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Multi-GNSS clock combination with refined clock alignment and code-phase bias integration for Precise Point Positioning

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INTRODUCTION

The International GNSS Service (IGS) delivers orbit and satellite clock correction products systematically through multiple Analysis Centers (ACs). Differences in modeling strategies, reference clocks, and systematic drifts among various ACs result in variations in the quality and consistency of satellite products. To address modeling errors and data gaps inherent to individual ACs, the GNSS community develops and refines procedures for receiving a single, robust combined product. While the IGS has recently extended its combination products with demonstrational multi-GNSS solutions for GPS, Galileo, and GLONASS, these are not yet final operational products and do not include BeiDou.

CLOCK COMBINATION METHODOLOGY

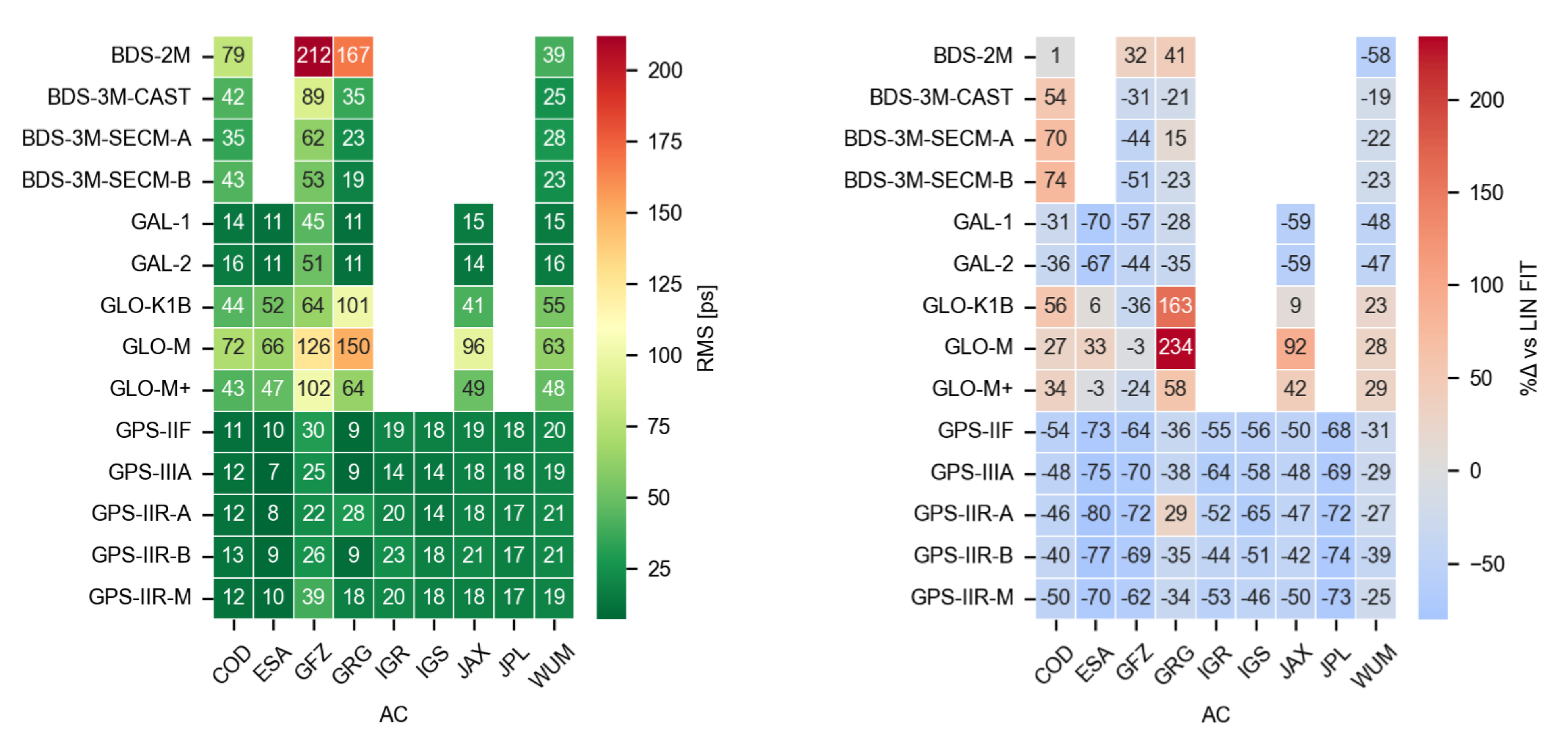
We refine the clock alignment step in the clock combination workflow by replacing linear alignment with an epoch-wise strategy to mitigate non-linear reference clocks in ACs clock products (Geng et al. 2024). A detailed view of the epoch-wise clock-alignment step is shown below.

