EUMETSAT

COSMIC/JCSDA Workshop and IROWG-10

Sept. 12-18, 2024

Comparative Analysis of Differential Code Bias Estimation Techniques for LEO GNSS receivers: Methodological Insights.

Riccardo Notarpietro(1),
Douglas Hunt(2), Jade Morton(3), Lei Liu(3), Marc Gasbarro(4),
Axel von Engeln(1), Christian Marquardt(1), Saverio Paolella(1),
Sebastiano Padovan(1), Veronica Rivas Boscán(1)

1) EUMETSAT, Darmstadt, Germany
2) UCAR/COSMIC, Boulder, Colorado, USA
3) University of Colorado Boulder, Boulder, Colorado, USA

Outline

- LEO DCB processing approaches
- Pros/Cons
- Dataset / processing
- LEO DCB comparative analysis
- Conclusion / Way forward

LEO DCB processing approaches: Zero TEC (0TEC)

- Firstly introduced by Zhong et al.

Assumption #1: TEC at high latitude, during night, high elevation angles **is negligible**.

$$sTEC_{abs} = sTEC_{meas} + DCB^{TX} + DCB_{RX} = sTEC_{rel} + DCB_{RX}$$

$$min\{sTEC_{abs}\} = min\{sTEC_{rel}\} + DCB_{RX} \sim 0$$

$$DCB_{RX} = -min\{sTEC_{rel}\}.$$

Cons

Observations must be selected where ionospheric effects are weak.
By formulation, the 0TEC can overestimate the LEO DCB (1 TECU, see Zhong et al. 2016, or even more in case of high solar activity).

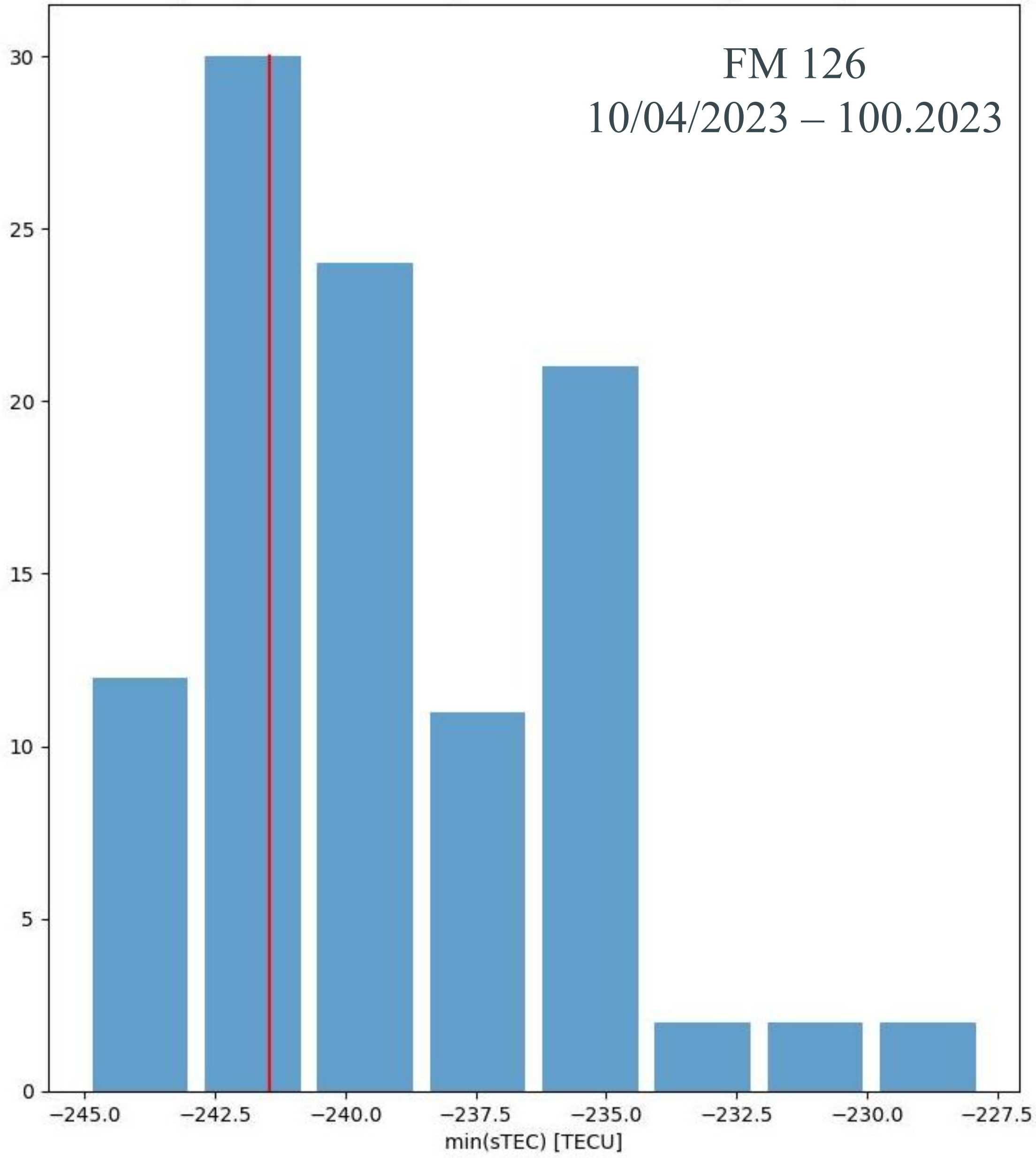
Zhong, J., Lei, J., Yue, X., & Dou, X. (2016a). Determination of differential code bias of GNSS receiver onboard low Earth orbit satellite. IEEE Transactions on Geoscience and Remote Sensing, 54(8), 4896-4905.

