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GNSS satellite hardware biases stability over time: impact of the flex power

C. Gazzino[1], F. Mercier[1], S. Loyer[2], A. Santamaria[1]

[1] CNES (French Space Agency)
[2] CLS

ORGANIZING INSTITUTIONS

IGS INTERNATIONAL GNSS SERVICE

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FACULTAD DE INGENIERÍA

DEPARTAMENTO DE INGENIERÍA GEOESPACIAL Y AMBIENTAL

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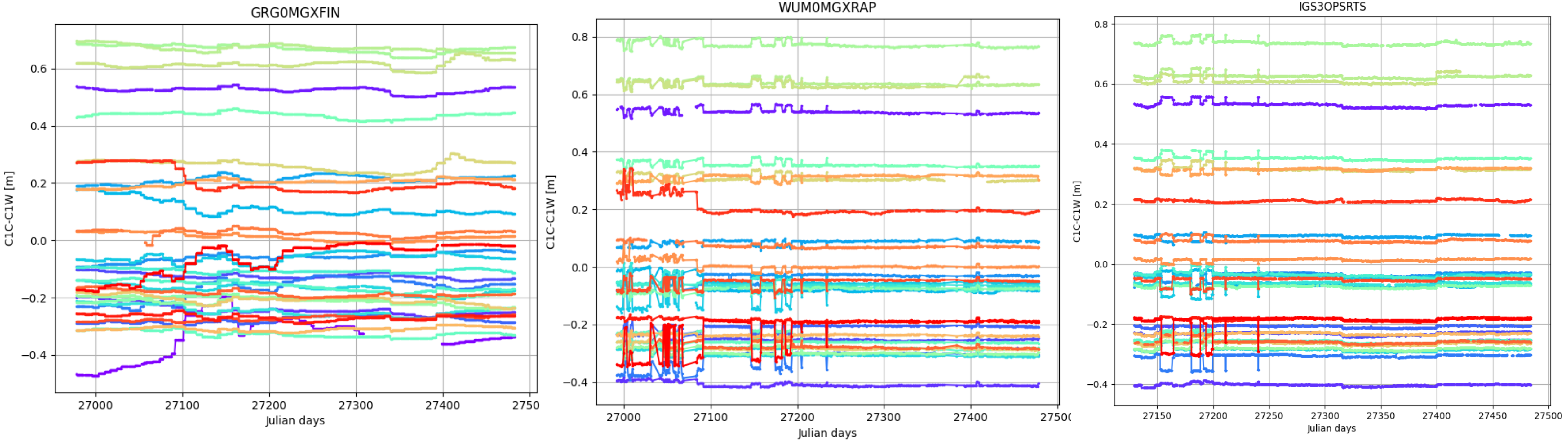
Introduction

- GNSS hardware errors: instrumental biases [Håkansson et al. (2017)]
  - These instrumental biases stem from imperfections and/or physical limitations in the electronics of satellite instruments and receivers
  - Temporal offsets of events that should have occurred simultaneously depend on the observable, the frequency, and the modulation
  - They are considered stable over time, but this stability can be distorted by residuals from other error sources that are incorporated into the biases
  - It is generally accepted that the residual instrumental bias can be decomposed into a transmitter (GNSS satellite) part and a receiver part
- Some receivers acquire the GPS civil L1 C/A and L2C signals but the available constellation products are on the military P(Y) modulations
  - ❖ Need for the GNSS satellites intermodulation biases on C1C and C1W

Intermodulation biases at IGS

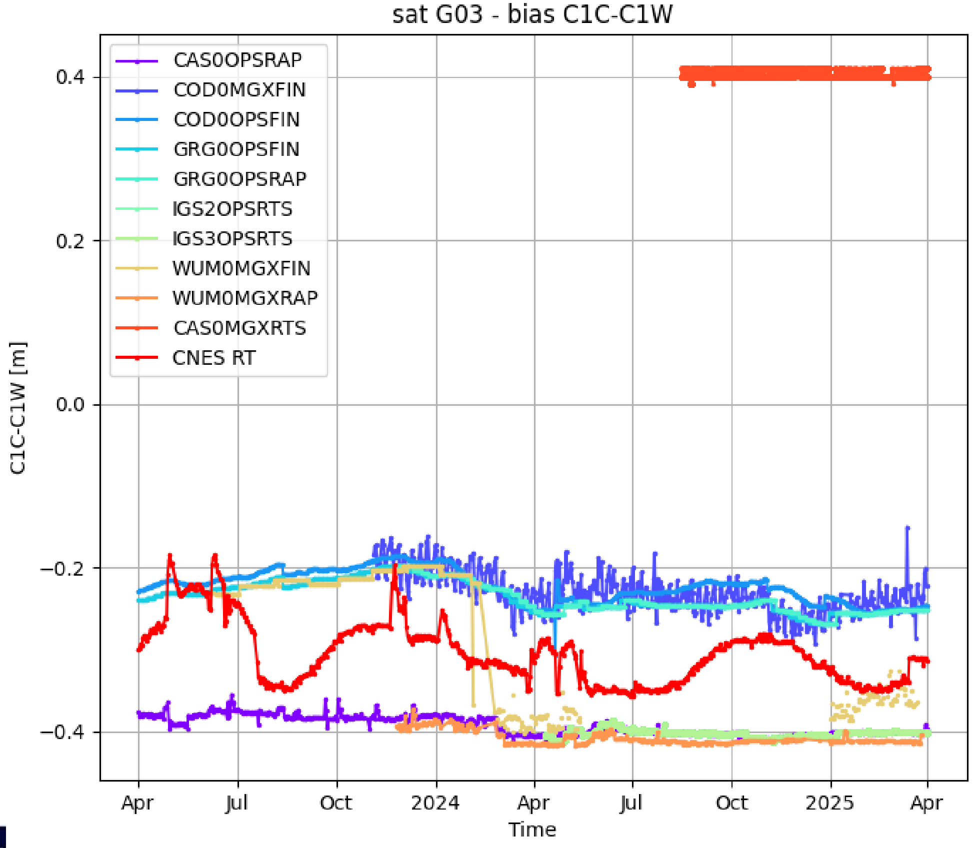
- Intermodulation bias C1C-C1W from several analysis centers
  - final, rapid, real-time biases
  - the solution of different analysis centers have different behaviors
  - note: GRG0MGXFIN taken from the p1c1bias.2000p from Bern

