

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

T. Springer², M. Otten², V. Mayer³, F. Gini¹, E. Schoenemann¹

¹ Navigation Support Office, ESA/ESOC, Darmstadt, Germany

² PosiTim @ ESA/ESOC, Darmstadt, Germany

³ SSC Space @ ESA/ESOC, Darmstadt, Germany

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)



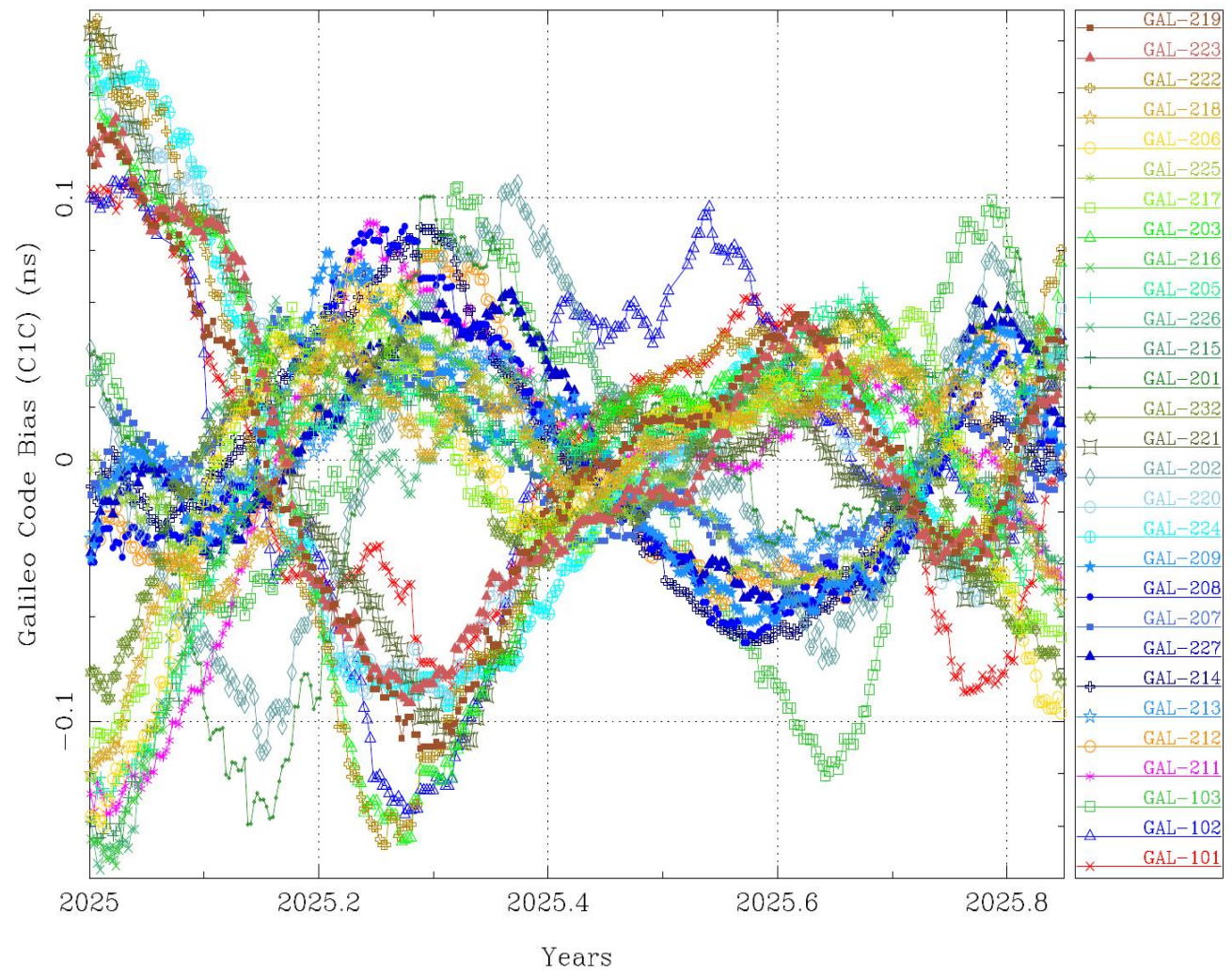
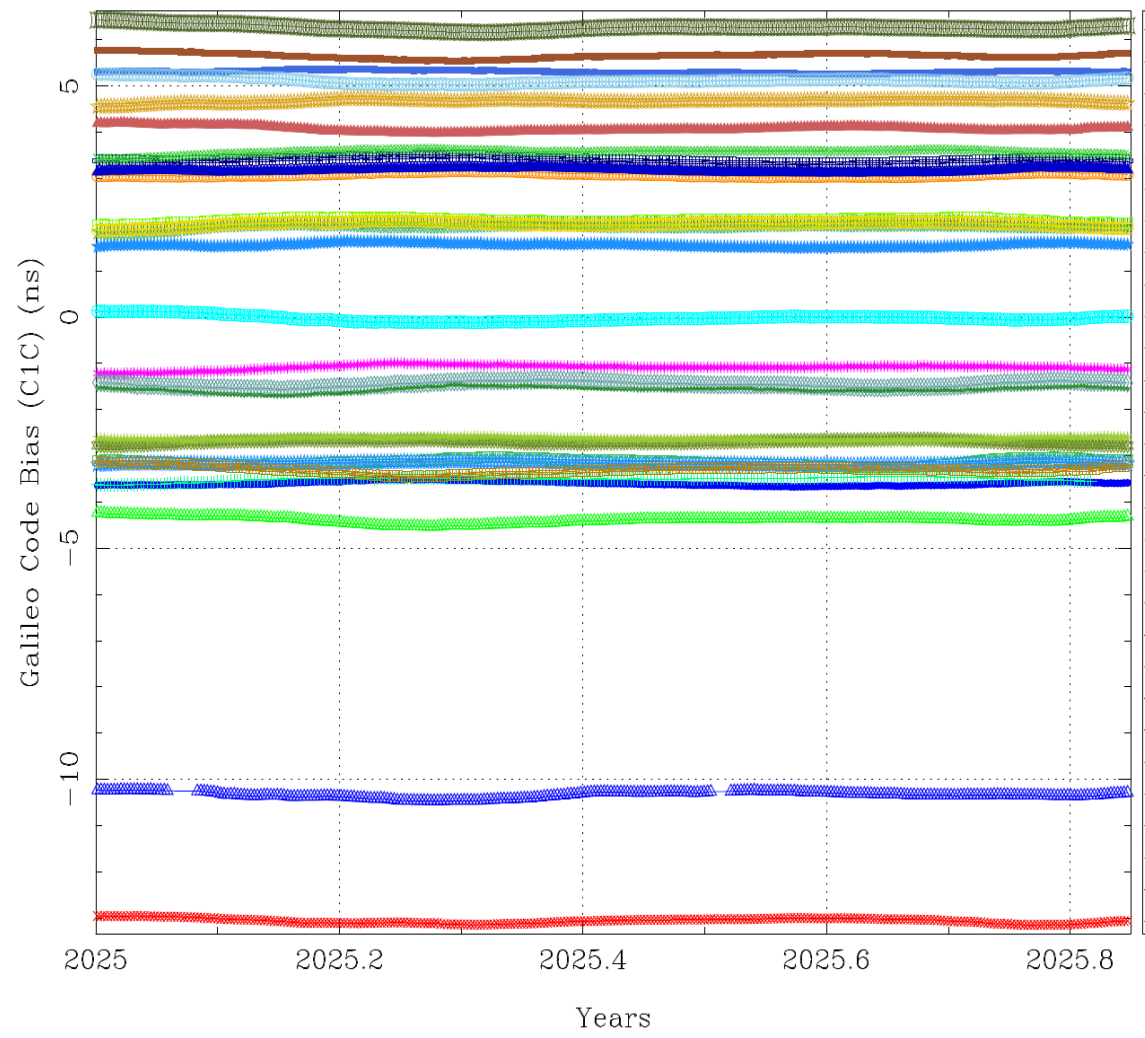
- We are generating our own set of code biases
 - For *all* signals from *all* GNSS as tracked by the IGS network
 - We exclude GLONASS because of FDMA
- Based on the stability of the code biases we have defined what we call a Bias Reference Frame (BREF)
 - The biases of the satellites are aligned to 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 will be presented at the upcoming IGS workshop