LEO DCB processing approaches: Zero TEC (0TEC)

$$DCB_{RX} = -min\{sTEC_{rel}\}.$$

Assumption #2: LEO DCB ~ constant over a given interval (day/s).

- In this case one can compute the distribution of available $min\{sTEC_{rel}\}$ …
- … and consider a certain percentile as representati for the LEO DCB.
- Generally, the 25th percentile is selected (to avoid outliers).



LEO DCB processing approaches: **Least Square Solution (LSS)**

Firstly introduced by Yue et al.

Assumption #1: same vertical TEC for contemporaneous slant TEC measurements for any given pair of satellites.

Assumption #2: spherical distribution of ionosphere.

$$vTEC_{abs}(\vartheta_1) = vTEC_{abs}(\vartheta_2)$$

$$[sTEC_{rel}(\vartheta_1) + DCB_{RX}]m(\vartheta_1) = [sTEC_{rel}(\vartheta_2) + DCB_{RX}]m(\vartheta_2)$$

$$DCB_{RX} = \frac{sTEC_{rel}(\vartheta_2)m(\vartheta_2) - sTEC_{rel}(\vartheta_1)m(\vartheta_1)}{m(\vartheta_1) - m(\vartheta_2)}$$

The LEO DCB can then be estimated as the Least Square Solution of a system of stacked equations like the previous one (one per each pair available) .

Yue, X., Schreiner, W. S., Hunt, D. C., Rocken, C., & Kuo, Y. H. (2011). Quantitative evaluation of the low Earth orbit satellite based slant total electron content determination. Space Weather, 9(9).

Assumption #3: which mapping function m(ϑ) to use?

- Widely used for LEO applications is the Foelsche and Kirchengast [2002] mapping function:

$$m(\vartheta) = \frac{\sin(\vartheta) + \sqrt{\frac{r_{ion}}{r_{LEO}} - \cos(\vartheta)}}{1 + \frac{r_{ion}}{r_{LEO}}}$$

$$r_{ion} = r_{Earth} + IEH = r_{Earth} + \frac{\int_{h_{LEO}}^{h_{GNSS}} N_e(h)\, h\, dh}{\int_{h_{LEO}}^{h_{GNSS}} N_e(h)\, dh} = r_{Earth} + [(0.0027F_{10.7} + 1.79)h_{LEO} - 5.52F_{10.7} + 1350]$$

- The IEH is the Ionosphere Effective Height. Here above is the formulation proposed by Zhong et al.
- $\mathrm{IEH}_{\mathrm{Zhong}}$ for a LEO flying at ~500 km is approximately 1300 km.
- But one can use any other different IEH value ("outside" ionosphere, i.e. 4000 km)

Foelsche, U., & Kirchengast, G. (2002). A simple "geometric" mapping function for the hydrostatic delay at radio frequencies and assessment of its performance. Geophysical Research Letters, 29(10), 111-1.

Zhong, J., Lei, J., Yue, X., & Dou, X. (2016a). Determination of differential code bias of GNSS receiver onboard low Earth orbit satellite. IEEE Transactions on Geoscience and Remote Sensing, 54(8), 4896-4905.

LEO DCB processing approaches: **Least Square Solution (LSS)**

Cons:

- Strongly based on ionospheric spherical symmetry distribution assumption. Care must be taken in selecting "good" pairs of observations.

- "good" pairs of observations **should be close between them, but not too close**.
  The $m(\vartheta_1) - m(\vartheta_2) >$ threshold… and results depend on this threshold (see later on).

$$DCB_{RX} = \frac{sTEC_{rel}(\vartheta_2)m(\vartheta_2) - sTEC_{rel}(\vartheta_1)m(\vartheta_1)}{m(\vartheta_1) - m(\vartheta_2)}$$