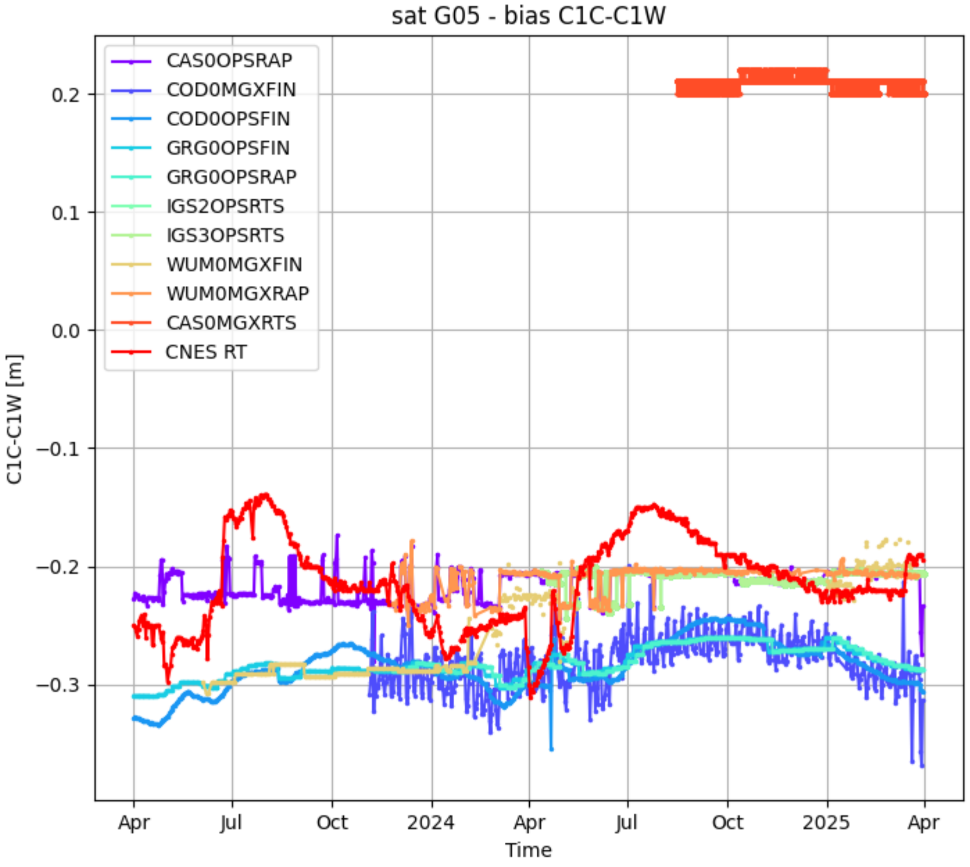


Intermodulation biases at IGS

❑Variability for a given satellite

- the bias behavior depends on the analysis center
- we can see several products ‘families’, as for instance COD/GRG – CAS/WUMRAP/IGSRTS – WUMFIN/CNES TR
- is such a variability physically meaningful?



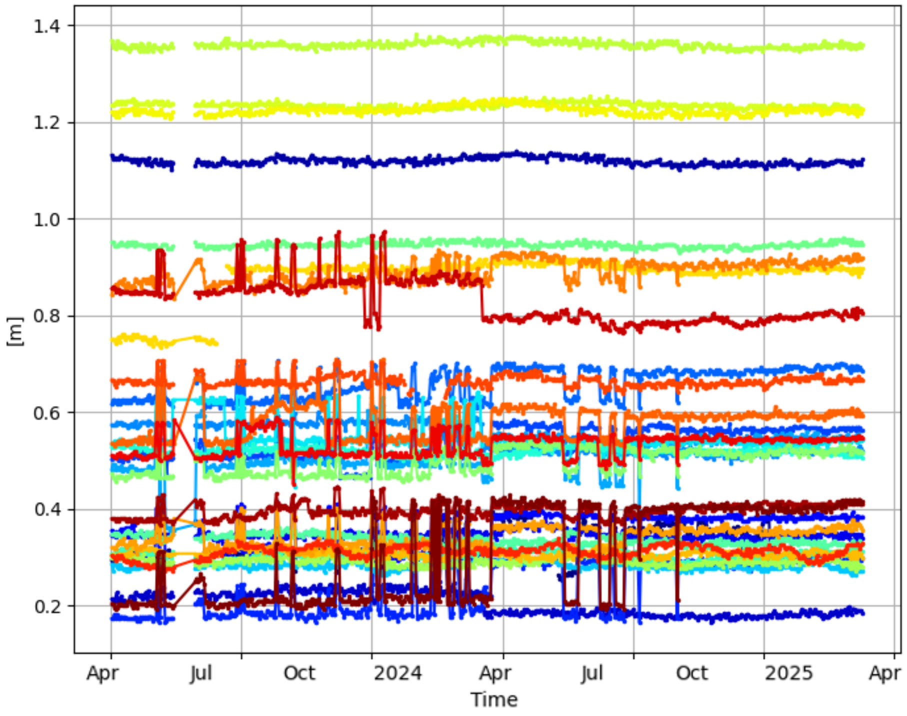


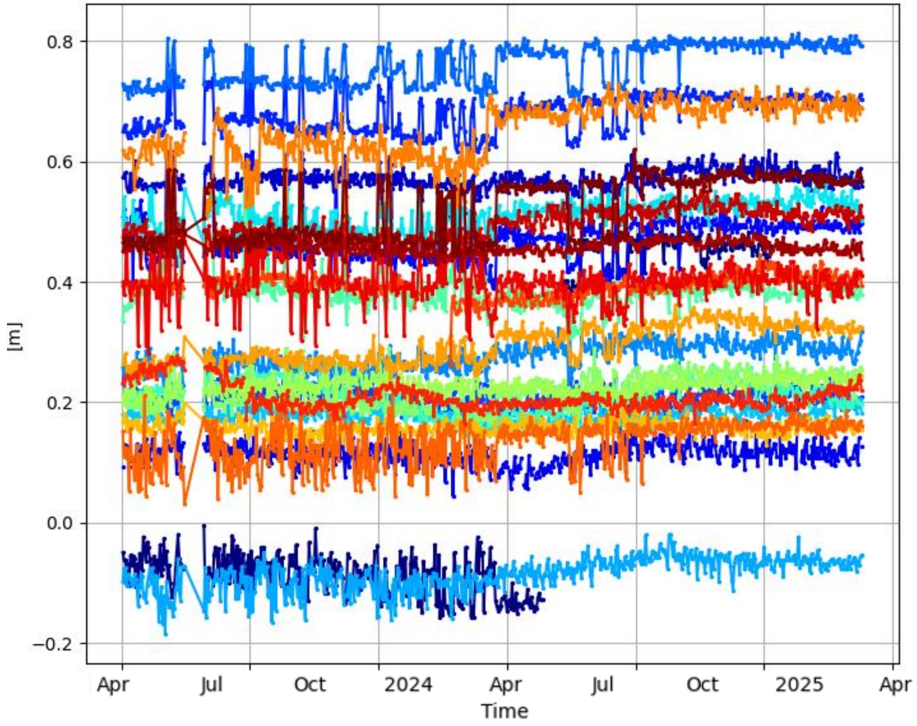
Bias observation from ground stations

GNSS satellite

GNSS receiver

- Code measure differences for two modulations: $C^{s}_{r,1C} - C^{s}_{r,1W} = b^{s}_{r,1C} - b^{s}_{r,1W} = b_{r,1C-1W} - b^{s}_{1C-1W}$
  - STJO ground station case (Saint John's, Canada)
  - Each point is the mean of the measurements from each satellite over one day

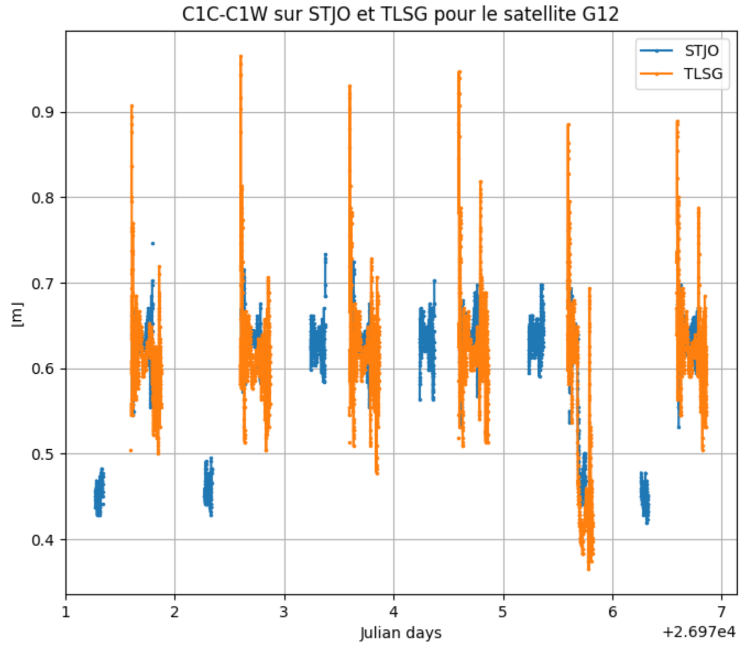


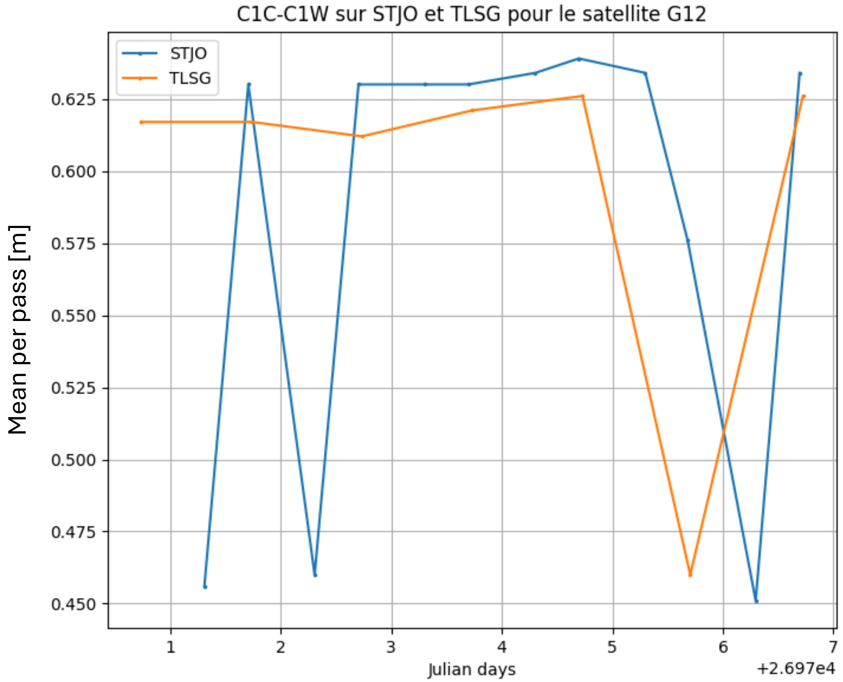


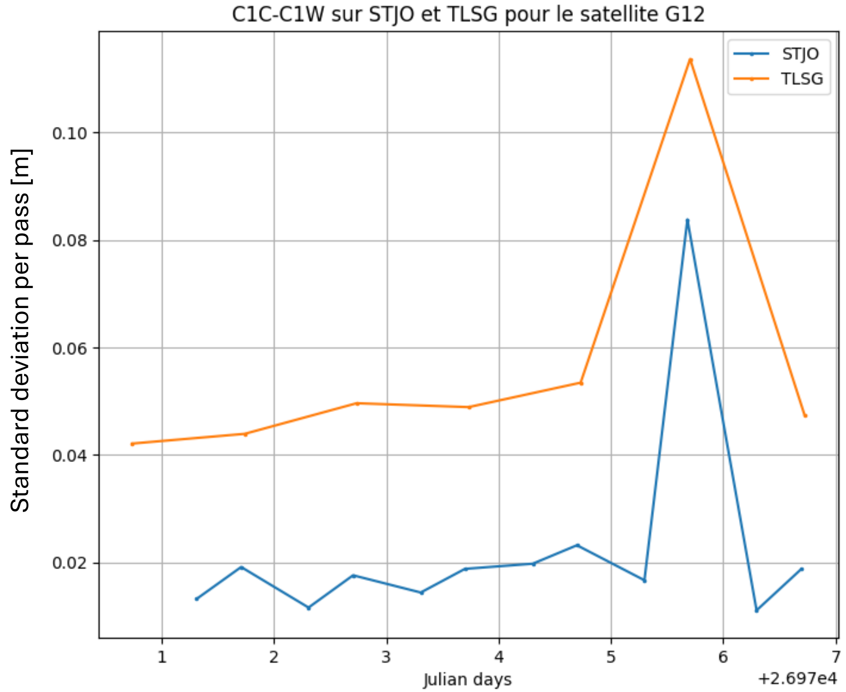
- Two types of behaviors
  - satellites with constant biases
  - satellites with bias jumps, at the same time for each satellite

Bias observation from ground stations

- More detailed analysis on the jumps over a pass
  - Satellite G12, measurements C1C-C1W from STJO and TLSG
  - STJO with passes per day, different biases: the bias is constant for each pass (low standard-deviation)
  - for some passes, a jump occurs inside a pass: the standard deviation is increased



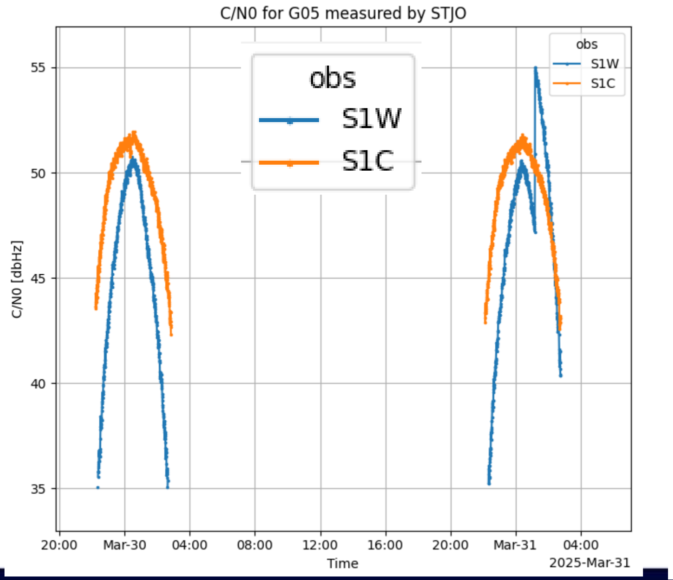


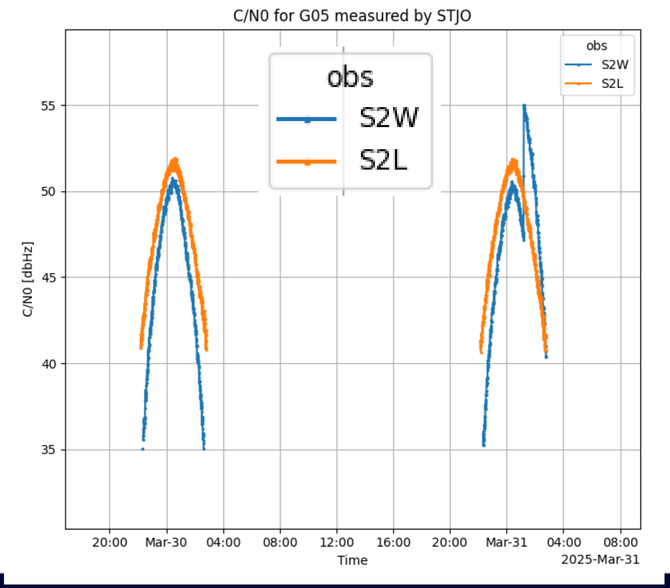


Bias computation from ground stations

- **Link with GPS flex power**
  - Flex power is the capacity of GNSS satellites to enhance the transmit power on individual signal components
  - GPS and Beidou are equipped with such a system
  - This has an impact on differential code biases
  - for GPS signals, impact on C1C-C1W and C2L-C2W, for Block IIR-M and Block IIF

  - flex power can be seen on carrier to noise ratio
  - flex power can be switched on and off within a single day





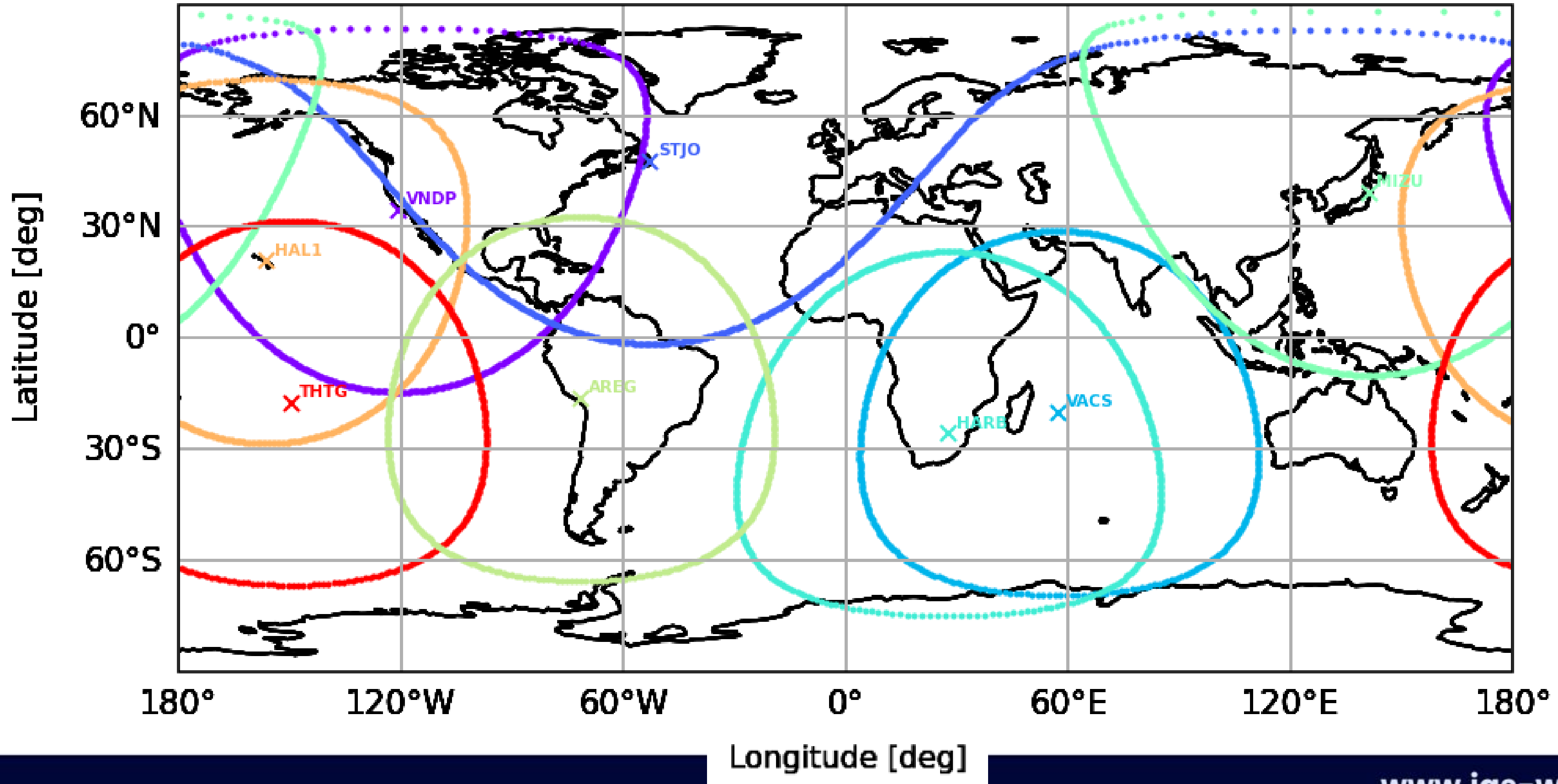
- **Studies already done for flex power detection based on C/N0 analysis:**
  - Yang et al. (2022), Tang et al (2022), Esenbuğa et al. (2023), Meng et al. (2024), Du et al. (2025), Wu et al. (2025), Su et al (2026), Zhang et al. (2025)

- **Studies display the DCB during flex power events:**
  - Steigenberger et al. (2019): analysis from spectral densities
  - Esenbuğa and Hauschild (2020): assume a localization of the flex power events on the Earth, and assume no flex-power on the L2 band, use a core network of station for DCB estimation
  - Liu et al. (2025): 15 min smoothing for DCB estimation
  - Su et al (2026), Zhang et al. (2025b): estimation combined with C/N0 and DCB variations

Bias computation from ground stations

- Application
  - we propose a method to compute constant intermodulation biases of GPS satellite by defining intervals on constant DCB values, with a reduced number of stations
  - output: constant biases on flex-power-off and flex-power-on regimes

- Network of stations to observe the constellation
  - Station equipped with Septentrio POLARX5 receivers
  - Earth map with visibility circles at GPS altitude



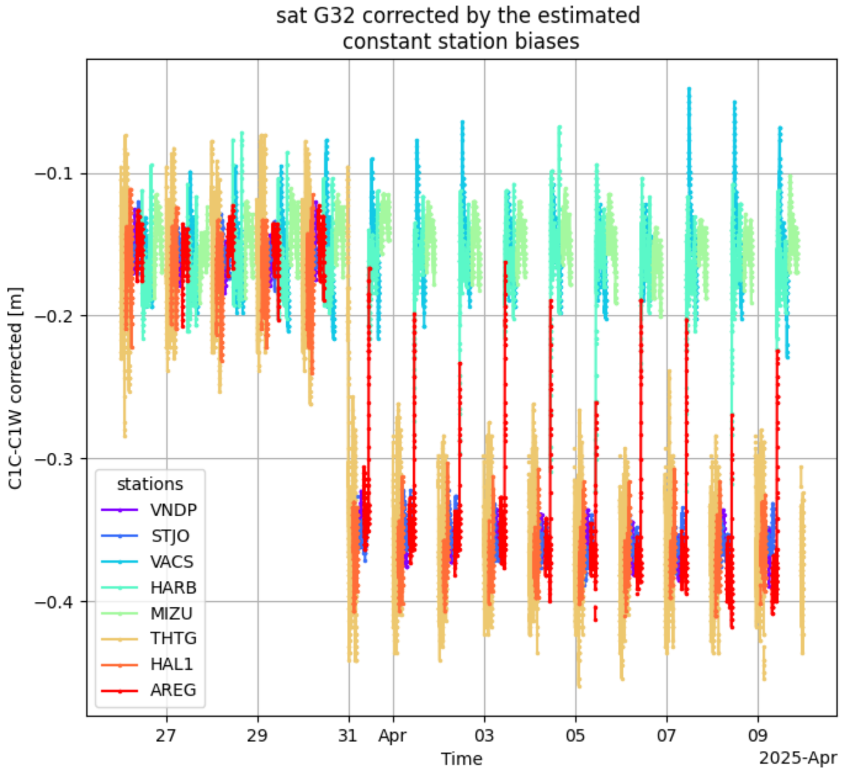
Bias computation from ground stations

- **Step 1: solve for constant satellite and receiver biases for satellites without flex power: GPSIII satellites**
  - create the measurements C1C-C1W for all the satellites and stations of the network
  - build the observation matrix for all the observables between each satellite and each station
  - add a zero-mean observability constraint
  - solve for an overdetermined least-square problem $Mx = b$, with x containing the constant biases

$$
\begin{array}{r c}
 & \begin{array}{cccccc} sat_1 & \cdots & sat_n & sta_1 & \cdots & sta_m \end{array} \\
\begin{array}{r} \text{satellite-station} \\ \text{measurements} \\ \\ \\ \\ \\ \\ \text{zero-mean constraint} \end{array} & M = \left[\begin{array}{cccccc}
-1 & & & 1 & & \\
\vdots & & & & \ddots & \\
-1 & & & & & 1 \\
 & \ddots & & & & \\
 & & -1 & 1 & & \\
 & & \vdots & & \ddots & \\
 & & -1 & & & 1 \\
\hline
1 & \cdots & 1 & 0 & \cdots & 0
\end{array}\right]
\end{array}
\qquad
b = \left[\begin{array}{c}
(C1C - C1W)\ sat_1 sta_1 \\
\vdots \\
(C1C - C1W)\ sat_1 sta_m \\
\vdots \\
(C1C - C1W)\ sat_n sta_1 \\
\vdots \\
(C1C - C1W)\ sat_n sta_m \\
\hline
0
\end{array}\right]
$$

Bias computation from ground stations

- **Step 1: solve for constant satellite and receiver biases for satellites without flex power: GPSIII satellites**
  - when removing the station bias, the corrected measurements from each satellite align around a constant values, with some jumps



Sat	C1C-C1W [m]	C2L-C2W [m]
G01	-0.249	0.139
G04	-0.235	0.222
G11	-0.279	0.159
G14	-0.249	0.129
G18	-0.275	0.116
G23	-0.268	0.165
G28	-0.261	0.130

- GPSIII biases are almost all the same for C1C-C1W
- The combinaison on C2L-C2W is noisier

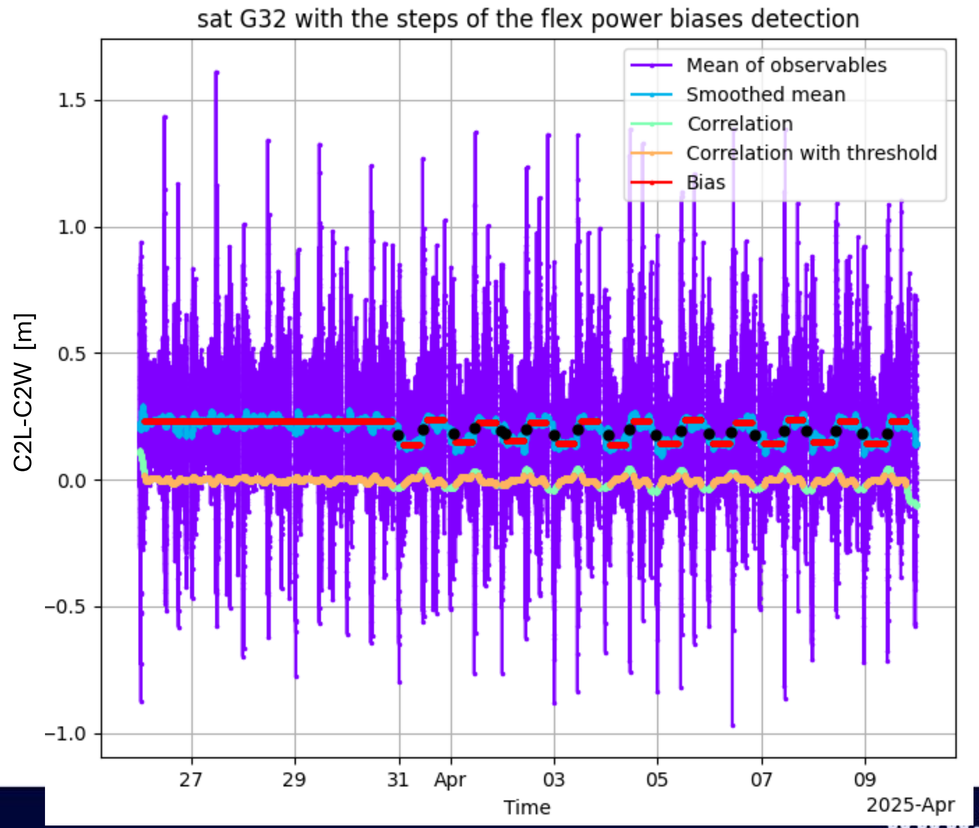
station	C1C-C1W [m]	C2L-C2W [m]
VNDP	0.559	0.326
STJO	0.567	0.328
VACS	0.546	0.395
HARB	0.537	0.371
MIZU	0.553	0.406
THTG	0.458	0.371
HAL1	0.441	0.387
AREG	0.444	0.383

All the stations have nearly the same biases

Bias computation from ground stations

- **Step 2: determination of the flex-power intervals for each satellite**
  - remove the previously determined station constant biases
  - compute the mean of the corrected observables per epoch
  - smooth the mean with a low-pass filter, to remove the effect of noisy observables
  - detect the transition by correlation with a step function

- Example on the G32 satellite with the steps displayed forthe C1C-C1W and C2L-C2W computations

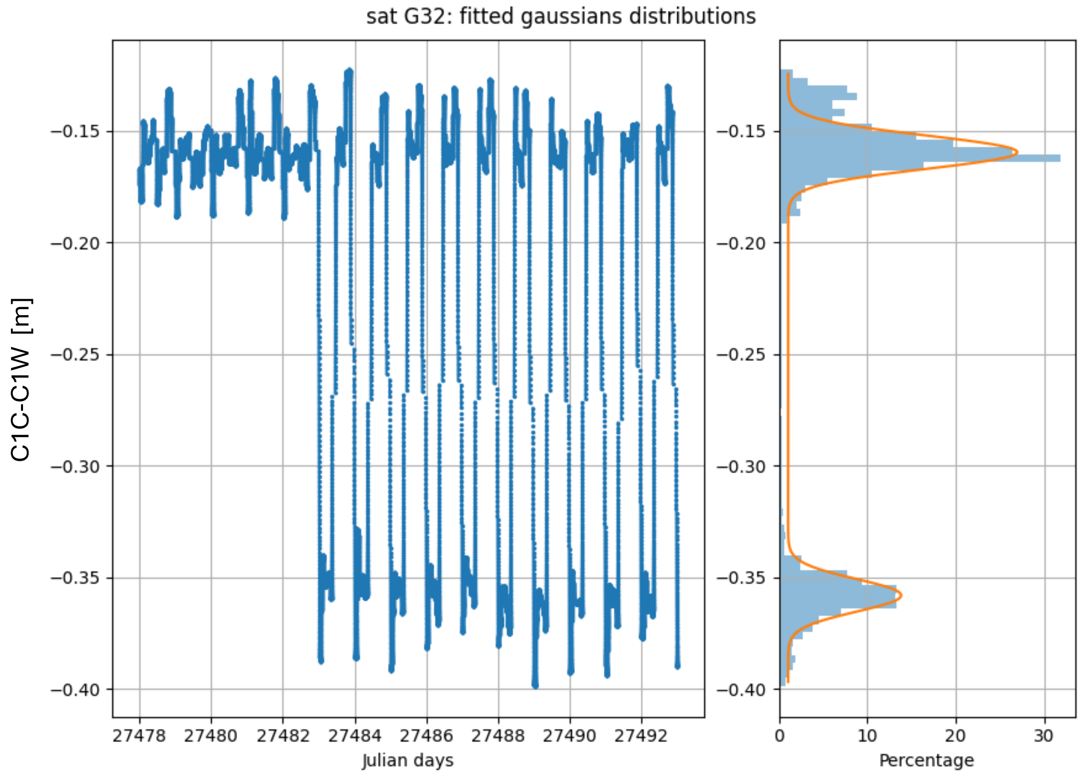


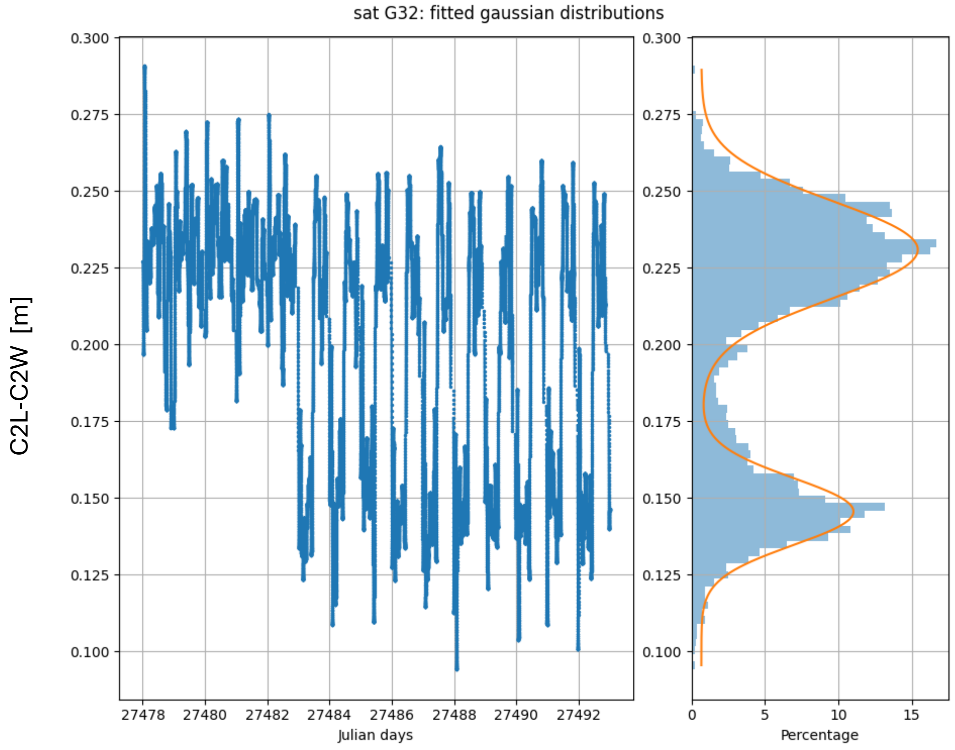
The black dots represent the detected transitions

Bias computation from ground stations

- **Step 3: consolidation of the estimated biases with histograms**
  - plot the histograms of the smoothed biases
  - fit two gaussians on the histograms
  - the means of each gaussian are the biases

- Example on the G32 satellite with the histograms displayed for the C1C-C1W and C2L-C2W computations





Bias computation from ground stations

❑ Computed values

- the satellites have been separated in blocks
- computation on a time span from the day 2025-025 (March 26th , 2025) to the day 2025-099 (April 9th , 2025)
- the flex power is activated from 2025-030 (April 1st, 2025)

Sat	Bias [m]	Bias during FP [m]
G05	-0.173	-0.257
G07	0.003	-0.092
G12	-0.037	-0.122
G15	-0.226	**not observed**
G17	-0.035	-0.090
G29	-0.021	-0.130
G31	-0.154	-0.188

C1C-C1W: Block IIR-M

Sat	Bias [m]	Bias during FP [m]
G03	-0.380	-0.414
G06	-0.266	-0.388
G08	0.124	0.044
G09	-0.044	-0.004
G10	-0.196	-0.025
G26	0.037	-0.030
G27	0.095	**not observed**
G30	0.233	0.194
G32	-0.160	-0.358

C1C-C1W: Block IIF

Sat	Bias [m]	Bias during FP [m]
G05	0.153	0.029
G07	-0.123	**not observed**
G12	0.195	0.1140
G15	0.051	-0.011
G17	-0.101	-0.145
G29	0.050	-0.042
G31	0.129	**not observed**

C2L-C2W: Block IIR-M

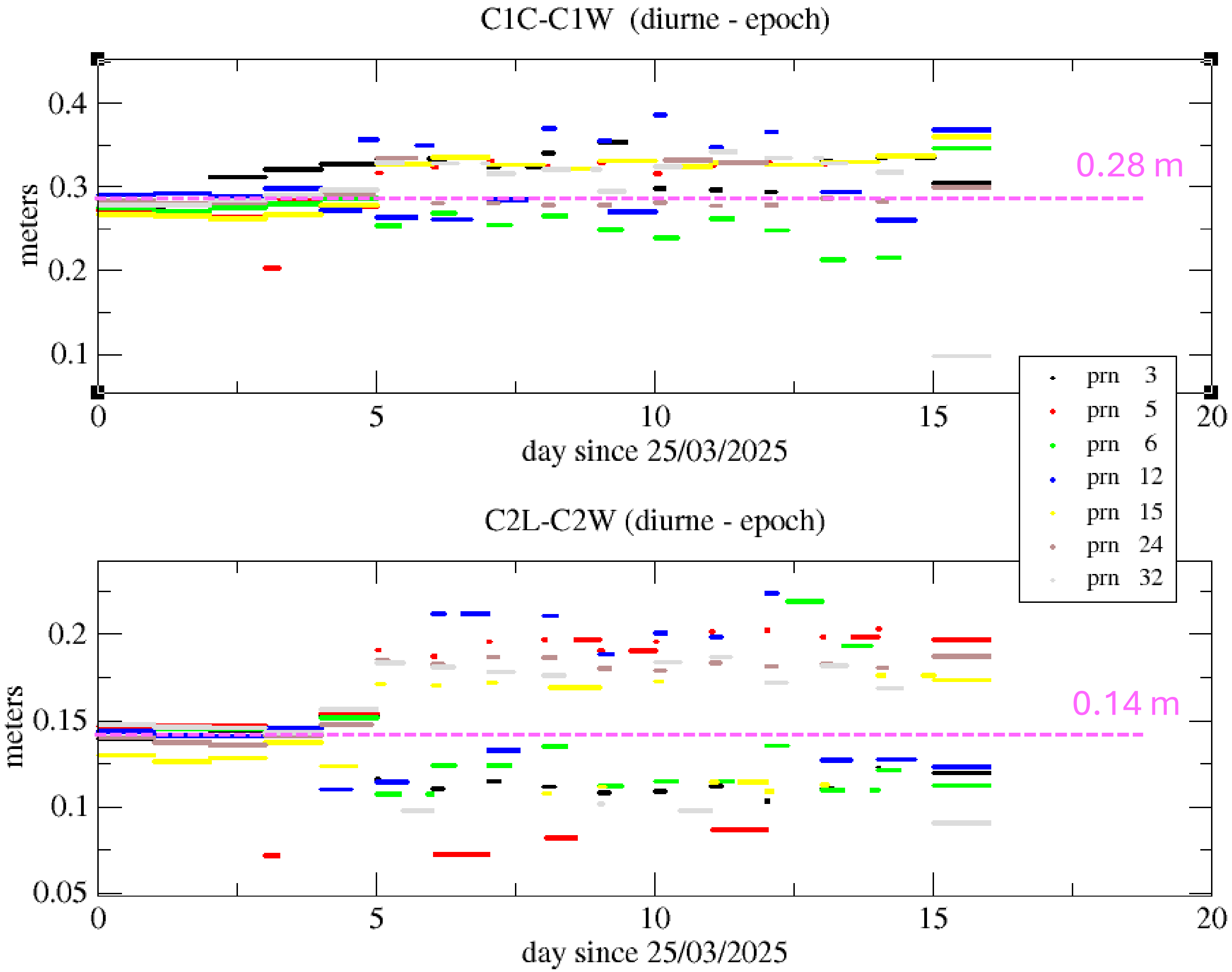
Sat	Bias [m]	Bias during FP [m]
G03	0.248	0.168
G06	0.379	0.295
G08	0.465	0.366
G09	-0.036	-0.081
G10	-0.403	**not observed**
G26	-0.171	-0.271
G27	0.082	**not observed**
G30	0.182	**not observed**
G32	0.236	0.150

C2L-C2W: Block IIF

Comparison with daily products

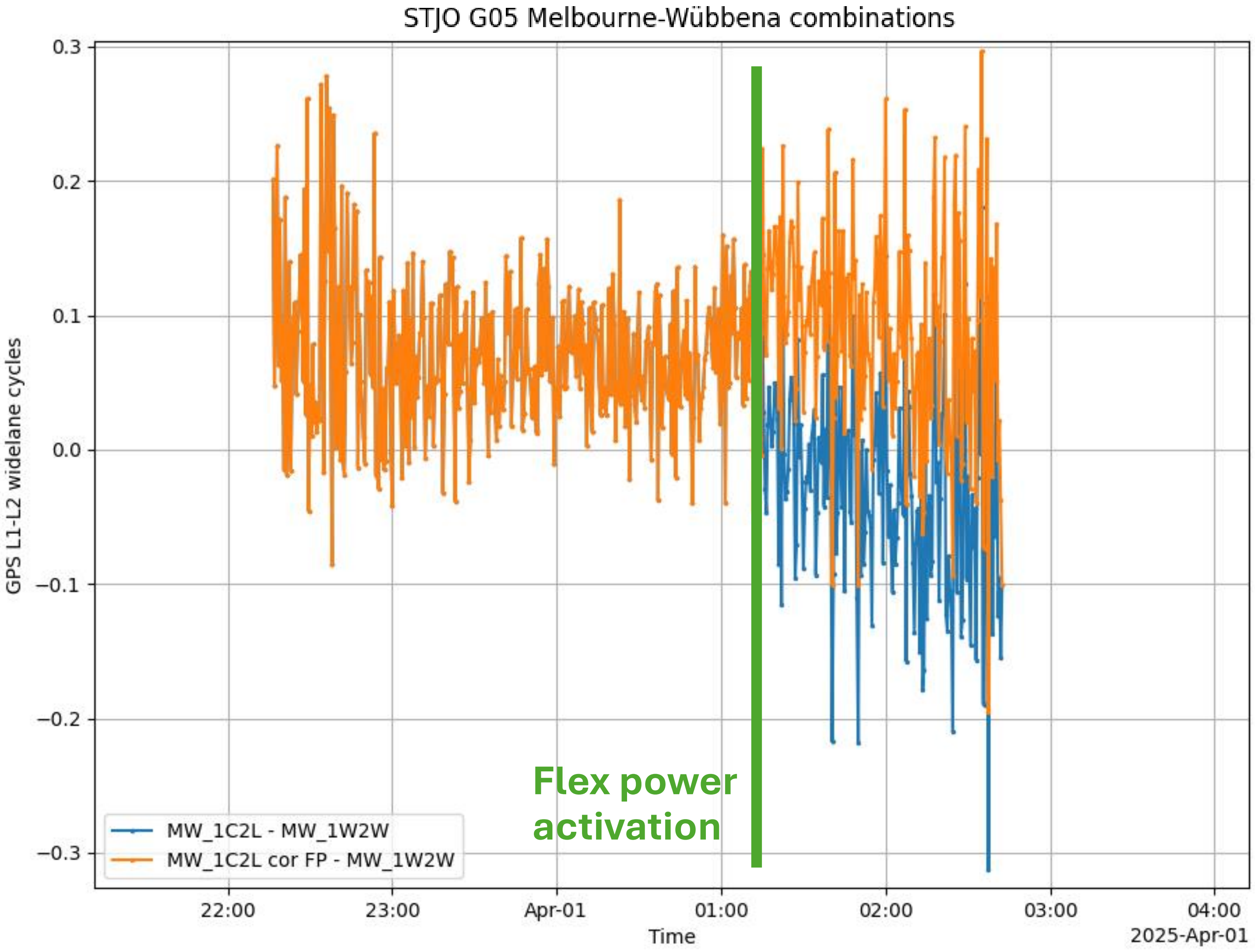
❑ **Comparison with GRG products**

- daily mean values w/o considering Flex Power
- before the flex power event, the biases are grouped together:
  - ❖ common difference of around 0.28 m for C1C-C1W,
  - ❖ common difference of around 0.14 m for C2L-C2W,
- after the beginning of the flex power event, the differences are spread around the previous mean values



Application to-Melbourne Wübbena combination

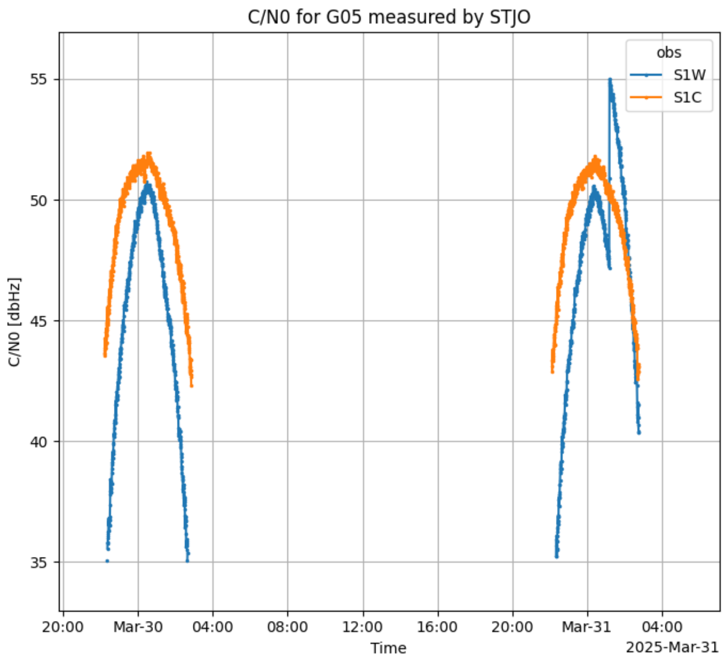
- **Flex Power effect on the Melbourne-Wübbena (MW)**
  - The change of the C1W and C2W biases can be seen on the MW combination between the bands 1 and 2
  - Computation of the 1W-2W MW and 1C-2L MW
  - Computation of the 1W-2W MW and 1C-2L MW correction with the computed biases
  - Example on the G05 satellite
  - $\Delta\mu = \left(\frac{\lambda_1-\lambda_2}{\lambda_1+\lambda_2}\right)\left(\frac{\Delta C_1}{\lambda_1}+\frac{\Delta C_2}{\lambda_2}\right) = -0.11\ WL\ cycles$
  - The correction with the computed flex power bias realigns the combination to a constant fractional receiver bias

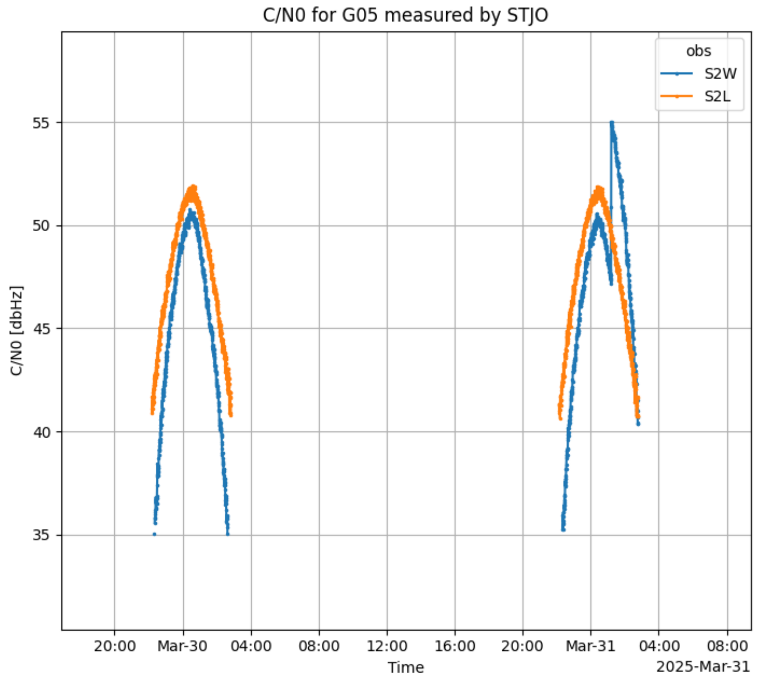


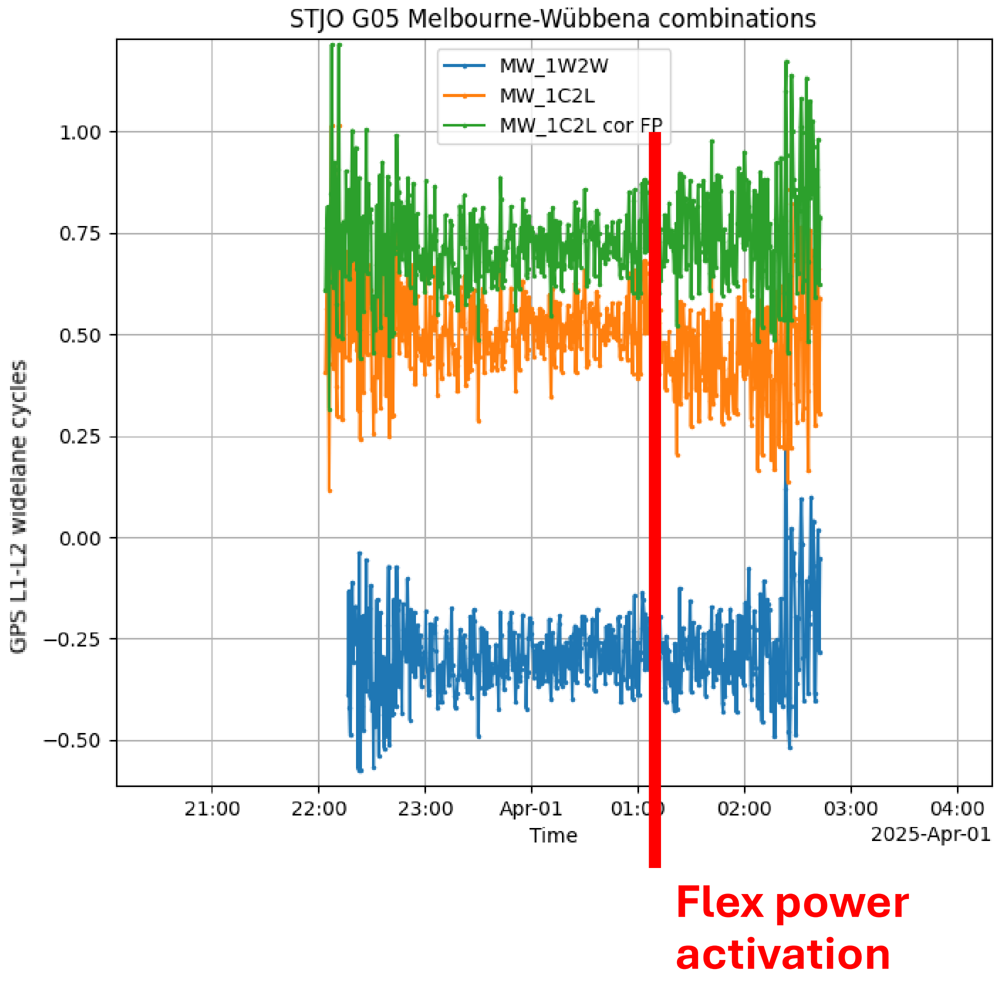
Application to-Melbourne Wübbena combination

❑ Flex Power effect on the Melbourne-Wübbena (MW)

- Wich signal is jumping?
- Draw the military MW, the civil MW and the FP-corrected civil MW
- The civil MW is jumping whereas the SNR increase is seen on the military signals







Conclusion

- For GPS measurements treatments, GPS satellites intermodulation have to be used
  - the GPS satellite biases are given on military signals
  - some satellites receive only the civil signals
  - for integer ambiguity the modulation of the GPS satellites biases must match the modulation of the measurements

- Intermodulation biases can be retrieved from analysis centers (ACs)
  - this biases come from hardware delays, and should be nearly constant (if the payload remains constant)
  - the ACs usually provide 1 value per day, but the values can vary significantly on a large time span
  - intra days variations have been observed, caused by GPS flex power
  - the accurate description of the biases in flex power on phases requires to define sub-daily values in the SINEX files

- Separation between ‘flex power on’ and ‘flex power off’ regimes
  - a technique has been set up in order to detect the flex power activation and deactivation times
  - the GPS satellites biases are constant on each regime

- Evolutions
  - Beidou Flex Power has to be investigated
  - this study demonstrated that the biases are constant, except during flex power events, GPSIII satellites have constant biases values
  - these features have to be used in a real time context

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