

Progress on DORIS Clock Correction Strategies from the IDS WG

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GFZ Helmholtz-Zentrum für Geoforschung
 gmw
 TUM
 DTU

Introduction

The DORIS Ultra-Stable Oscillators (USO) on board altimeter satellites are perturbed when crossing the South Atlantic Anomaly (SAA), where they exhibit rapid variations in oscillator frequency and, consequently, phase measurements. SAA-induced USO perturbations affect derived products such as station positioning in the SAA region and, to a lesser extent, precise orbit positioning. Fortunately, recent satellites such as Sentinel-3A/-3B, and Sentinel-6 MF are equipped, in addition to the DORIS receiver, with a GNSS receiver connected to the same DORIS USO. It is then possible to correct the clock of DORIS observations using estimated GNSS clock corrections. The IDS Clock Working Group aims at exploring this possibility for current DORIS satellites and in preparation for the upcoming Genesis mission. Some results of the working group will be presented in terms of characterization of the DORIS USO frequency excursions in relation with the Earth's radiative environment, correction of the DORIS clock through the link with the GNSS receiver, impact of the corrected clock on satellite and station positioning, expected radiative environment at the altitude of the future European geodetic mission Genesis.

An Overview of the South Atlantic Anomaly's Effects

SAA: Origin and Impact on the DORIS USO

- Van Allen Belts – trapped high energy protons and electrons.
- Earth magnetic field is asymmetric w.r.t. Earth surface.
- The SAA is the near-Earth region where the Earth's magnetic field is weakest relative to an idealized Earth-centered dipole field.
- The increased flux of energetic particles in this region can disrupt the USO that are the heart of the DORIS system, causing both short-term and long-term changes in frequency behavior.

