in E5CPC, BUT again need to correct ionospheric term

* * * * *

5. Tests with Simulated Data

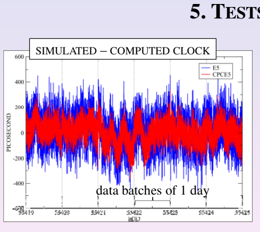

Fig. 3. Differences between the simulated clock and the computed clock obtained with either E5 code directly (**blue**) or the E5CPC combination (**red**) for 6 consecutive days. The average difference for each data batch is below 50 ps for both of them

➔ These results confirm that the noise of the clock solution obtained from the CPC combination is half the noise level of the solution obtained directly from the E5 pseudoranges but the correctness is similar.

2. Using E5 For Time Transfer

To keep the precision of E5, it must be used without combining it with another existing GNSS code, otherwise we will lose its advantages.

Observation equation for E5

to be determined

$$\boxed{E_5 = \| x_{rec} - x^{sat} \| + c\Delta t^{sat} - c\Delta t_{rec} + Iono_5 + Trop + \delta_5^E + \varepsilon_5^E \ \text{[m]}}$$

known from very precise products (e.g., IGS) — to be corrected for — hardware biases known from calibration

- Tropospheric path delay (*Trop*): can be determined as in PPP o taken from external products
- Ionospheric path delay (*Iono*$_5$): is the major limitation for doing time transfer with E5

Ionospheric delay correction for E5

<u>Single Frequency</u>: need for external products

- Global ionospheric maps: only correct for the long-wavelength and long-term variations (above 2 hours)
➔ not sufficient for accurate time transfer [Defraigne and Petit, *Metrologia*, 2003]
- Regional ionospheric maps: better resolution in time/space, could meet the required precision (work in progress)

<u>Dual Frequency</u>: take benefit of the dispersive property of the ionosphere

- **Strategy:** use the geometry-free combination of carrier phases with L1/L5:

$$L_{GF} = L_1 - L_5 = \boxed{Iono_5 \left(1 - \frac{f_5^2}{f_1^2}\right)} + \hat{N}_{GF} + \varepsilon_{GF}^L \ \text{[m]}$$

BUT ambiguous observable!

➔ Use also the geometry-free combination of codes with E1/E5:

$$E_{GF} = E_5 - E_1 = \boxed{Iono_5 \left(1 - \frac{f_5^2}{f_1^2}\right)} - c(DCB_{rec} + DCB^{sat}) + \varepsilon_{GF}^E \ \text{[m]}$$

Inter-frequency hardware biases, known from external products (e.g., from CODE analysis center)

* * * * *

4. Two Approaches: E5 or CPC with E5

Geometry-free ➔ ionospheric delay

E5-only

- Correct E5 for the ionospheric delay and solve for the receiver clock

E5CPC

- Correct E5CMC for the ionospheric delay and determine its ambiguity
- Correct E5CPC for its ambiguity and solve for the receiver clock

It is demonstrated analytically that **both approaches lead to an equivalent transfer solution in terms of "correctness"** (defined here as the the quality of the time offset – absolute value – retrieved by the analysis, only affected by code noise and multipath, not by calibration) due to the fact that a second code on a second frequency is needed to get rid of the ionospheric delays. Nonetheless, the **noise level of** the clock **solution** retrieved by the **E5CPC approach** is **two times lower than** the one of the **solution** determined with the **E5-only approach**.

Moreover, E5-only and E5CPC time transfer solutions are also equivalent in the same way to the current dual-frequency ionosphere-free time transfer solutions.

* * * * *

6. Conclusions and Perspectives

1. This paper presented some strategies to take benefit of the Galileo E5 code for time transfer in a single-station approach.
2. The E5 code, exhibiting a very low range noise and multipath error, is very promising for improving the medium-term stability of time transfer.
3. E5 must not be combined with any other existing code in order to keep its full potential for time transfer performances
   - The main limitation to use E5 for time transfer is the ionospheric error
4. The E5CPC combination (ionosphere-free) has a reduction of factor 2 in the noise and multipath error with respect to the E5 code. E5CPC is although ambiguous: necessary to determine accurately its ambiguity to use it for time transfer.
5. When a second code is used to determine either the ionospheric delays (E5-only approach) or the ambiguity of E5CPC, both approaches produce equivalent results in the medium-term stability as with the classical dual-frequency ionosphere-free approach.

ACKNOWLEDGEMENTS: This work was supported in part by Spanish Science and Technology Ministry (Project AYA2010-22039-C02-01), ACOMP/2001/196, of the Conselleria de Empresa, Universidad y Ciencia of the Generalitat Valenciana, the Solar - Terrestrial Centre of Excellence (STCE, 2011), and by the Association Dynamics of the Solar System.