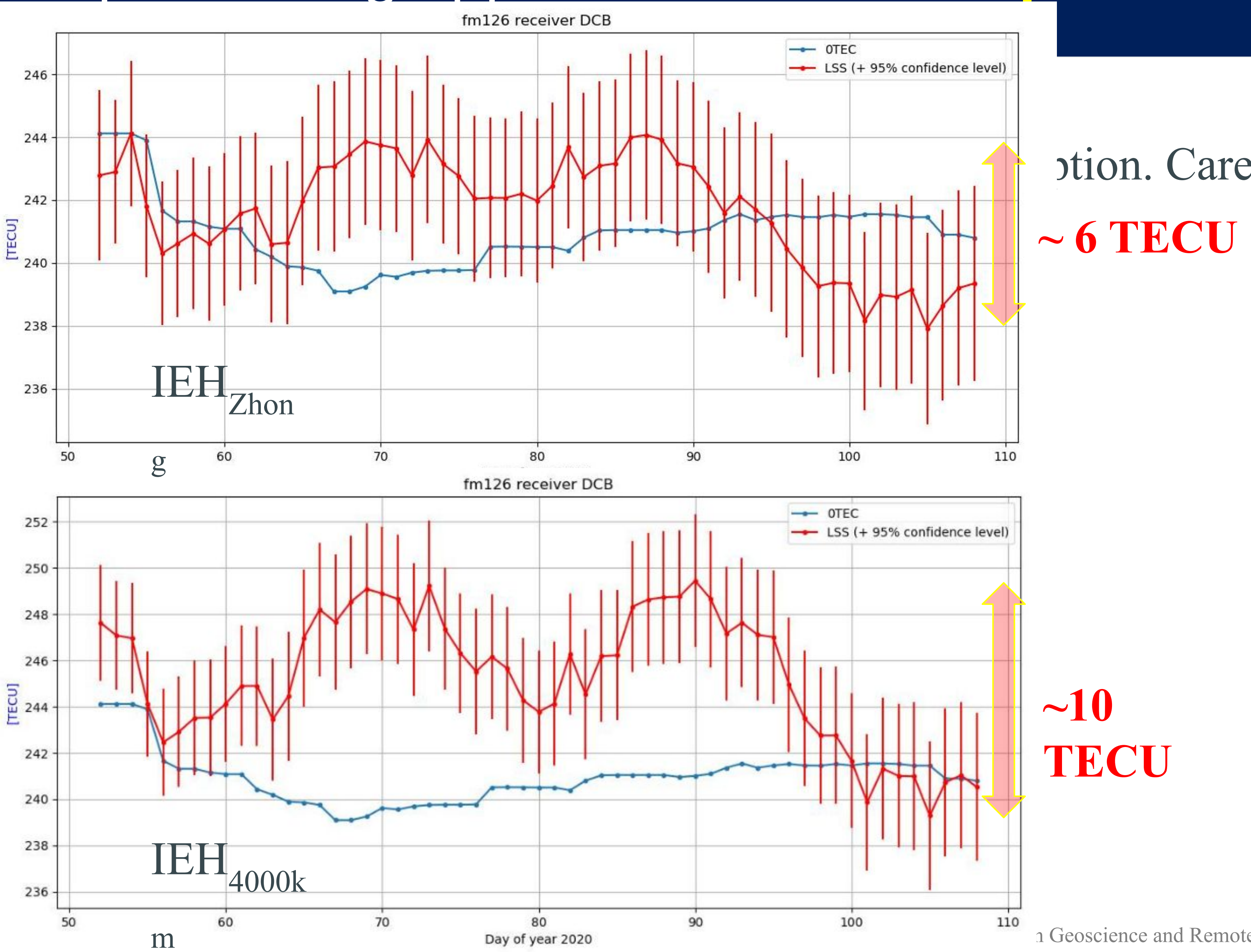
- Strongly depends on the IEH used to compute the mapping function.

Zhong, J., Lei, J., Yue, X., & Dou, X. (2016a). Determination of differential code bias of GNSS receiver onboard low Earth orbit satellite. IEEE Transactions on Geoscience and Remote Sensing, 54(8), 4896-4905.

LEO DCB processing approaches: Least Square Solution (LSS)

Cons:

- Strongly base… …ption. Care must be taken in selec…
- "good" pairs … The $m(\vartheta_1)$ - n… g
- Strongly dep… m



Zhong, J., Lei, J., Yue, X., & Dou, X… …n Geoscience and Remote Sensing, 54(8), 4896-4905.

Dataset / Processing strategy

- SPIRE Level0 navObs. ~18 sats considered 21/02/2023 (052.2023) and 18/04/2023 (108.2023). Acknowledgement to the NOAA Commercial Space Weather Data Pilot Project

- Data pre-processing (Blewitt et al.): detect cycle slips / split arcs; considering only arcs taken at **latitudes > 50 deg** and **longer than 240 sec**.
- GNSS DCBs from CODE.
- Carrier-phase to pseudorange slant TEC levelling (see Pedatella et al, 2021), w/o local multipath correction (**observations > 45 deg elevation angle only**).
- 7 days history.

- (**0TEC**): LEO sat and IPP @ 1300 km in the Sun/Earth's umbra region.
- (**LSS**): $\vartheta_1 - \vartheta_2 < 40\text{deg}$ and $m(\vartheta_1) - m(\vartheta_2) > 0.1$.

Blewitt, G. (1990). An automatic editing algorithm for GPS data. Geophysical research letters, 17(3), 199-202.

Pedatella, N. M., Zakharenkova, I., Braun, J. J., Cherniak, I., Hunt, D., Schreiner, W. S., & Wu, Q. (2021). Processing and validation of FORMOSAT-7/COSMIC-2 GPS total electron content observations. Radio Science, 56(8), 1-12.