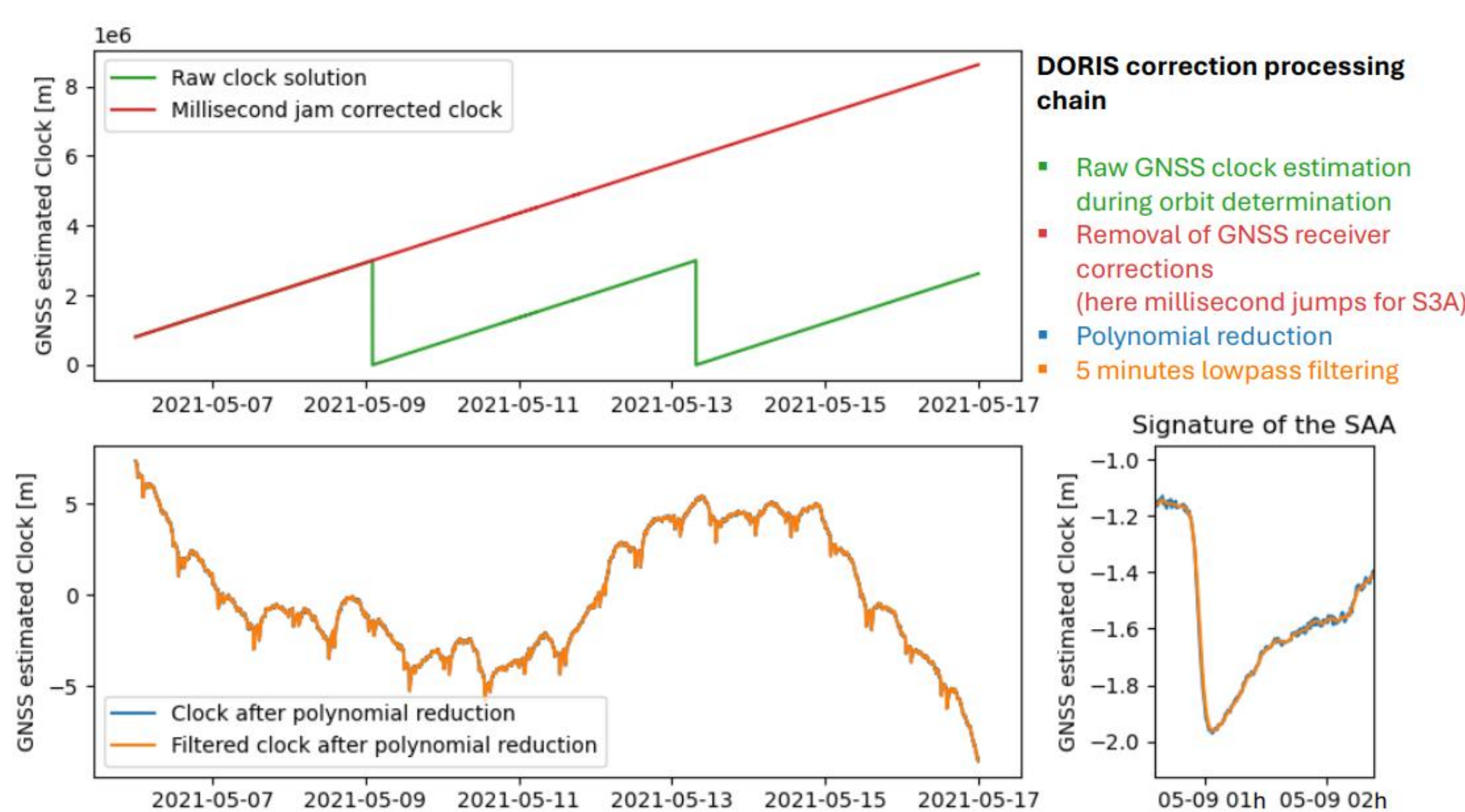


SAA Stations

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

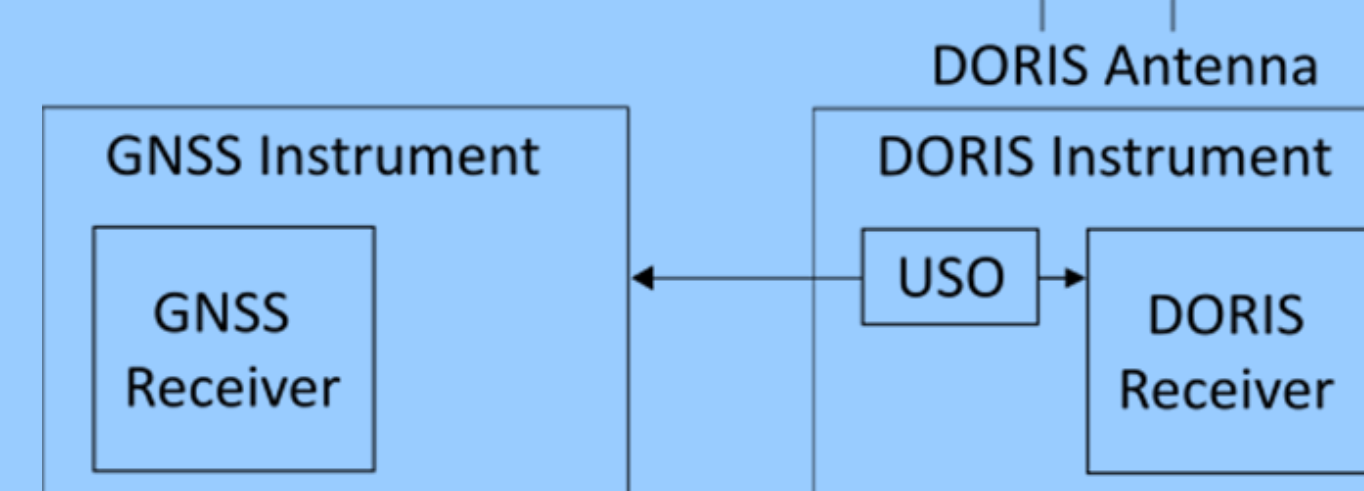
Determine the USO behavior from GNSS observations

- The GNSS clock estimates are used to characterize the high-frequency behavior of the USO, particularly when passing through the SAA.



Sentinel Satellites on-board architecture

The USO drives both DORIS and GNSS instrument frequency



- We use the GNSS filtered clock provided by the CNES and GMV 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.

