The impact using GNSS Clocks to improve DORIS measurements, both onboard Sentinel satellites and at Co-Located Stations, on POD and Station Position Estimation

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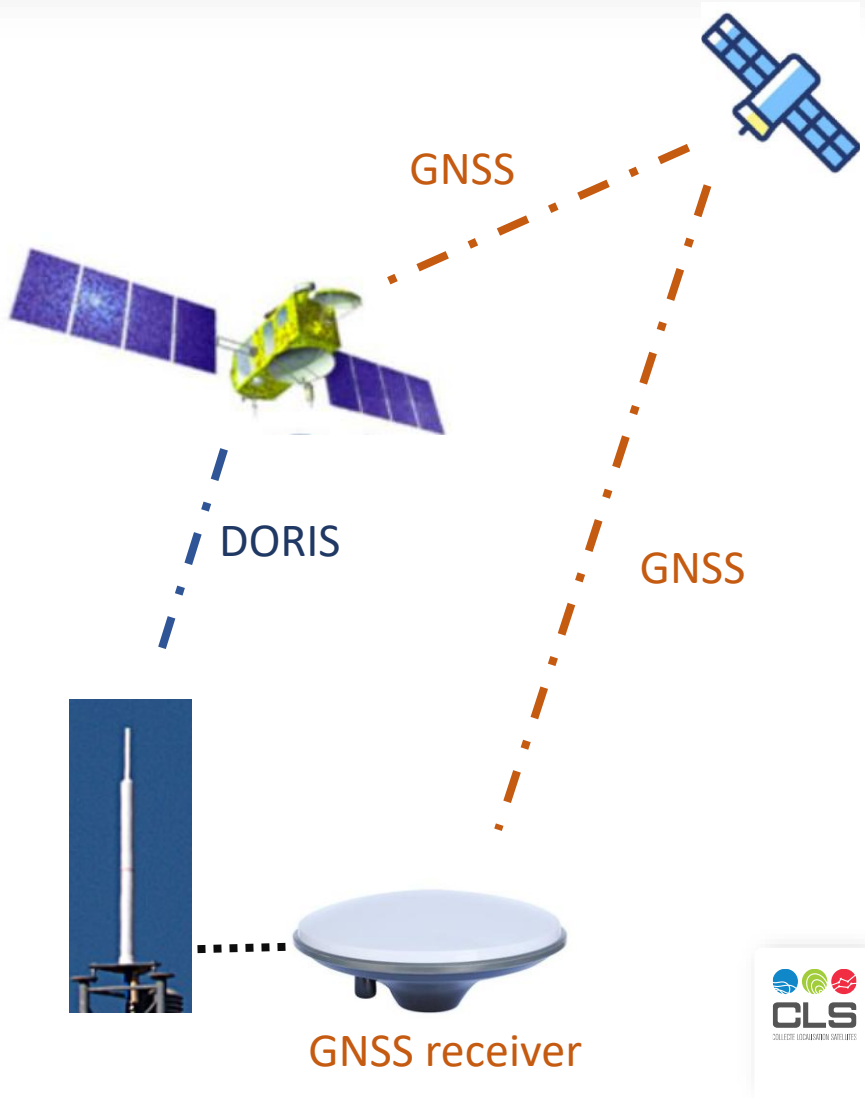
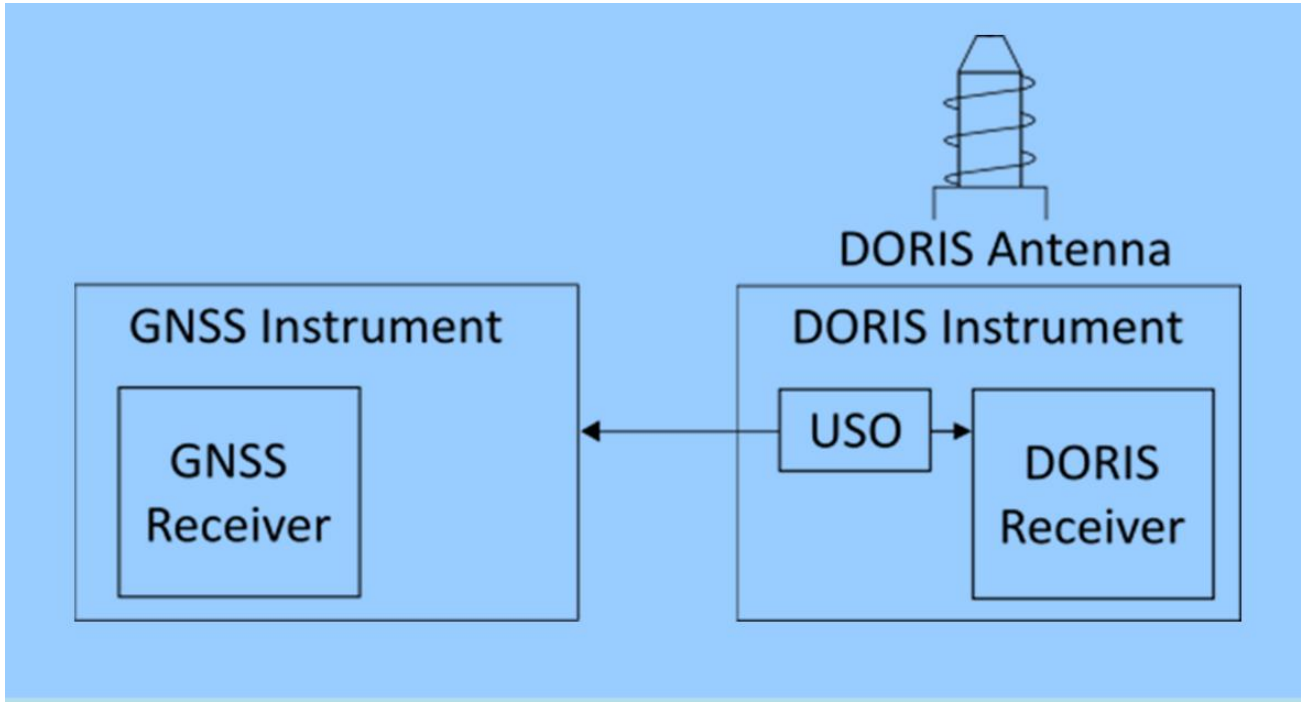