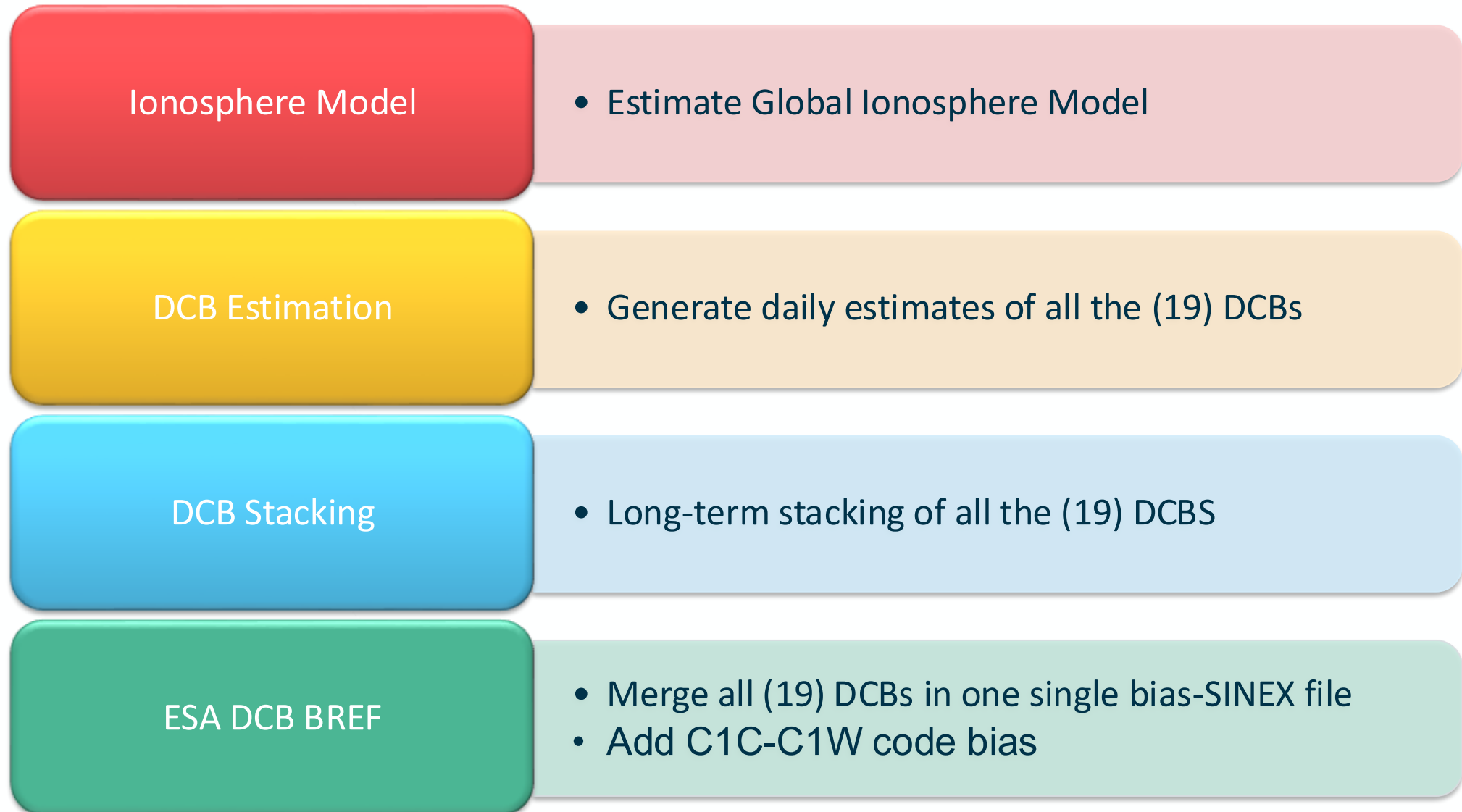


Signals Covered by the ESA BREF

| | 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 | |

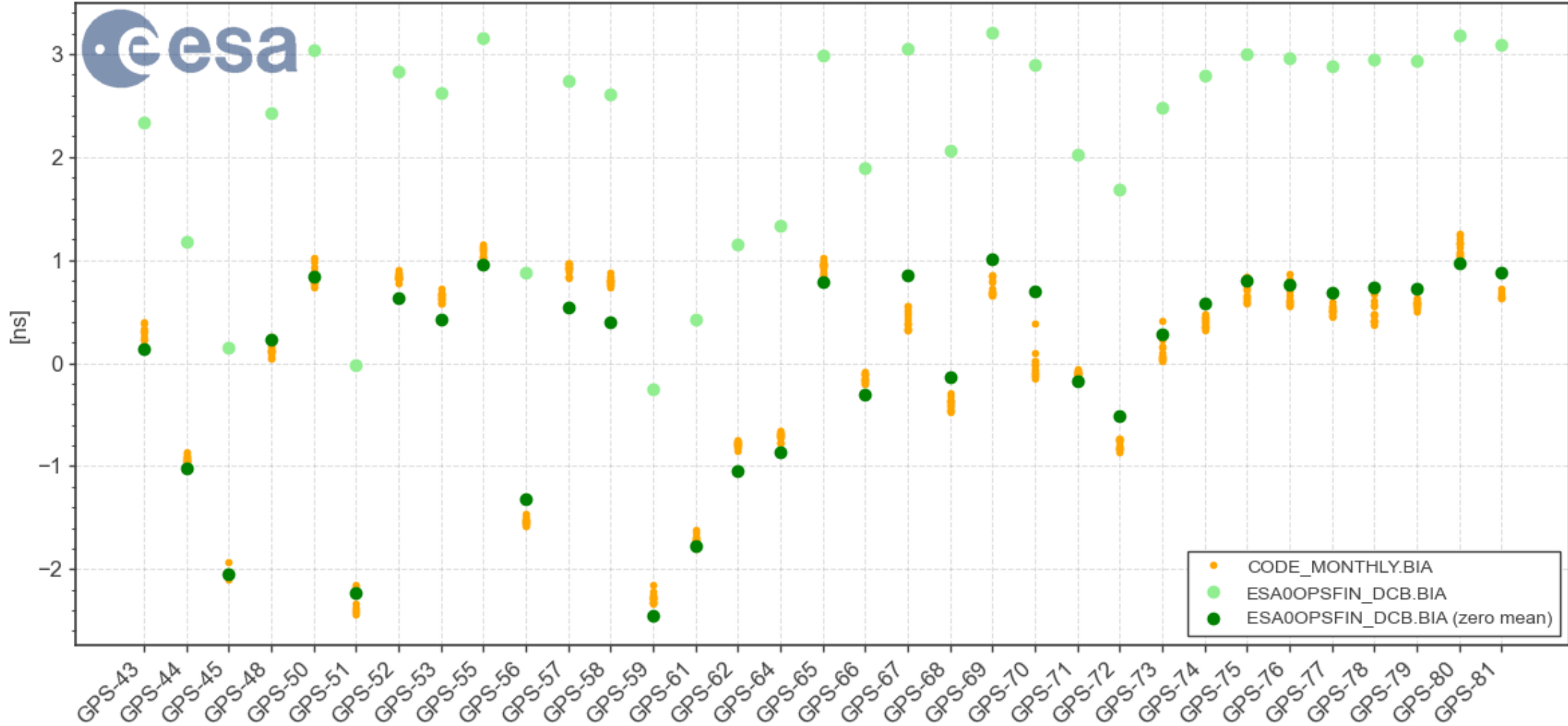
Stability of the code biases





Difference between BREF and zero-mean

Comparison of P1C1 corrections in 2025



- 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 |

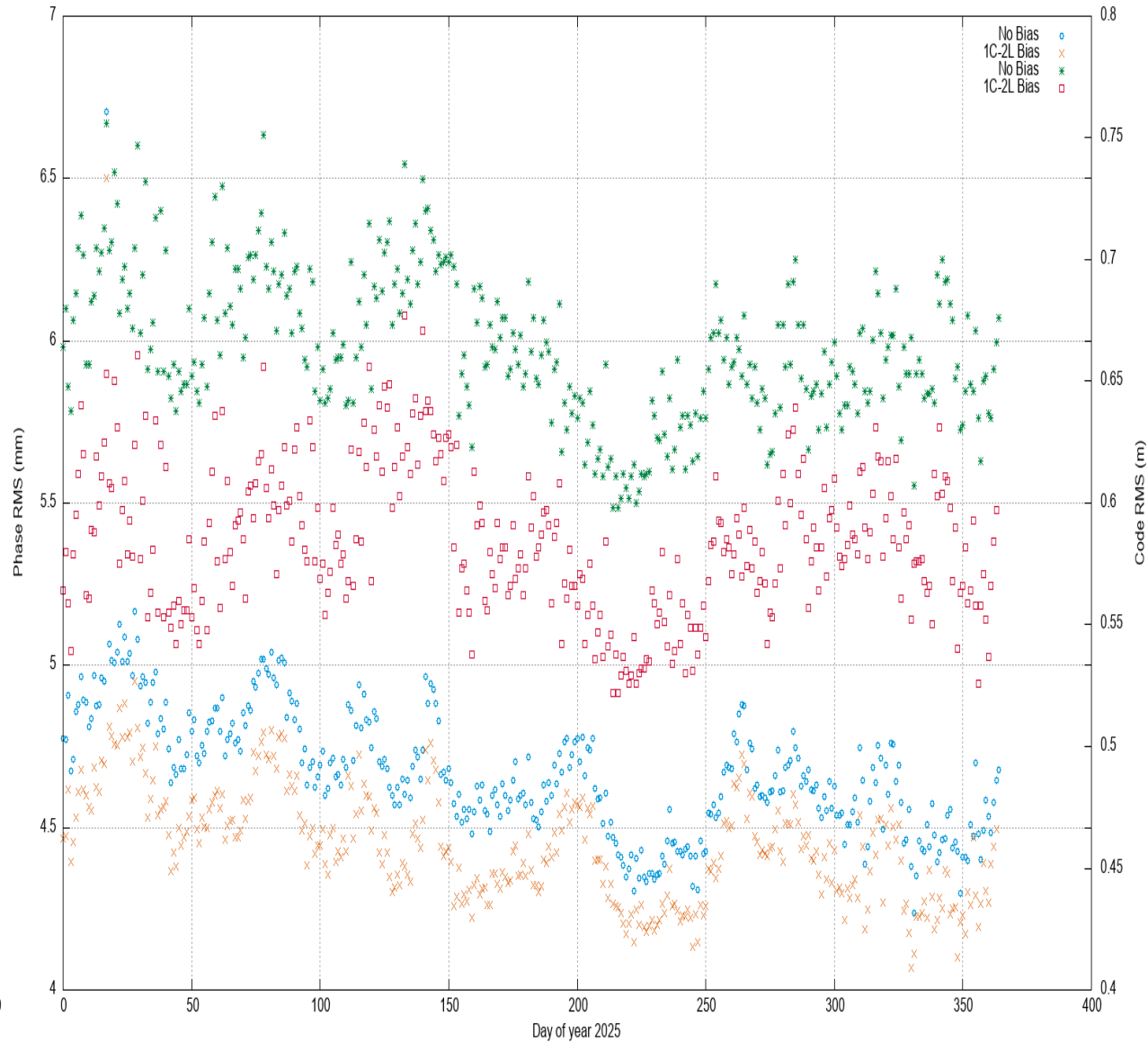
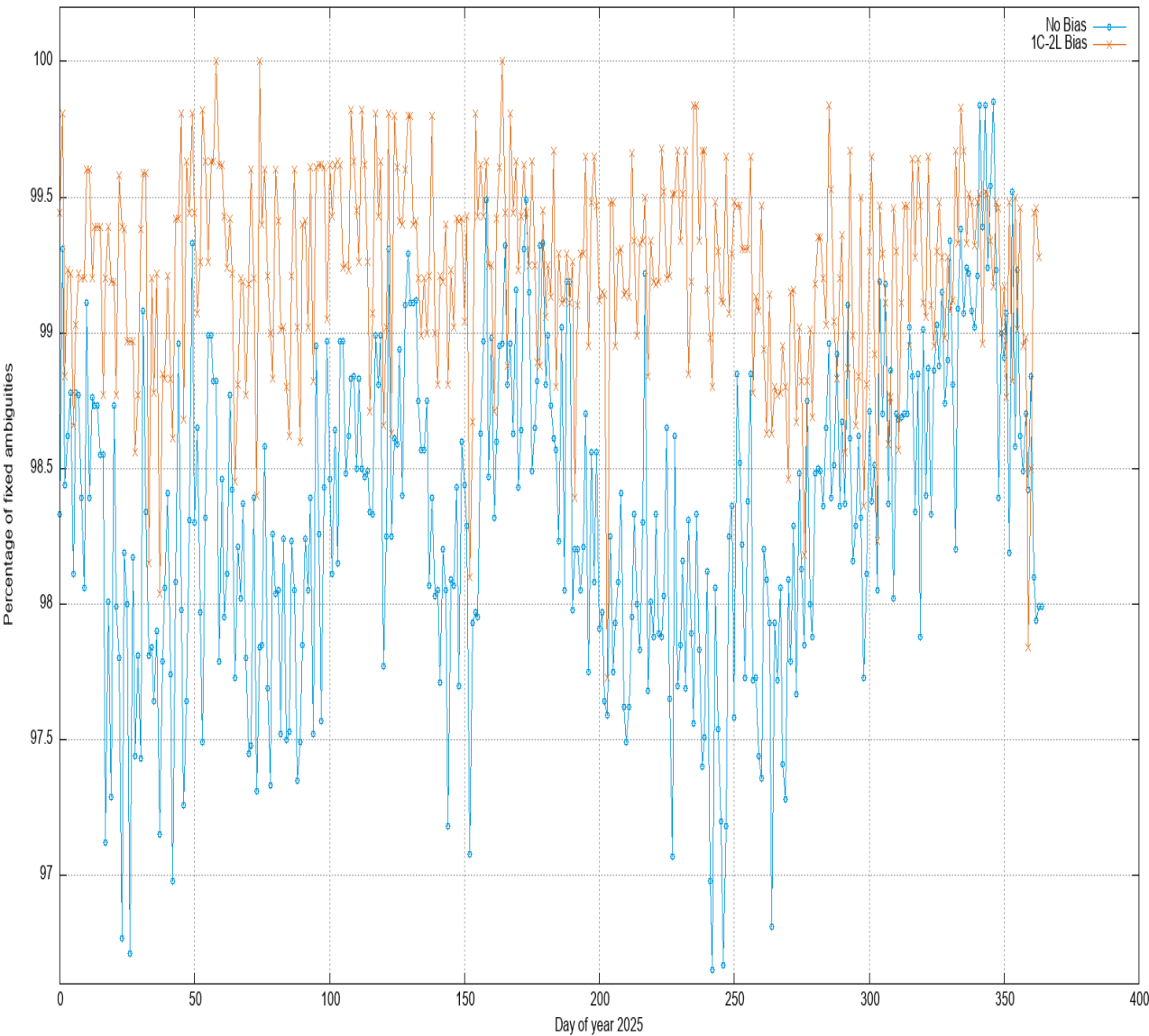
| | | | | #Obs | #Rej | Mean (mm) | RMS | #Obs | #Rej | Mean (m) | RMS |
|-------|--------|---------|------|--------|------|-----------|--------|--------|------|----------|-------|
| ESA1: | FLOAT: | SENT-6A | L401 | 121462 | 538 | -0.000 | 5.289 | 121462 | 538 | 0.000 | 0.781 |
| | FIXD0: | SENT-6A | 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)

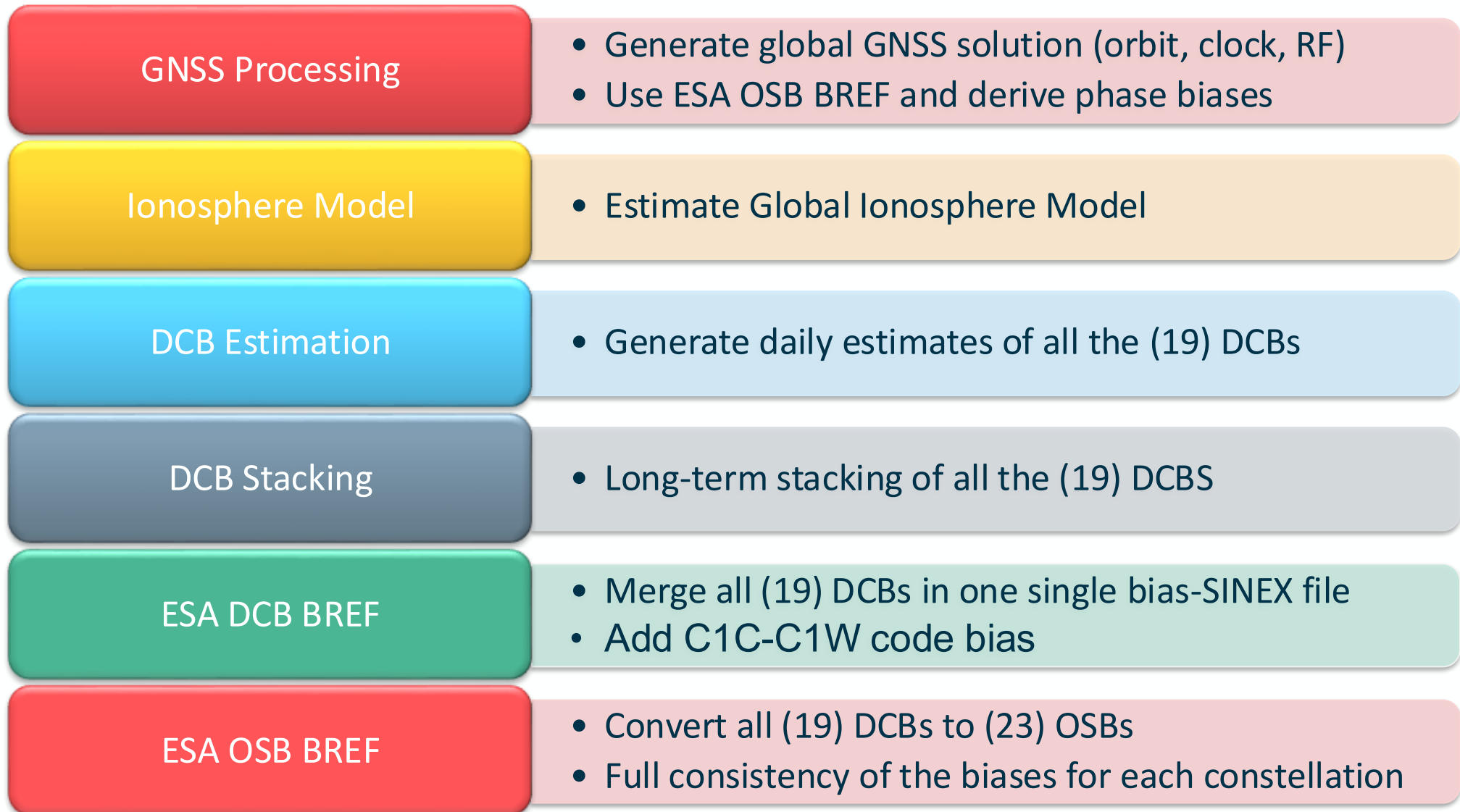


- To enable switching between different code signals whilst remaining able to use the fractional phase biases one need to define, generate and use a consistent set of code biases
- There are several ways to do this and our BREF is one example
 - However, the common way of doing things in GNSS is to process 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



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



Thank you for your attention!

Bye-bye bias!

Dr. Tim Springer
Navigation Support Office at ESA/ESOC
EGU26-19887 Session G2.4 room K1 06/05/2026

Determination of GNSS pseudo-absolute code biases and their long-term combination, 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)

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

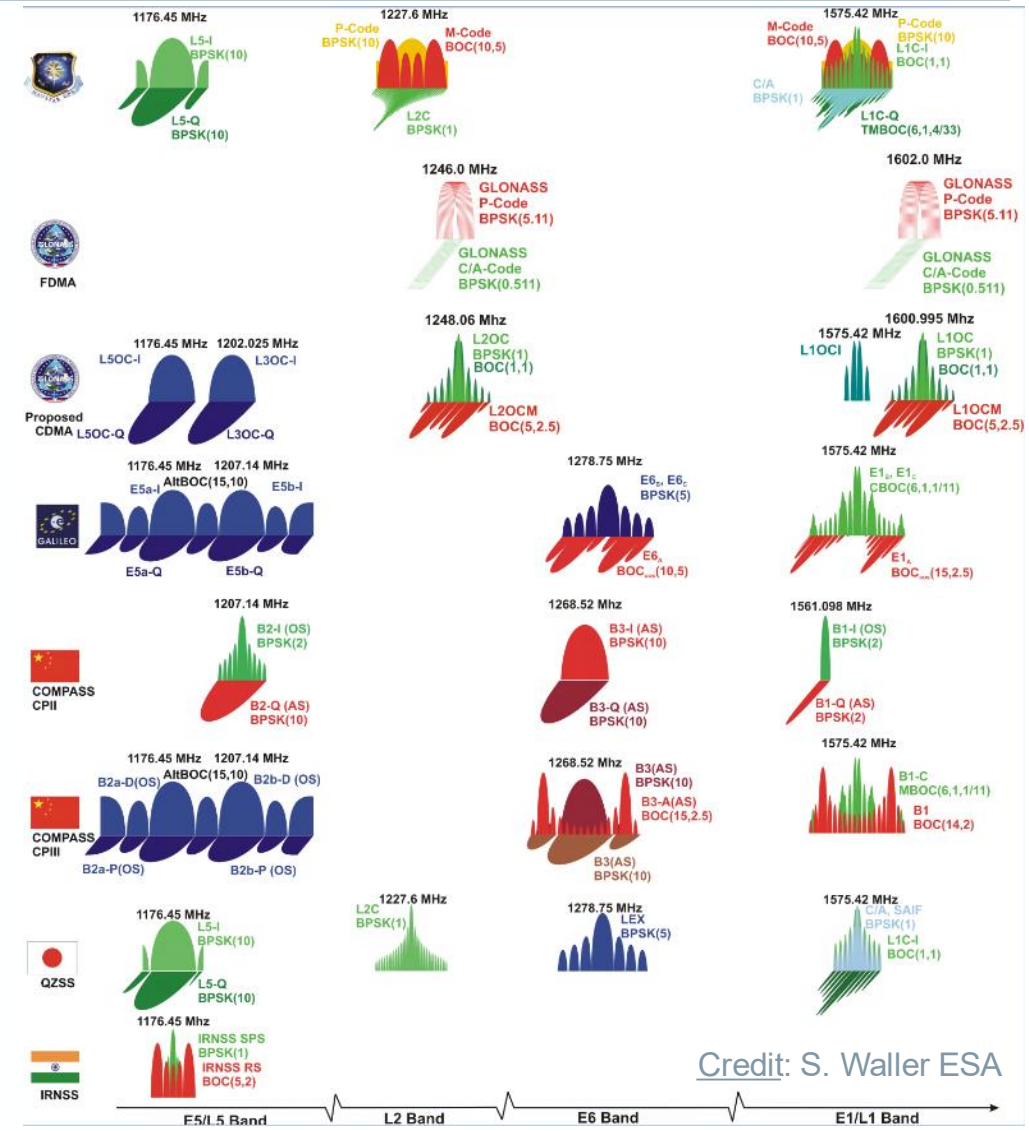
- More DCB such as can be derived

- $DCB(C1W, C1C) = DCB(C1W, C2W) - DCB(C1C, C2W)$

- $DCB(C2W, C2L) = DCB(C1C, C2W) - DCB(C1C, C2L)$

| | 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 |