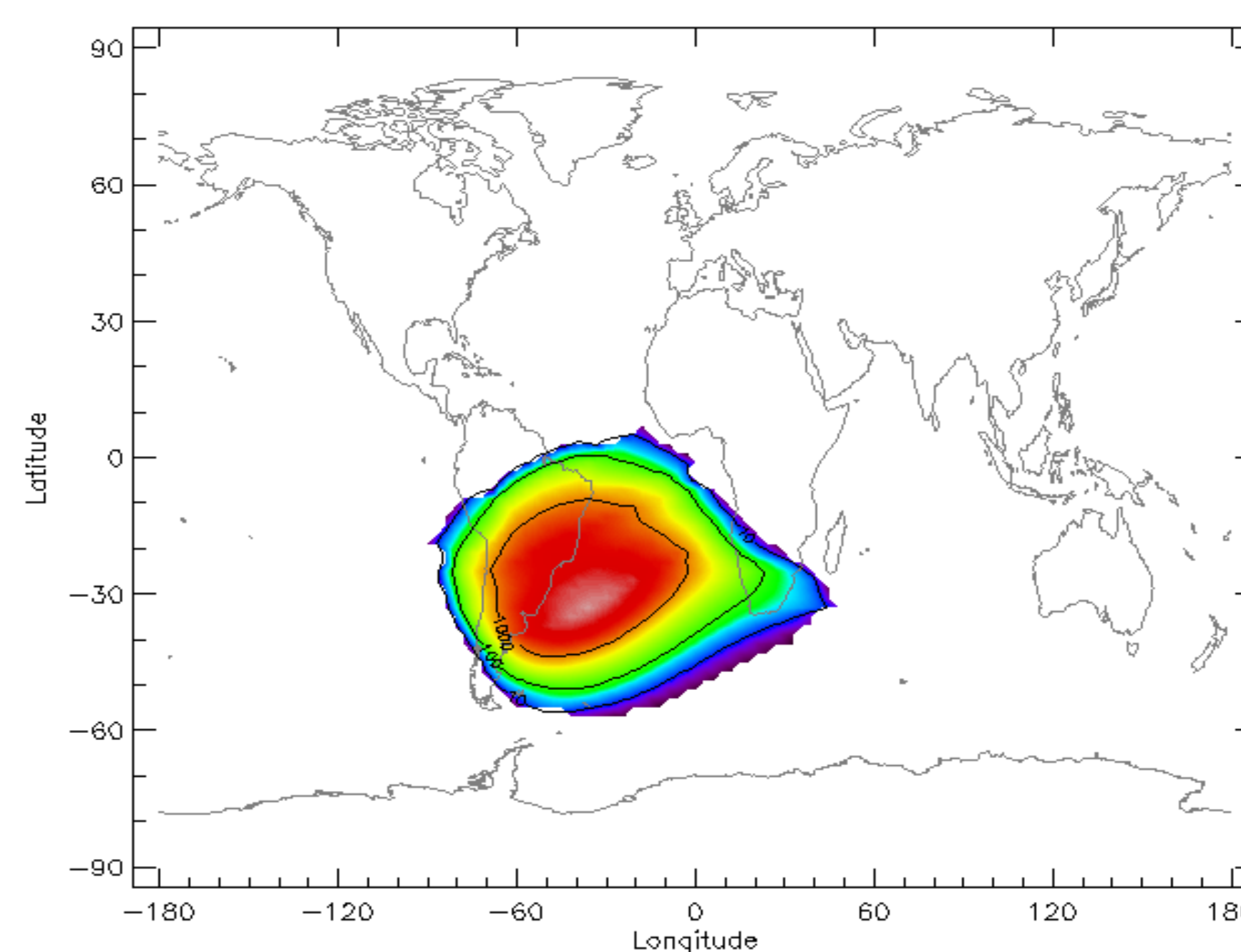
TUM Contribution

SAA Proton Flux

- Trapped protons in the Van Allen Belts affect the frequency of the onboard Ultra Stable Oscillator (USO).
- SPENVIS (SPace ENVironment Information System) is an integrated platform developed by ESA to model the space environment based on a set of models.
- Flux of trapped protons with energies above 50 MeV are displayed in the left figure for the height of the Sentinel-3 orbit based on the SPENVIS AP-8 model.
- The frequency variations of the USO can be compared with the modelled proton flux from SPENVIS and with the proton flux measured by the MEPED (Medium Energy Proton and Electron Detector) on MetOp.

Proton Flux at Genesis Orbit

- The Genesis-1 satellite will fly a DORIS receiver and is equipped with an USO.
- The right figure shows the expected flux of trapped protons with energies above 50 MeV for the orbit height 6000 km of Genesis.
- The USO will be affected two times per revolution by the protons in the Van Allen Belts
- Appropriate shielding of the USO as well as continuous monitoring of the USO frequency using GNSS measurements is essential for the successful analysis of Genesis DORIS tracking data.