Sentinel Satellites on-board architecture

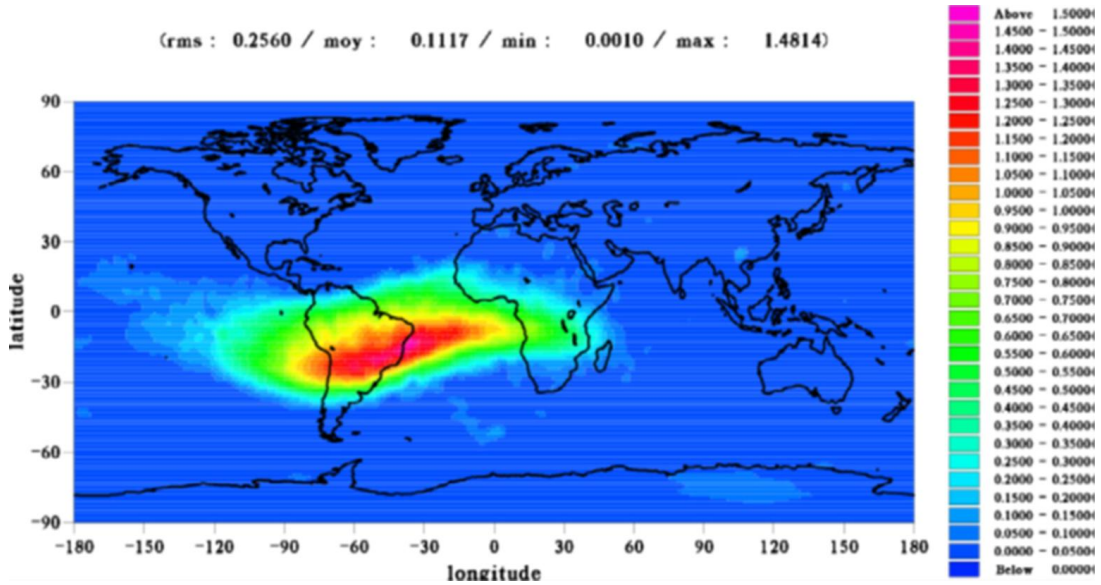
- The USO (ultra-stable-oscillator) drives both DORIS and GNSS instruments
- Determination of the USO behavior from GNSS observations
- The GNSS clock estimates are used to characterize the high-frequency behavior of the USO, particularly when passing through the SAA.



An Overview of the South Atlantic Anomaly's Effects

- **SAA (South Atlantic Anomaly)**
  → Region where the magnetic field is weaker
- **Consequence**
  → Increased flux of energetic particles
- **Impact on DORIS (USO)**
  → Disruptions of the Ultra-Stable Oscillator
  → Frequency variations (short- and long-term)

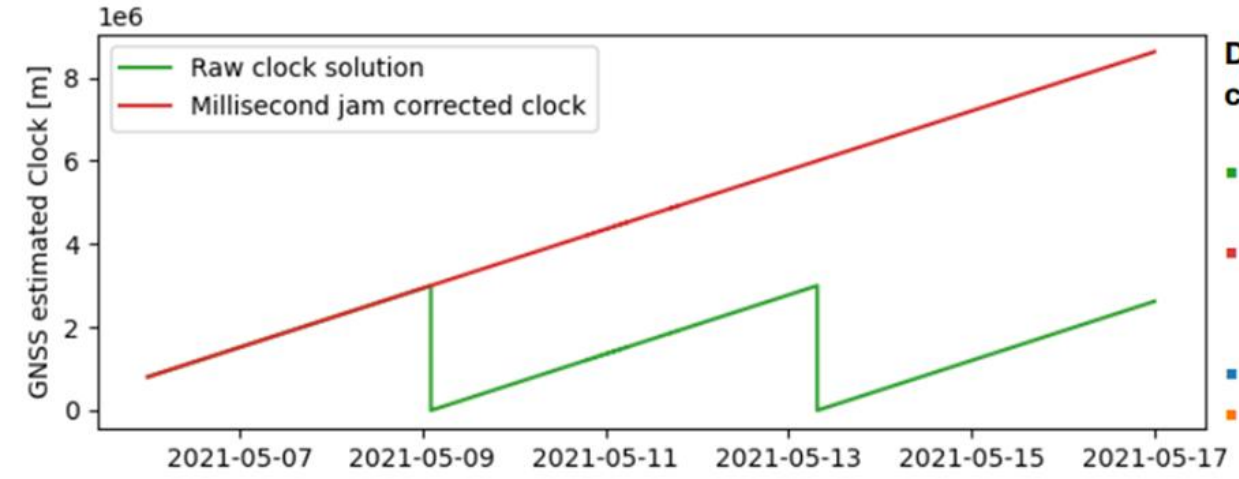
SAA Stations
Cachoeira (CADB)
Arequipa (ARFB)
San Juan (SJVC)
Kourou (KRWB)
Ascension (ASEB)
Le Lamentin (LAOB)
Sal (SARC)
ST-Helena (HEMB)
Libreville (LICB)
Tristan Da Cunha (TRJB)



Plot of the DORIS derived relative dose exposure in 2002–2005 at 1300 km altitude (dimensionless units).

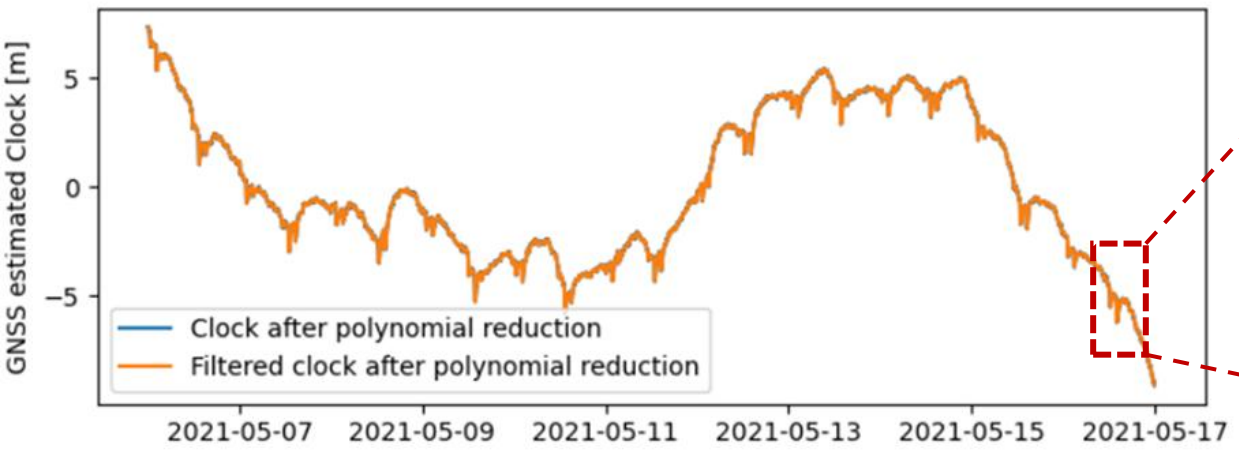
SAA strongly perturbs DORIS clocks

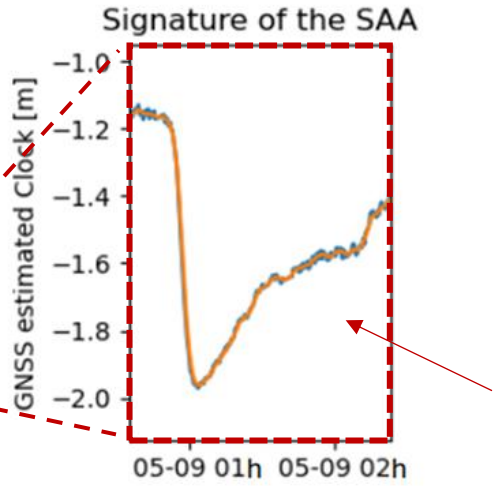
USO determination from GNSS observations



DORIS correction processing chain

- Raw GNSS clock estimation during orbit determination
- Removal of GNSS receiver corrections (here millisecond jumps for S3A)
- Polynomial reduction
- 5 minutes lowpass filtering





- We use the GNSS filtered clock provided by the CNES POD team within the framework of the International DORIS Service Working Group on “Integrated Clock Correction Strategies for DORIS.”