Processing strategies from other centres

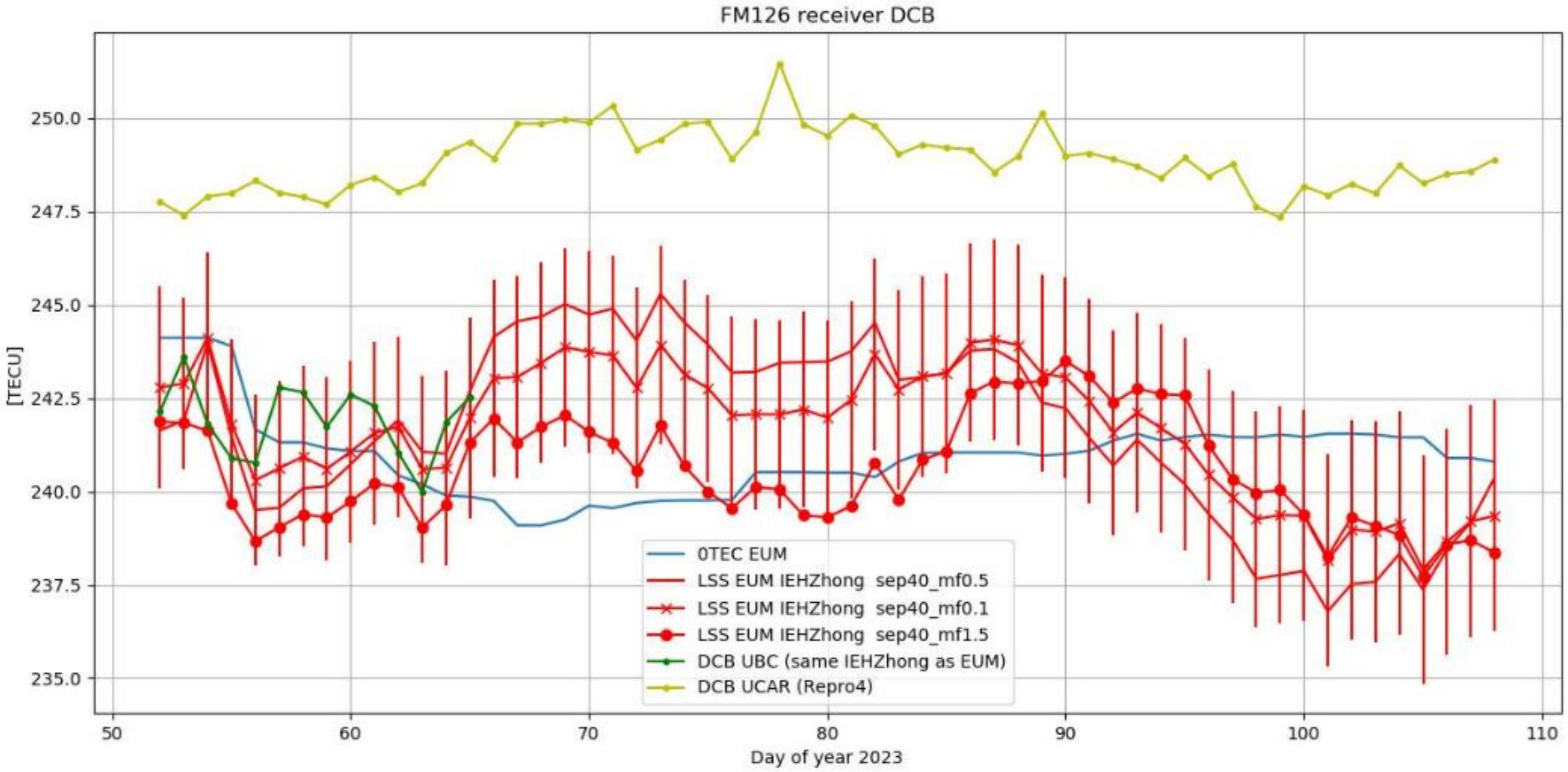
- Within the same project, also UCAR (**UCR**) and University of Colorado Boulder (**UCB**) provided their own estimates of the SPIRE DCBs.

- The following table summarizes the different approaches:

Proc. Centre	Algorithm	Observations	Mapping Function	IEH
UCR (Repro 40)	LSS	Occ and POD	F&K	IEH_{4000km}
UCB	LSS LSS	Occ and POD Occ and POD	F&K F&K	IEH_{4000km} IEH_{Zhong} (1300 km)*
EUM	LSS 0TEC	POD POD	F&K ---	IEH_{4000km} IEH_{Zhong} (1300 km) ---

* Limited to the first 14 days only

LEO DCB comparisons (1/3) – **time series**



Blue: EUM 0TEC

Red: EUM LSS (IEH_{Zhong}) and $m(\vartheta_1) - m(\vartheta_2)$ thresholds (0.15 / 0.1 / 0.05)

Green: UCB (LSS, IEH_{Zhong})