Flux of trapped protons (E > 50 MeV) at height of Sentinel 3

Flux of trapped protons (E > 50 MeV) at height of Genesis orbit

GFZ Contribution

Clock Correction Approach

- A dedicated preprocessing script was implemented to apply clock corrections to standard DORIS RINEX observation files and to generate corrected observation datasets
- This enables the provision of a ready-to-use dataset for users
- CNES and GMV clock corrections for Sentinel-3A were applied and tested within the standard POD processing at GFZ

1. Geographic Residual Analysis

- Post-fit DORIS residuals were analysed geographically using their median (Fig. 1)
- Clock corrections reduce the systematic effect related to the South Atlantic Anomaly (SAA)
- GMV clock solutions result in a noisier spatial pattern, possibly due to the absence of prior clock smoothing or filtering

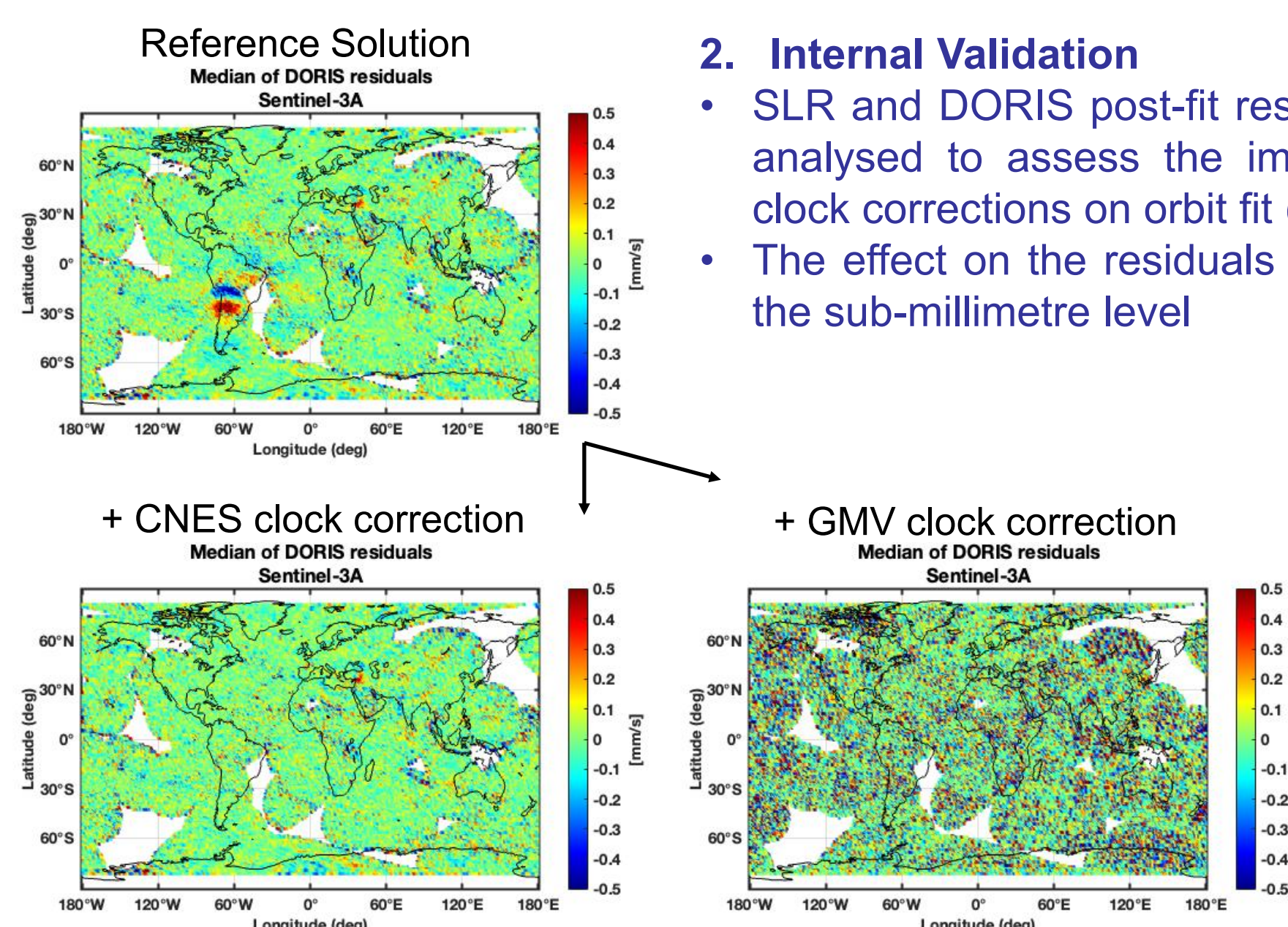


Fig. 1: Median of post fit DORIS residuals

2. Internal Validation

- SLR and DORIS post-fit residuals were analysed to assess the impact of the clock corrections on orbit fit (Tab. 1)
- The effect on the residuals is limited to the sub-millimetre level

