gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

A methodology to improve the long-term estimation of GNSS clock corrections and phase biases using multi-frequency GNSS measurements

J. M. Juan, **J. Sanz**, A. Rovira-Garcia, G. González-Casado
Research group of Astronomy and Geomatics
Universitat Politècnica de Catalunya (gAGE/UPC)

J. Ventura-Traveset, L. Cacciapuoti, E. Schoenemann
European Space Agency (ESA)

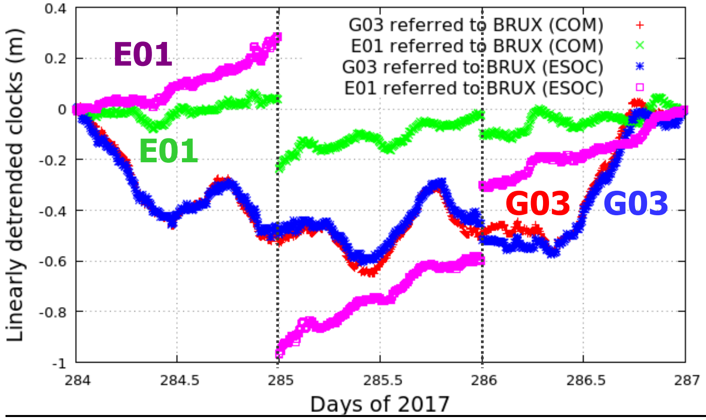
8th International Colloquium on Scientific and Fundamental Aspects of GNSS
14-16 September 2022 | Sofia, Bulgaria

Contents

Introduction

Satellite clocks are typically computed on daily basis, i.e. with the data of each day being processed independently from other days. **This approach produces the well-known day-boundary discontinuities (DBDs) on clock estimates that stem from the estimation process, rather than to the nature of the atomic clock itself**.

In general, the DBDs, that can reach some nanoseconds, are not an issue on applications like Precise Point Positioning (PPP) technique using IGS precise products, because the clocks and orbits are consistent on each batch. Nevertheless, **studies like the Gravitational Redshift Experiment with eccentric sATellites (GREAT) project may benefit from having satellite continuous clocks** for the statistical characterization of long-term phenomena correlated with the on-board clocks.



In this work we present a strategy to estimate the satellite and receiver clock offsets that removes the DBDs observed in precise products of different IGS analysis centers, ultimately improving the accuracy of clock estimates.

Contents

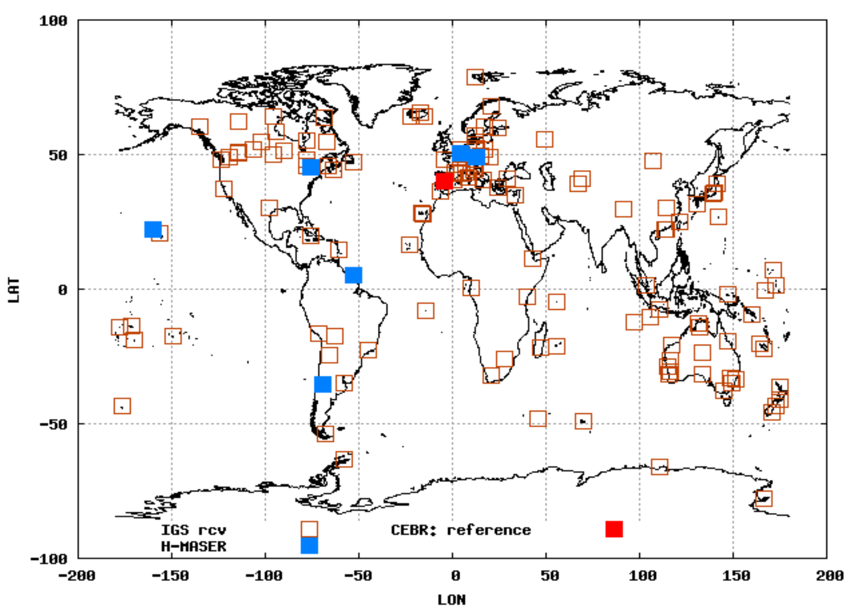
Data Set

- RINEX data at a 30 s Sampling Rate (SR)
- 153 receivers from the International GNSS Service (IGS)
- 7 receivers equipped with H-MASER frequency standard

- Comparison with Satellite clocks (SR of 30 s) from four IGS Analysis Centres
  - **CNES:** Centre National D'Etudes Spatiales
  - **GFZ**: Deutsches GeoForschungsZentrum
  - **CODE:** Centre for Orbit Determination in Europe
  - **ESOC**: European Space Operation Centre from ESA

- Campaign of 340 days analyzed in 2017:

Selected periods DoYs 191-230 and 281-310 of 2017.

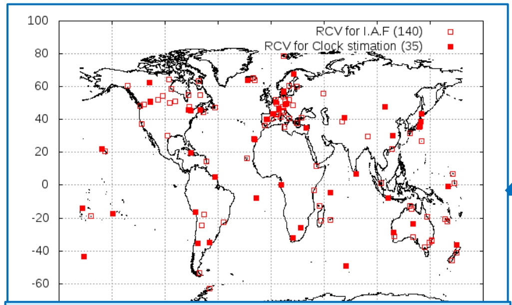


gAGE/UPC research group of **A**stronomy and **G**eomatics
Barcelona**TECH**, Spain

Contents

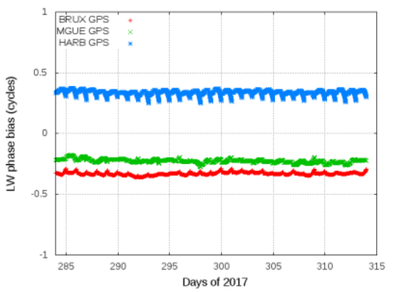
Methodology

ESOC Precise Orbit and Clock products

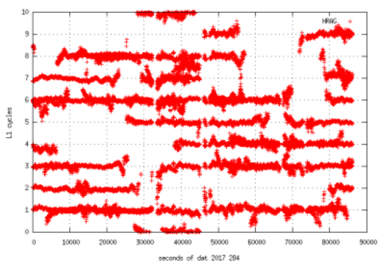


IGS RINEX DATA

Raw phase biases estimation: Extra-Wide-Lane, Wide-Lane and L1



Un-differenced Ambiguity Resolution



Kalman filter: Receiver and Satellite clocks and Refined Phase biases

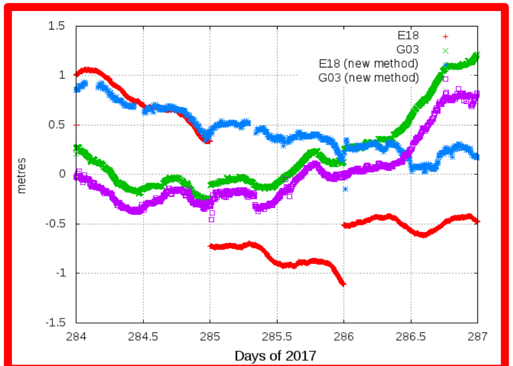
$$\Delta L_{1}{}_i^j = c\left(T_i - T^j\right) - \alpha_1 I_i^j + k_{1_i} + k_1{}^j$$

$$\Delta L_{5}{}_i^j = c\left(T_i - T^j\right) - \alpha_5 I_i^j + k_{5_i} + k_5{}^j$$

$$\Delta L_{7}{}_i^j = c\left(T_i - T^j\right) - \alpha_7 I_i^j + k_{7_i} + k_7{}^j$$

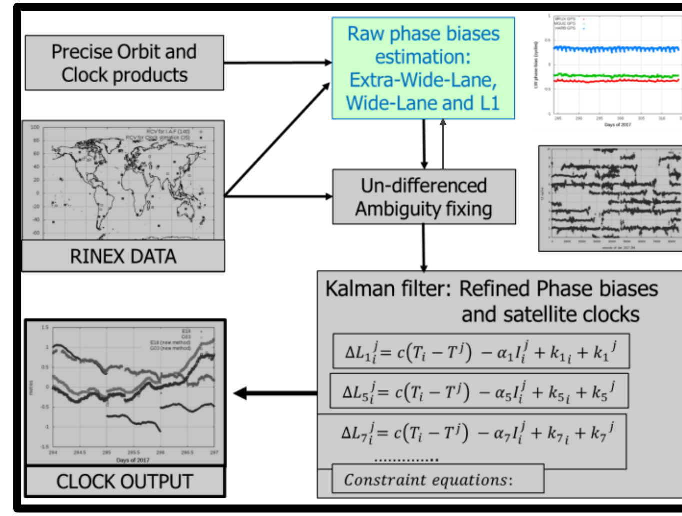
....