Choice of the reference AC (most median)

Computing and removing per-epoch mean clock offset of each AC to the reference AC for each constellation

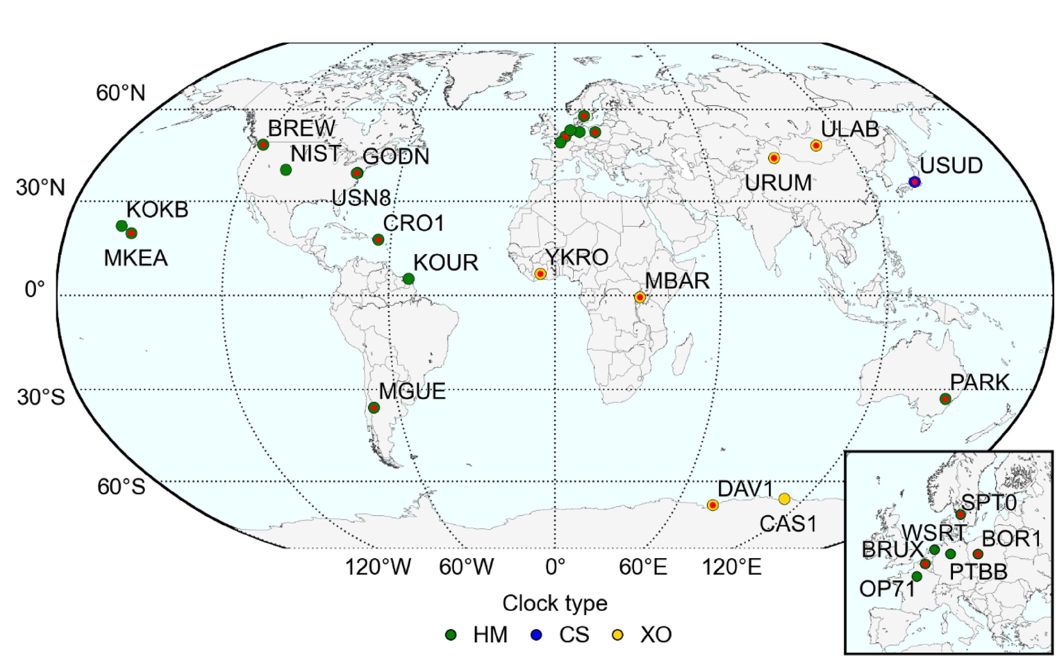
Computing and removing daily satellite-specific clock offsets of each AC to the reference AC for all satellites