Tab. 1: Internal Validation RMS

	SLR [cm]	DORIS [mm/s]
Reference	1.30	0.40
+ CNES clock	1.36	0.46
+ GMV clock	1.95	0.61

3. External Validation

- Processed orbits were compared with the Copernicus Quality Working Group combined solution (Tab. 2)
- GMV clock corrections remain under further investigation

Tab. 2: External Orbit Validation against CPOD

	Orbit Difference RMS [cm]		
	R	T	N
Reference	1.36	1.81	2.66
+ CNES clock	1.34	1.80	2.59
+ GMV clock	3.22	5.91	11.90

4. TRF Evaluation

- Station repeatability was assessed via the STD of the SAA station coordinate differences with respect to the a priori solution (DPOD2020) (Fig. 2).

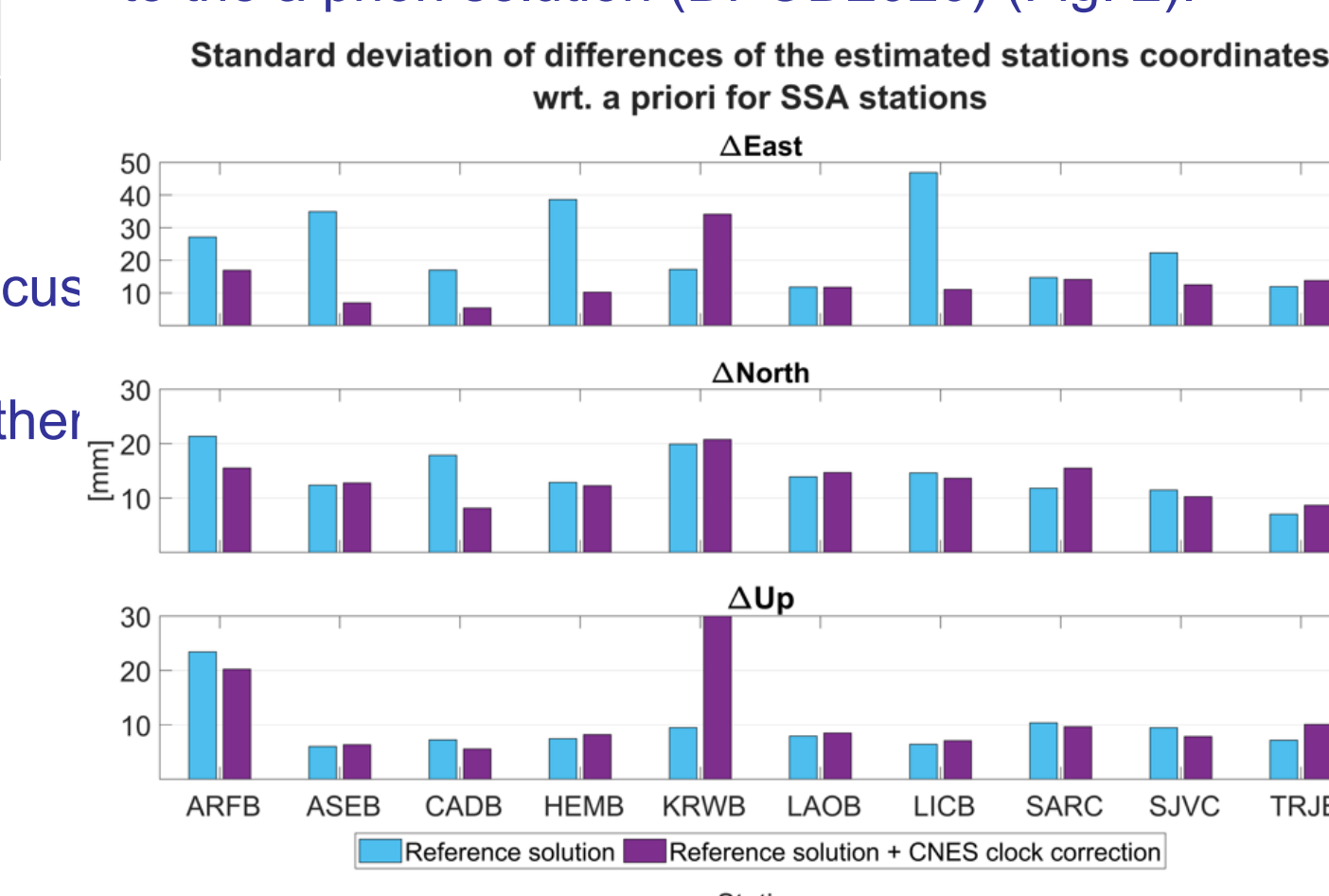
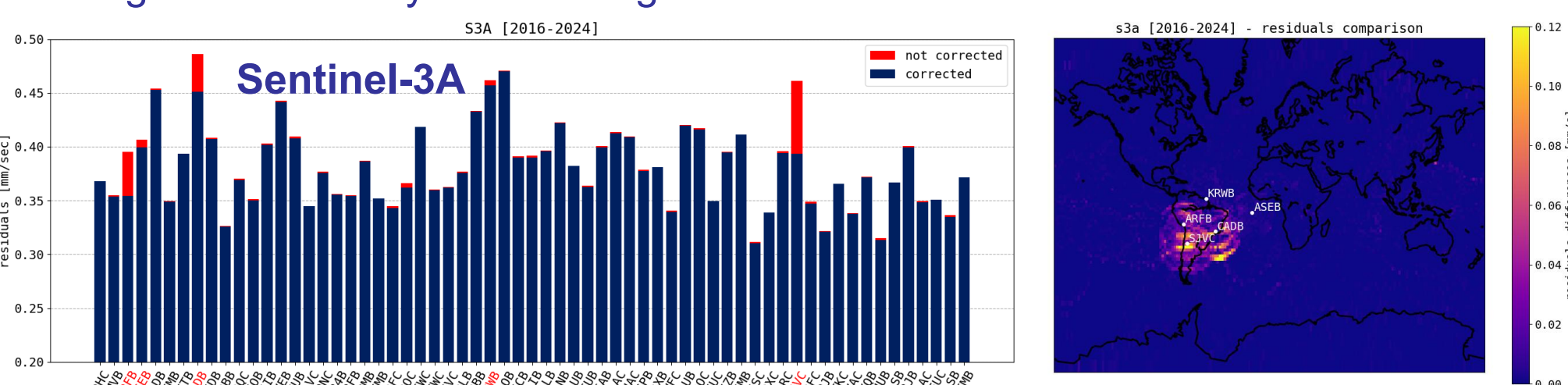


