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CyCLOPS

Sensitivity of daily GNSS displacement estimates to processing-model configurations in the CyCLOPS regional network of Cyprus

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Aim of the study

How sensitive are daily regional GNSS coordinate estimates to the processing configuration?

Goal:

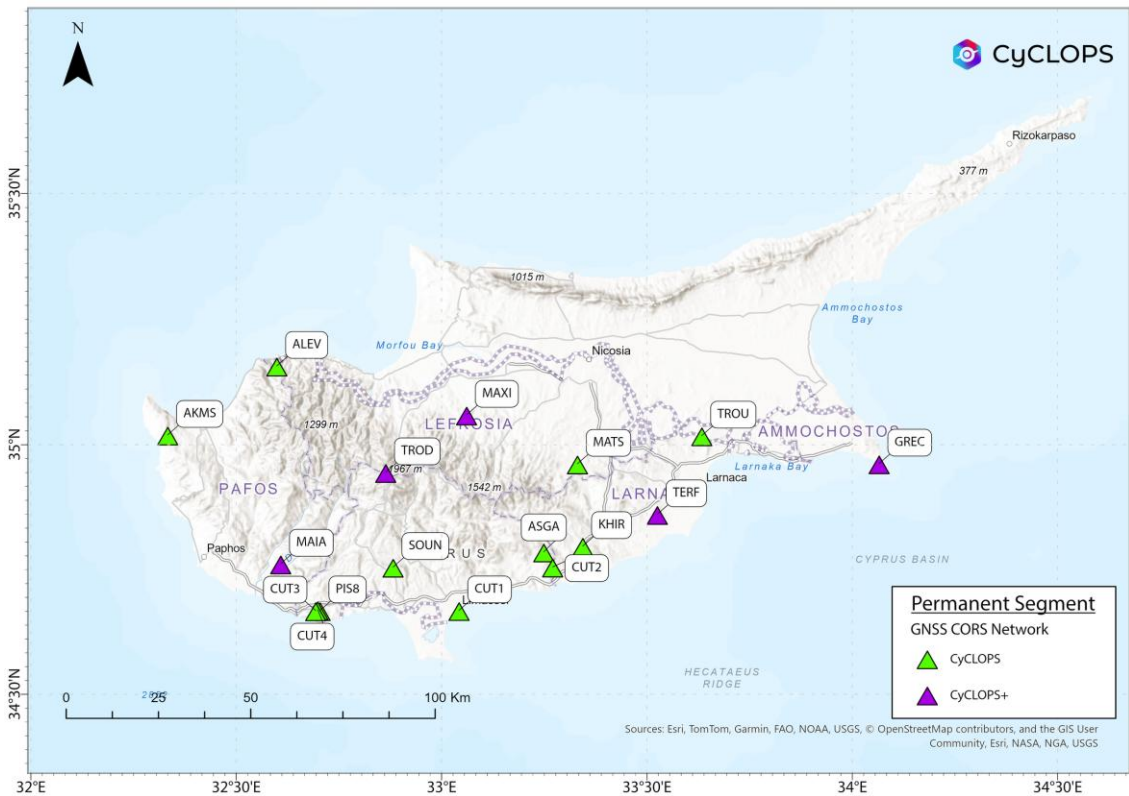
To quantify how selected GNSS processing configurations affect daily coordinate estimates and to identify the configuration that provides the most stable and physically interpretable displacement time series.

- **Processing configurations:** alternative tropospheric-delay modelling and the application of non-tidal atmospheric, oceanic and hydrological loading corrections.
- **Controlled comparison:** apart from the investigated configuration, the processing strategy, network geometry, reference stations and datum realization are kept fixed.
- **Network and software:** daily double-difference processing of the CyCLOPS network together with selected IGS/EPN stations, using Bernese GNSS Software v5.4.
- **Assessment:** effects on daily coordinate variability, linear and seasonal motion parameters, solution differences, residual spectral characteristics and network-common behaviour.

GNSS network used in the processing

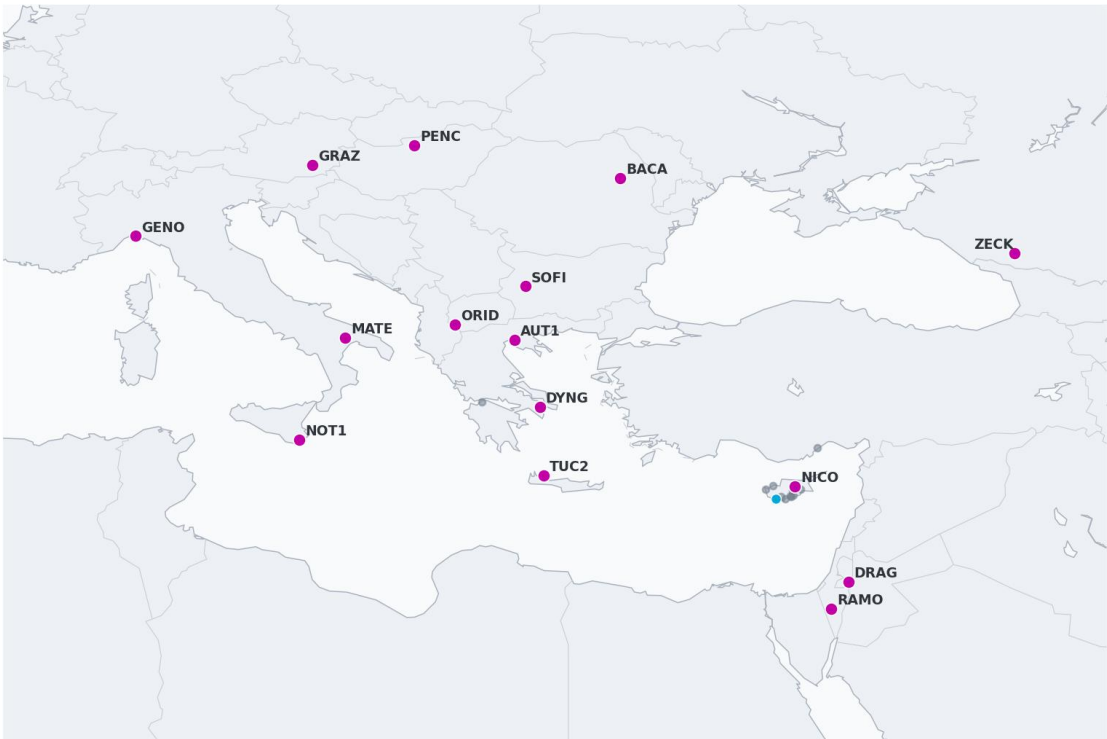
Daily regional solutions combine CyCLOPS stations with 15 selected IGS/EPN reference stations

CyCLOPS network in Cyprus



Purple CyCLOPS+ stations: less than one year of data; shown for network completeness but not used.

15 selected IGS/EPN reference stations



The same 15 IGS/EPN stations are used for the minimum-constraint (No-Net-Translation, NNT) datum realization in all solutions.

Processing interval: 30 July 2021–30 June 2026

Pissouri: significant ground deformation, 2021–2026

The Pissouri GNSS cluster monitors an actively deforming area within the CyCLOPS network

Pissouri GNSS cluster



Observed surface and structural damage



The PIS stations monitor spatially variable ground motion across the affected area.