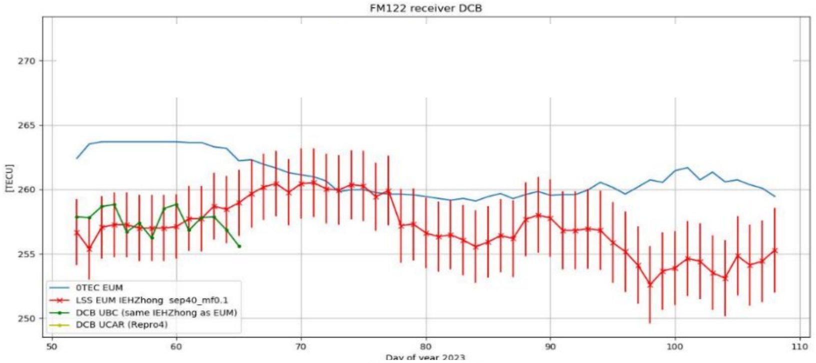
Yellow: UCR (LSS, IEH_{4000km})

- Cannot compare LSS solutions using different IEH.
- Good agreement between 0TEC and LSS (when lower IEH [IEH_{Zhong}] is used).
- Quite strong sensitivity to t $m(\vartheta_1) - m(\vartheta_2)$ threshold used (as anticipated).

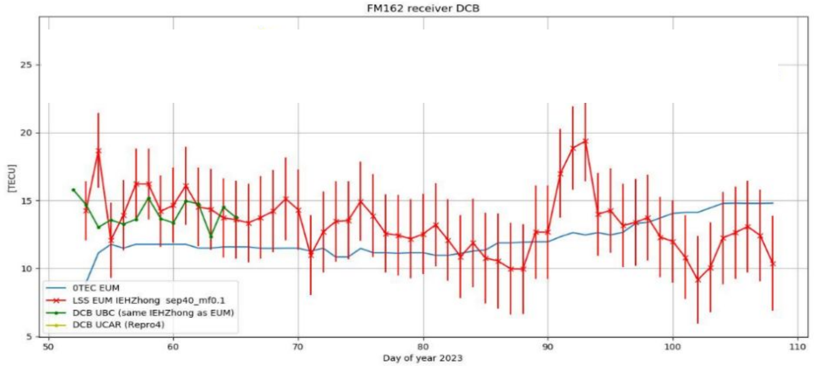
LEO DCB comparisons (2/3) – **time series**

$\text{IEH}_{\text{Zhong}} \sim 1300$ km

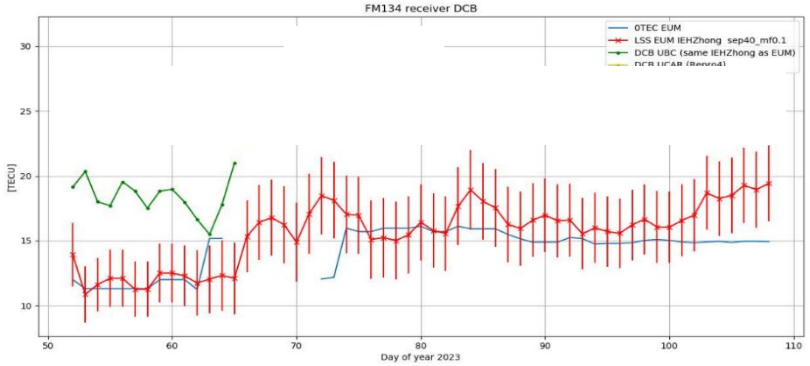
FM122



FM162



FM134



Blue: EUM 0TEC

Red: EUM LSS

$$m(\vartheta_1) - m(\vartheta_2) > 0.1$$

Green: UCB LSS

Yellow: UCR LSS

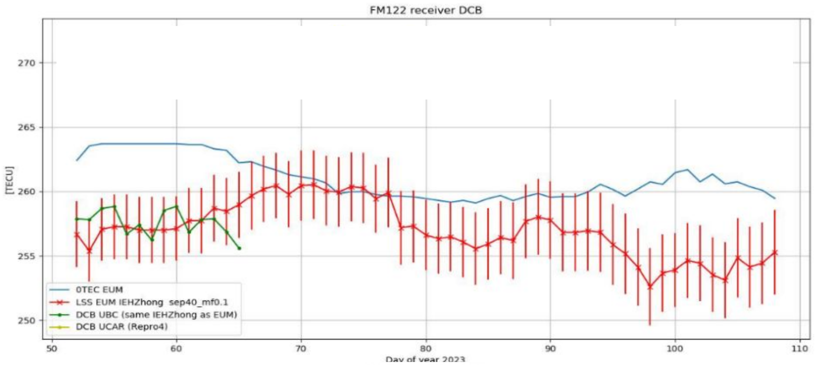
LEO DCB comparisons (2/3) – **time series**

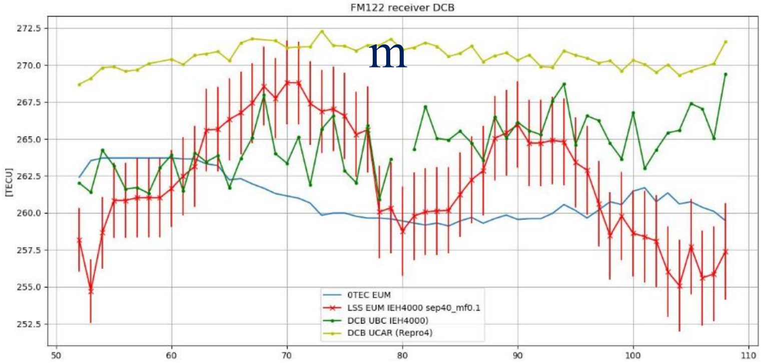
www.eumetsat.int

IEH$_{Zhong}$ ~ 1300 km

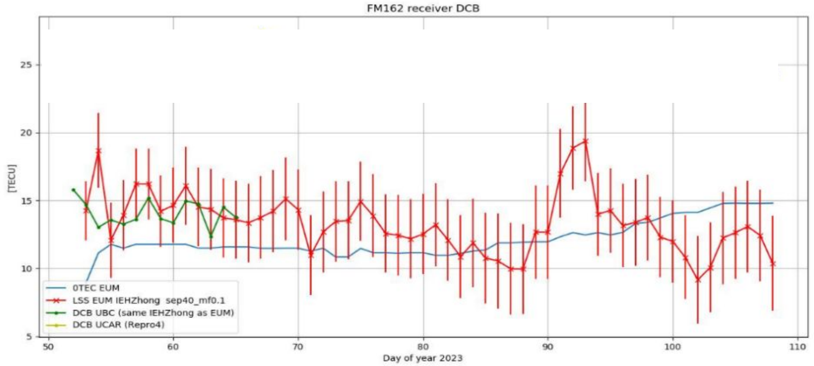
IEH$_{4000k}$ m

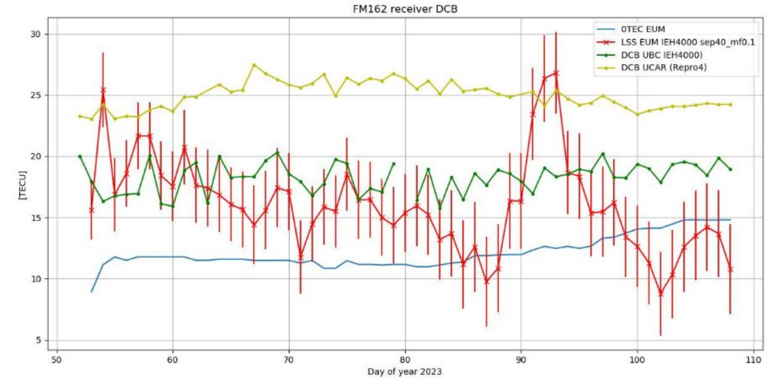
FM122



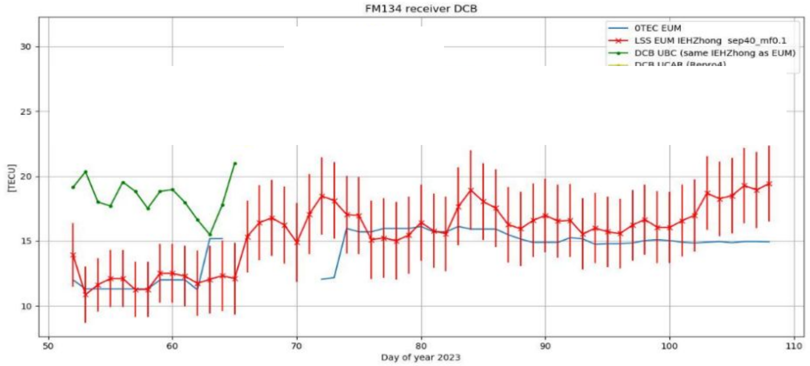


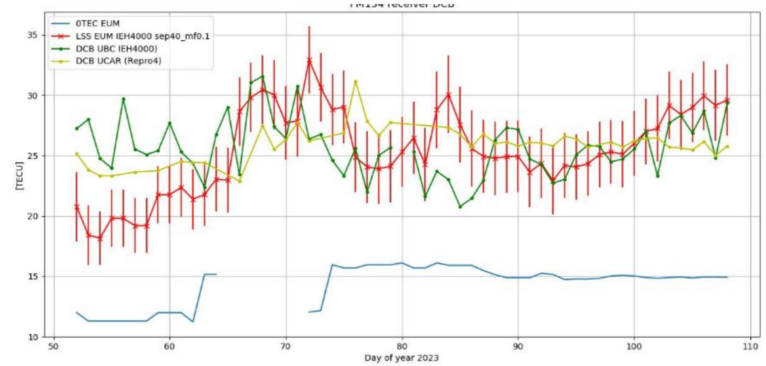
FM162





FM134





Blue: EUM 0TEC

Red: EUM LSS

$$m(\vartheta_1) - m(\vartheta_2) > 0.1$$

Green: UCB LSS

Yellow: UCR LSS

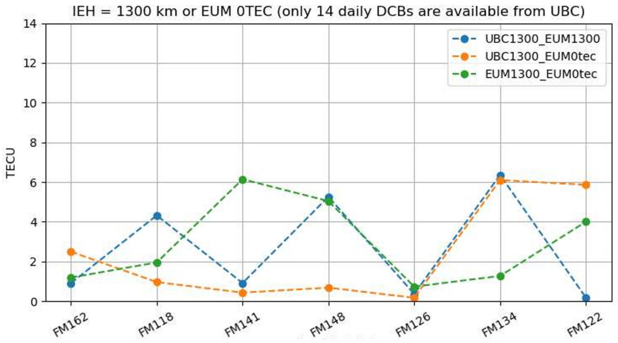
0TEC does not depend on IEH: seems that using the lower IEH$_{Zhong}$ is better

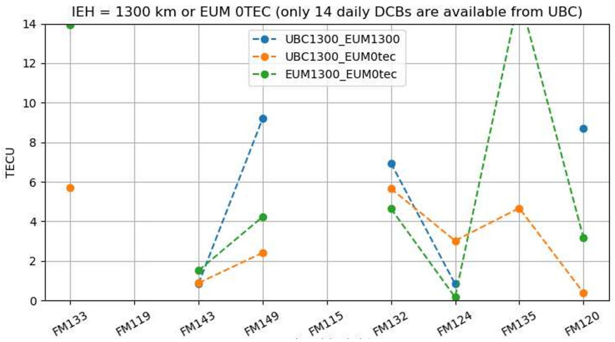
LEO DCB comparisons – **mean daily DCBs difference**

Difference between daily DCBs averaged over the entire period, stratified by satellite

$\text{IEH}_{\text{Zhong}}$

(or 0TEC)

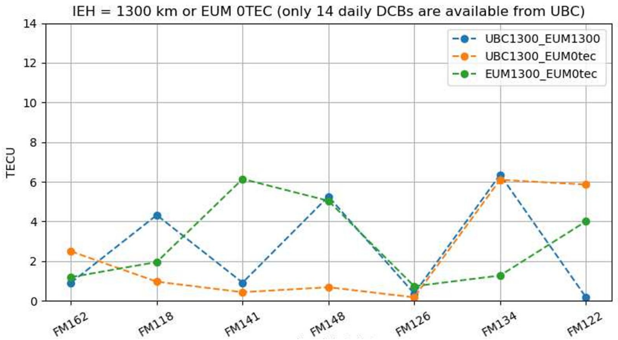


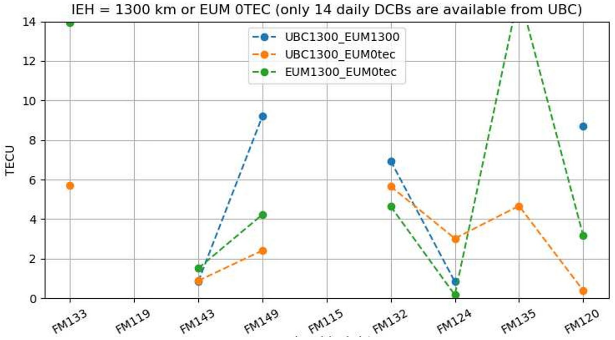


LEO DCB comparisons – **mean daily DCBs difference**

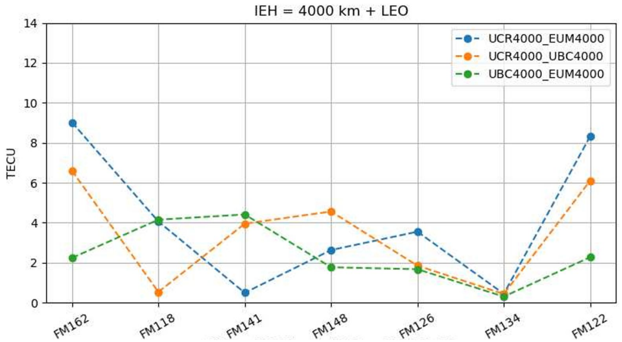
Difference between daily DCBs averaged over the entire period, stratified by satellite

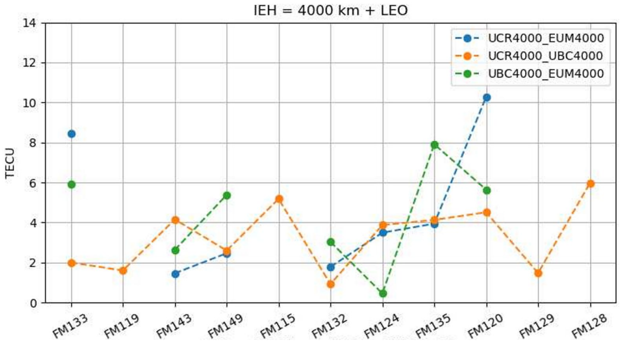
IEH_{Zhong} (or 0TEC)





IEH_{4000km}

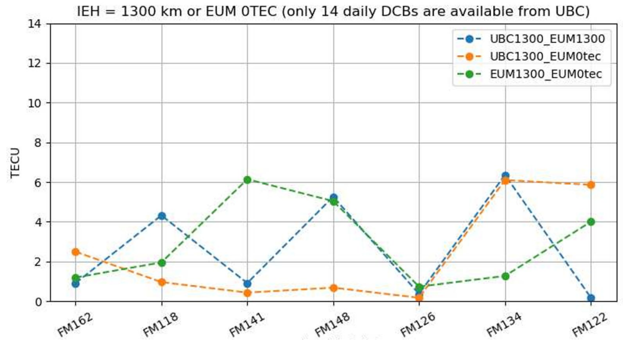


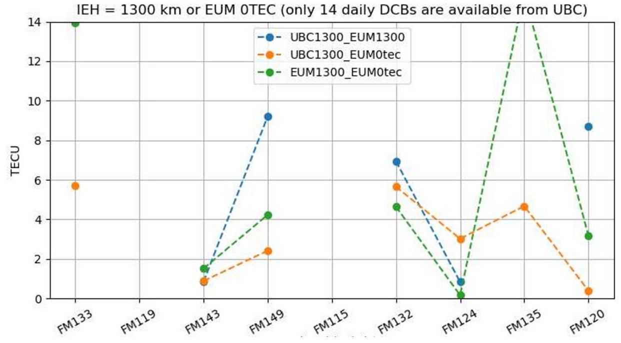


LEO DCB comparisons – **mean daily DCBs difference**

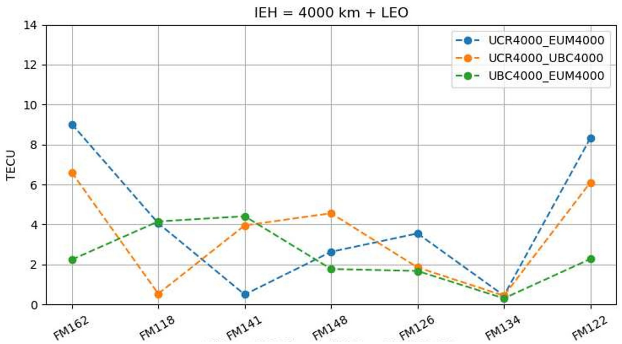
Difference between daily DCBs averaged over the entire period, stratified by satellite

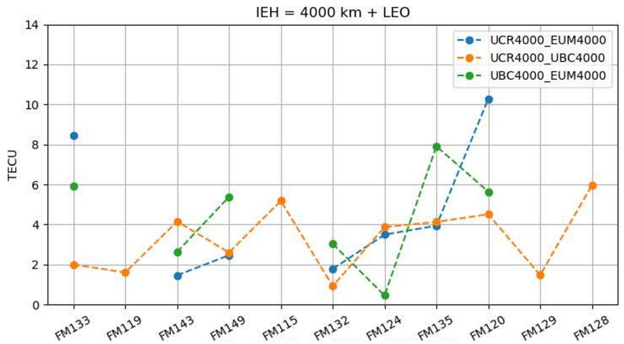
IEH_{Zhong} (or 0TEC)



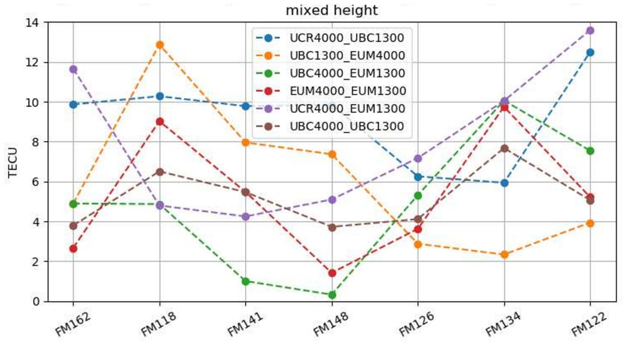


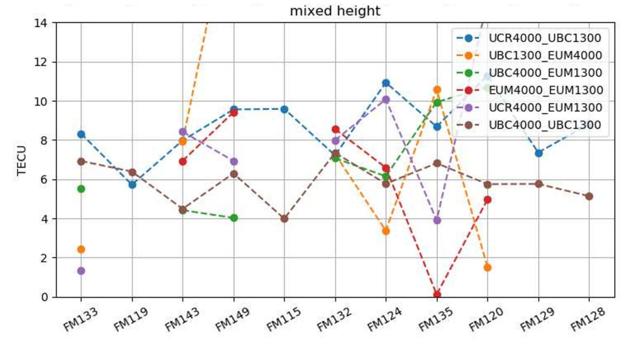
IEH_{4000km}





Mixed approaches





- LSS results agree within 5-6 TECU between different processing approaches, provided similar IEH are used.
- LSS with IEH ~ 1300 km (Zhong approach) are in good agreement with 0TEC.
- Comparisons of LSS solutions obtained with different IEHs are worse.

Conclusion / Way Forward

- Scope here is not to compare estimates from different processing centres, but to raise a “warning” on the sensitivity to data selection and to parameters like the IEH.

- Assimilate DCB free sTEC measurements (i.e. from carrier phases) is probably the best option.

- If you need to do a DCB validation, it should be performed only against an independent LEO DCB estimate.

  Like, for example, **assimilate DCB free measurements** (dual freq carrier phases, relative TEC, dual freq bending angle differences) and then estimate the LEO DCB as a side product of DA (see Hernandez-Pajares et al).

Hernández-Pajares, M., Olivares-Pulido, G., Hoque, M. M., Prol, F. S., Yuan, L., Notarpietro, R., & Graffigna, V. (2023). Topside ionospheric tomography exclusively based on LEO POD GPS carrier phases: Application to autonomous LEO DCB estimation. Remote Sensing, 15(2), 390.

Thank you!

Questions are welcome …

… or write to

Riccardo.Notarpietro@eumetsat.int