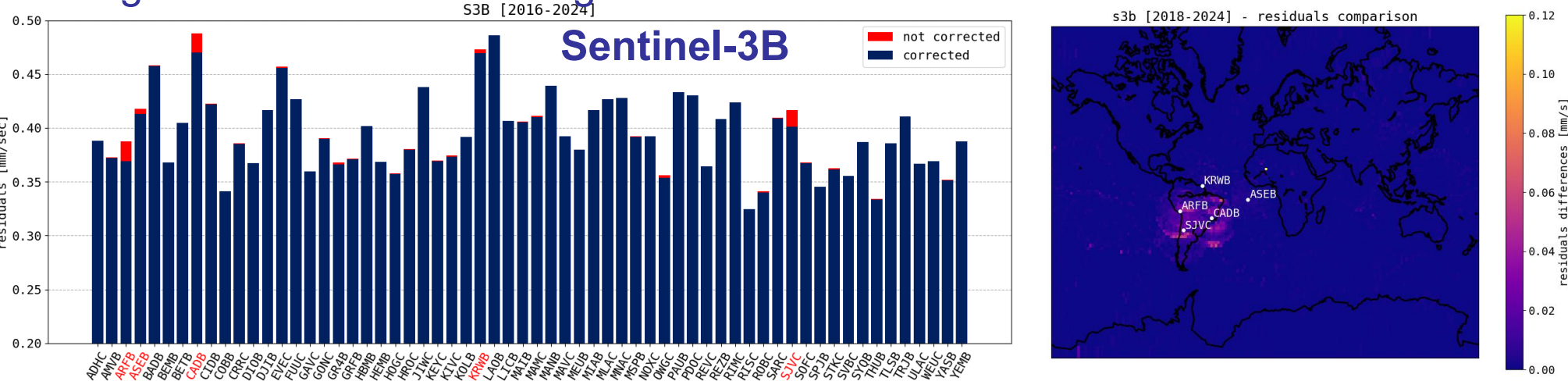
Fig. 2: STD of estimated corrections to the a priori station coordinates for SSA stations (DPOD2020)