The observed damage is consistent with substantial real ground motion.

Processing changes should reduce artificial daily variability—not suppress genuine ground motion.

Pissouri: significant ground deformation, 2021–2026

The Pissouri GNSS cluster monitors an actively deforming area within the CyCLOPS network

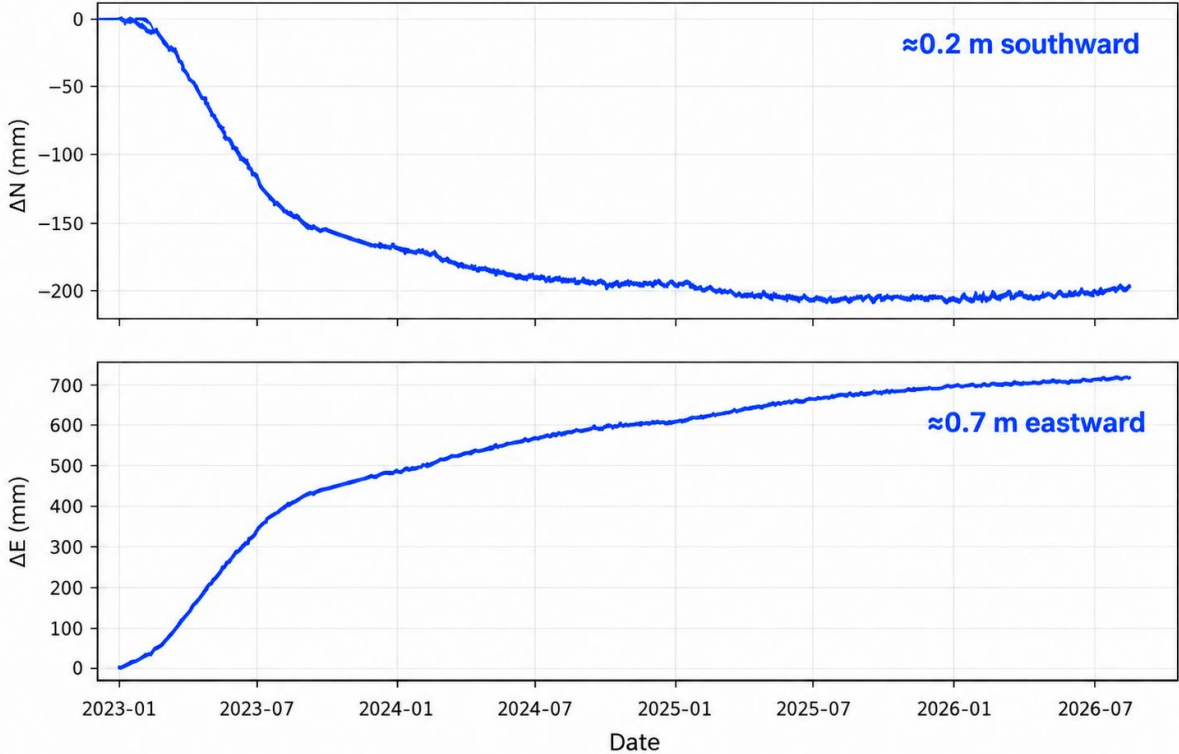
Pissouri GNSS cluster



The PIS stations monitor spatially variable ground motion across the affected area.

PIS2 cumulative displacement

Cumulative horizontal displacement over the study period



Processing changes should reduce artificial daily variability—not suppress genuine ground motion.

Processing configurations

The tropospheric modelling is first changed; non-tidal loading is then applied at two processing levels

Solution	Tropospheric modelling	Non-tidal loading	Application level
REP	Global Pressure and Temperature 3 (GPT3)	Not applied	—
VMF3	Vienna Mapping Functions 3 (VMF3)	Not applied	—
NTL	Vienna Mapping Functions 3 (VMF3)	Applied	Normal-equation level
NOL	Vienna Mapping Functions 3 (VMF3)	Applied	Observation level

NTL source: **GFZ** atmospheric, oceanic and hydrological loading products

Fixed in all configurations: **CODE** repro3 satellite products, daily double-difference strategy, station network, the same 15 reference stations, minimum-constraint NNT datum realization in the **IGS20 reference frame**, and all remaining processing settings.

Evaluation of the coordinate time series

The effect of each processing configuration is examined at daily, short-term and long-term temporal scales

Short-term deformation monitoring

1. Daily coordinate repeatability

$$\Delta x_c(d) = x_c(d) - x_c(d-1), \quad c = N, E, U$$

RMS of coordinate differences between consecutive daily epochs.

2. Short-term motion

$$\hat{v}_{c,14}(t)$$

Linear velocity estimated within a 14-day moving window.

Long-term parameters and solution diagnostics

3. Long-term motion parameters

$$x_c(t) = x_{0,c} + v_c(t-t_0) + \text{annual} + \text{semiannual} + \text{steps} + r_c(t)$$

Comparison of linear velocities and annual/semiannual amplitudes and phases.

4. Post-fit residual stability

$$r_c(t) = x_c(t) - \hat{x}_c(t)$$

Residual RMS, generalized Lomb–Scargle spectra and spectral band power.

5. Direct solution differences

$$\delta x_{A-B,c}(t) = x_{A,c}(t) - x_{B,c}(t)$$

Direct processing effects, network translations and common-mode behaviour.

Daily repeatability changes are small and component-dependent

Median station-level percentage improvement in RMS of consecutive daily coordinate differences

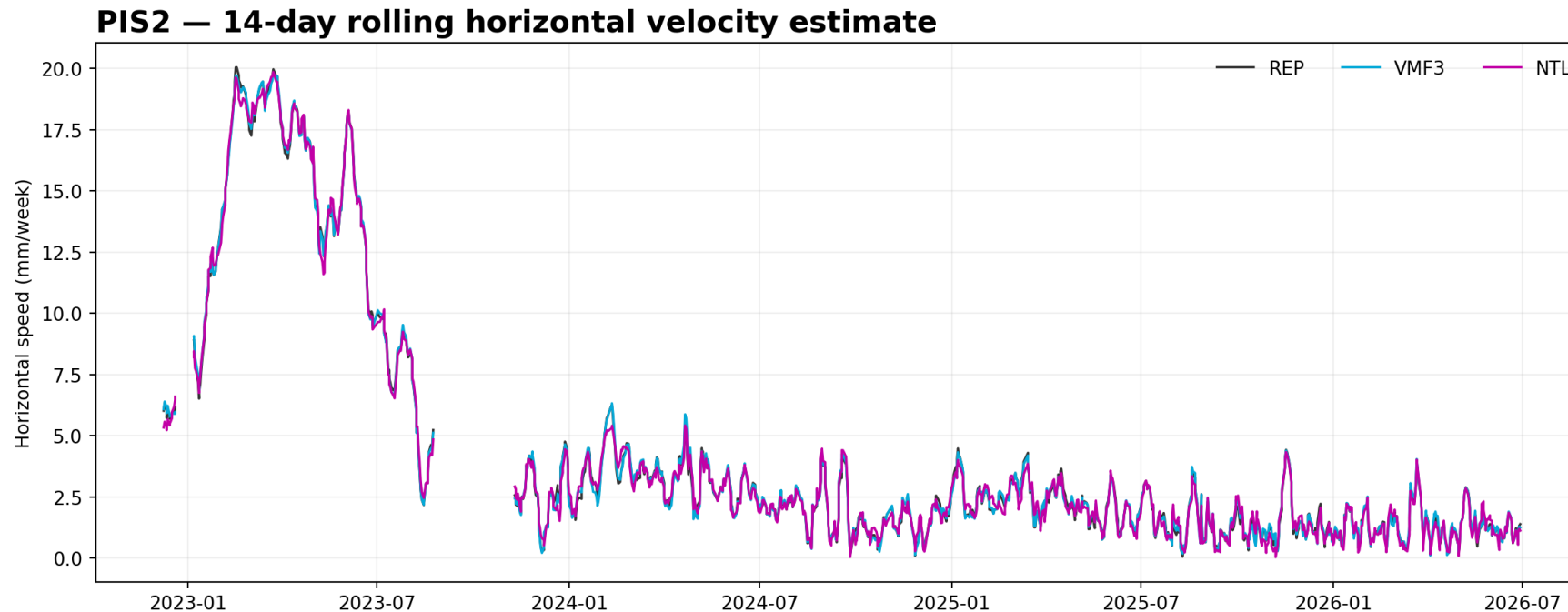
Station group	Comp.	VMF3 vs REP	NTL vs VMF3	NOL vs NTL
Reference stations (15)	N	+0.27%	+0.27%	+0.59%
	E	+0.29%	+2.47%	-0.56%
	U	+2.75%	+1.12%	+0.07%
CyCLOPS stations (14)	N	-0.29%	-0.05%	-0.21%
	E	-0.10%	+1.79%	-0.34%
	U	+1.72%	+0.19%	+0.17%
Pissouri stations (7)	N	-0.60%	+0.65%	-0.69%
	E	+0.37%	+0.06%	-0.32%
	U	+3.04%	-0.49%	+0.32%

Improvement (%) = 100 × [RMS(modelB) – RMS(modelA)] / RMS(modelB); positive values indicate lower RMS.

VMF3 mainly improves Up; NTL mainly improves East; North changes are small.

Short-term velocity evolution is preserved

PIS2 14-day horizontal velocity is nearly identical across REP, VMF3 and NTL



- **Main velocity peak:** nearly identical across REP, VMF3 and NTL.
- **Acceleration timing:** preserved across the three solutions.
- **Quiet periods:** small differences remain, but the main evolution is unchanged.

Direct coordinate differences between processing configurations

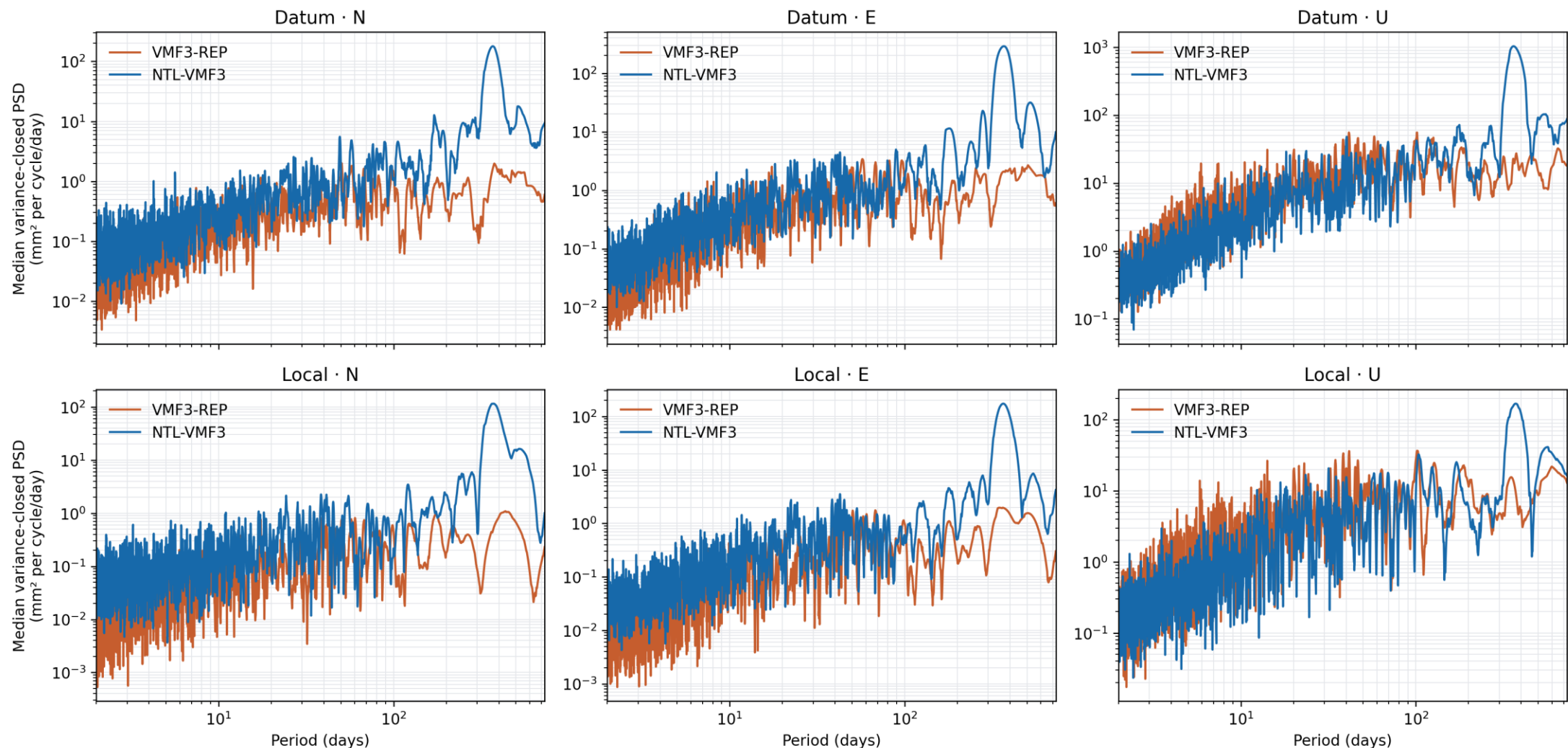
Median station RMS of same-day coordinate differences between successive processing configurations (mm)

Station group	Comp.	VMF3-REP	NTL-VMF3	NOL-NTL
Reference stations (15)	N	0.269	0.628	0.255
	E	0.314	0.667	0.226
	U	1.524	1.529	0.673
CyCLOPS stations (14)	N	0.173	0.462	0.136
	E	0.194	0.470	0.142
	U	1.043	0.886	0.422
Pissouri stations (7)	N	0.163	0.468	0.128
	E	0.180	0.423	0.094
	U	0.854	0.834	0.227

VMF3-REP differences are predominantly vertical; NTL-VMF3 adds larger horizontal differences with a comparable Up effect.

The dominant coherent signal in the solution differences is near one year

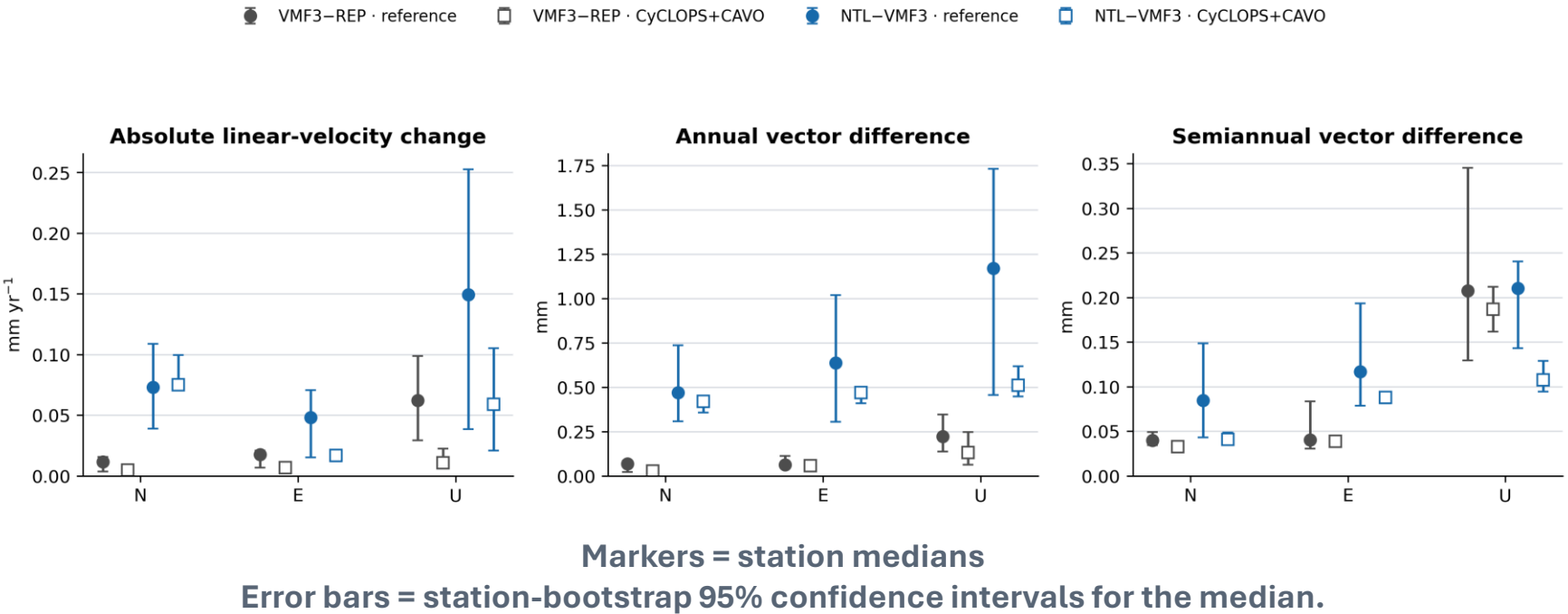
Generalized Lomb–Scargle spectra of VMF3–REP and NTL–VMF3 differences across all analysed periods



Pissouri stations excluded because they contain non-stationary deformation!

NTL changes the annual parameters more than the linear trend

Differences between processing solutions fitted on exact pairwise-common epochs



KEY RESULTS

- The annual term shows the strongest NTL sensitivity.
- Largest annual-vector difference: ≈ 1.17 mm in reference Up.
- Linear-velocity differences remain ≤ 0.15 mm yr⁻¹.

NTL reduces horizontal annual amplitudes; the Up response is phase- and station-dependent

IGS20 time-series fits using VMF3 and NTL solutions

Annual-amplitude change

Median [95% station-bootstrap confidence interval], in mm

Group	North	East	Up
Reference	-0.44 [-0.64,-0.13]	-0.46 [-0.98,-0.13]	-0.10 [-1.35,+0.17]
CyCLOPS	-0.15 [-0.40,+0.00]	-0.35 [-0.40,-0.11]	+0.12 [-0.21,+0.32]

- NTL reduces North/East amplitude by 0.15–0.46 mm; the reduction is clear except for borderline CyCLOPS North.
- Up annual behaviour changes substantially, but not through a consistent network-wide amplitude reduction.

Absolute annual phase change, $|\Delta\phi|$

Median [95% station-bootstrap confidence interval], in degrees

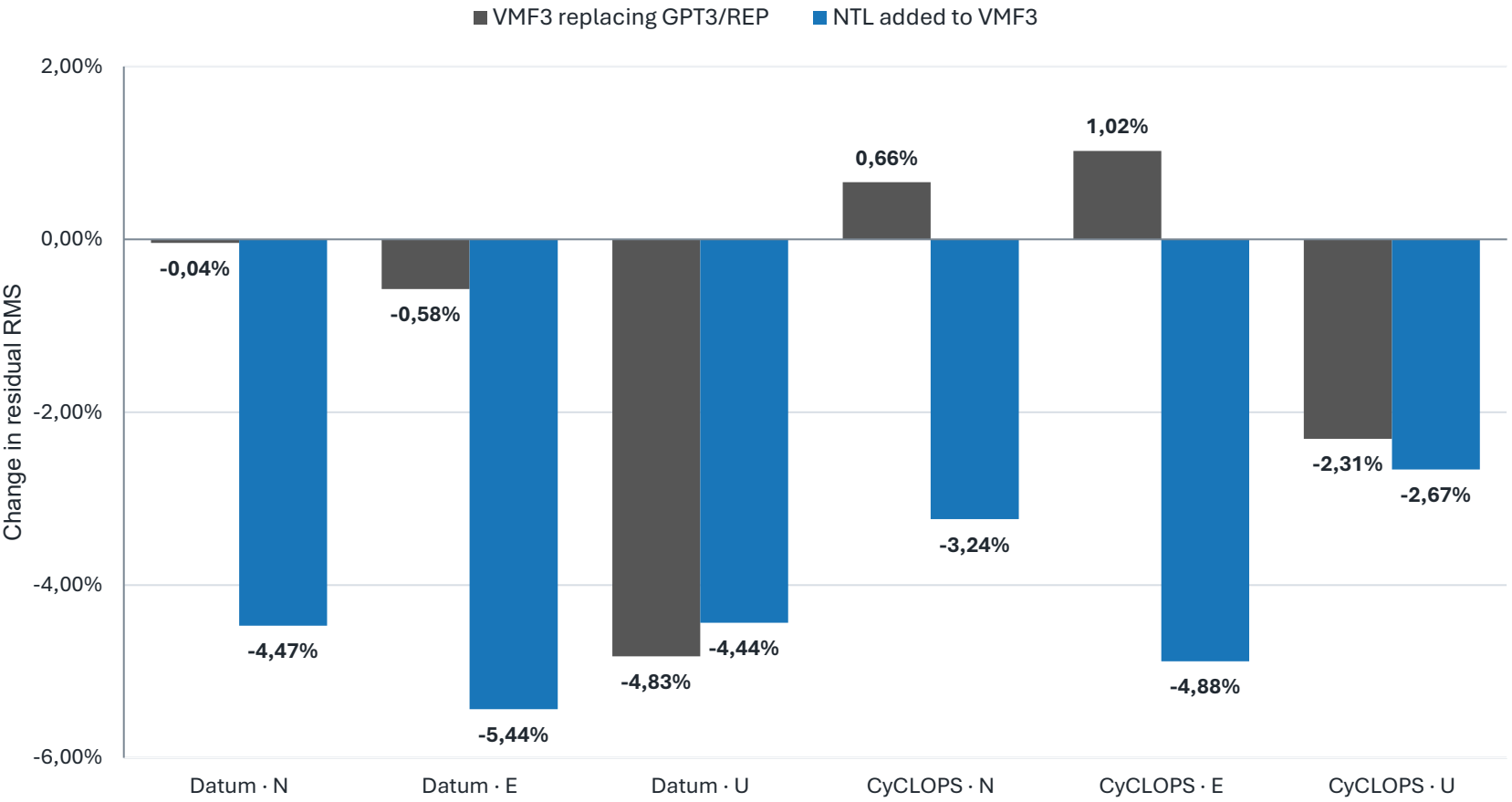
Group	North	East	Up
Reference	17.4° [5.0°, 48.9°]	11.6° [6.2°, 37.8°]	37.1° [10.7°, 63.5°]
CyCLOPS	15.8° [11.0°, 32.3°]	22.4° [9.7°, 40.0°]	15.3° [9.3°, 28.2°]

- Absolute annual phase changes span 11.6°–37.1°; the largest median occurs in reference Up.
- Phase values are absolute $|\Delta\phi|$, not signed shifts.

- **NTL clearly reduces horizontal annual amplitude**
- **The strong Up annual difference is mainly explained by phase changes and station-dependent amplitude changes not by a uniform amplitude reduction.**

NTL leaves the lowest post-fit residual scatter

Residual RMS after removing trend, annual, semiannual and discontinuities



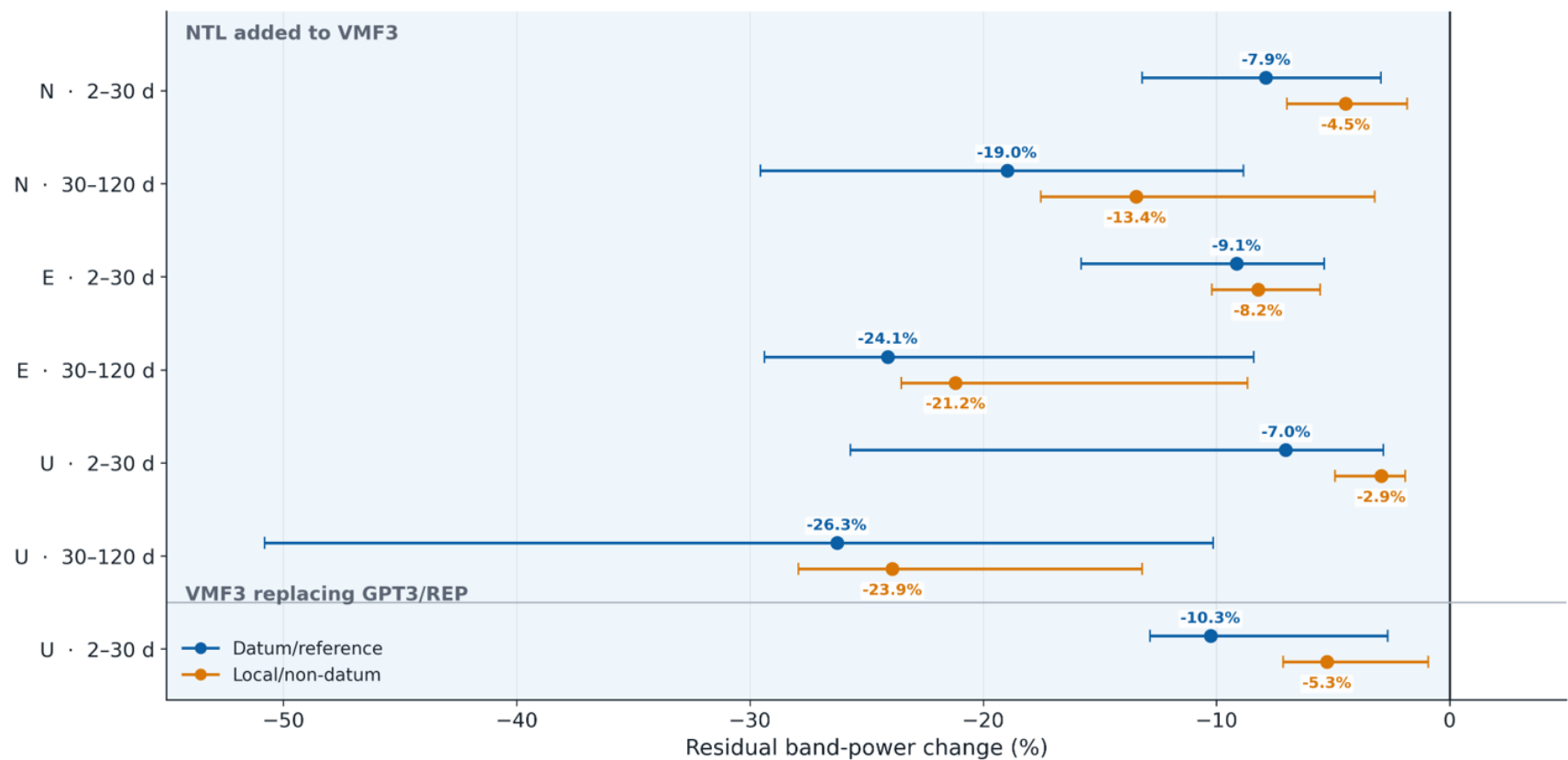
Columns show the median percentage RMS change across stations.
Negative values show lower post-fit residual RMS.

KEY RESULTS

- NTL reduces residual RMS in every component by 2.7–5.4%.
- Largest NTL improvement occurs in East: -5.44% reference; -4.88% local.
- VMF3 improvement is concentrated in Up: -4.83% reference; -2.31% local.

NTL reduces residual power most at 30–120 days

Event-aware post-fit residuals · paired 30-day block-bootstrap 95% confidence intervals



Points = station-median power changes.
Bars = paired 30-day block-bootstrap 95% confidence intervals.

KEY RESULTS

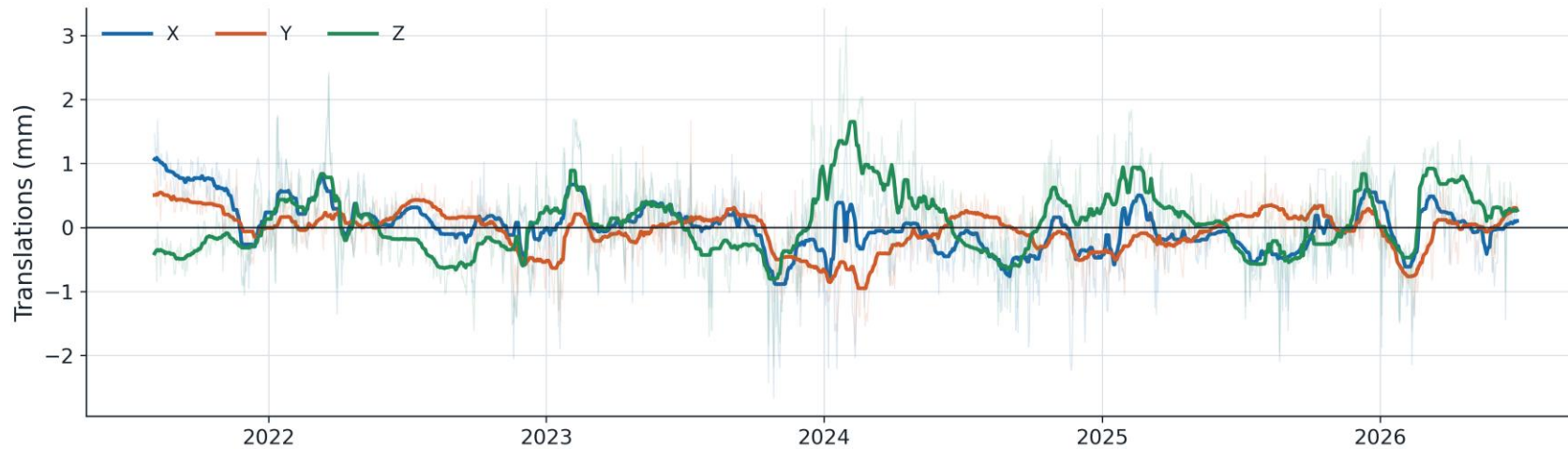
- **NTL:** Reduction is strongest at 30–120 days: –13.4% to –26.3%.
- **VMF3** has a short-period effect mainly in Up: –10.3% reference; –5.3% local.

Translation removal separates network-common and local NTL effects

Daily XYZ translations estimated from NTL-VMF3 differences at the 15 reference stations

Empirical common-mode test:

1. Daily translations (T_X, T_Y, T_Z) from NTL-VMF3 differences at the 15 reference stations.



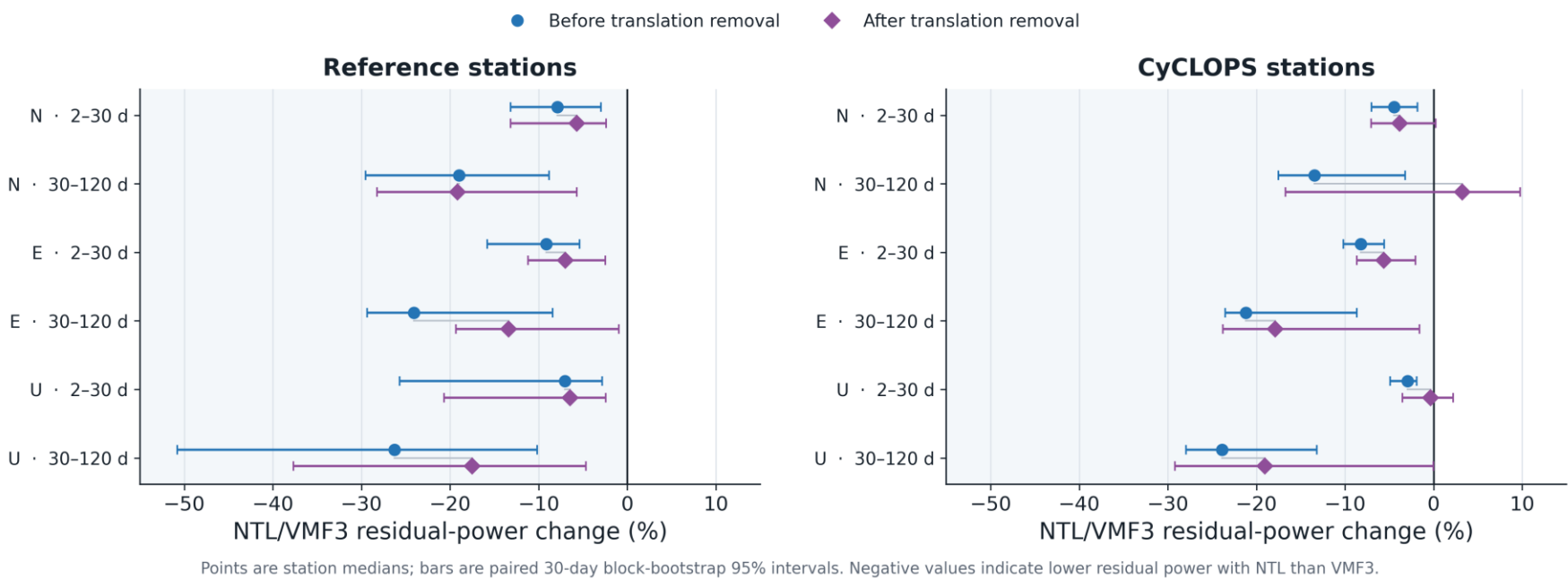
WHAT THE TEST SHOWS

- Faint traces show daily translations; thick curves are centred 30-day rolling medians.
- Annual amplitudes: X 0.14 mm, Y 0.28 mm and Z 0.49 mm.

2. Subtract the common translation from the NTL coordinates only; VMF3 remains unchanged,
3. Refit the corrected NTL,
4. Recompute post-fit residual spectra and band-power changes.

Most NTL residual-power reductions persist after translation removal

Bars are paired 30-day block-bootstrap 95% intervals; crossing zero means the change is unresolved



AFTER TRANSLATION REMOVAL

- Reference stations: all six N/E/U reductions remain significant.
- CyCLOPS East remains significant in both bands; Up at 30–120 days remains significant.
- CyCLOPS North in both bands and Up at 2–30 days become uncertain.

TAKEAWAY

NTL combines a network-common contribution with station-dependent improvements; it is not solely a datum-translation artefact.

Conclusions

Processing-model choice affects millimetre-level stability while preserving real deformation

- **Controlled comparison:** same network, 15 reference stations and IGS20 datum in all solutions.
- **VMF3** gives a modest improvement, mainly in the **Up component**.
- **NTL** gives the largest overall improvement in residual stability.
- NTL reduces post-fit residual RMS by about **2.7–5.4%** and residual power most strongly at **30–120 days**.
- NTL changes the **annual signal more than the linear velocity**; part of this response is network-common, but station-dependent improvements remain.
- Applying the loading corrections at the observation level or at the normal-equation level gives very similar coordinate behaviour.
- The main **Pissouri deformation is preserved** across REP, VMF3 and NTL.



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CONSORTIUM



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For further information

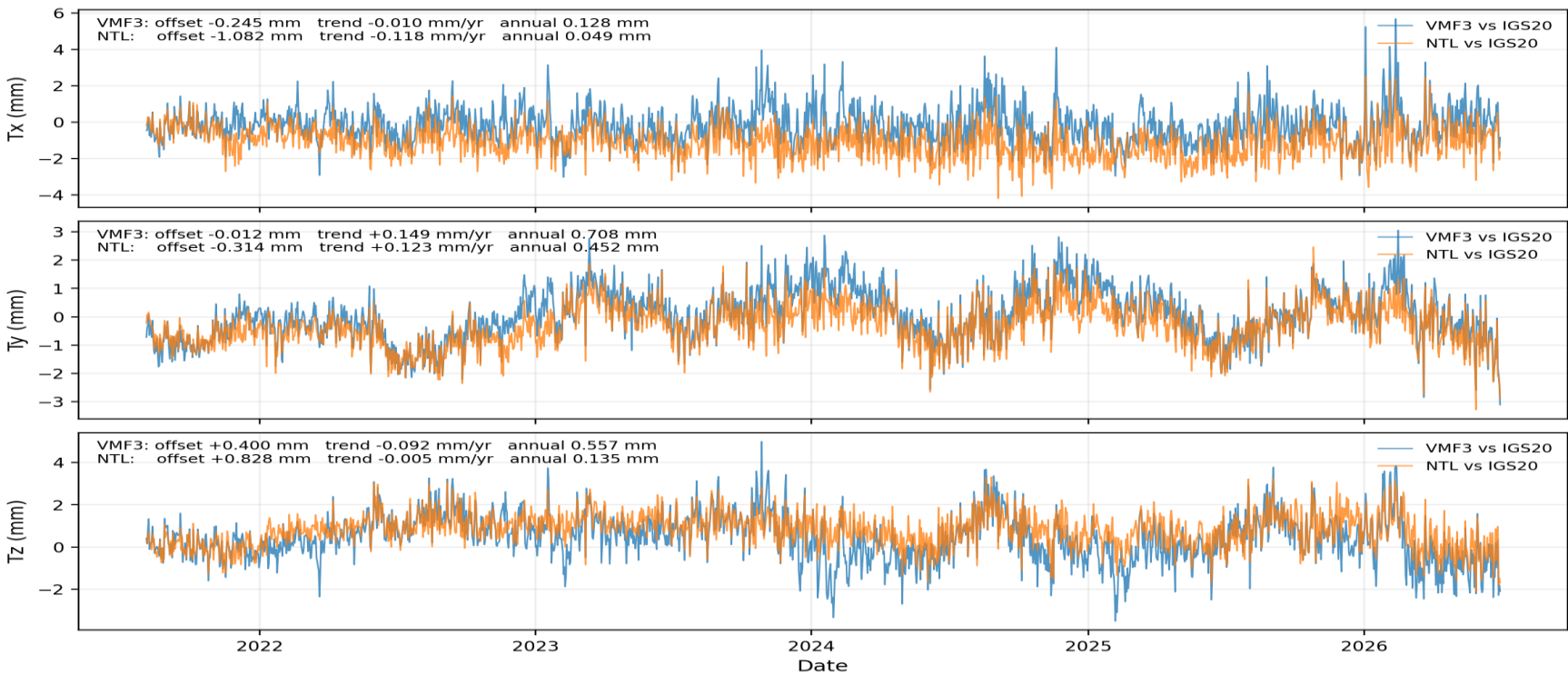
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THANK YOU

Appendix • NTL stabilizes the IGS20 realization but increases the mean translation offset

Daily 3-parameter Helmert translations relative to propagated IGS20



NTL gives a more stable daily IGS20 realization, but with a larger mean offset from IGS20.

KEY RESULTS

Larger mean offsets with NTL:

Tx -1.08 vs -0.25 mm
Ty -0.31 vs -0.01 mm
Tz +0.83 vs +0.40 mm

Annual translation amplitudes are smaller with NTL in Tx, Ty and Tz.

The strongest reduction is in Tz:
0.557 mm to 0.135 mm, 76%.

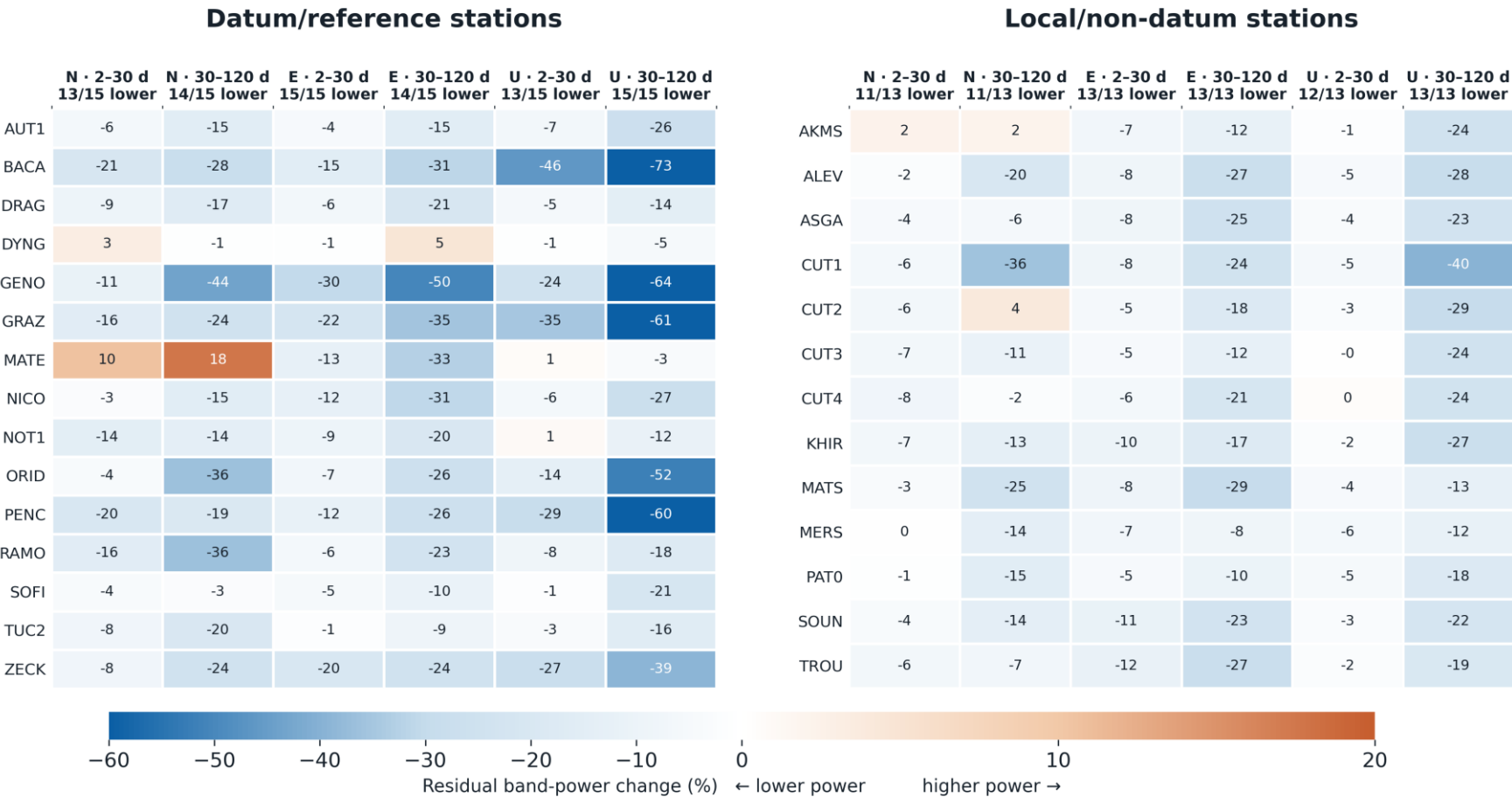
Ty decreases from 0.708 to 0.452 mm;
Tx from 0.128 to 0.049 mm.

Appendix • The NTL improvement is network-wide, not station-driven

Most stationary stations show lower 2–120-day residual power

Station-by-station NTL consistency

NTL versus VMF3 residual band-power change (%)

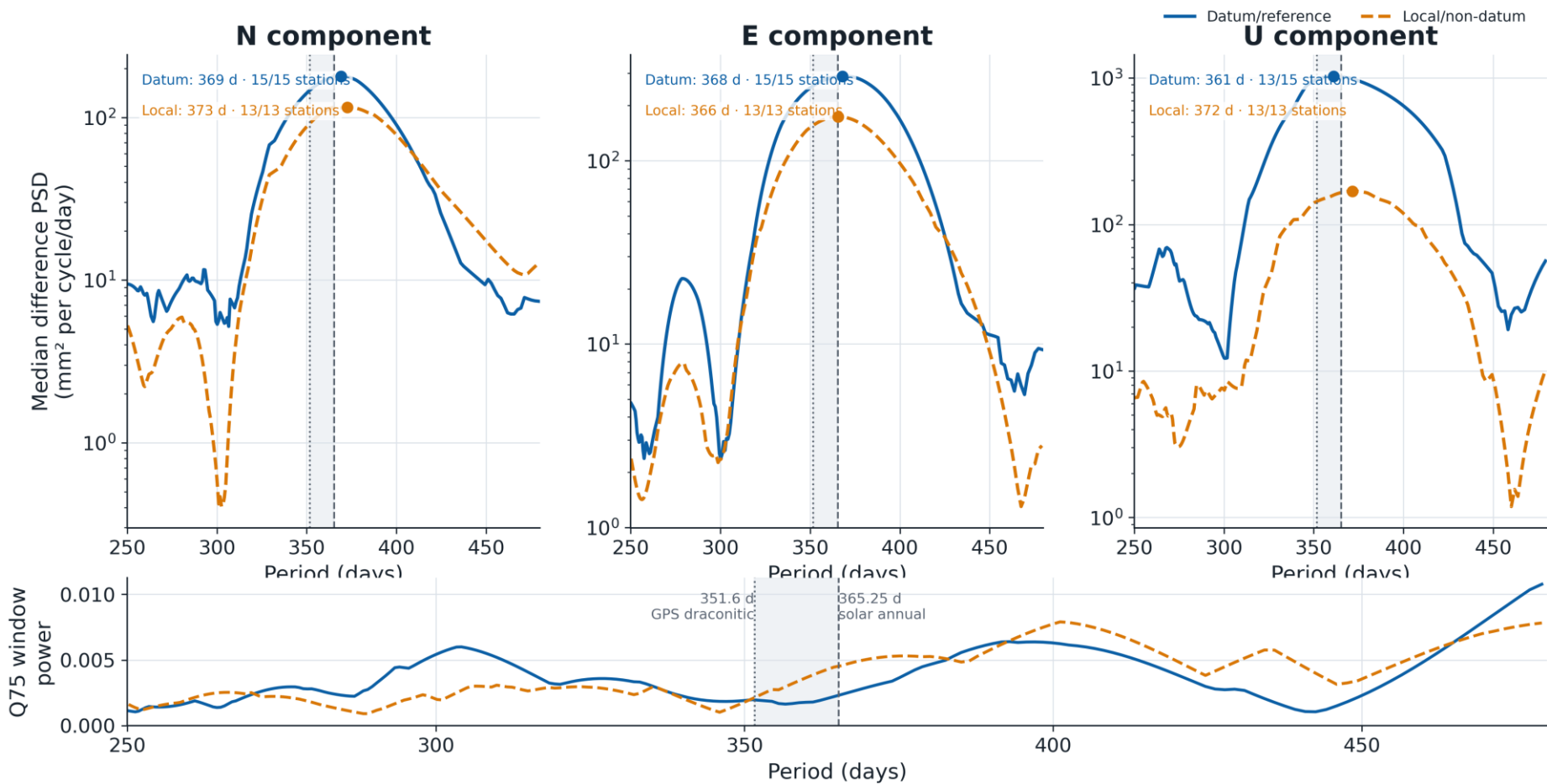


Appendix • NTL changes the annual neighbourhood

Coherent 361–373-day signal • physical attribution remains unresolved

NTL–VMF3 spectrum in the annual/GPS-draconitic neighbourhood

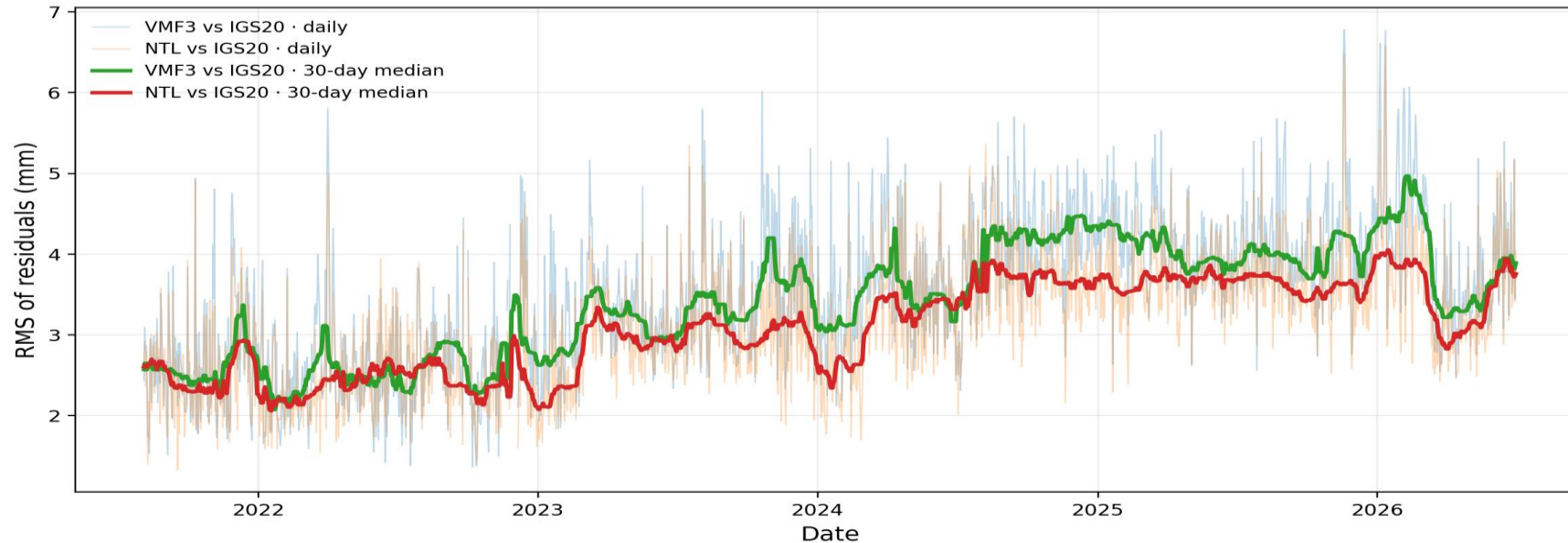
Detrended, event-aware direct differences; annual and semiannual terms retained



Appendix • NTL improves the stability of the daily IGS20 realization

Daily 3-parameter Helmert alignment to propagated IGS20 using the reference stations

Daily RMS of residuals after the 3-parameter Helmert transformation (translations).



NTL reduces the median daily RMS from 3.50 to 3.16 mm, a 9.7% reduction in post-Helmert residual scatter.