BLOCK-SPECIFIC RMS OF CLOCK RESIDUALS

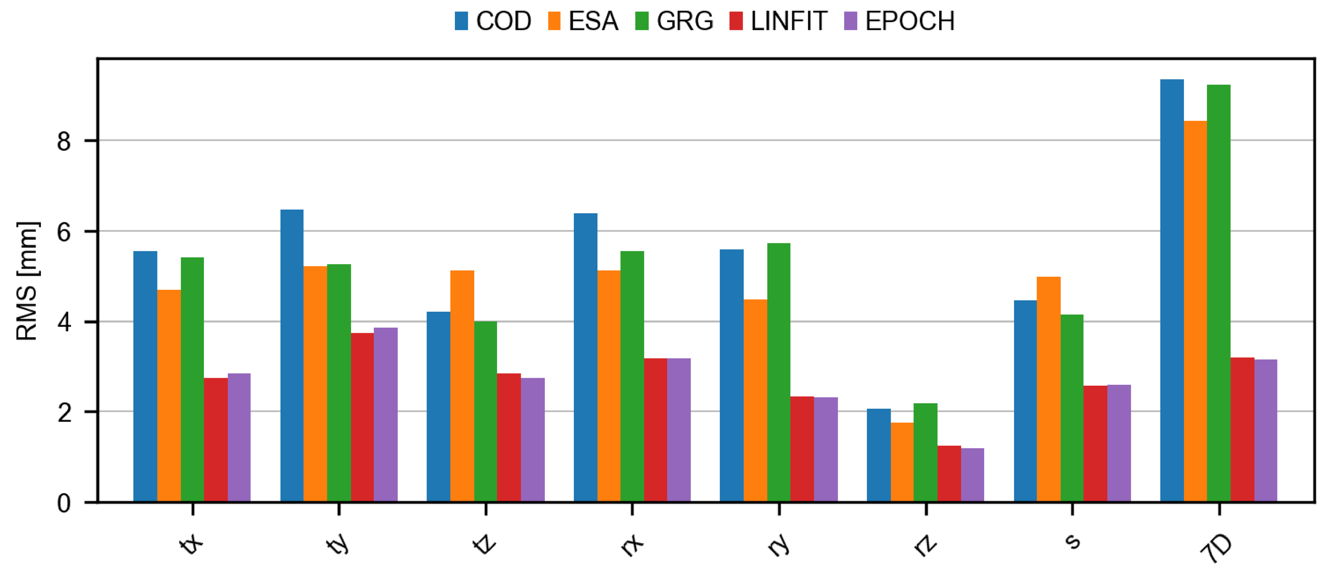


Satellite block-specific RMS assessment of AC clock consistency**.** **Left:** 90th percentile of RMS differences between individual AC clocks and the EPOCH-based combined solution. **Right:** relative RMS change of EPOCH with respect to LIN FIT, negative values indicate an improvement of the epoch-wise alignment.

HELMERT TRANSFORMATION



The Helmert transformation is employed to evaluate the consistency of the terrestrial frame realized by SPOCC and individual ACs' products with ITRF2020-u2023. The analysis is conducted for the network of 15 IGS stations, marked with red dots on the map above.



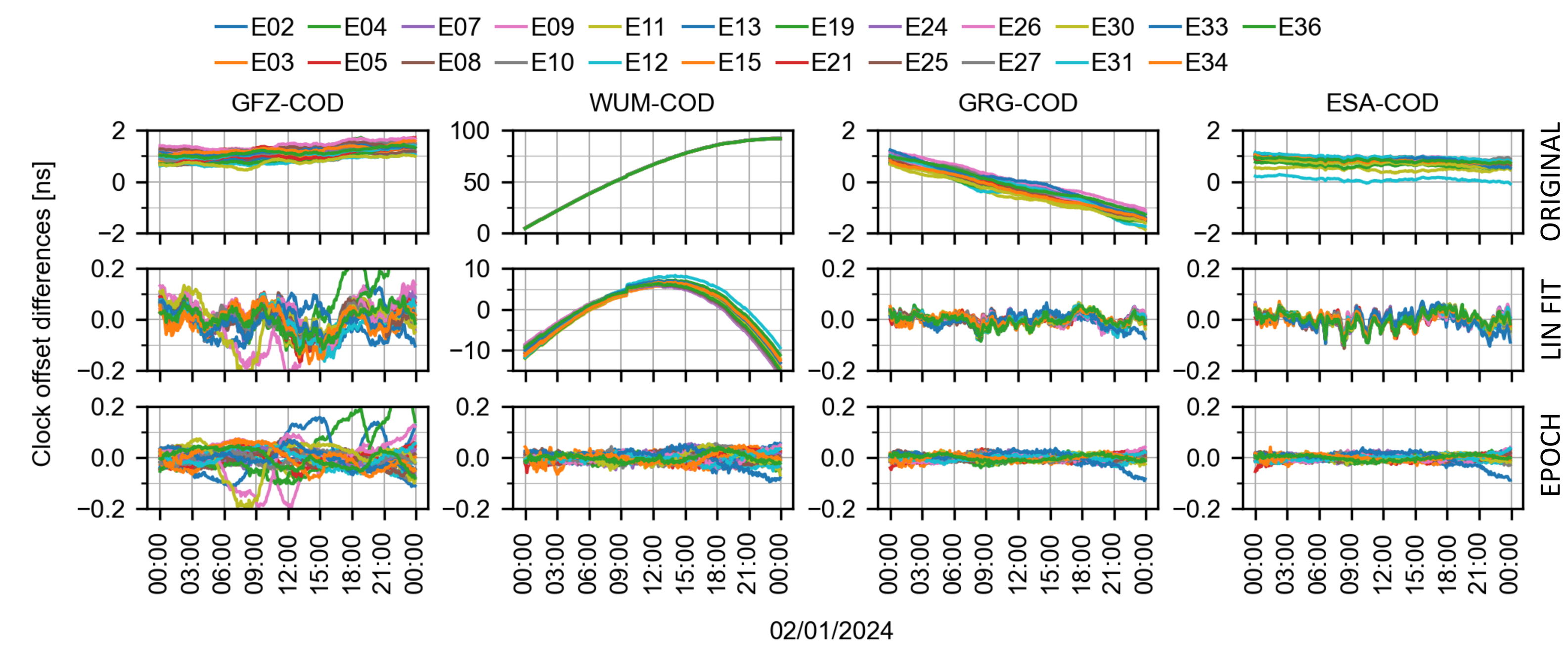
The figure above exhibits the RMS of Helmert parameters repeatability across different solutions with respect to the monthly mean values. The rotation parameters and the scale are expressed in metric units on the Earth's surface for a consistent comparison.

MOTIVATION

The open source Software for Precise Orbit and Clock Combination (SPOCC) was released in 2025 (Mansur, G. et al. 2024). While the orbit combination has already been extensively fine-tuned (Zajdel et al. 2025) the multi-GNSS clock combination still poses a challenge. This study introduces a comprehensive framework for multi-GNSS clock combination, covering GPS, Galileo, GLONASS, and BeiDou, using an epoch-wise alignment strategy and variance component estimation (VCE). The quality of the combined clocks is assessed from a user perspective using pairwise AC comparisons, a frequency stability analysis, and Precise Point Positioning (PPP) results for IGS stations.

SPOCC

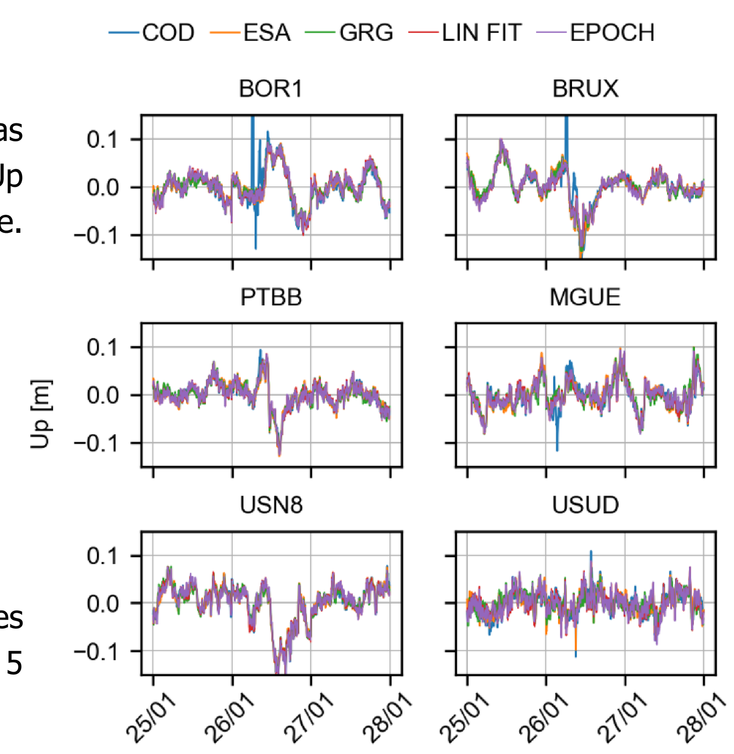
COMPARISON OF ALIGNED CLOCK OFFSETS



Original clock products are compared with products aligned to reference AC through linear-fit (LIN FIT) and epoch-wise strategy (EPOCH). The EPOCH approach successfully mitigates the non-linear trend in WUM-COD differences. It also reduces the clock signal amplitude to approximately 0.05 ns.

PPP RESULTS

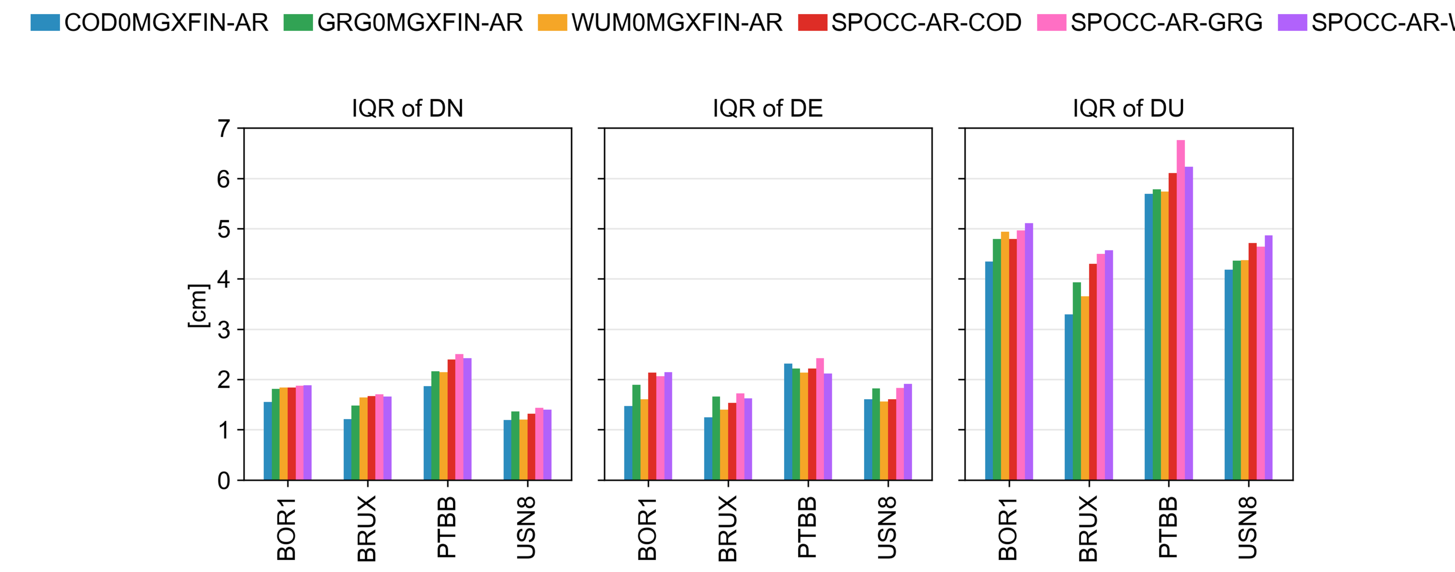
Kinematic PPP was computed for 23 IGS stations in GNSS-WARP software as the float solution (Marut et al. 2024). Figure on the right illustrates the Up component residuals for selected stations with respect to the mean Up value.



[mm]	COD	ESA	GRG	LIN FIT	EPOCH
North	12.7	16.2	16.4	18.1	**10.6**
East	12.1	15.7	11.4	10.5	**10.4**
Up	25.7	24.6	28.1	24.7	**21.4**
3D	31.1	33.4	34.5	32.4	**26.1**

The table depicts mean standard deviations of epoch-to-epoch differences for the North, East, and Up components for 23 IGS stations and for 5 reference orbits and clocks after outlier removal. Values are given in mm.

PPP AMBIGUITY RESOLUTION (AR)



Since SPOCC has not yet provided combined bias products, we were wondering what the results would be of using combined orbits and clocks with biases (OSB) from individual ACs for a PPP-AR solution. The figure above depicts the interquartile range (IQR) of the North, East, and Up components' residuals repeatability from the kinematic PPP solutions with AR and OSB from different sources.

CONCLUSIONS

- SPOCC combination framework with epoch-wise clock alignment delivers internally consistent, high-quality orbit and clock products suitable for precise positioning and reference frame applications.
- The epoch-wise strategy ensures a methodologically correct approach for aligning the ACs clock offsets in the process of clock combinations, successfully removing non-linear trends from the clock offsets.
- The combined clock products are comparable or even better than individual ACs in terms of stability, consistency, and precision of the estimated coordinates from PPP.

REFERENCES

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