# Bye-bye bias! The ESA Multi-GNSS Bias Reference Frame

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# Introduction: Why bother with biases?

- In general, with the large number of different signals available we can not expect that receivers deliver the same signals as those which were used to generate the GNSS products (orbits and clocks) we provide. In case other signals are used, in particular for PPP and PPP-AR, the biases between the signals used to generate the orbit and clock products and the signals that are available will have to be considered
- Example 1: Not all receivers deliver 1W data for GPS
  - So, we must correct the 1C data for the 1C-1W code bias differences (done since decades within the IGS)
- Example 2: Latest Sentinel GPS tracking gives us:
  - For the GPS IIR satellites: 1C-, 1W-, 2W-observations
  - For the GPS IIR-M, IIF, III satellites: 1C- and 2L-observations
    - How to process the 1C and 2L observations using products bases on 1W and 2W observations
- Example 3: PPP with integer ambiguity resolution (PPP-AR)
  - Requires phase biases

# The ESA Bias Reference Frame (BREF)

- We are generating our own set of code biases
    - For ***all*** signals from ***all*** GNSS as tracked by the IGS network
        - We exclude GLONASS because of FDMA
- Based on the stability of the code biases we have defined what we call a Bias Reference Frame (BREF)
    - The biases of the satellites are aligned to this BREF
        - Initialized using a zero-mean condition over a certain starting period
        - Tightly constrained to those values
    - But with automatic detection and handling of discontinuities on signals from individual satellites
        - Handled similarly as station discontinuities
- We are using our own C1C-C1W biases based on our ESA BREF
- More details about the ESA BREF will be presented at the upcoming IGS workshop

# Signals Covered by the ESA BREF

| | Frequencies | Component | Equal to | # Signals |
|---|---|---|---|---|
| Galileo | L1, L6 | B,C,X | C | 5 |
| | L5, L7, L8 | I,Q,X | Q | |
| GPS | L1 | C | C | 6 |
| | L1, L2 | P | W | |
| | L1, L2 | S,L,X | L | |
| | L5 | I,Q,X | Q | |
| BeiDou | L1, L5, L8 | D,P,X | P | 6 |
| | L2 L6 | I | I | |
| | L7 | D,P,Z | D | |
| QZSS | L1, L2, L6 | S,L,X | L | 6 |
| | L5 | I,Q,X | Q | |
| | L5s | D,P,Z | P | |
| | L8 | D,P,X | X | |

# Signal Types

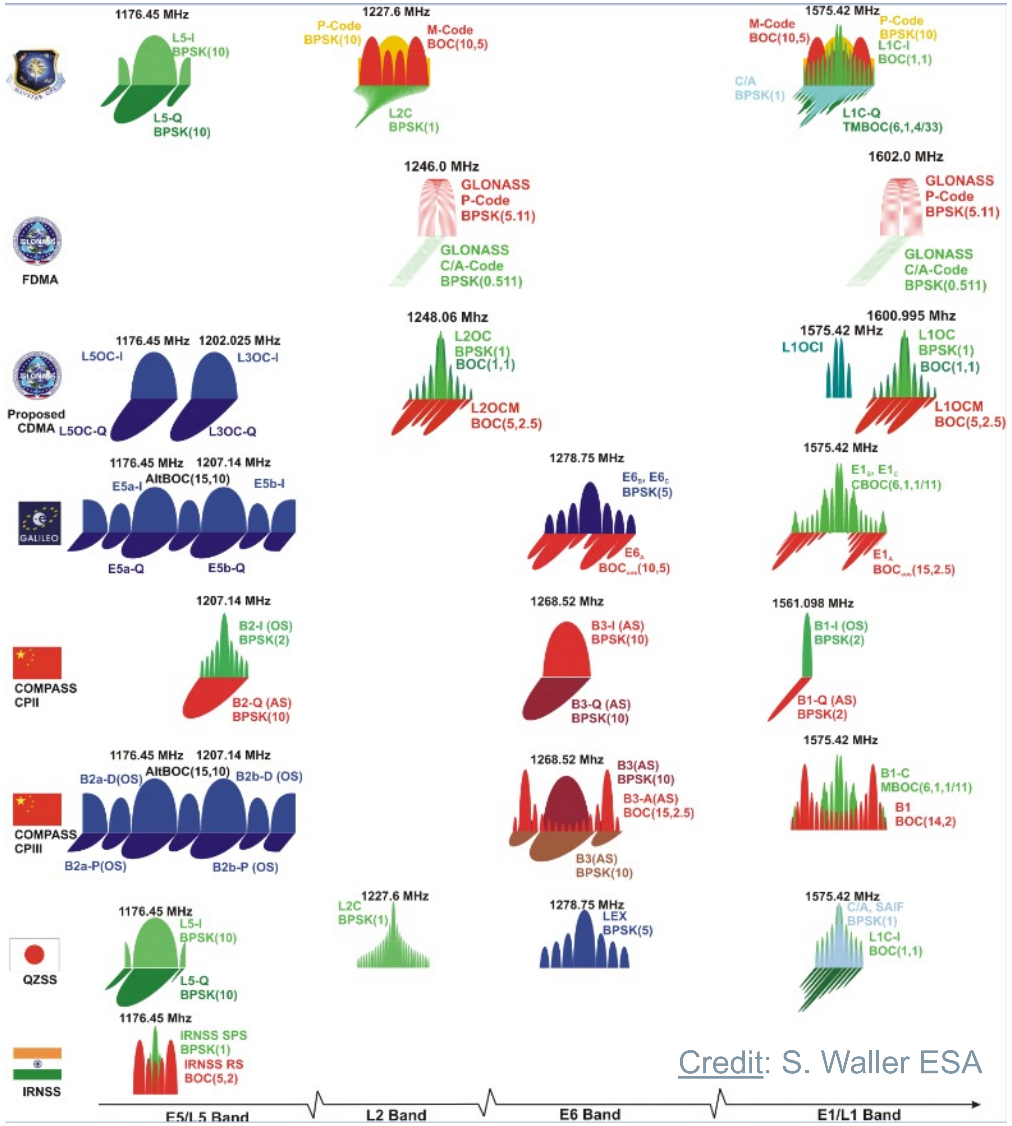
- The GNSS environment has grown significantly.
  - The combined use of modern and legacy GNSS signals has proven beneficial

- 19 CDMA signal combinations considered

- More DCB such as can be derived
- $DCB(\text{C1W,C1C})$ =
  $DCB(\text{C1W,C2W})$ - $DCB(\text{C1C,C2W})$
- $DCB(\text{C2W,C2L})$ =
  $DCB(\text{C1C,C2W})$ - $DCB(\text{C1C,C2L})$

| | S1 | S2 |
|---|---|---|
| Galileo | C1C | C5Q |
| | C1C | C6C |
| | C1C | C7Q |
| | C1C | C8Q |
| GPS | C1C | C2L |
| | C1C | C2W |
| | C1W | C2W |
| | C1C | C5Q |
| | C1L | C5Q |
| BeiDou | C1P | C5P |
| | C1P | C6I |
| | C1P | C7D |
| | C1P | C8X |
| | C2I | C6I |
| QZSS | C1L | C2L |
| | C1C | C5Q |
| | C1L | C5P |
| | C1L | C5Q |
| | C1Z | C5Q |

RINEX Signal Codes



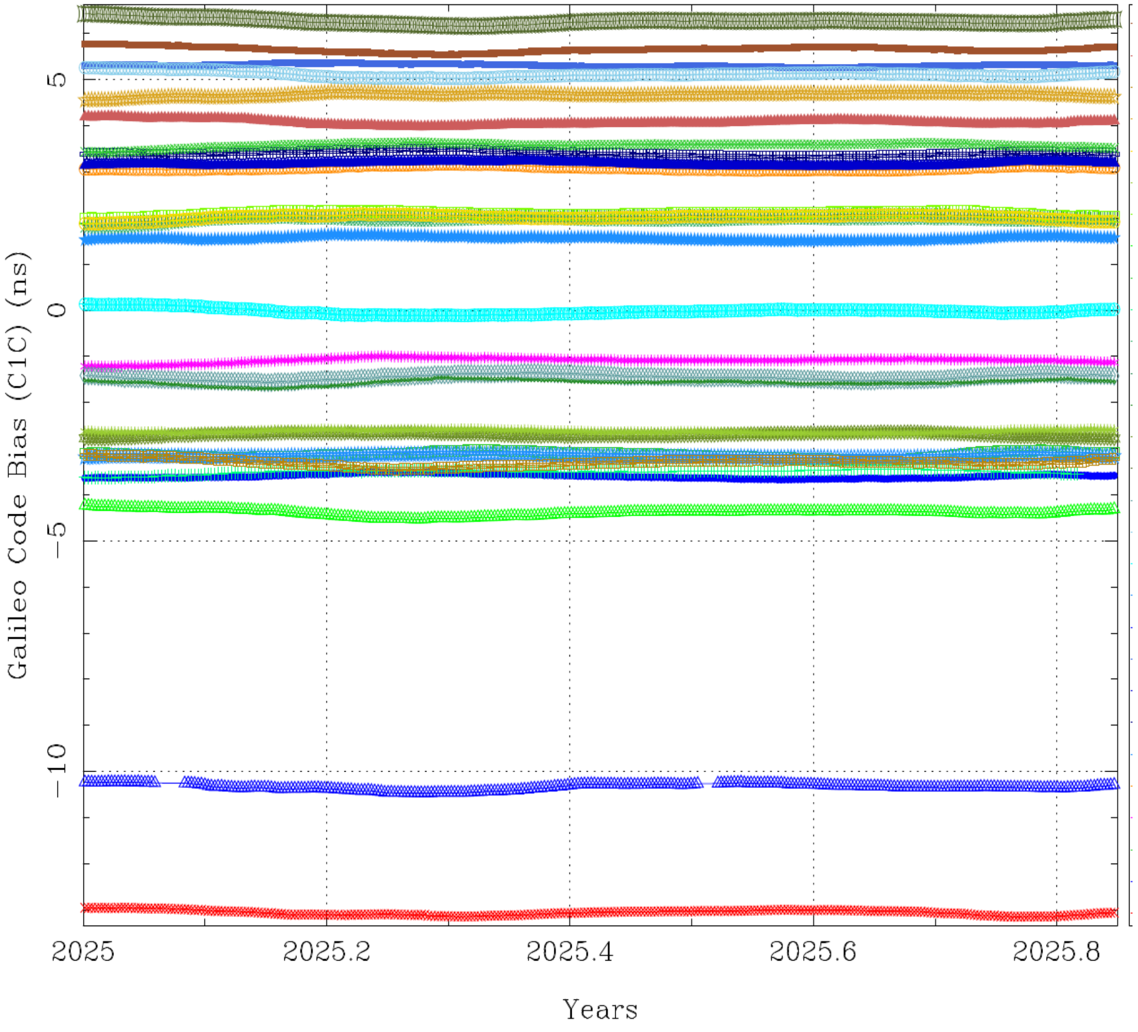

Credit: S. Waller ESA

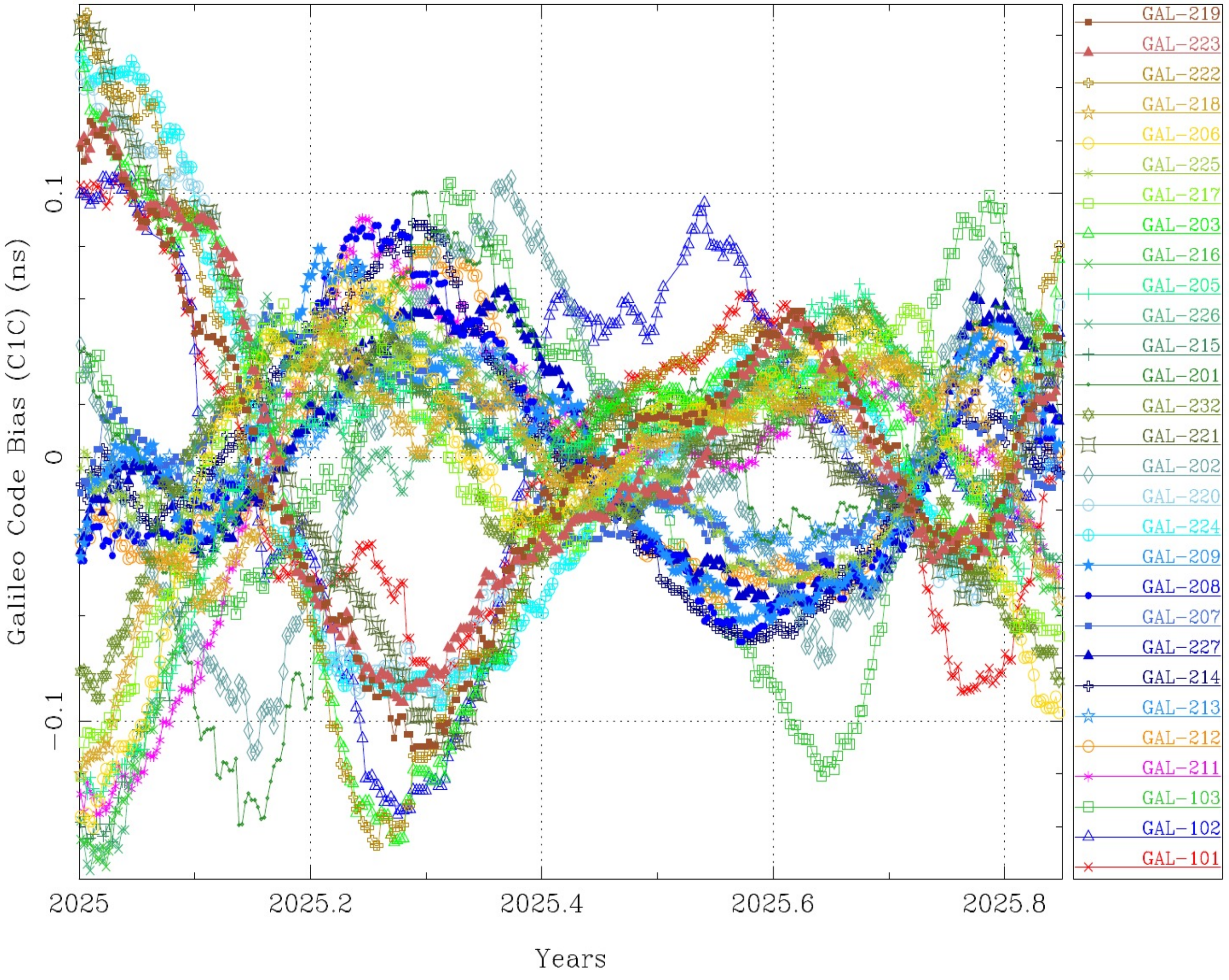
# Signal Component considered equal

- GNSS signals often consist of a Data and a Pilot component
  - Data component is navigation-message modulated
  - Pilot component is unmodulated, enabling improved tracking
- Components can be tracked individual or jointly (providing the X component)
- ESA confirmed identical signal delays for data and pilot components
- Estimating a single code bias per signal sufficient

| | Frequencies | Component | Equal to |
|---|---|---|---|
| Galileo | L1, L6 | B,C,X | C |
| | L5, L7, L8 | I,Q,X | Q |
| GPS | L1, L2 | P | W |
| | L1, L2 | S,L,X | L |
| | L5 | I,Q,X | Q |
| BeiDou | L1, L5, L8 | D,P,X | P |
| | L7 | D,P,Z | D |
| QZSS | L1, L2, L6 | S,L,X | L |
| | L5 | I,Q,X | Q |
| | L5s | D,P,Z | P |
| | L8 | D,P,X | X |
| GLONASS | L3 | I,Q,X | Q |

# Stability of the code biases



# The ESA Bias Reference Frame (BREF)

esa

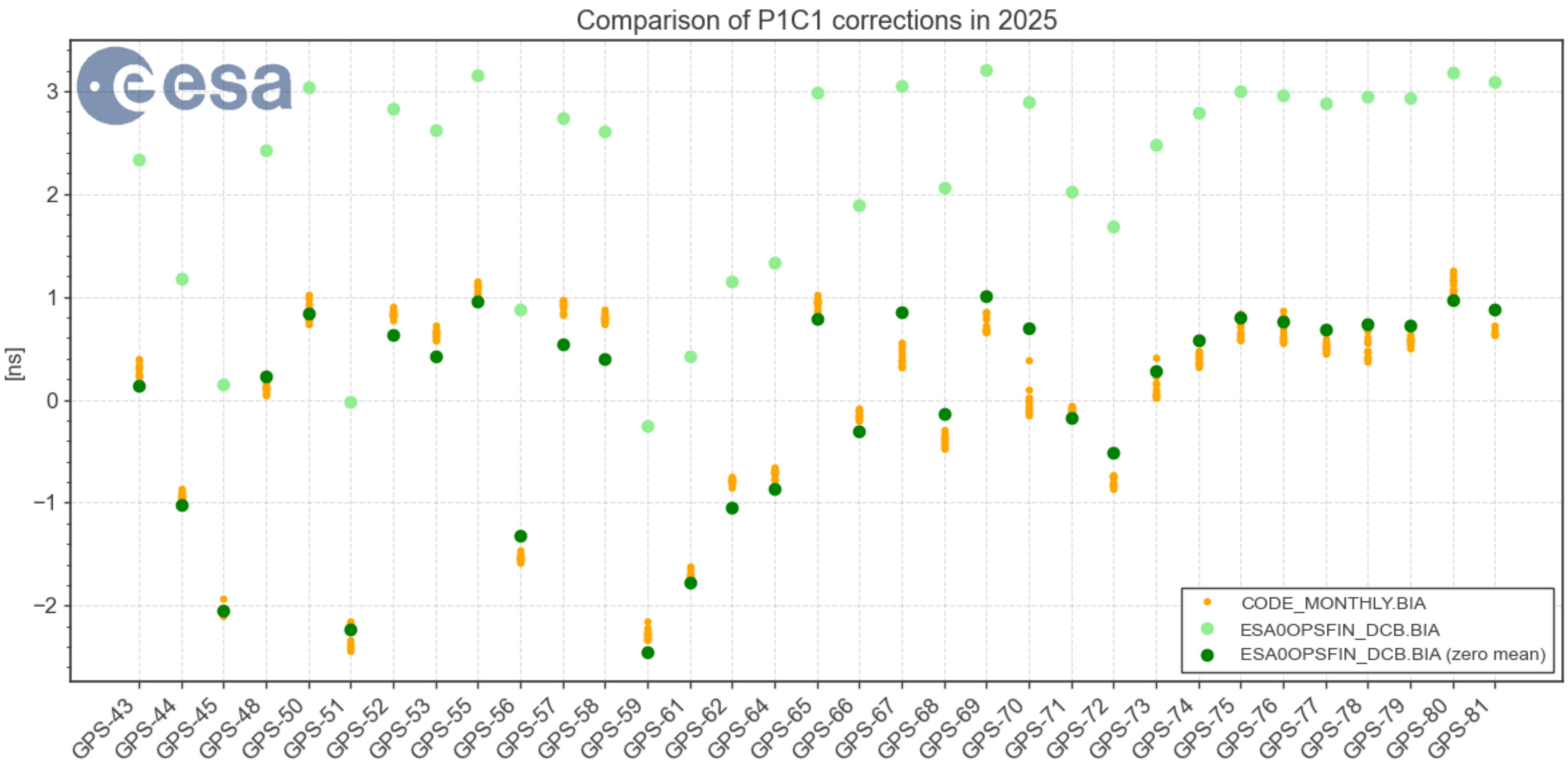
**Ionosphere Model**
- Estimate Global Ionosphere Model

**DCB Estimation**
- Generate daily estimates of all the (19) DCBs

**DCB Stacking**
- Long-term stacking of all the (19) DCBs
- Automatic detection of discontinuities

**ESA DCB BREF**
- Merge all (19) DCBs in one single bias-SINEX file
- Add C1C-C1W code bias

# Difference between BREF and zero-mean



# Phase Biases

- At ESA we have been generating and using fractional phase biases for PPP-AR since many years
    - For GPS our phase biases come from processing the GPS 1W-2W observations
    - We also do them for Galileo (1C/X - 5Q/I), BeiDou (1P/X - 5P/X) and QZSS (1L/X/S - 5Q/I/X)
- The latest Sentinel satellites provide us with Galileo 1C-5Q and GPS 1W-2W but also GPS 1C-2L observations
    - So how can we use our GPS 1W-2W based products (orbit, clock and phase biases) to process that data!?
- When correcting the code observations, we must ensure that the phase biases, remain usable
- For many years we have been converting GPS 1C to 1W observations and this has proven to work perfectly fine when doing PPP-AR of 1C-2W data with 1W-2W based products
    - So logically we should be able, in a similar way, to produce 2L-2W biases which make the 2L observations compatible with the 2W phase biases
    - The disadvantage here is that these 1C-1W and 2L-2W biases can not be part of a set of consistent bias products
        - This because the implicit assumption was that the 1W and 2W observations were bias free
- How can we solve this more elegantly?

# Sentinel: Using 1C-1W and 2L-2W biases

| TestID | IIR | IIRM IIF/III | AC Prod | Code Biases | Phase Biases | Remarks |
|---|---|---|---|---|---|---|
| ESA1 | 1C/2W | 1C/2L | ESA | None | ESA | |
| ESA2 | 1C/2W | 1C/2L | ESA | ESA (1C-1W, 2L-2W) | ESA | Code biases applied |

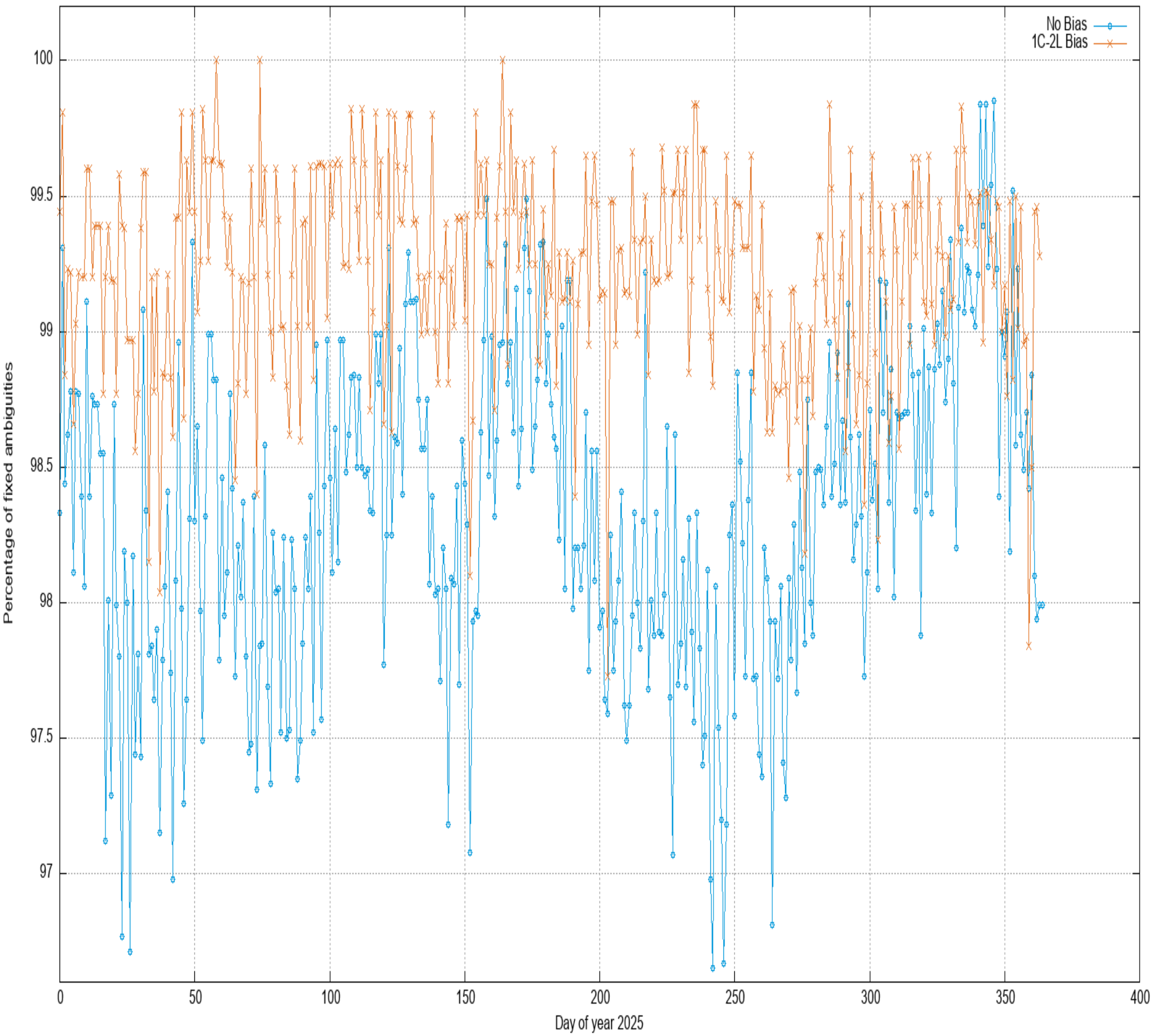
```
                                #Obs      #Rej   Mean (mm) RMS    #Obs      #Rej   Mean (m)  RMS
ESA1: FLOAT:  SENT-6A  L401 |  121462     538  -0.000   5.289|  121462     538  0.000   0.781|
      FIXD0:  SENT-6A  L401 |  121462       0  -0.022  27.521|  121462       0  0.000   0.781|
      FIXDL:  SENT-6A  L401 |  120834     628   0.000   6.424|  120834     628  0.001   0.781|

ESA2: FLOAT:  SENT-6A  L401 |  121328     672  -0.000   5.243|  121328     672  0.000   0.608|
      FIXD0:  SENT-6A  L401 |  121328       0  -0.026  26.934|  121328       0  0.000   0.608|
      FIXDL:  SENT-6A  L401 |  120768     560   0.000   6.392|  120768     560 -0.000   0.608|
```

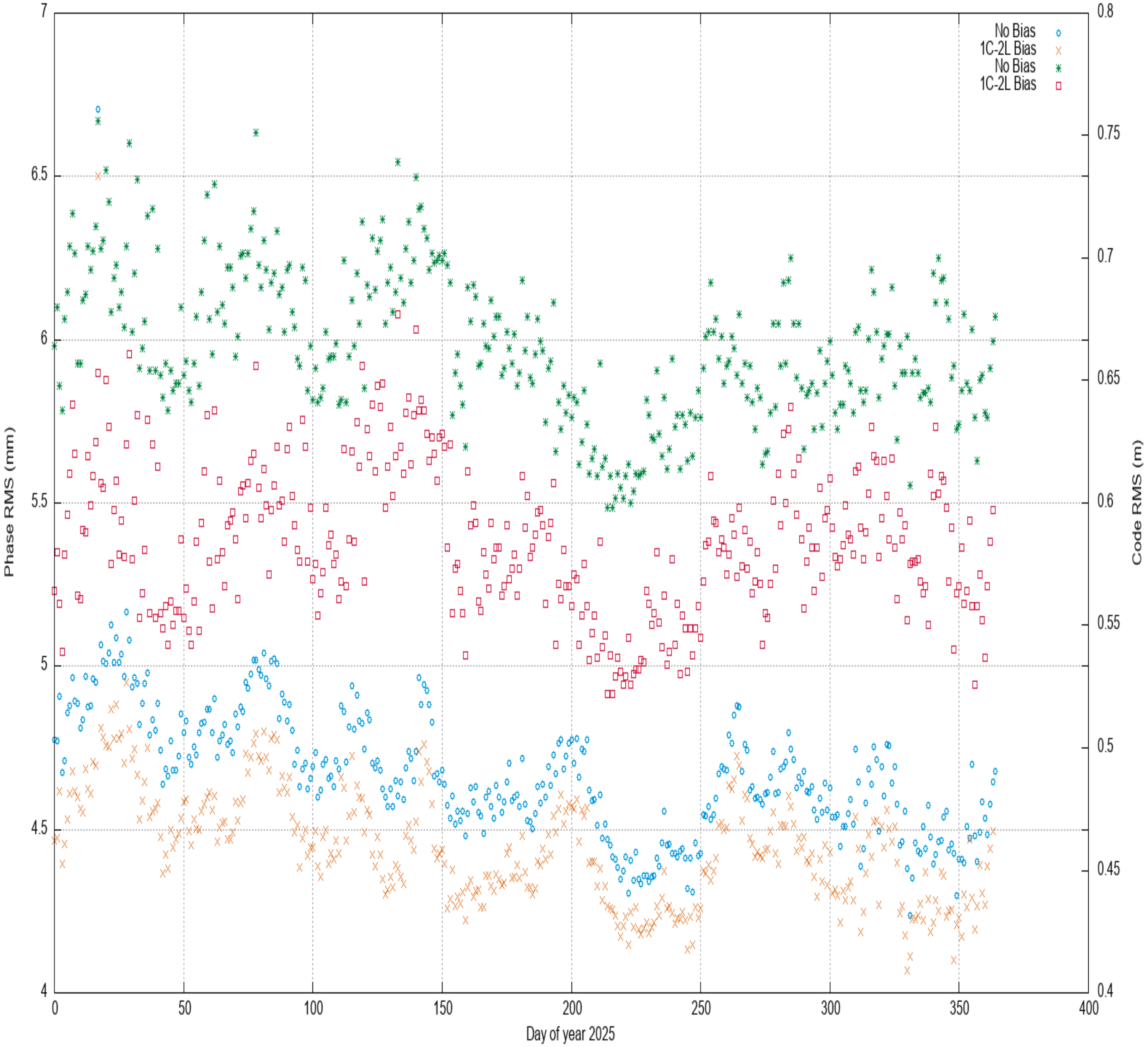
- Lower code and phase RMS in FLOAT solution
- Lower phase RMS after integer ambiguity resolution (FIXD0)
- Lower Final code and phase RMS in FIXED last iteration (FIXDL)
- More rejection in FLOAT solution, less rejections after ambiguity resolution (FIXD)

# From DCB to OSB

- To enable switching between different code signals whilst remaining able to use the fractional phase biases one need to define, generate and use a consistent set of code biases
- There are several ways to do this and our BREF is one example
    - However, the common way of doing things in GNSS is to process two (main) signals and consider them to be bias free
    - E.g. the IGS GPS clock products are based on the ionosphere free linear combination of the 1W-2W observations accounting for any code biases
- One way to generate code biases which are consistent with the IGS GPS products is to:
    - Define that the IF linear combination of the C1W and C2W biases is zero
    - And to apply a zero-mean condition for the C1W biases
- Similar constraints can be defined for Galileo, BeiDou and QZSS where the two (main) frequencies are those that were used to generate the fractional phase biases
- We have implemented this approach in the step where we convert our ESA BREF from DCBs to OSBs

# Sentinel: Using 1C-1W and 2L-2W biases



# The ESA Bias Reference Frame with phase biases

| | |
|---|---|
| GNSS Processing | • Generate global GNSS solution (orbit, clock, RF)<br>• Use ESA OSB BREF and derive phase biases |
| Ionosphere Model | • Estimate Global Ionosphere Model |
| DCB Estimation | • Generate daily estimates of all the (19) DCBs |
| DCB Stacking | • Long-term stacking of all the (19) DCBS |
| ESA DCB BREF | • Merge all (19) DCBs in one single bias-SINEX file<br>• Add C1C-C1W code bias |
| ESA OSB BREF | • Convert all (19) DCBs to (23) OSBs<br>• Full consistency of the biases for each constellation |

# Sentinel: Using COD products with ESA code OSBs

| TestID | IIR | IIRM IIF/III | AC Prod | Code Biases | Phase Biases | Remarks |
|---|---|---|---|---|---|---|
| ESA3 | 1W/2W | 1C/2L | COD | ESA OSBs | COD | COD products but ESA code OSBs |
| COD1 | 1W/2W | 1C/2L | COD | COD OSBs | COD | COD products |

```
                                #Obs      #Rej    Mean (mm) RMS    #Obs      #Rej    Mean (m)  RMS
ESA3: FLOAT:  SENT-6A  L401 |  126062     827    0.000    5.276|  126062     827    0.000    0.607|
      FIXD0:  SENT-6A  L401 |  126062       0   -0.025   19.798|  126062       0    0.000    0.607|
      FIXDL:  SENT-6A  L401 |  125246     816   -0.000    6.549|  125246     816    0.001    0.607|

COD:  FLOAT:  SENT-6A  L401 |  126007     882    0.000    4.979|  126007     882    0.000    0.631|
      FIXD0:  SENT-6A  L401 |  126007       0   -0.018   18.397|  126007       0    0.000    0.631|
      FIXDL:  SENT-6A  L401 |  125488     519    0.000    5.876|  125488     519   -0.001    0.632|
```

- The RMS of the code observations indicates that the ESA code OSBs may be doing a better job at removing the code biases
- But the results with the consistent COD code and phase biases seem to be a bit better
    - Phase RMS a bit lower in all three cases
    - Less rejections after ambiguity resolution
- So clearly even for the code biases consistency seems more important than accuracy!
    - But the results show that the ESA OSB biases are pretty accurate

# Conclusions

- We generate and maintain a long-term differential code bias product
    - The ESA Bias Reference Frame (BREF)
    - Available from our web-site (https://navigation-office.esa.int/products/)
- We generate phase biases for all GNSS systems
    - GPS, Galileo, BeiDou and QZSS (GLONASS excluded for obvious reasons (FDMA))
    - Not (yet) publicly available
- Our code and phase bias products are state-of-the-art
    - Using our phase biases requires special biases when used with other code signals
        - For C1C one would need the well know C1C-C1W biases
        - For C2L one would need the C2L-C2W biases
- Our ESA BREF is currently containing only DSBs
    - We will generate and maintain an OSB version of it (soon)
    - We will generate phase biases consistent with our ESA OSB BREF

# Thank you for your attention!

# Bye-bye bias!

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# Interesting Publications

Determination of GNSS pseudo-absolute code biases and their long-term combinaton, Arturo Villiger, Stefan Schaer, Rolf Dach, Lars Prange, Andreja Susnik, Adrian Jäggi, 2019

The CODE ambiguity-fixed clock and phase bias analysis products: generation, properties, and performance, S. Schaer, A. Villiger, D. Arnold, R. Dach, L. Prange, A. Jäggi, 2021

Analysis of different observation-specific signal bias products for carrier phase ambiguity fixing in precise orbit determination of the Copernicus Sentinel satellites, Heike Peter, Carlos Fernandez Martin, Tim Springer, Presented at REFAG, 2026 (paper to be published)