Constraint equations:

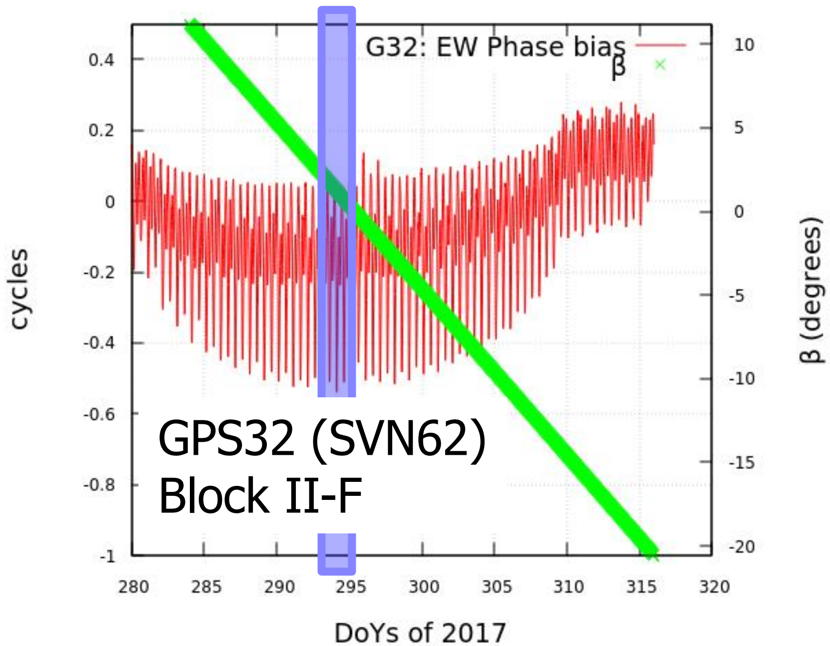


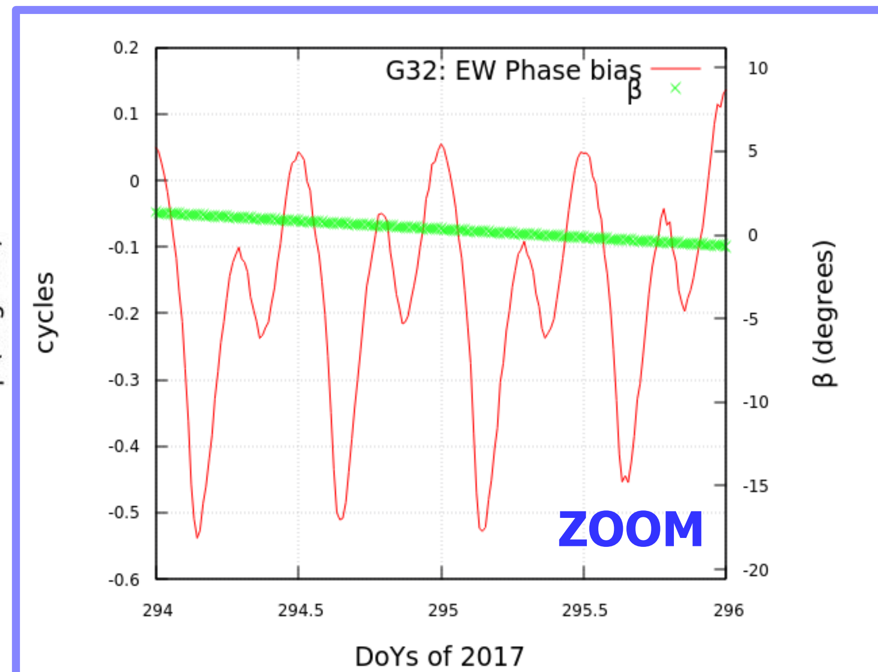
CLOCK OUTPUT

Raw phase biases

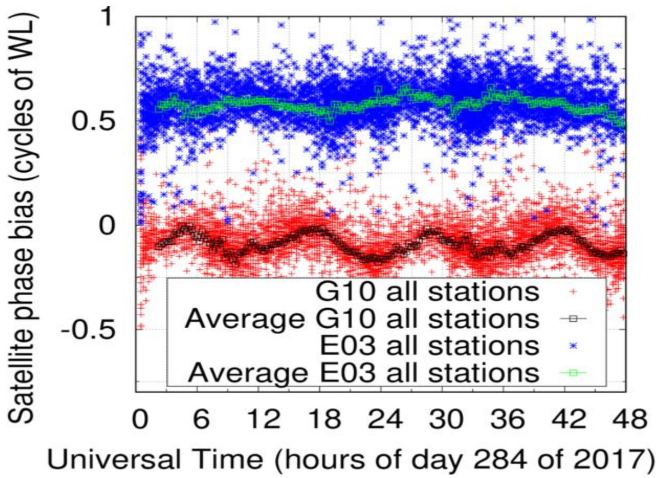


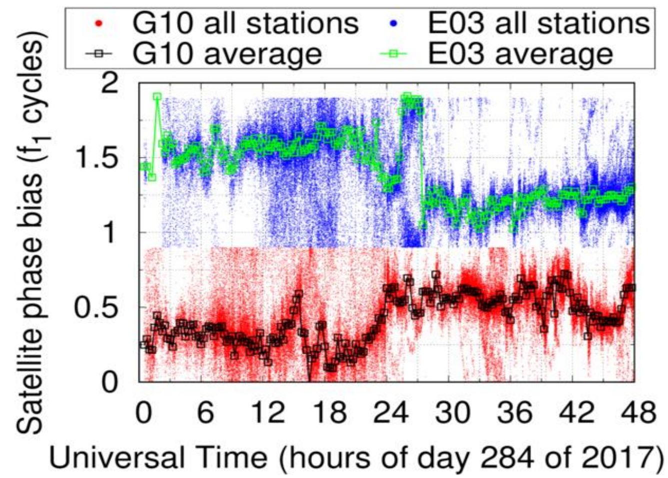
- Estimation process:
  - Extra Wide Lane: (L2,L5), (E5a,E5b)
  - Wide Lane: (L1,L2), (E1,E5a)
  - Single Freq.: L1, E1
    ➔L2, L5, E5a, E5b
- Temperature dependencies observed by other authors, Montenbruck (2012)