CNES/CLS Contribution

Impact of the integration of CNES GPS clocks on the orbit RMS of fit (in mm/s) per DORIS stations from GRG POD processing



Average from June 2018 through December 2024 for Sentinel-3B

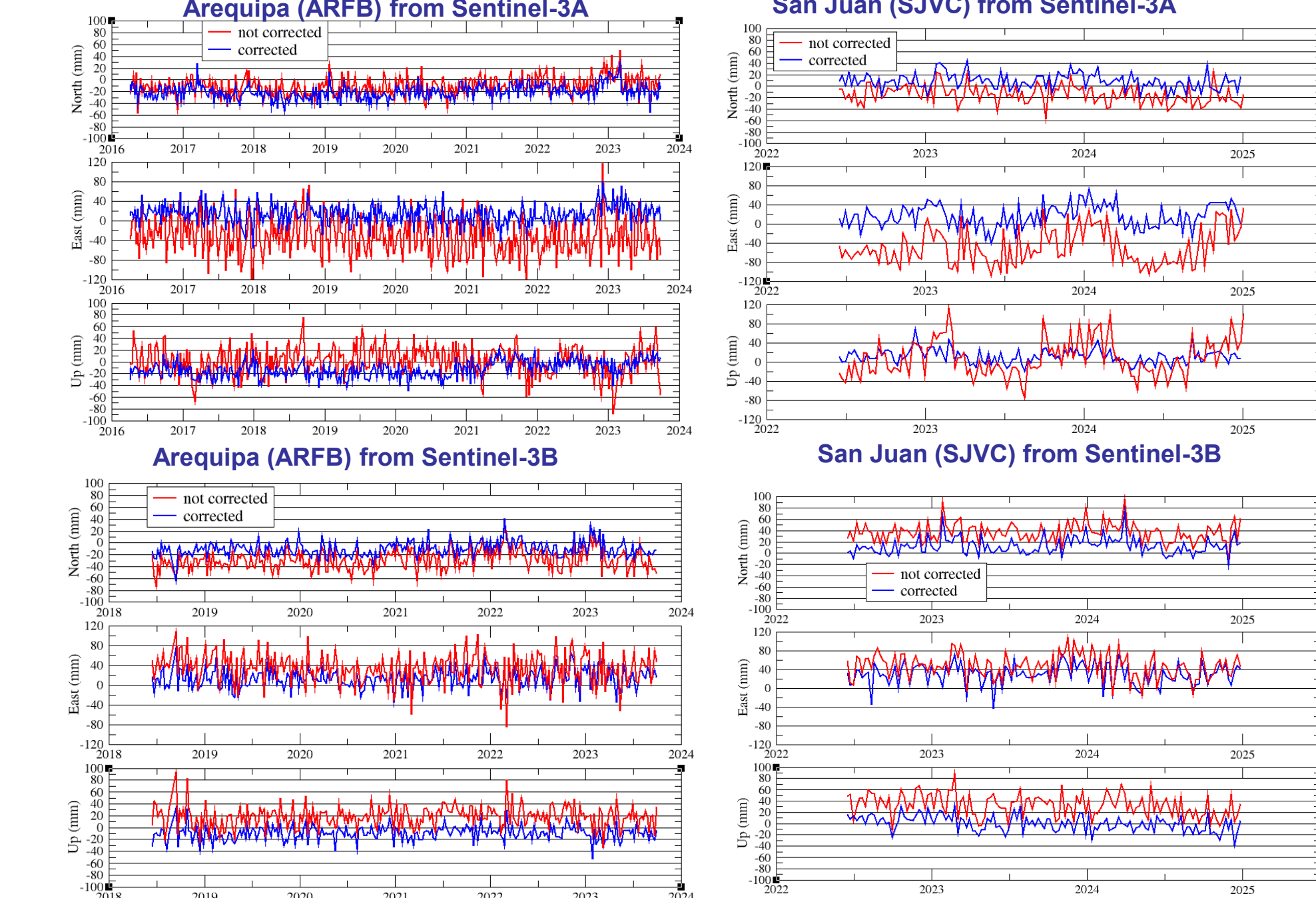


For Sentinel-3A and Sentinel-3B:

The correction significantly reduces the RMS residuals of SAA stations.

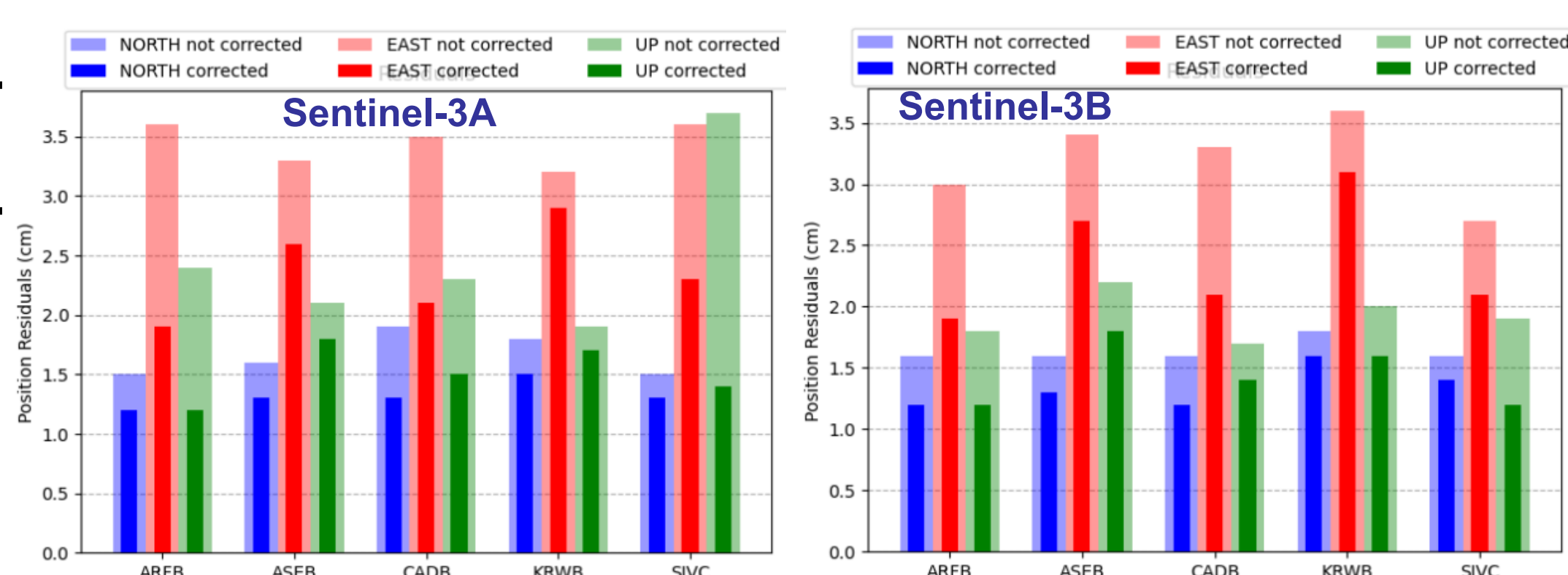
Impact of the integration of GPS clocks on the station position estimation (Single satellite Solution compared to DPOD2020 (computed by CATREF))

Time series of DORIS coordinates wo and w correcting the SAA stations



Positioning Residual STD (Station repeatability)

Time series of DORIS coordinates wo and w correcting the SAA stations. After removing the long-term trend, we compare the residual noise levels (STD) in NEU components.



- 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. Unlike Sentinel-6A, the impact of the SAA effect does not diminish over time (results presented at EGU 2025).

Conclusions

- Measurements of a GNSS receiver connected to the DORIS USO allow a detailed monitoring of the frequency variations in the SAA.
- ESA's SPENVIS tool and MEPED measurements from MetOp allow the analysis of the USO frequency as a function of proton flux.
- Genesis will orbit in a harsher radiation environment. Apart from a good shielding of the USO it is essential to monitor the frequency behavior of the USO using GNSS measurements and to apply corresponding corrections to the DORIS measurements.
- External clock corrections implemented at GFZ effectively reduce SAA-related systematics in the DORIS residuals, while affecting the overall orbital fit only at the sub-millimetre level. The effect on station coordinate repeatability is not uniform; ongoing analyses aim at further optimization.
- The integration of Sentinel GPS clocks by CNES/CLS helps to mitigate the RMS of fit from POD processing for DORIS stations located in the SAA region, for both Sentinel-3A and Sentinel-3B and as for Sentinel-6A show in a previous study. And significantly reduces the non-physical drift in the coordinate time series for stations located in the SAA region and the standard deviation (STD) of positioning residuals.