- These clock corrections are applied to the phase measurements (2 GHz and 400 MHz) in the DORIS RINEX files.

$$L_{1|2} \mathrel{+}= clock \cdot \frac{f_{1|2}}{c}$$

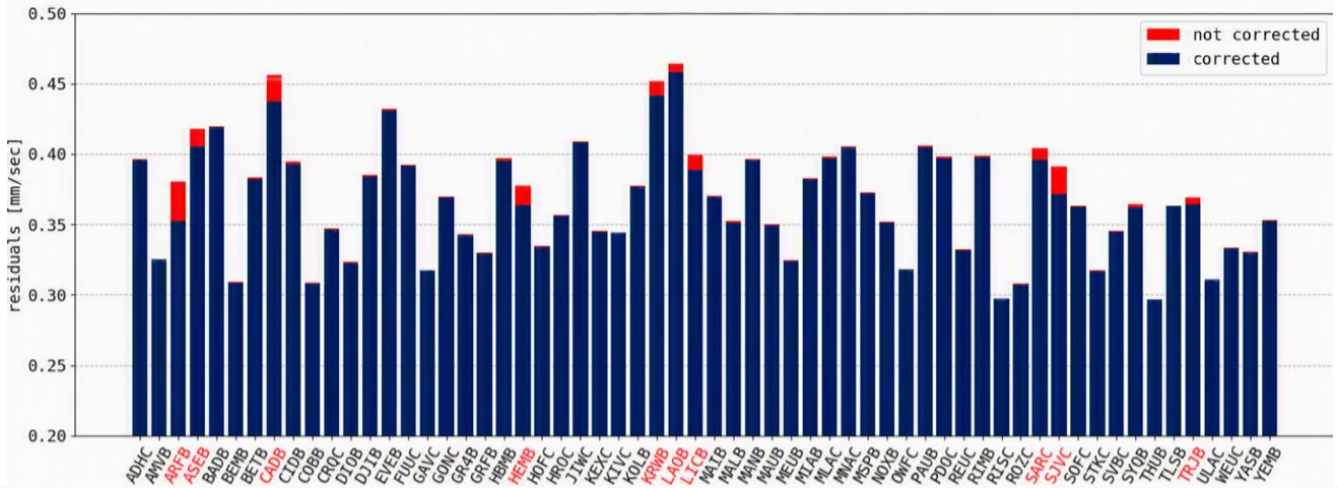
This pattern arise when the satellite go through the SAA

Impact of the onboard clock correction on the orbit

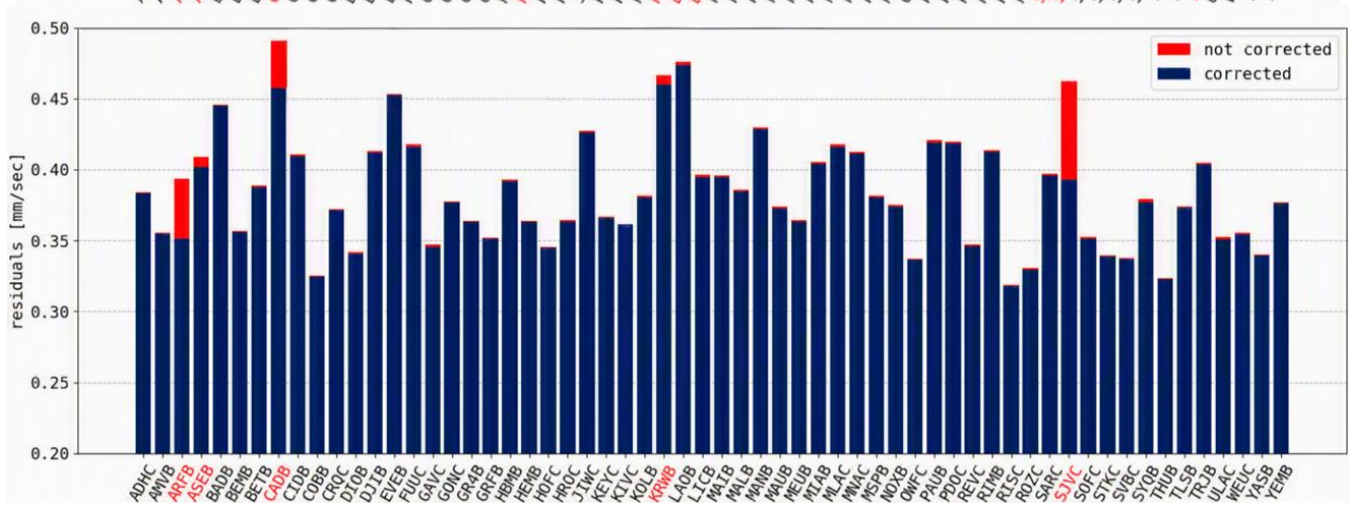
RMS of DORIS observation residuals (mm/s) per station from GRG POD processing

Average from January 2021 through December 2024, only SAA stations where corrected

S6A



S3A



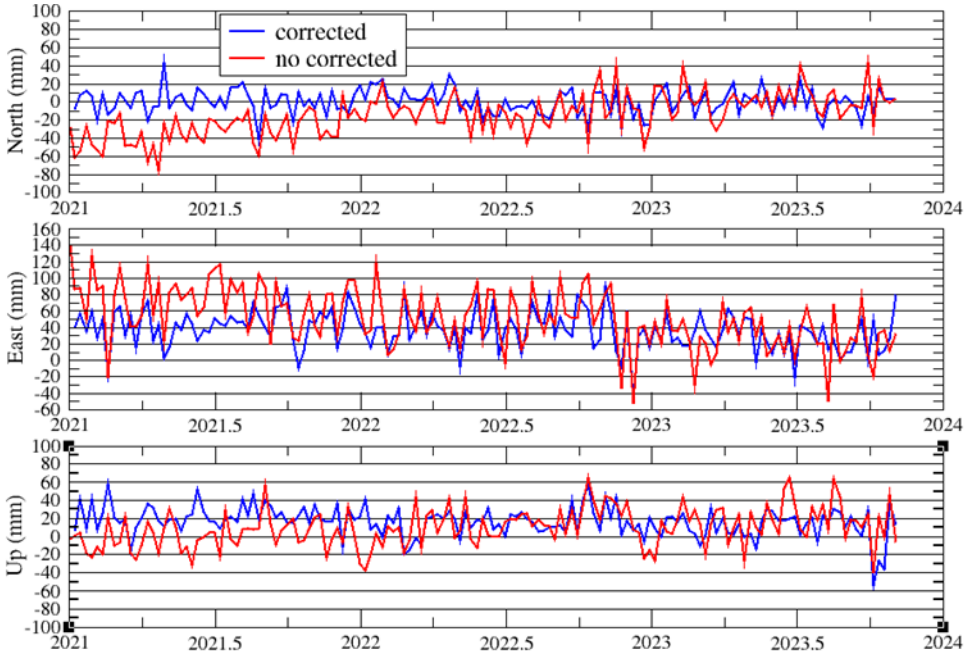
- *The correction significantly reduces the RMS residuals of SAA stations.*
- *However, the overall impact on orbit determination remains relatively limited.*