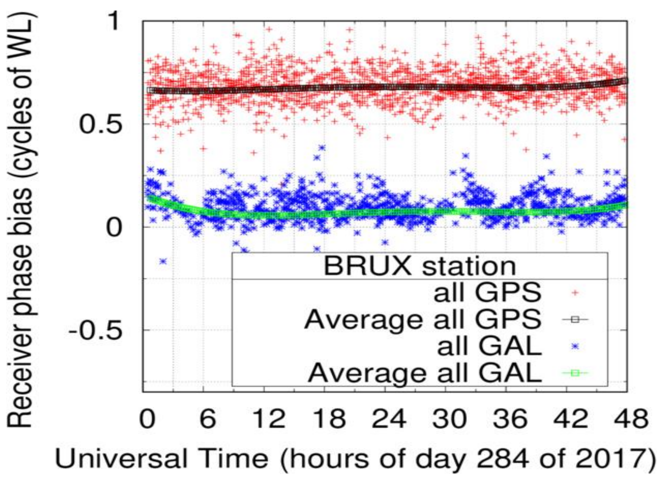


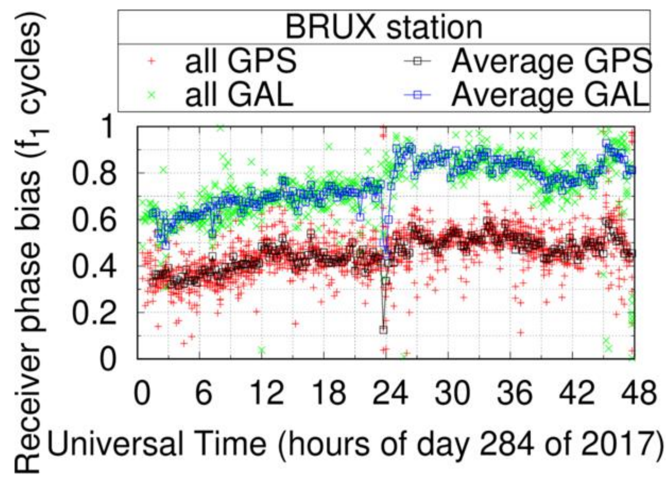


Raw phase biases









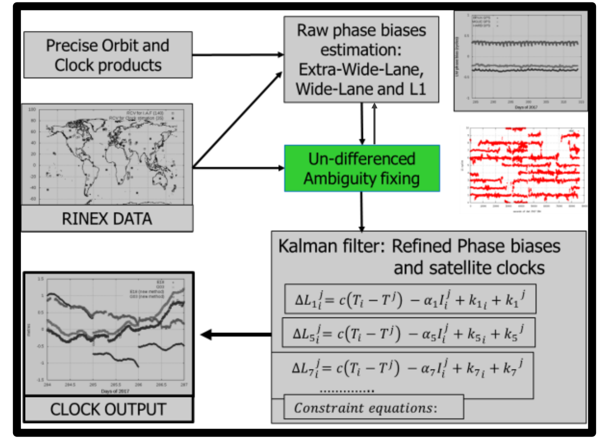
Phase biases can be well determined in EWL, WL and L1.
Phase biases associated to L1/E1 are more scattered than WL combination:

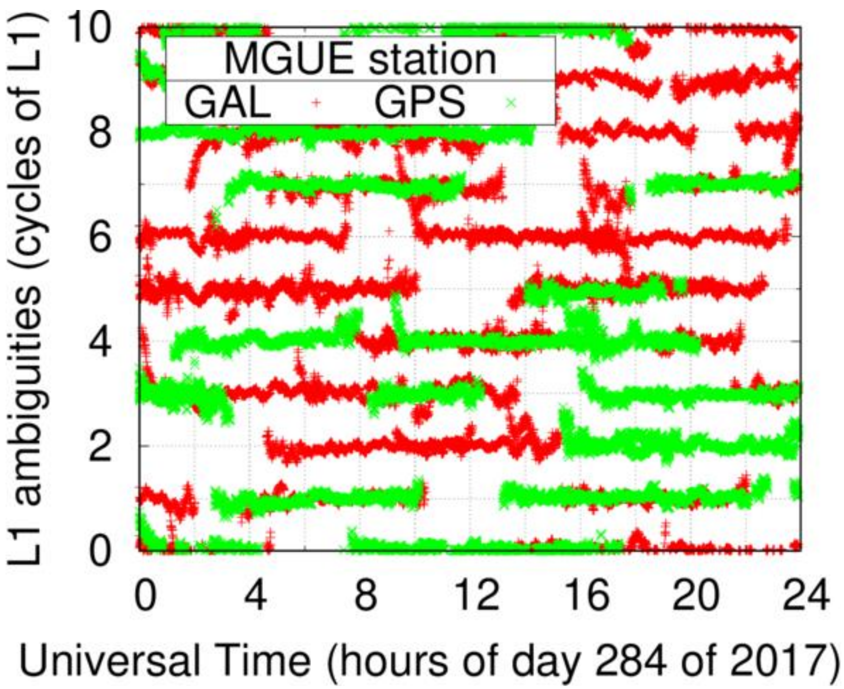
- a-priory satellite orbits and clocks products from ESOC
- potential slightly different modellings (e.g. Antenna Phase Centers)

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

Integer Ambiguity Resolution

1) Extra Wide Lane (L2,L5) , (E5a,E5b)
2) Wide Lane (L1,L2), (E1,E5a)
3) Single freq. L1, E1 ambiguities
 ➔ L2, L5, E5a, E5b





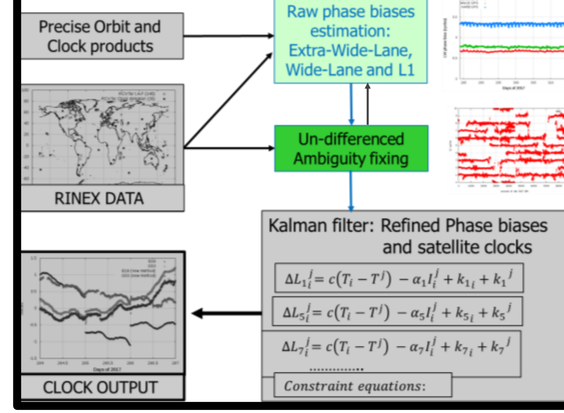
Example of L1/E1 float ambiguities, before IAR, in undifferenced mode, after satellite and receiver phase biases are determined and removed

About 90% of time of L1/E1 ambiguities are fix for all satellites and receivers of the network.

gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

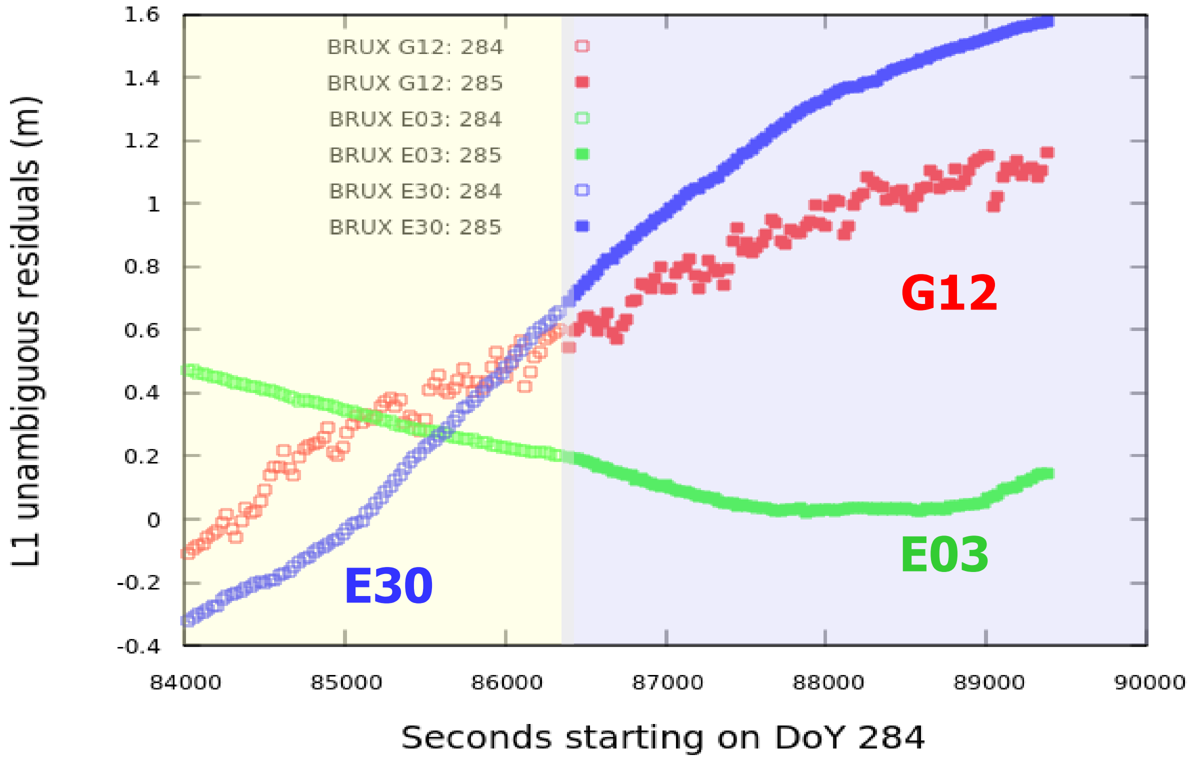
Integer Ambiguity Resolution



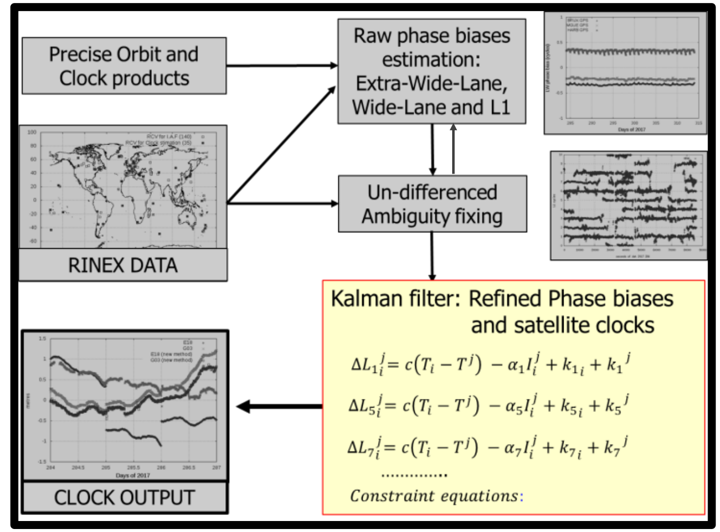
IAR module outputs carrier-phases:

- Very precise "pseudoranges" (from unambiguous carriers)
- Continuous: No Inter-day discontinuities

→ Input data used in the Kalman filter



Kalman Filter



- Uncombined IAR measurements $\Delta L_{f\,i}^{\,j}$
- Each day is estimated independently with forward & backward filter.
- Satellite T^j and receiver T_i clocks treated as white noise processes.
- Ionosphere delays I_i^j are treated also as white noise processes.
- Satellite $k_f^{\,j}$ and receiver k_{f_i} phase biases are treated as random walk (10^{-4} m^2 / h) to cope with any temperature dependency.

Only carrier-phase are used

Kalman filter: Receiver and Satellite clocks and Refined Phase biases

$$\Delta L_{1\,i}^{\,j} = c\left(T_i - T^j\right) - \alpha_1 I_i^j + k_{1_i} + k_1^{\,j}$$

$$\Delta L_{5\,i}^{\,j} = c\left(T_i - T^j\right) - \alpha_5 I_i^j + k_{5_i} + k_5^{\,j}$$

$$\Delta L_{7\,i}^{\,j} = c\left(T_i - T^j\right) - \alpha_7 I_i^j + k_{7_i} + k_7^{\,j}$$

....

Constraint equations:

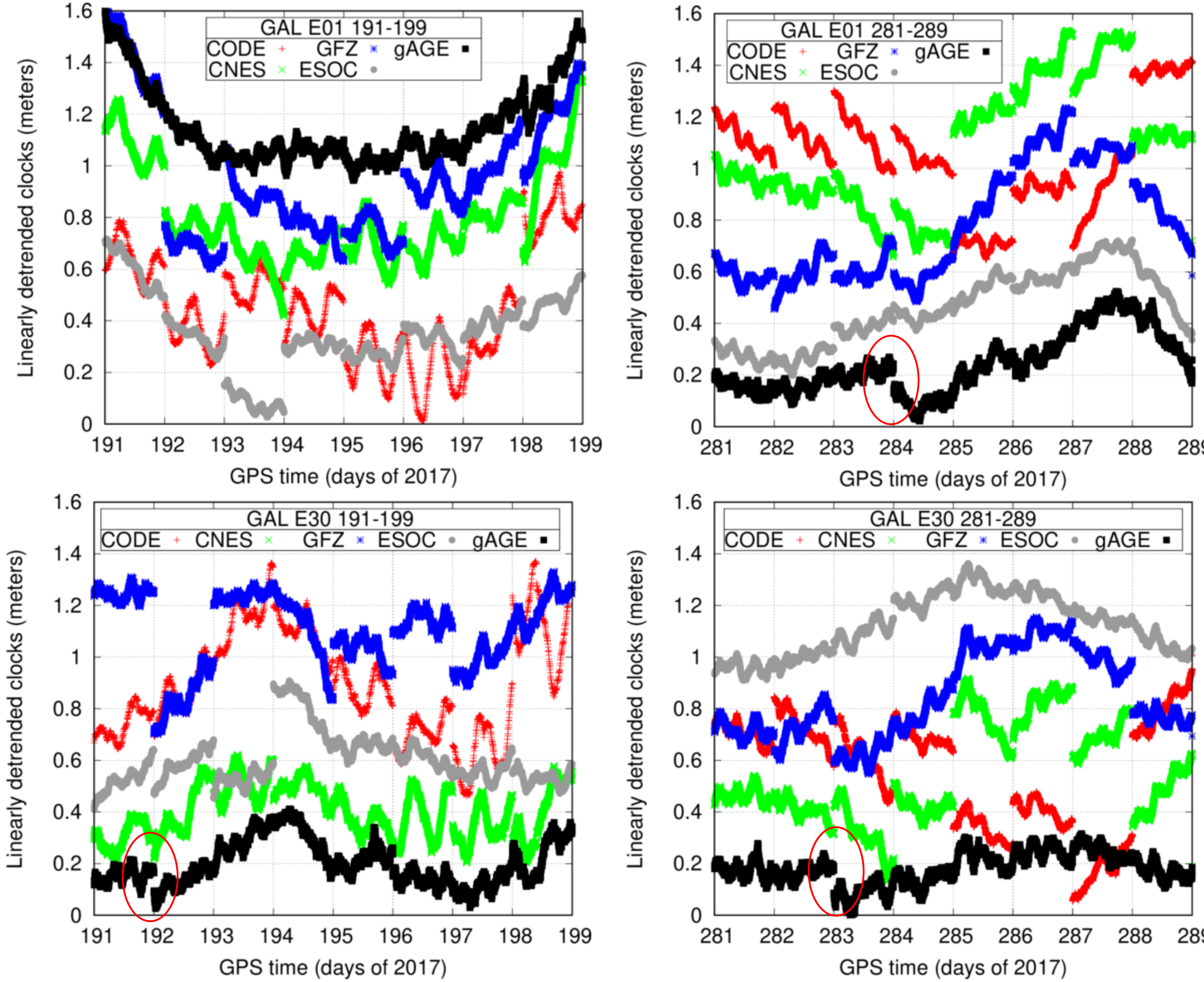
gAGE

Contents

gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

Results: Satellite and Receiver clocks



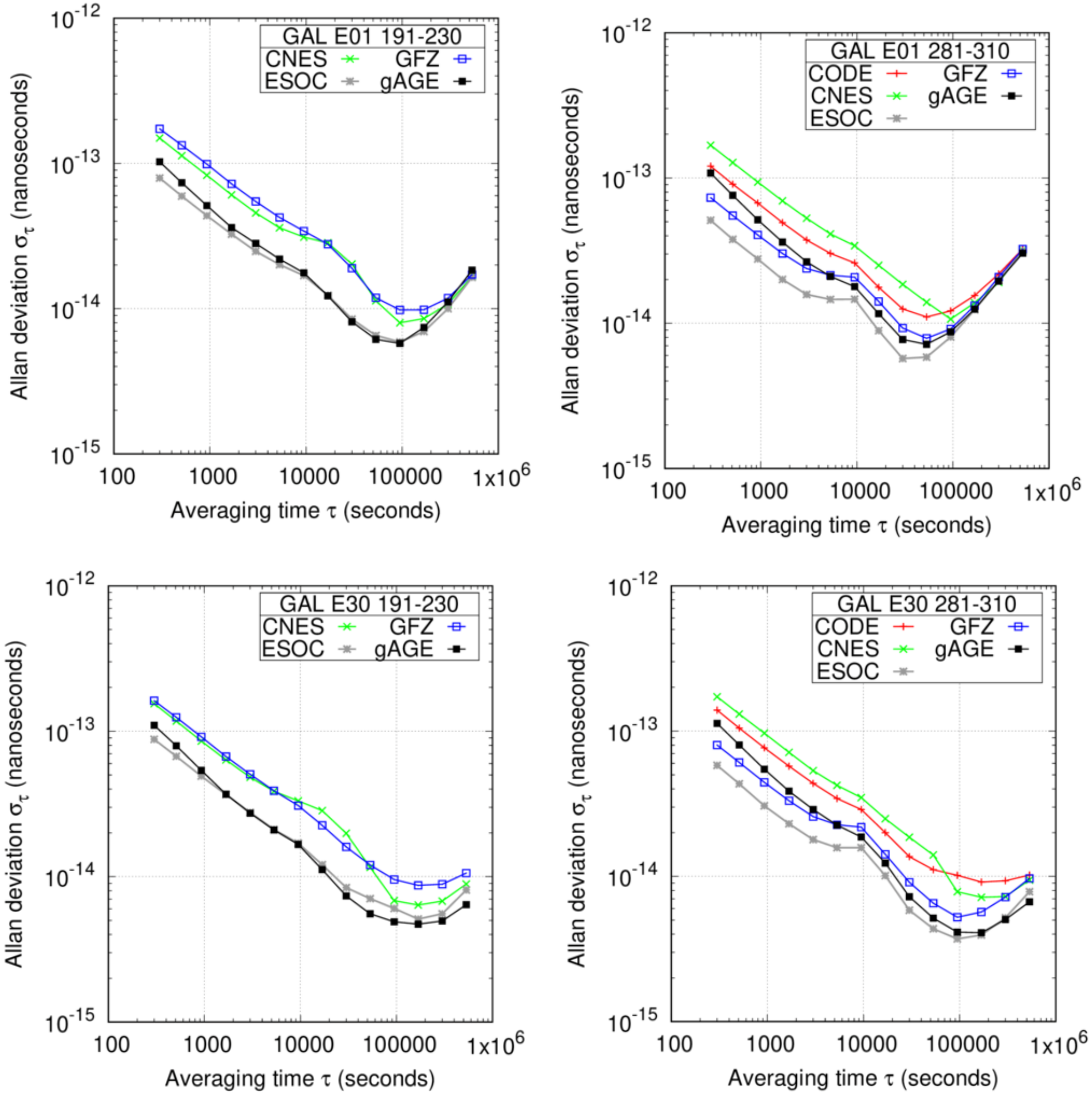
The DBD are basically removed in (gAGE) clocks (in black).
The root of small jumps on 192, 283, 284 were analysed and are related to errors in the a priori reference products (orbit or clocks) used.

Testing Satellite clocks

- ***Allan deviation (AD)***
  This is the standard metric used to assess the stability of clocks. Roughly speaking AD measures the non-linearity of clocks. A stability at the level of 1E-14, at $\tau=10^4$ s, is expected for an H-maser oscillator.

- ***Day-to-day predictability:* 1 hour predictability of the following day.**
  The linear trend of the clock is adjusted by the values (clock estimates) of the last hour of a given day and the predictions of this model are compared with the values of the first hour of the following day. This test measures inter-day clock jumps.

Allan deviation:

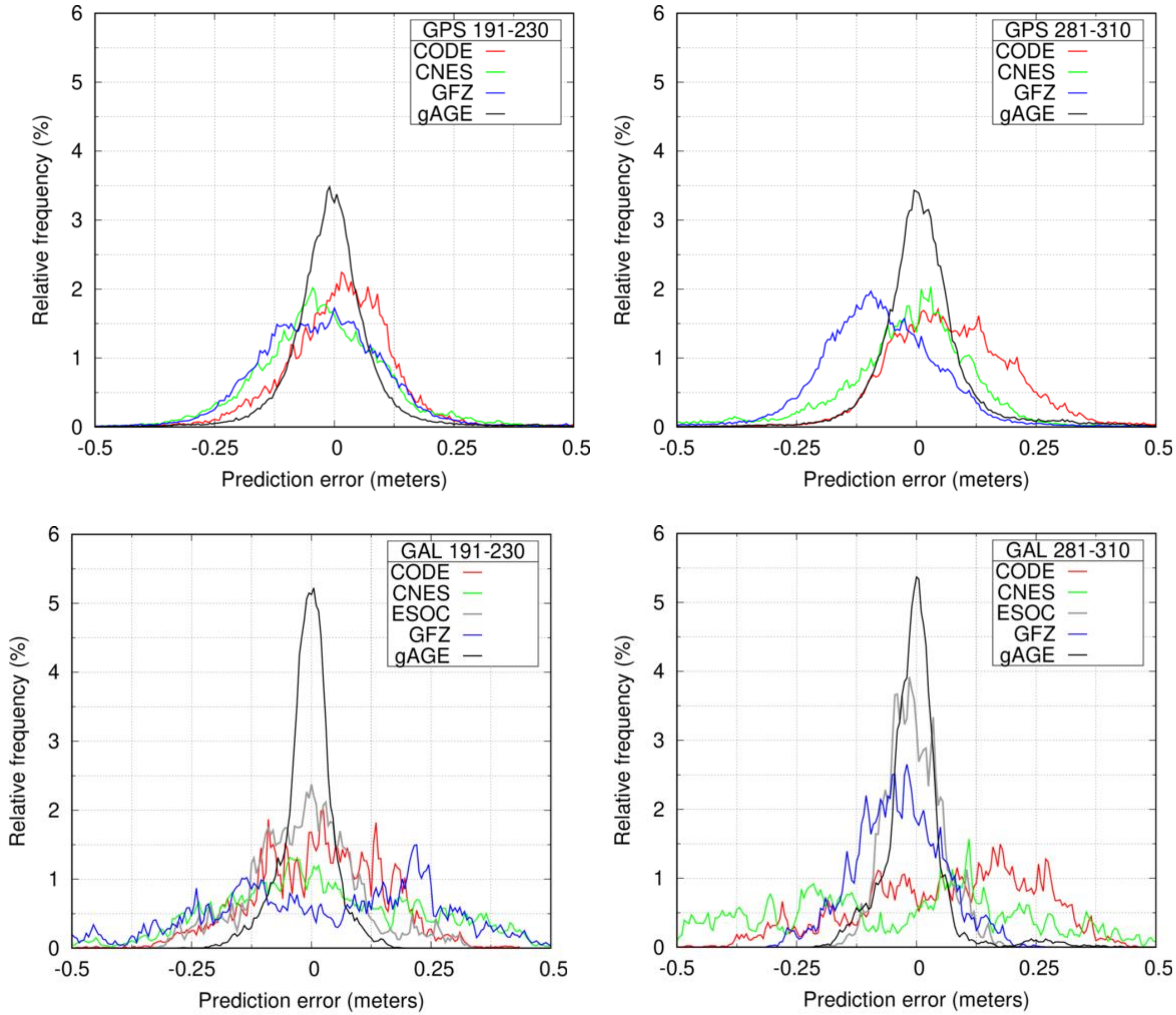


The proposed approach is at the level or better than well-stablished IACs

gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

Day-boundary discontinuities: Satellites



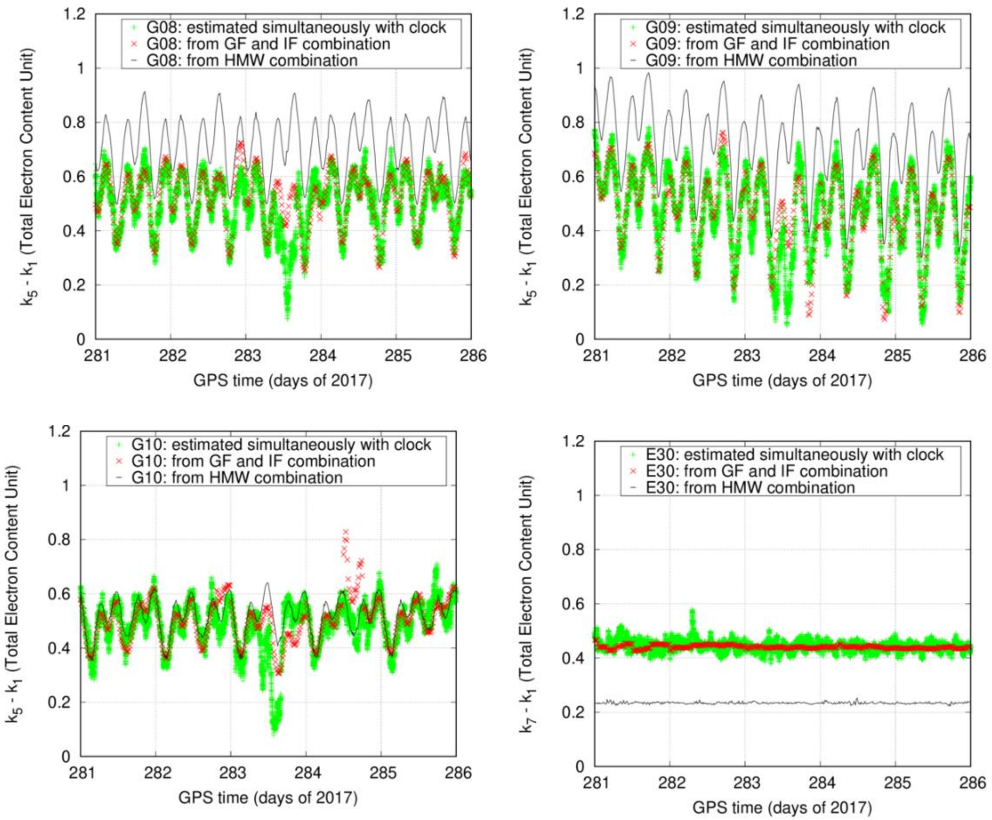
Among the inter-day discontinuities, the stability of satellites clocks is also affecting the extrapolation error of this test. Indeed, Galileo clocks exhibit lower extrapolation errors.

gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

Refined phase biases

The refined phase biases (carrier hardware delays) are estimated as random walk processes, instead of computing them as constant parameters. This treatment of the process noise allows us to take into account the dependency of the temperature of some of these biases, Montenbruck et al. (2012).



In figures show the agreement when comparing the Phase Biases estimated simultaneously with clock (green) with two independent estimations, calculated directly from measurements:

- From GF and IF (red)
- From HMW (grey)

Contents

Conclusions

Our approach relies on the use of unambiguous, undifferenced and uncombined carrier phase measurements collected by a network of permanent receivers on ground.

- The key point of this strategy is to exploit the natural continuity over days of the carrier phase biases (carrier phase hardware delays) .
- An initial rough estimate of phase biases, allows to fix the ambiguities into their integer values, ultimately obtaining continuous unambiguous carrier phase measurements on the boundaries between adjacent days. It is worth to say that this "day-to-day" continuity on the fixed carriers is achieved even if the integer ambiguity resolution is performed on daily batches.
- The results show a strong mitigation (typically removal) of day-boundary-discontinuities on clock estimates computed with these "day-to-day" continuous and unambiguous carrier phase measurements, improving the clock estimates.
- Because the estimation process uses three frequencies, clocks offsets are estimated jointly with the carrier phase biases. These refined hardware delays are estimated as random walk processes, instead of computing them as constant parameters. It allows us to take into account, for instance, the dependency of the temperature of some of these biases.

More details in:

Rovira-Garcia A, Juan JM, Sanz J, Gonzalez-Casado G, Ventura-Traveset J, Cacciapuoti L, Schoenemann E (2021) "A multi-frequency method to improve the long-term estimation of GNSS clock corrections and phase biases" NAVIGATION: Journal of the Institute of Navigation 68(4):815-828. DOI 10.1002/navi.453

Rovira-Garcia A, Juan JM, Sanz J, Gonzalez-Casado G, Ventura J, Cacciapuoti L, Schoenemann E (2021) "Removing day-boundary discontinuities on GNSS clock estimates: methodology and results" GPS Solutions 25(2):A35:1-12. DOI 10.1007/s10291-021-01085-3

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

Thank you !!

Contact: **jaume.sanz@upc.edu**
Campus Nord UPC Jordi Girona 1-3, 08034 Barcelona (Spain).

Back up slides

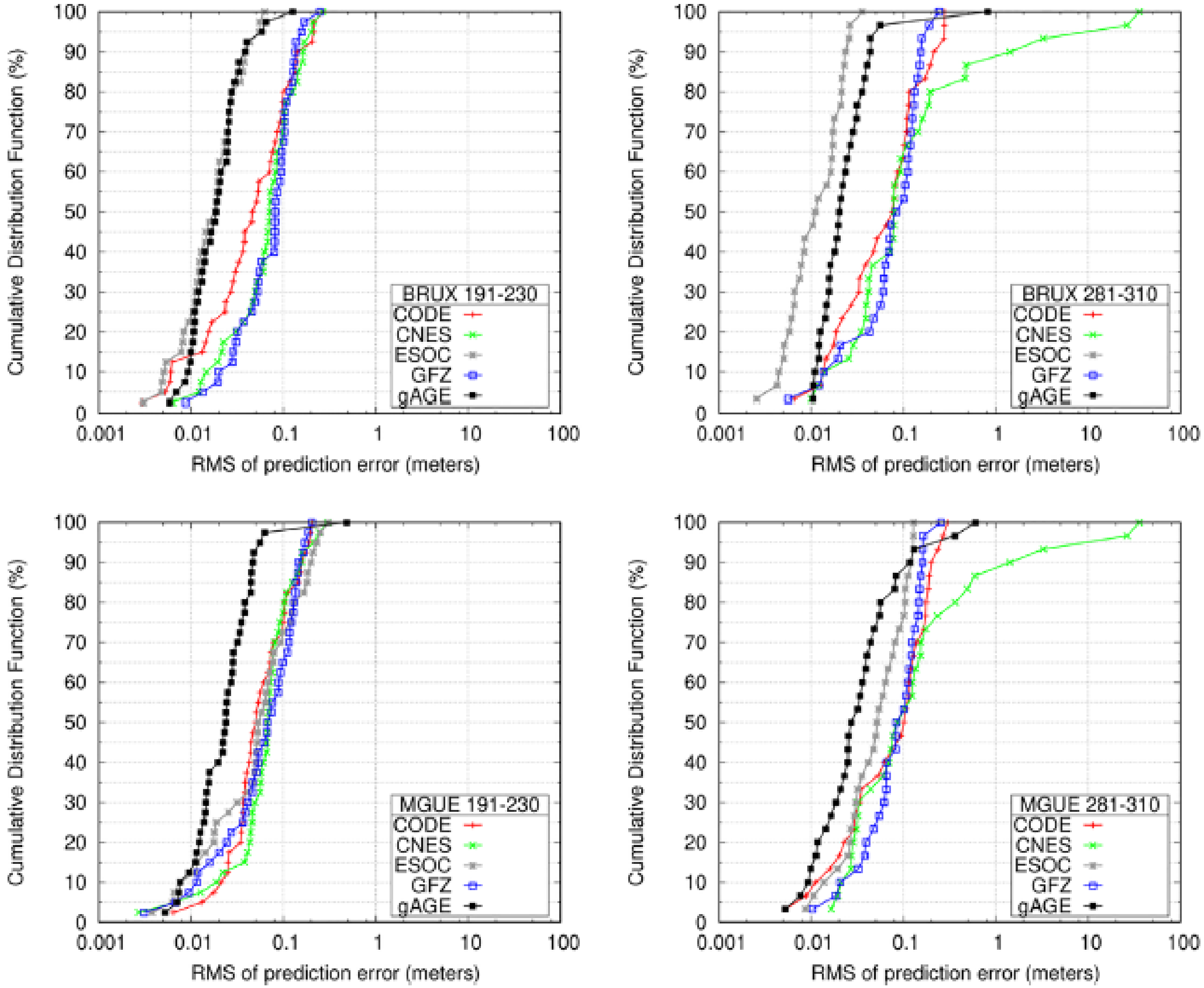


FIGURE 7 CDF of the daily RMS values of the prediction errors after linear extrapolation for permanent stations equipped with a PHM clock: BRUX (top row) and MGUE (bottom row), estimated by the proposed approach (black), ESOC (grey), CODE (red), GFZ (blue), and CNES (green); the left column corresponds the first study period in 2017, whereas the right column depicts the second period [Color figure

