Experimental CODE products based on GPS L1/L5 signals

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Technische Universität München

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Outline

1. Motivation
2. Experimental products
3. PPP (Precise Point Positioning) and
   LEO POD (Low Earth Orbit Precise Orbit Determination)
4. Summary

Motivation

1 Transition to the modernized L2C and **L5** signals

Better interoperability with other modern GNSS systems:

- Galileo E5a,
- BeiDou B2a,
- QZSS L5-compatible services.

Current GPS signal characteristics are expected to remain unchanged until at least two years after there are **24** operational satellites broadcasting **L5** with fully functional navigation messages.
The availability of **24** satellites broadcasting the **L5** signal is estimated to occur in **2027**.
https://www.gps.gov

2 Some LEO satellites rely exclusively on **L1/L5** observations

e. g. EUMETSAT Polar System Second Generation (EPS-SG)

Demand for L1/L5-based GNSS products

- PPP (Precise Point Positioning) applications
- Geodesy and Earth science communities
- Space agencies and satellite operators
- ...

Processing scheme and input data

Satellites (GE)
- GPS **L1/L2/L5**, Galileo **E1/E5a**

220 stations meeting the following requirements
- GPS **L1/L2/L5**, Galileo **E1/E5a** observations
- antenna with “ROBOT” calibration for the relevant frequencies

Antenna patterns (ANTEX)
- **IGS**
- **LMB** (Lockheed Martin and Boeing)

many thanks to O. Montenbruck

Bernese GNSS Software
(operational CODE processing routines)

Double-difference processing
GNSS orbits (GPS, Galileo)
ERP (Earth Rotation Parameters)

→ CLK (Satellite clock corrections)
OSB (Observable Specific Biases

test solutions

Test solutions

SOLUTIONS			SATELLITES	
			GPS	Galileo
$L12a_{IGS}$	$L12a_{LMB}$	**(62 sat.)**	32 (L1/L2)	30 (E1/E5a)
$L12_{IGS}$	$L12a_{LMB}$	**(50 sat.)**	11 IIF, 9 IIIA (L1/L2)	30 (E1/E5a)
$L15_{IGS}$	$L12a_{LMB}$	**(50 sat.)**	11 IIF, 9 IIIA (L1/L5)	30 (E1/E5a)

10 GPS Block IIIA satellites from 25 April 2026

Main output files
SP3 (GNSS orbits)
ERP (Earth Rotation Parameters)
CLK (Satellite Clock Corrections)
OSB (Observable Specific Bias)

STATISTICS & VALIDATION
based on 10 days: 1-10 March 2026

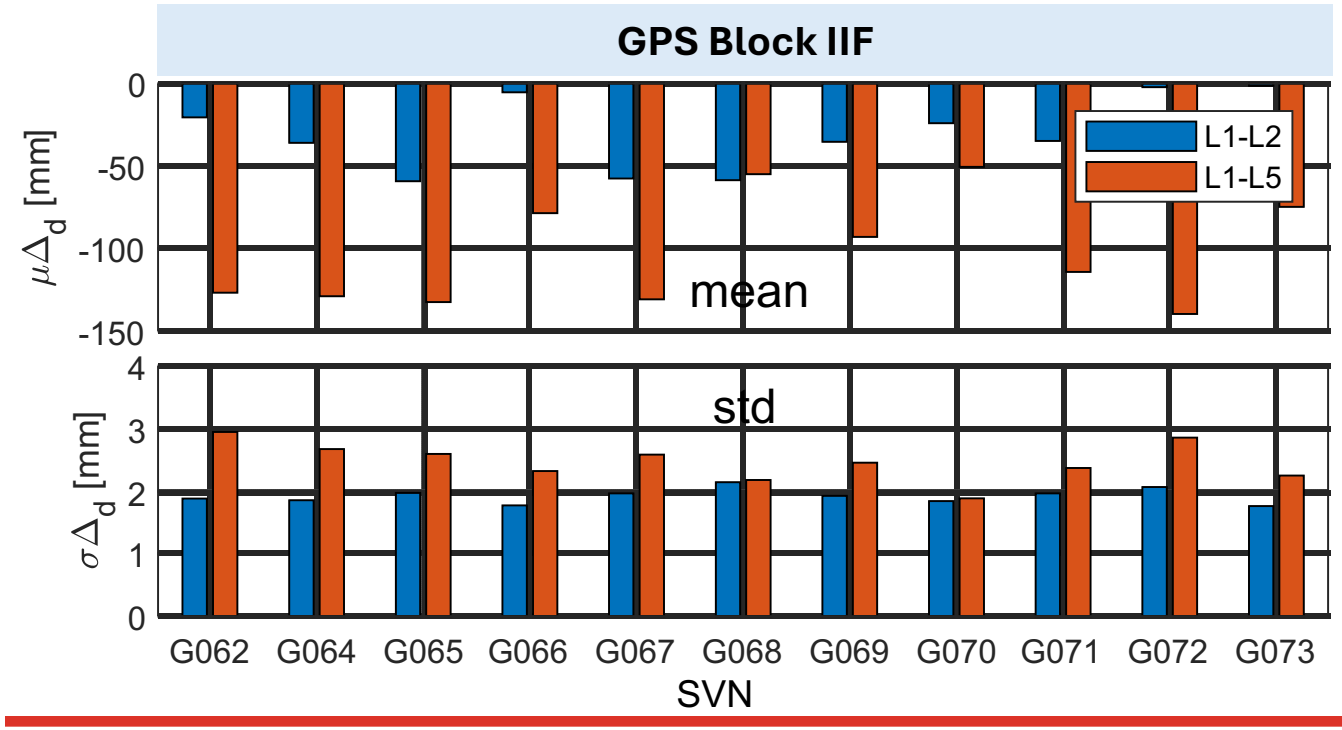
- Orbit comparison to the legacy (GRE) solution
- Orbit misclosures at day boundaries
- Satellite clock corrections: L1/L2 vs. L1/L5
- PPP and LEO POD based on test products

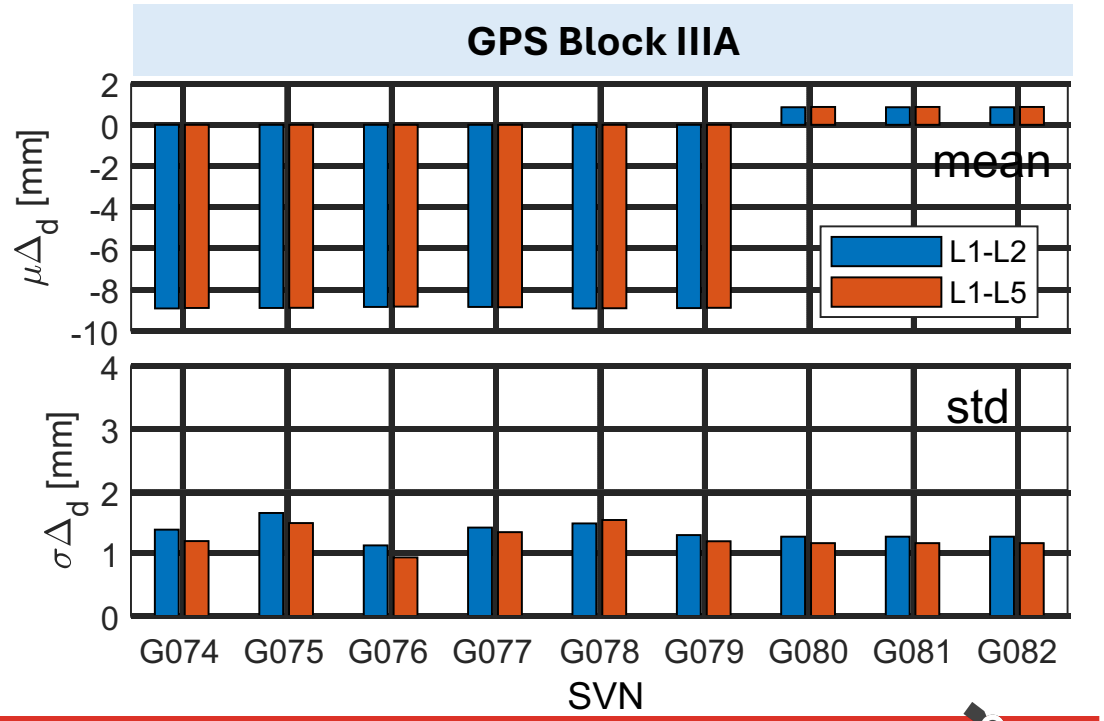
ANTEX: IGS vs. LMB

	IGS (0°-18°)	LMB (Lockheed Martin, Boeing) (0°-30°)
GPS Block IIF	est. $\Delta(E)$ (L1 = L2) **L2→L5**	cal. $\Delta(E,A)$ L1, L2, L5
GPS Block IIIA	cal. $\Delta(E)$ L1, L2, L5	cal. $\Delta(E,A)$ L1, L2, L5

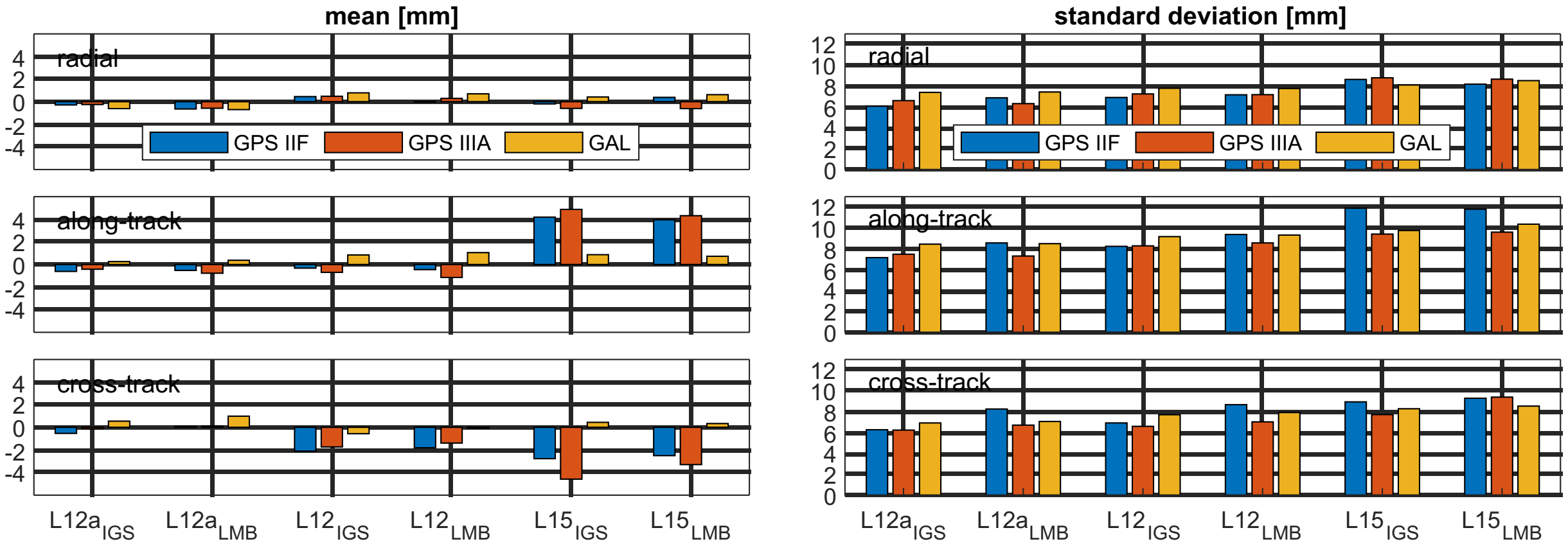
E: elevation
A: azimuth

Difference between IGS and LMB antenna patterns $E \in [0^o, 14^0]$

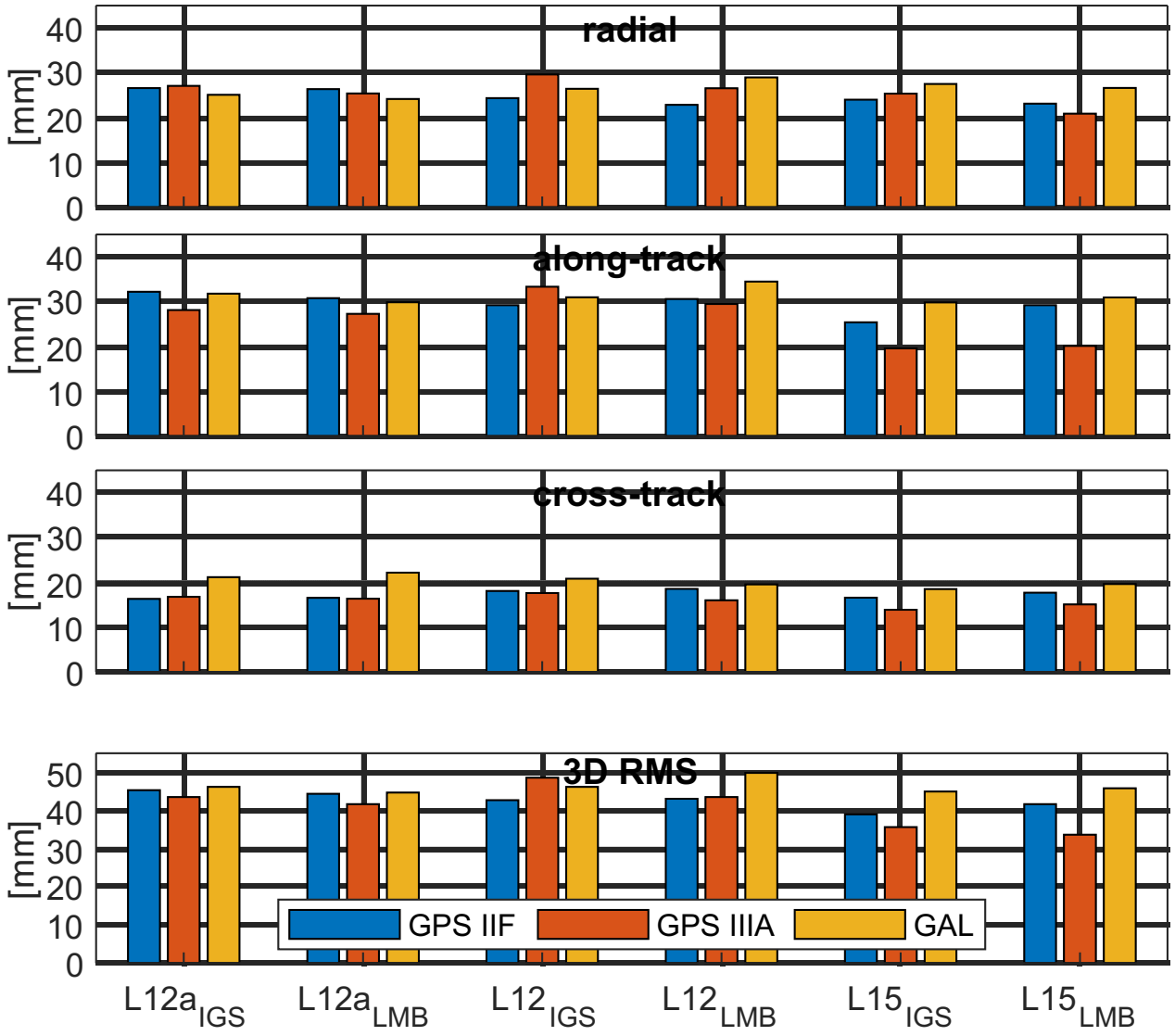




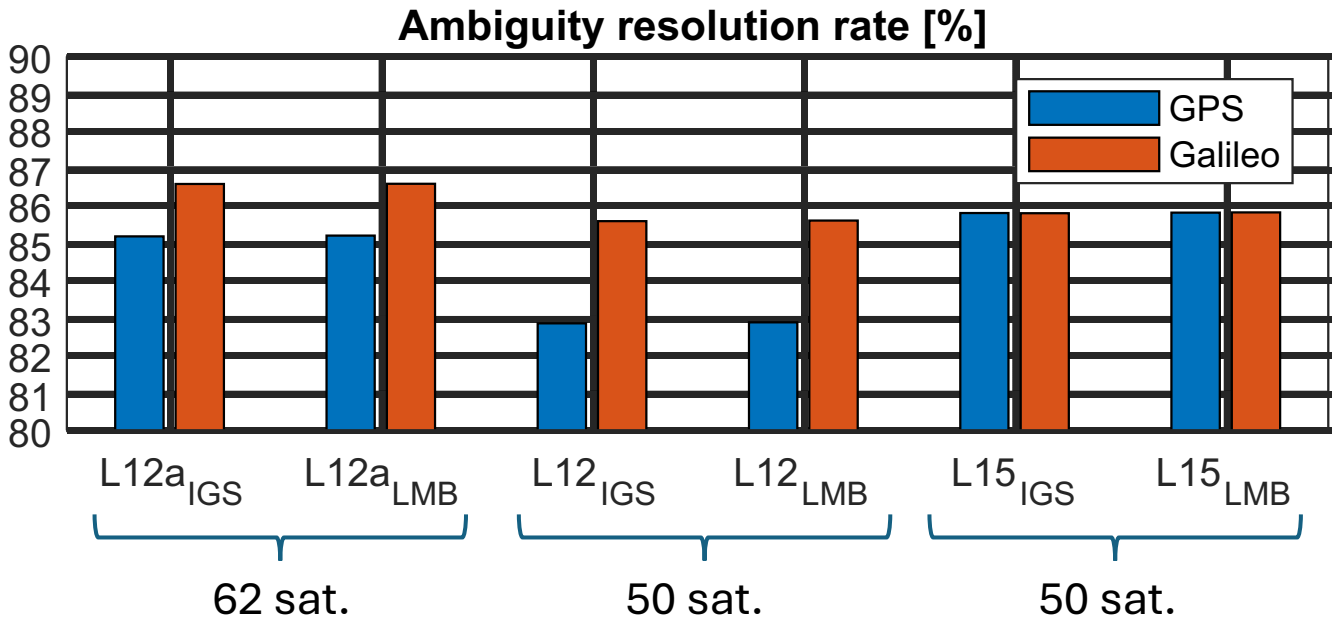
GNSS orbits: differences with respect to legacy (GRE) 1-day solution



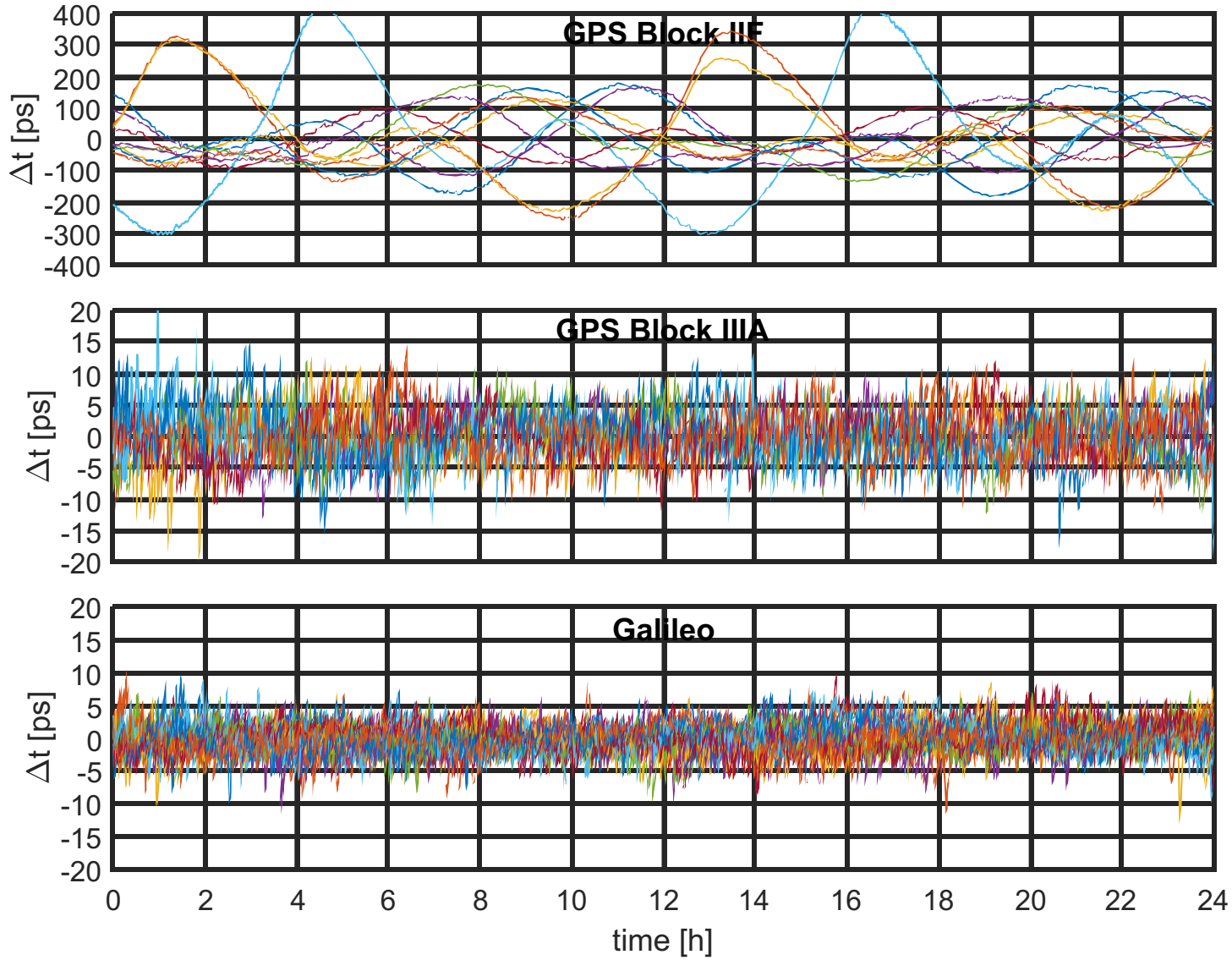
GNSS orbits: misclosures at day boundaries (RMS over 10-days)



Ambiguity resolution



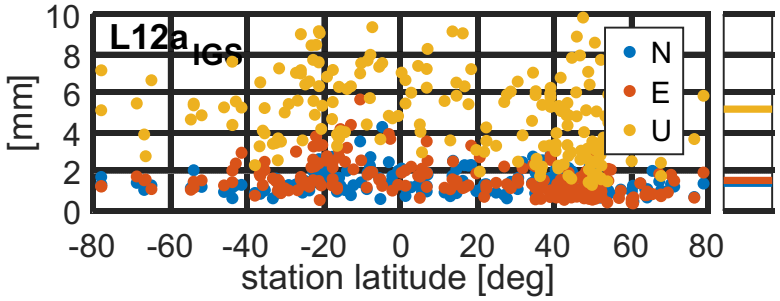
Satellite clock corrections: **L1/L2** vs. **L1/L5**

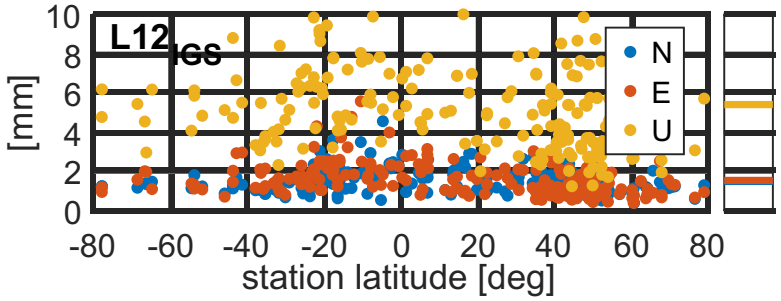


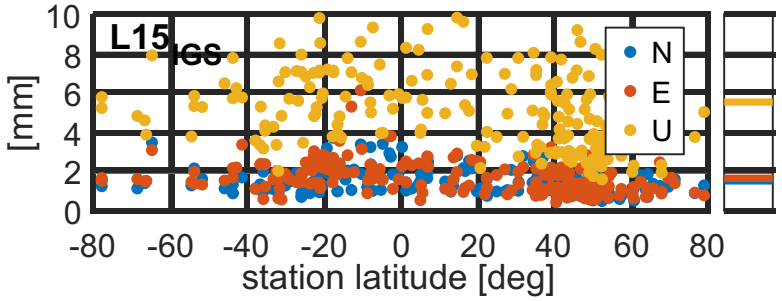
! **L1/L2**-based GNSS orbits were used for **L1/L5** clock estimation

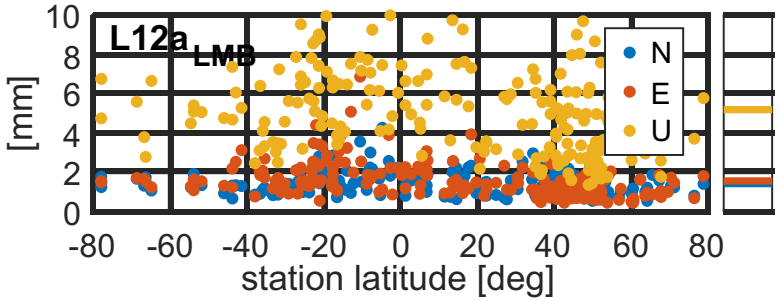
10 ps ≈ 3mm

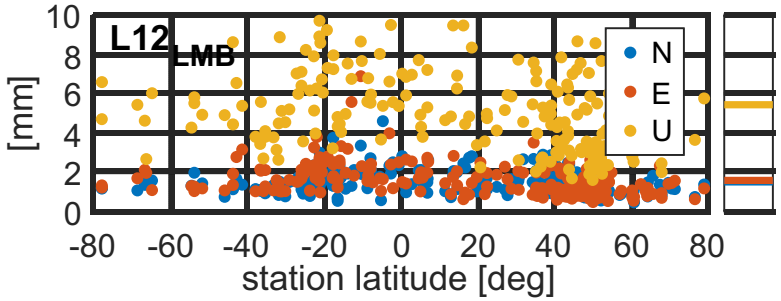
Precise Point Positioning: coordinate repeatability (RMS over 10-days)

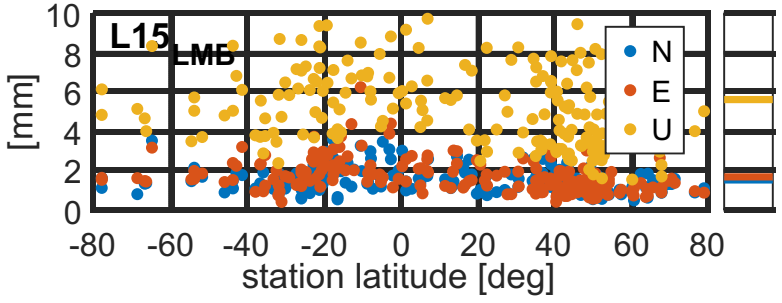


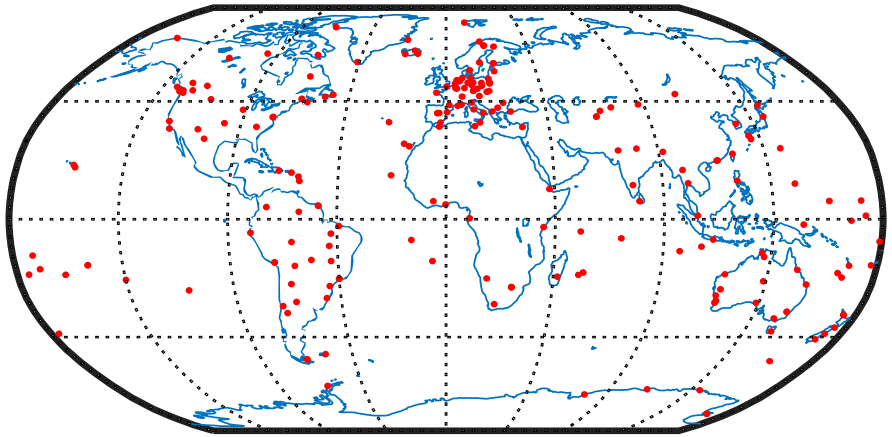


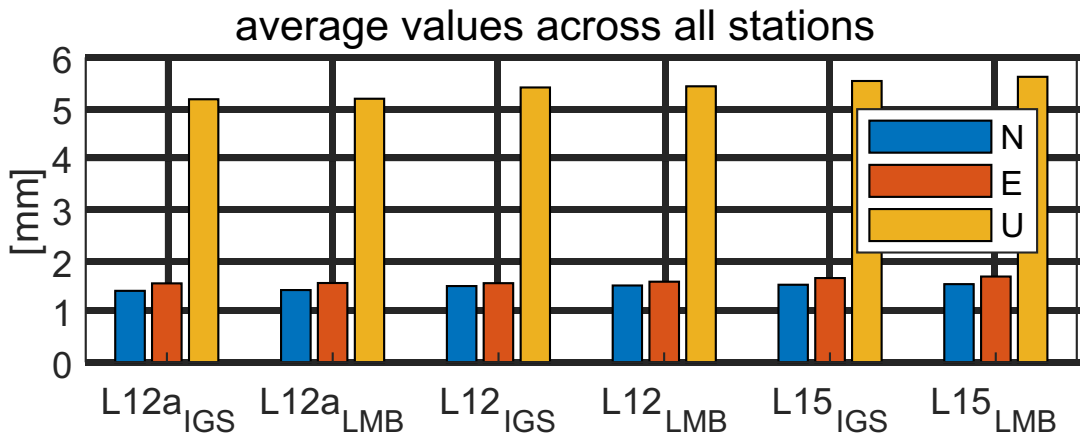






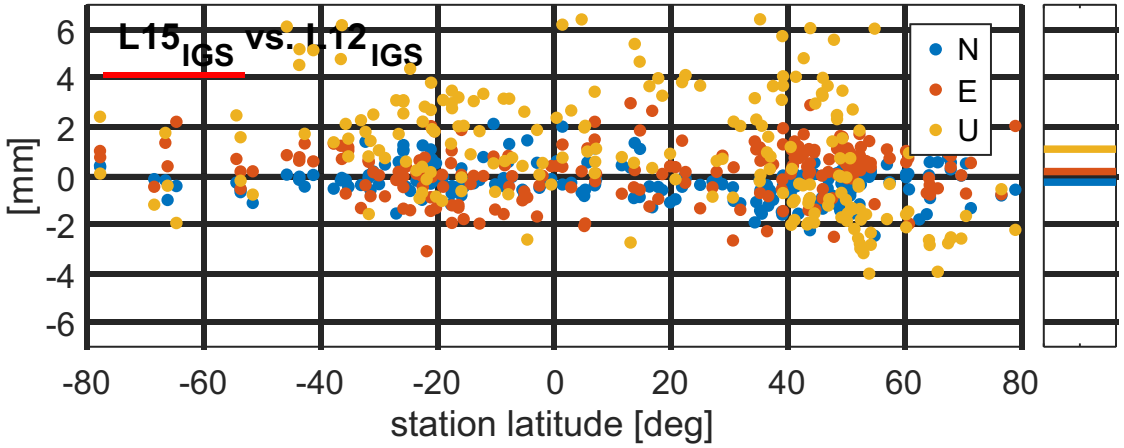


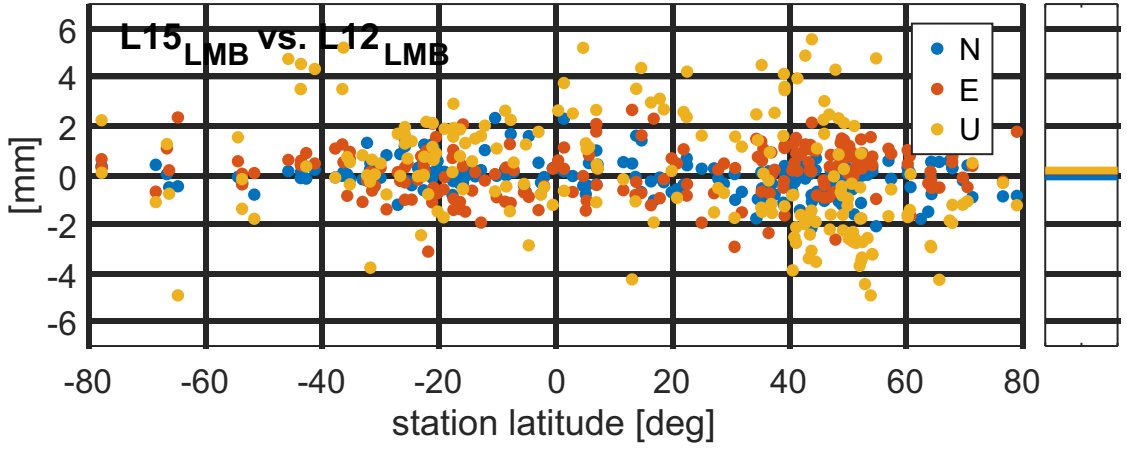




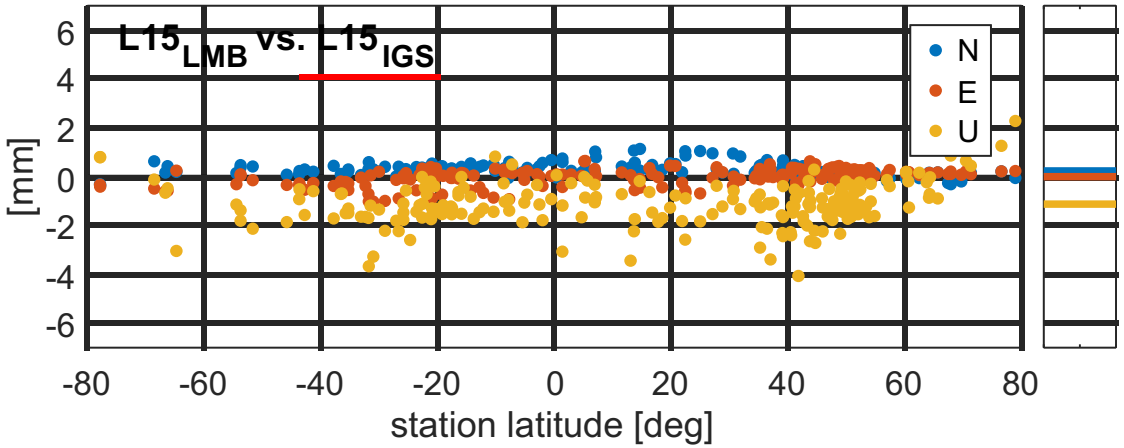
Precise Point Positioning: average station coordinate differences

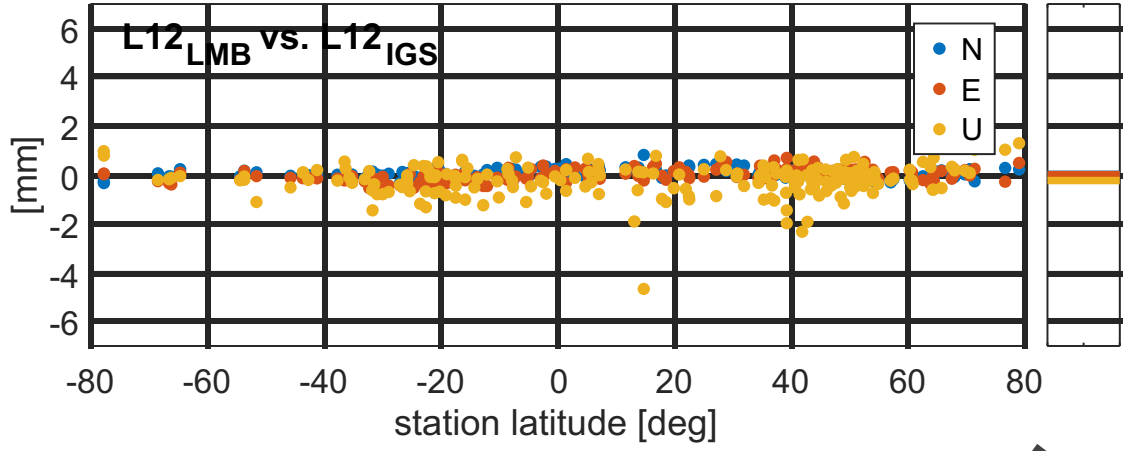
different observations, the same ANTEX





different ANTEX, the same observations



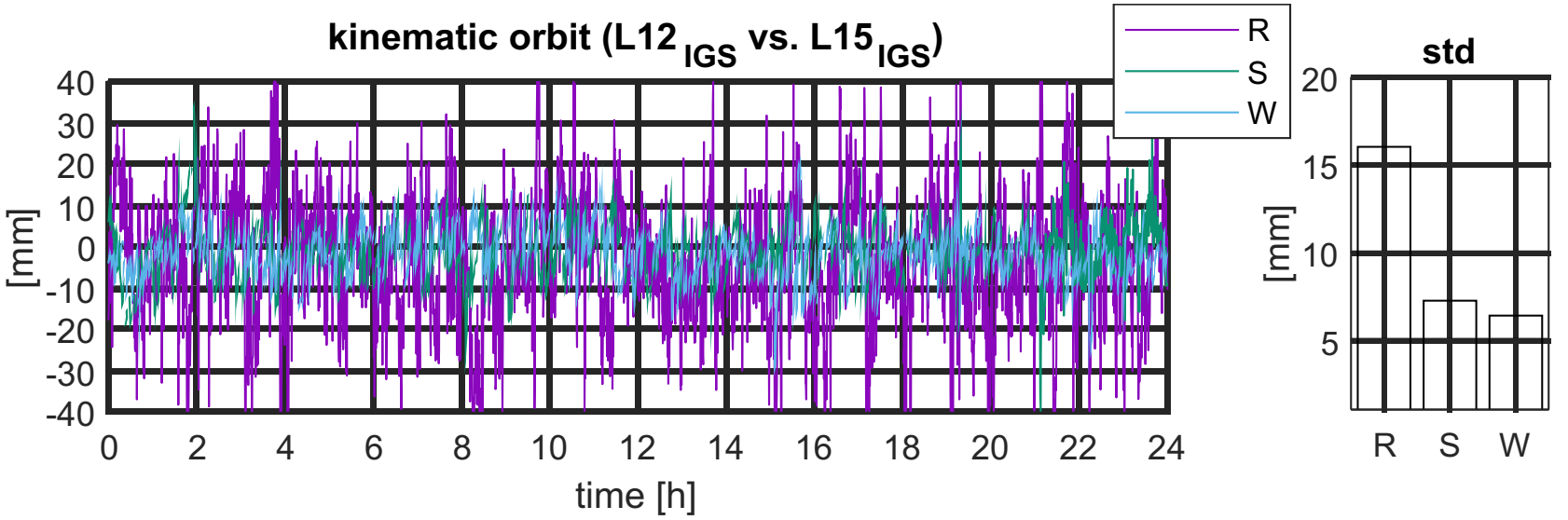


LEO POD: Sentinel-6A

Precise **O**rbit **D**etermination of a **L**ow **E**arth **O**rbit Satellite

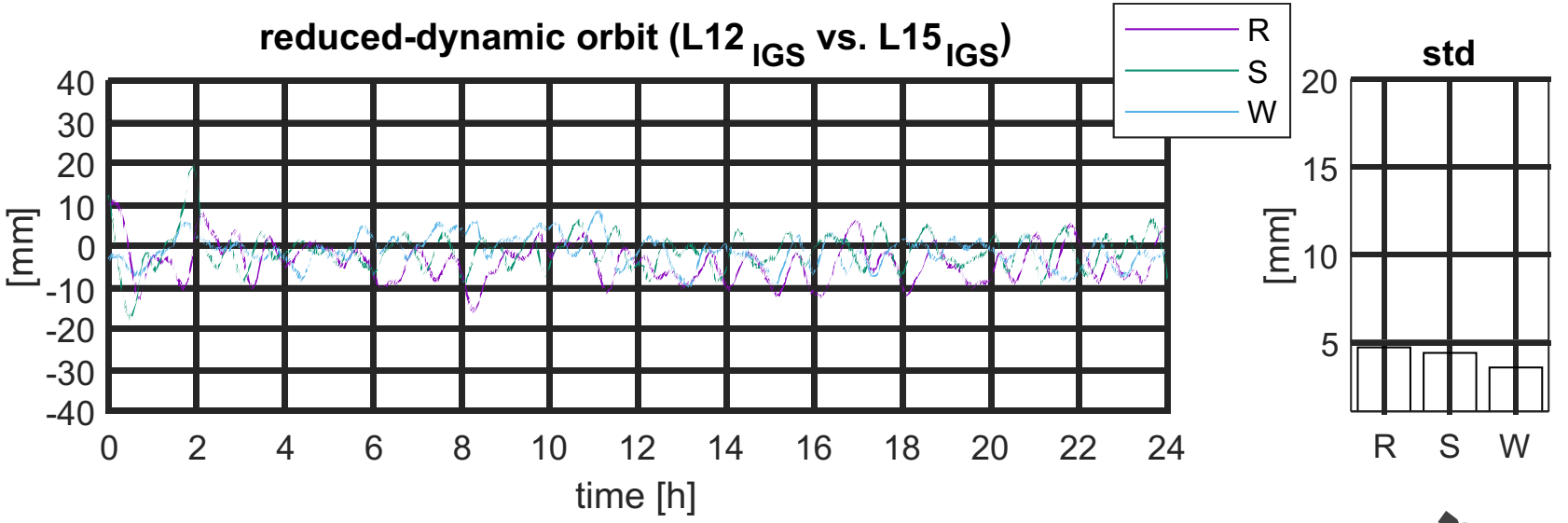
S6AN: nominal antenna
GPS **L1/L5**, Galileo **E1/E5**

S6AR: redundant antenna
GPS **L1/L5**, Galileo **E1/E5**



Ambiguity resolution rate [%]

	GPS(L1/L2) GAL (E1/E5)		GPS(L1/L5) GAL (E1/E5)	
GNSS	**WL**	**NL**	**WL**	**NL**
GPS	**81.1**	**79.4**	**97.6**	**93.4**
Galileo	96.9	96.5	98.5	98.1
TOTAL	90.8	89.9	98.1	96.3



Summary

1. L1/L5-based GNSS products are comparable in quality to those derived from L1/L2 observations.

2. Satellite clock corrections derived from L1/L5 observations can be generated using the L1/L2-based orbit solution

3. PPP and LEO POD achieve comparable or superior performance when using L1/L5-based products.

4. Consistent L5 antenna patterns should be applied for GPS Block IIF satellites.

5. User applications should employ fully consistent products.

Next steps

1. Enable operational processing to generate **L1/L5**-based products
   (rapid and final products equivalent to the **L1/L2**-based products)

2. What naming convention should be used for the **L1/L5**-based products?
   What about **L1/L2/L5** products?

References

1. Montenbruck O, Steigenberger P, Mayer-Gürr T, (2023) Manufacturer calibrations of GPS transmit antenna phase patterns: a critical review. Journal of Geodesy, 98 (1). Springer. doi: 10.1007/s00190-023-01809-y

2. Montenbruck O, Hugentobler U, Dach R, Steigenberger P, Hauschild A, (2011) Apparent clock variations of the Block IIF-1 (SVN62) GPS satellite. GPS Solutions, 16(3), pp. 303-313. Berlin: Springer. doi: 10.1007/s10291-011-0232-x