Impact of the onboard clock correction on the station position estimation

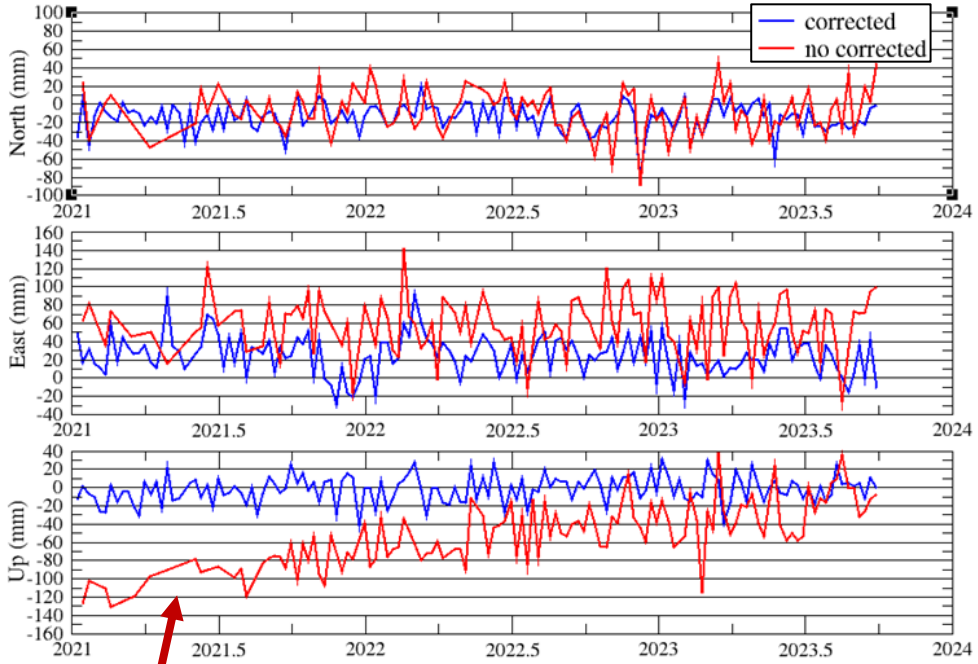
Single satellite station position solution compared to DPOD2020 (computed by CATREF)

Time Series of SAA DORIS station positions

Cachoeira (CADB) from Sentinel-6A



Arequipa (ARFB) from Sentinel-6A



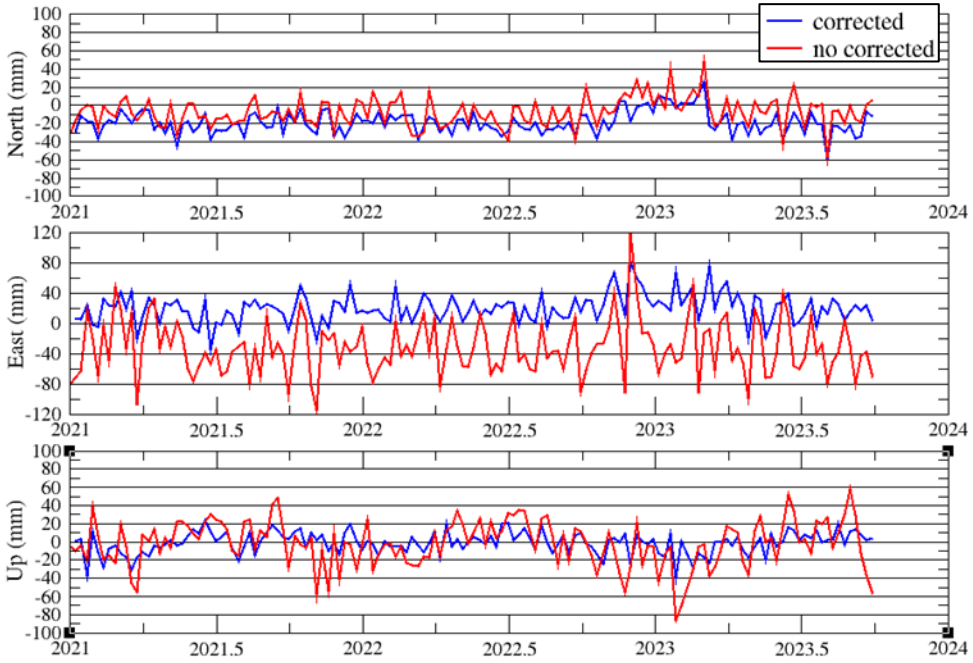
The integration of Sentinel GPS clocks significantly reduces the non-physical drift in time series and the positioning residual standard deviation (STD) for stations located in the SAA area.

Impact of the onboard clock correction on the station position estimation

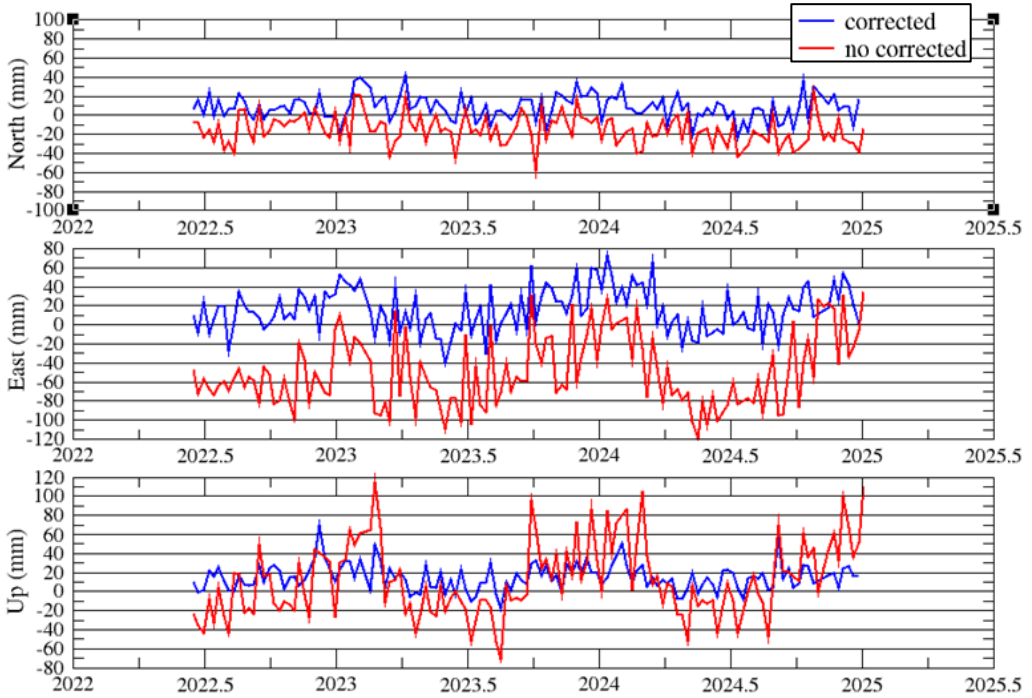
Single satellite Solution compared to DPOD2020 (computed by CATREF)

Time Series of SAA DORIS station positions

Arequipa (ARFB) from Sentinel-3A



San Juan (SJVC) from Sentinel-3A



Onboard clock correction reduce the offset on east component compared to DPOD2020

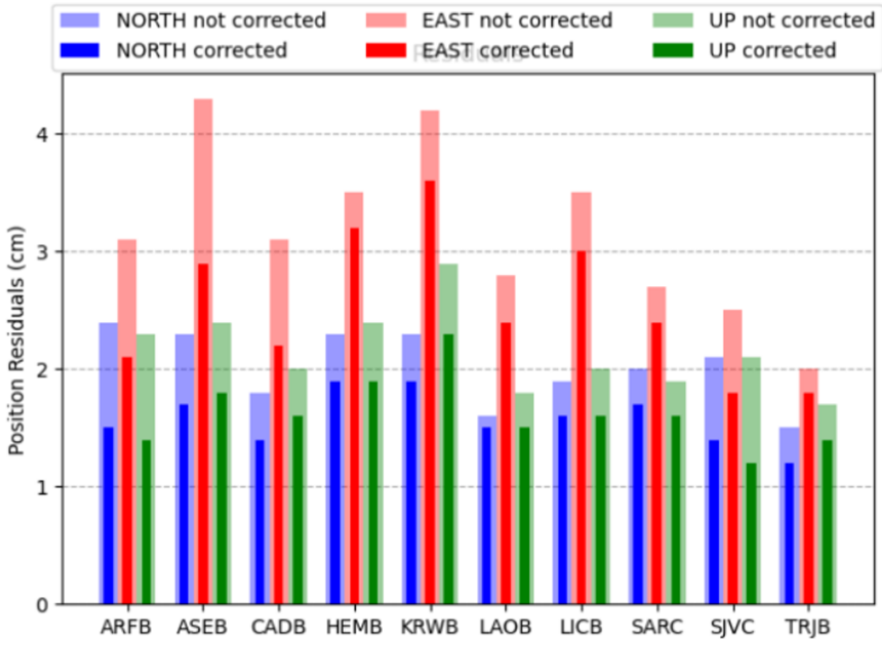
Impact of the onboard clock correction on the station position estimation

Single satellite Solution compared to DPOD2020 (computed by CATREF)

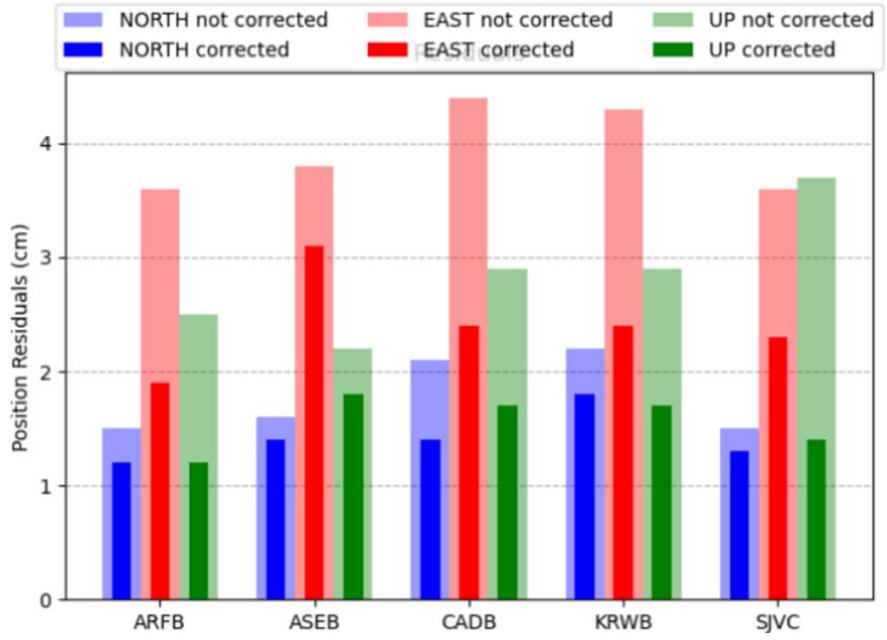
Positioning Residual STD of DORIS coordinates with and without correcting the SAA stations.

After removing the long-term trend, we compare the residual noise levels (STD) in NEU components.

Sentinel-6A

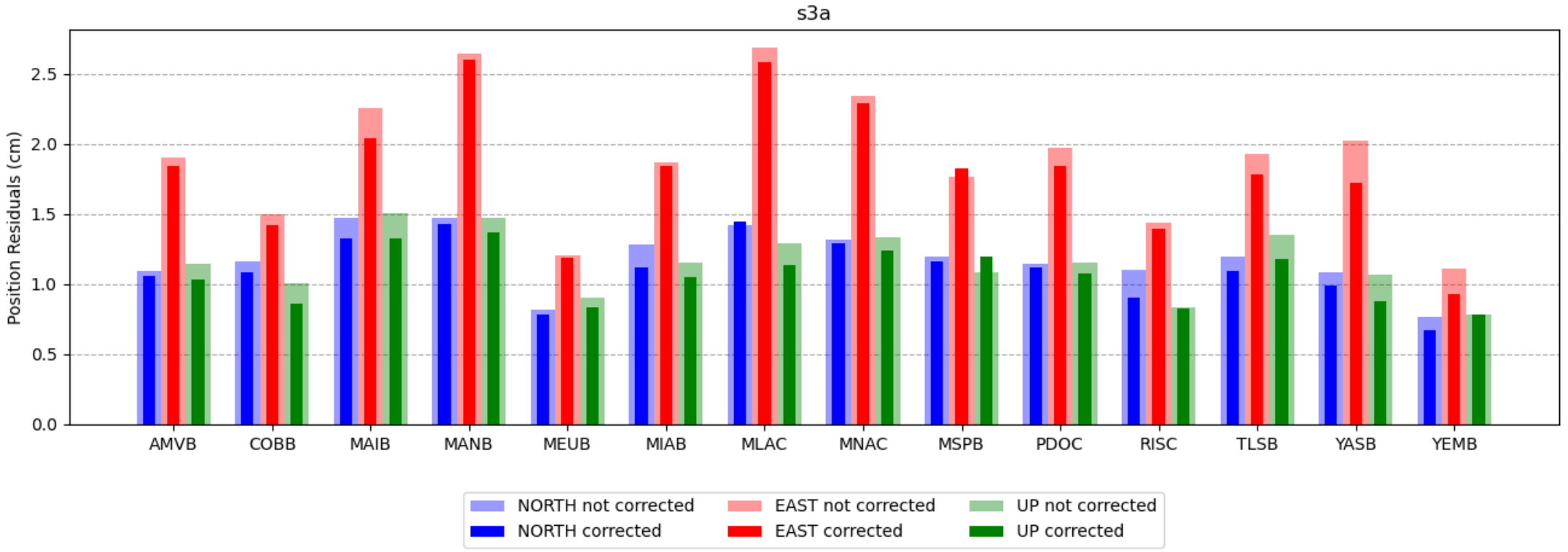


Sentinel-3A



- *The integration of Sentinel GPS clocks corrections significantly reduces the positioning residual standard deviation (STD) for stations located in the SAA area.*

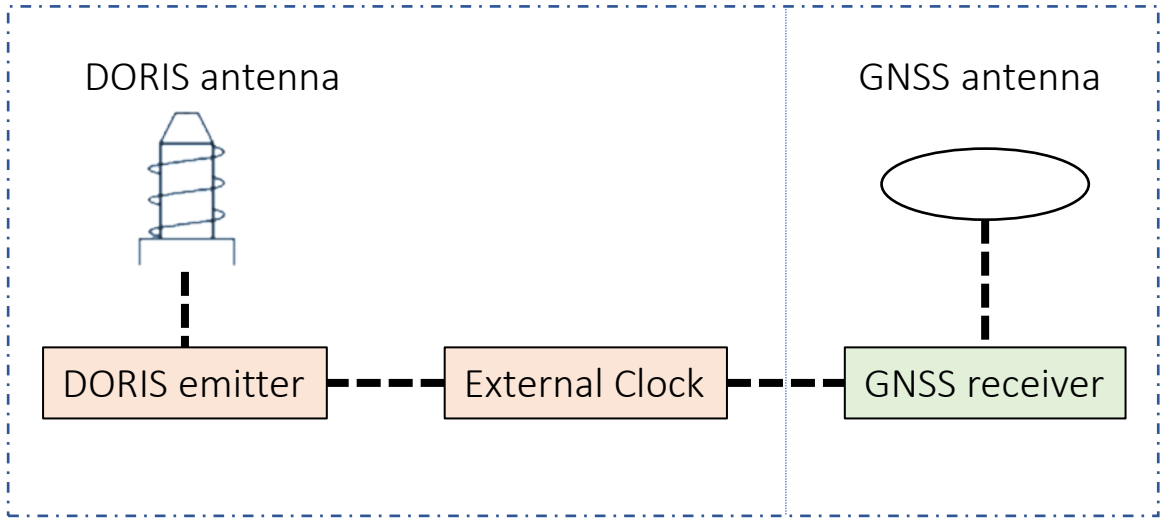
Impact of correcting non-SAA stations

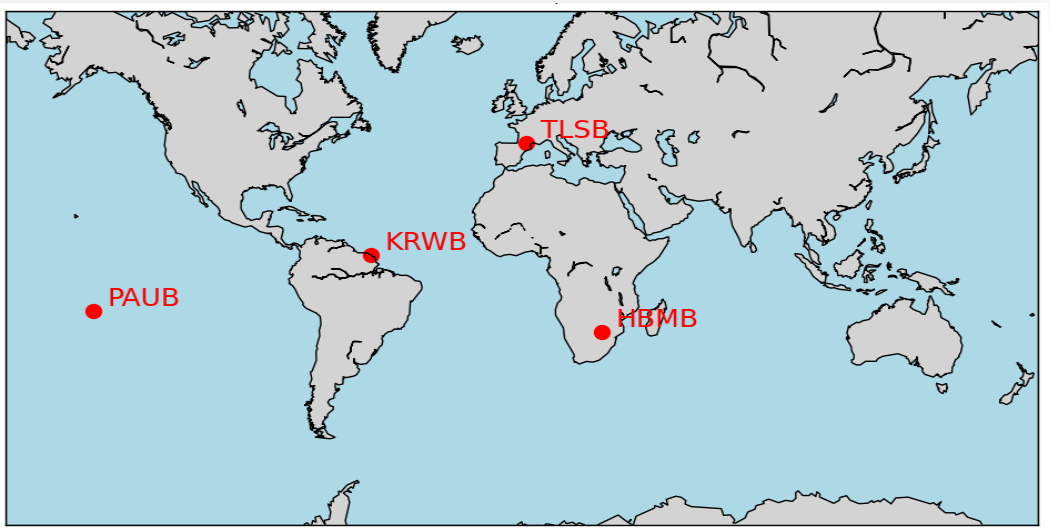


Applying onboard S3A clocks corrections give limited results for non-SAA stations

Ground clock corrections

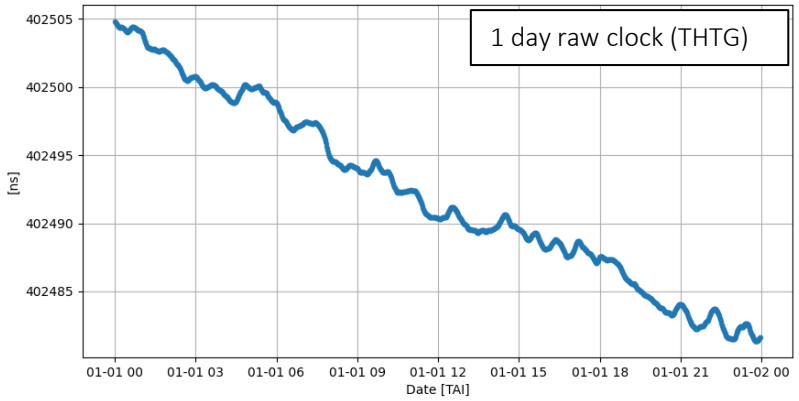
- 4 GNSS receivers are currently connected to DORIS clock
- All these beacons are master beacons
- GNSS receivers are part of the GNSS REGINA network (CNES)
- Link information between GNSS receiver and the external clock can be found in the REGINA sitelogs (https://regina.cnes.fr)



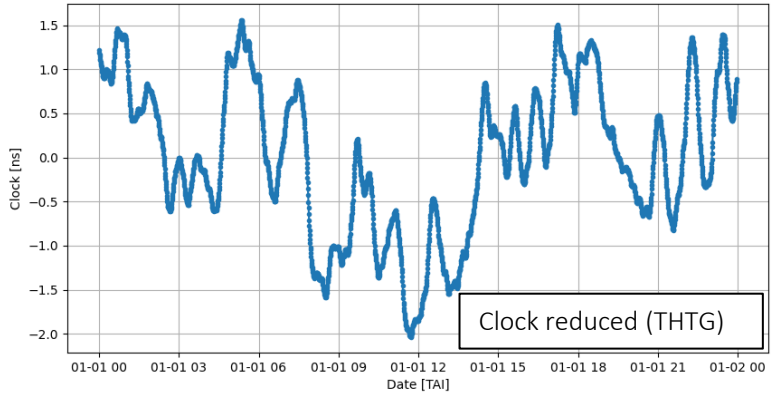


	DORIS	GNSS	Connected since
Hartebeesthoek	HBMB	HARB	1999 (discontinuous)
Kourou	KRWB	KOUG	2015
Toulouse	TLSB	TLSG	2015
Tahiti/Papeete	PAUB	THTG	2019

Clock estimation through the GNSS receiver



Polynomial reduction



1. Clock is estimated by doing a precise point position (PPP)
   - 30 sec processing step
   - GPS only
   - Fixed ambiguities does not seem to be necessary
   - Weekly solution to avoid daily breaks
2. Then, the DORIS RINEX are directly corrected
   - Spline interpolation used to interpolate to DORIS epochs
   - L1 and L2 are corrected

DORIS RINEX correction on L1 and L2

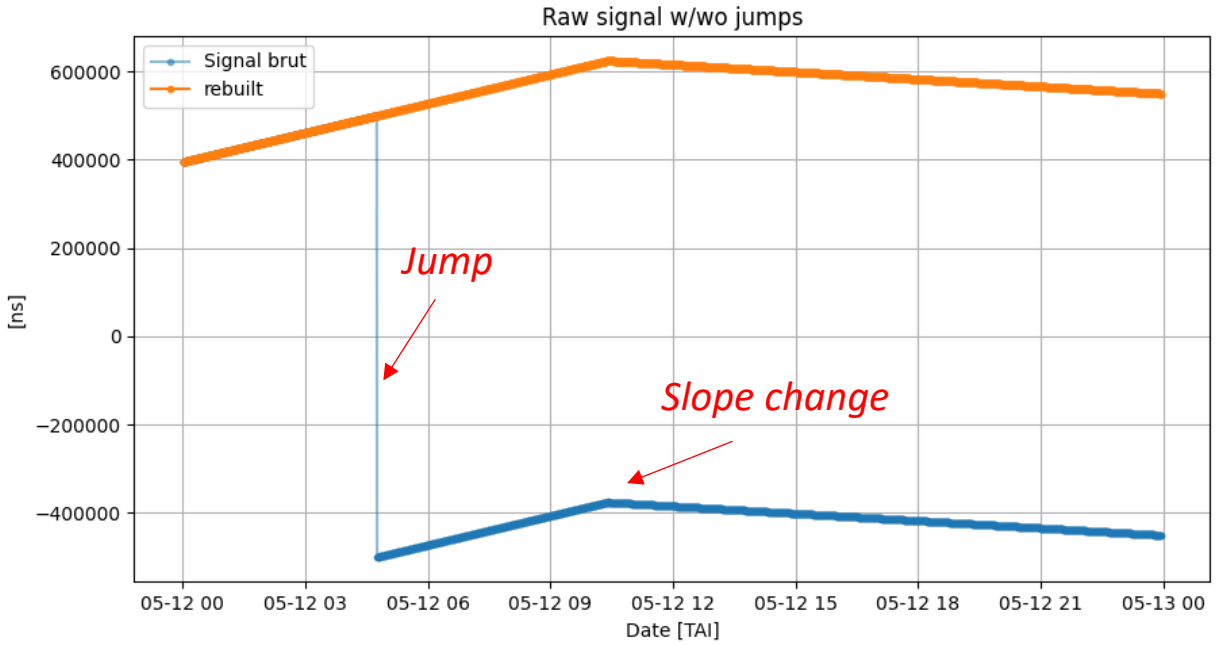
$$L_{1|2} \; -= clock \; . \frac{f_{1|2}}{c}$$

Corrected RINEX

Clock estimation through the GNSS receiver

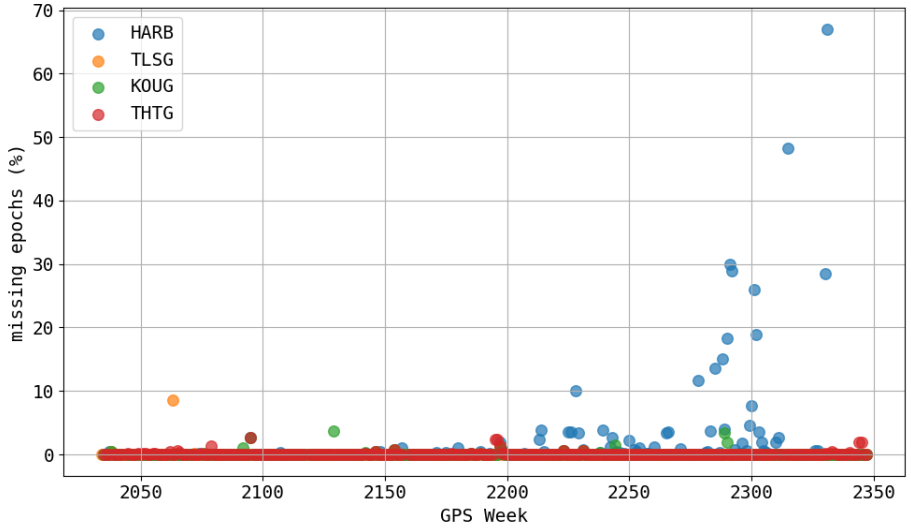
Sometimes, the clock needs to be fixed before polynomial reduction

- jumps
- Slope change
- Missing data



1 day raw clock (TLSG)

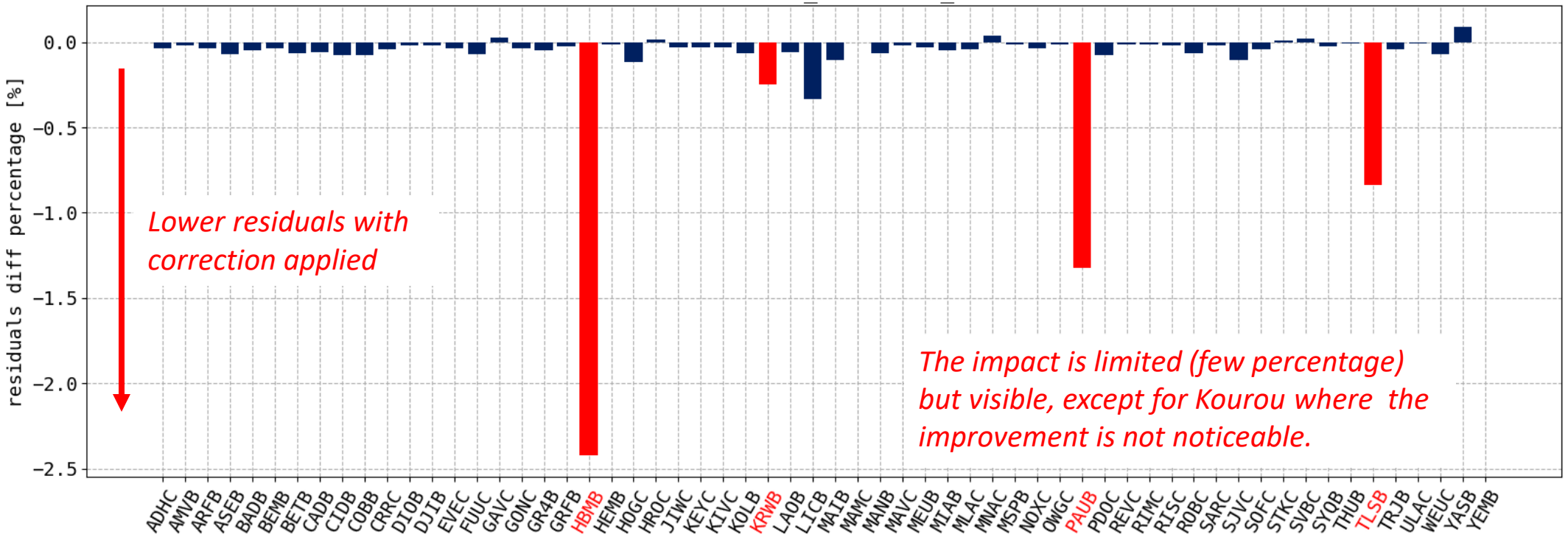
Percentage of missing epochs in weekly clock solutions from year 2021 to 2024



- *Up 50% of missing data for HARB around GPS week 2300 (beginning of year 2024)*

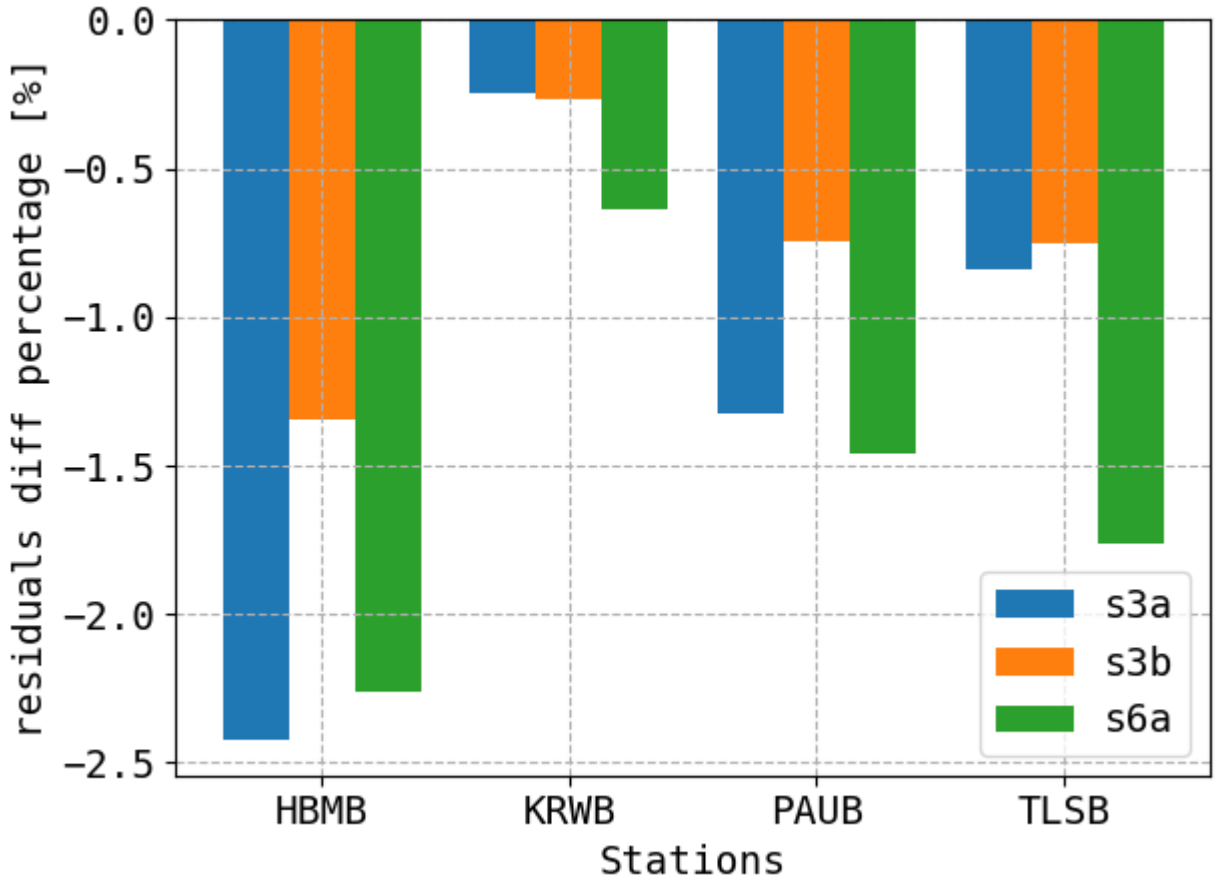
Impact of the ground clocks corrections on the orbit

S3A: RMS of DORIS observation residuals (mm/s) per station from GRG POD processing
Average difference percentage between corrected and uncorrected correction from January 2021 through December 2024.



DORIS beacon with clock connected to GNSS receiver are in red.

Impact of the ground clocks corrections on the orbit



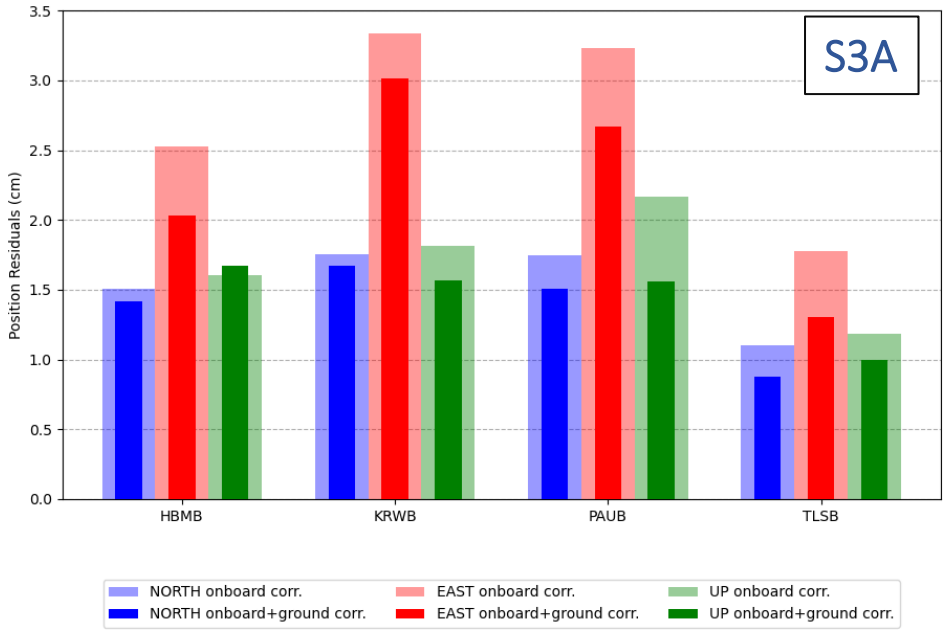
- *The impact is the same in all the Sentinel mono-satellite solutions*
- *Kourou is less impacted probably because the residuals are more driven by the SAA effect.*

Impact of the ground clocks corrections on the station position estimation

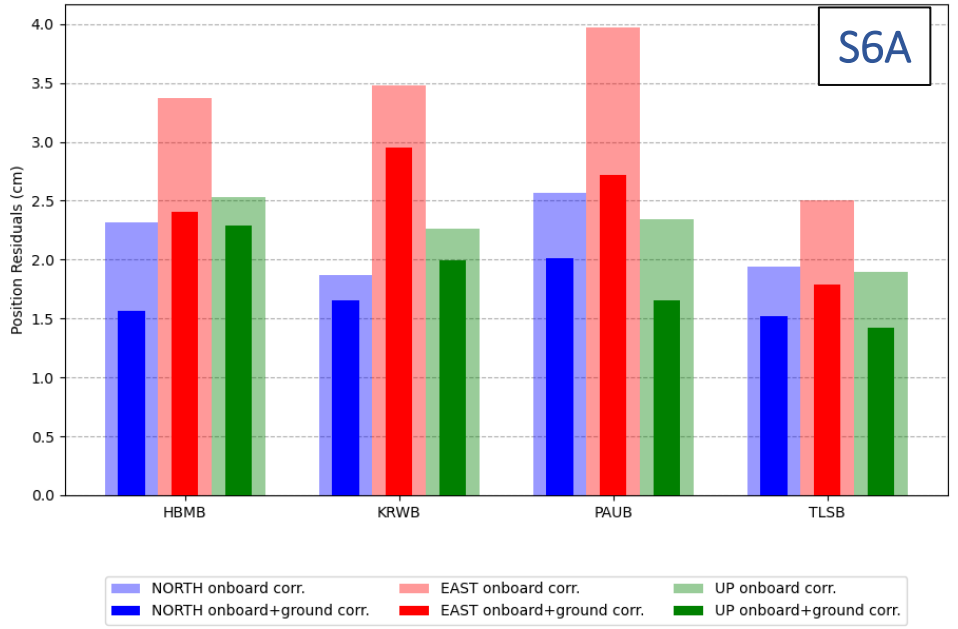
Single satellite Solution compared to DPOD2020 (computed by CATREF)

Positioning Residual STD of DORIS coordinates with and without correcting the DORIS stations connected to GNSS stations. Period: 2021-2024.

After removing the long-term trend, we compare the residual noise levels (STD) in NEU components.



S3A: the impact is visible mainly on the east component



The improvement is even more significant for the S6A mono-sat station position solution

Conclusion

- When available, GNSS observations reduce the impact of the SAA effect on DORIS processing by correcting onboard clock.
- Both onboard and ground corrections improve station position solutions.
- Currently, only the best beacons are co-located with GNSS receivers; further improvements could be expected for other DORIS beacons operating with lower-quality clocks.

Thank you for your attention !