We can observe that the prediction error of gAGE clock estimates is the lowest, with values at the level of 3 cm (approximately 100 ps).

gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

$$P_{m_i}^{\ j} = \rho_i^j + c\left(T_i - T^j\right) + Trop_i^j + \alpha_m\left(I_i^j + D_{m_i} + D_m^{\ j}\right) + \varepsilon$$

$$L_{m_i}^{\ j} = \rho_i^j + c\left(T_i - T^j\right) + Trop_i^j - \alpha_m\left(I_i^j + D_{m_i} + D_m^{\ j}\right) + \lambda_m\left(\delta_{m_i} + \delta_m^{\ j} + N_{m_i}^{\ j}\right) + \epsilon$$

Wide Lane processing

The first step of the proposed IAR process employs the Hatch-Melbourne-Wübenna (HMW) combination (Hatch 1982). That is, the difference of the wide lane (WL) combination of carrier phases and the narrow lane (NL) combination of code pseudoranges:

$$HMW_{mn} = WL_{mn} - NL_{mn} = \frac{f_m L_m - f_n L_n}{f_m - f_n} - \frac{f_m P_m + f_n P_n}{f_m + f_n} \qquad (4)$$

where m and n refer to one pair of frequencies, which in our study correspond to f_1 and f_2 for GPS and f_1 and f_5 for Galileo. Substituting (1) and (2) into (4), the HMW combination is expressed in terms of differences of phase biases δ and differences of integer ambiguities N:

$$HMW_{mn_i}^{\ j} = \frac{c}{f_m - f_n}\left(\delta_{m_i} - \delta_{n_i} + \delta_m^{\ j} - \delta_n^{\ j} + N_{m_i}^{\ j} - N_{n_i}^{\ j}\right) + \epsilon_{NL_{mn}} \qquad (5)$$

$$HMW_{mn} = WL_{mn} - NL_{mn} = \frac{f_m L_m - f_n L_n}{f_m - f_n} - \frac{f_m P_m + f_n P_n}{f_m + f_n} \qquad (4)$$

where m and n refer to one pair of frequencies, which in our study correspond to f_1 and f_2 for GPS and f_1 and f_5 for Galileo. Substituting (1) and (2) into (4), the HMW combination is expressed in terms of differences of phase biases δ and differences of integer ambiguities N:

$$HMW_{mn_i}^{j} = \frac{c}{f_m - f_n}\left(\delta_{m_i} - \delta_{n_i} + \delta_m^j - \delta_n^j + N_{m_i}^j - N_{n_i}^j\right) + \epsilon_{NL_{mn}} \qquad (5)$$

Raw WL phase biases

The procedure starts by selecting one receiver as a reference, e.g., CEBR in our study, in which the values of its phase biases and of its integer ambiguities are taken as zero, i.e., $\delta_{m_{ref}} = \delta_{n_{ref}} = N_{m_{ref}}^j = N_{n_{ref}}^j = 0$. In this first step, the phase biases of every "j" satellite in view from the reference receiver are determined directly with the HMW combination of the reference receiver:

$$HMW_{mn_{ref}}^{j} = \lambda_{WL}\left(\delta_m^j - \delta_n^j\right) \qquad (6)$$

HB for **satellites** in view from ref station

Note that the phase biases can be greater than one cycle, but the absolute value has no actual meaning. Then, the process continues with a second receiver "i" close to the reference station. This is a reason to have multiple receivers within the network depicted with empty squares in Fig. 2. At every epoch, we use the satellite phase biases derived in (6) to compute as many differences of HMW combinations, as the number of satellites in common view with the reference receiver:

$$HMW_{mn_i}^{j} - \lambda_{WL}\left(\delta_m^j - \delta_n^j\right) = \lambda_{WL}\left(\delta_{m_i} - \delta_{n_i} + N_{m_i}^j - N_{n_i}^j\right) + \epsilon_{NL_{mn}} \qquad (7)$$

In such "ith" receiver, in order to eliminate the ambiguity term $N_{m_i}^j - N_{n_i}^j$, we perform the modulo λ_{WL} operation, resulting in:

HB for **stations** having sat. in view from ref station.

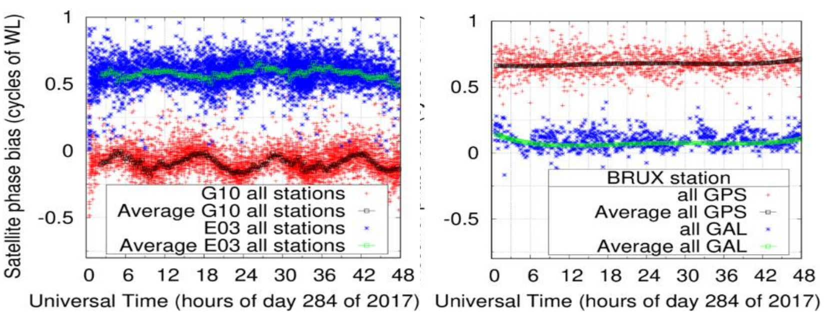
$$HMW_{mn_i}^{j} - \lambda_{WL}\left(\delta_m^j - \delta_n^j\right) = \lambda_{WL}\left(\delta_{m_i} - \delta_{n_i}\right) + \epsilon_{NL_{mn}} \qquad (8)$$

From (8), the receiver phase bias $\delta_{m_i} - \delta_{n_i}$ can be determined with the common satellites in view with the reference receiver. For a "k" satellite not in view by CEBR, we use the receiver phase bias estimated in (8) to determine the satellite phase value $\delta_m^k - \delta_n^k$:

HB for **satellites** NOT in view from ref station

$$HMW_{mn_i}^{k} - \lambda_{WL}\left(\delta_{m_i} - \delta_{n_i}\right) = \lambda_{WL}\left(\delta_m^k - \delta_n^k\right) + \epsilon_{NL_{mn}} \qquad (9)$$

The process described by (7)–(9) continues for all the 150 receivers within the network of Fig. 2. In this regard, the first



gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

$$\frac{(B_{IF})^j_{mn_i}}{\lambda_{NL}} - \frac{f_n}{f_m-f_n}\left(N^j_{m_i}-N^j_{n_i}\right) = \frac{f_m\delta_{m_i}-f_n\delta_{n_i}}{f_m-f_n} + \frac{f_m\delta^j_m-f_n\delta^j_n}{f_m-f_n} + N^j_{m_i} \quad (13)$$

where $\lambda_{NL} = \frac{c}{f_m+f_n}$ is the wavelength of the NL combination and is equal to approximately 11 cm for both the GPS frequencies f_1 and f_2 or the Galileo frequencies f_1 and f_5.

The procedure to resolve $N^j_{m_i}$ to an integer value in (13) repeats the previous steps (6) to (10). That is, first, we assume that the phase biases and ambiguities of the reference receiver are zero: $\delta_{m_{ref}} = \delta_{n_{ref}} = N^j_{m_{ref}} = 0$. That choice determines the satellite phase biases $\frac{f_m\delta^j_m-f_n\delta^j_n}{f_m-f_n}$, of the satellites in view by the reference receiver:

$$\frac{(B_{IF})^j_{mn_{ref}}}{\lambda_{NL}} = \frac{f_m\delta^j_m-f_n\delta^j_n}{f_m-f_n} \quad (14)$$

The difference of phase biases estimated in (14) is propagated to nearby receivers:

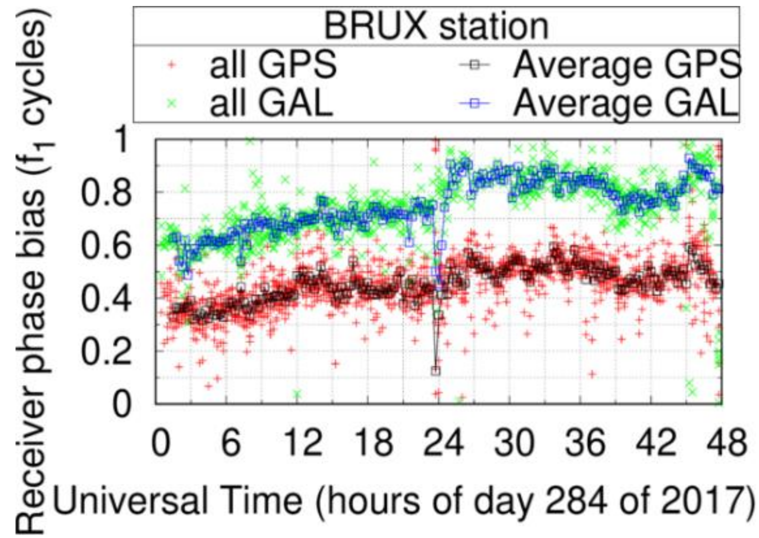
$$\frac{(B_{IF})^j_{mn_i}}{\lambda_{NL}} - \frac{f_n}{f_m-f_n}\left(N^j_{m_i}-N^j_{n_i}\right) - \frac{f_m\delta^j_m-f_n\delta^j_n}{f_m-f_n} = \frac{f_m\delta_{m_i}-f_n\delta_{n_i}}{f_m-f_n} + N^j_{m_i} \quad (15)$$

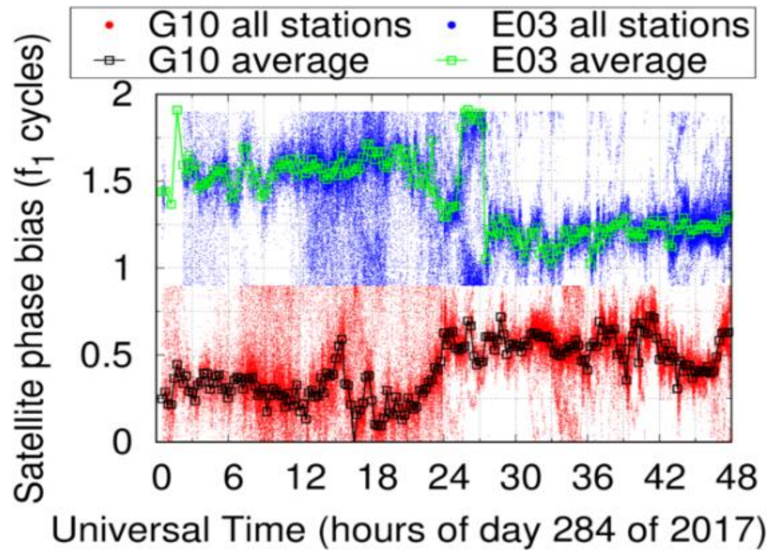
Again we eliminate the ambiguity $N^j_{m_i}$ performing a modulo λ_{NL} operation:

$$\frac{(B_{IF})^j_{mn_i}}{\lambda_{NL}} - \frac{f_n}{f_m-f_n}\left(N^j_{m_i}-N^j_{n_i}\right) - \frac{f_m\delta^j_m-f_n\delta^j_n}{f_m-f_n} = \frac{f_m\delta_{m_i}-f_n\delta_{n_i}}{f_m-f_n} \quad (16)$$

From which the receiver phase biases of all permanent stations within the network are estimated using (16). For a "k" satellite not in view by the reference station, its satellite phase bias is determined using the estimate of the receiver phase bias:

$$\frac{(B_{IF})^k_{mn_i}}{\lambda_{NL}} - \frac{f_n}{f_m-f_n}\left(N^k_{m_i}-N^k_{n_i}\right) - \frac{f_m\delta_{m_i}-f_n\delta_{n_i}}{f_m-f_n} = \frac{f_m\delta^k_m-f_n\delta^k_n}{f_m-f_n} \quad (17)$$

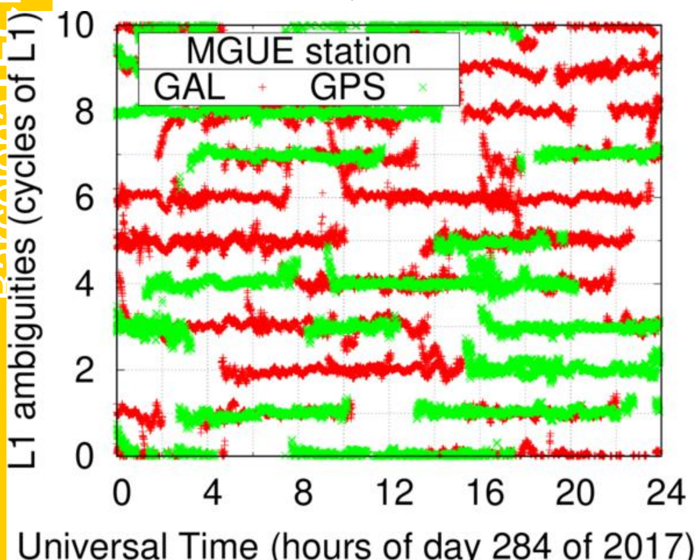


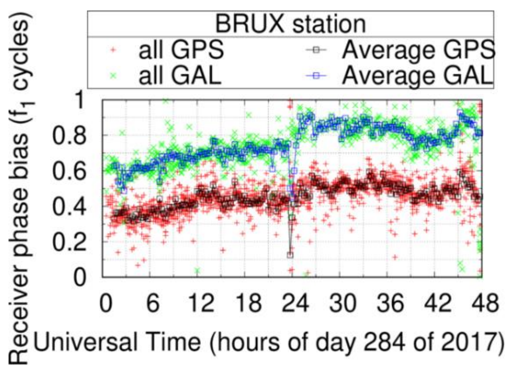


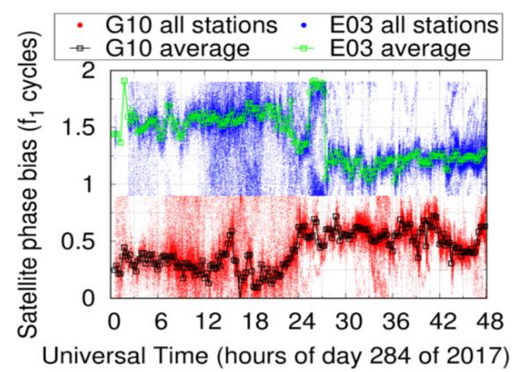
Once the satellite and receiver phase biases are determined in (14)–(17), we subtract such estimates to (13), in order to resolve the $N_{m_i}^{j}$ ambiguity:

$$\frac{(B_{IF})_{mn_i}^{j}}{\lambda_{NL}} - \frac{f_n}{f_m - f_n}\left(N_{m_i}^{j} - N_{n_i}^{j}\right) - \frac{f_m\delta_{m_i} - f_n\delta_{n_i}}{f_m - f_n} - \frac{f_m\delta_m^{j} - f_n\delta_n^{j}}{f_m - f_n} = N_{m_i}^{j} \qquad (18)$$

WL amb fixed — Rec. HW bias — Sat. HW bias







Kalman filter: Refined Phase biases and clocks

$$\Delta L_{1}{}_i^j = c\left(T_i - T^j\right) - \alpha_1 I_i^j + k_{1_i} + k_1{}^j$$

$$\Delta L_{5}{}_i^j = c\left(T_i - T^j\right) - \alpha_5 I_i^j + k_{5_i} + k_5{}^j$$

$$\Delta L_{7}{}_i^j = c\left(T_i - T^j\right) - \alpha_7 I_i^j + k_{7_i} + k_7{}^j$$

....

Reference Clock and phase biases:

$$T_{CEBR} = 0$$

$$k_{f_{CEBR}} = 0$$

Constraint equations:

Reference frequency for satellites:

$$k_1{}^{GALj} = k_5{}^{GALj}$$

$$k_1{}^{GPSj} = k_2{}^{GPSj}$$

Reference clock for receivers

$$k_{1_{RECi}} = k_{2_{RECi}}$$

Equivalent to take the *IF* combination of GAL/GPS carrier phases in E1/E5 and L1/L2 as the satellite/receiver clock reference.

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain