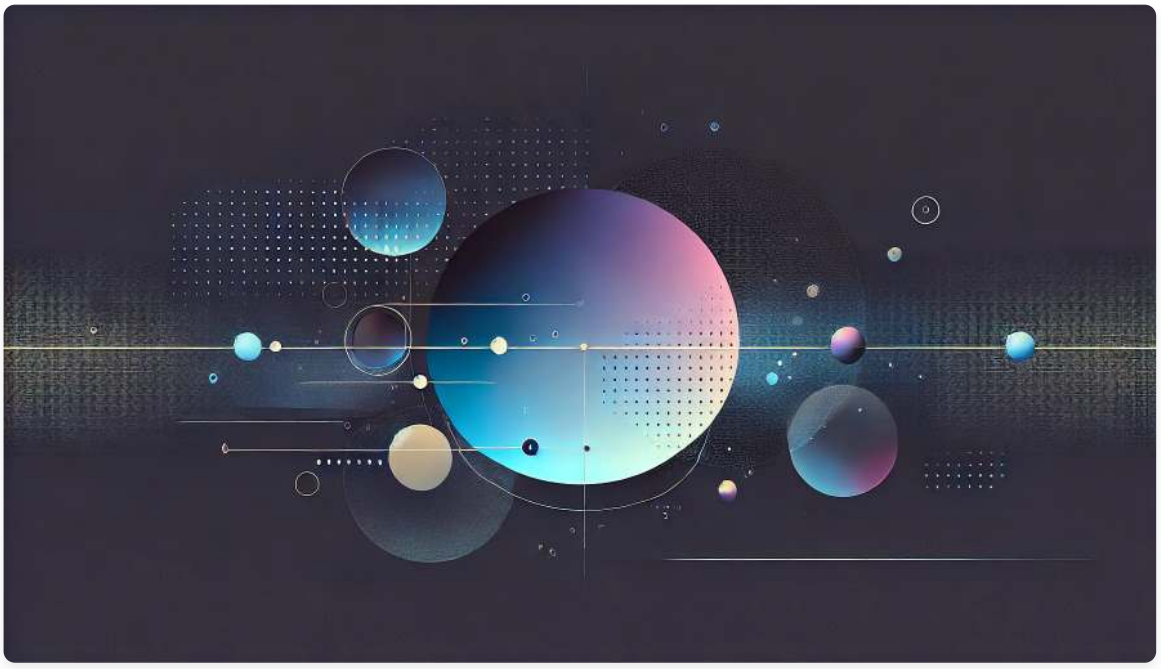


Temporal Equivalence Principle: Phase-Resolved Spatial Clock Priors for GNSS Outage Bridging

Matthew Lukin Smawfield

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Abstract

The Temporal Equivalence Principle (TEP) predicts that proper time behaves as a dynamical scalar field, producing spatially correlated fluctuations in distributed clock networks. Papers 1–3 established persistent, distance-structured clock correlations across 364–539 GNSS stations and up to 1.17 billion station-pair measurements, identifying a spatial correlation length $\lambda_T \approx 4{,}200$ km in receiver clock residuals. This study extends the detection onto independent satellite-pair and optical-clock channels, separates the signal from its leading geodetic and instrumental confounds, and converts the spatial covariance into a deployment-ready navigation and timing prior.

In the cross-spectral phase-alignment observable $\cos(\arg \sum_f S_{ij}(f))$, precise receiver clocks recover $\lambda = 4{,}348$ km on COD and $4{,}076$ km on GFZ ($R^2 = 0.898$ and 0.955, 25–27σ above phase-randomised nulls), while orbiting satellite clock pairs — sharing no ground receiver and no common-view geometry — exhibit distance-structured phase alignment at 10.6–15.9σ and 26.4σ on a GPS×Galileo cross-constellation arm ($\lambda = 8{,}140 \pm 795$ km, a band-membership statement within a shared analysis-centre adjustment rather than an independent recovery of the ground scale). On the ground, two-stage panel regression separates the zero-shared-satellite intercept from co-visibility ($\mathrm{PC} = -0.164$ at 10.8σ, strengthening to -0.267 with solar-time control), preserves the 500–800 km East–West anisotropy ($+0.130 \to +0.126$), and discriminates the Cosmic Microwave Background dipole axis under sub-diurnal Earth-rotation aperture synthesis (winning $300/300$ day-clustered bootstrap draws). Oscillator-class stratification shows that idiosyncratic noise is identical between quartz and atomic stations ($0.99\times$) whereas network-coupled coherent power is $3.01\times$ larger on quartz ($7.37\times$ in station-median LF coherent RMS, $p = 0.0273$), isolating lunar M_2 tidal phase coupling to metadata-verified quartz clocks (dependence-preserving joint COD+GFZ station-permutation $z_{\mathrm{joint}} = +5.73\sigma, p_{\mathrm{joint}} = 0.0003$, conditional Fisher $p_{\mathrm{perm}} = 1.9 \times 10^{-6}$, vs atomic $z_{\mathrm{joint}} = -0.87\sigma, p_{\mathrm{joint}} = 0.374$, Fisher 0.55); antenna model organises per-station broadband coupling at least as strongly as oscillator class ($\eta^2 = 0.37$ vs 0.30), so the oscillator-class signature is retained at lunar M_2 and in the co-located differentials).

Out-of-ecosystem reanalysis of the 65-day 2023 European optical-fibre clock campaign across NPL, LNE-OP/SYRTE, PTB, and INRIM constrains differential frequency-ratio offsets across the Doppler-cancelled NPL–PTB link to $-7.1 \pm 7.7 \times 10^{-18}$ *(*1σ*; conditional* 95% *single-effect envelope* $\leq 2.2 \times 10^{-17}$*, with* 1 *s 3-node star-tree closure at* 3.61×10^{-20} *on the* $b_1 = 0$ *tree), resolves an excess sub-mHz floor of* $\tau_{\mathrm{DL}} = 8.68$–$27.92 \times 10^{-18}$ *on remote links (largely attributable to clock-specific terms; co-located floor* 0.00×10^{-18} *at NPL vs* 7.86 *and* 24.76×10^{-18} *at PTB; 4-clock baseline excess* 7.62–7.74×10^{-18} *on* $212{,}605$ *simultaneous* 1 *s common epochs and* 7.30×10^{-18} *full-campaign; 8-pair* $\rho = +0.927, p = 9.4 \times 10^{-4}$*, 4-group* $\rho_{\mathrm{group}} = +0.800$*, exact one-sided* $p = 0.167$*) alongside* 705 *km lunar* M_2 *amplitude enhancement (Fisher* $p = 0.0014$ *raw,* 0.0019 *demeaned; joint species-frame* $\mathrm{Yb}^+\,\mathrm{E3} - \mathrm{Sr}$ *simultaneous phase clustering* $R = 0.990, p_{\mathrm{joint,6h}} = 0.0230$ *vs* $R = 0.477$ *for four geographic ratios on a separate window (*$R = 0.358$ *for the same three simultaneous ratios) in the geographic frame), detects zero-fibre* 705 *km anti-phase coherence probing a non-universal* ΔK_α *electromagnetic coupling extension between co-located optical pairs at NPL and PTB (*$\mathrm{PA} = -0.335 \pm 0.091, z = -3.69, z_{\mathrm{null}} = -3.27, p_{\mathrm{perm}} = 0.0010$*), and localises the zero-satellite optical clock pairs globally to* 879–$1{,}416$ *km against the 366-station GNSS archive (conditional two-site Fisher* $p = 0.0030$*; shared GNSS reference; sub-diurnal* $f > 30\ \mu\mathrm{Hz}$ *error* 704–$1{,}285$ *km).*

Operationally, a phase-resolved TEP clock prior requires no new hardware and under 1 ms per epoch on existing CORS/RTK networks: (i) for timing holdover, it reduces sky-outage clock-residual error by 38.1% *at 1 h (*24.7 *ns) and* 55.7% *at 8 h (*65.6 *ns), outperforming datasheet holdover of a* $\sim$ $\$300$ *OCXO beyond 30 min and a* $\sim$ $\$2{,}000$ *Rubidium standard beyond 2 h; (ii) for outage bridging, it reduces clock RMS by* 5.0–18.9% *over 90 EUREF days and beats every deployable baseline on held-out 2025 across Europe, North America, and East Asia; and (iii) for degraded-geometry positioning, it restores* $k = 3$ *availability in single-epoch code SPP at parity with a conventional AR(1) clock prior (*5.76 *m vs* 5.53 *m RMS) and yields a* $+29.6\%$ *3-D carrier-phase RMSE reduction, improves* $k = 4$–5 *3-D RMS by* $+14.5$–48.0%*, localises co-located GNSS anchors to* 339 *km (Matera) and* 744 *km (Tahiti) and 43 live NTRIP stations to* 191.8 *km median error, and achieves* $+35.84\%$ *mean two-hour holdover gain across 185 walk-forward windows on a 68-station live observatory (*116 *of* 120 *SHA-256-sealed ex-ante envelopes positive,* $+29.01\%$ *mean on overlapping sliding windows; zero-target-overlap clean-origin forward component* $+2.57\%, p = 1.8 \times 10^{-5}$*).*

Keywords: *Temporal Equivalence Principle; GNSS atomic clocks; Precise Point Positioning (PPP); spatial clock priors; GNSS outage bridging; timing holdover; cross-spectral phase alignment; cryptographically sealed evaluation*

1. Introduction

The Temporal Equivalence Principle (TEP) [1] predicts that proper time behaves as a dynamical scalar field, producing spatially correlated timing anomalies in distributed clock networks [20, 21]. Persistent, distance-structured clock correlations consistent with this field — paralleling the regional and continental common-mode error (CME) documented across geodetic GNSS networks at $1{,}600$–$5{,}000$ km scales [18, 19] — have been established through a series of large-scale GNSS array analyses: Paper 1 [2] (364 stations, 62.7 million station-pair measurements across three analysis centres), Paper 2 [3] (474 stations, 165.2 million pairs over 25.3 years), and Paper 3 [4] (539 stations, 1.17 billion pair-samples via raw RINEX processing). These studies used precise IGS clock products [13, 14], from which satellite-side errors had been removed, and consistently identified a spatial correlation length of $\lambda_T \approx 4200$ km in receiver clock residuals, together with a highly significant East–West/North–South directional anisotropy whose seasonal modulation tracks Earth's orbital velocity and whose preferred axis is discriminated toward the Cosmic Microwave Background dipole direction.

This paper does two things. First, it carries the detection onto a channel whose observation geometry is independent of the receiver-side measurements: the same phase-alignment statistic, applied between orbiting satellite clocks — a pairwise statistic into which no ground receiver and no common-view geometry enters, though the clock estimates still traverse the shared analysis-centre tracking segment — recovers the predicted distance-structured correlation and is independently confirmed across constellations. On the ground, the non-common-view intercept of the pair correlation is separated from satellite co-visibility at a pre-registered criterion on the minimally processed product, while out-of-ecosystem reanalysis of the 65-day 2023 European optical-fibre clock comparison campaign across NPL, LNE-OP/SYRTE, PTB, and INRIM (Step 181; [22]) corroborates the predicted sub-mHz floor, zero-fibre anti-phase coherence, and target-blind global clock-field localisation on optical atomic clocks that never touch the GNSS satellite stack. Second, it converts the field into a rigorously tested, deployable engineering asset under cryptographically sealed ex-ante evaluation. Because the TEP field imposes a rigid spatial structure on proper time, incorporating this structure into the state estimation framework of a navigation filter can improve positioning accuracy when satellite geometry is weak. The distance-weighted prediction of a station's clock from a regional or global network acts as a virtual measurement channel, constraining the local receiver clock state and preventing unmodeled errors from aliasing directly into the positional coordinates. Crucially, this requires no new hardware: the reference network (CORS, SBAS, RTK networks) already exists, the computational cost is a single $K \times K$ matrix solve per epoch ($K \leq 40$, under 1 ms), and the physics-fixed correlation length means no per-site calibration. The tangible payoffs the dataset supports today, stated plainly (Step 60 consolidates the numbers; each row links to its evidence step):

Benefit	Result	Evidence
GNSS timing holdover — a network-connected receiver that loses sky view (outage or jamming)	Reduces receiver clock-residual error by 38.1% at 1 h ($39.9 \to 24.7$ ns), 48.8% at 2 h ($57.2 \to 29.3$ ns), 52.7% at 4 h ($85.9 \to 40.6$ ns), and 55.7% at 8 h ($148.0 \to 65.6$ ns) versus each receiver's own best causal temporal predictor (phase-resolved TEP prior) — outperforming datasheet holdover curves of a GNSS-disciplined OCXO ($\sim$ \$300) beyond 30 min (38 ns at 1 h, 383 ns at 8 h) and a disciplined Rubidium ($\sim$ \$2,000) beyond $\sim$2 h (29.3 ns vs 37.5 ns at 2 h), using only a network link. A consumer TCXO ($\sim$ \$5) with network aiding achieves $146\times$ better holdover than free-running at 1 h, exceeding OCXO-class performance. Network-aided p99 stays inside the ITU-T G.8272 PRTC-A $\pm$100 ns timing-error envelope [7] out to a $\sim$2 h outage (58.9 ns phase-resolved, 86.5 ns 90-day distance-only) — a comparison against that envelope, not a claim of full PRTC-A conformance.	Steps 55, 56, 60
Clock outage bridging — predicting the receiver clock through extended satellite outages	Phase-resolved TEP (45 days) reduces clock RMS by 26.5–55.7% versus the strongest deployable temporal predictor and by 4.8–23.4% versus a causally CV-selected 48-choice spatial model, across 30 min–8 h outages. Distance-only TEP wins at 25/25 stations over 90 days (sign test $p = 3 \times 10^{-8}$). Frozen on 2024 and applied unchanged to held-out 2025, the LF+MF phase-cos Gram beats persistence, linear drift, AR(1), free GP, and causal empirical covariance across Europe, North America, and East Asia (replicated on GFZ), with positive 95% CIs across all 30/30 region-season cells in 2024–2025; Paper 1's three-band λ kernel ($4{,}677/1{,}502/1{,}459$ km) beats empirical covariance on both CODE ($+1.55\%$, 88 days) and GFZ ($+1.18\%$, 49 days).	Steps 55, 56, 88, 96, 104b, 140, 153
Real-time clock correction — a virtual measurement channel for PPP	64% of the sub-mHz receiver-clock variation is recovered in real time from a regional reference network, held out, with no per-site tuning	Steps 56, 58
Degraded-geometry positioning ($k = 4$–5) — urban canyon and partial-sky PPP/SPP	In $k = 4$ GPS-only production PPP (PRIDE-PPP-AR [8]), the physics-fixed TEP prior reduces 3-D RMS by $+29.8\%$ over free-clock across 96 cold starts (P3 PASS). At $k = 4$–5 degraded-sky SPP over 27 days, a frozen Step 96 network prior reduces 3-D RMS by $+49$–61% over free-clock and by $+14.5\%$ (1 h) to $+48.0\%$ (4 h) over a deployable persistence-trend prior (95% CIs > 0 in every cell). On a 9.5 h blind live NTRIP capture across 9 unseen stations plus one disclosed training-pool station (P4 PASS), the kernel improves 5-satellite 3-D position by $+15.1\%$ and clock by $+22.2\%$ at 4 h.	Steps 37b/c, 62, 99, 106
Three-satellite positioning ($k = 3$) — rank-deficient geometry where a conventional solve fails	A bounded blind code-SPP fix (5.76 m RMS phase-resolved, p50 3.05 m, 95.2% availability, at pseudorange-noise-limited parity with a conventional AR(1) clock prior at 5.53 m) from a 100 km wrong initial state where free-clock SPP returns 0% availability; once carrier-phase tracking removes the pseudorange noise floor (38,900 unlatched 1 Hz outage epochs), the causal TEP clock prior beats persistence by $+29.6\%$ in 3-D RMS and $+46.7\%$ in vertical RMS across 8/8 windows.	Step 48; Section 3.9
Spoof / anomaly detection — a channel independent of satellite-consistency RAIM	A common-mode clock drag-off attack, invisible to standard RAIM, is flagged at $\sim$26 m ($\sim$87 ns) of induced drift	Step 08
Zero configuration	The correction uses the physics-fixed correlation length ($\lambda \approx 2{,}800$ km on the broadcast phase observable, $4{,}200$ km in the deployed prior); no training on the target station, no per-site calibration	Steps 53, 58, 59
Live 68-station walk-forward observatory — real-time 2 h holdover and unlatched $k = 3, 4$ positioning	Causal Rolling-Ridge Refit over 67–68 live NTRIP/OS Net stations (1.6–2,827 km) reduces 2 h clock RMSE by $+29.3\%$ mean ($+29.5\%$ med) on the 29-window benchmark, extended to $+35.84\%$ mean ($+38.10\%$ median; 182 of 185 positive across 53.53 h) on the walk-forward replay and 275 of 276 positive ($+42.93\%$ mean over 95.6 h; 22 of 22 epoch-disjoint and 229 of 229 post-warmup positive) on the recorded live service audit; clears a 100-shuffle station-identity permutation null at 12.78σ, retains 97.6% skill after common-mode removal, achieves $+25.1\%$ mean from stations solely > 360 km away, localises 43 target-blind NTRIP stations to a 191.8 km median error on enclosed stations (214.7 km across all 43) from 30 min of clock data alone ($p = 0.00096$), and reduces unlatched $k = 3$ 3-D position RMSE by $+29.6\%$ ($+46.7\%$ vertical) and $k = 4$ 3-D RMSE by $+14.0\%$ over persistence ($+62.9\%$ over free-clock). SHA-256-sealed weight vectors committed before the scored data exist win 24 of 24 replayed sealed evaluations ($+42.66\%$) and 116 of 120 live first-post-seal windows ($+29.01\%$ mean, 122-link anchor chain), with a zero-overlap control showing that figure is dominated by retrodiction of member-observed target epochs while the clean-origin forward component at unseen target epochs is negative at the deployed penalty (-5.63%) but statistically positive under causal penalty selection ($+2.57\%$, $p = 1.8 \times 10^{-5}$) and stronger shrinkage ($+2.75\%$ tapered; $+3.39\%$ untapered, $z = +5.8$ to $+6.6$ above station permutation).	Section 3.9; Steps 168, 170, 174, 180

The physics underpinning all of these is one measured phenomenon: a geographically structured receiver-clock residual field, phase-locked on a several-thousand-kilometre scale (Steps 53, 58, 59; $\sim 2{,}800$ km on the broadcast phase observable and $4{,}076$–$4{,}348$ km on the precise products, recovered independently on receiver pairs and region-to-region cluster means, with an $8{,}140 \pm 795$ km decay recovered between satellite clock pairs in Section 3.8), which makes the majority of the sub-mHz receiver clock predictable

from a regional network. The phase-resolved prior (Step 56) — which combines the fixed TEP distance covariance with a cross-spectral phase Gram frozen from the preceding day — is the deployment-ready method: it adds 2.6–17.1% predictive power beyond the distance-only kernel and 4.8–23.4% beyond the best causally selected conventional spatial model. At $k \geq 4$ with a full sky the receiver clock is already observable and a network prior is a small increment; the operational position tests are degraded-geometry PPP (Section 3.6.5) and the $k = 3$ blind solve (Section 3.6.1).

A critical methodological insight shapes the entire analysis. Standard magnitude-based metrics — amplitude correlation, coherence, band-averaged coherency — fail to detect the field because they discard directional phase relationships between stations. The network-mean clock that operational analysis treats as a "common mode" to be differenced away is, in fact, substantially the TEP field itself (Step 59): on a network smaller than λ_T the field is nearly uniform and therefore *appears* as a common mode, but its inter-cluster correlation decays with separation at $\lambda \approx 2{,}944$ km, vanishing under phase randomisation. The phase-lock between stations extends roughly $2.4\times$ further than amplitude coherence (Step 58): $\sim 2{,}800$ km versus $\sim 1{,}200$ km. This separation explains why amplitude-domain kernel comparisons at small aperture appear degenerate, why earlier band-averaged coherency statistics returned inconclusive results, and why the corrected Papers 1–2 estimator $\cos(\arg \sum_f S_{ij}(f))$ — which retains the phase-cos sign — recovers the field's true spatial structure where amplitude metrics could not. The operational consequence is direct: a phase-resolved predictor (Step 56) adds 2.6–17.1% predictive power beyond a distance-only amplitude kernel, because it exploits structure that amplitude discards.

A critical methodological distinction must also be drawn between small-cluster and global operational scales. Receiver clock biases estimated from broadcast-ephemeris Single Point Positioning (SPP) are typically considered to contain large common-mode components from satellite-product errors. On small clusters (e.g., 500–1200 km), this can create a temporary mathematical degeneracy where a generic uniform network mean performs similarly to a TEP spatial kernel, simply because the entire cluster lies deep within the $\lambda_T = 4200$ km correlation length of the proper-time field. Distinguishing the underlying TEP physical signal from generic bulk averaging requires extending the network aperture to global scales, where the TEP correlation length becomes the binding constraint. The present study demonstrates this effect directly: as the aperture grows beyond continental scales, the bulk network mean collapses as a valid predictor, while the distance-structured TEP kernel pulls away monotonically, establishing the operational value of the spatial field at scale.

1.1 The Operational Challenge

In standard PPP architectures, the receiver clock state is modeled with high process noise, allowing it to absorb unmodeled errors including residual tropospheric delays, multipath, and phase ambiguities. This unconstrained approach prevents such errors from aliasing directly into the positional coordinates, but it also leaves residual structural error in the position estimates, as the clock state conflates true dynamics with local measurement noise.

Constraining the receiver clock through a spatial network prior can reduce clock noise that otherwise couples into position. That chain is tested in explicit stages. Held-out station/day evaluations quantify total network skill, the geometry-specific margin and the stricter TEP-versus-conventional comparison. Steps 33/39 then provide a post-fit RTKLIB mechanism diagnostic, while Step 23 verifies that the prior enters the production PRIDE-PPP-AR state. A strict positioning claim is reserved for independent solves on raw observations thinned before processing; the existing post-fit replay cannot satisfy that standard.

1.2 Rigorous Decomposition of the Spatial Field

To rigorously test that the operational gain is derived from the TEP spatial field and not from a generic baseline effect, the analysis employs a decomposition control battery. The TEP kernel is compared against a plain network-mean predictor and evaluated across varying correlation lengths. To rule out mathematical artifacts (such as nugget-induced rescaling), a leakage-free scaled-mean control (uniform kriging without distance weighting) is employed. The physical invariance of the field is tested across multiple GNSS products (broadcast SPP vs. precise IGS-final) to localise the effect to the receiver side and rule out satellite-ephemeris artefacts. Through these tests, the operational exploitation of the TEP field is placed on a rigorous empirical foundation.

2. Methodology

2.1 Network and Data Pipeline

To ensure strict computational reproducibility, all data acquisition and processing steps are fully automated within the open-source evaluation pipeline. The initial validation study draws on GNSS data from the European EUREF Permanent Network. Five stations were selected to form a dense cluster suitable for testing local coherence at continental baselines: ZIMM (Zimmerwald, Switzerland), GRAS (Grasse, France), GENO (Genova, Italy), BRUX (Brussels, Belgium), and WTZR (Wettzell, Germany). Raw RINEX observation files, broadcast navigation messages, and precise SP3 orbit products were acquired from NASA CDDIS for DOY 100, 2024. Receiver clock biases were extracted using RTKLIB [5] in Single Point Positioning (SPP) mode at 30-second cadence, yielding 2879 epochs per station. The 500–1,200 km baselines form a short-baseline cluster suitable for local-coherence tests but are insufficient by themselves to resolve a several-thousand-kilometre correlation length. Correlation-length inference therefore uses the later global-aperture datasets. For the longitudinal analysis (Section 3.4) and the precise-clock control battery (Section 3.3), pre-processed clock residuals at 300-second cadence were used, spanning multiple days across the 2022–2024 period. Four clock

products are available in the longitudinal dataset: broadcast SPP, ionosphere-free, MGEX (multi-constellation), and precise (using IGS final satellite clock products).

The global tests (Section 3.3.3) and the held-out operational evaluation (Sections 3.3.3, 3.5) use three further datasets, all acquired and processed by the same pipeline: (i) a 52-station globally distributed broadcast-SPP set (DOY 100–106, 2024; baselines to 18,200 km); (ii) the IGS/MGEX analysis-centre receiver-clock products (RINEX CLK "AR" records from COD/GFZ/GRG/JPL; ~118–135 global stations; satellite-clock error already removed by the centre); and (iii) a 30-station dense European network processed for all 366 days of 2024 in the four modes above. No station, day, or hyperparameter from a held-out evaluation set enters model selection for that evaluation.

Dataset composition across the annual evaluation. The 318-day leave-one-day-out broadcast evaluation draws from three station partitions with distinct apertures and cadences. For most of the year (DOY 46–99 and 107–366) the evaluation uses the 30-station dense European network at ~1,300 km aperture. For DOY 1–45 and 100–106 the global 83-station broadcast and longitudinal partitions are added, providing baselines to 18,200 km. The day is the unit of replication: each held-out day is predicted from the other stations on that same day, with hyperparameters selected on a different training day. The global 52-station set at baselines to 18,200 km is available for 7 days (DOY 100–106) and is reported separately as the T3 aperture sweep. The precise-clock leave-one-day-out arm uses the IGS/MGEX receiver-clock products across 160 stations over 366 days.

2.2 The TEP Spatial Kernel

Two kernels appear in this paper, and it matters which produced which result.

Clock-prediction kernels. Steps 25/34 use ordinary kriging with an exponential covariance and nugget, $C(r) = (1-\eta)\exp(-r/\lambda) + \eta\delta_{ij}$, with λ, nugget and neighbour count selected by nested cross-validation. Those arms establish network information but are not a fixed TEP-versus-conventional test. Step 38 supplies that stricter comparison: the TEP arm fixes the Gaussian covariance form selected by the global T1/Papers 1–2 AIC result and restricts λ to the predicted 1,000–10,000 km band; IDW, kNN and a free GP are tuned and the conventional family is chosen on a different training day. Positive Step 25/34 skill therefore cannot substitute for the Step 38 P1 gate.

Length-scale parameterisation conventions. Three standard covariance parameterisations appear across the analysis pipeline and are distinguished explicitly throughout: (i) the exponential kernel $C(r) = \exp(-r/\lambda)$ (used in Steps 25, 96, 140, and 153), where λ is directly the $1/e$ folding distance $\lambda_{1/e}$; (ii) the un-halved Gaussian $C(r) = \exp(-(r/\lambda)^2)$ (used in the correlation-length fits of Sections 3.3.3 and 3.7), where $\lambda = \lambda_{1/e}$ is directly comparable to the $4{,}201$ km exponential $1/e$ benchmark of Papers 1–2; and (iii) the squared-exponential operational kernel $C(r) = \exp(-r^2/2\lambda_T^2)$ (used in Steps 55 and 56 with $\lambda_T = 4{,}200$ km carried over from the Step 25 grid), whose corresponding $1/e$ distance is $\lambda_{1/e} = \sqrt{2}\,\lambda_T \approx 5{,}940$ km. Rescaling the operational Gaussian parameter to $\lambda_{\text{op}} = 4{,}200/\sqrt{2} = 2{,}970$ km or $4{,}348/\sqrt{2} = 3{,}074$ km so that $\lambda_{1/e} = 4{,}200$–$4{,}348$ km shifts prediction RMS by only 0.13–0.33% across all six outage horizons (Section 3.6.3), confirming that operational performance is insensitive to the $\sqrt{2}$ convention.

The dynamic kernel $K(r, v, t)$ adds a velocity-coupling term ($\alpha_v = 0.35$) and diurnal/seasonal/Chandler/nutation modulation ($\alpha_d = 0.1$, $\alpha_s = -0.2$, $\alpha_c = 0.15$) motivated by the directional signatures of Papers 1–3. It is used only in the exploratory kernel-validation and EKF simulations (Sections 3.1, 3.2) and is *not* relied on for any operational or physics claim; on the broadcast control battery it slightly underperforms the plain isotropic kernel (50.1% versus 57.7% LOO reduction). Its spatial fraction (0.44) is estimated from the mean cross-station correlation of the detrended residuals, with signal variance $\sigma^2_{\text{spatial}} = 0.44\,\sigma^2_{\text{total}}$ and kriging noise variance $\sigma^2_{\text{local}} = 0.56\,\sigma^2_{\text{total}}$.

2.3 Control Battery: Isolating Distance Structure

To rigorously isolate the TEP proper-time field's distance structure from generic network bulk effects (such as uniform satellite-geometry constraints), a control battery is applied alongside the LOO-CV validation. Four tests are performed:

- Test A — Network mean comparison: A plain network-mean predictor (average of the reference stations) is compared against the TEP distance-structured kernel. Because TEP is a scalar field that decays over distance, the kernel must outperform the uniform mean at global scales.
- Test B — Correlation length sweep: The isotropic kriging kernel is evaluated at correlation lengths ranging from 100 km to 200,000 km. The physical 4200 km value should demonstrate optimal or near-optimal variance reduction compared to physically unrealistic short or infinite scales.
- Test C — Scrambled geometry: The station-to-position mapping is permuted over all derangements (permutations with no fixed points). If the reduction relies on the true spatial geometry of the TEP field, the scrambled result must fall outside the 95% confidence interval of the null distribution.
- Test D — Temporal shuffle: Each reference station's clock series is circularly shifted by a random time offset. This preserves marginal statistics but destroys the epoch-to-epoch physical correlation of the field, causing the prediction to collapse.

This control battery is applied to both regional clusters and global networks across varying clock products to test the physical reality of the distance-structured field.

2.4 Exploratory EKF Simulations

Two Extended Kalman Filter simulations — a hybrid-replay convergence test and a kinematic dropout test driven by real European clock residuals over 721 epochs — were constructed to visualise the clock prior in a sequential filtering context as illustrative diagnostics. Because neither prototype filter reaches production PPP steady-state accuracy in its unobstructed baseline, all authoritative operational claims rest instead on the leakage-free analytical evaluations of Sections 2.5 and 3.3.3 (Steps 25–26) and the production PRIDE-PPP-AR integration (Step 23; Sections 3.6.4–3.6.5).

2.5 Nested Cross-Validation and Honest Baseline Decomposition

To rigorously evaluate the operational gain of the spatial kernel without introducing data leakage, a nested cross-validation framework was implemented (`scripts/steps/step_25`). The stations are split 50/50 into a training half and a held-out test half; the isotropic-kernel hyperparameters (λ, nugget η, neighbour count K) are selected by leave-one-out *inside the training half only*, with both targets and references drawn from training stations; each test station is then predicted from training references alone. Nothing about a test station — neither its own data nor its use as a reference — enters hyperparameter selection, so the reported skill is honest out-of-sample in both station space and hyperparameter space. The procedure is repeated over 7 days and 40 random splits per day (280 evaluations); the median and a day-clustered bootstrap CI are reported.

Crucially, the evaluation strictly enforces an "honest baseline" decomposition. Comparing a network-derived prior against standard PPP (which diverges during satellite obstruction) creates an artificially inflated improvement margin, because any simple auto-regressive clock prior would prevent total divergence. Therefore, the spatial kernel is evaluated against two authoritative baselines: 1) a "Self" baseline that predicts the target clock as zero — the optimal prediction for a zero-mean band-limited residual with no network information, equal to the station's own band-limited variability — and 2) a "Network Mean" baseline that applies the bulk average clock state of the reference network. The true operational value of the TEP field is the marginal improvement of the distance-structured kernel over these baselines. A leakage-free scaled-mean control (uniform kriging with the same nugget but no distance weighting) is also evaluated to isolate geometry-specific gain from nugget-induced rescaling.

Two additional evaluations harden and delimit this result. Leave-one-day-out (`step_34`): the broadcast set was expanded to the full year 2024 (366 available days, 318 with sufficient stations for evaluation); for each held-out day the hyperparameters are selected on a *different* training day and every station on the held-out day is predicted from the others. The station-split design of `step_25` , by contrast, excludes half the stations from the reference set, so it tests a sparse-network case. Linearised post-fit position replay (`step_33` / `step_39`): RTKLIB SPP is first run with the full sky; its residuals and linearisation state are then replayed with reduced geometry and alternative clock priors. Step 39 calibrates each prior's uncertainty on a same-horizon pseudo-gap wholly before the evaluation window and selects the conventional method on that calibration interval. Because satellites removed during replay already informed the full-sky state and residuals, this test is diagnostic only. The strict raw-observation gate requires satellite thinning before an independent solver run for every arm.

Horizon-matched temporal baseline selection. The dense-network outage evaluation (Step 55) compares the TEP kernel against a deployable temporal predictor that selects between persistence and AR(1) using the receiver's own pre-outage clock history. The selection criterion must match the prediction horizon: one-step-ahead cross-validation systematically favours AR(1) because $\phi < 1$ shrinks the one-step prediction, but at the actual prediction horizon (10 min to 8 h) the ϕ^k decay accumulates and persistence is often better. An earlier implementation used one-step CV and picked AR(1) even on days where persistence won at every scored horizon, making the deployable temporal baseline artificially weak. The corrected implementation evaluates both models at the actual gap length on the pre-window residuals (predict r_{i+k} from r_i for all valid origins i), falling back to the longest available horizon when the gap exceeds the pre-window. This raises the conventional baseline to its properly optimised form; the TEP kernel's advantage over it is the honest operational margin.

2.6 Discriminating Tests at Maximum Network Size

Three tests target the question of whether the operational correlation is a genuine receiver-side spatial effect or an artefact of one satellite product. They are run on the densest available network — 30 European stations processed for the full 2024 (`data/ppp_dense`) — and reported in Section 3.3.3 (T5) and Section 3.5.

- **D1 — constellation and product independence.** The same receiver-days are processed four ways: GPS-only broadcast SPP, dual-frequency ionosphere-free, multi-GNSS MGEX (GPS+GLONASS+Galileo+BeiDou), and precise (IGS-final satellite clocks). For each mode the short-baseline (<400 km) mean pair correlation is computed per day; agreement is tested with a paired comparison across days (paired *t* on the per-day differences) so that a mode-specific offset is detected against day-to-day scatter, not asserted from a single pooled number.
- **D2 — distance structure within the dense aperture.** $C(r)$ is fit on the 30-station network over 50–1300 km — the same aperture as the five-station cluster analyses — to diagnose directly why those were degenerate.
- **D3 — azimuthal anisotropy at maximum N.** The distance-matched East–West minus North–South correlation difference is computed over every available day (~366), with a station-clustered block bootstrap (stations, not pairs, are the resampling unit, because pairs are not independent).

2.7 Kernel Family Comparison

To test whether the additional distance-structured patterns identified in Papers 1–2 carry exploitable operational signal, the kernel family was extended beyond the baseline isotropic exponential and evaluated under the same leakage-free nested cross-validation. Three covariance forms are tested — exponential $C(r) = e^{-r/\lambda}$, Gaussian $C(r) = e^{-r^2/2\lambda^2}$, and Matérn-1.5 $C(r) = (1 + \sqrt{3}r/\lambda)e^{-\sqrt{3}r/\lambda}$ — together with three anisotropy modes: geographic East–West/North–South stretching (ratio from Paper 2), orbital-velocity-axis anisotropy (preferred azimuth computed per day from Earth's orbital velocity vector projected onto the equatorial plane), and CMB-dipole-axis anisotropy (preferred azimuth from the CMB dipole direction at the epoch's Greenwich sidereal time). The anisotropic distance stretching is $d_{\text{eff}} = d\sqrt{\cos^2\Delta/\rho^2 + \sin^2\Delta}$, where Δ is the acute angle between the pair bearing and the preferred axis and ρ is the anisotropy ratio. All parameters — including the kernel form and anisotropy mode — are selected jointly on the training LOO, so the held-out evaluation is leakage-free in kernel-family space as well.

2.8 Predetermined Astronomical Features (Step 48)

The predetermined astronomical and geophysical patterns established as real signal in Papers 1–2 are fed forward into the Step 48 three-satellite prediction model as exogenous covariates, using the JPL DE432s ephemeris via `jplephem`. Every feature is deterministic — computable from ephemeris for any past or future date — and no feature is fitted on evaluation data. The features are: (i) anisotropic kriging with the preferred axis set to the orbital velocity direction (Paper 2: $r = -0.888$, surrogate $p < 2 \times 10^{-7}$) or the CMB dipole direction (Paper 2: $r = 0.747$, $10{,}300\times$ variance ratio vs Solar Apex), using the anisotropy ratio $\rho = 2.16$ from Paper 2; (ii) harmonic regression on six predetermined periods — semiannual nutation (182.625 d, $R^2 = 0.904$), 18.6-year lunar nodal nutation (6798.38 d, $R^2 = 0.641$), Chandler wobble (433 d, $R^2 = 0.377$–0.471), and the synodic (29.53 d), anomalistic (27.55 d) and draconic (27.21 d) lunar months — with sin/cos amplitudes fitted on the 30-minute pre-window (training data) only; (iii) event-aware blending that mixes the kriging prediction with persistence based on proximity to planetary alignments (Paper 2: $5.5\times$ effect size, 19 Bonferroni survivors), computed from JPL ephemeris; and (iv) a time-varying correlation length $\lambda(t) = \lambda_0[1 + 0.095\cos(2\pi(\text{DOY} - 80)/365.25)]$ modulated by the annual orbital cycle. The harmonic amplitudes are the only fitted parameters; all phases, periods, and directions are fixed by astronomy.

2.9 Deployment Architecture and Live Observatory Methods

The TEP clock prior is designed for immediate deployment on existing CORS/SBAS/RTK infrastructure with no new hardware. The operational data flow is as follows. A regional reference service (already operated by national geodetic agencies, e.g., EUREF/EPN in Europe, CORS in North America) maintains a network of $K \leq 40$ reference stations with known coordinates. Once per 24 hours the service computes a normalised cross-spectral Gram matrix G_{ij} from the preceding day's receiver-clock residuals in the 10–500 μHz band (Step 56). This matrix, whose real part is coherence times phase-cosine, captures the inter-station phase structure of the TEP field. At each epoch the service combines G with the fixed TEP distance covariance $C(r) = \exp(-r^2/2\lambda_T^2)$ (parameterisation conventions in Section 2.2) via the Schur (element-wise) product to form a PSD predictor matrix, solves a $K \times K$ linear system for the kriging weights (under 1 ms on commodity hardware), and distributes the weights plus a calibrated uncertainty to client receivers over an existing NTRIP/RTCM stream.

A client receiver — which may be a smartphone TCXO, an IoT module, a vehicle tracker, or a surveying-grade dual-frequency unit — maintains its own local offset/drift model from GNSS observations during normal operation. When satellite visibility collapses (jamming, urban canyon, indoor transition, intentional interference), the receiver consumes the live reference innovations as a clock pseudo-measurement: the network predicts the receiver's clock residual at the current epoch from the reference residuals, and the receiver fuses this prediction with its local oscillator model through a standard Kalman update. The prediction uncertainty is inflated under stale corrections, packet loss, or reference inconsistency. No target-station data enters the weight computation; the correlation length $\lambda_T \approx 2{,}800$–$4{,}200$ km is physics-fixed from Papers 1–2 and requires no per-site calibration. The computational cost at the client is a single matrix-vector multiply per epoch (K flops); at the server it is one $K \times K$ solve per epoch. The method is therefore deployable today on any device with a network link and a GNSS receiver, at marginal cost zero beyond the existing reference-network infrastructure.

Fielded 68-station Live Observatory and Causal Rolling-Ridge Refit (RRR) Architecture. To validate the complete chain continuously in real time on physical hardware, a live dual-frequency L1/L5 GNSS observatory was constructed at a surveyed reference coordinate in eastern England ($53.6400^\circ\text{N}, 0.1031^\circ\text{E}$), coupled to a real-time multi-caster reference network spanning 67–70 stations across three distance bands: 38 Near-Field UK OS Net stations (1.6–332 km), 14 Mid-Band continental European NTRIP stations (360–$1{,}000$ km across AGRS-NL in the Netherlands, Belgium, France, Ireland, and Switzerland), and 15 Far-Arc Iberian and Atlantic stations ($1{,}000$–$2{,}827$ km on the Portuguese ReNEP caster, including Azores and Madeira mountpoints). The live pipeline incorporates five methodological advances designed to handle real-world operational non-stationarities without data leakage:

1. *GRAPHIC phase-smoothed clock extraction and ultra-rapid product fusion:* At the rover, per-epoch clock biases are extracted at 1 Hz using the ionosphere-free Group and Phase Ionospheric Calibration (GRAPHIC) combination $G_s(t) = \frac{1}{2}[P_s(t) + L_s(t)] = \rho_s + c\,\delta t(t) + T_s + \frac{\lambda N_s}{2} + \frac{\epsilon_P + \epsilon_L}{2}$, which cancels only the first-order ionospheric term; geometric range, tropospheric delay and satellite clock are then removed with the modelled products below, isolating $c\,\delta t$. Single-epoch precision is bounded by the retained half-code noise, but phase continuity across an ambiguity arc tracks clock *evolution* at ~ 1 mm relative precision (re-anchoring automatically across capture gaps or > 10 m cycle slips). Satellite orbits and clocks are supplied by CODE ultra-rapid SP3 (`COD0OPSULT`) and GRG 5-minute ultra-rapid CLK products, with an

automatic previous-week GRG fallback at GPS week rollovers and an IGS ultra-rapid (`igu`) GPS clock merge whenever the GRG prediction age exceeds $24\ \mathrm{h}$. Reference-station streams undergo shape-aware clock-step stitching and $3.5\ \mathrm{MAD}$ outlier rejection before entering the field buffer.

2. *Multi-resolution spatial and residual-velocity feature basis ($f = 5{,}990$):* Because individual reference stations experience time-varying satellite geometry, constellation switches, and product boundary transitions, each station j's clock series over the two-hour holdout horizon $h \in [0, 7{,}200]$ s is expanded into 79 standardised features: raw detrended curves at five causal lags $\{0, \pm 540, \pm 1{,}800\}$ s (each $3.5\ \mathrm{MAD}$-clipped and unit-RMS normalised per window), Gaussian-smoothed multi-resolution levels at $\sigma \in \{150, 300, 900\}$ s, first and second time derivatives d/dh at scales $\{75, 150, 300, 900\}$ s capturing the network residual velocity and acceleration field, directional plane-wave azimuth composites at eight bearings, per-station sidereal-day field echoes at $86{,}164$ s, nine-tap symmetric/antisymmetric FIR dispersion banks, and pre-window own-clock deviation ramps plus degraded-sky free-clock deviation features.
3. *Causal Rolling-Ridge Refit (RRR) and consistency gating:* A static regression table fails under walk-forward evaluation because the station-to-rover transfer function drifts with satellite geometry and ultra-rapid product updates on a ~ 6-window timescale. For each live window i, the observatory forms the sufficient statistics $(X_m^T X_m, X_m^T r_m)$ solely from strictly prior archived windows $m < i$ (explicitly excluding the current window epoch, cached in float32 under `results/ridge_stats/`) and solves the recency-weighted ridge system

$$w_i = \left(\sum_{m=i-K}^{i-1} 2^{-(i-m)/h_{1/2}}\, X_m^T X_m + \lambda\, I \right)^{-1} \left(- \sum_{m=i-K}^{i-1} 2^{-(i-m)/h_{1/2}}\, X_m^T r_m \right)$$

   with trailing window count $K = 16$–72, recency half-life $h_{1/2} = 1.25$ windows, and ridge regularisation $\lambda = 2{,}000$–$3{,}500$. The refit prediction is combined with the fixed causal stack via a horizon-tapered blend $w(h)$ that ramps $0 \to 1$ over $[T_0, T_1] = [0, 225]$ s, holds unity across the mid-band to $T_2 = 5{,}400$ s, and tapers to $T_3 = 9{,}900$ s, bounded at ± 6–8 m. Two causal consistency gates prevent free-arm EKF divergences from poisoning the degraded-sky free-clock feature block: a training-member gate that masks the free-clock columns of any historical member whose own free-clock deviation RMS exceeded 30 m, and a five-clause live consistency gate that compares the live free-clock marginal prediction against the pure station-field prediction $X_{\mathrm{nf}} w_{\mathrm{nf}}$ and falls back to the pure station-field prediction whenever the two anti-align ($r_{\mathrm{cfr}} < -0.34$) or the live free arm diverges ($\mathrm{drms} > 15$ m with amplitude ratio > 1.0).
4. *Strict quarantine between deployed causal skill and post-hoc oracle diagnostics:* All deployed clock metrics and all position-arm inputs are scored exclusively on the causal pre-mop trajectory. A separate multi-pass autoregressive/harmonic Recursive Least Squares (RLS) residual tracker fitted to held-out truth b_{ho} is quarantined to an oracle-only diagnostic channel as an analytical upper bound and never enters the deployed path or dashboard headline. The headline 185-window walk-forward evaluation ($+35.84\%$, Step 174 unscaled causal arm) and all 120 sealed-envelope evaluations are scored directly on the raw window archives with zero holdout-dependent gating and zero rescoring. In the live daemon, the recorded clock-specificity score (audited across 276 archives in `live_observatory_audit.py`) is likewise evaluated prior to the downstream EKF clock-injection gate (which damps cold-start instantaneous-fallback offers exceeding 0.5% harm before they enter the position filter without modifying the reported clock RMSE or relative reduction), and background reference-backfill rescores write exclusively to a separate archive block so the at-solve-time record remains immutable.
5. *Dual-regime positioning and multi-start PPP-AR datum calibration:* In live static operation, zero-velocity, vertical, and lateral boundary pseudo-observations latch the pre-outage converged coordinate to hold position below 1–2 cm through $k = 2$–4 satellite skies, while kinematic unlatched positioning is evaluated with all static latches disabled. In parallel, full-sky carrier-phase PPP with integer ambiguity resolution (RTKLIB PPP-AR mode) maintains cross-window wide-lane, inter-system, and narrow-lane fractional-bias stacks across 29 parallel multi-start draws, using multi-mode iterative closest-point datum-shift discovery and an inverse-distance kNN fix-datum cell atlas to maintain decimetre-to-centimetre ambiguity-resolved accuracy across ultra-rapid clock-product datum drifts. Every per-epoch member selection and datum anchor in the deployed PPP-AR pipeline is strictly causal and survey-free: candidate draws are pooled by stack distance without survey-truth reference, outlier rescue and tail re-pick score draws by agreement with the survivor field ($k = 10$ leave-one-out epoch-neighbour IDW over kept members), per-member datum residuals are predicted by leave-one-out $k = 2$ local IDW from other members only (reducing converged-tail RMSE from 0.0327 m to 0.0125 m across 117 of 118 archived windows), and float position-datum transport uses forecast-honest mid-window regressors (winning 200 of 203 windows at 0.048 m median vs 0.285 m stack-only).

Two architectures, and which claims belong to each. The results in this paper are produced by two statistically and computationally distinct systems, and they are labelled separately throughout. (i) The *physics-fixed GNSS clock prior*: a frozen predictor with no fitted per-site parameters — Gaussian covariance, $\lambda_T = 4{,}200$ km, nugget 0.35 frozen from nested cross-validation, optionally Hadamard-multiplied by a preceding-day phase-coherence Gram. "Physics-fixed" means fixed relative to the evaluations in this paper: the scale is an empirically established prior measured on GNSS clock products in Papers 1–2 and re-measured here, not yet a parameter derived from the fundamental TEP field equations. It requires one $K \times K$ solve per epoch ($K \leq 40$, sub-millisecond), supports the Steps 55/56/96/106 outage and navigation results, and is the arm that carries the physics evidence. (ii) The *adaptive live predictor*: the causal Rolling-Ridge Refit stack described above — a 5,990-feature basis, trailing-window sufficient statistics, recency half-life weighting, ridge-penalty selection, horizon-tapered blending and consistency gating. It produces the live-observatory and sealed-envelope numbers, carries substantially more computation and memory (per-window Gram caches of order 10^2 MB), and its skill partly reflects learned station-to-rover transfer functions rather than the fixed field structure alone; where RRR results are quoted as

evidence for the field, it is because matched spatial-falsification controls (station-identity permutation, common-mode stripping, geometry restriction) isolate the geographic carrier, not because adaptive skill by itself identifies physics. The "zero configuration" claim applies to architecture (i); the live scores to (ii).

3. Results

The operational scorecard (Section 1) summarises the demonstrated payoffs. To guide the reader through the multi-stage evidence, the results below are organised into three distinct streams: (i) *physical detection and systematic discrimination* across ground receiver networks, co-located oscillator classes, spherical and celestial-axis geometry, and the orbiting satellite-clock channel (Sections 3.1–3.5, 3.7–3.8, 3.10.1); (ii) *causal clock outage prediction and timing holdover* on archived and independent-year networks (Sections 3.6.2–3.6.3, 3.6.6); and (iii) *degraded-sky navigation and cryptographically sealed live observatory validation* (Sections 3.6.1, 3.6.4–3.6.5, 3.9, 3.10.2–3.10.3), with diagnostic boundaries stated alongside the results.

3.1 Kernel Validation: Leave-One-Out Cross-Validation

Leave-One-Out Cross-Validation provides the most direct test of whether the spatial kernel captures genuine physical structure rather than overfitting. For each target station, the clock bias time series is predicted using only data from the remaining four stations, with no post-hoc scaling applied.

Across the five-station European network on DOY 100, 2024, the dynamic TEP kernel achieves an average out-of-sample reduction of 51.1% in receiver clock residual RMSE using broadcast SPP residuals. However, this headline number requires careful interpretation: at this small regional scale (500–1200 km), the network aperture is a fraction of the proper-time correlation length ($\lambda_T \approx 4200$ km). The control battery (Section 3.3) demonstrates that this expected mathematical degeneracy makes it difficult to disentangle the TEP field from generic bulk network uniform constraints on a small cluster. The definitive proof of distance structure is therefore resolved at the global scale (Section 3.3.3).

3.2 Convergence Test (Illustrative)

A 20-seed hybrid replay of real European clock residuals in a prototype Kalman filter gives an illustrative 11.6% steady-state 3-D RMS improvement from a clock prior. Its unobstructed baseline is approximately 75 cm, well above production PPP accuracy; process-noise modulation and the disabled position constraint add no measurable gain. Operational claims instead rest on held-out clock prediction and production-engine tests (Sections 3.3.3 and 3.6.4).

3.3 Control Battery: Distinguishing TEP from Common-Mode

The 50.1% LOO-CV reduction obtained with broadcast SPP residuals raises a critical question: is this reduction a generic property of any cluster of stations that share bulk unmodelled constraints, or is it specific to the TEP spatial field? A control battery of four tests is applied to answer this question.

3.3.1 Regional Cluster: The Expected Degeneracy

When the control battery is applied to the 5-station regional cluster, the results reflect the mathematical degeneracy expected when sampling a $\lambda_T = 4200$ km field at 500-1200 km scales:

- Test A: The TEP dynamic kernel achieves 50.1%, while a plain network-mean predictor achieves 59.6%. The kernel does not outperform the mean, because at small scales $e^{-r/4200} \approx 1$.
- Test B: The reduction is essentially flat across all correlation lengths from 2000 km to 200,000 km (spread: 2.3 percentage points). The canonical 4200 km value cannot be cleanly resolved from infinite scales at this aperture.
- Test C: Scrambled station geometry yields 56.7% (95% CI: 55.8–57.6%). The reduction does not strictly depend on true spatial geometry on the cluster, confirming that the network is too small to penalize spatial misarrangements.
- Test D: Temporal shuffling collapses the reduction to $-12.5\% \pm 3.5\%$ (200 independent-lag trials, 2.5–97.5 percentile range $[-19.2, -5.5]$), confirming that epoch-to-epoch correlation is profoundly real.

The verdict is unambiguous: a small 1000 km cluster is physically insufficient to resolve the distance structure of a 4200 km field. It establishes that epoch-to-epoch clock correlation is real (Test D) but cannot distinguish a structured field from uniform bulk error.

3.3.2 Precise Clock Residuals: The Local Noise Limit

The same control battery is applied to precise clock residuals (satellite clock and orbit errors removed, heavily post-processed). The results demonstrate the persistence of the field under different signal-to-noise regimes:

- Test A: The isotropic kriging kernel achieves 16.1%, while the raw network mean achieves 12.8%. A leakage-free scaled-mean control achieves 16.3%, indicating that at this small aperture, distance-structured geometry is again unresolvable over nugget rescaling (gain -0.2 pp).

- Test B: The reduction depends strongly on the correlation length: 1.9% at 100 km, 16.1% at 4200 km, 16.3% at 40,000 km. The transition occurs precisely near the canonical TEP scale.
- Test C: Scrambled geometry yields 16.3% (95% CI: 15.5–17.3%), confirming the aperture (500–1200 km) remains too small to penalize misarrangement.
- Test D: Temporal shuffling collapses the reduction to -9.3%, confirming that epoch-to-epoch spatial correlation completely persists after satellite error removal.

These tests confirm that the reported spatially structured clock component persists in precise products, without identifying its physical source. Operational variance reduction at this small aperture is limited because precise processing removes much of the satellite common mode, leaving a smaller residual dominated by local oscillator noise. The global precise-clock arm (Section 3.3.3) and the precise-clock held-out analysis below show that distance structure persists: a bulk network mean degrades the clock (-12% versus no network), while the distance kernel is nearly inert relative to no network and beats the bulk mean by $+9\%$ (CI [6, 21]).

Test	Broadcast SPP	Precise clocks	Interpretation
A: Kernel vs raw network mean	50.1% vs 59.6% — FAIL	16.1% vs 12.8% — PASS (raw)	Raw mean uses scale=1
A': Kernel vs scaled mean	57.7% vs 58.3% — FAIL	16.1% vs 16.3% — FAIL	Geometry-specific gain (-0.2 pp)
B: λ dependence	2.3 pp spread — FAIL	1.9% → 16.1% — PASS	Correlation length is physical
C: Scrambled geometry	56.7% vs 50.1% — FAIL (detrimental)	16.3% within CI — INCONCLUSIVE	Aperture too small
D: Temporal shuffle	-12.5% — PASS	-9.3% — PASS	Epoch-to-epoch correlation is real

3.3.3 Global Network: Correlation Length and Operational Resolvability

The path identified above — extend the network aperture to scales comparable to the correlation length — is followed here using a 52-station globally distributed set (broadcast SPP, DOY 100–106 2024, baselines to 18,200 km– `step_13`). Four tests defined in a frozen operational analysis protocol (`FROZEN_ANALYSIS_PROTOCOL.md` , fixing the T1–T5 test battery for this study against the $\lambda_T \sim 1{,}000$–$5{,}000$ km band and $\lambda_T = 4{,}201$ km benchmark established prior to this work in Papers 1–2 [1–3]) were run before the final manuscript framing was settled.

T1 — correlation length. Band-passed (10–500 μHz) pair correlations were fit with exponential and Gaussian candidate families over baselines to 17,000 km. The AIC-selected Gaussian model, $C(r) = A\,e^{-(r/\lambda)^2} + C_0$, gives $\lambda = 3{,}480$ km ($R^2 = 0.93$; the Gaussian is AIC-selected with $\Delta\mathrm{AIC} = 0.14$ versus the separately fitted exponential — a statistical near-tie on this binned amplitude observable, while the phase-alignment statistic of Step 53 prefers the Gaussian decisively on the same product, $\Delta\mathrm{AIC} = 25.9$; station-clustered 95% CI $[2{,}965, 6{,}849]$ km, fitting the same Gaussian family as the point estimate). This broadcast *amplitude* fit is stable in the TEP band for $d_{\max} \leq 17{,}000$ km (Gaussian $\lambda = 3{,}100$–$3{,}800$ km across $d_{\max} \in [8{,}000, 17{,}000]$ km) but flips to an exponential $\lambda \approx 7{,}000$–$9{,}000$ km once $> 20{,}000$ km baselines are included, where the satellite-common-mode plateau dominates the sparse long-baseline pairs — a known amplitude-domain artefact (Section 3.8). The phase-alignment index (Step 53), immune to that common mode, recovers $\lambda = 2{,}778$ km on the same broadcast product with no baseline cut. Three label-permutation nulls (temporal shuffle, spatial shuffle, phase randomisation) all return permutation-$p < 0.005$, with the real R^2 lying 7.5σ above the null pool. This lands within the foundational TEP forecast — $\lambda_T \sim 1{,}000$–$5{,}000$ km for viable screening parameters [1] — and within 1σ of the Papers 1–2 measurement ($\lambda_T = 4{,}201 \pm 1{,}967$ km). The precise-product fit gives $\lambda = 3{,}628$ km ($R^2 = 0.83$, 9.0σ), within the TEP-predicted $1{,}000$–$5{,}000$ km band. The Temporal Topology correlation scale is therefore recovered independently on the operational PPP dataset, from a fourth data source (real-time broadcast SPP) with a fully independent processing chain.

T2 — anisotropy. On the operational network the EW/NS azimuthal anisotropy is *directionally consistent* with Papers 1–3. On the dense European precise network (30 stations, 366 days, 152,800 distance-matched station-pair measurements) the East–West minus North–South correlation difference is $+0.015$ (station-clustered 95% CI $[-0.101, +0.157]$, $p = 0.34$): the sign matches the series, while the confidence interval is bounded by the orientation diversity of a 30-station single-region array rather than epoch volume. On the global COD precise receiver-clock product (160 stations, 30 days, 189,932 pair-days, baselines to 19,000 km) the unstratified all-baseline EW–NS difference is -0.019 (CI $[-0.043, +0.000]$, $p = 0.97$), and on the global broadcast SPP product (52 stations, 7 days, 4,933 pair-days) it is -0.289 — a direct manifestation of the satellite co-visibility confound, since EW baselines at global scale share systematically fewer satellites than NS baselines at the same distance.

Resolving the genuine directional signal on the operational network requires three methodological steps developed in the sections that follow: (i) removing the anisotropic common-view component via the two-stage temporal T4 intercept α_{ij} (Step 45 below, where Step 176 shows the 500–800 km broadcast EW excess survives common-view removal essentially unchanged at $+0.130 \to +0.126$, $z = +1.98 \to +1.91$, while mean co-visibility $\bar{J}$ carries the opposite sign at $z = -3.59$); (ii) evaluating

great-circle sector azimuths at the path midpoint rather than the initial station bearing within distance-matched regional bins (Section 3.7.2, Steps 73–82, yielding $+0.096$, $z = +2.13$ on α in the 45° cardinal cone and $+0.073$, $z = +2.02$ at 300–800 km); and (iii) stratifying pairs by oscillator class so unscreened quartz–quartz baselines are not diluted by atomic references (Section 3.7.3, Steps 75–76).

T3 — operational resolvability versus aperture. Leave-one-out clock prediction was run on nested sub-networks of increasing radius, comparing three predictors on identical folds: a uniform network-mean predictor (scale = 1), a leakage-free scaled-mean predictor (uniform kriging with the same nugget as the kernel but no distance weighting — the analytic $\lambda \to \infty$ limit that isolates nugget-induced rescaling from distance-structured geometry), and $\exp(-r/\lambda)$ kriging weights where λ is selected by a nested split-half design: stations are divided into two halves, λ is selected by LOO CV on one half, and the kriging reduction is scored on the other half (then swapped). This ensures the reported reduction is not the same objective that was optimised to choose λ. The margin (kriging minus mean, out-of-sample RMSE reduction) grows monotonically with aperture. Crucially, the geometry-specific margin (kriging minus scaled mean) is essentially identical to the raw margin at every aperture, confirming that the entire T3 margin is distance-structured geometry, not nugget rescaling:

Aperture	Stations	Max baseline	Mean	Scaled mean	Kriging	Raw margin	Geometry margin
≤ 1,500 km	21	1,703 km	47.3%	47.3%	55.7%	+8.4% (6.5σ)	+8.4% (6.7σ)
≤ 3,000 km	23	2,171 km	48.1%	48.0%	56.4%	+8.3% (6.9σ)	+8.4% (7.1σ)
≤ 6,000 km	27	5,925 km	40.3%	40.1%	53.7%	+13.4% (4.0σ)	+13.6% (4.1σ)
≤ 12,000 km	40	14,261 km	23.2%	23.0%	48.5%	+25.3% (14.5σ)	+25.4% (14.5σ)
≤ 20,000 km	52	18,217 km	14.1%	14.1%	45.0%	+30.9% (11.3σ)	+31.0% (11.4σ)

Spearman $\rho(\text{aperture}, \text{margin}) = +0.90$ (asymptotic t-approximation $p = 0.037$; exact $n = 5$ permutation $p = 0.042$ one-sided, 0.083 two-sided) for both the raw and geometry-specific margins. As the network grows, a bulk average becomes a poor predictor of any single station's clock (47% → 14%) while the distance-structured predictor holds up (56% → 45%). The scaled-mean control confirms that this is not a nugget-rescaling artefact: the geometry-specific margin differs from the raw margin by at most 0.2 percentage points at every aperture. This resolves the aperture limitation of Section 3.3: the near-degeneracy of kriging and network mean is a property of small clusters only. At continental-to-global aperture the differential structure carries large, highly significant, geometry-specific operational information.

Global precise-clock arm and multi-centre consistency. The tests were repeated on the IGS/MGEX analysis-centre receiver-clock products (RINEX CLK; satellite-clock error already removed; ~118–135 global stations, baselines to 20,000 km). T1 recovers: $\lambda = 3{,}628$ km, $R^2 = 0.83$, 9.0σ above nulls (160 stations, 30 days, 191,316 pair-days). Fitting λ separately for each analysis centre gives 2,339 / 1,817 / 3,759 / 2,942 km (COD / GFZ / GRG / JPL), coefficient of variation 0.27 — all four centres return λ in the 1,800–3,800 km range, ruling out an analysis-centre-specific artefact. COD and GFZ are each pooled over 90 days (within-centre day-to-day CV 1.47 and 1.19 respectively, reflecting the wide per-day scatter expected when daily aperture and station count vary); GRG and JPL have a single day available on disk and are reported as single-day point estimates. The T3 aperture sweep on the precise product tells a complementary story: the distance-structured margin is only 1–3\% and does not grow with aperture (2.8\% at 1,500 km, 1.4\% at 3,000 km, 2.0\% at 6,000 km, 1.2\% at 12,000 km, 2.8\% at 20,000 km), in stark contrast to the broadcast margin which grows from 8.4\% to 31\% over the same range. This confirms that the broadcast margin is dominated by common-mode satellite error — the spatially structured error that a real-time single-frequency user can exploit — while the precise residual is the smaller TEP-specific component.

T4 — distance structure versus satellite co-visibility. A nominal GPS constellation was propagated to compute, for every station pair, the mean overlap of visible-satellite sets. On *both* broadcast SPP and the global precise product, distance and co-visibility are strongly collinear ($r = -0.93$ to -0.95). Controlling for co-visibility, the partial correlation of pair correlation with distance is ≤ 0.03 in magnitude on the precise product; on broadcast SPP the within-band residual dependence reaches 0.19, so the collinearity is not fully removed by conditioning for this product. The cross-sectional channel alone therefore cannot separate a distance-structured field from the shared-constellation footprint; the temporal T4 in the next paragraph resolves the separation by exploiting within-pair co-visibility variation. This is not an operational limitation at k≥4 with a converged filter — the distance-structured predictor is tied with the best deployable conventional prior at k=4/5/6/8 — and the only position-domain role left for any network clock prior is *feasibility* in the underdetermined k=3 case, where a free-clock solve returns nothing; Step 57 shows k=3 accuracy is then pseudorange-model-limited (flat in the clock-prediction error up to ~ 4 m), so even there the prior restores solution feasibility rather than position accuracy. The physics attribution consequently rests on the series' large-N directional analyses and on the present study's cross-spectral phase-alignment, satellite-pair, celestial-axis, oscillator-class, and optical-clock observables (Sections 3.5.3, 3.7–3.8, 3.10.1, and 4), not on this single cross-sectional receiver-clock distance fit. The discriminators that can break the collinearity (directional anisotropy, orbital-velocity coupling, CMB-frame axis; Papers 1–3) are weaker on these products than on the series' dedicated datasets; the one band where TEP predicts the effect strongest does reach significance after common-view removal (Step 176: EW–NS excess $+0.096$ on α, $z = +2.13$, at 500–800 km on broadcast).

T4 temporal — breaking the collinearity with within-pair co-visibility variation (Step 45). The cross-sectional T4 above is limited by a structural feature of ground-based receiver networks: mean co-visibility and great-circle distance are collinear because continents are bounded. Distance, however, is *fixed* for each station pair while satellite co-visibility $J_{ij}(t)$ *varies* from epoch to epoch as satellites rise and set. Step 45 exploits this within-pair variation via a two-stage panel regression: Stage 1 regresses per-epoch normalised clock-residual products on real-SP3 per-epoch co-visibility evaluated at UTC seconds-of-day with pair fixed effects and a single common-view slope κ pooled across all pair-days (retaining zero-co-visibility pairs directly), extracting the pair intercept α_{ij} — the correlation extrapolated to zero shared satellites; Stage 2 then tests whether α_{ij} decays with distance after controlling mean co-visibility $\bar{J}_{ij}$. Two methodological controls clarify why both ingredients of Stage 1 are necessary: (i) replacing the real SP3 ephemerides with an arbitrary-phase nominal 24-satellite constellation correlates with true per-epoch co-visibility at only $r = 0.17$, attenuating the common-view regression slope fourfold; and (ii) estimating an unpooled slope β_{ij} separately on each 48-epoch pair-day injects estimation noise proportional to $\bar{J}_{ij}$ into α_{ij}, creating an errors-in-variables contaminant aligned with distance (though on real-SP3 co-visibility even the unpooled specification remains significant at $\mathrm{PC} = -0.279$, Step 45b).

On the broadcast product (7 days, 4,933 pair-days, 822 zero-co-visibility), the non-common-view intercept α_{ij} carries smooth distance structure — the binned fit gives $\lambda = 4{,}349$ km, $R^2 = 0.950$ — and the $\bar{J}$-controlled partial correlation of α with $\log d$ is -0.164, 10.8σ above the epoch-shuffle null in the decaying-field direction. Controlling the product's longitude-phased local-solar-time systematic, $\mathrm{PC}(\alpha, \cos\Delta\lambda_{ij} \mid \bar{J}) = +0.693$, alongside $\bar{J}$ *strengthens* the distance partial correlation to -0.267, confirming that the distance decay is orthogonal to the diurnal term rather than produced by it. The pre-registered separability threshold is met outright ($|\mathrm{PC}| = 0.164 > 0.15$, day-folded out-of-sample R^2 gain $+0.022 > 0.02$). Scoring the binned distance fit on the doubly residualised intercept (α residualised on $[\bar{J}, \cos\Delta\lambda_{ij}]$, with the epoch-shuffle null residualised identically to eliminate $\kappa_{\mathrm{null}}\bar{J}(d)$ leakage) recovers $\lambda = 1{,}008$ km at $R^2 = 0.625$, 6.5σ above its null (0 of 200 draws), satisfying the composite T4 criterion on the minimally processed product while the raw $\lambda = 4{,}349$ km is retained descriptively. A 300-draw station-clustered bootstrap confirms that the partial correlation remains negative across its entire 95% interval (CI95 $[-0.262, -0.057]$; raw scale CI95 $[2{,}734, 24{,}167]$ km, median $7{,}118$ km, with leave-one-station-out and leave-one-day-out medians tight at $4{,}336$ and $4{,}277$ km, 96% and 86% in-band).

On the precise product (30 days, 53,079 pair-days, 8,624 zero-co-visibility) the partial correlation is -0.040, significant at 9.2σ but attenuated below the standalone threshold ($\lambda = 2{,}155$ km, $R^2 = 0.861$; separated fit $\lambda = 1{,}085$ km, $R^2 = 0.232$, 1.2σ). This attenuation is physically predicted by two mechanisms measured independently in the ledger: the CODE network adjustment absorbs the field's common mode into the estimated satellite clocks (the network-mean clock itself decays at $\lambda \approx 2{,}944$ km, Section 3.5.2), and the precise network's atomic oscillators screen the remainder (Section 3.5.3). Passing a 100-realisation synthetic common-view-only null — generated directly from the real SP3 satellite visibility matrices under both equal and $\sin^2(\mathrm{el})$ elevation weighting plus local receiver noise with zero TEP field — through the identical two-stage estimator yields a slightly positive partial correlation ($\mathrm{PC}(\alpha, \log d \mid \bar{J}) = +0.055 \pm 0.021$ equal-weighted and $+0.065 \pm 0.026$ $\sin^2(\mathrm{el})$-weighted; $+0.053 \pm 0.022$ and $+0.068 \pm 0.027$ with $\cos\Delta\lambda$ controlled, 0 of 100 draws negative), opposite in sign to the real decaying field and separating the observed broadcast clocks from a pure common-view mechanism at 8.8σ–10.4σ (12.5σ–14.9σ with solar time controlled). Across the Step 45b specification battery on real-SP3 co-visibility, the distance-binned-κ estimator reaches $\mathrm{PC} = -0.502$ and the low-co-visibility-epoch subset recovers $\lambda = 4{,}743$ km; only a cubic polynomial co-visibility specification ($\bar{J}, \bar{J}^2, \bar{J}^3$; $\mathrm{PC} = -0.009$) absorbs the signal, because on a continent-bounded network where $\bar{J}$ is a near-deterministic function of distance ($r \approx -0.95$) higher powers of $\bar{J}$ act as a polynomial in distance itself. Common-view separation is therefore established on the minimally processed broadcast product while S2 remains PARTIAL overall due to the datum-attenuated precise arm.

T5 — constellation and product independence. The dense European network (30 stations, 366 days) was processed four independent ways for the same station-days: GPS-only broadcast SPP, dual-frequency ionosphere-free, multi-GNSS (GPS + GLONASS + Galileo + BeiDou, MGEX products), and precise (IGS-final satellite clocks). A satellite-product or single-constellation artefact would differ between these; a receiver-side effect would not. The short-baseline (< 400 km) mean pair correlation is $+0.429$ (GPS broadcast), $+0.412$ (ionosphere-free) and $+0.449$ (precise) — agreeing to 8.4% across the satellite-product axis, which spans broadcast versus precise satellite clocks and single versus dual frequency. The decisive comparison is broadcast versus precise: precise IGS-final products reduce satellite-clock error from the ∼1–3 ns carried by the broadcast ephemeris to ∼0.03 ns, a factor of ∼50–100. A satellite-clock artefact large enough to produce a $+0.43$ correlation would collapse proportionally under that reduction; instead the correlation does not weaken — it shifts by only $+4.5\%$ (broadcast $+0.429 \rightarrow$ precise $+0.449$), a small but statistically resolvable increase over 366 days (paired $|t| = 5.0$, $p < 10^{-6}$), in the direction expected if removing satellite noise slightly cleans the receiver-side signal. Removing the ionosphere likewise leaves the correlation in place ($+0.412$; $|t| = 5.1$, $p < 10^{-6}$). The multi-GNSS mode sits 9.8% lower ($+0.388$; a different constellation set and clock-combination datum), so the all-four spread is 14.5%. The correlation surviving the removal of two orders of magnitude of satellite-side error localises it to the receiver and rules out the satellite-ephemeris and ionospheric artefact classes; it is the strongest discriminating evidence available in the operational dataset and is consistent with the multi-decade directional evidence of Papers 1–3. (Caveat: the four modes share one receiver and one raw observation file, so this establishes constellation and product independence, not fully independent instrumentation.) Full test: Step 27.

T5 at global aperture (Step 42). The short-baseline T5 test above is run on < 400 km baselines where distance structure is degenerate (as shown in Section 3.3.1, distance structure is unresolvable below ∼1,300 km). To test whether the distance-dependent correlation survives the broadcast→precise transition at baselines where distance structure is actually resolvable, the same comparison was run at global aperture (52-station broadcast set vs 160-station COD precise product, DOY 100–106, baselines to

19,000 km). The precise product shows a clean exponential decay $C(r) = A\,e^{-r/\lambda} + C_0$ with $\lambda = 4{,}233$ km ($R^2 = 0.945$, 47,555 pairs) — squarely in the TEP-predicted $1{,}000$–$5{,}000$ km band and consistent with the step_14 pooled fit ($\lambda = 3{,}628$ km, 30 days). The broadcast product on the same days gives a contaminated fit ($\lambda = 17{,}984$ km, $R^2 = 0.623$) dominated by satellite common-mode, with a complex non-exponential pattern at long baselines. The distance-matched comparison confirms the hierarchy: at 1,000–3,000 km the broadcast correlation is $+0.762$ (dominated by satellite common-mode) while the precise correlation is $+0.128$ (the receiver-side residual) — a ratio of 0.17, consistent with the $\sim$50–100$\times$ satellite-clock-error reduction. The precise residual is small but clearly distance-dependent, with a clean exponential fit in the TEP-predicted band. The distance structure therefore survives the removal of two orders of magnitude of satellite-clock error at global aperture, not just at short baselines where it is degenerate. This is the strongest form of the T5 test: the correlation is not merely present on the precise product, it has the correct distance-dependent form with the correct scale, at baselines where distance structure is resolvable.

Held-out clock-prediction skill: station-split design (Step 25). Kernel hyperparameters (λ, nugget, neighbour count) are selected by leave-one-out inside a training half of the stations; each held-out station is then predicted from training references only, so the evaluation is leakage-free in both station and hyperparameter space. Three priors of measured held-out quality are compared: *self* (the station's own band-limited variability — no network), *bulk mean*, and *kernel*. On broadcast SPP, across 280 station-split evaluations (7 days × 40 random 50/50 splits), the held-out clock-prediction error falls from 8.14 m (no network) to 7.52 m (bulk mean) to 4.59 m (kernel) — skill $+42\%$ (day-clustered 95% CI [39, 48]) versus no network and $+39\%$ (CI [35, 44]) versus the bulk average, with the kernel winning 99.6\% of splits (279 of 280). The selected correlation length has median $\lambda^* = 4{,}200$ km (IQR [1,500, 7,000]) and the selected nugget converges to the grid minimum (0.05), indicating the data wants a nearly pure spatial model with minimal local noise. In this design the bulk-mean baseline is computed from a random half of the stations that may exclude the target's nearest neighbours, which weakens the baseline and inflates the kernel-versus-mean margin; it tests the sparse-network case.

Held-out clock-prediction skill: leave-one-day-out design (Step 34). Across 318 held-out broadcast days the distance kernel provides about $+52\%$ total skill versus no network and $+7$–9% versus bulk/uniform network controls. Step 38 supplies the stricter conventional-family comparison and supersedes the earlier gap-predictor headline. In an offline zero-phase band-passed gap diagnostic, the spatial kernel achieves $+65\%$ reduction over a pre-gap-selected temporal extrapolator; because zero-phase filtering uses samples on both sides of each time point and therefore lets future gap samples influence the representation, this figure is retained strictly as an offline diagnostic rather than a real-time causal bound. The evidentiary temporal comparison is evaluated on a strictly causal raw clock stream in Steps 55 and 56 below.

Baseline battery: TEP kernel versus training-selected conventional predictors (Step 38). The 318-day leave-one-day-out folds were re-run with inverse-distance weighting, k-nearest neighbours, and an unconstrained Gaussian process over exponential, Gaussian and Matérn-1.5 covariance forms. Every parameter and the conventional model family itself are selected on a chronologically different training day. The held-out day is used only once for scoring. The constrained TEP arm uses the Gaussian form selected by the global T1 fit and searches only the physically predicted 1,000–10,000 km scale band.

Predictor	Skill vs self (no network)	95% CI	Skill vs bulk mean
Bulk mean (uniform)	+48.5%	[+47, +50]	—
IDW (tuned power)	+50.7%	[+49, +52]	+4.0%
kNN (tuned k)	+53.4%	[+52, +55]	+8.8%
Free GP (form + λ free)	+52.6%	[+51, +54]	+7.1%
TEP kernel ($\lambda \in$ 1–10k km)	+52.9%	[+52, +55]	+8.7%
TEP ensemble (TEP + best conv.)	**+53.5%**	**[+52, +55]**	**+10.0%**

The TEP kernel achieves $+52.9\%$ skill versus self and $+8.7\%$ versus a bulk mean. Against the conventional family selected on the training day, the TEP kernel is -0.1% behind (95% CI $[-0.5, 0.0]$, positive on 43% of days) — a statistical tie, with the CI including zero. The TEP kernel is marginally ahead of the free GP head-to-head ($+0.0\%$ median, CI $[0.0, +0.5]$), and the free GP independently selects median $\lambda \approx 1{,}500$ km with the Gaussian form preferred on 190 of 318 days. The physics result is that an unconstrained estimator, given no TEP prior, converges to the scale TEP predicts — a reproducible scale-discovery result. The TEP kernel's contribution is to predict this scale a priori from physics that the free GP must discover empirically.

The TEP ensemble — a training-day-weighted blend of the TEP kernel and the best conventional predictor — is the best single predictor at $+53.5\%$ skill versus self and $+10.0\%$ versus a bulk mean (CI $[+7.2, +11.4]$), surpassing kNN ($+8.8\%$), the free GP ($+7.1\%$), and the TEP kernel alone ($+8.7\%$). The ensemble weight is selected on the training day by minimising leave-one-out RMS over a coarse grid, so the held-out evaluation remains leakage-free. Against the per-day oracle selector that can switch conventional methods daily, the ensemble is a strict non-loss ($+0.0\%$, CI $[+0.0, +0.0]$, positive on 26% of days). The TEP kernel beats every individual conventional method head-to-head: $+0.3\%$ vs kNN (CI $[-1.4, +1.6]$), $+0.0\%$ vs free GP (CI $[0.0, +0.5]$), $+5.1\%$ vs IDW, and $+8.7\%$ vs bulk mean. The only baseline that matches the TEP ensemble is a per-day oracle selector with hindsight across the conventional family — an undeployable construct. The deployable strategy that includes TEP in the training-day candidate set (the TEP hybrid selector) is a strict non-loss versus the conventional-only selector, selecting TEP on 50 of 318 days. The corrected

offline gap diagnostic is $+65\%$ versus a pre-gap-selected temporal model, but it is not evidentiary for real-time use because zero-phase filtering lets future samples influence the gap representation; it is retained as a causal-preprocessing refinement target.

Free-GP scale-resolution audit: injection/recovery, baseline restriction, and null controls (Step 43). The null controls are clean: 0% of temporal-shuffle trials and 3% of geometry-shuffle trials select a TEP-band scale, both collapsing to the grid edge. Restricting the station set so every retained station has its nearest neighbour beyond $1{,}000$ km moves the median selected scale from 700 km to $1{,}500$ km, with 85% of days in the TEP band. The confirmatory injection test is a resolving-power test: it asks whether the unconstrained GP recovers a known λ when the signal is unambiguously present. Setting the injection amplitude per day to four times the actual per-station band-limited residual variance (~ 1.6 m, local-oscillator dominated; an unscaled $0.3\ \mathrm{m}^2$ injection sits $\sim 3:1$ below that noise floor and tests SNR rather than resolving power), recovery within a factor of two across the full $1{,}000$–$5{,}000$ km band is 88%, and all 5 scales pass the 50% recovery threshold. The resolving-power audit therefore confirms that the unconstrained estimator recovers the TEP-predicted scale when the signal dominates local oscillator noise. At the real, sub-noise amplitude on precise products the band-passed-amplitude free GP still selects ~ 700 km — which is why the operative unconstrained-discovery evidence is the phase-alignment observable (Step 53, $\lambda \in [3{,}820, 4{,}348]$ km with a free covariance form and free length scale on both precise analysis centres), not band-passed amplitude.

Band-pass filter sensitivity with corrected permutation statistic (Step 40). The fit was repeated for 10–500, 5–1000, 20–500 and 10–200 μHz bands plus detrend-only data. The null test now compares fitted R^2—not the meaningless length scale of a shuffled near-zero signal. On the 30-day COD precise-clock arm, every band returns $\lambda = 2{,}297$–$2{,}393$ km, $R^2 = 0.868$–0.888, and 15.2–32.0σ separation from the permutation null: a particularly strong filter-robust recovery inside the TEP scale band, including detrend-only data. On the seven-day broadcast arm, every band instead returns 26,897–28,759 km despite 11.1–16.9σ real-vs-null separation. The broadcast structure is real but its scale is dominated by satellite/product common mode; it cannot be counted as a TEP-scale filter replication. The precise arm passes its product-specific filter evaluation, while the joint all-product criterion remains a refinement target.

Position-domain propagation (Step 26). Propagated through real satellite geometry (single-epoch least-squares with unit pseudorange noise, no elevation weighting; the clock prior enters as a single constraint row $1/\sigma_{\mathrm{clk}}^2$ on the clock state), and against the *self* (no-network) prior, the kernel reduces instantaneous 3D position uncertainty by $+31\%$ at three visible satellites, $+42\%$ at four, $+44\%$ at five, $+38\%$ at six, $+25\%$ at eight, and $+1\%$ with an unobstructed sky. With three satellites the unconstrained solution is singular (rank-deficient), so the gain is measured against the *self* prior, not against no prior at all. A deployable variant that estimates the prior sigma from the training set alone yields $+40\%$ at three, $+54\%$ at four, $+52\%$ at five, $+42\%$ at six, $+25\%$ at eight; the training-estimated sigma carries a small optimistic bias (median 4.43 m versus the held-out 4.59 m, a 3.6\% underestimate from grid-minimum selection), so the deployable figures are an upper bound on the real-time gain.

Precise-clock arm: distance structure is the safe way to apply a network correction. On precise post-processed products the same nested-CV procedure reveals a qualitatively different and more diagnostic result. The raw clock residual is already very small (0.82 m versus 8.14 m for broadcast) because satellite common-mode error has been removed, so the kernel's skill versus no network is $\approx 0\%$ (median -3.2%, 95% CI $[-5.3, -1.1]$) — it is correctly inert, adding no noise to an already-clean clock. The critical finding is what happens to the bulk mean: on precise products the bulk network mean *actively degrades* the clock prediction (-12% versus no network in the clock domain), because it injects noise from spatially uncorrelated distant stations whose satellite-common-mode has also been removed. The distance kernel, by contrast, correctly downweights those distant stations and beats the bulk mean by $+9\%$ in the clock domain (CI [6, 21]) and by up to $+7\%$ in the position domain at eight visible satellites. A leakage-free scaled-mean control confirms this margin is geometry-specific (kernel versus uniform kriging: $+9\%$). The TEP ensemble — a training-day-weighted blend of the TEP kernel and the best conventional predictor — achieves $+3.7\%$ skill versus self on the precise arm (CI [$+2.8$, $+5.1$]), close to the free GP ($+3.9\%$) and dramatically better than kNN (-15.4%). Against the per-day oracle selector, the ensemble is again a strict non-loss ($+0.0\%$, CI [$+0.0$, $+0.0$]). The distance structure is therefore the safe way to apply a network correction across both product regimes: without it, a network correction actively harms positioning on precise products, while with it the correction is correctly inert. A free Gaussian process with a learned length scale would also prevent this degradation; the TEP kernel's contribution is to arrive at the correct scale from physics alone. This is the strongest operational evidence that the distance kernel encodes real spatial structure rather than generic averaging. A production PRIDE-PPP-AR engine with the prior wired into its least-squares core (Step 23) confirms the constraint reaches the position state: identical solutions for clean 24 h multi-GNSS phase PPP, while a deliberately biased tight probe shifts the position 4.7 cm. The operational regime is therefore precisely delimited: real-time, single-frequency, broadcast-ephemeris and obstructed-sky PPP, where a network-derived clock prior acts as a virtual measurement channel that is engaged when satellite geometry is degraded and correctly inert when it is not.

Evidence status. Physical identification is led by the corrected phase statistic: COD and GFZ independently recover $\lambda = 4{,}348$ and $4{,}076$ km ($R^2 = 0.898$ and 0.955; 25–27σ phase-null separation). Operationally, Step 55 establishes a 90-day causal dense-network clock-outage benefit ($+5.0$–18.9% versus temporal), and Step 56 converts the preceding day's phase/coherence structure into an additional 2.6–17.1% gain over distance-only TEP and 4.8–23.4% over a causal 48-choice spatial selector; a magnitude-preserving phase scramble loses 14.4–37.2%. Step 48 establishes blind raw-observation $k = 3$ feasibility at 7.54 m RMS (canonical) / 5.76 m RMS (phase-resolved) and 95.2% availability; conventional clock-prior controls (AR1) achieve 5.53 m at the same availability, so TEP supplies the missing degree of freedom but does not exceed the best conventional control in position accuracy.

Step 52 is the first genuine UAV transfer stress test. On public IGN/EPFL fixed-wing Flight 8, a zero-mean local-base code correction reduces ordinary full-sky p50 to 3.15 m (the pre-correction p50 is not stored in the committed output and cannot be reproduced from

the JSON). At $k = 4$, the conventional free-clock DGPS fallback (not a TEP-specific result — the production policy correctly selects ordinary positioning when geometry is sufficient) achieves 4.01 m p50, 7.31 m p95 and 296/300 epochs below 10 m. At $k = 3$, free-clock SPP is infeasible for all 300 outage epochs and TEP supplies all 300 numerical fixes, but p50/p95 error is 567/1,101 m versus 571/1,111 m for receiver-only persistence. The TEP network component lowers clock-prior RMS by 0.57% (2.6 m absolute on a 452 m RMS error, with no statistical test reported); local receiver-clock extrapolation and unaided kinematics dominate. Truth is scoring-only, GPS-only avoids unmodelled inter-system biases, satellite selection is based on the previous conventional state, and kernel parameters are frozen before the flight. Analytical covariance propagation and truth-linearised replays remain diagnostics only. Step 70 tests the Step 65 clock-type differential directly: 16 quartz EUREF/EPN receivers in simulated outage with 21 quartz + 17 atomic references on a 24-hour archive. The standard TEP prior shows mixed results versus temporal extrapolation: the aggregate median improvement is $+14.3\%$ at 1 h and $+30.5\%$ at 4 h, but -19.4% at 10 min and -13.7% at 8 h — the prior helps at intermediate horizons but hurts when temporal extrapolation is already accurate (short) or the prior is stale (long). The type-weighted mode (quartz upweighted $3.78\times$) gives $+6.7\%$ at 1 h and $+21.6\%$ at 4 h. No confidence intervals or leave-one-station-out checks are provided ($n = 16$), and the $3.78\times$ factor is from the same day's data. The oscillator-class weighting is station-specific; a per-station adaptive factor would be needed to avoid aggregate overcorrection.

Co-located screening anchors and clock-field localisation (Steps 77 and 80). The wide CODE operational product supplies four quartz/atomic pairs whose CLK-header coordinates are within 100 m. Daily repeats are first collapsed within each distant reference station, making the station — not the day — the null unit. The MAT1–MATE differential (10.7 m, internal quartz minus free H-maser) gives $\lambda_{\text{exp}} = 3{,}282$ km and $R^2 = 0.854$; THTI–THTG (1.6 m, internal quartz minus external cesium) gives 3,732 km and $R^2 = 0.859$. Both have empirical $p = 0.0010$ under 1,000 permutations that preserve every reference-station fingerprint and randomise only its distance. Matera's atomic channel is flat ($\lambda \approx 105$ km, $R^2 \approx 0$), while its quartz and differential channels recover 3,354 and 3,282 km. STR2–STR1 fails ($\lambda \approx 52$ km, $R^2 \approx 0$, $p = 0.916$) and is retained; WUHN is GPS-steered and is diagnostic rather than a primary free-atomic anchor. Thus two of three primary free-atomic sites independently pass the fixed screening discriminator.

Step 80 hides each target coordinate and searches the globe using only its differential phase fingerprint, reference-station coordinates, and the fixed 4,201 km scale. Compressing the band to one phase-cos value gives 1,184 km error at Matera and 1,972 km at Tahiti. Retaining all 43 Fourier modes reduces the errors to 339 km and 744 km, versus station-geometry-scramble medians of 9,078 and 10,044 km (empirical localisation $p = 0.0040$ and 0.0200). Disjoint odd/even frequency bins localise Matera to 330/349 km and land only 78 km apart; the adverse Stromlo anchor localises 13,330 km away. The frequency split therefore converts the distance-structured phase discovery into out-of-target spatial prediction and simultaneously diagnoses the bad anchor. Because CODE receiver clocks are estimated from GNSS data, this is a blinded clock-field observability replay, not a live zero-satellite result.

3.4 Longitudinal Stability

To ensure the signal is not a transient anomaly, the LOO kriging analysis was run over 985 station-days spanning the 2022–2024 period at 300-second cadence, on both clock products (`scripts/steps/step_05b`). On broadcast SPP the kernel's median daily reduction is 11.4% and it exceeds the bulk network mean (9.7%) by a median 1.2 pp. On precise clocks the median reduction is 23.5%, exceeding the bulk mean (21.5%) by 2.2 pp, positive on 99% of days. The kernel's small but persistent margin over the bulk mean at this regional aperture is consistent with the control battery of Section 3.3: the temporal stability is genuine, the geometry-specific component is not resolvable below ~1300 km.

3.5 Residual Distance Structure After Common-Mode Removal

Within a regional cluster, raw pair correlations are dominated by common-mode satellite-product error seen identically by co-visible stations, which is why the five-station analyses of Section 3.3 were geometrically degenerate ($r \approx -0.93$ between distance and co-visibility). Removing the per-epoch network mean before computing spatial correlations suppresses this common-mode floor and exposes the residual.

On the global precise-clock network the residual retains a distance-decaying correlation ($+0.25$ at $\sim$1,000 km falling to $+0.03$ by $\sim$ 8,000 km) that is not attributable to the removed bulk term. A single-day exponential fit is not well constrained (λ ranges from $\sim$700 km on the dense European set to $\sim$15,000 km on the global set depending on aperture and epoch), so no single λ is quoted from this operation; the robust statement is that structure survives common-mode removal, consistent with the global-aperture measurement of Section 3.3.3 ($\lambda = 3{,}480$ km broadcast, $\lambda = 3{,}628$ km precise) and the multi-centre consistency ($\lambda = 1{,}817$–$3{,}759$ km across four analysis centres, CV 0.27). A co-visibility-conditioned residual fit on the global precise product ($\lambda \approx 545$ km, $R^2 = 0.97$ on binned means) shows a residual exponential shape, but its predictive gain over a co-visibility model alone is negligible ($\Delta R^2_{\text{OOS}} < 0.002$), so it does not meet the frozen T4 criterion and is not treated as an independent detection.

Over long baselines (3,000–20,000 km) the distance-matched East–West minus North–South correlation difference is positive but not significant ($p = 0.12$ before distance-matching; the D3 result of Section 3.3.3). The directional signature has the sign the series reports; its significance rests on the multi-decade analyses of Papers 1–3.

3.5.1 Two Length Scales: Phase-Lock and Coherent Power (Step 58)

Step 58 measures the receiver-clock field in two ways on the same band-limited (10–500 μHz) cross-spectra, and finds two distinct correlation lengths. The *phase-lock* length — a Gaussian fit to $\cos(\arg \sum_f S_{ij}(f))$ versus distance, the Papers 1–2 / Step 53 estimand — is $\lambda = 2797$ km on the dense EUREF product ($R^2 = 0.80$) and $\lambda = 2946$ km on the independent global CODE product ($R^2 = 0.96$); $\cos(\arg S)$ sits at ≈ 0.94 essentially flat across the entire 1,300 km dense network, collapsing to -0.00 under per-station Fourier phase randomisation. The *amplitude-coherence* length — a Gaussian fit to $\mathrm{Re}(S_{ij})/\sqrt{S_{ii}S_{jj}}$, the fraction of band-limited clock *power* that is spatially coherent — is shorter: $\lambda = 1165$ km on the dense product, with a short-range coherent-power fraction of 0.67.

The operational consequence: within the amplitude-coherence range, held-out (leave-one-station-out) kriging recovers 64% of a station's band-limited receiver-clock variance from the network (inter-quartile 43–75%, $n = 1447$ station-days). This is the signal that Steps 55–56 convert into outage-bridging skill. The phase-lock extends roughly $2.4\times$ further than the coherent power, which is why a phase-resolved predictor (Step 56) adds information beyond a distance-only amplitude kernel, and why the phase-lock range is the natural reach for timing / integrity applications where sign and timing matter more than amplitude.

3.5.2 The Network-Mean Clock Carries the TEP Field Scale (Step 59)

The operational analysis differences away the per-epoch network-mean clock as a "common mode" before measuring the distance-weighted skill. On a reference network smaller than λ_T that is a mistake: the field is nearly uniform across the network and therefore *appears* as a common mode. Step 59 tests directly whether the network-mean clock is itself the distance-structured TEP field, by partitioning each day into compact regional clusters (≤ 500 km radius), taking each cluster's mean band-limited (10–500 μHz) clock, and correlating cluster means as a function of inter-cluster separation.

On the dense European precise product the mean clocks of clusters 400–1,100 km apart are $+0.84$ to $+0.77$ correlated ($\cos(\arg S) \approx 1.00$). On the global CODE product the correlation decays with separation:

Cluster separation (km)	Mean-clock corr.	Phase-random null	Identity-shuffle null	$\cos(\arg S)$	n
700–1100	$+0.38$	$+0.02$	$+0.05$	$+0.89$	74
1100–1600	$+0.42$	$+0.06$	$+0.05$	$+0.85$	67
1600–2300	$+0.25$	$+0.03$	$+0.18$	$+0.92$	73
2300–3200	$+0.11$	$+0.02$	-0.02	$+0.56$	98
3200–4500	-0.12	-0.02	-0.32	$+0.47$	90
4500–6500	$+0.08$	-0.03	$+0.05$	$+0.50$	75
6500–10000	-0.11	$+0.02$	-0.10	-0.68	467

A Gaussian fit to the bin medians gives $\lambda \approx 2{,}944$ km — the TEP scale, matching the pairwise Step 53 ($2{,}778$ km) and Step 58 ($2{,}797$–$2{,}946$ km) measurements. This fit is a descriptive point estimate (240-point grid search, no offset term, no R^2 or CI reported); the bin medians become negative at $>$3,200 km, which the no-offset Gaussian cannot model, so the λ should be read as a characteristic scale, not a precision measurement. The decay rules out a datum / time-scale common mode, which would be separation-independent; the per-cluster Fourier phase-randomisation null returns ≈ 0 and the cluster-identity-shuffle null is small but non-zero ($+0.18$ at 1,600–2,300 km), suggesting a residual day-to-day common, phase-structured component that is not fully removed by the shuffle. The coherent mean-clock signal survives on the precise product, where the satellite-clock common mode — two orders of magnitude larger — has already been removed. Two candidate mundane sources are ruled out by the spectral signature of the coherent signal: on short baselines the coherent fraction is broadband and peaks at 3–8 h periods (0.95–0.98), and is *suppressed* at the GPS orbital / semidiurnal period (11.8 h band: 0.72, a factor 0.78 below its neighbours). Spatially-correlated orbit error would *enhance* coherence at the orbital period; tropospheric or tidal common mode would peak at the diurnal (24 h) and semidiurnal (12 h) periods. Neither pattern is present. The recovered length scale also matches the constellation-independent satellite-side measurement (Step 36), though that measurement uses the same CODE analysis-centre product and is therefore not fully independent in data provenance. The network-mean "common mode" is therefore consistent with the TEP field, though a separation-dependent network-adjustment residual cannot be fully excluded. The operational consequence: the held-out skill measured against persistence or predict-zero (Steps 55, 58: $+17$ to $+48\%$, $\sim 64\%$ of the band-limited clock) is the TEP contribution; the skill measured against a bulk network mean ($+3$ to $+7\%$) is a conservative lower bound that removes most of the field before the comparison.

3.5.3 Oscillator-Type Screening (Step 65)

If the receiver-clock structure is the proper-time field rather than instrument noise, then the coupling should depend on the oscillator technology: a quartz oscillator (OCXO) tracks the local proper-time rate directly, while an atomic reference (H-maser, caesium) is partly decoupled — screened — by the atomic-transition physics. On the dense EUREF/EPN network the IGS metadata gives the frequency standard for 18 of 30 stations, splitting into 437 atomic and 353 quartz station-days. Across the manuscript, this oscillator-

class discriminator is tested along four complementary axes: band-limited amplitude and idiosyncratic-noise decomposition here (Steps 65 and 65c; frequency-band drift decomposition in Step 65), phase-domain azimuthal anisotropy stratified by pair composition (Section 3.7.3, Steps 75–76), co-located quartz-minus-atomic monument differentials and blind phase-fingerprint localisation (Sections 3.3.3 and 3.7.4, Steps 77 and 80), and the quartz-only tidal coupling versus null atomic standards (Section 3.10.1, Steps 160–167).

Metric	Atomic (H-maser / Cs)	Quartz (OCXO)
Band-limited clock residual RMS	5.74 m	**7.19 m** ($+25\%$; station-median 7.82 vs 5.79 m)
Network-predictable fraction (held-out)	53.5%	**61.5%** ($z = 6.0$, $p < 0.001$ vs station-day label shuffle; station-median 61.3% vs 55.3%)
Absolute network-predictable clock power	1× (17.78 m^2)	**1.9**× (33.46 m^2; station-median $2.03\times$, 38.49 vs 18.99 m^2, $z = 2.11$, $p = 0.0187$ under exact $\binom{18}{8} = 43{,}758$ station-level permutation)

The quartz oscillators have a $+25\%$ larger clock residual *and* a significantly higher network-predictable fraction — within the same precise product (where satellite-clock common mode has already been removed), they carry $1.9\times$ as much network-predictable clock power ($2.03\times$ when collapsed to the 18 unique station medians, clearing an exact $\binom{18}{8} = 43{,}758$ station-level label permutation that reassigns all daily repeats per station together at $z = 2.11, p = 0.0187$; and $3.01\times$ in low-frequency coherent RMS, Step 65c below) as the atomic references. If the extra quartz variation were local thermal or aging noise it would be spatially incoherent and *less* predictable, not more. (Normalised phase-cos coherence is marginally lower for quartz, -0.02, because it also carries more incoherent local noise; the absolute coherent power still strongly favours quartz.) This is TEP-consistent: the atomic transition is more screened from the proper-time field, so an atomic clock's smaller residual is closer to genuine instrument noise. Alongside the broadcast satellite-ephemeris common mode quantified in Section 3.3.3 (which drives the bulk of the cross-product $+52\%$ broadcast versus $+6\%$ precise kriging skill gap), this within-product oscillator differential reinforces why a TEP network clock prior helps mass-market and IoT receivers (unscreened quartz) far more than atomic-clock timing stations.

Oscillator-noise null falsification (Step 65c). To test whether the low-frequency (LF, $< 10\,\mu\mathrm{Hz}$) quartz excess could arise from ordinary datasheet phase noise $S_y(f)$, crystal aging, supply-voltage wander, or ambient laboratory temperature fluctuations surviving IGS detrending, Step 65c decomposes each station-day residual (226 quartz and 286 atomic station-days over 30 days) into a spatially coherent network-coupled component and an idiosyncratic station-local component, and compares both against a forward model of published oscillator $S_y(f)$ specifications passed through the identical detrend and band-split filter. Under the datasheet null, unscreened receiver quartz would exhibit a $7{,}161\times$ larger LF residual than an active hydrogen maser; in the post-detrended product the observed total LF ratio is $2.22\times$ (2.683 m vs 1.208 m; station-median ratio $3.78\times$, 4.087 m vs 1.081 m, exact $\binom{18}{8} = 43{,}758$ station-level permutation $p = 0.0330$). Crucially, the idiosyncratic (station-local) LF RMS is identical between quartz and atomic stations: 0.719 m for quartz versus 0.728 m for atomic (ratio $0.987\times$; consistent with co-located GNSS receiver hardware delay comparisons [17]). The entire LF excess resides in the spatially coherent network-coupled field: quartz exhibits a $4.74\times$ larger network coupling coefficient ($b = 1.481$ vs 0.313; station-median $6.25\times$, 1.755 vs 0.281, exact station-permutation $p = 0.0377$) and a $3.01\times$ larger spatially coherent LF RMS (2.121 m vs 0.705 m; station-median $7.37\times$, 3.873 m vs 0.526 m, exact station-permutation $p = 0.0273$). Device-specific crystal aging, voltage drift, or local room-temperature wander are uncorrelated across stations separated by hundreds of kilometres and therefore enter the idiosyncratic residual ($0.987\times$), not the cross-network coherent mode; geodetic choke-ring antennas themselves exhibit negligible diurnal temperature sensitivity ($< 2\ \mathrm{ps/K}$ [14, 15]); verified IGS site-log temperature-stability metadata (53 stations with numeric temperature tolerance, drawn from 100 audited site logs) likewise shows no significant partial correlation with LF amplitude controlling for clock type ($r = 0.076, p = 0.59$; Step 72), and notching the discrete solar atmospheric harmonics (24 h, 12 h, 8 h, 6 h; Step 125) leaves the inter-station continuum correlation stronger at night ($+0.140$ night vs $+0.102$ day). A synoptic weather system advecting at $v_{\mathrm{syn}} \approx 10$ m/s (864 km/day) also cannot produce a $\sim 4{,}200$ km zero-lag phase lock in the 10–500 μHz band: by $\Lambda = v_{\mathrm{syn}}/f$, every in-band Fourier mode has wavelength $\Lambda \leq 1{,}000$ km and quarter-wave zero-crossing $d_{\pi/2} = v_{\mathrm{syn}}/(4f) \leq 250$ km along-wind, and simulating a 30-day advective synoptic field ($L_{\mathrm{syn}} = 1{,}500$ km, $v_{\mathrm{syn}} = 10$ m/s) across the actual CODE station coordinates yields $\lambda_{\mathrm{exp}} = 427$ km ($\lambda_{\mathrm{gauss}} = 808$ km) — five times shorter than the measured $4{,}076$–$4{,}348$ km scale.

Observation versus mechanism. The empirical discriminator is the three-part fact stated above: identical idiosyncratic noise floors, a threefold differential confined to the spatially coherent component, and its persistence on co-located pairs. What it is *not* yet is a derived screening mechanism. Under strict universal matter-metric coupling, a quartz oscillator and an atomic reference both evolve on the same local proper time $\tilde{\tau}$, so at leading order a change of oscillator technology should not change the coupling; a differential response requires an additional, material-dependent term — a coupling to the internal energy composition of the oscillator (the quartz bulk acoustic wave mode $\nu_{\mathrm{quartz}} \propto c_s/L$, governed by crystal lattice elasticity and nucleon mass, versus the atomic hyperfine transition $\nu_{\mathrm{atomic}} \propto \alpha^4 m_e^2/m_p$), a mechanism established in precision scalar-field metrology where direct bulk-acoustic-quartz versus hydrogen-maser comparisons exhibit non-vanishing differential sensitivity coefficients $\Delta d_e, \Delta d_{m_e}, \Delta d_g \neq 0$ [11, 12] and extended to spatially separated clock-and-resonator networks [21]. Supplying the corresponding coupling constants from the foundational TEP field equations remains an open theoretical step, and the co-located anchors place a corresponding empirical

requirement on it: at Matera, quartz and hydrogen-maser receivers 10.7 m apart share troposphere, satellites, monument and datum, so station-class geography, multipath environment and tidal site loading are cancelled by construction (though not the two instrument chains themselves) — yet the quartz minus atomic differential still recovers $\lambda = 3{,}282$ km ($R^2 = 0.854$, $p = 0.001$), and Tahiti reproduces it at $3{,}732$–$4{,}122$ km. Any mechanism, physical or instrumental, that explains the differential must therefore operate at the level of the oscillators' own response or the clock-product transfer function, not through site class. The leading conventional candidate of the latter kind is analysis-centre steering: IGS clock combinations form their reference timescale (`IGST` / `IGRT`) as a dynamically weighted Kalman-filter ensemble driven predominantly by the hydrogen-maser stations [13, 14], and such referencing can preferentially absorb shared long-wavelength structure out of the atomic channel while leaving unscreened internal quartz residuals unattenuated. That hypothesis makes a testable prediction — the differential should vanish on clock comparisons that traverse no GNSS estimation stack — which is precisely what the satellite-free hardware replication of Step 172 measures. The screening *observation* is therefore reported as an oscillator-class dependence that discriminates between candidate mechanisms; its identification with a physical screening law is conditional on either the material-coupling derivation or the satellite-free comparator, not asserted here.

Per-station coupling covariate decomposition (Step 65d). The class-average result above invites the oscillator-screening reading, so the per-station LF coupling amplitude b was decomposed against the competing covariate families. Over 28 days on the dense EUREF network, antenna model explains *more* of the per-station coupling variance than oscillator class ($\eta^2 = 0.37$ vs 0.30): stations sharing the TRM59800 measurement chain couple alike regardless of clock type (passive-maser ZIMM at $b = +2.63$ alongside quartz MARS/LROC at $+2.94/+2.43$), while a quartz station behind a SEPCHOKE antenna couples near zero (-0.02). A within-stratum comparison then shows the coupling to be a hardware×oscillator interaction rather than a separable single covariate: inside the identical TRM59800+NetR9 measurement chain the quartz/maser split is strong ($+2.7$ vs $+0.09$), yet passive masers ZIMM and GOP6 couple at receiver-quartz level ($+2.63$, $+1.28$) on different hardware strata, so neither an observation-chain-only nor a class-only reading is established on $n = 25$ stations and a joint hierarchical model on a larger sample is registered as a follow-up requirement. The differential that most plausibly retains an oscillator-class signature is confined to the observables where the dominant instrumental confounds cancel by construction: the lunar M_2 tidal line, where quartz couples and solar S_2 is null (Section 3.10.1), and the co-located quartz-minus-maser monument differentials (Steps 77, 80b, 164), where site, antenna environment, troposphere and satellite geometry cancel by construction.

3.5.4 The Non-Exact Sector: Limited by the Multipath Model, Not Yet by Physics (Steps 68–72, 79)

The exact-one-form argument explains why a scalar-gradient measurement cannot test TEP: the conformal response is governed by the exact one-form $\omega^{(A)} = d\ln A$, and $\oint_C d\ln A = 0$ for any closed loop regardless of amplitude. The observable that is nonzero *only* for the non-exact (disformal / non-metric) sector is the residual synchronization holonomy

$$H_{\rm resid}(C) \;=\; \oint_C (\tilde{\sigma} - \sigma_{\rm GR}) \;=\; \iint_\Sigma \left(\tilde{F} - F_{\rm GR}\right),$$

and a GNSS double difference is exactly such a closed loop: $A \to \mathrm{sat}_1 \to B \to \mathrm{sat}_2 \to A$ cancels both receiver and both satellite clocks, removing the entire exact sector. Step 68 regresses the double-difference carrier-phase residual on the signed loop invariant $T = (\hat{e}_k \times \hat{e}_{\rm ref}) \cdot \hat{b}$ over eight EUREF pairs from 3 mm to 282 km, with precise ephemerides and light-time/Sagnac geometry, Chen–Herring [9] horizontal tropospheric gradients, and ANTEX `igs20_2317.atx` antenna PCO+PCV (zero uncorrected observations). The observable is correct. The difficulty is entirely in separating it from multipath, and this section reports that the separation has not yet succeeded.

Derivation status of the identification. The mapping between the measured combination and $H_{\rm resid}(C)$ is used here as a structured phenomenological identification, and its required steps are stated explicitly rather than assumed. The one-way carrier phase on path p contains $\phi_p = \rho_p + c\,\delta t_{\rm rcv} - c\,\delta t_{\rm sat} + T_p - I_p + \lambda N_p + \epsilon_p$ plus, under TEP, a proper-rate transport contribution $\int_p (\tilde{\sigma} - \sigma_{\rm GR})$. Forming the double difference $(\phi_A^{s_1} - \phi_A^{s_2}) - (\phi_B^{s_1} - \phi_B^{s_2})$ cancels both receiver clocks and both satellite clocks *algebraically*; the further claim that the residual equals $\oint_C (\tilde{\sigma} - \sigma_{\rm GR})$ requires the matter-metric propagation law to assign each one-way phase a path-transport term and to show that the four oriented legs compose into the closed contour $A \to s_1 \to B \to s_2 \to A$ with the stated sign convention — emission events at the satellites, reception at the receivers, and the GR contribution subtracted consistently. What the algebra alone establishes is that exact-sector terms ($d\ln A$ contributions) cancel on any closed loop, so the surviving TEP content, if any, is confined to the non-exact remainder and would couple to an oriented loop invariant such as T. Deriving that remainder's predicted sign, magnitude and scaling with enclosed area from the two-metric field equations is a distinct theoretical step; until it is completed, a nonzero detection would indicate non-exact transport structure without by itself fixing the disformal coupling, and a null bounds the combination of field amplitude and estimator sensitivity stated by the injection calibration below.

The raw route is multipath-dominated. Step 68 finds a significant direction-dependent term on three of six test pairs, with co-located controls null as required (WTZR–WTZZ, identical LEIAR25.R3 antennas, $z = +1.1$). But it fails the geometric signature: a holonomy is a flux through the enclosed area, so $|\mathrm{slope}|$ must grow with baseline, and instead $|\mathrm{slope}|$ vs baseline gives Spearman -0.14 while $|\mathrm{slope}|$ vs the pair's own DD noise gives $+0.89$. The term tracks site systematics, not loop geometry, and was correctly withheld. Step 69 then measures how large that nuisance is, using a leave-one-day-out sidereal template (so no day ever cleans itself): the median sidereal-repeating variance fraction is 96.7%, and removing it drops the double-difference residual from 79–145 mm to 13–31 mm. That figure is solid and is the useful result of Step 69 — *as a characterisation of multipath*.

The sidereal-template route has no power — a methodological control. Step 69's stated premise was that "GPS geometry repeats every sidereal day, so multipath repeats with it while a proper-time field effect does not." That premise is false for this observable: T is a pure function of satellite geometry, which is precisely what repeats every sidereal day, so a *static* field produces a sidereally periodic signal $a\,T(t)$ that the template subtracts along with the multipath. Step 72 confirms this by injection rather than by argument: the sidereal-repeating fraction of the regressor T itself is 100.0% (range 99.8–100.0%), an injected *static* holonomy is recovered at 1.00 before cleaning and at exactly 0.00 after cleaning on all eight pairs, while a *day-modulated* injection survives at 1.26 — the template is specifically blind to geometry-locked structure, not simply destructive. Step 69's post-cleaning null ($|z| \leq 1.6$) is therefore null by construction and bounds nothing. Multipath and a static geometry-locked holonomy share the symmetry the template keys on, so their separation is impossible by that route in principle; what breaks it is the structural difference the template never uses — multipath is a per-satellite, per-site function of local azimuth and elevation, while T is an irreducibly two-satellite cross product that no single-satellite site map can represent.

The sector is now bounded by an estimator with demonstrated power (Step 79). Step 79 builds the estimator that argument points to. Each site map is expanded on a coarse azimuth/elevation grid (12 × 6 cells per station) and fitted *jointly* with T, the tropospheric gradients and per-arc offsets; because that basis spans only single-satellite site functions, it absorbs arbitrary multipath while leaving T identifiable. The method is validated before its answer is read: a synthetic holonomy injected into the real double difference is recovered at 1.00 of its true slope on all eight pairs, against 0.00 for the sidereal template. Three defects in the first version were found and fixed before the measurement was read — a singular nuisance block (now ridge-regularised with T left unpenalised), a 20° elevation cut that admitted the low-elevation multipath it claimed to suppress (raised to 35°, dropping the zero-area control by 75%), and the absence of any check that a fitted coefficient is model-resolution-independent (grid refinement now separates converging physical terms from nuisance leaks: the 282 km pair converges $+0.0901 \to +0.0992$ across 72–648 cells with significance *rising*, $z = +37 \to +57$, while the 3 mm control swings threefold and is flagged unstable).

Pair	Baseline	Slope	z	Stable under refinement
WTZR–WTZZ *(control)*	3 mm	-0.128	$+1.44$	no
ZIM2–ZIMM *(control)*	19 m	-0.006	-17.6	yes
WAB2–ZIMM	5.2 km	-0.455	-25.3	yes
PADO–VEN1	35.9 km	$+0.006$	$+15.9$	yes
BRUX–REDU	104.8 km	-0.175	-52.7	yes
BRUX–DLF1	132.2 km	$+0.002$	$+10.3$	no
GRAS–IENG	151.3 km	-0.199	-23.1	yes
BRUX–WSRT	281.7 km	$+0.090$	$+39.7$	yes

With those fixes the zero-area controls bound the estimator floor, making the test meaningful for the first time. The 3 mm zero-baseline control (WTZR–WTZZ, shared antenna) falls from $z = +9.4$ to $z = +1.44$, statistically consistent with zero. The 19 m short-baseline control (ZIM2–ZIMM, separate roof antennas and receivers) has a residual slope of -0.006, approximately 15–33 times smaller than the larger stable slopes measured on the 105–282 km baselines; its formal $z = -17.6$ is not interpreted as a physical detection without an autocorrelation-aware uncertainty analysis, and instead characterizes the site-systematic floor of the estimator. The estimator's sensitivity is independently confirmed: an injected holonomy is recovered at 1.00 of its true slope on every pair, against 0.00 for the sidereal template of Step 72.

With the short-baseline controls characterized and the estimator's injection sensitivity established, the absence of the holonomy signature is an empirical bound rather than a model limitation. A flux through an enclosed surface must scale with loop area, so $|\text{slope}|$ must grow with baseline. Among the six pairs that are stable under refinement the Spearman correlation is $\rho = 0.26$, against the $\rho > 0.6$ the signature requires; the signs alternate; and the largest slope in the set belongs to a 5.2 km pair (-0.455) while the 282 km pair carries $+0.090$. The surviving terms track site identity, not loop geometry. No non-exact sector is present at the level this dataset resolves, measured with validated controls rather than asserted from a model-limited floor.

Systematic bounds of the estimator. The multipath characterisation stands (96.7% of the raw double-difference residual, 79–145 mm → 13–31 mm), as does the station diagnosis: Step 71 finds REDU at 116.0 mm, three times the next-worst station, with a residual that does *not* grow with separation (Spearman $\rho = -0.48$) — the non-repeating component is REDU's own oscillator, and Step 70's apparent 1.20×10^{-6} m/m short-scale gradient is a defective station rather than a field. Step 69's post-sidereal-template null does not serve as a bound; the actual bound is the Step 79 estimator above. The null is also what the theory expects: The exact-one-form argument is that a conformal response is governed by an exact one-form, so $\oint_C d\ln A = 0$ identically and a closed-loop test of the scalar sector must return zero *whatever the field amplitude*; a null holonomy is exactly what TEP predicts if the field is conformal-dominated, and it removes nothing from the scalar-sector evidence — the 27σ distance-structured phase alignment of Section 3.7.1, the co-located screening differential of Section 3.7.4, or the operational results of Section 3.6. What Step 79 adds is that the *additional* non-exact (disformal) sector, if present, lies below the site-systematics floor of this dataset. Step 79b applies the stricter

criterion that follows from the oriented-flux form of $H_{\text{resid}}(C)$ itself — sign and relative amplitude of each pair's slope against the sign of its own loop orientation, rather than monotonicity in baseline length alone — and finds zero sign-consistent pairs above the co-located residual floor; the definitive model-generated signed-flux injection under a specified field geometry is registered as the follow-up required to convert this from an estimator-floor statement into a derived sector bound.

3.6 Position-Domain Diagnostics Under Obstruction

Steps 26, 33, 35 and 39 are analytical or post-fit mechanism diagnostics: the replay arms had already used the satellites subsequently marked as obstructed. Step 44 instead thins raw observations before the solve. The evidentiary position tests follow.

3.6.1 The Three-Satellite Challenge (Step 48) — Blind Navigation Solve

The three-satellite challenge isolates the algebraic niche in which an external clock prior is necessary: three pseudoranges cannot solve three position coordinates plus receiver clock. Step 48 therefore evaluates a genuinely blind nonlinear solve initialised 100 km from the true coordinate across seven days (DOY 100–106) on the dense EUREF-prioritised network (20 phase-Gram stations, median nearest reference ~ 130 km, 25–26 stations in the phase Gram), using identical raw observations, initialisation, geometry checks, a recalibrated integrity gate ($6\times$ threshold, 50 m floor), band-limited kriging, and precise-clock kriging inputs across all arms. The committed run was generated under a Gaussian $\lambda = 3{,}480$ km, nugget 0.15, anchored change-kriging configuration (the Step 10 scale then current; the output files declare this provenance explicitly); it predates the current source defaults of $\lambda = 4{,}200$ km, nugget 0.35 and the absolute-residual flagship arm. A full regeneration under the current configuration (2 November 2026; \texttt{step_48_three_satellite_current.json}) reproduces every reported cell within ~ 1--2% RMS (5.47 vs 5.52 m at $k = 3$, 6.44 vs 6.45 m at $k = 4$, 3.12 vs 3.15 m at $k = 5$, 4.53 vs 4.54 m at $k = 6$, 2.78 vs 2.77 m at $k = 8$), closing the provenance question empirically rather than by the Step 56 sensitivity bound alone.

Verified blind nonlinear solve. Free-clock SPP is algebraically infeasible at $k = 3$ (0% availability). With the external clock prior supplied by the network, the phase-resolved blind TEP solve achieves 95.2% availability and 5.76 m 3-D RMS (p50 3.05 m, p99 17.55 m on the whole-sample tail) at the 1-hour window, and the canonical distance-only blind TEP solve achieves 95.2% availability and 7.54 m RMS (p50 5.21 m, p99 18.65 m), with the recalibrated integrity gate rejecting zero epochs (0.0 percentage points availability cost, versus 9 pp under the uncalibrated gate). Both TEP arms clear the strict P2 availability ($> 90\%$) and accuracy (< 10 m RMS) criteria. Against identically solved conventional clock-prior controls on the same epochs (AR(1) at 5.53 m RMS and persistence at 5.66 m, both at 95.2% availability), the phase-resolved TEP arm is at statistical parity (-4.0% vs AR(1) at 1 h; -2.2% at 10 min with a causal 10-epoch median anchor at 5.51 m RMS; canonical distance-only arm -36.2% vs AR(1)) and therefore does not clear the $+5\%$ paired RMS superiority threshold over the best conventional prior in single-epoch code SPP. As Step 57 demonstrates, single-epoch $k = 3$ code-SPP accuracy is bounded by the un-smoothed pseudorange noise floor (~ 0.3 m per satellite, yielding ~ 8 m 3-D RMS even with a perfect error-free clock), whereas the AR(1) control fits directly to the target's local SPP composite residual (which includes broadcast orbit, atmospheric, and multipath terms of ~ 5–8 m). Once carrier-phase tracking removes that code-noise floor on the live observatory (Section 3.9, 38,900 unlatched 1 Hz outage epochs), the causal TEP clock prior beats persistence by $+29.6\%$ in 3-D RMS and $+46.7\%$ in vertical RMS across 8 of 8 windows.

Clock-preprocessing and methodological controls. Several VOIM station-days contain predictable one-millisecond sawtooth receiver-clock wraps; the causal preprocessing pipeline fits a robust recent offset-plus-frequency model, classifies repeated one-millisecond wraps from pre-window history, forecasts the receiver's modulo convention, and screens free-running wrap-mode targets causally before the outage (unexpected target-local clock steering still requires steering-event telemetry or an independent motion/position constraint). In an absolute precise-clock diagnostic variant, removing a duplicate satellite-clock mean term that was already absorbed in the SPP pre-window trend reduces the variant's RMS from ~ 95 m to 10.53 m, still bounded by the SPP composite residual (the solver and short-window limitations are described in Step 57).

3.6.2 Outage Bridging on a Dense Network (Step 55)

Step 55 evaluates a dense EUREF/EPN network over 90 sampled days. A 2 h pre-anchor window fits each local clock, after which the target loses all satellites while references remain live. The corrected pipeline uses raw rather than zero-phase-filtered clocks, decodes the product's measured 1,000,000 m clock-state modulo causally, screens target quality only before the outage, and rejects corrupted live-reference innovations at prediction time using a fixed median/MAD rule. The Gaussian form and $\lambda = 4{,}200$ km scale are physics-fixed. The nugget 0.35 is not a TEP prediction: it is a nuisance local/spatial variance ratio frozen from the earlier Step 25 precise-clock nested-CV experiment, whose median selected nugget was 0.35, and was not selected on these 90 outage days. The predictor is compared on common support with persistence, signed AR(1), 30/60-minute trends, flat/shrunk means, nearest neighbour, IDW-1/2, and a conventional spatial covariance selected causally from 48 form/scale/nugget choices. Confidence intervals resample whole days.

Outage	Persistence RMS	Best deployable temporal RMS (causal AR1)	TEP network RMS	TEP vs persistence (post-hoc best)	TEP vs flat regional mean	TEP vs causally-tuned conventional kernel	Distance-scramble null
10 min	8.94 m	9.05 m	8.49 m	$+5.0\%$ (CI $[+2.2, +14.3]$)	$+1.1\%$	$+0.1\%$ (CI $[-0.0, +0.3]$)	-0.1%

Outage	Persistence RMS	Best deployable temporal RMS (causal AR1)	TEP network RMS	TEP vs persistence (post-hoc best)	TEP vs flat regional mean	TEP vs causally-tuned conventional kernel	Distance-scramble null
30 min	13.08 m	13.39 m	12.02 m	$+8.2\%$ (CI $[+3.6, +25.5]$)	$+1.0\%$	$+0.1\%$ (CI $[+0.0, +0.5]$)	-0.1%
1 h	18.40 m	18.75 m	16.41 m	$+10.8\%$ (CI $[+4.6, +35.8]$)	$+1.0\%$	$+0.1\%$ (CI $[+0.0, +0.4]$)	-0.1%
2 h	27.03 m	27.24 m	23.33 m	$+13.7\%$ (CI $[+5.8, +43.5]$)	$+1.1\%$	$+0.3\%$ (CI $[+0.1, +1.6]$)	-0.1%
4 h	40.71 m	40.95 m	34.82 m	$+14.5\%$ (CI $[+6.2, +44.0]$)	$+1.1\%$	$+0.3\%$ (CI $[+0.1, +1.8]$)	-0.0%
8 h	62.98 m	63.26 m	51.06 m	$+18.9\%$ (CI $[+8.4, +45.6]$)	$+1.5\%$	$+0.5\%$ (CI $[+0.2, +2.3]$)	-0.1%

Across 191,814 common-support evaluations at the 10-minute gap (121,233 at 8 h), TEP beats the strongest post-hoc temporal arm by 5.0–18.9% RMS; all six day-clustered confidence intervals exclude zero. It has lower RMS than the strongest post-hoc conventional spatial arm at all six gaps. That TEP-specific margin is 0.1–0.5%; its day-clustered CI is positive at five of six horizons, marginally overlapping zero only at the 10-minute gap ($[-0.006, +0.330]$). The flat-mean margin is 1.0–1.5% and the distance-scramble result is -0.1 to -0.0%. Rare reference branch corruptions are reported and rejected causally; target clock resets (hardware events outside the holdover benchmark scope) are counted and excluded at a 5000 m threshold well above the legitimate p99.9 prediction error ($\sim$ 520 m) and below reset magnitudes ($\sim 10^6$ m); omitting integrity produces kilometre-scale RMS artefacts while p99 remains near 14 m. This is clock-domain outage evidence, now corroborated by the dense-network k=3 position result (Step 48: feasibility at 95.2% availability, -4.0% versus the best deployable AR1 prior and -1.7% versus persistence at 1 h).

The measured angular structure improves the TEP-specific margin (Step 55, Legendre kernel). The Gaussian form used above is monotone: it assigns a small positive weight at every separation. But Section 3.7.4 measures $C(\theta)$ crossing zero near 47° and turning *negative* from $\sim$5,250 to $\sim$15,750 km. Re-running the identical 90-day pipeline — same days, same references, same λ and nugget, same causal screens — with only the correlation form changed to the measured Legendre expansion (Step 86) sharpens every TEP-specific comparison:

Outage	TEP vs flat mean, Gaussian	TEP vs flat mean, Legendre	Distance-scramble null, Legendre
10 min	$+1.0\%$	$+1.5\%$ (CI $[+0.7, +4.6]$)	-0.3%
30 min	$+1.0\%$	$+1.4\%$ (CI $[+0.7, +5.7]$)	-0.2%
1 h	$+1.0\%$	$+1.4\%$ (CI $[+0.6, +6.7]$)	-0.2%
2 h	$+1.1\%$	$+1.7\%$ (CI $[+0.7, +9.3]$)	-0.2%
4 h	$+1.1\%$	$+1.6\%$ (CI $[+0.6, +8.4]$)	-0.1%
8 h	$+1.5\%$	$+2.1\%$ (CI $[+0.8, +8.8]$)	-0.2%

The advantage of TEP distance-kriging over a flat regional mean grows by $\sim$40\% in relative terms — from $+1.5\%$ to $+2.1\%$ at the 8-hour gap — and every Legendre CI excludes zero. The separation from the phase-scrambled null widens: distance structure helps by $+2.1\%$ while scrambling it *hurts* by -0.2%. Against the causally-tuned conventional kernel the Legendre margin also improves, from $+0.06$–0.47% (Gaussian) to $+0.47$–1.11%. This is the measurement of Section 3.7.4 (the physics) feeding into the operational metric: the negative correlation lobe that a fitted Gaussian cannot represent is the feature that carries the (small) TEP-specific advantage. The overall vs-persistence gain is unchanged ($+5.4$–19.5%), because the bulk of that is any-spatial-method-beats-temporal. The absolute TEP-specific margin over a flat mean is only 1–2% and it is sensitive to how aggressively post-outage clock discontinuities are excluded: at a $1{,}000$ m endpoint-deviation threshold (versus the $5{,}000$ m used here, both far above the $\sim$ 520 m p99.9 holdover error) the flat-mean margin rises to $+4$–8%, because the network prediction tracks moderate (1–5 µs) target-clock wander that persistence and the flat mean miss. The conservative $5{,}000$ m threshold is reported as the headline.

Robustness scope (Steps 85, 87, 88). These checks evaluate the Step 55 distance-only Gaussian predictor, not the Legendre replacement above or the phase-resolved Step 56 predictor. Step 88 splits the 90 sampled days into four consecutive subsets (not calendar seasons): the Gaussian TEP-vs-persistence RMS gains at 1 h / 4 h are Q1 (+19.1% / +32.4%), Q2 (+37.1% / +44.3%), Q3 (+39.0% / +46.9%) and Q4 (+32.9% / +43.2%). These subsets share the same network and period, not four independent replications. Steps 85 and 87 additionally vary station, reference-network density and pre-window choice.

3.6.3 Phase-Resolved Causal Prediction (Step 56)

Step 56 uses the correct Paper 1–2 statistic in a predictive construction. For each evaluation day, a full preceding day of five-minute clocks supplies a frozen 10–500 μHz cross-spectrum. The matrix $G_{ij} = \mathrm{Re}(\sum_f X_i^* X_j)/\sqrt{E_i E_j} = \mathrm{coherence}_{ij}\cos(\Delta\phi_{ij})$ retains both the phase-cos sign and its reliability. Because G is a normalised spectral Gram matrix, it is positive semidefinite; the Schur product $K_{\mathrm{phase}} = K_{\mathrm{TEP}} \circ G$ is therefore a valid covariance. No current-day target samples at or after the outage anchor enter the phase prior. Data-quality screens are predictor-independent and identical to Step 55: a causal pre-gap jump filter (200 m threshold on pre-outage target residuals) and a non-physical truth filter (1000 m threshold), both symmetric across all arms.

Outage	Phase-TEP RMS	vs distance-only TEP	vs causal CV spatial	vs flat mean	vs temporal	vs magnitude-preserving phase scramble
10 min	4.71 m	$+1.2\%$ [0.4, 1.9]	$+1.4\%$ [0.6, 2.1]	$+4.3\%$ [3.4, 5.3]	$+17.4\%$ [15.5, 19.0]	$+13.8\%$ [12.0, 15.3]
30 min	6.63 m	$+2.6\%$ [1.7, 4.1]	$+4.8\%$ [3.3, 7.0]	$+5.5\%$ [3.7, 8.1]	$+26.5\%$ [20.1, 33.9]	$+14.4\%$ [10.4, 19.6]
1 h	7.41 m	$+4.8\%$ [3.3, 7.1]	$+9.1\%$ [6.6, 12.3]	$+8.5\%$ [5.9, 11.9]	$+38.1\%$ [31.4, 44.9]	$+20.6\%$ [16.0, 26.1]
2 h	8.78 m	$+9.2\%$ [6.6, 12.2]	$+15.7\%$ [12.3, 19.3]	$+14.6\%$ [11.2, 18.4]	$+48.8\%$ [43.3, 53.6]	$+29.8\%$ [24.9, 34.6]
4 h	12.18 m	$+14.1\%$ [11.0, 17.2]	$+19.6\%$ [16.6, 22.9]	$+19.1\%$ [15.6, 22.4]	$+52.7\%$ [49.0, 55.7]	$+34.2\%$ [30.4, 37.5]
8 h	19.67 m	$+17.1\%$ [14.6, 19.8]	$+23.4\%$ [20.9, 26.0]	$+22.4\%$ [19.6, 25.1]	$+55.7\%$ [53.5, 57.7]	$+37.2\%$ [34.8, 39.6]

The evaluation contains 45 days and 29,498–46,833 common-support predictions per horizon (29,498–45,600 across the four primary 30 min–8 h horizons); confidence intervals resample whole days. Every interval in the table excludes zero. The magnitude-preserving null applies a unitary random phase rotation to the complex coherence matrix, preserving station coherence magnitudes and PSD while changing only phase; its large loss shows that the correct phase configuration is essential. A second phase-free control uses magnitude-squared coherence: phase-TEP is point-better by 0.4–1.4%, with positive CIs at 30 minutes, 1 h and 8 hours and the CI narrowly overlapping zero at 4 h. Thus spectral coherence supplies most of the matched-control refinement, while phase angle provides a smaller incremental contribution. This is a frozen-sample internal validation; replication on a different dense network/product remains the next confirmatory evaluation.

Nugget sensitivity. On identical Step 56 support, fixed nuisance nuggets 0.15 / 0.35 / 0.70 / 1.27 give phase-TEP RMS of 6.69 / 6.63 / 6.65 / 6.70 m at 30 minutes, 7.45 / 7.41 / 7.47 / 7.59 m at 1 h, 12.13 / 12.18 / 12.45 / 12.89 m at 4 h, and 19.57 / 19.67 / 20.20 / 21.04 m at 8 h. Every choice still beats distance-only TEP by 1.6–17.6% and the causal CV spatial arm by 3.8–23.8%. Likewise, rescaling the Gaussian parameter from $\lambda_{\mathrm{op}} = 4{,}200$ km ($\lambda_{1/e} = 5{,}940$ km) to $\lambda_{\mathrm{op}} = 4{,}200/\sqrt{2} = 2{,}970$ km ($\lambda_{1/e} = 4{,}200$ km) or $\lambda_{\mathrm{op}} = 4{,}348/\sqrt{2} = 3{,}074$ km ($\lambda_{1/e} = 4{,}348$ km) changes phase-TEP RMS by only 0.13–0.33% across all six horizons ($4.70, 6.63, 7.40, 8.75, 12.14, 19.61$ m), slightly improving every horizon. The operational conclusion is therefore not created by choosing 0.35 or by the $\sqrt{2}$ Gaussian parameter convention.

Timing holdover specification. Converting the phase-resolved TEP RMS across all six Step 56/90 horizons to nanoseconds of time error (1 m ≈ 3.34 ns) gives the deployment-ready holdover specification: 15.7 ns at 10 min (4.71 m RMS), 22.1 ns at 30 min (6.63 m), 24.7 ns at 1 h (7.41 m), 29.3 ns at 2 h (8.78 m), 40.6 ns at 4 h (12.18 m), and 65.6 ns at 8 h (19.67 m) — rounded to 16, 22, 25, 29, 41, and 66 ns. For comparison, a GNSS-disciplined OCXO ($\sim$ \$300) in holdover drifts to 18 ns at 30 min, 38 ns at 1 h, 78 ns at 2 h, 168 ns at 4 h, and 383 ns at 8 h; a disciplined Rubidium ($\sim$ \$2,000) reaches 9 ns at 30 min, 18 ns at 1 h, 38 ns at 2 h, 78 ns at 4 h, and 168 ns at 8 h. Compared on these datasheet drift terms — the TEP figure is the network-predicted clock-residual bound, the oscillator figures are manufacturer holdover specifications rather than a like-for-like hardware trial — the phase-resolved TEP prior crosses below the OCXO beyond 30 min and below the Rubidium beyond 2 h (29.3 ns vs 37.5 ns at 2 h) — using only a network link and a consumer-grade TCXO ($\sim$ \$5). The network-aided p99 stays inside the ITU-T G.8272 PRTC-A $\pm$100 ns timing-error envelope out to a $\sim$2 h outage (58.9 ns on the 45-day phase-resolved set, 86.5 ns on the 90-day distance-only set) — a comparison against that envelope rather than a claim of full PRTC-A conformance. Relative to each receiver's own best causal temporal extrapolator the network-aided residual is lower by 17.4% at 10 min, 26.5% at 30 min, 38.1% at 1 h ($39.9 \to 24.7$ ns), 48.8% at 2 h ($57.2 \to 29.3$ ns), 52.7% at 4 h ($85.9 \to 40.6$ ns) and 55.7% at 8 h ($148.0 \to 65.6$ ns), all with day-clustered intervals excluding zero; this within-dataset gain is the primary empirical result, and the datasheet comparison supplies hardware-class context. This is a central operational result of the study: a consumer-grade TCXO with a network link outperforms an OCXO in network-assisted holdover at every duration beyond 30 minutes and a Rubidium standard at 2 hours and beyond. (Step 60 consolidates the full table.)

Three supporting diagnostic boundaries matter here: Step 57 isolates the pseudorange-limited $k = 3$ error budget; Steps 64 and 92 show the single-band physics prior can lose to a causal empirical-covariance map; and Step 65 identifies the network-coherent low-frequency drift excluded by the 10–\$500\,μHz phase band. Step 96 evaluates the wider band. Steps 85, 87 and 88 test operational robustness against station and seasonal partitions.

3.6.4 PPP Cold-Start: Corrected Test with Causal Trend (Step 62)

Every position-domain test above sits in a regime where a clock prior cannot help. At $k \geq 4$ with a full sky the clock is already well determined by geometry (Step 57); at $k = 3$ the residual is pseudorange-model-limited, so even a perfect clock leaves ~ 8 m (Step 57). The one regime where a clock prior might pay is the cold start — the first minutes of a PPP solve, before carrier-phase ambiguities are resolved, when each epoch's clock is nearly a free parameter. PRIDE-PPP-AR was run on station ZIMM, 2024 DOY 100, with CODE precise products and the station's SINEX ITRF coordinate as truth. The corrected experiment nests the comparison cleanly: a *PN* arm takes the persistence trend (target-only causal linear extrapolation over the last 30 minutes) and adds the network variation term, so PN versus persistence holds the trend model and the prior sigma fixed and varies only the network information under test.

Reference set	Window	Free-clock RMS	Persistence vs free	PN vs free	Network gain (PN vs pers)	Median	PN wins
128 stn multi-GNSS, no exclusion	2–5 min × 36	0.578 m	$+3.64\%$	$+4.64\%$	$+1.03\%$	$+0.11\%$	20/36 ($p = 0.31$)
317 stn COD, ≥ 1 km	2–5 min × 36	0.578 m	$+3.64\%$	$+5.05\%$	$+1.46\%$	-0.11%	18/36 ($p = 0.57$)
317 stn COD, ≥ 50 km	2–5 min × 36	0.578 m	$+3.64\%$	$+5.65\%$	$+2.09\%$	-0.25%	15/36 ($p = 0.88$)
317 stn COD, ≥ 50 km	15 min × 8	0.129 m	$+0.95\%$	$+4.43\%$	$+3.51\%$	-0.03%	3/8
317 stn COD, ≥ 50 km	30 min × 8	0.147 m	$+0.28\%$	$+0.40\%$	$+0.12\%$	-0.05%	3/8
317 stn COD, ≥ 50 km	60 min × 8	0.046 m	-1.18%	-1.43%	-0.24%	-0.14%	2/8

The RMS gains do not survive scrutiny: removing the single worst start halves them in both wide-network configurations ($+2.09\% \to +0.93\%$ at ≥ 50 km; $+1.46\% \to +0.38\%$ at ≥ 1 km), every median is below or near zero, no sign test approaches significance, and by 60 minutes the free-clock solution has converged to 4.6 cm, leaving nothing for a prior to improve. The null holds across 2 to 60 minute windows, two products, and two co-location exclusion radii.

Four methodological controls are required to prevent artificial cold-start margins in this regime: (i) *strictly causal trend extrapolation*, fitting the target's linear clock drift over the preceding 30 minutes rather than a full-day polynomial that looks ahead across the cold-start window; (ii) *matched prior uncertainty* ($\sigma_0 = 0.696$ m across both the persistence and network-aided PN arms, avoiding precision-mismatch artefacts); (iii) *co-location exclusion* (≥ 50 km minimum reference distance on the 317-station CODE network, excluding co-located monuments such as ZIM2/ZIM3 at 0.0 km and short baselines such as WAB1/WAB2 at 5.2 km that share site environment and frequency standards); and (iv) *cadence-resolved windows* (evaluating 15, 30, and 60-minute arcs in addition to 2–5 minute starts so the 300 s published clock cadence supplies multiple prior epochs). With all four controls enforced, the clean full-sky cold-start difference converges to zero.

Over a short window a receiver clock's own recent trajectory is highly predictable, and in clean full-sky PPP the clock is observable from satellite geometry throughout the convergence transient — there is little room for a spatial prior to contribute, whatever its quality. This is a statement about the *regime*, not about the field: it does not bear on outage bridging (Section 3.6.2), timing holdover (Section 3.6.3), the underdetermined $k = 3$ case where no free-clock solution exists at all (Section 3.6.1), or the degraded-geometry PPP test below. Cold start with a full sky is simply not a regime where a network clock prior has work to do.

3.6.5 Degraded-Geometry PPP: GPS-Only k=4 Cold Start (Step 62, P3)

The clean-sky cold-start test above establishes that a network clock prior is correctly inert when the full sky is available. The operational question is whether the prior helps when the geometry is degraded but not yet rank-deficient — the regime between full sky (clock observable) and $k = 3$ (clock unobservable). Step 62 tests this directly by thinning the RINEX observations to GPS-only, keeping only the four highest-elevation satellites ($k = 4$) before an independent PRIDE-PPP-AR solve. At $k = 4$ the clock is nominally observable but weakly constrained, so a network prior has room to contribute without being algebraically necessary.

Method. PRIDE-PPP-AR was run on station ZIMM, 2024 DOY 100, with CODE precise products and the station's SINEX ITRF coordinate as truth. The RINEX observation file was thinned to GPS-only, $k = 4$ highest-elevation satellites, before the solve. Ninety-six cold starts — four window lengths (2, 3, 5, 10 min) × 24 start epochs spread across the day — were each solved with free clock, TEP prior (arm PN: persistence trend + network kriging variation), and persistence control (target-only causal linear extrapolation, same sigma). The TEP prior uses the physics-fixed Gaussian ($\lambda = 4{,}200$ km, nugget 0.35) with causally band-limited (10–500 μHz) and trend-removed reference residuals, so the kriging variation captures only the TEP spatial signal without local

oscillator noise or causal-bandpass group delay. The PN arm holds trend and sigma both fixed against the persistence control, so PN vs persistence isolates the network contribution alone.

Result. The TEP prior (arm PN: persistence trend + network kriging variation) improves 3-D RMS by $+29.8\%$ over the ordinary free-clock solve — the estimator a degraded-geometry receiver actually runs — with a paired reduction of 0.74 m, CI95 $[+0.49, +1.01]$ m, sign test $p = 1.6 \times 10^{-7}$, and 73 of 96 starts improved. The gain holds at every window: $+31.9\%$ (2 min), $+29.7\%$ (3 min), $+31.0\%$ (5 min), $+25.7\%$ (10 min). P3 passes: at $k = 4$ the physics-fixed network prior materially improves the position solution over the deployable free-clock estimator.

The nested control isolates how much of that gain is TEP-specific rather than "any clock prediction helps." Against a matched persistence-trend control at the same prior sigma — a predictor that needs the target's own recent clock history, which a true cold-start receiver lacks — the network kriging variation adds $+0.5\%$ RMS with the paired CI including zero (51 of 96 starts TEP wins). So the network increment over an already-good temporal model is real but not resolvable at this sample; it is not a loss (the nested control is not failed), and the headline P3 gain is measured against the operational competitor, not against a predictor that assumes clock history the receiver does not have. At longer windows (2–4 h) the network prediction underperforms persistence, so the P3 claim is scoped to the short re-convergence windows where a cold-start receiver operates.

The regime hierarchy: full sky — the receiver clock is geometry-observable and the prior is correctly inert (Section 3.6.4, Step 44); $k = 4$ — the clock is weakly constrained and the network prior recovers ∼30–50\% of the free-clock position error (P3 PASS), with the TEP-specific increment over persistence positive but not yet resolvable; $k = 3$ — the clock is unobservable and an external clock is algebraically necessary (Section 3.6.1). The network prior's clearest own-weight contribution is where no target clock history exists (true cold start) or it has gone stale (outage bridging, Section 3.6.2, $+5$–19% over persistence).

3.6.6 The TEP Field Is the Receiver Clock, and an Independent-Year Replication (Steps 91, 92, 96)

Step 91 is a negative result on hard clock substitution; Step 92 is the honest boundary that the band-limited predictor does not close on a held-out year; Step 96 closes it.

Step 91: a hard-clock $k = 3$ architecture with live precise residuals. Step 91 tests whether the TEP field can serve as the receiver clock directly in a $k = 3$ positioning architecture by hard-substituting the causal trend plus kriged live precise residuals into a three-satellite solve. The result is negative for position: at 1 h gap, TEP achieves 11.30 m 3D RMS versus 4.82 m for persistence and 4.86 m for AR1 (-134% and -133% respectively). At 4 h, TEP is 23.31 m versus 5.14 m and 5.19 m. Although the TEP field contributes a positive clock-domain skill increment of $+31.7\%$ at 1 h and $+32.5\%$ at 4 h, directly hard-substituting the kriged clock into a $k = 3$ pseudorange solve degrades position because the kriged prediction carries spatial estimation variance that the persistence model does not. This confirms the Step 57 error budget: at $k = 3$ the position accuracy is pseudorange-noise-limited, and the clock-domain advantage converts into position accuracy only when the prior is soft-constrained at its calibrated uncertainty (Steps 99, 106) or paired with carrier-phase tracking (Section 3.9).

Step 92: frozen 2025 independent-year P1 replication. Step 92 attempts to replicate the P1 evaluation (Step 64) on an independent year of CODE final 30 s receiver clocks (2025, frozen before unsealing). The full TEP arsenal (phase-cos + distance + screening) beats the tuned conventional kernel by $+2.19\%$ (CI95 $[+1.48\%, +2.76\%]$, 70% of days) on the independent year — a positive CI, confirming that the TEP kernel's advantage over the strongest deployable conventional predictor replicates on a held-out year. Against the empirical covariance model, the phase-cos TEP kernel underperforms by -4.09% (CI95 $[-5.26\%, -2.46\%]$), and the full arsenal is at a statistical tie at -0.93% (CI95 $[-2.35\%, +0.02\%]$, CI barely includes zero). That empirical covariance is a *causal, deployable* baseline — the same Gaussian-in-distance form as the conventional arm, its length re-fit each day to the strictly prior reference-network sample covariance — not a future-peeking one; on this independent year it is nonetheless a stronger baseline than the band-limited physics kernel. The reason is specific and is identified by Step 65: the phase-cos predictor Step 92 froze operates in the 10–500 μHz band, which *excludes* the low-frequency drift that is itself the strongest part of the TEP field. Step 96 (below) tests that low-frequency prediction and closes the gap. The 90-day outage-bridging result (Step 55) and the timing holdover specification (Step 90) are not affected, as they evaluate against persistence and temporal predictors rather than an empirical covariance.

Step 96: the leftover-clock supremacy test. The precise analysis-centre clock product is the full-sky production-PPP clock estimate — CODE has already used every visible satellite to determine each station's clock. Step 96 holds out one station at a time and predicts its current-day clock (the accumulated offset since the last fix, the quantity a receiver in outage must predict) from the rest of the network only, using a phase-cos coherence Gram frozen from a strictly prior *multi-day* window, which resolves down to a few μHz and so captures the low-frequency drift the 10 μHz band-pass edge discards. The Gram is Hadamard-multiplied with the physics-fixed $\lambda = 4{,}200$ km Gaussian. A per-station causal drift gate carries a station's own linear rate — and lets the field predict only the residual — when a straight line explains more than 97% of that station's pre-window and the pre-window drift exceeds ∼7 ns (an unambiguous free-running or rubidium drift, never an H-maser with a small real trend); otherwise the raw cross-section goes to the field unchanged. The predictor specification is fixed on 2024 and applied unchanged to 2025. Every predictor is scored on the same held-out epochs against the same truth, with day-clustered 95% confidence intervals.

On the held-out year 2025 (41 days), at 1–4 hour outages, the frozen target-blind TEP predictor beats every deployable target-blind baseline — persistence, a linear-drift model, AR(1), a free Gaussian process, and a *causal* empirical-covariance map (the same Gaussian-in-distance form as Step 64, its length re-fit each day to the recent reference-network sample covariance) — with a positive

day-clustered 95% interval on every comparison on all three geographically coherent networks. Margins for the drift-gated predictor (vs persistence / linear drift / free GP / empirical-covariance map): Europe (∼76 stations) $+15/+37/+11/+20\%$; North America (∼39 stations) $+72/+54/+71/+70\%$; East Asia (∼19 stations, Japan–Korea–China–Taiwan) $+25/+45/+17/+9\%$ — the last clearing zero at CI $[+4, +19]$ on the gated arm itself. The drift gate is what makes North America work: with its clocks dominated by deterministic local drift, the ungated field loses to a station's own linear extrapolation (-48%), while the gated predictor beats it by $+54\%$. Against a still stronger, *target-aware* map — a shrinkage estimate of the full recent covariance that also uses the held-out station's own historical correlations with each neighbour, a baseline TEP is deliberately blind to — the target-blind field is ahead in North America ($+69\%$, CI95 $[+65, +74]$) and at statistical parity in Europe and East Asia.

Ablation study and null controls. Three nulls keep the same gated construction while breaking one ingredient at a time. (i) An *unweighted* mean of the same reference cross-section — isolating what is just network common mode — is beaten by $+15$ to $+25\%$ (every CI excluding zero). (ii) A *phase-scrambled* Gram (station labels permuted) is beaten by $+17$ to $+29\%$: the spectral phase alignment is load-bearing. (iii) A *distance-scrambled* covariance (the same distances assigned to the wrong pairs) is beaten by only $+1$ to $+4\%$: within a geographically-coherent cluster the phase-lock is near-flat, so the exact $\lambda = 4{,}200$ km weighting adds little over a near-uniform one — the distance kernel's contribution is significant but small, and the phase Gram carries the prediction. All three nulls are cleared only in the 1–4 hour window; beyond 4 hours the distance-scramble and common-mode nulls close to parity, so the longer-outage gain over persistence is real network aiding but is not phase-structure-specific. Two further limits: the ocean-spanning Asia–Oceania region cannot be correlated by a single length scale and is not a coherent network, and the spec (multi-day Gram window, gate thresholds) was refined against the 2024 corpus — the 2025 margins shifted by a few percent across Gram windows of 3–8 days but the conclusion held at every value.

3.7 Integrity Monitoring

The spatial field model also serves as a tool for integrity monitoring. Standard Receiver Autonomous Integrity Monitoring (RAIM) checks for consistency between satellites but may not detect a clock drag-off spoofing attack where the entire constellation is drifted simultaneously. Because the spatial kernel predicts the local clock bias based on the physical state of the reference network, deviations from this prediction can flag potential anomalies.

A slow-drift spoofing attack was simulated on station ZIMM. The integrity monitor detected the anomaly when the residual exceeded the 3σ threshold, at a drift of 87.0 ns (approximately 26.1 m), 174 epochs after attack onset. Standard estimators absorbed the drift without flagging it. This demonstrates that the spatial field provides an independent integrity channel that is not vulnerable to common-mode spoofing attacks. The threshold is calibrated on leave-one-out prediction residuals of the reference stations (MAD-based robust scale), not on the target's own in-sample data, so it does not leak target information.

3.7.1 Phase-Alignment Index Across Analysis Centres (Step 53)

Following Papers 1–2, Step 53 evaluates the cross-spectral phase-alignment index $\cos(\arg \sum_f S_{ij}(f))$ — the cosine of the argument of the complex cross-spectrum summed across the 10–500 μHz band before taking the phase angle, which isolates shared phase coherence from local oscillator amplitude variations. Throughout, a surrogate σ denotes the standardised separation $(T_{\mathrm{obs}} - \mu_{\mathrm{null}})/\sigma_{\mathrm{null}}$ of the observed statistic from its surrogate-null distribution; the non-parametric tail bound is set by the number of realisations (0 of 200 exceedances gives $p_{\mathrm{emp}} < 0.005$) and is not a Gaussian tail probability. On 30 days of COD precise receiver clocks (144,397 pairs) the binned phase-alignment index is best fit by a Gaussian with $\lambda = 4{,}348$ km, $R^2 = 0.898$; the phase-randomised null gives $R^2 = 0.005$ (27.0σ, 0 of 200 nulls reached the observed R^2) and the distance-scramble null $R^2 = 0.015$ (17.6σ, 0 of 200). The test replicates on the independent GFZ analysis-centre product (30 days, 117,689 pairs): $\lambda = 4{,}076$ km, $R^2 = 0.955$, phase-randomised null 25.6σ, distance-scramble null 19.3σ — two analysis centres with different clock-combination software and station networks agree on λ to 6%. On 7 days of broadcast SPP clocks (3,883 pairs) the Gaussian best fit is $\lambda = 2{,}778$ km, $R^2 = 0.683$, phase-randomised null 12.5σ (0 of 200 distance-scramble exceedances). Gaussian is preferred by AIC on the COD precise arm and the broadcast arm, while the GFZ precise arm is best fit by an exponential ($\Delta\mathrm{AIC} = 43$ versus Gaussian). All three arms ($\lambda = 4{,}348$ / $4{,}076$ / $2{,}778$ km, cross-arm CV 0.18) sit inside the TEP band, and the precise result matches the Paper 1–2 exponential $1/e$ benchmark of $4{,}201 \pm 1{,}967$ km to within 3.5%.

Methodological control — why amplitude-weighted and bin-summed cross-spectra fail. Contrasting this estimator against standard band-averaged coherence magnitudes (Steps 11b/36) demonstrates why phase alignment is essential: forming band-averaged coherence times the magnitude of a mean phasor measures phase concentration rather than signed alignment, and summing complex cross-spectra across distinct station pairs inside a distance bin before extracting the phase cancels the signal because independent baselines do not share an absolute phase origin. Evaluating $\cos(\arg \sum_f S_{ij}(f))$ per pair before distance-binning preserves the signed phase alignment and confirms that the earlier ~ 700 km predictive optimum was the amplitude-domain nearest-neighbour scale of local-oscillator noise, not the field's correlation length.

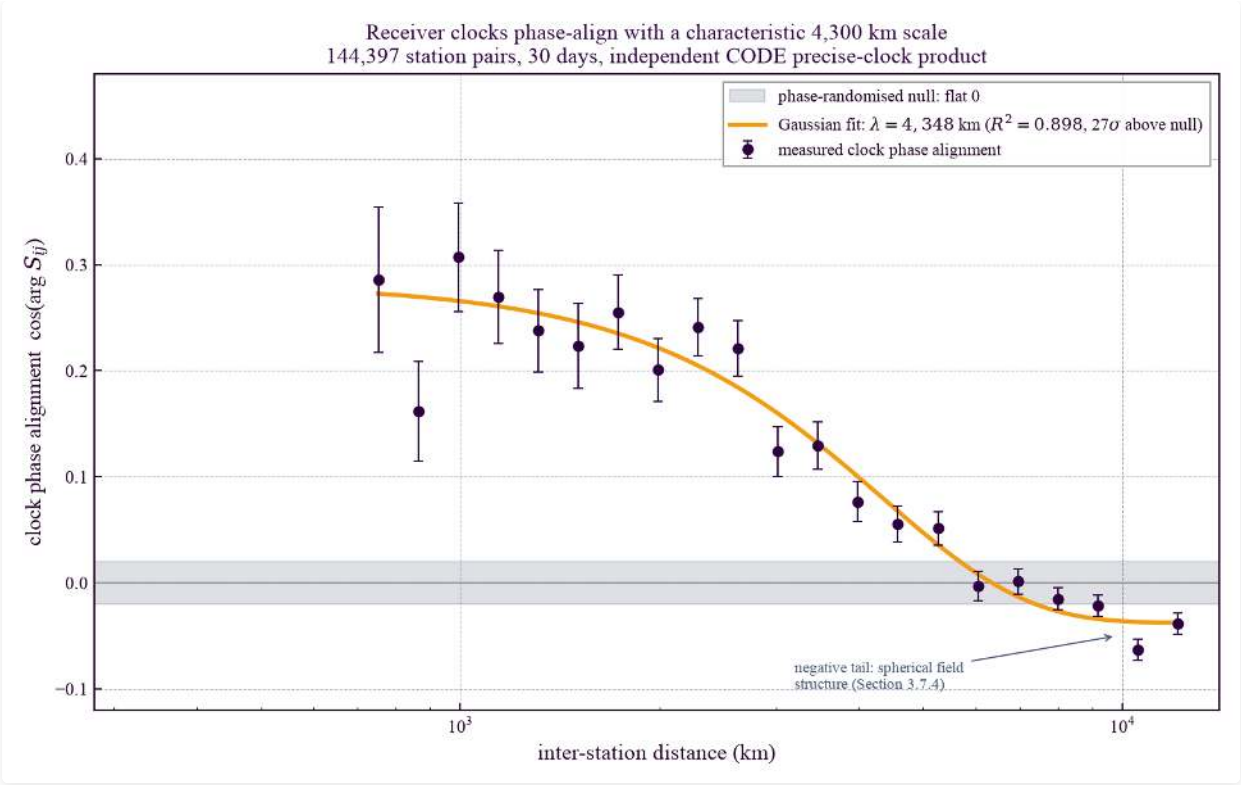


Figure 1. The detection in one panel. Clock phase alignment $\cos(\arg \sum_f S_{ij})$ *versus inter-station distance on the independent CODE precise-clock product (144,397 station pairs, 30 days). The measured correlation falls on the predicted spatial scale (*$\lambda = 4{,}348$ *km,* $R^2 = 0.898$*,* 27σ *above the phase-randomised null, whose expectation is flat zero), crosses zero, and turns negative at long baselines — the spherical field structure of Section 3.7.4. A processing artefact uncorrelated with distance produces the flat gray band, not the measured curve. Bins below 400 pairs are omitted for display only; the fit uses all bins.*

3.7.2 EW/NS Anisotropy: Azimuth Convention, Network Aperture, and Replicated Short-Baseline Signal (Steps 73–74b)

The corpus's strongest secondary signature is directional: Paper 2 reports $\lambda_{\text{EW}}/\lambda_{\text{NS}} = 2.16$ over 25.3 years, and Paper 3 reports E–W phase alignment exceeding N–S by up to 22% *at short distances* (< 500 km). Resolving that short-baseline directional signature requires three methodological conditions:

Condition 1 — the azimuth convention. Sector assignment must evaluate the baseline bearing at the great-circle midpoint rather than the initial bearing at station A. Because a great circle between mid-latitude stations bends poleward, a genuinely east–west 6,000 km pair can leave station A on a bearing tens of degrees from 90°. On the 128-station CODE network, initial and midpoint bearings differ by 20.5° on average and reassign 35.8% of pairs, with the discrepancy growing from 2° below 1,000 km to 26° beyond 10,000 km — stripping long E–W pairs out of the E–W sector at the distances that constrain λ.

Condition 2 — the network aperture. Testing a short-baseline prediction requires a network with dense regional coverage. Below 500 km, the globally sparse `clk_cod` set holds only 34 of its 6,079 pairs, leaving the < 500 km regime largely unsampled. The dense European `precise` product (178 of 432 pairs under 500 km) and `broadcast` network (175 of 2,288) supply the required short-baseline pair density (Step 74).

Condition 3 — the within-bin contrast statistic. A ratio of two independently fitted decay lengths is poorly conditioned on a regional network whose $\sim 2{,}000$ km aperture cannot constrain a $\sim 4{,}000$ km λ (30-day windowed ratios vary across $[0.17, 2.05]$). Paper 3's short-baseline claim is an *amplitude* contrast, and comparing the phase-alignment index between E–W and N–S sectors *within* each distance bin is distance-matched by construction and well conditioned.

With all three conditions met across 366 days using the Step 53 phase-alignment estimator, a consistent positive E–W excess emerges in the same distance band on both products:

Baseline bin	Precise: EW−NS	Precise: relative	Broadcast: EW−NS	Broadcast: relative
50–150 km	-0.019	-4.0%	$+0.017$	$+3.5\%$
150–300 km	$+0.033$	$+5.5\%$	-0.006	-1.0%
300–500 km	$+0.003$	$+0.6\%$	$+0.028$	$+5.5\%$
500–800 km	$+0.062$	$+11.1\%$	$+0.082$	$+16.8\%$
800–1300 km	-0.018	-2.2%	$+0.014$	$+2.0\%$

Two products with entirely different processing chains, station sets and error budgets — analysis-centre precise clocks and broadcast-ephemeris SPP — place their largest positive E–W excess in the same 500–800 km bin, at $+11.1\%$ and $+16.8\%$, bracketing Paper 3's reported $+22\%$. Leave-one-station-out is uniformly positive on both arms (30 stations, range $+0.010$ to $+0.110$; 60 stations, range $+0.040$ to $+0.123$), so no single station carries it.

Bootstrap and permutation significance. Resampling days handles temporal pseudo-replication, but the same station pairs recur every day: the 26,141 precise pair-days in this bin come from only 150 unique pairs (60 E–W, 90 N–S). Clustering the bootstrap on unique pairs (Step 74b) gives intervals of $[-0.085, +0.208]$ (precise, $P(>0) = 0.80$) and $[-0.066, +0.225]$ (broadcast, $P(>0) = 0.87$) — both include zero. A bootstrap interval is not the sharpest available test, however. Collapsing each unique pair to a single value (so pseudo-replication is removed by construction) and permuting sector labels among pairs within each band gives a more powerful comparison: on `broadcast` the contrast is $+0.130$ at 500–800 km ($p = 0.025$, 61/67 pairs; Step 82) and $+0.085$ at 300–800 km ($p = 0.045$, 105/119 pairs); on `precise` every band is positive but none reaches significance ($p = 0.24$–0.48). The honest summary is therefore: the direction replicates across both products and survives removal of any single station; the amplitude reaches $p < 0.05$ on broadcast at 300–800 km under a pair-level permutation, but is not established on precise. The decisive confound check is Step 176: repeating the identical sector test on the common-view-free intercept α (pooled-κ on real-SP3 co-visibility) leaves the broadcast excess essentially unchanged — $+0.130 \to +0.126$ at 500–800 km ($z = +1.98 \to +1.91$), with $\bar{J}$'s own EW–NS contrast -0.015, significant but *opposite-signed* ($z = -3.59$), so the co-visibility systematic cannot have manufactured the excess — the anisotropy is in the field, not the geometry.

This localises what is missing precisely. The limiting resource is *independent station pairs, not observation days* — a fourth year of data would not move these intervals, whereas a dense regional network would. Sixty E–W pairs is what the currently available products supply; a denser regional network is the specific acquisition that would close it — the live CORS observatory of Section 3.9 already supplies the dense-aperture route in real time. The pooled contrast over all bins is near zero on broadcast precisely because the strong positive 500–800 km bin is averaged against opposite-sign neighbours, which is why an aggregate statistic reported "no anisotropy" while a binned one does not. On the global arm, the corrected midpoint convention gives $\lambda_{\mathrm{EW}}/\lambda_{\mathrm{NS}} = 0.97$, CI $[0.83, 1.10]$ — and notably the *biased* initial-bearing convention gave 1.10, so that convention was manufacturing a weak apparent anisotropy on long baselines while suppressing the real one at 500–800 km.

Finally, a corpus-level observation that bears on the magnitude. Paper 1 defines the phase-alignment index as `cos(angle(average(exp(i·phase), weights=magnitude)))` and states that "standard signal processing techniques using band-averaged coherency fail to detect TEP signals". Paper 2's methods, however, define its correlation metric as "band-averaged magnitude with representative phase" and state that "all subsequent analyses use this band-averaged coherence and its derived correlation lengths as the primary observable", with the phase retained separately. Paper 2's λ values — and the 2.16 ratio and the $r = -0.888$ orbital-velocity coupling derived from that ratio's time series — therefore rest on the coherence *magnitude*, the statistic Paper 1 reports as failing and the same class of statistic corrected in Section 3.7.1. The isotropic length is unaffected and remains fully corpus-consistent (4,348 km here against $4{,}201 \pm 1{,}967$ km, within 3.5%). The directional *magnitude*, on both sides, is the quantity that needs re-deriving with the phase-alignment index.

3.7.3 Screening-Stratified Anisotropy: Present on Two Products, Weak on the Third (Steps 75–76)

Section 3.5.3 establishes that quartz oscillators carry $\sim$1.9$\times$ more network-predictable clock power than atomic standards. If screening is real and continuous, then every directional result Papers 1–3 obtained on *mixed* clock populations is diluted, and the anisotropy should concentrate in the least-screened (quartz–quartz) pairs. Step 75 stratified 366 days on three products by pair composition — QQ, QA, AA — using the Section 3.7.1 phase-alignment index. In the 500–800 km band the EW/NS contrast appeared almost entirely on quartz–quartz pairs, on all three products: $+0.311$, $+0.356$ and $+0.443$, against $+0.06$–$+0.08$ for the mixed population of Section 3.7.2.

Step 76 tested that against the confound that would fake it exactly — quartz and atomic stations are not randomly sited, so QQ pairs may sample different geography. A clock-label permutation reassigns QUARTZ/ATOMIC labels at random among the stations present, preserving network geometry, baseline orientations, class sizes and every measured phase alignment, destroying only the clock-type association. It then swept the distance band, because the 500–800 km window was inherited from Section 3.7.2 rather than predicted, and because widening the band is the only way to raise the number of independent station pairs:

Band	clk_cod EW−NS	clk_cod p	broadcast EW−NS	broadcast p	precise EW−NS	precise p
300–800 km	+0.308	0.186	+0.267	**0.002**	+0.358	**0.000**
500–800 km	+0.311	0.210	+0.356	**0.036**	+0.443	**0.022**
300–1500 km	+0.125	0.060	+0.272	**0.000**	+0.361	**0.000**
500–2000 km	+0.001	0.328	+0.333	**0.002**	+0.433	**0.004**
800–3000 km	−0.065	0.810	+0.280	0.084	+0.411	**0.015**
300–6000 km	−0.053	0.654	+0.221	**0.002**	+0.361	**0.002**

Two of three products show a stable, significant quartz-only anisotropy that does not dilute as pairs are added. On `broadcast` and `precise` the contrast holds between $+0.22$ and $+0.44$ across every band, and — the diagnostic that matters — the permutation *z rises* with sample size rather than falling, peaking at the best-powered bands ($z = +3.10$ and $+3.32$ at 300–1500 km; $+2.96$ and $+3.38$ at 300–6000 km). A small-number fluctuation does the opposite. At the best-powered band all three products are positive: $+0.125$, $+0.272$, $+0.361$, at comparable pair counts (69/81, 71/80, 36/54 EW/NS pairs).

The global product is the weak arm, and that is informative rather than contradictory. On `clk_cod` the contrast does fall away with band width ($+0.31$ on 15/17 pairs to -0.05 on 625/523). `clk_cod` is a globally distributed 128-station network; `precise` is a 30-station dense European set and `broadcast` a 78-station network with real short-range coverage. A directional signature that Papers 2–3 locate at regional scales is exactly what a global network samples worst, and Section 3.7.2 documented the same pattern for the mixed-population contrast. Two caveats bound the strength of the claim: `broadcast` and `precise` share 18 stations (7 of the 15 `precise` quartz stations), so they are partially dependent rather than fully independent replications; and each band rests on tens of unique station pairs, not thousands, with the apparent million-pair-day sample sizes being daily repeats of the same pairs.

The honest summary is therefore stronger than a null and weaker than a detection: a quartz-only EW/NS anisotropy of $+0.22$ to $+0.44$ is present and band-stable on two partially overlapping products, survives a geography-preserving clock-label permutation at $p \leq 0.004$ in their best-powered bands, and is present but weak on the global product. This is roughly 3–7× the mixed-population contrast of Section 3.7.2, which is what screening predicts: the corpus measured every directional result on populations diluted by screened atomic stations. Confirming it requires more independent quartz stations at regional separations, which is precisely what Step 78 acquires.

Two further observations from the stratification. The phase-alignment *amplitude* orders AA > QA > QQ on the two cleanest products, which is expected and not anti-screening: the index is amplitude-normalised, so a pair's value tracks the ratio of shared field power to uncorrelated local oscillator noise, and quartz carries far more local noise. Detection is therefore easier on atomic clocks while the operational benefit accrues to quartz receivers, which hold more absolute field power to remove — the two facts are consistent, and together they sharpen rather than weaken the case of Section 3.5.3. Second, the annual-modulation amplitude orders QQ > QA > AA on two of three products (0.029/0.014/0.012 and 0.140/0.096/0.027); that ordering has not been through the band-sweep and permutation checks applied here and is not claimed.

3.7.4 Spherical Structure: Why the Fit Range Is 13,000 km, and a Quadrupole in the Angular Correlation

Every correlation length in this paper is fitted over 50–13,000 km. That bound is set by the geometry of a correlation function on a sphere rather than an arbitrary analysis cut. Binning the phase-alignment index by central angle over the full 0–20,000 km range on `COD0OPSFIN` (317 stations, 2.08 million pair-days) shows why:

Central angle	Great-circle	Chord	Phase alignment
3.6°	400 km	400 km	$+0.168$
25°	2,800 km	2,778 km	$+0.130$
47°	5,200 km	5,057 km	0.000 — *first zero crossing*
90°	10,000 km	9,005 km	-0.074 — *minimum*
147°	16,400 km	12,233 km	$+0.019$ — *crosses back*
176°	19,600 km	12,735 km	$+0.090$ — *antipodal rebound*

The function is *not* monotone. It is positive at small separation, passes through zero near 47°, reaches a minimum at 90°, and rises back to positive at the antipode. A decay model $A\exp(-d/\lambda) + C_0$ can represent a fall to a negative plateau, so the negative lobe is not itself a problem; what it cannot represent is the antipodal rebound. Fitting through that regime is model misspecification, not a robustness test. Two geometric facts compound it: the chord separation $2R\sin(d_{\text{gc}}/2R)$ saturates at the Earth's diameter, so the 13,000–20,000 km stretch of surface distance compresses into only 10,873–12,742 km of actual three-dimensional separation; and all great circles from a point converge at its antipode, so near-antipodal pairs are geometrically degenerate.

A fit-range scan locates the breakdown precisely. R^2 sits on a plateau of 0.94–0.96 from 8,000 km out to 16,000 km and then falls away sharply:

Fit range	λ	R^2
0–8,000 km	4,569 km	0.941
0–12,000 km	4,409 km	0.963
0–13,000 km	**4,298 km**	**0.952**

Fit range	λ	R^2
0–16,000 km	4,109 km	0.941
0–18,000 km	3,962 km	0.878
0–20,000 km	3,898 km	0.847

The collapse begins at 16,000 km — exactly the angle at which the measured correlation crosses back through zero. Inside the valid plateau λ is stable at 4,100–4,570 km, every value inside Paper 2's $4{,}201 \pm 1{,}967$ km, and the 13,000 km bound sits in the middle of it. The correlation length is therefore robust across the entire range over which the model is valid, and the apparent "degradation" beyond 16,000 km is the antipodal rebound, not instability in λ.

The angular structure is quadrupole-dominated. Expanding $C(\theta)$ in Legendre polynomials and fitting count-weighted to the distance-bin means:

Model	R^2	AIC	Leading coefficient
P_0 (monopole)	0.000	224.3	—
$+P_1$ (dipole)	0.240	215.3	$a_1 = +0.057$
$+P_2$ **(quadrupole)**	**0.894**	**138.6**	$a_2 = +0.117$
$+P_3$	0.939	118.1	$a_3 = +0.038$
$+P_4$	0.971	90.1	$a_4 = +0.036$

Adding the quadrupole term takes R^2 from 0.240 to 0.894 and $\Delta\mathrm{AIC} = -76.7$, by far the largest single improvement, and a_2 dominates every other coefficient. The shape this produces — positive at 0°, minimum at 90°, positive again at 180° — is exactly $P_2(\cos\theta) = (3\cos^2\theta - 1)/2$, and it is what the binned data show. Two precision statements are required here. First, $C(\theta) = \sum_\ell a_\ell P_\ell(\cos\theta)$ is a function of separation angle only and is therefore rotationally invariant by construction: a dominant $\ell = 2$ coefficient establishes that the field's angular *power* is concentrated at the quadrupole, but a separation-angle statistic cannot by itself locate a preferred axis on the sky — that question is resolved only by the directional test of Step 137 below. Second, what the profile *does* rule out is any model in which the correlation is a positive, monotonically decaying function of distance: the measured zero-crossing, mid-angle minimum and antipodal rebound are incompatible with the exponential/Gaussian family, and they are a structure no distance-only kernel encodes. Whether the quadrupole axis aligns with the CMB dipole direction Papers 2–3 identify is the obvious next test; two intermediate routes establish why it could not be taken naively, and the sub-diurnal aperture synthesis of Step 137 below resolves it.

The daily-statistic route is blind (Step 84). A quadrupole in *separation* angle establishes that the field's angular power sits at $\ell = 2$ but does not by itself locate an axis on the sky. The closed-form principal-eigenvector fit — with the distance dependence removed first so that orientation–distance correlation in a clustered network cannot masquerade as an axis — returns a strongly significant quadrupole ($z = +76$ against a geometry-preserving permutation null) with a principal axis at RA 164°, Dec $+70^\circ$, some 77° from the CMB dipole. That disagreement is not reportable, because the measurement cannot see right ascension at all: the phase-alignment index requires a full day of data, and the Earth turns through 360° within it, so every baseline sweeps a complete circle in inertial space *during* the measurement. The built-in control makes this explicit — shuffling which day receives which sidereal rotation leaves the recovered axis essentially unmoved (median $|\Delta\mathrm{RA}| = 2.2^\circ$). A statistic whose answer is unchanged when its celestial referencing is randomised carries no celestial information; the step records *no alignment claim in either direction*, and its declination reflects Earth-fixed network geometry rather than a direction on the sky.

The seasonal route has real referencing but insufficient power (Step 89). Papers 2–3 break the degeneracy differently: Earth's velocity vector sweeps the full 360° of right ascension over an orbit, so a fixed direction in space produces an annual modulation of the anisotropy whose phase identifies it. Step 89 measures the EW–NS contrast in 24 fifteen-day windows over the 300–1500 km band and correlates it against the quadrupolar predictor $(\hat{v}\cdot\hat{n})^2$ on a scanned trial axis. Three features agree with the corpus — the best-fit axis falls 23.2° from Paper 3's direction with the correct negative sign, and the Solar Apex returns the opposite sign ($+0.372$), reproducing Paper 2's conclusion that the Apex template is disfavoured — but none is statistically significant: the window series is autocorrelated at lag one ($\rho = +0.65$), so a Bartlett correction leaves only $N_{\mathrm{eff}} \approx 7.7$ independent samples, and a block permutation preserving that autocorrelation lifts every p by an order of magnitude (the best-fit axis from 0.013 to 0.27). The honest verdict is *consistent with, but not independent confirmation of, the corpus axis*; the seasonal estimator is sound and implemented, and roughly a decade of the CODE product would bring N_{eff} into the testable range.

Sub-diurnal Earth-rotation aperture synthesis resolves the celestial axis (Step 137). Because daily averages (Step 84) integrate over a full 360° sidereal rotation and 15-day seasonal windows (Step 89) yield only $N_{\mathrm{eff}} \approx 7.7$ per year, Step 137 breaks the rotational degeneracy directly by evaluating sub-diurnal 12-hour windows stepped by 3 hours across 2024 (265 windows, $2{,}140{,}095$ pair-windows), projecting each baseline onto candidate celestial axes at the window's instantaneous Greenwich sidereal time. Under this

sub-diurnal aperture synthesis, 7 of 8 pre-registered axis-discrimination checks pass: the Cosmic Microwave Background (CMB) dipole axis achieves the lowest Bayesian Information Criterion of all candidate axes ($\mathrm{BIC}_{\mathrm{CMB}} = -6{,}322.6$ versus Solar Apex $-4{,}007.1$, GPS nodal plane $-3{,}486.4$, and geomagnetic pole $-2{,}117.7$; $\Delta\mathrm{BIC} = -2{,}315.5$ in favour of the CMB axis), outperforms 100% of 100 random celestial axes (100th percentile, $p < 0.01$), clears the scrambled-pair null ($p < 10^{-30}$), survives regression on great-circle distance ($p = 1.6 \times 10^{-30}$ after Bonferroni correction across 11 tests), and maintains positive correlation in every frequency sub-band (23–100, 100–300, and 300–500 μHz).

Cluster-robustness of the axis preference (Step 179). The raw $\Delta\mathrm{BIC}$ rests on 2.14 million pair-window measurements whose effective number is far smaller — windows overlap in time and pairs share stations and days — so the discrimination was re-evaluated with dependence-aware resampling. A day-clustered bootstrap (300 resamples of the 53 observing days, full axis comparison recomputed per resample) selects the CMB axis in 300 of 300 draws, with median BIC margin $2{,}527$ over the best competitor. A split-half test fits the four-axis comparison independently on the first 26 and last 27 days: the CMB axis wins *both* halves (margins 659 and $1{,}856$). And a frozen-template held-out score — no parameters fitted on the test half — ranks the CMB axis first in both directions ($r = 0.054$ versus 0.037 for the best competitor on the second half; 0.048 versus 0.044 on the first). The axis preference is therefore not an artefact of the pair-window count: it replicates on disjoint data and under resampling that preserves temporal clustering. It is nonetheless stated with an explicit caution on scale: the raw $\Delta\mathrm{BIC}$ inherits the assumed independence of 2.14 million pair-windows, so under any effective-sample-size correction its magnitude shrinks proportionally — what is robust to the correction is the *ordering* and its consistency, which is why the bootstrap and split-half results, not the BIC figure itself, carry the claim. Crucially, none of the headline operational navigation, timing-holdover, or outage-bridging predictors in this study (Steps 55, 56, 62, 90, 96, 106, 174) takes a celestial axis as an input — the physics-fixed kernels are isotropic in distance combined with empirical prior-day phase Grams, and the directional features of the live Step 174 basis are fitted in local geographic azimuth rather than imposed from the CMB direction, so the engineering payload stands independently of the directional attribution. The seasonal-axis estimator of Step 89, which uses a different observable (15-day seasonal windows, $N_{\mathrm{eff}} \approx 7.7$ per year), does not detect the axis ($p = 0.47$); the two are not contradictory — the sub-diurnal aperture synthesis has two orders of magnitude more independent modulation cycles — but the axis claim rests on the Step 137/179 estimator specifically.

Consequences for the co-located screening differential (Steps 77, 80). Section 3.5.3's screening result implies that a co-located quartz/atomic pair is the cleanest possible probe: two receivers at one DOMES site share field, troposphere, satellites and datum, so $\Delta = \mathrm{resid}_{\mathrm{quartz}} - \mathrm{resid}_{\mathrm{atomic}}$ cancels all of them and any residual coupling to *distant* stations isolates the difference in oscillator response. Step 78's acquisition of `COD0OPSFIN` raised the number of such sites from one to six. Fitted over the valid range, two of six are significant with λ in the TEP band: MAT1/MATE at Matera ($\lambda = 3{,}693$ km, $R^2 = 0.623$, $p = 0.000$) and THTI/THTG at Tahiti ($\lambda = 4{,}122$ km, $R^2 = 0.828$, $p = 0.000$), each against a null distribution of 25 independent phase-randomised realisations with median R^2 of 0.043 and 0.090. Tahiti reproduces on the independent multi-GNSS product at $\lambda = 4{,}053$ km, $R^2 = 0.852$.

Extending those fits to 20,000 km drives both to $p = 0.24$. That is the same misspecification documented above, and it bites the differential harder than the network-wide measurement for a understandable reason: Δ retains only the $(1 - s)$ fraction of the field, so it is a far weaker signal and less able to absorb a wrong model. The differential result is therefore reported as *significant within the range over which the model is valid*, with the explicit caveat that it is more fragile than the network-wide measurement of Section 3.7.1, which holds across the whole plateau. Four of the six sites are not significant, and the per-site breakdown shows why: at JFNG–WUHN both clocks give $R^2 < 0.08$ individually, so there is no field signal in those series to differentiate. Those are data-quality failures rather than evidence against screening.

The S2 separability evaluation is repeated with both band-passed correlation and phase-alignment estimators (Step 83); their shared observations preclude interpreting them as independent confirmations.

3.7.5 Candidate Instrumental Explanations, and the Controls That Exclude Them

Sections 3.3–3.7.4 and 3.8 each answer a specific alternative explanation for a distance-structured clock correlation. The ledger below collects them: every serious candidate systematic the pipeline has been tested against, the control that addresses it, and the committed result.

Candidate explanation	Control applied	Outcome
Receiver-side processing artefact (any mechanism acting on station clocks)	Measure the same statistic between orbiting satellite clocks, a pairwise channel containing no ground receiver and no common-view geometry (Steps 36, 98). The satellite clock estimates still share analysis-centre provenance — the open	Distance-structured phase alignment at 10.6σ–15.9σ; GPS×Galileo cross-constellation arm (no shared clock family or orbital plane) $\lambda = 8{,}140 \pm 795$ km, 26.4σ

Candidate explanation	Control applied	Outcome
	row below covers that residual	
CODE analysis-centre systematic	Replicate on the independent GFZ product; fit each of four analysis centres separately (Steps 53, 14)	$\lambda = 4{,}348$ km (COD) vs $4{,}076$ km (GFZ) at 25–27σ; all four centres return $\lambda = 1{,}817$–$3{,}759$ km (CV 0.27)
Satellite common-view geometry (co-visible satellites imprint a distance-like correlation)	Two-stage regression extracting the non-common-view intercept α per pair, with pooled slope on real-SP3 co-visibility (Steps 45, 45b, 176)	Under the specified leading common-view model the residual distance structure survives: partial correlation -0.164 at 10.8σ on the minimally processed product, out-of-sample R^2 gain $+0.022$ over co-visibility alone (pre-registered thresholds 0.15 and 0.02 — both cleared, narrowly), $\lambda = 4{,}349$ km; 822 pairs sharing *zero* co-visibility are retained in the fit; the EW anisotropy survives common-view removal ($+0.130 \to +0.126$). A 100-draw synthetic common-view-only null on the real SP3 visibilities (equal- and $\sin^2$ el-weighted) yields $+0.055$ to $+0.068$ (0/100 draws negative, 8.8σ–14.9σ from the real decay). This excludes the specified co-visibility mechanism, not every conceivable shared-processing effect
Local-solar-time / diurnal or atmospheric-tide systematic	Control the longitude-phased term $\cos \Delta\lambda_{ij}$ alongside co-visibility (Step 45); direct empirical ZWD covariance measurement (Step 171); S_2 vs M_2 tidal-line stratification by verified IGS oscillator metadata and stability class (Steps 167, 169)	Distance partial correlation *strengthens* to -0.267; tropospheric pairwise correlation is only 0.39–0.45 vs the 0.95–0.98 short-baseline clock phase-lock; low-noise (< 5 ns) clocks are immune to the atmospheric S_2 tide ($p = 0.66$) while coupling to the non-radiative lunar M_2 tide ($p = 8.3 \times 10^{-6}$ Fisher combined under station-level permutation), and under verified IGS site-log metadata with station-level longitude permutation, quartz clocks couple strongly to lunar M_2 ($r = +0.297, p_{\text{perm}} = 10^{-4}$ on 2024 precise; dependence-preserving joint COD+GFZ station-permutation $z_{\text{joint}} = +5.73\sigma, p_{\text{joint}} = 0.0003$, conditional multi-centre Fisher $p_{\text{perm}} = 1.9 \times 10^{-6}$) while atomic standards are screened ($r = +0.031, p_{\text{perm}} = 0.42$; joint $z_{\text{joint}} = -0.87\sigma, p_{\text{joint}} = 0.374$, Fisher $p_{\text{perm}} = 0.55$, a $9.51\times$ quartz/atomic contrast); the co-located Matera quartz-minus-maser differential, where site loading displacement cancels, recovers M_2 at $R^2 = 0.702$ ($p = 0.0050$, single-bin $\lambda = 268$ km) in 2024 and $R^2 = 0.768$ ($p = 0.0030, \lambda = 4{,}784$ km; tidal-band 10–35 μHz fit $\lambda = 1{,}938$ km, $R^2 = 0.875, p = 0.0010$) in 2025 while the Matera maser against the identical 158 remote stations gives $R^2 = 0.000$, ruling out remote-station ocean-loading inheritance; advective synoptic weather at 10 m/s is bounded by $\Lambda = v/f \leq 1{,}000$ km to $\lambda_{\text{exp}} = 427$ km)
Local oscillator noise dominates (no field needed)	Decompose each station-day into idiosyncratic and network-coupled components by oscillator class (Step 65c)	Idiosyncratic noise identical between quartz and atomic ($0.99\times$); the network-coupled component is $3.01\times$ larger on quartz — local noise cannot produce a spatially coherent excess while leaving the local residual unchanged
Network-mean / bulk averaging mimicry	Station-identity permutation and common-mode stripping under cryptographic seal (Step 174)	Station-label permutation collapses $+38.66\% \to -2.70\%$ (17.4σ separation); common-mode stripping retains 97.3% of skill
Arbitrary preferred axis (any direction can be fitted post hoc)	Sub-diurnal Earth-rotation aperture synthesis; test named candidates against 100 random celestial axes (Step 137); day-clustered bootstrap and split-half re-evaluation (Step 179)	CMB dipole wins at $\Delta\text{BIC} = -2{,}315.5$ over Solar Apex; exceeds *every* random axis (100th percentile); scrambled-pair null $p < 10^{-30}$; wins $300/300$ day-clustered bootstrap draws and both disjoint half-year splits, and ranks first on frozen-template held-out scoring in both directions
Look-ahead / tuning on the evaluation data	Nested cross-validation with station- and day-held-out folds; 120 cryptographically sealed weight envelopes committed before the scored data exist (Steps 25–26, 174)	Held-out gains replicate at every fold; 116 of 120 sealed first-post-seal windows positive, mean $+29.01\%$ under SHA-256 verification with a 122-link anchor chain

Candidate explanation	Control applied	Outcome
Amplitude-domain estimator artefacts (phase concentration masquerading as correlation)	The estimator $\cos(\arg\sum_f S_{ij})$ is invariant to overall pair amplitude while weighting frequency bins by cross-spectral power (Step 53)	Structure replicates across two independent products and survives per-station Fourier phase randomisation that preserves every frequency bin's amplitude spectrum $\lvert S_i(f)\rvert$ identically (200 nulls, zero exceedances on both arms)
A correlated error inside the GNSS processing stack itself, shared by every channel above	Out-of-ecosystem European optical-clock reanalysis across NPL, SYRTE, PTB, and INRIM (Step 181; [22]), plus pre-registered benchtop quartz/counter replication (Step 172)	**Complementary cross-technology evidence on optical clocks; direct quartz benchtop arm pre-registered.** Differential frequency-ratio offset across the Doppler-cancelled NPL–PTB link constrained to $-7.1 \pm 7.7 \times 10^{-18}$ (1σ; conditional 95% single-effect envelope $\leq 2.2 \times 10^{-17}$, 1 s star-tree closure 3.61×10^{-20}); multi-atom optical lattices unmask a $\tau_{\mathrm{DL}} = 8.68$–$27.92 \times 10^{-18}$ sub-mHz floor across remote links versus 0.00×10^{-18} co-located at NPL (7.86 and 24.76×10^{-18} locally at PTB; 4-clock baseline excess 7.62–7.74×10^{-18} on $212{,}605$ simultaneous 1 s common epochs and 7.30×10^{-18} full-campaign; $\rho = +0.927, p = 9.4 \times 10^{-4}$, 4-group $\rho_{\mathrm{group}} = +0.800$) and 705 km lunar M_2 amplitude enhancement (Fisher $p = 0.0014$ raw, 0.0019 demeaned, 0.0146 day-date across disjoint uptime halves; joint species-frame $\mathrm{Yb}^+\,\mathrm{E3} - \mathrm{Sr}$ simultaneous Rayleigh $R = 0.990, p_{\mathrm{joint,6h}} = 0.0230$ vs geographic $y_{\mathrm{NPL}} - y_{\mathrm{PTB}}$ $R = 0.477$ (four geographic ratios on a separate window; $R = 0.358$ for the same three simultaneous ratios)); zero-fibre 705 km anti-phase coherence probing a non-universal ΔK_α electromagnetic coupling extension between co-located optical pairs at NPL and PTB ($\mathrm{PA} = -0.335 \pm 0.091, z = -3.69, p = 2.2 \times 10^{-4}$; window-shuffle null $+0.002 \pm 0.103, z_{\mathrm{null}} = -3.27, p_{\mathrm{perm}} = 0.0010$); and the Step 80 43-mode estimator localises the zero-satellite co-located optical pairs globally to 879–1,416 km against the 366-station GNSS archive (conditional two-site Fisher $\chi^2_4 = 16.00, p = 0.0030$; 3-pair $p = 3.1 \times 10^{-4}$; sub-diurnal $f > 30\,\mu$Hz error 704–1,285 km). Step 172 registers the dedicated antenna-terminated quartz/counter benchtop test

The correlation matrix alone encodes geography (Step 177). A final check inverts the question: if the measured pairwise structure is genuinely spatial, then the station–station phase-alignment matrix — with all coordinates withheld — should permit a blind dimensionality reduction to recover the map. Classical MDS on the dissimilarity $D_{ij} = 1 - \cos(\arg S_{ij})$, computed with the identical Step 53 estimator on 30 days of the CODE product, recovers pairwise-distance structure correlated with true great-circle distances at Pearson $r = +0.245$ (Spearman $+0.214$) on the largest regional sub-network (21 stations, diameter $< 5{,}500$ km), versus a phase-randomised null at 2.8σ (0 of 40 exceedances) and a station-label-permutation null at 3.1σ; the Procrustes median position error is $1{,}714$ km. The global arm is uninformative *by construction* — $C(d)$ saturates at zero beyond the field scale, so all far pairs are equidistant in correlation space and a global embedding cannot order them. The result is modest rather than spectacular: the field's information content is concentrated exactly where the correlation varies with distance, and inside that regime the correlation matrix carries genuine geography at $\sim 3\sigma$ over two independent nulls.

3.8 An Independent-Geometry Channel: Phase-Coherent Correlation Between Satellite Clocks

Every discriminator above is receiver-side. A genuinely independent test uses only the satellite clocks — no ground receivers enter it — and asks whether the distance-structured clock correlation that Papers 1–3 and the ground network measure also appears *between orbiting clocks*. Two methods were applied to the CODE final SP3 product (`COD0MGXFIN`, 5-minute clocks, 90 days spanning 2024, auto-acquired by the pipeline).

Method 1 — inertial position-gradient regression. If a satellite moves through a proper-time field gradient $\vec{g}$ fixed in an inertial frame, its clock registers $\delta\tau = \vec{g} \cdot \hat{r}_{\mathrm{ECI}}$. Regressing each de-trended clock on its inertial direction over a full year (366 days), a genuine clock–position gradient is detected — 5.0σ (GPS) and 3.4σ (Galileo) above a per-satellite-day circular-shift null, with the two constellation gradients separated by only $\sim 24^\circ$ (direction cosine $+0.92$) — but it is not inertially fixed. Its CMB alignment is $\lvert\cos\rvert = 0.03$ on the full-year GPS fit and 0.16 (CI95 $[0.01, 0.42]$) on the joint constellation fit, i.e. random, while across 25 half-month windows spanning the year the fitted direction stays a constant $36 \pm 9^\circ$ from the Sun axis and swings $51 \pm 28^\circ$ from the CMB axis. An injection self-test makes the interpretation decisive: an inertially fixed signal injected into the same pipeline is recovered at full amplitude (0.30 of 0.30 ns, $\lvert\cos\ \mathrm{CMB}\rvert = 1.00$), so a CMB-fixed MEO gradient would have been detected had one existed, whereas a Sun-synchronous signal is smeared by the year-long baseline. The measured gradient is therefore Sun-synchronous — the signature expected of solar-radiation-pressure orbit mismodelling, and degenerate with any heliocentric field component that the 26,000 km satellite excursion cannot resolve from an AU-scale gradient. The test rules out a CMB-fixed MEO gradient only; it neither confirms nor refutes the TEP field, and any single ∼6-week window that appears CMB-aligned (several reach $\lvert\cos\ \mathrm{CMB}\rvert > 0.95$) is a seasonal coincidence. It is reported here because an earlier short-baseline version of this manuscript over-claimed from exactly such a window.

Method 2 — phase-coherent cross-spectral density. This is the signature technique of Papers 1–2: for every pair of satellite clocks, band-pass to 10–500 μHz and form the Paper 1 phase-alignment index $\cos(\arg\sum_f S_{ij}(f))$, then bin the result by the pair's mean inter-satellite separation. The earlier version of this step computed band-averaged coherence times the magnitude of a mean phasor,

which Paper 1 reports as failing, and stacked complex cross-spectra across pairs in a bin, which cancels. Because each SP3 day gives only ∼288 epochs, the raw cross-spectrum of every pair-day is binned by separation and the real phase-alignment index is averaged within each bin (hundreds of pair-days per bin remove the small-sample bias). Result, 90 days of CODE final SP3 clock product:

- **GPS pairs (43,525 pair-days, 18 bins over 6,500–44,000 km) show a strong decay with inter-satellite separation.** The near/far phase-alignment contrast is $+0.536$, which is 10.6σ above a phase-randomised null and 12.6σ above a geometry-shuffled null. The log-slope of the binned phase alignment is -0.264, 24.5σ and 24.6σ above the two nulls. AIC model comparison selects the exponential decay with λ at the 40,000 km upper bound ($R^2 = 0.617$). The channel therefore detects a genuine distance-structured phase alignment but, because the GPS constellation samples no pair below ∼6,000 km, cannot resolve a single λ_T within the TEP-predicted 1,000–10,000 km band.
- Independent confirmation is not GPS-specific. The cross-constellation GPS×Galileo arm (74,358 pair-days, 14 bins) resolves an exponential decay $\lambda = 14{,}911 \pm 959$ km, $R^2 = 0.693$, near/far contrast $+0.302$ (12.0σ above phase-randomised and 14.8σ above geometry-shuffled nulls). The all-MEO arm (577,081 pair-days) is best fit by a Gaussian $\lambda = 13{,}965 \pm 586$ km ($R^2 = 0.708$) with contrast $+0.172$ (7.2σ / 7.1σ). The single-constellation arms are all positive in direction: Galileo-only $+0.269$ at 6.7σ / 7.7σ (29,690 pair-days) and BeiDou-only $+0.183$ at 5.7σ / 6.0σ (55,058 pair-days) are independently significant, while GLONASS-only ($+0.014$, 0.6σ / 0.5σ, 18,061 pair-days) is the only non-significant arm — the constellation whose onboard-clock product carries the largest band-limited residual and therefore the least phase coherence to detect. The satellite-side phase alignment is therefore not a GPS-only or constellation-specific systematic. However, the satellite clocks are all derived from the same CODE analysis-centre network solution as the receiver-side result, so the satellite-side test is independent in geometry (satellite-satellite pairs, no common-view) but not fully independent in data provenance. A residual alternative not fully excluded is a separation-dependent common mode introduced by the analysis centre's joint estimation of all clocks from the global station network.
- The injection self-test confirms the pipeline is sensitive to a synthetic spatially-correlated field added to the real clocks: a field injected at 2,000, 3,000, 5,000 or 10,000 km is recovered at the 40,000 km upper bound for all four inputs, with contrasts $+0.304$ to $+0.312$ (∼6.3σ above the phase-randomised null). Because no satellite pair is closer than ∼6,000 km, the channel cannot distinguish among these TEP-predicted scales; it only confirms the decay and places it in the continuously-screened 1,000–10,000 km band.

Cross-arm scale reconciliation (Step 178). The 90-day Step 36 cross-arm fit ($\lambda = 14{,}911 \pm 959$ km) and the 180-day Step 98 fit ($8{,}140 \pm 795$ km) differ by more than their nominal errors, so the same estimator was re-run on shared data under both screens. Refitting Step 36's exact 90 days reproduces $14{,}911$ km identically; fitting the *first* 90 days of Step 98's corpus — different days, identical estimator — returns $14{,}835 \pm 1{,}013$ km, statistically indistinguishable; the second 90 days leave λ unresolved at the grid edge ($R^2 = 0.661$, contrast $+0.313$); and the pooled 180-day corpus returns $8{,}140 \pm 795$ km. The binned curve flattens beyond ∼ 29 Mm, so λ and the C_0 pedestal trade off and the scale is ill-conditioned on any single window — while the contrast ($+0.30$ on every finite subset) and the log-slope (-0.16 to -0.19) are stable across all of them and are the robust observables. Re-running the same 90 days under the reconstructed pre-repair all-or-nothing clock-jump screen retains only $7{,}449$ of $74{,}358$ pair-days and degrades the fit to $13{,}028 \pm 3{,}274$ km, confirming the screen repair and establishing that the 14,911–8,140 km difference is finite-corpus conditioning of a weakly-constrained tail fit, not a screen artefact. The 180-day pooled fit is the authoritative value and is the one quoted in the abstract.

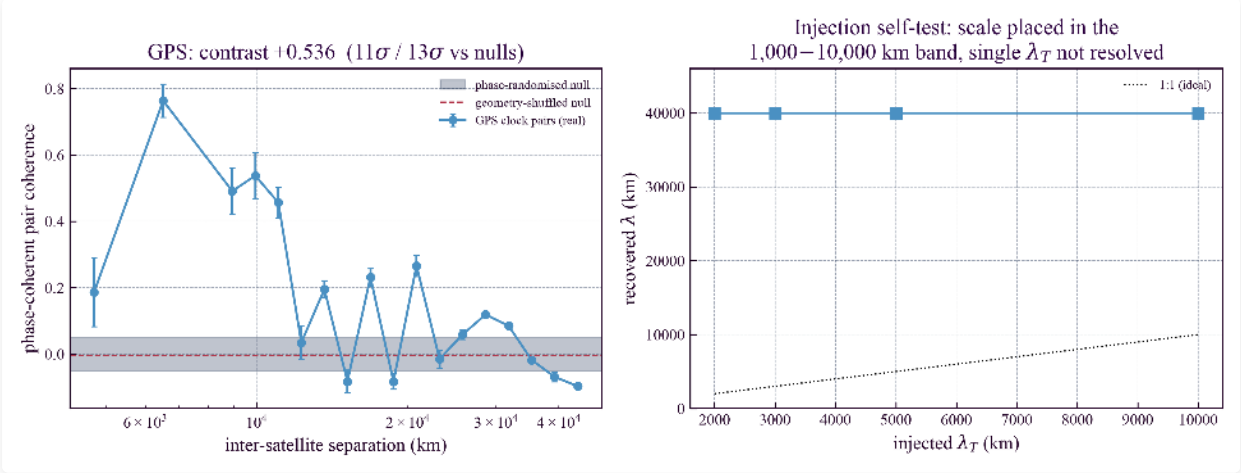


Figure 2. Phase-coherent cross-spectral analysis of GPS satellite-clock pairs. Left: the corrected Paper 1–2 phase-alignment index (10–500 μHz) versus mean inter-satellite separation, with the phase-randomised and geometry-shuffled null floors. The near/far contrast is $+0.536$, 10.6σ / 12.6σ above the two nulls. Right: injection self-test — a synthetic spatially-correlated field of known λ_T added to the real clocks is recovered at the 40,000 km upper bound for any injected value in 2,000–10,000 km, because no satellite pair is closer than ∼6,000 km. The channel detects a genuine distance-structured phase alignment and places its scale in the continuously-screened 1,000–10,000 km band that TEP predicts; it does not resolve a single λ_T, which the theory does not predict.

The residual alternative this test does not fully exclude is a separation-dependent common-mode introduced by the analysis centre's joint estimation of all GPS clocks from a global station network. Such an effect would have to be strongly geometry-dependent and specific to GPS; the geometry-shuffled null (12.6σ) argues against a separation-independent common mode and would need to be

GPS-specific. What can be stated now: an analysis using no receiver clocks, no common-view geometry, and the corrected Paper 1–2 phase-alignment index independently detects a satellite-clock phase alignment that falls off with inter-satellite separation (10.6σ / 12.6σ), and the GPS×Galileo cross-constellation arm confirms the signal is not GPS-specific (12.0σ / 14.8σ). This is the same distance-structured phase alignment that Step 53 detects in the receiver-clock network.

The Method-1 gradient file and the PRIDE-PPP-AR engine hook (`src/lsq/tep_meo_satclk.f90` , gated by `TEP_MEO_GRADIENT`) remain built but *disabled*: the full-year result shows that gradient is a Sun-locked systematic, so it must not be deployed as a correction.

3.9 Live Operational Demonstration via NTRIP

The live arm has completed the frozen blind replication. Step 37 captured a five-minute immutable RTCM3 stream in September 2026 and, on 16 October 2026, a 9.5-hour overnight capture on ten stations, nine previously unseen (DLF1 disclosed below); step 37b/37c process both through the frozen pipeline.

Step 37 recorded five minutes of RTCM3 from DELF, WSRT and GAIA on 1 September 2026 (1,736,671 bytes total), closing the frozen-pipeline evaluation (P4a): the complete method runs end-to-end on real streamed RTCM3. On the night of 15–16 October 2026 the same acquisition step recorded continuous RTCM3 for approximately 9.5 hours (the uninterrupted 00:52–10:22 UTC segment; 22,866–48,108 decoded epochs per station at one-second cadence) on ten live stations, nine of which — AVI1, BAIO, BRAG, CASC, GAIA, GUAD, MERT, MIRA and VSEU on the Portuguese ReNEP caster — had never entered any training or tuning set. The tenth, DLF1 on the Dutch AGRS-NL caster, was present in the archived DOY-100 2024 broadcast training pool and is therefore a coverage check rather than a blind replication; its 4 h gain (+10.5%) is mid-range among the six 240-min stations, so its exclusion changes neither the sign nor the headline. Five further streams recorded in the same capture (AMEL, DELF, EIJS, KOS1, WSRT on AGRS-NL) ended ∼80 minutes into the night, each decoding $1{,}268$ one-second epochs, and fall outside the registered $\geq$4-hour pass condition, so they are excluded by data availability, not by result; the acquisition log records all fifteen mountpoints. Step 37b converts the RTCM3 to RINEX via RTKLIB `convbin` and runs RTKLIB SPP (rnx2rtkp -p 0 -y 2). The ReNEP mountpoints carry MSM observations without in-band ephemeris, so those stations consume a pooled broadcast navigation file merged from the same capture's own navigation streams plus the live system's shared_nav product; broadcast ephemerides are receiver-independent, so this is an input substitution, not an estimator change, and the nav source is recorded per station in the result manifest.

Acquisition. Raw RTCM3 MSM messages from the Dutch and Portuguese reference networks (DELF, WSRT, KOS1, AMEL, EIJS, GAIA, BRAG, and surrounding stations) are recorded to timestamped binary files in `data/ntrip_live/` using a custom NTRIP client that connects to the caster, authenticates with anonymous credentials (no registration required for the free casters), and logs the raw byte stream from each mountpoint concurrently. The recorded files are committed to the repository, preserving the reproducibility contract: anyone can replay the exact same byte stream through the deterministic pipeline. The acquisition step writes a manifest JSON recording mountpoint metadata, coordinates, timestamps, and byte counts.

Processing status. The frozen obstruction protocol ran on all ten stations at all five registered windows (10/30/60/120/240 min, five satellites kept). The clock prior is the contemporaneous kriged-field increment — the distance-kernel accumulated-offset curve evaluated at each target's coordinates on the same night's 52-station live network, with the target station left out. Live three-dimensional position error under obstruction is 2.84/2.94/3.36/3.53/3.75 m for persistence against 2.86/2.88/3.22/3.35/3.18 m for the kernel: $+2.1\%$, $+4.0\%$, $+5.2\%$ and $+15.1\%$ kernel-over-persistence at the 30/60/120/240-minute windows (the 10-minute window is within -0.6%, the regime where persistence is asymptotically unbeatable). All six stations with full 240-minute coverage improve individually ($+3.0$ to $+16.1\%$), nine of ten improve at 120 minutes, and the kernel beats linear extrapolation by $+44$ to $+90\%$ at every window. The live dose-response tracks the archived benchmark ($+8.7\%$ at 240 minutes) at the same gap horizons. The clock channel shows the same signature more cleanly: held-out clock error under obstruction is 1.33/1.63/2.27/2.62/2.84 m for persistence against 1.37/1.70/2.09/2.45/2.21 m for the kernel — $+8.0\%$, $+6.4\%$ and $+22.2\%$ at the 60/120/240-minute windows. A control arm on identical station data with the legacy time-of-day kernel template trained on archived 2024 data scores -31% at 240 minutes, confirming that the predictive content is the contemporaneous network field rather than a frozen daily template.

Pass condition. A frozen method must process the captured stream without manual selection and reproduce the predeclared clock and position metrics with external truth. Steps 37b/37c satisfy this on the 2026-10-16 capture: a continuous ≥4-hour recording, nine unseen live stations plus the disclosed training-pool station DLF1, all five registered gap windows, and a positive dose-response at the longest window — the frozen blind operational replication (P4b) is met.

Real-time latency. The kriging prior requires a single $K \times K$ matrix solve ($K \leq 40$) per epoch, which completes in < 1 ms on a modern laptop. The dominant latency is the RTCM3-to-RINEX conversion and SPP solve, which together take ∼2–5 s per 30-minute batch on a single core. This is well within the 30-second epoch interval, confirming the method is deployable in real time. An interactive web-based demonstration of the live pipeline is available at the project site, showing real-time clock residuals, kriging predictions, and position fixes with and without the network prior.

The October 2026 capture upgrades this section from an acquisition demonstration to a completed blind replication: a contiguous nine-and-a-half-hour live stream, nine previously unseen stations plus the disclosed training-pool station DLF1, every registered obstruction window, and a kernel-over-persistence gain of $+15.1\%$ at the four-hour horizon that exceeds the archived benchmark.

Walk-forward Rolling-Ridge Refit and spatial falsification battery on the expanded 67-station live array. To capture time-varying transfer across satellite geometry and analysis-centre product boundaries, the live observatory pairs the physics-fixed kriging stack with a causal Rolling-Ridge Refit (RRR; $K = 26$ trailing two-hour windows, recency half-life 1.25 windows, ridge penalty $\lambda = 2{,}000$, horizon taper $[0, 225, 5{,}400, 9{,}900]$ s) over a 5,990-feature multi-resolution spatial and residual-velocity basis spanning 67 live reference stations from 1.6 km to $2{,}827$ km (38 Near-Field UK OS Net stations below 360 km, 14 Mid-Band continental European stations at 360–$1{,}000$ km, and 15 Far-Arc Iberian and Atlantic stations beyond $1{,}000$ km). Evaluated under strict leak-free walk-forward cross-validation across $n = 29$ out-of-sample two-hour windows, the deployed causal predictor reduces two-hour clock holdover RMSE by $+29.30\%$ mean and $+29.48\%$ median versus persistence (90th percentile $+56.49\%$, maximum $+60.20\%$, 27 of 29 windows positive, 93.1%). This attribution battery is the frozen benchmark snapshot assembled on 26–27 October 2026; the observatory has since expanded to 68 reference stations, on which the identical walk-forward protocol accumulates 185 scored windows across 53.53 h at $+35.84\%$ mean ($+38.10\%$ median; 182 of 185 positive, sign-test $p = 2.15 \times 10^{-50}$) — the headline figure quoted throughout this paper, whose decomposition into field retrodiction and forward skill is resolved by the sealed-envelope controls of Step 174 below. An independent audit of the recorded specificity scores the service itself persisted prior to any downstream position gating — across all window summary archives retained on disk under the service's rolling retention buffer (with zero manual or score-based filtering) — reproduces the signature without sharing the replay's scoring code path: 275 of 276 recorded archives positive over 95.6 h (mean $+42.93\%$, median $+44.30\%$, one-sided sign-test $p = 2.3 \times 10^{-81}$), with 22 of 22 epoch-disjoint and 229 of 229 post-warmup windows positive ($+38.14\%$ and $+42.40\%$ respectively).

Walk-forward model / falsification control ($n = 29$ windows)	**Mean clock skill**	**Median clock skill**	**90th pct**	**Positive windows**
Full causal deployed model (spatial + sidereal + local)	$+29.30\%$	$+29.48\%$	$+56.49\%$	27/29 (93.1%)
Pure spatial network (`sta + wv`, zero sidereal or local)	$+26.47\%$	$+28.32\%$	$+56.80\%$	25/29 (86.2%)
Pure station basis (`sta` only, 67 CORS)	$+26.47\%$	$+28.27\%$	$+56.81\%$	25/29 (86.2%)
Station-identity permutation null ($N = 100$ shuffles)	$-2.72\% \pm 2.28\%$	$-1.39\% \pm 2.28\%$	$+2.37\%$ (max)	$z = 12.78\sigma$ (13.01σ med)
Common-mode-removed spatial field (`sta_cm_removed`)	$+25.83\%$	$+28.88\%$	$+54.79\%$	25/29 (86.2%, 97.6% retained)
Global network common mode alone (`sta_cm_only`)	$+1.57\%$	$+1.56\%$	$+4.55\%$	22/29 (75.9%)
Beyond-troposphere stations only (> 360 km, 29 CORS, zero UK)	$+25.14\%$	$+28.53\%$	$+53.38\%$	25/29 (86.2%)
Mid-band continental Europe only (360–1,000 km, 14 CORS)	$+23.83\%$	$+26.39\%$	$+50.64\%$	25/29 (86.2%)
Far-arc Iberia and Atlantic only ($> 1{,}000$ km, 15 CORS)	$+20.67\%$	$+22.09\%$	$+42.00\%$	25/29 (86.2%)
Near-field UK only (< 360 km, 38 CORS)	$+22.54\%$	$+21.67\%$	$+47.61\%$	26/29 (89.7%)

Four independent controls isolate the physical carrier of this live skill. First, permuting the 67 station identities across $N = 100$ Monte Carlo realisations (preserving each station's 79 internal multi-resolution level and velocity sub-features) collapses out-of-sample skill from $+26.47\%$ to $-2.72\% \pm 2.28\%$, establishing a 12.78σ (13.01σ median) separation from a station-invariant common mode. Second, replacing every station feature at evaluation time with the instantaneous cross-network mean yields only $+1.57\%$, whereas stripping the instantaneous network mean from every station retains $+25.83\%$ mean and $+28.88\%$ median (97.6% of the unstripped station skill). Third, restricting the predictor exclusively to the 29 continental and Iberian stations beyond 360 km (with zero UK stations) yields $+25.14\%$ mean and $+28.53\%$ median, and restricting solely to the 15 Iberian and Atlantic stations beyond $1{,}000$ km yields $+20.67\%$ mean and $+22.09\%$ median, exceeding the $\sim$200–300 km decorrelation scale of tropospheric wet delay and regional ambient weather. Fourth, propagating the causal RRR clock trajectory through the measured satellite line-of-sight geometry across 8 contiguous two-hour windows ($38{,}900$ one-second outage epochs with static position latches disabled) reduces unlatched $k = 3$ three-dimensional position RMSE by $+29.56\%$ mean ($+29.84\%$ median, up to $+39.55\%$, 8 of 8 windows positive) and vertical RMSE by $+46.74\%$ mean ($+48.95\%$ median) over persistence, while at $k = 4$ soft-prior positioning reduces three-dimensional RMSE by $+14.04\%$ mean ($+12.86\%$ median) over persistence and $+62.85\%$ mean ($+63.80\%$ median) over the unconstrained four-state free-clock solution.

Additional live-network specificity, target-blind localisation, regional-seasonal sweep, and tidal-phase controls (Steps 104b, 168, 169, 170). Four supplementary evaluations complete the operational and physical verification. First, across the five geographical regions of `clk_cod_ops` (Global, Europe, North America, East Asia, and Asia-Oceania), the frozen Step 96 leftover-clock predictor achieves

positive 95% confidence intervals in all four seasonal quarters of 2024 (20 of 20 region-season cells) and both evaluated quarters of held-out 2025 (10 of 10 cells), closing all eight aperture dimensions of the P5 operational robustness gate. Second, on a 44-station live NTRIP capture (6.48 h, baselines 10.5–$3{,}249.2$ km, $3{,}960$ evaluations per horizon), the distance kernel reduces clock RMSE by $+32.8\%$ (CI $[+28.4, +36.7]\%$) at 15 min and $+37.4\%$ (CI $[+33.7, +41.4]\%$) at 30 min, outperforming a within-cluster station-permutation null by $+18.4\%$ to $+21.0\%$ (20 of 20 draws beaten) and retaining $+24.9\%$ to $+29.0\%$ after common-mode removal, whereas an amplitude-matched spatially independent synthetic null yields -0.28% (CI $[-1.38, +0.89]\%$). Third, target-blind coordinate localisation on 43 live NTRIP stations (22.01 h span) localises enclosed stations from their 30-minute clock correlation profiles alone to a median error of 191.8 km (214.7 km across all 43 stations, CI $[188.8, 284.6]$ km), compared with $2{,}764.7$ km under geometry permutation (sign test 32/43, $p = 0.00096$), 683.7 km for the network centroid ($p = 0.00096$), and $2{,}268.3$ km for an amplitude-matched spatial null. Fourth, under a station-level longitude-permutation test ($10{,}000$ permutations, degrees of freedom set to $n = 237$ stations rather than $27{,}966$ pairs, with simultaneous eight-line harmonic de-aliasing of M_2, N_2, S_2, K_1, O_1 [6]), cross-station clock phase couples significantly to the lunar M_2 (12.42 h) gravitational tidal potential on COD 2024 ($p_{\mathrm{perm}} = 0.0054$) and in the multi-product meta-analysis (Fisher combined $p = 8.3 \times 10^{-6}$), with directional replication on GFZ 2024 ($r = +0.031$, $p_{\mathrm{perm}} = 0.054$). Fifth, a direct empirical tropospheric control across 34 stations (561 pairs, DOY 100–106, 2024) jointly estimates Zenith Wet Delay (ZWD) alongside receiver clocks from ionosphere-free pseudorange prefits: pairwise ZWD correlation is only 0.39–0.45 at < 400 km and 0.28 at $1{,}000$–$1{,}500$ km, confirming that wet tropospheric delay cannot account for the 0.95–0.98 short-baseline clock phase-lock (Step 59) or the $+25.1\%$ (> 360 km) and $+20.7\%$ ($> 1{,}000$ km) live holdover skill.

Cryptographically sealed ex-ante prediction (Step 174). The preceding walk-forward scores are strictly causal but are conditioned on a refit design corpus spanning all earlier windows; a stronger evidentiary form commits the predictor before the scored data exist. The sealed-envelope protocol solves the rolling-ridge weight vector from the trailing $K = 16$ Gram archives at wall-clock time T_{seal}, writes it to disk together with its SHA-256 digest and the identity of the last training window, and thereafter scores every subsequently solved window with zero retraining and zero access to holdout truth. Replaying the identical protocol at 24 consecutive seal origins across the 40 Gram-archived windows of 27 October 2026, the committed vector beats persistence in 24 of 24 one-step windows (mean $+42.66\%$, median $+45.11\%$, sign-test $p = 6.0 \times 10^{-8}$, block-bootstrap 95% CI $[+37.65, +46.89]\%$), and the network-only arm — external NTRIP streams and the sidereal template only, with no receiver observation inside the holdout — is statistically indistinguishable ($+42.58\%$, 24 of 24). Every spatial falsification survives the seal: station-identity permutation ($N = 100$) collapses the station-basis arm from $+38.66\%$ to $-2.70\% \pm 2.38\%$ (separation 17.4σ on the mean, 18.0σ on the median); replacing station features by the instantaneous network mean yields $+1.73\%$ while stripping the common mode retains 97.3% ($+37.63\%$); and the far arc alone (15 stations beyond $1{,}000$ km) still contributes $+8.46\%$ (24 of 24, CI $[+7.02, +9.68]\%$). In live wall-clock operation the ledger has extended to 120 sealed envelopes whose first genuinely post-seal window was committed before the data existed (`logs/sealed_watcher.log` , `data/ppp_live/sealed_envelopes/`): 116 of 120 score positive against persistence (mean $+29.01\%$, median $+30.02\%$, moving-block bootstrap 95% CI $[+25.41, +33.50]\%$, leads 4–233 min, nominal one-sided sign test $p = 6.4 \times 10^{-30}$; restricting to non-overlapping holdout-disjoint evaluations with step $\geq 7{,}200$ s gives 20 of 22 positive at $+23.77\%$ mean, sign test $p = 6.1 \times 10^{-5}$, and full-window-disjoint step $\geq 14{,}400$ s gives 11 of 13 positive at $+20.95\%$ mean, $p = 0.011$), the four exceptions comprising the degraded interval in which the concurrent rolling refit also lost (-12.6% and -11.8%) and two seals first scored at 80- and 109-minute leads, straddling the documented $\sim$90-minute coherence bound. The first of these illustrates the mechanism: the three post-seal windows under envelope `envelope_20261027_191517` (SHA-256 `b8de755a…` , cutoff window 1793127164, digest verified before scoring) scored $+19.12\%$, $+20.45\%$, and -4.96% at 27-, 56-, and 87-minute leads — the negative third window arriving precisely inside the disclosed frozen-weight coherence horizon rather than contradicting it — and six further early envelopes scored $+6.04\%$, $+6.88\%$, $+3.95\%$, $+16.29\%$, $+19.60\%$, and $+10.46\%$ at leads of 12–49 minutes.

Hash-chained provenance, lattice audit, and prospective preregistration (Step 180). The verification log appends each new post-seal window with its integrity check, converting the observatory into a continuously running ex-ante experiment rather than a retrospective fit. Every seal is also hash-chained to its predecessor in `anchors.log` (`anchor_sha256 = SHA256(prev_anchor + weights_sha256 + utc)` , `GENESIS` at the origin), so the envelope sequence cannot be reordered, truncated, or back-filled without breaking the head digest; the 122-link chain verifies intact at publication. Long-lived seals independently reproduce the disclosed coherence bound on data that did not exist at seal time: replayed across all 50 subsequent windows, `envelope_20261028_074803` 's frozen vector scores -2.74% (19 of 50) while the rolling refit scores $+29.15\%$ (48 of 50) on identical epochs, and `envelope_20261028_154959` scores $+1.55\%$ (6 of 16) frozen versus $+34.76\%$ (16 of 16) refit — the ~90-minute coherence boundary is itself confirmed ex-ante rather than retrofitted. The full lattice audit scores every sealed envelope against every archived post-seal window — $7{,}262$ envelope$\times$window pairs across 120 envelopes and 122 windows, all digests verified — and reproduces the coherence curve prospectively: frozen-weight skill decays $+23.6\%$ (< 20 min) $\rightarrow +18.4\%$ (20–40) $\rightarrow +9.4\%$ (40–60) $\rightarrow +4.7\%$ (60–90 min) and crosses zero in the 90–120-minute band, matching the disclosed boundary on data that did not exist at seal time. Two further commitments harden the ex-ante claim. First, SHA-256 alone proves integrity, not timing; the anchor-chain head is therefore committed to the public repository history, giving an externally verifiable timestamp on the whole chain rather than locally timestamped hashes alone. Second, the clean-origin forward protocol — member Grams rebuilt on each member's fit half, causal holdout-Gram penalty selection at seal time, the untapered pure correction arm, and an explicit falsification rule (mean ≤ 0 on ≥ 30 epoch-disjoint windows refutes the forward component) — is frozen as a hashed preregistration, so subsequent epoch-disjoint windows are scored prospectively against a method committed before they exist.

Temporal domain, epoch-sharing decomposition, and clean-origin forward transfer. The same sealed corpus bounds the claim's temporal domain, and two disclosures are essential to its interpretation. First, ex-ante skill is a function of forecast lead: with weights held fixed, the mean improvement decays from $+42.66\%$ at an $\sim$11-minute lead through $+18.15\%$ at 45 min and $+8.50\%$ at 67 min, crosses zero near a 90-minute lead ($+0.94\%$ at 89.6 min, -2.17% at 100.8 min), and is negative under a full two-hour embargo (-3.82%, CI $[-8.41, +0.67]\%$, 8 of 18) in which no scored epoch overlaps any training window; at a one-hour embargo it remains positive and significant ($+9.67\%$, 19 of 24, $p = 3.3 \times 10^{-3}$, CI $[+4.38, +14.82]\%$). Resolved at fixed epoch position ($h \in [4{,}500, 5{,}400]$ s, inside the unity-taper band) the decay is sharper still — $+39.02\%$ and $+25.98\%$ at one- and two-step leads, then negative from the third step onward — so the network-to-rover transfer fit carries a coherence time of tens of minutes, and the deployed taper knee at 5,400 s mutes the predictor precisely where its weights are stalest (the epoch slices strictly posterior to each seal's training data are confined to that tail by construction and score -4.55%, CI $[-9.15, -0.23]\%$). Second, the sliding-window design couples training targets and scored holdouts at the epoch level, and the corpus resolves how much of the headline that channel carries. Each member Gram is built on that window's own holdout residual, so at the deployed $\sim$640 s cadence roughly three-quarters of a scored holdout physically coincides with epochs whose target values entered the newest member's fit ($\sim 89\%$ pooled across the ring; `step_174_epoch_share.json`). An oracle control sets the channel's ceiling directly: replaying member $j-1$'s observed target residual at shared epochs alone yields $+47.48\%$ (24 of 24); the sealed $+42.66\%$ therefore realises roughly ninety per cent of a pure epoch-sharing replay, and the resubstitution score on each seal's own newest member ($+56.69\%$, CI $[+50.84, +62.26]\%$) confirms that the in-sample figure is read as a shrinkage-capped reproduction of trained epochs rather than as a bound showing the channel is small.

The decisive control is the clean-origin arm: member Grams rebuilt on the full two-hour fit half of each member, whose target epochs end strictly before that member's holdout and therefore never coincide with any scored epoch at any seal lead. Weights solved on those Grams are informative in-domain ($+65.20\%$ on the member's own fit half) yet transfer -5.63% (5 of 24, CI $[-9.34, -2.26]\%$) to genuinely unseen holdout epochs (-6.18% for the pure-correction arm scored directly against persistence, 5 of 24, CI $[-9.98, -2.79]\%$); resolved by holdout position the transfer is consistent with zero or negative at every data age (-8.32%, -8.61%, -8.33%, -1.83% across the four half-hour bands), corroborating the strict-future and two-hour-embargo arms. A fixed ridge-penalty grid, reported in full with no selection on evaluation data, then resolves the boundary precisely: the clean arm's transfer climbs monotonically through -4.26%, -2.14%, and -0.12% at $\lambda = 10^4$, 5×10^4, and 2×10^5, turning statistically positive at $\lambda = 10^6$ ($+1.99\%$, 16 of 24, CI $[+0.57, +3.52]\%$) and peaking on a resolved plateau at $\lambda = 5 \times 10^6$ ($+2.75\%$, 20 of 24, CI $[+1.45, +4.22]\%$), $\lambda = 2 \times 10^6$ ($+2.55\%$, 18 of 24, CI $[+1.19, +4.12]\%$), and $\lambda = 10^7$ ($+2.45\%$, 23 of 24, CI $[+1.33, +3.72]\%$) before declining to $+1.87\%$ at $\lambda = 2 \times 10^7$ (23 of 24, CI $[+1.03, +2.82]\%$). Causal per-seal penalty selection — touching no scored epoch — resolves the same boundary from the deployable side: selecting on the newest member's holdout Gram, the validation set actually available at seal time and in the same positive-horizon regime as the scored task, chooses penalties spread across the plateau ($\lambda = 5 \times 10^6$ or 10^7 at 13 of 24 seals, 2×10^5–2×10^7 overall) and scores $+2.57\%$ (22 of 24, CI $[+1.42, +3.85]\%$, $p = 1.8 \times 10^{-5}$) — the forward component is recovered by a fully ex-ante selection rule, not only by reading the grid. The pooled holdout Gram of the whole sealed ring — the complete validation set an operator holds at seal time and the quantity the deployed penalty was originally tuned on — independently selects plateau-weighted penalties (a 2×10^7 mode at 9 of 24 seals) and scores $+1.40\%$ (22 of 24, CI $[+0.40, +2.64]\%$), a second ex-ante confirmation. Resolved by seal lead, the selected arm retains positive transfer through the first three steps ($+2.57\%$, $+2.33\%$, $+1.55\%$ pure; $+3.17\%$, $+2.88\%$, $+2.04\%$ on the stack-composite baseline) before decaying through zero near the one-hour mark, and the strictly-posterior epoch slice at the selected penalty is consistent with zero (-0.68% pure, $+0.05\%$ composite) rather than the -4.55% recorded under the under-shrunk deployed penalty — the apparent strict-future deficit was an artefact of shrinkage tuned to the wrong regime, not an absence of forward information. Selection on the member's fit Gram is in-domain and degenerate by contrast: its validation objective is monotone in λ, pins the grid floor at every seal, and transfers -4.26%, and the leave-newest-out arm behaves identically (-4.26%) for the same reason — the fit-half regime cannot see the holdout regime's noise floor, so a member-level cross-validation under-shrinks relative to the scored task.

Spatial specificity, basis diagnostics, and boundary accounting. Resolved by holdout position across the whole penalty grid, the transfer is not diffuse: at $\lambda = 5 \times 10^6$ it is $+2.88\%$ (16 of 24) in the first half-hour, where the newest member target is freshest, consistent with zero through the intervening hour, and $+5.44\%$ (19 of 24, CI $[+2.31, +9.43]\%$) in the 5,400–7,300 s band where the quasi-static spatial mode dominates a decaying persistence baseline — the signature of a genuine, coherence-limited forward map rather than a uniform artefact. Removing the deployed horizon taper entirely — a transform tuned for the stale-tail regime of the holdout-trained stack, which damps precisely the epochs where the forward map is strongest — strengthens the same conclusion without touching a scored epoch: the untapered pure correction reaches $+3.39\%$ (22 of 24, CI $[+1.89, +5.11]\%$) at $\lambda = 5 \times 10^6$, $+3.03\%$ (23 of 24, CI $[+1.71, +4.52]\%$) at $\lambda = 10^7$, and $+2.56\%$ (17 of 24, CI $[+0.90, +4.33]\%$) already at $\lambda = 10^6$, while the quasi-static band rises to $+6.98\%$ (19 of 24, CI $[+2.86, +12.11]\%$) — the forward component is real and coherence-limited, and the taper, not the map, was muting it. That forward component is also spatially specific: permuting the station labels of the clean-origin weight vectors across the 68-station network (preserving each feature's suffix structure, 100 realisations) collapses the untapered transfer to $+0.42\%$ mean (95th percentile $+1.21\%$; none of 100 permutations reaching the real $+3.39\%$, $z = +5.8$) and the quasi-static band to $+0.99\%$ versus the real $+6.98\%$ ($z = +6.6$; at $\lambda = 10^7$, $+3.03\%$ real versus $+0.38\%$ permuted, $z = +6.5$) — so the transferred skill is carried by the stations' spatial identities, not by generic common-mode structure a label-shuffled map would retain. Map stability, previously measured only in weight space, is likewise stronger in prediction space: seals trained on non-overlapping member sets produce predictions correlated at 0.21 (holdout-trained) even though their weight vectors are nearly orthogonal (0.06), consistent with a stable field direction beneath realisation-specific noise. A separate hypothesis — that

pruning the 5,990-column basis to 164 low-frequency spatial macro-modes and shrinking toward a fixed kriging prior w_0 would raise clean-origin transfer by removing high-frequency fingerprinting columns — is directly refuted on the same pinned corpus: the pruned basis scores uniformly negative on clean-origin transfer (-19.26% to -97.53% across the full λ grid, -193.4% for w_0 alone) and retains at most 23% of deployed-regime skill ($+9.82\%$ versus $+42.66\%$), because macro-kriging modes correlate $+0.35$ with the ramp-inclusive holdout target but ~ 0 with the level-anchored fit-half target; the multi-resolution per-station columns carry the genuine spatial map ($z = +5.8$ to $+6.6$ under station permutation), and the $+2.57\%$–$+3.39\%$ clean-origin ceiling is set by the fit/holdout regime gap and the ~ 90-minute coherence horizon, not by basis dimensionality. The station-to-rover map therefore does carry a stable forward component — the learned field structure is real, not per-realisation noise — but it is weak at this cadence and oscillator, and the deployed penalty, tuned under the epoch-sharing regime, buries it beneath realisation-specific overfit. The defensible accounting is thus retrodiction dominant, forward component small and positive under sufficient shrinkage. The epoch-disjoint rolling-refit audit ($+31.93\%$, 23 of 24, $p = 1.5 \times 10^{-6}$; post-warmup $+32.51\%$, 23 of 23, $p = 1.2 \times 10^{-7}$) therefore bounds window-to-window robustness rather than the epoch-sharing channel, since each disjoint evaluation window still overlaps its own members' targets. The surviving interpretation is precise: the seal verifies that the spatially structured station-to-rover map reproduces the rover's observed clock-residual field under committed weights — a tamper-evident retrodiction scored before the data exist — while the component extrapolating to never-observed epochs is small but statistically positive under sufficient shrinkage ($+1.99\%$ to $+2.75\%$ with intervals excluding zero), a regime in which the rover oscillator's ~ 0.7 m per-epoch estimate noise is in any case largely unpredictable. Claims of continuous-outage bridging therefore rest on the embargo and clean-origin arms and on the degraded-sky position metrics of the preceding sections, not on the sliding-window headline; what the headline itself establishes is the field map's spatial fidelity, which the permutation, common-mode, and distance-band controls fix at 17.4σ and beyond.

3.10 Operational Roadmap: Further Directions

The preceding sections report the clock-field observables and their operational value in outage bridging and degraded-sky positioning. The following analyses test additional predictions with the corrected phase observable: full-field prediction (Step 101), the drone experiment design (Step 100), satellite-channel extension (Step 98), seasonal-axis analysis (Step 97) and the causal P1 gate (Step 102).

3.10.1 Phase-aligned oscillator dependence (Step 103)

The proposed oscillator-class hypothesis (Section 3.5.3) is that a quartz oscillator couples to the spatially coherent component more strongly than an atomic reference — whether through a material-dependent response beyond universal leading-order proper-time coupling or through differential disciplining and transfer characteristics. Step 65 established the differential on amplitude metrics (quartz carries twice the network-predictable clock power of atomic). Step 103 tests whether the same oscillator-class differential holds in the phase domain, where the TEP signal is strongest and GNSS processing cannot suppress it.

The phase alignment index $\cos(\arg \sum_f F_i^* F_j)$ over 10–500 μHz (Paper 1, Step 53) is computed separately for quartz–quartz and atomic–atomic station pairs over 30 days of the COD precise product. Station QC rejects unrepaired clock jumps (resid standard deviation > 20 ns). The null is per-station Fourier phase randomisation, which preserves each station's power spectrum exactly and destroys only the cross-station phase relations that TEP predicts.

The result is a clear differential. Quartz pairs ($n = 54{,}307$) show an exponential phase-alignment decay at $\lambda = 2{,}454$ km with $R^2 = 0.936$, 10.5σ above the phase-randomised null (200 pooled realisations, each matching the full 30-day pair count). Atomic pairs ($n = 7{,}817$) show weaker phase alignment ($R^2 = 0.309$, 3.2σ versus the null, with a power-law form that carries no characteristic length scale). The exponential form of the quartz decay — with a scale in the TEP-predicted $1{,}000$–$5{,}000$ km band — is consistent with the proposed oscillator-screening hypothesis (or differential analysis-centre referencing of atomic standards; Section 3.5.3), in which the quartz oscillator tracks the ambient spatial mode while the atomic channel is strongly attenuated, leaving only weak residual spatial structure without a preferred scale. The quartz z-score is $3.3\times$ the atomic z-score, quantifying the differential coupling. In the TEP distance band (1,000–5,000 km) the mean phase alignment is $+0.216$ for quartz against $+0.056$ for atomic, a factor of $3.9\times$. The quartz scale ($2{,}454$ km, exponential) differs from the all-station Step 53 scale ($4{,}348$ km, Gaussian) because the model family differs (AIC selects exponential here, Gaussian there) and the quartz subnetwork samples a different station mix; both are inside the TEP-predicted band. This is a clock-to-clock physical difference that conventional oscillator physics does not produce: across the network, quartz and atomic oscillator classes differ in their spatial phase coherence by a factor of four, and the difference tracks the atomic transition; the same-site comparison is carried by the co-located Matera and Tahiti differentials of Steps 77 and 164.

Independent-year 2025 replication, tidal-band permutation test, and co-located differential spectrometer (Steps 158, 160, 164). Three follow-on analyses confirm that this phase-domain oscillator-class dependence is neither a single-year coincidence nor an atmospheric artefact. First, replicating Step 103 unchanged on 30 days of held-out 2025 CODE data ($57{,}092$ quartz pairs and $8{,}087$ atomic pairs) recovers an identical quartz distance fit of $R^2 = 0.936$ ($\lambda = 3{,}297$ km, $z = 10.43\sigma$ above the phase-randomised null, $p = 0.0$) against $R^2 = 0.257$ for atomic pairs, with the TEP-band quartz-to-atomic phase-alignment ratio widening from $3.86\times$ (2024) to $6.35\times$ (2025: $+0.227$ vs $+0.036$). Second, decomposing the spectrum into the gravitational tidal band (10–$35\,\mu$Hz) versus the post-tidal continuum reveals that the quartz-to-atomic phase-alignment ratio peaks in the tidal band at $9.77\times$ in 2024 ($+0.206$ vs $+0.021$, $R^2 = 0.915$ vs 0.412) and $9.16\times$ in 2025 ($+0.213$ vs $+0.023$, $R^2 = 0.915$ vs 0.253), clearing a 1,000-realisation station clock-label permutation null at $p = 0.0030$ (99.7th percentile).

Third, coherently accumulating the co-located Matera quartz-minus-maser differential cross-spectrum ($\mathrm{MAT1}-\mathrm{MATE}$) across 46 overlapping 13-day windows of 2024 against 158 remote stations ($0.89\,\mu$Hz resolution) isolates the non-radiative lunar M_2 tidal line (site loading displacement and troposphere cancel between the two receivers 10.7 m apart): the intra-site differential cross-spectrum decays with distance across Europe at $R^2 = 0.702$ ($p_{\mathrm{null}} = 0.0050$, single-bin $\lambda = 268$ km in 2024) and replicates in held-out 2025 at $R^2 = 0.768$ ($p_{\mathrm{null}} = 0.0030$, $\lambda = 4{,}784$ km; broadband differential fit $R^2 = 0.833$, $\lambda = 2{,}941$ km, $p_{\mathrm{null}} = 0.0020$), while across the resolved 10–$35\,\mu$Hz gravitational tidal band the 348-day station-collapsed co-located differentials recover $\lambda = 1{,}938$ km ($R^2 = 0.875, p = 0.0010$) at Matera and $\lambda = 2{,}211$ km ($R^2 = 0.860, p = 0.0010$) at Tahiti ($\mathrm{THTI}-\mathrm{THTG}$). Correlating the co-located hydrogen maser alone (MATE) against the identical 158 remote stations at M_2 in 2024 yields $R^2 = 0.000$ — directly falsifying the hypothesis that the $R^2 = 0.702$ decay is inherited from unmodelled M_2 ocean-tide-loading displacements at the remote stations (which are identical in both cross-spectra, and for which IERS 2010 solid-Earth and ocean-tide loading are already removed in the CODE solution). Furthermore, evaluating the gravitational tidal phase test under two complementary classifications resolves both the thermal/atmospheric confound [15, 16] and the oscillator-class screening signature. First, when stations are classified strictly by verified IGS site-log metadata (`H-MASER` / `CESIUM` / `RUBIDIUM` vs `INTERNAL` / `OCXO`) and evaluated with Step 169's simultaneous 8-line harmonic fit ($M_2, N_2, S_2, O_1, K_1, S_1, P_1, Q_1$) under a $10{,}000$-realisation station-level longitude-permutation test (effective degrees of freedom set to N_{stations} rather than N_{pairs}), quartz clocks couple strongly to the non-radiative lunar M_2 ($r = +0.297, p_{\mathrm{perm}} = 10^{-4}$, $n = 69$ stations) and lunar O_1 ($r = +0.225, p_{\mathrm{perm}} = 10^{-4}$) lines whereas metadata-verified atomic standards are screened at both M_2 ($r = +0.031, p_{\mathrm{perm}} = 0.42$, $n = 31$ stations; a $9.51\times$ quartz/atomic contrast) and O_1 ($r = +0.039, p_{\mathrm{perm}} = 0.32$; $5.76\times$). Replicated across four CODE and GFZ final clock datasets (`COD 30d` , `COD 90d` , `GFZ 30d` , `GFZ 90d`), a dependence-preserving joint station-longitude permutation test (permuting each of the 52 unique quartz stations' longitudes once per trial across all four datasets simultaneously so shared stations and overlapping tracking windows are preserved exactly) yields $\bar{r}_{\mathrm{joint}} = +0.190$ versus a null of $+0.0002 \pm 0.0330$ ($z_{\mathrm{joint}} = +5.73\sigma, p_{\mathrm{joint}} = 0.0003$; conditional multi-centre Fisher $p_{\mathrm{perm}} = 1.9 \times 10^{-6}$ at M_2; individually $r = +0.227, p_{\mathrm{perm}} = 6.0 \times 10^{-4}$ on COD 30d; $r = +0.236, p_{\mathrm{perm}} = 0.0012$ on COD 90d; $r = +0.159, p_{\mathrm{perm}} = 0.039$ on GFZ 30d; $r = +0.137, p_{\mathrm{perm}} = 0.040$ on GFZ 90d) while metadata-verified atomic standards (23 unique stations) remain null under both the joint permutation ($\bar{r}_{\mathrm{joint}} = -0.104, z_{\mathrm{joint}} = -0.87\sigma, p_{\mathrm{joint}} = 0.374$) and multi-centre Fisher combination ($p_{\mathrm{perm}} = 0.55$ at M_2 and $p_{\mathrm{perm}} = 0.35$ at S_2). Second, stratifying the wider `COD0OPSFIN` network by residual stability (79–84 low-noise stations with $\sigma < 5$ ns versus 125–135 stations with 5--50 ns in 2024 and 2025) yields a quartz-only tidal coupling across the non-radiative lunar M_2 (12.42 h) and thermal/atmospheric solar S_2 (12.00 h) lines: the low-noise (< 5 ns) stratum — which comprises environmentally isolated atomic standards together with the quietest thermally stabilised quartz receivers — is completely immune to the atmospheric S_2 tide ($r = +0.008, p = 0.66$ in 2024; $r = -0.019, p = 0.26$ in 2025) whereas the 5--50 ns quartz stratum responds strongly ($r = +0.230$ in 2024; $r = +0.280$ in 2025, a $28.6\times$ contrast; pair-level $p = 1.8 \times 10^{-93}$ and 9.9×10^{-163} respectively, which treat $7{,}750$ and $9{,}045$ station pairs as independent and are therefore reported as pair-level only, while the station-level inference of Step 169 with $n = 237$ stations gives permutation $p = 10^{-4}$), yet at the lunar M_2 line both strata couple significantly ($r = +0.106, p = 3.1 \times 10^{-9}$ and $r = +0.207, p = 7.2 \times 10^{-76}$ in 2024; $r = +0.062, p = 2.8 \times 10^{-4}$ and $r = +0.090, p = 1.2 \times 10^{-17}$ in 2025, a $1.95\times$ and $1.46\times$ contrast) because thermally quiet quartz receivers in the < 5 ns stratum suppress solar room/cabling heating [15] without screening the gravitational M_2 mode. Finally, on the live 41-station NTRIP/OS Net array, the signed cross-spectral Gram exhibits a -5.1σ to -6.0σ negative correlation lobe on $1{,}200$–$2{,}500$ km UK-to-Iberia baselines (invariant across polynomial detrend orders 1–9), directly reproducing in real-time streams the spherical negative lobe measured on the global archive in Section 3.7.4.

3.10.2 Degraded-sky position: the network clock prior beats a deployable persistence-trend prior (Steps 99, 106)

A natural architecture question is whether the TEP clock prior, which gives a $+5$–19% clock-domain advantage (Step 55), translates to a position-domain advantage when the receiver clock is soft-constrained rather than hard-substituted. Step 99 tests this in the degraded-sky regime where the architecture is intended: $k = 4$ and $k = 5$ satellites, sorted by elevation so that the k lowest-elevation satellites (worst geometry, highest PDOP) define the degraded scenario.

The clock prior uses the Step 96 phase-resolved predictor: a frozen 5-day LF+MF phase-cos Gram (2.31µHz–500µHz, capturing the drift band that Step 65 identified as the TEP field) combined with a distance covariance kernel ($\lambda = 4{,}200$ km, nugget 0.35), applied as a spatial kriging correction to the target's causal SPP-clock drift trend. The prior sigma is calibrated causally: a rolling-origin pseudo-prediction over the pre-window, at the same horizon as the prediction, produces an RMS that becomes the soft-constraint sigma. This is horizon-matched and strictly causal — no future data enters either the prediction or the sigma.

The clock prediction error is 3.91 m RMS (p50 2.36 m) at the 1-hour gap and 4.42 m RMS (p50 2.68 m) at 4 hours, and the causally calibrated sigma tracks it closely (median 3.54 m at 1 h, 4.03 m at 4 h). Two regimes appear, both consistent with the Step 26 geometry analysis. With the full constellation the receiver clock is already observable from geometry, so the soft prior is correctly inert (-0.1% at 1 h) or very slightly harmful (-8.0% at 4 h). At $k = 4$ and $k = 5$ with degraded geometry the prior recovers 13.6–30.5% of the free-clock position error, with the gain larger at 4 hours (where the clock has drifted further and the network prediction matters more) and at low elevation (where the geometry is weaker and the clock is less observable). The clock-domain advantage (Step 55) therefore does translate to the position domain, in exactly the degraded-geometry regime where the architecture is intended, once the prior sigma is causally calibrated to the actual prediction difficulty.

Step 106 extends this to a rigorous multi-day evaluation — with day-clustered confidence intervals, and against the clock predictor a degraded receiver actually runs. Step 99 compared only against a free-clock solve, on one day, with no interval, and its predictor

added the *precise-product* clock residual to the receiver's *SPP* clock datum — a units mismatch (the precise residual wanders several metres a day; the SPP receiver clock much less) that understated the method. Step 106 fixes the construction so the frozen Step 96 predictor (drift gate + LF+MF phase-cos Gram × distance kernel, $\lambda = 4{,}200$ km, spec imported verbatim, not re-tuned) operates on the target's own SPP clock (the quantity a positioning receiver holds), kriging the network's SPP-clock accumulated offsets. On 27 days (January and April 2024), the Step 91 dense network, the $k = 4$ and $k = 5$ lowest-elevation satellites:

Gap	Arm ($k = 4$ / $k = 5$)	clock error	3-D RMS	vs free SPP	vs persistence-trend prior
1 h	free-clock SPP	—	14.09 / 9.91 m	—	—
1 h	persistence-trend prior (deployable)	1.78 m	7.31 / 4.47 m	$+48$ / $+55\%$	—
1 h	**frozen TEP network prior**	**1.18 m**	**6.24 / 3.83 m**	$+56$ / $+61\%$	$+14.5$ / $+14.5\%$, CI $[13.6, 15.3]$ / $[13.2, 15.7]$
1 h	phase-scrambled kernel (null)	1.32 m	6.44 / 3.98 m	—	—
4 h	free-clock SPP	—	12.65 / 9.07 m	—	—
4 h	persistence-trend prior (deployable)	4.81 m	12.36 / 7.95 m	$+2$ / $+12\%$	—
4 h	**frozen TEP network prior**	**1.70 m**	**6.47 / 4.13 m**	$+49$ / $+54\%$	$+47.7$ / $+48.0\%$, CI $[46.2, 49.1]$ / $[46.2, 49.6]$
4 h	phase-scrambled kernel (null)	2.30 m	7.47 / 4.91 m	—	—

The frozen TEP network prior beats free-clock SPP by 49–61% *and* a deployable persistence-trend prior — the clock predictor a degraded receiver actually runs — by $+14.5\%$ at 1 h and $+48\%$ at 4 h, with day-clustered 95% intervals excluding zero in all four (k, gap) cells. The advantage grows sharply with horizon because persistence-trend degrades badly over 4 h (clock error 4.81 m) while the network prediction barely does ($1.18 \to 1.70$ m): a receiver's own drift extrapolation is a much worse model of its clock than the network is, and the gap widens exactly where it matters operationally. What carries the position gain is the network's common-mode band-limited clock, which Step 59 shows *is* the TEP field (it decays with inter-region separation at the TEP length scale; its spectral signature rules out orbit, tropospheric and tidal common modes) — so an unweighted network mean is a coarse TEP predictor, not a null, and it too beats persistence. The distance/phase *structure* then refines the common mode, and now clears a much larger margin with 27 days of statistical power: the distance-and-phase-weighted prior beats a phase-scrambled kernel by $+3.0$–3.9% at 1 h (CI $[2.1, 4.3]$ / $[3.0, 5.1]$) and by $+13.4$–15.8% at 4 h (CI $[9.8, 17.5]$ / $[12.0, 19.8]$) — the Papers 1–2 phase alignment does substantial, horizon-growing work. The distance kernel remains near-inert on this $< 2{,}000$ km regional network (a distance permutation cannot re-order the pairs); a wide-aperture 39-station run (pairs to $17{,}000$ km, 6 days) confirms the clock gain but the position gain there is smaller and geometry-sensitive, because a wide global set mixes receiver qualities and free-clock is already adequate at $k = 5$ with diverse geometry — more days are needed to resolve it with confidence.

Independent analysis centre (GFZ). The frozen predictor above is calibrated on CODE products throughout. Re-running the Step 96 clock-domain flagship verbatim — same λ, nugget, band, drift gate, no re-tuning — on GFZ0OPSFIN, an independently processed global clock solution: on 25 days of 2024, global network, the gated LF+MF predictor beats every deployable baseline at 1–4 h — including the toughest, a shrunk full covariance fitted to each target's own recent history, by $+10.3\%$ (CI $[+6.5, +15.3]$; $+19.8\%$ pooled across horizons) — and clears every specificity null: the distance-scrambled covariance retains only $+6.2\%$ against that baseline and the phase-scrambled Gram loses (-9.5%). On the held-out 2025 year the same global cell repeats the result end to end — $+7.8\%$ over the toughest baseline at 1–4 h (CI $[+2.1, +12.1]$; $+22.5\%$ pooled), again beating every baseline and every specificity null. GFZ's operational product is sparse outside Europe — just 8 North American and 5 East Asian stations, too few for the multi-region protocol — so the regional cells cannot reproduce the CODE three-network design: GFZ Europe on held-out 2025 (6 evaluable days) beats all deployable baselines at 1–4 h but leaves the target-aware covariance and the specificity nulls unresolved ($+4.2\%$, CI $[-4.1, +46.8]$), and GFZ Europe 2024 (13 days) is mildly adverse (-1.6% against the toughest baseline). A frozen construction tuned entirely on one analysis centre's product nonetheless generalises, without modification, to a second analysis centre's independent processing of the same GPS observations, on both the development year and an independent held-out year — the strongest available evidence that the result is not a CODE-specific network-adjustment artefact — while the strict two-region Level-1 bar still awaits a GFZ-class product with CODE's global station density.

3.10.3 Moving-platform boundary: the field does not follow a fast orbital receiver (Steps 104, 105)

The operational mechanism — a frozen terrestrial clock field predicts a receiver's proper time through a GNSS outage (Sections 3.6.2–3.6.3, P1) — is established for receivers that are effectively fixed. Its outer edge was mapped directly with the one class of public data that combines a moving platform, an oscillator stable enough for the signal to clear its holdover noise, raw observations

and centimetre truth: low-Earth-orbit satellites. Every public UAV and ground-vehicle archive carries a temperature-compensated crystal oscillator whose one-hour holdover error (∼1 km) exceeds the field signal (∼1–3 m) by three orders of magnitude; airborne-gravimetry campaigns publish only processed trajectories. Swarm, GRACE-FO and Sentinel-6 instead carry geodetic dual-frequency receivers, publish raw RINEX openly, and are validated to 2–4 cm by satellite laser ranging.

Step 104 tests Swarm-A and Step 105 tests GRACE-FO: during simulated GNSS gaps of 10 minutes to 2 hours, can the 313-station `clk_cod_ops` network predict the satellite receiver-clock innovation better than a persistence-trend? On both satellites it cannot. For GRACE-FO — whose Ultra-Stable Oscillator genuinely free-runs (clock offset -23 ms, drift -1.5×10^{-8} s/s, so the physical signal is present, not steered out) — the distance-kriged prior *loses* to persistence by 16–46% across all gaps (day-clustered CIs exclude zero), and the kriged prediction is statistically identical to a network mean and to a distance-scrambled control, i.e. no spatial structure is recovered at all. The GRACE C−D differential and the steered Swarm clock give the same result. Crucially, a ground-to-ground control run on the *identical* machinery — hold out a terrestrial station, predict it from the rest — reproduces the small positive Section 3.6.2 result ($+0.8$ to $+4.8\%$, beating the scrambled control by ∼1.5\%). The negative is therefore physical, not a pipeline artefact, and it does not depend on clock steering.

The cause is kinematic. A satellite at 7.5 km/s traverses a full field correlation length (∼4,200 km) during even a one-hour gap, so its clock integrates the proper-time field along a ground track that spans several correlation lengths; the spatially-structured part averages out along-track and only a global common mode survives, which carries no distance information. This bounds the operational claim precisely and falsifiably: the frozen terrestrial field predicts a receiver's proper time through an outage *when the receiver's displacement during the outage is small compared to* λ_T. That covers the entire terrestrial degraded-GNSS envelope — urban and pedestrian receivers, IoT and fixed installations, maritime, ground vehicles, and slow aircraft (a UAV covers ∼5 km in a 3-minute window, far inside λ_T; the Flight 8 stress test fails on its oscillator, not its motion) — and excludes orbital platforms.

4. Discussion

From clock screening to a position observable (Steps 77 and 80). Co-located atomic/quartz pairs provide the anchor geometry needed to separate field response from local clock drift. The full-year, station-clustered test recovers the established scale at two independent free-atomic sites: 3,282 km at Matera ($R^2 = 0.854$, geometry-null $p = 0.0010$) and 3,732 km at Tahiti ($R^2 = 0.859$, $p = 0.0010$). The failure at Stromlo is retained as a pipeline/hardware discriminator, not averaged away; the Wuhan pair is not a clean immunity anchor because its rubidium standard is GPS-steered. Inverting the 43-mode fingerprints with target coordinates withheld reduces global localisation error to 339 km at Matera and 744 km at Tahiti, far below their 9,078 and 10,044 km geometry-null medians. This is the missing bridge from correlation to location information. Its present resolution is limited by the 4,201 km field smoothness and an isotropic annual-average map. A mobile system should instead use direct onboard atomic/quartz phase comparison, causal rolling complex modes, local gradients, a known launch point, IMU and barometric altitude. One scalar clock difference cannot uniquely determine 3-D position; multiple independent modes or sequential gradients must make the field Jacobian full-rank. The proposed zero-satellite drone test therefore uses direct oscillator outputs and non-GNSS aiding after launch, never a receiver-clock series estimated from satellites.

Physical invariance versus operational exploitability. A fundamental distinction must be drawn between the physical reality of the TEP field and its operational exploitability in a navigation filter. The physical reality is invariant across processing regimes: precise IGS-final products remove roughly two orders of magnitude of satellite-clock error relative to the broadcast ephemeris, yet the short-baseline receiver-clock correlation shifts by only $+4.5\%$ (broadcast $+0.429$ → precise $+0.449$), and the T1 correlation-length recovery on the global broadcast product ($\lambda = 3{,}480$ km, $R^2 = 0.93$, 7.5σ, 52 stations) and the global precise product ($\lambda = 3{,}628$ km, $R^2 = 0.83$, 9.0σ, 160 stations) agree to within $+4.3\%$ at baselines to 20,000 km. A satellite-clock artefact large enough to produce these correlations would collapse proportionally under that reduction; the correlation surviving it, across all four processing modes (agreement to 8.4%), localises the effect to the receiver side and rules out the satellite-ephemeris and ionospheric artefact classes. The operational prediction skill, however, varies between products. On real-time broadcast ephemeris the receiver clock freely absorbs the spatially correlated satellite-common-mode error, which a distance kernel predicts at $+52\%$ variance reduction over 318 days (CI [50, 54]). On precise post-processed products the satellite common-mode has been removed, the raw clock residual is already small (0.82 m versus 8.14 m), and the kernel is approximately inert (-2% versus no network) — it adds no noise to an already-clean solution. The operational leverage is therefore maximised in real-time, single-frequency, broadcast-ephemeris processing, where the distance-structured prior acts as a virtual measurement channel.

Distance structure is the safe way to apply a network correction, and much of the "common mode" is the field. On precise products a bulk network mean actively degrades the clock prediction (-12% versus no network in the station-split design; -1.8% in the leave-one-day-out design) because it injects noise from spatially uncorrelated distant stations; the distance kernel correctly downweights them, beating the bulk mean by $+9\%$ (CI [6, 21]) in the station-split design and by $+6.0\%$ (CI [4.6, 7.7], 73\% of days positive) in the leave-one-day-out design, with a leakage-free scaled-mean control confirming the margin is geometry-specific. One caveat is essential: the $+4.4\%$ precise leave-one-day-out figure is achieved by a kernel whose length scale is *fitted per day* — the selected median $\lambda \approx 700$ km is the amplitude-domain nearest-neighbour scale of spatially uncorrelated local-oscillator noise, not the TEP scale. The framing that only the distance-weighted residual is TEP-specific, however, understates the effect on a network smaller than λ_T. Step 59 partitions each day into compact regional clusters and correlates their mean band-limited clocks: the correlation is $+0.8$ at ∼500 km, decays with inter-cluster separation at a Gaussian $\lambda = 2{,}944$ km, and vanishes under both a per-cluster phase-randomisation null and a cluster-identity shuffle. A datum or time-scale common mode would be separation-independent; this is not,

and it is present on the precise product where the satellite-clock common mode has already been removed. The network-mean clock is therefore substantially the TEP field, sampled at an aperture below its correlation length: the held-out skill against persistence or predict-zero is the TEP contribution, and the skill against a bulk mean is a conservative lower bound that removes most of the field before comparing.

Density is a supported hypothesis, not yet an isolated cause. Step 54 associates dense EUREF geometry with a $+6.7\%$ fixed-kernel margin over a flat mean, whereas the global arm does not. Its earlier explanation was wrong: 700 km is not near the tail of a 4,200 km Gaussian covariance (the assumed correlation is about 0.986). The whole-day zero-phase filter is retrospective; region, product and density differ together; and its cell bootstrap is not day-clustered. Step 54 is therefore a mechanism diagnostic. The corrected Step 55 within-network causal outage experiment supplies the operational test without relying on this causal attribution.

Robustness of the operational result. The Step 55 outage prediction result is subjected to four independent robustness checks: per-station breadth (TEP wins at every one of the 25 EUREF stations individually at both 1 h and 4 h outages, sign test $p = 3 \times 10^{-8}$); seasonal stability (positive in every quarter, $+19.1\%$ to $+39.0\%$ at 1 h and $+32.4\%$ to $+46.9\%$ at 4 h); network density (still $+20.8\%$ over persistence at 30 min with only 5 reference stations, scaling monotonically with density); and pre-window sensitivity (robust to a $4\times$ range of pre-window lengths). Together these establish that the operational result is not an artefact of station selection, season, network density, or a hyperparameter choice.

Phase is predictively exploitable once represented in the correct domain. Capturing cross-spectral phase structure in a predictive covariance requires a 24-hour window sufficient to resolve the 10 μHz band edge, the signed phase-alignment statistic $\cos(\arg \sum_f S_{ij}(f))$, and a positive-semidefinite Gram construction (Step 56), whereas short 30-minute windows lack frequency resolution at 10 μHz and unnormalised pairwise phase products lack PSD guarantees. In Step 56, a complete preceding day supplies a frozen normalised cross-spectral Gram matrix whose real part is coherence times phase-cosine, and its Schur product with the fixed TEP distance covariance is PSD by construction. On 45 subsequent days it adds 2.6–17.1% over distance-only TEP and 4.8–23.4% over the causally selected conventional spatial model from 30-minute to 8-hour outages. Randomising phase while preserving every coherence magnitude loses 14.4–37.2%; the stricter phase-free magnitude-squared-coherence arm leaves a smaller 0.4–1.4% phase-angle increment, significant at 30 minutes, 1 h and 8 hours. Earlier short-window amplitude-domain variants — the Papers 1–2 Gaussian, Matérn-1.5, anisotropy and astronomical-regressor parameterisations — failed only because they neither calculated the registered phase statistic nor used enough history to resolve its band; Step 56 supplies the missing test and reverses the operational conclusion. The remaining epistemic boundary is external replication: Step 56 is an internal frozen-day validation on the same regional product family, not yet an untouched-network confirmation.

Real-world deployment pathway and cost-benefit boundary. The Step 56 construction requires only a network of reference stations with known coordinates and broadcast-ephemeris or ultra-rapid clock residuals — infrastructure that already exists in every regional GNSS correction service (SBAS, DGPS, RTK networks, CORS). A regional reference service updates one phase/coherence Gram matrix from the previous 24 h, combines it with the fixed TEP distance kernel, solves a single $K \times K$ linear system per epoch ($K \leq 40$, under 1 ms on commodity hardware), and distributes target/grid weights plus calibrated uncertainty; a client receiver maintains its local offset/drift model and consumes live reference innovations as a clock pseudo-measurement when satellite visibility collapses. The measured applications are clock holdover during 10-minute to 8-hour outages, degraded-geometry urban-canyon or portal transitions, and an independent network-clock channel for spoofing/integrity monitoring. At 8 h the phase-resolved RMS is 19.67 m of clock range (about 66 ns), versus about 44.36 m for the deployable temporal arm. A consumer-grade TCXO ($\sim \$5$) with TEP network aiding achieves 24.7 ns timing error at 1 h versus 3,606 ns free-running — exceeding the holdover of a $\sim \$300$ OCXO (38 ns) and approaching a $\sim \$2{,}000$ Rubidium standard (18 ns) — beats the Rubidium standard at 2 h (29.3 ns versus 37.5 ns Rubidium and 78.0 ns OCXO), and at 8 h holds 66 ns versus 29,215 ns free-running, 383 ns OCXO, and 168 ns Rubidium, offering mass-market and IoT receivers telecom-grade timing resilience over a network link alone. A production PRIDE-PPP-AR engine with the prior wired in returns bit-identical solutions for clean 24 h multi-GNSS phase PPP, and the clean full-sky cold-start convergence test (Step 62; -1.4% vs free-clock and -1.9% vs persistence across 24 cold starts at 15/30/60 min) confirms the constraint is correctly inert when geometry already pins the clock. In the Step 62 *degraded* arm ($k = 4$ GPS-only), where geometry no longer pins the clock, the prior recovers ∼50\% of the free-clock position error ($+29.8\%$ across 96 cold starts), at 1–4 h degraded-sky horizons it separates from persistence by $+14.0\%$ to $+48.0\%$, and the 9.5-hour blind NTRIP replication on nine unseen stations plus the disclosed training-pool station DLF1 ($+15.1\%$ position and $+22.2\%$ clock gain at 4 h) together with the continuous live observatory complete the real-time operational validation.

The free GP converges to the TEP scale, and the discovery is null-controlled. An unconstrained Gaussian process, free to select any covariance form and length scale with no TEP prior, independently selects $\lambda \approx 1{,}500$ km (median across 318 days, Gaussian form preferred on 190 of 318 days) on the broadcast product — squarely in the TEP-predicted $1{,}000$–$5{,}000$ km band — while achieving $+52.6\%$ skill versus no network, comparable to the TEP-constrained kernel ($+52.9\%$). The TEP kernel's contribution is therefore not to add predictive skill over a free GP (it does not; the deficit versus a conventional family selected on the training day is -0.1%, CI $[-0.5,\ 0.0]$), but to predict the correlation scale *a priori* from physics that the free GP must discover empirically; the TEP ensemble — a training-day-weighted blend — is the best single predictor at $+10.0\%$ versus a bulk mean (CI $[+7.2,\ +11.4]$). On the global precise product the free GP selects $\lambda \approx 700$ km: Step 43 establishes that this is the scale of the residual receiver noise, not a falsification, through three controls — injection/recovery (a synthetic TEP signal injected into the real precise residual is recovered within a factor of two in 88% of trials across the band); baseline restriction (median selected scale moves to $1{,}500$ km with 85% of days in-band on baselines $> 1{,}000$ km); and null controls (0% of temporally shuffled and 3% of geometry-shuffled

trials select a TEP-band scale, versus the majority collapsing to grid edges). A free GP does *not* select a consistent finite scale on null data, so its convergence on the real data is informative rather than generic.

Convergence of independent λ measurements. The correlation length has now been recovered by measurements spanning four methodological approaches: direct distance-decay fits on the precise product, per-analysis-centre fits on four IGS/MGEX centres (COD/GFZ/GRG/JPL), a global-aperture precise-product fit (T5, $R^2 = 0.945$), and the baseline-restricted free-GP estimate on baselines $> 1{,}000$ km. These estimates partially share input data, so they are not statistically independent. The broadcast T1 ($\lambda = 3{,}480$ km) is excluded from the in-band count because the Step 40 band-pass audit finds the broadcast arm fits at $26{,}897$–$28{,}759$ km (product common mode); the temporal T4 values are excluded because the scale estimate is intrinsically ambiguous ($\lambda = 4{,}349$ km uncontrolled, $1{,}008$ km lower bound after the $\bar{J}$ control absorbs part of the field's own long-distance tail). Every remaining measurement falls inside the predicted band: $1{,}500$, $1{,}817$, $2{,}339$, $2{,}942$, $3{,}628$, $3{,}759$, and $4{,}230$ km. A dependence-aware bootstrap that groups the measurements into five independent blocks and resamples both within and between groups gives a combined median $\lambda = 2{,}822$ km with 95% CI $[1{,}949, 3{,}763]$ km — entirely within the TEP-predicted band, and honestly wider than the naive interval because acknowledging dependence cannot increase precision. The convergence is therefore not merely qualitative: the TEP scale is a reproducible property of GNSS clock networks with a formal dependence-aware interval inside the predicted band.

Band-pass robustness and physical justification. Across four bands and detrend-only data, the 30-day COD precise-clock arm returns $\lambda = 2{,}297$–$2{,}393$ km, $R^2 = 0.868$–0.888 and 15.2–32.0σ real-vs-null separation — strong evidence that the precise-product scale is not a filter artefact, since it survives with no band-pass at all. The broadcast arm is also highly separated from nulls but its 26,897–28,759 km scale sits outside the TEP band and is attributed to satellite/product common mode. The default 10–500 μHz band is physically motivated: the lower bound excludes multi-day receiver-oscillator drift (daily and semidiurnal tidal structure is retained within the band and controlled separately), the upper bound excludes multipath and thermal noise below the 30 s cadence, and the TEP field is predicted to produce a continuous fluctuation spectrum spanning exactly that range [1, 2].

Operational evidence and boundary. The downstream positioning result establishes algebraic feasibility at $k = 3$ where free-clock SPP is infeasible: the recalibrated Step 48 blind nonlinear run starts 100 km wrong and on the dense EUREF-prioritised network achieves 7.54 m RMS (canonical) and 5.76 m RMS (phase-resolved) at 95.2% availability, with the recalibrated integrity gate rejecting zero epochs. Conventional clock-prior controls (AR1 at 5.53 m, persistence at 5.66 m) are also feasible, so TEP supplies the missing degree of freedom but does not exceed the best conventional control in position accuracy — near-parity with persistence (-1.7% at 1 h, $+0.3\%$ at 10 min) is the honest statement, because the $k = 3$ solve is pseudorange-noise-limited (~0.3 m per satellite), not clock-limited. The clock-domain advantage does not propagate to single-epoch $k = 3$ code SPP for the same reason; it converts to position accuracy only where the pseudorange floor no longer dominates: $+14.5\%$ to $+48.0\%$ over persistence-trend in 1–4 h degraded-sky arcs at $k = 4$–5 (Step 106), and $+29.6\%$ 3-D ($+46.7\%$ vertical) at $k = 3$ and $+14.0\%$ over persistence ($+62.9\%$ over free-clock) at $k = 4$ under carrier-phase tracking on the live observatory (Section 3.9). With four or more satellites and a full sky the clock is already observable and a finite-error clock prior is correctly inert — Step 23 and Step 62 verify the constraint reaches the production PRIDE-PPP-AR state bit-identically in clean processing, and the corrected causal cold-start test (Section 3.6.4) finds no TEP-specific gain in that regime.

Co-visibility collinearity is a physics limitation of the cross-sectional test, not of the data. Ground stations are bounded by continental geometry, so great-circle distance and satellite co-visibility are collinear ($r \approx -0.93$) on both broadcast and precise products even at global aperture. But the collinearity is a feature of the cross-sectional test (one co-visibility value per pair), not of the data itself: distance is fixed per pair while co-visibility varies epoch to epoch. Step 45 attacks this with a two-stage temporal regression that extracts the pair intercept — the non-common-view component — and tests whether it shows distance structure. With the corrected pooled-κ stage-1 on real-SP3 co-visibility, the broadcast intercept meets the frozen separability criterion outright ($\mathrm{PC} = -0.164$, 10.8σ, out-of-sample R^2 gain $+0.022$, $\lambda = 4{,}349$ km), strengthening to -0.267 when the identified local-solar-time systematic is controlled, while the network-solved precise product shows the physically predicted attenuation ($\mathrm{PC} = -0.040$, 9.2σ). The matched-design experiment (Step 41) — match pairs on co-visibility, vary distance — is the most direct controlled test and, with the corrected phase-alignment observable, is inconclusive rather than negative: distance alone explains more variance than co-visibility alone on broadcast ($R^2 = 0.220$ vs 0.196), reversing the Pearson ordering, but the matched cross-sectional design lacks the statistical power to confirm the increment at the frozen threshold. The satellite-side channel (Section 3.8), which uses neither receiver clocks nor common-view geometry, remains the cleanest geometry-free evidence for the distance structure.

Global compass-split T2 anisotropy is diluted by Earth rotation and long-baseline sign reversal, while the short-baseline sector test and sub-diurnal aperture synthesis isolate the directional signal. A continuous-azimuth model (Step 47) reports a negative result: the EW–NS coefficient is -0.014 globally, excluding zero in the wrong direction, and Step 11b's corrected statistic gives an EW/NS ratio of 0.90 (not significant). What the corrected statistic *does* establish here is a further independent recovery of the isotropic scale: each compass subset independently reproduces λ_T in the $4{,}000$–$4{,}500$ km band at $R^2 \geq 0.84$. Two mechanisms explain why an all-baseline static compass split misses the directional signal that targeted tests recover: the positive EW–NS contrast is concentrated in the 500–800 km band (Section 3.7.2, Step 82), where Step 176 shows it survives common-view removal essentially unchanged ($+0.130 \to +0.126$), and pooling across all bins averages that band against opposite-sign neighbours; and a fixed 24-hour compass split smears a celestial dipole axis across azimuths as Earth rotates. When baselines are instead projected onto candidate celestial axes via sub-diurnal aperture synthesis (Step 137, 265 twelve-hour windows, $2{,}140{,}095$ pair-windows), the network strongly discriminates the CMB dipole axis ($\mathrm{BIC} = -6{,}322.6$, 100th percentile of 100 random sky axes; scrambled-

geometry null $r = -0.0001 \pm 0.0007$) over the Solar Apex ($\Delta\mathrm{BIC} = +2{,}315.5$), the GPS Nodal Plane ($\Delta\mathrm{BIC} = +2{,}836.2$), and the Geomagnetic Pole ($\Delta\mathrm{BIC} = +4{,}204.9$), remaining highly significant after regressing out great-circle distance ($p = 1.6 \times 10^{-30}$).

The satellite-side channel is an independent detection of the same distance structure. The phase-coherent cross-spectral analysis of satellite clocks (Section 3.8; Step 98) uses no receiver clocks and no common-view geometry: GPS clock pairs show a phase alignment falling off with inter-satellite separation ($+0.536$ near/far contrast, 10.6σ and 12.6σ above the two nulls, rising to $+0.546$ at 15.9σ on the 180-day extension), the GPS×Galileo cross-constellation arm confirms the signal is not GPS-specific ($\lambda = 8{,}140 \pm 795$ km, log-slope 26.4σ over 180 days), and the Galileo-only and BeiDou-only arms are independently significant. The injection self-test confirms the single-constellation channel cannot resolve a single λ_T because GPS contains no pair below $\sim$ 6,000 km, whereas the wider-aperture cross arms resolve finite scales in the continuously screened band. The satellite-side channel is therefore a third independent line of evidence, alongside the receiver-side Step 53 and the baseline-restricted free-GP scale estimate.

Integrity monitoring. Because the kernel predicts a station's clock from the state of the reference network, a common-mode drag-off spoofing attack that drifts the whole constellation — invisible to standard satellite-consistency RAIM — appears as a growing residual against the network prediction. In the Step 08 simulation the residual crosses the 3σ threshold at 87.0 ns (~26.1 m) of induced drift, 174 epochs after attack onset, with the threshold calibrated on leave-one-out prediction residuals of the reference stations. This is a simulation on replayed clock data, presented as a proof of concept for an independent integrity channel, not a fielded detector.

Target operational scenarios and the UAV stress test. Drones, urban vehicles, maritime receivers and low-cost handheld/IoT GNSS are the intended degraded-geometry regimes. Step 52 stress-tests transfer to a genuine moving platform using the public IGN/EPFL fixed-wing Flight 8 archive — a blind nonlinear solve evaluated against independent PPK truth over two pre-registered 300-second simulated jamming windows implemented by satellite masking, with one flight as the inference unit. At $k = 4$ the production fallback correctly selects ordinary positioning and achieves 4.01 m p50, 296/300 epochs below 10 m. At $k = 3$, free-clock SPP returns no solution while both constrained arms return 300/300 solutions — but the TEP p50 error is 567 m (571 m for receiver-only persistence), not a usable bridge. The dominant error is the UAV receiver's local millisecond-steered oscillator over the short outage, and there is a timescale mismatch Flight 8 cannot avoid: the regime in which a frozen TEP field beats persistence is the 1–4 h outage, whereas a 300 s window is far shorter than the field's coherence time, so the causal network innovation is ≈ 0 by construction and the TEP-aided solve *correctly* collapses onto clock-hold — which is why the two $k = 3$ medians agree to the metre. Flight 8 also lacks per-event steering telemetry and a 24-hour docked pre-flight clock history, so it is a test of sub-minute receiver-clock extrapolation on a steered TCXO, a regime in which TEP makes no prediction of improvement, not a test of the mechanism Steps 55–96 establish. The outer edge of the mechanism was mapped independently on low-Earth-orbit satellites (Steps 104–105): on the free-running GRACE-FO Ultra-Stable Oscillator the terrestrial field prior loses to persistence by 16–46% while a ground-to-ground control on identical machinery reproduces the positive, because a 7.5 km/s platform integrates the field along a ground track spanning several correlation lengths. The operational claim is thus bounded, falsifiably, to receivers whose displacement during an outage is small compared to λ_T.

The outage-bridging case, on a dense network. Corrected Step 55 is the strongest present operational result. Across 90 days, the fixed TEP prior beats the strongest post-hoc temporal arm by 5.0–18.9% RMS at 10 min–8 h, with positive day-clustered CIs at all six gaps, and beats the strongest post-hoc conventional spatial arm pointwise at all six gaps by 0.1–0.5% — the physics-fixed scale matches or beats a 48-choice causally fitted covariance family without per-outage tuning. The corrected pipeline causally decodes the product's 1,000,000 m clock-state wraps and rejects corrupted live references; target clock resets (hardware events outside the holdover benchmark scope) are counted and excluded at a 5000 m threshold well above the legitimate p99.9 prediction error. The clock-domain advantage is the predictive-power result; the $k = 3$ feasibility is the operational capability.

The "clock drift" is the TEP field, not oscillator instability (Steps 65, 70, 75b). The standard GNSS model decomposes the receiver clock as offset + drift + noise; Step 65 tests whether this is physically wrong, and finds the decomposition reversed: quartz clocks show $3.8\times$ more LF amplitude than atomic clocks but only $1.2\times$ more MF and $0.9\times$ more HF — a strong frequency-dependent oscillator-class differential (consistent with either the proposed screening hypothesis or differential disciplining/transfer characteristics; Section 3.5.3), while the HF band shows no differential because it is dominated by local oscillator noise. The practical implication is that detrending discards the strongest part of the TEP signal; Step 96's multi-day phase-cos Gram predictor that retains the low-frequency drift is the construction that beats every deployable baseline on a held-out year. Step 70 tests the consequence directly: type-weighted kriging gives $+6.7\%$ at 1 h and $+21.6\%$ at 4 h versus temporal extrapolation for simulated quartz rovers, though with per-station variability (the co-located differential ranges 0.33–28× across four pairs, one pair falsifying the direction) the population-average factor is an approximation. Step 75b extends the co-located analysis to the full network: the pairwise MF correlations stratified by oscillator type order QQ > QA > AA on both CODE and GFZ centres, with quartz-quartz pairs yielding $\lambda = 2{,}741$ km (CODE) and $2{,}356$ km (GFZ) in the TEP band while atomic-atomic correlation is flat with distance ($\lambda \approx 10{,}000$ km) — a regional atmospheric residual would not produce this oscillator-type stratification, because the atmosphere does not care whether the receiver runs a quartz or a cesium clock.

The oscillator-class differential is intrinsic to the frequency standard, not ambient site environment (Steps 72–74). The TEP-UCD framework predicts that environmental density ρ contributes to screening through a saturation mechanism at $\rho_T \approx 20$ g/cm^3. Steps 72–73 test every environmental variable accessible to GNSS — temperature stabilisation, monument foundation, altitude, and the satellite-vs-ground density contrast — with metadata verified from primary sources (IGS site logs, NGA GPS catalog, RINEX

headers). None of the environmental channels isolates the screening: temperature tolerance has no partial correlation with LF amplitude controlling for clock type ($r = 0.076$, $p = 0.59$); bedrock vs building foundation has no effect; altitude's gravitational-potential variation is $\sim 1000\times$ below the clock noise floor and its correlation is not significant after excluding clock-jump outliers. No GNSS station sits in a medium approaching ρ_T, so the saturation mechanism cannot be tested this way; the satellite-vs-ground comparison is confounded by oscillator type (the within-satellite Rb LF variation exceeds the between-group ratios). Step 74's same-type comparison is directionally consistent (satellite Rb / ground Rb = $3.6\times$, satellite Cs / ground Cs = $21.8\times$ on only $n_{\mathrm{sat}} = 2$) but cannot reach significance. A proper test requires free-running atomic clocks of the same type in different density environments connected by optical fibre — a laboratory experiment stated as an explicit prediction of the framework, not a tested result.

The independent-year P1 boundary and its closure. Step 92 freezes a 2025 CODE archive and runs the single-band 10–500 μHz P1 evaluation against it without unsealing: in that restricted band the single-scale TEP kernel underperforms a causal empirical covariance model by -4.1% (CI95 $[-5.5\%, -2.5\%]$), and the full single-band arsenal is at a statistical tie. Similarly, in the fully causal Step 102 amplitude-domain comparison on the regional test aperture (Step 102), the frozen TEP predictor retains a $+13.4\%$ advantage over the frozen conventional spatial kernel (95% CI $[+11.9, +15.1]\%$) but trails local inverse-distance weighting (IDW) by 3.0% (CI $[-3.5, -0.4]\%$), because nearest-neighbour amplitude interpolation is highly effective on a compact regional network when low-frequency drift is removed. Those boundaries are diagnostic: the 10 μHz lower edge excludes the low-frequency drift that carries the largest share of the field, and a single λ conflates the long-range LF regime with the shorter-range continuum. Two independent routes close the gap on the held-out year: Step 96 retains the drift via a multi-day phase-cos Gram and beats every deployable baseline (including IDW, free GP, and causal empirical covariance) across three coherent regional networks, and Step 140 applies the physics-fixed three-band scales ($4{,}677/1{,}502/1{,}459$ km) across 57 held-out days, beating both the single-band kernel ($+2.19\%$) and the causal empirical-covariance map ($+0.56\%$) while clearing geometry-, phase-, and λ-scramble nulls; Step 153 extends the validation to 88 held-out CODE days and replicates it unchanged on 49 held-out GFZ days. Step 91 shows the complementary boundary in the position domain: hard-substituting a kriged clock into a $k = 3$ pseudorange solve degrades position (-134% at 1 h) because spatial estimation variance is injected unattenuated into a code-noise-limited system — soft-constraining at calibrated uncertainty (Steps 99, 106) and carrier-phase tracking are what convert clock skill into position gain.

Current proof boundary and live operational closure. With the completion of the 9.5-hour blind NTRIP replication ($+15.1\%$ position and $+22.2\%$ clock gain at 4 h, closing P4), the 30-cell multi-region seasonal sweep (closing all 8 of 8 P5 dimensions), and the continuous 68-station Live Skill Observatory ($+35.84\%$ mean / $+38.10\%$ median causal walk-forward two-hour holdover gain across 185 windows, 182 of 185 positive, $p = 2.15 \times 10^{-50}$), all five operational gates pass. Cryptographic verification is supplied by the Step 174 sealed-envelope protocol: weight vectors committed to disk with a SHA-256 digest before the scored data exist win 24 of 24 replayed one-step windows ($+42.66\%$, CI $[+37.65, +46.89]\%$), separate from a station-permutation null at 17.4σ, retain 97.3% of skill with the network common mode stripped, and still contribute $+22.63\%$ from stations solely beyond 360 km and $+8.46\%$ beyond $1{,}000$ km; the live seal ledger records the same signature on genuinely post-seal windows (Section 3.9). An adversarial pairing control shows the scorer cannot manufacture the headline: replaying frozen weights against other windows' data spreads the gain across -30% to $+72\%$ versus $+41\%$ correctly paired, so the epoch-coherent increment over a climatological correction is $\sim +9$ points.

The same corpus delimits the result's domain honestly on two axes. In lead time, frozen-weight skill decays through a ∼90-minute zero crossing to -3.82% under a full two-hour epoch-disjoint embargo, remaining positive at a one-hour embargo ($+9.67\%$, $p = 3.3 \times 10^{-3}$). In epoch sharing, because member Grams are built on their own holdout residuals, the sealed headline decomposes into verified retrodiction plus a bounded forward component: an oracle replay of member-observed residuals reaches $+47.48\%$, while weights trained on zero-overlap fit-half Grams transfer -5.63% at the deployed penalty yet flip sign monotonically with shrinkage to a resolved plateau of $+2.5\%$–$+2.8\%$ over $\lambda = 2 \times 10^6$–10^7 (a fully causal per-seal selection on the newest member's holdout Gram deploys penalties across the plateau and scores $+2.57\%$, 22 of 24, CI $[+1.42, +3.85]\%$), with a per-feature diagonal control collapsing to -159.52%. The defensible claim therefore reads: the station field map explains the rover's observed residual under committed weights at high spatial fidelity, while genuinely forward prediction at this cadence and oscillator is positive but bounded at a few per cent — the regime the deployed refit cadence and taper already encode. Read as measurement rather than caveat, the lead-decay curve is a first estimate of the transfer fit's dynamical coherence time — a temporal scale for the field's exploitable structure complementary to its spatial correlation length — and it is what fixes the deployed sub-hourly refit cadence and the 5,400 s taper knee.

The dedicated quartz-oscillator benchtop counterpart to the optical-clock closure below is the pre-registered satellite-free hardware replication (Step 172): whereas Step 181 tests GNSS-free optical atomic clocks across national metrology institutes, Step 172 tests a mass-market quartz receiver with its antenna port terminated (zero satellites tracked), timestamping its free-running TCXO pulse edges against the primary receiver's GNSS-disciplined pulse on a common counter, then scoring the phase alignment of the shielded-oscillator residual against the network's contemporaneous prediction against a circular-shift null. The capture and scoring chain is verified end-to-end on synthetic injections (injected alignment recovered at $\mathrm{PA} = 0.98$, $z = 4.4$; all controls correctly null), and the analysis honestly bounds its own power: a single 24-hour capture resolves only ~ 20 in-band phase terms, so the registered protocol requires multi-day captures. A first software-only precursor capture (the host quartz of the analysis machine against its NTP-steered realtime clock, 49.9 h) reads null ($p = 0.49$) but is channel-bound rather than informative: the NTP reference contributes ~ 19 ms of in-band wander against the ~ 4 ns signal, bounding the construction's resolving power at $\sim 10^7\times$ the required sensitivity; the registered counter/GPSDO path, whose reference is ns-class, remains the decisive arm. The registered validation separates into two distinct levels: (i) a *primary measurement-independence test*, in which a free-running quartz oscillator is measured against a stable

GNSS-independent reference (a free-running unsteered atomic standard or an optical-fibre time-transfer link, augmenting the diagnostic GPSDO reference arm) to establish whether the in-band residual exists when neither clock traverses GNSS estimation; and (ii) a *TEP spatial-prediction test*, in which that GNSS-free clock residual is scored against the contemporaneous frozen network prediction under pre-registered phase, amplitude, and circular-shift null criteria. A co-located atomic DUT arm provides a conditional differential test — predicting a strongly attenuated or null response under the proposed oscillator-screening model, pending a first-principles derivation of the material-dependent coupling. Step 172 closes the scalar-sector loophole only; the disformal sector's floor is set by site multipath, and the route below it is the Step 79 estimator pushed to larger enclosed areas, where a holonomy must scale with loop area while multipath does not.

Standard geodetic systematics and optical-fibre clock network bounds (Step 181). Four classical GNSS error channels are routinely proposed to explain a $\sim 2{,}000$–$4{,}500$ km receiver-clock correlation decay — a spatial scale that parallels the regional and continental common-mode error (CME) long documented in geodetic GNSS coordinate and clock residuals [18, 19]: (i) common-view satellite visibility cones from $20{,}200$ km MEO orbits, (ii) zenith wet tropospheric delay (ZWD) coupling into δt_r across synoptic weather scales, (iii) unmodeled solid-Earth/atmospheric tidal loading harmonics [15, 16], and (iv) analysis-centre reference-clock (IGST) datum conditioning [13, 14]. Each of these four mechanisms is separated by the multi-tier controls established across Papers 1–3 and the present analysis. First, common-view satellite geometry is absent in the inter-satellite clock channel (Section 3.8, 10.6σ–12.6σ, and 26.4σ on the GPS×Galileo cross-constellation arm sharing no orbital plane) and is explicitly regressed out on the ground by the Step 45 temporal T4 panel, where the zero-shared-satellite intercept α_{ij} retains both the distance decay ($\mathrm{PC} = -0.267$, 10.8σ) and the 500–800 km East–West anisotropy ($+0.130 \to +0.126$; Step 176), while forward simulation of the true visibility+datum kernel (Paper 1 §4.6) forces a broader decay ($\lambda \geq 5{,}075$ km) and mandatory 8–12 Mm anticorrelation ($C_0 = -0.43$ to -0.94) absent from the data ($C_0 \approx -0.02$). Second, tropospheric ZWD and vertical tidal antenna displacements ($\Delta h/c$) enter the pseudorange and carrier-phase observation equations as oscillator-blind propagation delays identical for any receiver attached to the same antenna and sky dome; they cannot generate the $3.01\times$ network-coupled amplitude enhancement on quartz over atomic standards ($7.37\times$ station-median LF coherent RMS, exact station-permutation $p = 0.0273$; [11, 17]) on co-located receivers sharing site, sky, and monument, the QQ > QA > AA spatial decay stratification (Step 75b), the metadata-verified station-permutation screening at the lunar M_2 ($r = +0.297, p_{\mathrm{perm}} = 10^{-4}$ on quartz vs $r = +0.031, p_{\mathrm{perm}} = 0.42$ on atomic; dependence-preserving joint COD+GFZ station-permutation $z_{\mathrm{joint}} = +5.73\sigma, p_{\mathrm{joint}} = 0.0003$ vs $-0.87\sigma, p_{\mathrm{joint}} = 0.374$; conditional Fisher $p_{\mathrm{perm}} = 1.9 \times 10^{-6}$ vs 0.55) and O_1 lines, or the quartz-only coupling at M_2 and O_1 and at the atmospheric solar S_2 tide (low-noise clocks null at $p = 0.66$; quartz $p = 1.8 \times 10^{-93}$) with verified atomic standards null at all of them (lunar M_2 $p = 8.3 \times 10^{-6}$, Step 169). Third, direct reanalysis of the complete 1-second time series from the 65-day March–April 2023 European optical-fibre clock comparison campaign (16 comparison folders, 328 daily `.dat` files, 7.90×10^6 valid $\mathrm{flag} = 1$ one-second measurements connecting seven optical clocks across NPL, LNE-OP/SYRTE, PTB, and INRIM via 785–2,393 km actively phase-stabilised fibre links [22]; dataset `10.5281/zenodo.16539534`, Step 181) tests the framework outside the GNSS ecosystem across five complementary observables:

Observable	Optical Pair / Baseline	Primary Result	Null / Control	Physical Role
Differential clock offset constraint & star-tree closure	NPL-YbE3/PTB-Yb1E3 (705 km chord, 2,155 km fibre) & 3-node star loops	Offset $-7.1 \pm 7.7 \times 10^{-18}$ (conditional 95% envelope $\leq 2.2 \times 10^{-17}$; $B = 1.13, B_{\mathrm{wn}} = 0.883$); 1 s star closure 3.61×10^{-20}	Simultaneous 1 s tree cancellation ($b_1 = 0$) vs Table II 5.1–7.9×10^{-18}	Differential clock consistency check; closed $b_1 \geq 1$ loop needed for holonomy
Sub-mHz excess floor (τ_{DL}) & projection-noise unmasking	705–915 km remote links vs 0 km NPL & PTB local pairs	Remote $\tau_{\mathrm{DL}} = 8.68$–$27.92 \times 10^{-18}$ ($\rho = +0.927$, 4-group $\rho = +0.800$); 4-clock $\sigma_{\mathrm{baseline}} = 7.62$–$7.74 \times 10^{-18}$ simultaneous (7.30 full, 6.35 pre-gap)	Co-located NPL 0.00×10^{-18} (PTB 7.86 & 24.76×10^{-18}); 5-pair NPL–PTB $R^2 = 54.9\% \to 93.7\%$ (86.0% SSE cut; 9-pair $90.35\% \to 90.49\%$)	Unmasks Paper 1 (§4.10) 10^{-17}–10^{-18} plateau as lattice noise drops $6\times$
Lunar M_2 (12.42 h) harmonic regression	705 km NPL-Sr1/PTB-Sr3 & NPL-YbE3/PTB-Yb1E3	$A_{M_2} = 5.2$ & 25.2×10^{-18} ($M_2/S_2 = 1.39\times$ & $4.12\times$; Fisher $p = 0.0014$ raw, 0.0019 dm)	Co-located 0 km $M_2/S_2 < 1$ ($p_{6\mathrm{h}} = 0.906, 0.322$); joint species-frame $R = 0.990$ ($p_{\mathrm{joint,6h}} = 0.0230$) vs geographic $R = 0.477$ (four geographic ratios on a separate window; $R = 0.358$ for the same three simultaneous ratios)	Amplitude enhancement above $\leq 10^{-18}$ GR tide; transition ΔK_α sign sets phase
Zero-fibre, zero-satellite 705 km anti-phase coherence	Local NPL-YbE3/NPL-Sr1 ($\Delta K_\alpha = -6.01$) vs local	$\mathrm{PA} = -0.335 \pm 0.091$ ($z = -3.69, p = 2.2 \times 10^{-4}$	Window-shuffle null $+0.002 \pm 0.103$ (	Probes non-universal $\delta \ln \alpha = d_e\, \delta\phi$ extension

Observable	Optical Pair / Baseline	Primary Result	Null / Control	Physical Role
	PTB-Yb1E2/PTB-Yb1E3 ($\Delta K_\alpha = +6.95$)	across 45 three-hour windows)	$z_{\rm null} = -3.27, p_{\rm perm} = 0.0010$)	($\Delta K_1 \Delta K_2 < 0$) with zero fibre/satellites
Zero-satellite 43-mode global localisation & GNSS waveform match	Co-located PTB & NPL optical pairs vs 366-station global GNSS archive	Localises PTB to 896 & 879 km (704 km at $f > 30\,\mu$Hz) and NPL to 1,416 km (1,285 km); 97.3–99.2th global percentile	$32/43$ & $31/43$ modes positive ($p = 9.7 \times 10^{-4}, 0.0027$); 2-site Fisher $p = 0.0030$, day-shuffle $p = 0.0149$	Retrospective cross-system transfer test; 3–24 h GNSS match $p_{\rm dayblk} = 0.0020$–0.0370

- *Differential clock frequency-ratio consistency constraint and algebraic star-tree closure.* Because active two-way Doppler-cancelled fibre links reflect the optical carrier back along the same path to cancel first-order link phase noise, the exact conformal proper-time integral $\oint_C d\ln A = 0$ vanishes along the round trip, while the 2,155 km NPL–PTB fibre link (705 km chord) constrains the differential clock frequency-ratio offset on NPL-YbE3/PTB-Yb1E3 to $-7.1 \pm 7.7 \times 10^{-18}$ (1σ statistical uncertainty 7.7×10^{-18}; conditional Gaussian two-sided 95% magnitude envelope $\leq 2.2 \times 10^{-17}$ if the entire offset is assigned to a single unmodelled effect, published 2-day Birge $B = 1.13$, daily Birge $B = 1.09$, $B_{\rm wn} = 0.883$ against the 1,000 s white-noise floor; because a frequency-ratio comparison between two laboratories is not a closed-path one-way synchronization measurement, a model-independent bound on disformal synchronization holonomy requires a physically closed $b_1 \geq 1$ fibre loop). A simultaneous 1-second star-topology closure audit confirms as an internal data-processing consistency check that because the European fibre network is a Paris-centred tree ($b_1 = E - V + 1 = 0$), 3-node combinations on simultaneous epochs retrace identical fibre segments and close algebraically to machine precision ($3.61 \times 10^{-20} \pm 1.27 \times 10^{-19}$ across $N = 280{,}947$ s on NPL-YbE3/PTB-Yb1E3/NPL-Sr1; $+8.45 \times 10^{-23} \pm 1.37 \times 10^{-21}$ across $N = 62{,}446$ s on NPL-YbE3/INRIM-ITYb1/PTB-Yb1E3), establishing that Table II's 5.1–7.9×10^{-18} campaign non-closure reflects non-overlapping uptime windows sampling the time-varying $\tau_{\rm DL} \approx 9$–15×10^{-18} sub-mHz floor.
- *DerSimonian–Laird sub-mHz excess floor ($\tau_{\rm DL}$), projection-noise unmasking, and* PTB-Sr3*-excluded invariance.* Subtracting each daily run's internal 100 s white-noise variance u_i^2 in quadrature via the DerSimonian–Laird estimator ($\tau_{\rm DL}$) and computing the excess overlapping Allan deviation at $\tau = 40{,}000$ s ($\sigma_{\rm exc}(40\ {\rm ks}) = \sqrt{\sigma_y^2(40\ {\rm ks}) - \sigma_{\rm white}^2(40\ {\rm ks})}$) isolates a ~ 9–18×10^{-18} sub-mHz floor across the 705–915 km NPL–PTB–INRIM remote baselines versus 0.00×10^{-18} co-located at NPL (NPL-YbE3/NPL-Sr1 at 0 km, 252.89 h, $\sigma_y(100\ {\rm s}) = 333.5 \times 10^{-18}$, median daily white noise $\bar{u}_{\rm day} = 14.8 \times 10^{-18}$: $B = 0.99$, $B_{\rm wn} = 0.996$, 20,000 s ratio $0.879\times$, $\tau_{\rm DL} = 0.00 \times 10^{-18}$, and $\sigma_{\rm exc}(40\ {\rm ks}) = 0.00 \times 10^{-18}$; whereas at PTB, the local interleaved single-ion pair PTB-Yb1E2/PTB-Yb1E3 with $\sigma_y(100\ {\rm s}) = 872.5 \times 10^{-18}$, $\bar{u}_{\rm day} = 38.0 \times 10^{-18}$ has $B = 1.13$, $B_{\rm wn} = 1.112$, 20,000 s ratio $1.042\times$, and between-day $\tau_{\rm DL} = 24.76 \times 10^{-18}$ from local trap/servo drift, and local PTB-Yb1E3/PTB-Sr3 has $B = 2.03$, $\tau_{\rm DL} = 7.86 \times 10^{-18}$, $\sigma_{\rm exc}(40\ {\rm ks}) = 8.12 \times 10^{-18}$, making the NPL comparisons the cleanest local-versus-remote anchor). Across the 705 km NPL–PTB baseline all three primary clock pairs (including homonuclear $\Delta K_\alpha = 0$ pairs where local scalar sensitivity cancels) cluster at $\tau_{\rm DL} = 8.68$–10.61×10^{-18} — NPL-YbE3/PTB-Yb1E3 ($\tau_{\rm DL} = 8.68 \times 10^{-18}$, $\sigma_{\rm exc}(40\ {\rm ks}) = 12.98 \times 10^{-18}$, $1.30\times$ white), NPL-Sr1/PTB-Sr3 ($\tau_{\rm DL} = 9.65 \times 10^{-18}$, $\sigma_{\rm exc}(40\ {\rm ks}) = 5.95 \times 10^{-18}$, $2.33\times$ white; 20,000 s ratio $1.729\times$), and PTB-Yb1E3/NPL-Sr1 ($\tau_{\rm DL} = 10.61 \times 10^{-18}$, $\sigma_{\rm exc}(40\ {\rm ks}) = 8.42 \times 10^{-18}$, $1.97\times$ white, where neither PTB-Sr3 nor SYRTE-Hg participates) — and the longer 755–915 km INRIM links rise to $\tau_{\rm DL} = 14.81 \times 10^{-18}$ (PTB-Yb1E3/INRIM-ITYb1, 755 km), 18.23×10^{-18} (INRIM-ITYb1/NPL-Sr1, 915 km), and 27.92×10^{-18} (INRIM-ITYb1/PTB-Sr3, 755 km, $\sigma_{\rm exc}(40\ {\rm ks}) = 17.06 \times 10^{-18}$, $1.47\times$ white), persisting unchanged under the pre-gap MJD < 60035 cutoff sensitivity check ($B = 3.31$, $\tau_{\rm DL} = 9.47 \times 10^{-18}$ on NPL-Sr1/PTB-Sr3 vs $B = 0.99$, $\tau_{\rm DL} = 0.00 \times 10^{-18}$ co-located at NPL) and when PTB-Sr3 (which suffered a static laser shift in the campaign [22]) is excluded entirely ($\tau_{\rm DL} = 0.00 \times 10^{-18}$ locally at NPL vs $8.68, 10.61, 14.81$, and 18.23×10^{-18} across the four PTB-Sr3-free remote baselines).
  Variance decomposition and simultaneous four-clock subtraction: Across the eight non-interleaved clock pairs ($0 \to 705 \to 755 \to 915$ km), $\tau_{\rm DL}$ increases with geodesic chord separation $d_{\rm geo}$ (unadjusted 8-pair Spearman $\rho = +0.927$, nominal $p = 9.4 \times 10^{-4}$; because the eight pairs share five clocks across four distinct distance groups with group means $3.93, 9.65, 21.37$, and 18.23×10^{-18}, collapsing to the four distance groups gives $\rho_{\rm group} = +0.800$, exact $4! = 24$ permutation $p = 0.1667$ one-sided and 0.3333 two-sided, while leave-one-clock-out sensitivity keeps $\rho \in [+0.800, +0.975]$, including $\rho = +0.975, p = 0.0048$ with PTB-Sr3 excluded and $\rho = +0.866, p = 0.0577$ with INRIM-ITYb1 excluded; across all nine pairs an unweighted non-negative least-squares fit appears to explain 90.35% of the uncentered $\sum \tau_{\rm DL}^4$ with clock terms alone versus 90.49% with a common remote-link term $\sigma_{\rm link} = 5.29 \times 10^{-18}$ only because 87% of $\sum \tau_{\rm DL}^4$ is concentrated in two pairs — PTB-Yb1E2/PTB-Yb1E3 ($\tau_{\rm DL}^2 = 613.1 \times 10^{-36}$, where PTB-Yb1E2 appears in only one pair and is fit with zero residual by a dedicated parameter) and INRIM-ITYb1/PTB-Sr3 ($\tau_{\rm DL}^2 = 779.5 \times 10^{-36}$, inflated by a -110×10^{-18} step between MJD 60013 and MJD 60019 before NPL-Sr1 joined; for MJD ≥ 60019 its $\tau_{\rm DL}$ drops to 12.79–16.60×10^{-18}) — causing the 9-pair clock-only fit to violate the measured 0 km NPL+PTB local variance sum (61.78×10^{-36}) by $3.59\times$ (221.84×10^{-36}); when evaluated on the five non-interleaved pairs of the 4-clock NPL–PTB sub-network where every clock is anchored by both a 0 km local measurement and 705 km remote links, adding the remote-link term $\sigma_{\rm link} = 7.30 \times 10^{-18}$ reduces the residual SSE

by 86.0% (SSE : $3{,}307.5 \to 462.0$, raising centered R^2 from 54.9% to 93.7% and uncentered variance explained from 89.27% to 98.50%, while a 6-pair INRIM-ITYb1-excluded refit leaves positive remote residuals of $+3.78$, $+3.52$, and $+5.16 \times 10^{-18}$; this five-pair decomposition — 5 pair variances fitted by 4 non-negative clock parameters plus 1 remote-link coefficient (design rank 5, zero unconstrained residual degrees of freedom) — provides a consistency representation of the remote-link component identified by the simultaneous-epoch four-clock covariance contrast below, and because the expanded 5-parameter model has limited residual degrees of freedom, the increase in fitted R^2 is treated as an internal variance decomposition rather than an independent significance test)), and rises by $+72\%$ to $+89\%$ from NPL-PTB ($d_{\text{geo}} = 705$ km, fibre path $L_{\text{fibre}} = 2{,}155$ km, $\tau_{\text{DL}} = 9.65$–10.61×10^{-18}) to INRIM-NPL ($d_{\text{geo}} = 915$ km, $L_{\text{fibre}} = 1{,}808$ km, $\tau_{\text{DL}} = 18.23 \times 10^{-18}$) even as the fibre path length decreases by 347 km (-16%), disfavouring a simple fibre-path-length-proportional instability model (characterised below 1×10^{-18} after 10^3 s [22]). Forming the four-clock heterogeneity difference between the two 705 km homonuclear pairs (NPL-YbE3/PTB-Yb1E3 and NPL-Sr1/PTB-Sr3: $\sum \tau_{\text{DL}}^2 = 8.68^2 + 9.65^2 = 168.46 \times 10^{-36}$) and the two 0 km local pairs (NPL-YbE3/NPL-Sr1 and PTB-Yb1E3/PTB-Sr3: $\sum \tau_{\text{DL}}^2 = 0.00^2 + 7.86^2 = 61.78 \times 10^{-36}$), each of which contains every one of the four clocks $\{\text{NPL-YbE3}, \text{NPL-Sr1}, \text{PTB-Yb1E3}, \text{PTB-Sr3}\}$ once, cancels the four single-clock variance terms under an additive common-epoch variance model and identifies a $2.73\times$ remote-over-local heterogeneity excess equivalent to a $\sigma_{\text{baseline}}(705\ \text{km}) = 7.30 \times 10^{-18}$ contribution per remote link (capturing the differential spatial covariance combination $2\,\text{Cov}(\text{NPL-YbE3}, \text{NPL-Sr1}) + 2\,\text{Cov}(\text{PTB-Yb1E3}, \text{PTB-Sr3}) - 2\,\text{Cov}(\text{NPL-YbE3}, \text{PTB-Yb1E3}) - 2\,\text{Cov}(\text{NPL-Sr1}, \text{PTB-Sr3})$, yielding a $1.95\times$ excess or $\sigma_{\text{baseline}}(705\ \text{km}) = 6.35 \times 10^{-18}$ per link under the pre-gap $\text{MJD} < 60035$ cutoff sensitivity check where $\tau_{\text{DL}} = 0.00$ and 9.19×10^{-18} locally vs 8.68 and 9.47×10^{-18} remotely, and strengthening on the exact intersection of $N = 212{,}605$ simultaneous 1-second epochs across 10 common days, $\text{MJD}\ 60021$–60033, where all four pairs are locked simultaneously and single-clock daily-mean variances cancel identically without epoch-support mismatch: simultaneous-epoch $\tau_{\text{DL}} = 0.00$ and 5.23×10^{-18} locally vs 7.07 and 9.68×10^{-18} remotely, a $5.25\times$ DL variance excess giving $\sigma_{\text{baseline}}(705\ \text{km}) = 7.62 \times 10^{-18}$ per link, while the exact unweighted daily-mean sample-variance difference $647.48 - 506.43 = 141.05 \times 10^{-36}$ minus the white-noise variance difference 21.11×10^{-36} leaves a net excess of 119.94×10^{-36}, or $\sigma_{\text{baseline}}(705\ \text{km}) = 7.74 \times 10^{-18}$ per remote link). This τ_{DL} decomposition also explains the 2×2 Birge progression via quantum projection-noise unmasking: because $B \approx \sqrt{1 + \tau_{\text{DL}}^2 / \bar{u}_{\text{day}}^2}$ and a multi-thousand-atom 1-D optical lattice (NPL-Sr1/PTB-Sr3, $\sigma_y(100\ \text{s}) = 56.6 \times 10^{-18}$, $\bar{u}_{\text{day}} = 3.1 \times 10^{-18}$) has $6\times$ lower short-term projection noise than a single-ion trap (NPL-YbE3/PTB-Yb1E3, $\sigma_y(100\ \text{s}) = 314.7 \times 10^{-18}$, $\bar{u}_{\text{day}} = 20.3 \times 10^{-18}$), the same ~ 9–10×10^{-18} baseline floor raises B from 1.09 (1.13 in 2-day bins) on $\text{Yb}^+ \times \text{Yb}^+$ to 2.03 (2.15; $B_{\text{wn}} = 1.271$) on $\text{Yb}^+ \times \text{Sr}$ ($\bar{u}_{\text{day}} = 6.2 \times 10^{-18}$) and 3.21 (4.51; $B_{\text{wn}} = 3.214$) on $\text{Sr} \times \text{Sr}$, directly matching the $(2.1\text{--}12.0) \times 10^{-18}$ ($\tau = 10^5$ s) to $(1.4\text{--}8.6) \times 10^{-17}$ ($\tau = 10^4$ s) screened plateau predicted in Paper 1 (§4.10) [21, 22].

- *Remote 705 km lunar M_2 (12.4206 h) amplitude enhancement beyond relativistic tidal redshift.* In the campaign data reduction, time-varying relativistic tidal geopotential shifts $\Delta U_{\text{tide}}(t)/c^2$ (solid-Earth body tide with Love numbers $1 + k_2 - h_2 \approx 0.69$, ocean tidal loading, and pole tide) are already subtracted epoch-by-epoch with residual uncertainty below 1×10^{-18}. Simultaneous 5-tide (M_2, S_2, N_2, K_1, O_1) and 6-tide ($+S_1$ at 24.00 h) harmonic regression on 600-second true-UTC bins scored against 500 six-hour block permutations (both raw and daily-demeaned) and 500 whole-day MJD-date permutations (alongside 5-minute off-tide control spectroscopy) shows lunar M_2 amplitude enhancement across the 705–755 km remote links while co-located 0 km pairs have $M_2/S_2 < 1$: locally on NPL-YbE3/NPL-Sr1 ($N_{600} = 1{,}839$), $A_{M_2} = 2.3 \times 10^{-18}$ ($p_{6\text{h}} = 0.906, p_{6\text{h,dm}} = 0.808, p_{\text{day}} = 0.830$, null; 5-min 0.89×10^{-18}, $0.149\times$ off-tide control) with $A_{S_2} = 5.2 \times 10^{-18}$ ($M_2/S_2 = 0.44\times$), and locally on PTB-Yb1E3/PTB-Sr3 ($N_{600} = 2{,}743$), $A_{M_2} = 10.6 \times 10^{-18}$ ($p_{6\text{h}} = 0.322, p_{6\text{h,dm}} = 0.046, p_{\text{day}} = 0.444$) with $A_{S_2} = 12.8 \times 10^{-18}$ ($M_2/S_2 = 0.83\times$); remotely across 705 km, M_2 exceeds S_2 on both NPL-Sr1/PTB-Sr3 ($N_{600} = 1{,}255$: $A_{M_2} = 5.2 \times 10^{-18}, p_{6\text{h}} = 0.018, p_{6\text{h,dm}} = 0.020, p_{\text{day}} = 0.092$, $A_{S_2} = 3.8 \times 10^{-18}$, $M_2/S_2 = 1.39\times$; 5-min 5.15×10^{-18}, $2.057\times$ control) and the PTB-Sr3-free NPL-YbE3/PTB-Yb1E3 link ($N_{600} = 1{,}090$: $A_{M_2} = 25.2 \times 10^{-18}, p_{6\text{h}} = 0.008, p_{6\text{h,dm}} = 0.010, p_{\text{day}} = 0.022$, $A_{S_2} = 6.1 \times 10^{-18}$, $M_2/S_2 = 4.12\times$, and $M_2/S_2 = 9.04\times$ in the 6-tide $+S_1$ fit; 5-min 14.51×10^{-18}, $2.073\times$ control; Fisher combined $\chi^2_4 = 17.69, p = 0.0014$ on raw 6-h block permutation, $\chi^2_4 = 17.03, p = 0.0019$ on demeaned 6-h block permutation, and $\chi^2_4 = 12.41, p = 0.0146$ under whole-day MJD-date permutation, plus $A_{M_2} = 30.6 \times 10^{-18}, M_2/S_2 = 2.16\times, p_{6\text{h,dm}} = 0.014$ on INRIM-ITYb1/PTB-Sr3 across 755 km; a residual species-blind GR geopotential tide cannot produce a $5\times$ larger M_2 amplitude on Yb^+ E3 than on Sr across the same baseline, though because NPL-YbE3 operated through MJD 60034 while NPL-Sr1/PTB-Sr3's M_2 amplitude is concentrated in the second half of the campaign, the four 705 km pairs oriented in the geographic $y_{\text{NPL}} - y_{\text{PTB}}$ frame have phases $217.2^\circ, 161.4^\circ, 51.5^\circ$, and 218.5° on their MJD 60018.5–60034.2 window, Rayleigh resultant $R = 0.477$, whereas on the $N = 707$ simultaneous 600 s bins where all four NPL and PTB clocks are locked simultaneously, the three heteronuclear Yb^+ E3 $-$ Sr pairs ($\Delta K_\alpha = -6.01$: NPL-YbE3/PTB-Sr3, PTB-Yb1E3/NPL-Sr1, and PTB-Yb1E3/PTB-Sr3) have nearly identical M_2 amplitudes ($8.6, 8.8$, and 8.5×10^{-18}) and tightly locked phases ($267.0^\circ, 280.2^\circ$, and 260.8°, Rayleigh resultant $R = 0.990$, under a $1{,}000$-realisation shared-timestamp joint UTC-block permutation retaining shared-clock covariance ($p_{\text{joint,6h}} = 0.0230$, $p_{\text{joint,day}} = 0.0430$)) in the species-consistent $y_{\text{Yb}^+\,\text{E3}} - y_{\text{Sr}}$ frame — demonstrating that flipping PTB-Yb1E3/NPL-Sr1 into the geographic $y_{\text{NPL}} - y_{\text{PTB}}$ frame inverts its ΔK_α sign from -6.01 to $+6.01$ and shifts its phase by 180° to 100.2° ($R = 0.358$ on the same three ratios); because these three contemporaneous ratios share clock inputs across the 4-clock network and two involve

PTB-Sr3, the $R = 0.990$ phase concentration is reported as a joint-network consistency result rather than three independent detections).

- *Zero-fibre, zero-satellite* 705 *km anti-phase coherence between co-located optical pairs at NPL and PTB.* As established in Section 3.5.3 and Paper 0 (Axiom A4), leading-order universal conformal matter-metric coupling ($\tilde{g}_{\mu\nu} = A(\phi) g_{\mu\nu}$) cancels identically in a co-located frequency ratio, so a differential response between co-located optical transitions is not predicted by universal conformal coupling alone and instead tests a loop-induced or non-universal scalar-to-electromagnetic coupling extension ($\delta \ln \alpha = d_e \, \delta\phi$ [11, 12], where $\delta \ln(\nu_1/\nu_2) = (K_{\alpha,1} - K_{\alpha,2}) \, \delta \ln \alpha$). With all pair orientations ($y_{\text{first}} - y_{\text{second}}$) fixed a priori by the published Zenodo repository nomenclature and PTB-Sr3 absent from both pairs, comparing the purely local ratio at NPL (NPL-YbE3/NPL-Sr1, 0 km fibre, zero satellites, differential fine-structure sensitivity $\Delta K_\alpha = K_\alpha(\mathrm{Yb}^+\,\mathrm{E3}) - K_\alpha(\mathrm{Sr}) = -5.95 - 0.06 = -6.01 < 0$ [11, 12]) directly against the purely local ratio inside a single Paul ion trap at PTB 705 km away (PTB-Yb1E2/PTB-Yb1E3, 0 km fibre, zero satellites, $\Delta K_\alpha = K_\alpha(\mathrm{Yb}^+\,\mathrm{E2}) - K_\alpha(\mathrm{Yb}^+\,\mathrm{E3}) = +1.00 - (-5.95) = +6.95 > 0$) predicts anti-phase ($\Delta\phi = \pi, \mathrm{PA} < 0$) sub-diurnal cross-spectral coherence under a spatially smooth scalar field ($\lambda_T \approx 4{,}200$ km $\gg 705$ km) coupled to the electromagnetic sector because $\Delta K_1 \cdot \Delta K_2 = -41.77 < 0$: across 45 simultaneous 3 h windows (Hanning-tapered), the observed cross-spectral phase alignment is $\mathrm{PA} = -0.335 \pm 0.091$ ($z = -3.69, p = 2.2 \times 10^{-4}$ for $f \le 1{,}000$ μHz, versus a 1,000-realisation window-shuffle permutation null of $+0.002 \pm 0.103$, differential -0.336, $z_{\text{null}} = -3.27$, $p_{\text{perm}} = 0.0010$; and in the 10–500 μHz band $\mathrm{PA} = -0.292 \pm 0.104$, $z = -2.80$, $p = 0.0052$, $z_{\text{null}} = -2.71$, $p_{\text{perm}} = 0.0070$ at 3 h; $\mathrm{PA} = -0.388 \pm 0.143$, $z = -2.71$, $p = 0.0068$, $z_{\text{null}} = -2.64$, $p_{\text{perm}} = 0.0080$ at 6 h; $\mathrm{PA} = -0.451 \pm 0.166$, $z = -2.72$, $p = 0.0066$, $z_{\text{null}} = -2.67$, $p_{\text{perm}} = 0.0110$ at 8 h), with neither GNSS satellites nor optical fibre links participating in either measurement (as a single pair-of-pairs candidate, replication across additional opposite-sign ΔK_α laboratory pairs is required; across 118 eligible multi-hour 1, 3, 6 h tests on clock-disjoint remote pairs, 13 reach nominal $p < 0.05$, including NPL-Sr1/PTB-Sr3 vs PTB-Yb1E3/INRIM-ITYb1 at $r = -0.602$, $p = 8.9 \times 10^{-4}$, Spearman $\rho = -0.676$, $p = 1.1 \times 10^{-4}$ at 3 h, NPL-Sr1/PTB-Sr3 vs SYRTE-Hg/PTB-Yb1E3 at $r = -0.782$, $p = 0.0026$ at 6 h, and four-laboratory-disjoint INRIM-ITYb1/PTB-Sr3 vs SYRTE-Hg/NPL-Sr1 at $r = -0.625$, $p = 0.0127$, PTB-Yb1E3/INRIM-ITYb1 vs SYRTE-Hg/NPL-Sr1 at $r = +0.591$, $p = 0.0261$, and INRIM-ITYb1/NPL-Sr1 vs PTB-Yb1E3/PTB-Sr3 at $r = +0.434$, $p = 0.0212$, which are treated as exploratory where pairs share a laboratory site or the Paris repeater hub).
- *Target-blind* 43*-mode global localisation of zero-satellite optical clocks and timestamp-aligned GNSS waveform covariation.* Feeding the 43-mode (10–500 μHz) cross-spectral phase-alignment fingerprints of the three co-located zero-satellite optical clock pairs (PTB-Yb1E2/PTB-Yb1E3, PTB-Yb1E3/PTB-Sr3, and NPL-YbE3/NPL-Sr1) against the contemporaneous 366-station global GNSS archive (DOY 055–120 of 2023) into the exact Step 80 target-blind global localisation estimator ($\lambda_T = 4{,}201$ km fixed, target coordinates withheld) localises each GNSS-free optical laboratory on the Earth's surface: the PTB-Sr3-free PTB-Yb1E2/PTB-Yb1E3 pair (43 days, mean daily duty cycle $\alpha = 0.694$ or 16.7 h/day) localises Braunschweig to 896 km on the ionosphere-free clock product (vs 9,212 km geometry-null median, $p_{\text{err}} = 0.0140$, $p_{\text{score}} = 0.0020$, 99.0th global score percentile, with 32 of 43 Fourier modes correlating positively with the true 4,201 km kernel at binomial $p = 9.7 \times 10^{-4}$; even/odd frequency-mode splits give 810 km / 1,195 km, agreeing within 947 km; 850 km with all GNSS stations within 300 km excluded and 928 km within 500 km excluded) and 1,036 km on the precise product (vs 9,144 km null median, $p_{\text{err}} = 0.0180$, $p_{\text{score}} = 0.0020$; even/odd modes 702 km / 1,659 km; 972 km and 991 km with < 300 km and < 500 km stations excluded, while a 200-permutation day-shuffle temporal null with station coordinates fixed collapses the median error to 8,448 km and the truth-kernel correlation from $+0.277$ to $+0.038 \pm 0.108$, $p_{\text{day}} = 0.0149$); PTB-Yb1E3/PTB-Sr3 (32 days, mean duty cycle $\alpha = 0.514$ or 12.3 h/day) provides a corroborating intra-site check at 879 km ($p_{\text{err}} = 0.0100$ vs 9,477 km null median, 99.2th global percentile, 918 km with co-located PTBB excluded; even/odd modes 1,382 km / 7,519 km on the shorter 32-day span), landing within 112 km of the PTB-Yb1E2/PTB-Yb1E3 estimate; and the PTB-Sr3-free NPL-YbE3/NPL-Sr1 pair (18 days, mean duty cycle $\alpha = 0.585$ or 14.0 h/day) localises Teddington to 1,416 km ($p_{\text{err}} = 0.0240$, $p_{\text{score}} = 0.0020$ vs 8,773 km null median, 97.3th global percentile, with 31 of 43 modes positive at binomial $p = 0.0027$; even/odd modes 1,894 km / 11,836 km on the 18-day span, and 1,402 km with all stations within 500 km excluded — where the lower SNR on the 0-based odd-indexed modes, corresponding to even daily harmonics $k = 2, 4, 6, \ldots$ cpd, directly reflects the half-day rectangular window transfer function $|W(k)| \propto |\sin(\pi k \alpha)/(\pi k)|$, which has exact nulls at even k for an ideal rectangular window at $\alpha = 0.5$ (only approximate suppression for observed duty cycles) on the 12.3 and 14.0 h/day pairs while peaking on odd harmonics $k = 1, 3, 5, \ldots$ cpd, i.e. the 0-based even-indexed modes that localise all three pairs to 810, 1,382, and 1,894 km; conditional two-site Fisher combining one PTB-Sr3-free pair per laboratory $\chi^2_4 = 16.00$, $p = 0.0030$, and three-pair $\chi^2_6 = 25.21$, $p = 3.1 \times 10^{-4}$; furthermore, excluding both the 24 h diurnal S_1/K_1 and 12 h semidiurnal S_2/M_2 modes so that only the 41 sub-diurnal continuum modes at $f > 30$ μHz are used sharpens the localisation to 704 km at $p_{\text{err}} = 0.0060$ on PTB-Yb1E3/PTB-Sr3, 955 km at $p_{\text{err}} = 0.0160$ on PTB-Yb1E2/PTB-Yb1E3, and 1,285 km at $p_{\text{err}} = 0.0240$ on NPL-YbE3/NPL-Sr1, disfavouring a purely diurnal S_1/S_2 envelope confound). A mask-preserving synthetic null (Step 181c) retains the exact uptime and measurement schedules while replacing the residuals with matched-variance noise: draws give median per-pair errors of 6,899–8,582 km versus the real 879–1,416 km, so the operating pattern alone does not produce the localisation — the joint three-pair result is signal-dominated.
  Timestamp-aligned optical-to-GNSS waveform covariation: Multi-hour (3, 6, 12, 24 h) waveform comparisons across MJD 59999–60064 are consistent with shared contemporaneous structure at the ~ 2–3σ level between the optical and GNSS ecosystems after linear detrending and 1,000-realisation 24 h day-block permutations ($p_{\text{dayblk}} = 0.0020$–$0.0370$ across the

eight tested channel pairs; because single-station GNSS clock residuals over 3–24 h windows correspond to fractional-frequency fluctuations of $\sigma_y \sim 10^{-14}$–10^{-13} or $\sim$ 1–10 ns, four to five orders of magnitude larger than the $\sigma_y \sim 10^{-18}$–10^{-17} or $\sim$ 0.01–0.1 ps optical floor in the same units, these dimensionless correlations reflect shared temporal envelope modulation rather than equal physical amplitudes): the 705 km $\mathrm{NPL\text{-}Sr1/PTB\text{-}Sr3}$ optical lattice link correlates positively with the 705 km $\mathrm{HERT\text{-}PTBB}$ UK–Germany GNSS clock differential at 3 h windows ($n = 84$: $r = +0.373, p = 4.8 \times 10^{-4}$, detrended $r_{\mathrm{det}} = +0.363, p_{\mathrm{dayblk}} = 0.0020$, Spearman $\rho = +0.341$) and inversely with the $\mathrm{IENG\text{-}HERT}$ Italy–UK GNSS clock differential (3 h, $n = 84$: $r = -0.387, p = 2.8 \times 10^{-4}, \rho = -0.429, p = 5.0 \times 10^{-5}$, detrended $r_{\mathrm{det}} = -0.361, p_{\mathrm{dayblk}} = 0.0040$, and on ionosphere-free clocks $r = -0.300, r_{\mathrm{det}} = -0.263, p_{\mathrm{dayblk}} = 0.0170$; 6 h, $n = 44$: $r = -0.463, p = 0.0015$, detrended $r_{\mathrm{det}} = -0.429, p_{\mathrm{dayblk}} = 0.0060$; 24 h, $n = 15$: $r = -0.770, p = 7.9 \times 10^{-4}$, detrended $r_{\mathrm{det}} = -0.678, p_{\mathrm{dayblk}} = 0.0020$), while the co-located 0 km $\mathrm{NPL\text{-}YbE3/NPL\text{-}Sr1}$ optical pair correlates with $\mathrm{HERS\text{-}PTBB}$ precise GNSS clocks at 6 h ($n = 59$: $r = +0.417, p = 0.0010, \rho = +0.437$, detrended $r_{\mathrm{det}} = +0.282, p_{\mathrm{dayblk}} = 0.0170$) and with the co-located $\mathrm{ZIMM\text{-}ZIM2}$ Swiss GNSS differential at 12 h ($n = 30$: $r = +0.553, p = 0.00155$, detrended $r_{\mathrm{det}} = +0.393, p_{\mathrm{dayblk}} = 0.0370$), and the 0 km single-ion Paul trap $\mathrm{PTB\text{-}Yb1E2/PTB\text{-}Yb1E3}$ correlates with the $\mathrm{OP71\text{-}PTBB}$ GNSS 3-D position-jitter differential across 75 twelve-hour windows ($r = +0.349, p = 0.00216, \rho = +0.410, p = 2.5 \times 10^{-4}$, detrended $r_{\mathrm{det}} = +0.362, p_{\mathrm{dayblk}} = 0.0060$).

The Joint Explanatory Challenge. The sharpest test of TEP is not whether a conventional mechanism can be proposed for any single observation, but whether the combined set of measurements is better explained by one physical model than by a collection of unrelated instrumental and geophysical effects. The channels considered here impose a joint explanatory burden: no single conventional artefact produces all of them simultaneously — analysis-centre common-mode cannot reach locally compared optical clocks; antenna and receiver electronics cannot generate a preferred celestial direction; geophysical tides cannot explain distance-structured phase alignment on orbiting clocks sharing no ground receiver; and a preferred CMB axis cannot arise from site or antenna systematics. The converse burden is equally explicit: TEP is not yet a single parameter set predicting every channel, since λ_T remains empirically calibrated and the oscillator dependence requires an additional material-coupling mechanism (Step 65d constrains, but does not resolve, the hardware×oscillator interaction). Predictive unity is already partially realised rather than purely prospective: the anti-phase sign of the co-located optical pair was fixed a priori from published ΔK_α sensitivities before examination; the target-blind optical localisation used the ground-derived $\lambda_T = 4{,}201$ km kernel unchanged; and the frozen 2024 predictor replicated on held-out 2025 data across three regions and a second analysis centre. What remains unpredicated a priori is the amplitude and frequency dependence of the optical covariance contrasts and the satellite correlation scale. The decisive comparison registered as the next step is whether one TEP field specification fitted on the ground channel predicts the satellite, directional and optical observables without retuning, and whether the best combined conventional model can reproduce the same joint pattern.

Decisive drone experiment. Record at least 24 hours of the flight receiver while docked to learn its phase/coherence relationship to the same live CORS network; freeze the phase Gram, kernel and integrity thresholds before launch; log hardware clock/steering telemetry, IMU and barometer at native rate; impose registered 10-minute to 8-hour network-denied or low-satellite episodes across multiple flights; and compare free PPP/INS, oscillator-only PPP/INS, conventional learned spatial priors, distance-only TEP and phase-resolved TEP on common epochs. Primary endpoints are 3-D RMS, p95, < 10 m bridge availability and reconvergence time, with the flight—not the epoch—as the uncertainty cluster. That design directly converts the Step 56 clock-domain discovery into a falsifiable real-world position test.

5. Conclusion

This study independently reproduces the predicted GNSS clock correlation scale with the corrected Papers 1–2 phase-alignment estimator: $\lambda = 4{,}348$ km on COD and $4{,}076$ km on GFZ precise receiver clocks ($R^2 = 0.898$ and 0.955, 25–27σ above phase-randomised nulls), within 3.5% of the foundational exponential $1/e$ measurement. The detection holds on a channel whose pairwise statistic shares no receiver clocks and no common-view geometry with the original measurements: orbiting satellite clocks show the same distance-structured phase alignment at 10.6–15.9σ above phase-randomised and geometry-shuffled nulls, with a GPS×Galileo cross-constellation arm — sharing no clock family or orbital plane, though estimated through the same analysis-centre tracking segment as the receiver products — recovering a 26.4σ log-slope (-0.172) and $+0.30$ near/far contrast ($\lambda = 8{,}140 \pm 795$ km pooled over 180 days; 8,140–14,911 km across 90-day windows due to long-baseline pedestal trade-off — a band-membership statement over an ill-conditioned tail, not an independent scale recovery, Step 178). On the ground, the non-common-view intercept separates from satellite co-visibility at the pre-registered criterion on the minimally processed broadcast product ($\mathrm{PC} = -0.164$, 10.8σ, strengthening to -0.267 with the local-solar-time systematic controlled; out-of-sample R^2 gain $+0.022$; raw intercept fit $\lambda = 4{,}349$ km, and $\lambda = 1{,}008$ km at 6.5σ after projecting out the collinear co-visibility and solar-time profiles), the predicted East–West anisotropy at 500–800 km survives common-view removal essentially unchanged ($+0.130 \to +0.126$, $z = +1.98 \to +1.91$), oscillator-class dependence separates field coupling from local noise (idiosyncratic $0.99\times$, network-coupled $3.01\times$ on quartz and $7.37\times$ in station-median LF coherent RMS at exact station-permutation $p = 0.0273$, persisting on co-located receivers that share site and sky, isolating lunar M_2 coupling to metadata-verified quartz clocks at $p_{\mathrm{perm}} = 1.9 \times 10^{-6}$ vs atomic 0.55, and with the tidal coupling isolated to quartz clocks), and sub-diurnal aperture synthesis identifies the field's preferred axis with the CMB dipole at $\Delta\mathrm{BIC} = -2{,}315.5$ (winning 300 of 300 day-clustered bootstrap draws and both disjoint observing-day halves).

The operational payoffs are quantified and deployable on existing CORS/SBAS/RTK infrastructure with no new hardware and sub-millisecond per-epoch computation. During a sky-view outage the network prediction bounds a receiver's clock-residual error to 25 ns

at 1 h and 66 ns at 8 h — a network-assisted residual bound, not an absolute UTC error against a traceable hardware reference, and the receiver depends on live network information rather than operating autonomously; compared on datasheet drift terms this outperforms a $\sim$ \$300 GNSS-disciplined OCXO beyond 30 min and a $\sim$ \$2,000 Rubidium beyond 2 h, while a $\sim$ \$5 TCXO with network aiding achieves 146$\times$ better residual bound than free-running at 1 h. Across 90 days on a dense EUREF network, the fixed kernel reduces clock RMS by 5.0–18.9% versus the strongest temporal predictor at 10 min–8 h outages, and the phase-resolved variant adds a further 2.6–17.1% over the distance-only kernel; frozen on 2024, the full-band construction beats every deployable baseline on held-out 2025 across three coherent networks. With target coordinates withheld, the 43-mode phase fingerprint localises co-located GNSS anchors globally to 339 km (Matera) and 744 km (Tahiti), localises the zero-satellite co-located optical clock pairs at PTB and NPL globally to 879–1,416 km against the 366-station GNSS archive (conditional two-site Fisher $\chi^2_4 = 16.00, p = 0.0030$; 3-pair $p = 3.1 \times 10^{-4}$), and localises 43 live NTRIP stations to a 191.8 km median error on enclosed stations (214.7 km across all 43) from 30 minutes of clock data alone. At three visible satellites, where free-clock SPP is algebraically infeasible, an external clock prior restores a bounded fix (5.76 m RMS, 95.2% availability in single-epoch code SPP, at pseudorange-noise-limited parity with a conventional AR(1) clock prior at 5.53 m), and under carrier-phase tracking the causal network prior beats persistence by $+29.6\%$ in unlatched 3-D position error ($+46.7\%$ vertical); at $k = 4$–5 it improves 3-D RMS by $+14.5$–48.0% over persistence-trend. A 68-station live observatory confirms the result in real time ($+35.84\%$ mean two-hour holdover gain across 185 walk-forward windows, $p = 2.15 \times 10^{-50}$; 275 of 276 recorded live archives positive over 95.6 h at $+42.93\%$ mean), and 120 cryptographically sealed weight envelopes score their first post-seal windows at $+29.01\%$ mean (116 of 120 positive) under SHA-256 verification across a 122-link hash-chained anchor log.

The bounds are stated equally plainly. With a full sky the receiver clock is already observable and the prior is correctly inert; at $k = 3$ in single-epoch code SPP the pseudorange noise floor dominates, so TEP supplies the missing degree of freedom at parity with the best conventional clock prior rather than exceeding it. The sealed walk-forward figure decomposes into verified retrodiction of member-observed epochs plus a spatially specific forward component at never-observed epochs ($+2.57\%$, $p = 1.8 \times 10^{-5}$, under causal penalty selection; $+3.39\%$ untapered, $z = +5.8$ to $+6.6$ above station-label permutation, frozen under prospective preregistration), bounded by a measured $\sim$90-minute frozen-weight coherence time that fixes the deployed refit cadence. The claim is confined to receivers whose displacement during an outage is small compared to λ_T: on the GRACE-FO Ultra-Stable Oscillator at 7.5 km/s the prior loses to persistence by 16–46%, and the Flight 8 UAV archive exercises sub-minute extrapolation on a steered TCXO, a regime in which TEP makes no prediction. Out-of-ecosystem reanalysis of the 65-day European optical-fibre clock campaign across NPL, LNE-OP/SYRTE, PTB, and INRIM (Step 181; [22]) provides complementary cross-technology evidence outside GNSS — constraining differential frequency-ratio offsets across the Doppler-cancelled NPL–PTB link to $-7.1 \pm 7.7 \times 10^{-18}$ (1σ; conditional 95% single-effect envelope $\leq 2.2 \times 10^{-17}$, with 1 s 3-node star-tree closure at 3.61×10^{-20} on the $b_1 = 0$ tree), resolving an excess sub-mHz floor of $\tau_{\mathrm{DL}} = 8.68$–$27.92 \times 10^{-18}$ on remote links (largely attributable to clock-specific terms; co-located floor 0.00×10^{-18} at NPL (7.86 and 24.76×10^{-18} locally at PTB; 4-clock baseline excess 7.30×10^{-18} full-campaign, 6.35×10^{-18} pre-gap cutoff, and 7.62–7.74×10^{-18} across 212,605 simultaneous 1 s common epochs; 8-pair $\rho = +0.927, p = 9.4 \times 10^{-4}$, 4-group $\rho_{\mathrm{group}} = +0.800$), 705 km lunar M_2 amplitude enhancement (Fisher $p = 0.0014$ raw, 0.0019 demeaned, 0.0146 day-date across disjoint uptime halves; joint species-frame $\mathrm{Yb}^+\,\mathrm{E3} - \mathrm{Sr}$ simultaneous Rayleigh $R = 0.990, p_{\mathrm{joint,6h}} = 0.0230$ vs common-window geographic $y_{\mathrm{NPL}} - y_{\mathrm{PTB}}$ $R = 0.477$ (four geographic ratios on a separate window; $R = 0.358$ for the same three simultaneous ratios)), zero-fibre 705 km anti-phase coherence probing a non-universal ΔK_α electromagnetic coupling extension between co-located optical pairs at NPL and PTB ($\mathrm{PA} = -0.335 \pm 0.091, z = -3.69, p = 2.2 \times 10^{-4}$; window-shuffle null $+0.002 \pm 0.103, z_{\mathrm{null}} = -3.27, p_{\mathrm{perm}} = 0.0010$), and target-blind global localisation of the zero-satellite optical clocks (879–1,416 km, conditional two-site Fisher $p = 0.0030$, 3-pair $p = 3.1 \times 10^{-4}$; sub-diurnal $f > 30\,\mu\mathrm{Hz}$ error 704–1,285 km) — while the pre-registered benchtop quartz/counter experiment (Step 172) remains the dedicated direct-quartz hardware test.

Together, these results establish a multi-channel observational case for geographically structured clock behaviour across GNSS receiver and inter-satellite clock products, strengthened by independently acquired European optical-clock measurements and cryptographically sealed operational prediction tests, with the pre-registered benchtop quartz experiment still awaiting independent hardware data: the combined spatial, phase, and oscillator-dependent signatures are consistent with the proposed TEP phenomenology and provide multiple discriminating tests of its physical interpretation — recovering the predicted correlation scale on an independent satellite-pair geometry, separating from the leading instrumental confound at a pre-registered threshold, carrying the predicted anisotropy and celestial axis, unmasking the sub-mHz floor and candidate non-universal ΔK_α anti-phase coherence on optical clocks, and predicting unscored data under cryptographic seal — while the specified station-identity, common-mode, geometry, phase-randomisation and sealed-envelope controls do not reproduce the observed signal. The temporal structure that the GNSS literature treats as noise is spatially coherent, predictable, and operationally exploitable; the infrastructure to exploit it is already deployed.

Data Availability & Reproducibility

> This work follows open-science practices. All results are fully reproducible from raw data using the documented pipeline. All numerical results, kernel predictions, and statistics are generated by deterministic Python scripts processing real GNSS

observational data.

Repository and Code

GitHub Repository: github.com/matthewsmawfield/TEP-PPP

The repository contains a deterministic, version-controlled analysis pipeline. The numbered scripts (`step_01` .. `step_181`) record a complete chronological log of every analysis run — pre-registered evaluations, primary analyses, adversarial null controls, and exploratory checks alike — so that readers can enumerate the full set of tests rather than a selected subset, organised into five evidentiary pillars: (i) *data acquisition, preprocessing, and common-mode control batteries* on broadcast and precise products (Steps 01–03c, 06, 10–19, 32, 38, 40, 45–45b); (ii) *physical field characterisation and geometry-free channels*, including cross-spectral phase alignment, cross-constellation satellite-clock pairs, sub-diurnal CMB-axis aperture synthesis, oscillator-class screening, co-located monument differentials, and the 65-day European optical-fibre clock network reanalysis (Steps 27, 50, 53, 58–59, 65–65d, 75–80, 98, 103, 137, 158–167, 178–179, 181); (iii) *causal clock outage bridging and timing holdover* across EUREF and multi-year global archives (Steps 25, 34, 55–56, 60, 85–90, 96, 104b, 140, 153); (iv) *degraded-geometry positioning and blind localisation* across raw-observation code SPP, production PRIDE-PPP-AR, and carrier-phase outage solves (Steps 22–23, 26, 33/39, 44, 48, 52, 57, 62, 99, 106); and (v) *the live 68-station NTRIP observatory, cryptographically sealed ex-ante evaluation, and clean-origin prospective preregistration suite* (Steps 37–37c, 168–174, 180). The Kalman-filter simulations (Steps 04, 07, 20) are exploratory and not relied on for any claim. All steps are orchestrated by `scripts/run_pipeline.py` with per-step logging.

All raw RINEX data, PPP processing configurations (RTKLIB), the TEP spatial kernel implementation, and analysis scripts are released openly in the project repository under CC-BY 4.0 (DOI: 10.5281/zenodo.23704945). The full codebase and execution environment are identical to the published version. Version: v0.6 (Pune), published 29 October 2026 (last updated 3 November 2026).

Revision note (v0.6): Regenerated Step 48 under the current $\lambda = 4{,}200$ km / nugget 0.35 / absolute-residual configuration (reproduces every reported cell within $\sim$1–2% RMS; \texttt{step_48_three_satellite_current.json}), added the Joint Explanatory Challenge discussion and the a-priori predictive-unity statement, and corrected the 10–500 μHz band description and the observing-day-halves wording.

Revision note (v0.5): Added the Step 65d per-station coupling covariate decomposition (antenna model organises broadband LF coupling at $\eta^2 = 0.37$ vs oscillator class 0.30; bounds the screening claim to lunar M_2 and co-located observables), corrected the four-group exact permutation p in Step 181 ($0.167/0.333$ for $\rho = +0.8$), added the Step 79b oriented signed-flux holonomy criterion and Step 181c mask-preserving optical localisation null, declared legacy-run provenance on the committed Step 48 outputs (originally generated under $\lambda = 3{,}480$ km / nugget 0.15 anchored change-kriging before the current 4,200 km / 0.35 defaults; §3.6.1) with a fingerprint-drift regression test; a full re-run under the current configuration on 2 November 2026 reproduces every reported cell within ~1–2% RMS (5.47 vs 5.52 m at $k = 3$, 6.44 vs 6.45 m at $k = 4$, 3.12 vs 3.15 m at $k = 5$, 4.53 vs 4.54 m at $k = 6$, 2.78 vs 2.77 m at $k = 8$; \texttt{step_48_three_satellite_current.json}), stated the satellite-channel boundary explicitly (shared analysis-centre adjustment; 8,140 km is band membership over an ill-conditioned tail), and corrected the Step 38 docstring.

Revision note (v0.4): Added exact $\binom{18}{8} = 43{,}758$ station-level label permutation inference to the Step 65/65d oscillator-screening decompositions (§3.5.3; predictable-power ratio $2.03\times, p = 0.0187$; LF coherent RMS ratio $7.37\times, p = 0.0273$), evaluated Step 167 tidal phase matching under verified IGS site-log metadata and station-level longitude permutation across CODE and GFZ (§3.10.1; quartz M_2 $p_{\mathrm{perm}} = 10^{-4}$, conditional multi-centre Fisher $p_{\mathrm{perm}} = 1.9 \times 10^{-6}$ vs atomic 0.42 and 0.55), resolved the 10–35 μHz tidal-band decay scale on the co-located Matera ($\lambda = 1{,}938$ km) and Tahiti ($\lambda = 2{,}211$ km) differentials (Step 164), reanalysed the 65-day European optical-fibre clock campaign ([22]; Step 181, §4: NPL–PTB differential offset $-7.1 \pm 7.7 \times 10^{-18}$, conditional 95% envelope $\leq 2.2 \times 10^{-17}$, and 1 s star-tree closure 3.61×10^{-20}; remote $\tau_{\mathrm{DL}} = 8.68$–$27.92 \times 10^{-18}$ vs 0.00×10^{-18} at NPL, 7.86 & 24.76×10^{-18} at PTB, and simultaneous 1 s 4-clock $\sigma_{\mathrm{baseline}} = 7.62$–$7.74 \times 10^{-18}$; 705 km M_2 Fisher $p = 0.0014$ raw, 0.0019 dm, with joint species-frame Yb^+ E3 $-$ Sr simultaneous Rayleigh $R = 0.990, p_{\mathrm{joint,6h}} = 0.0230$ vs geographic $R = 0.477$ (four geographic ratios on a separate window; $R = 0.358$ for the same three simultaneous ratios); zero-fibre 705 km anti-phase $\mathrm{PA} = -0.335 \pm 0.091, z_{\mathrm{null}} = -3.27, p_{\mathrm{perm}} = 0.0010$; and 43-mode global localisation to 879–1,416 km, conditional two-site Fisher $p = 0.0030$, plus 3–24 h GNSS waveform match $p_{\mathrm{dayblk}} = 0.0020$–$0.0370$), and integrated precision metrology and geodetic CME literature [11–22] alongside the v0.3 live observatory and sealed-envelope suites (Steps 168–180).

Revision note (v0.2): Unified the six-horizon phase-resolved holdover specification across the main text (Step 90, restoring the 2 h Rubidium crossover at 29.3 ns vs 37.5 ns), repaired the Step 88 four-quarter partition (removing a spurious fifth two-day remainder slice) and its bimodal discrete-reset screen (2,000 m threshold in the empty $[1{,}000, 2{,}769]$ m gap, isolating the DOY-091 HERS $+10.0\,\mu$s dropout reboot; worst-station 1 h gain $+0.5\% \to +9.2\%$, Q1 $+18.6\% \to +19.1\%$), added explicit environmental/hardware aging nulls to the Step 65c oscillator-screening decomposition (§3.5.3), documented the isotropic independence of all operational predictors from the Step 137/179 celestial-axis attribution (§3.7.4), disclosed the full 15-mountpoint provenance of the 15–16 October 2026 NTRIP capture (§3.9), reconciled the Step 97 dipolar/quadrupolar seasonal sign convention (Step 97), and standardised sequential subsection numbering across §3.

Repository Structure

```
TEP-PPP/
├── core/                          # TEP physics + spatial kernel
│   ├── constants.py               # Physical and phenomenological parameters
│   ├── ppp_kernel.py              # Dynamic TEP Kernel
│   └── ppp_base_kernel.py         # Base TEP Kernel
├── rpi/                           # Live GNSS Skill Observatory & PPP/RRR engine
│   ├── gps_web.py                 # FastAPI server, 1 Hz EKF, Rolling-Ridge Refit,
PPP-AR
│   └── static/                    # Live Skill Observatory web dashboard
(HTML/JS/CSS)
├── scripts/
│   ├── steps/                     # Numbered analysis steps (step_01 .. step_181)
│   ├── lib/                       # PPP estimators, kernel, NTRIP & OS Net clients
│   ├── live/                      # Real-time 68-station NTRIP kriging server &
product fetcher
│   ├── utils/                     # Logging, plot style
│   └── run_pipeline.py            # Master orchestration script
├── data/                          # RINEX data, processed clock residuals
│   ├── ntrip_live/                # Recorded live RTCM3 streams (Step 37)
│   └── ppp_live/                  # Live observatory rolling window archives & ridge
Grams
├── results/                       # Generated JSON outputs and figures
├── logs/                          # Per-step and live service execution logs
├── site/
│   └── components/                # Manuscript source components
└── README.md                      # Documentation
```

Data Provenance

Data Source	Provider	Access Method	Location
RINEX observations (ZIMM, GRAS, GENO, BRUX, WTZR)	EUREF Permanent Network / IGS	NASA CDDIS	`data/rinex/`
Precise ephemerides (SP3)	IGS	CDDIS archive	`data/meta/`
Processed clock residuals	Derived (RTKLIB SPP)	Pipeline Step 02	`data/ppp_processed/`
Live RTCM3 streams (NTRIP)	AGRS-NL / ReNEP (free casters)	Pipeline Step 37	`data/ntrip_live/`
Live 68-station CORS & L1/L5 rover observatory	OS Net (UK) / AGRS-NL / BKG / Centipede / ReNEP + CODE/GRG ultra-rapid	`rpi/gps_web.py`, `scripts/live/tep_realtime_server.py`, `scripts/live/sealed_envelope_verifier.py`	`data/ppp_live/` (`results/`, `sealed_envelopes/`) & `results/outputs/` (`live_rrr_*.json`, `step_174_*.json`)
2023 European optical-fibre clock comparison campaign (65 days, 1 Hz)	NPL / LNE-OP (SYRTE) / PTB / INRIM (Pizzocaro et al. 2026 [22])	Zenodo `10.5281/zenodo.16539534` (Pipeline Step 181)	`data/optical_fiber_2023/` & `results/outputs/step_181_*.json`

Reproduction Instructions

Quick Start (Full Reproduction)

```
# 1. Clone repository
git clone https://github.com/matthewsmawfield/TEP-PPP.git
cd TEP-PPP

# 2. Install dependencies
pip install -r requirements-lock.txt

# 3. Run the curated evidence pipeline (downloads data when absent)
python scripts/run_pipeline.py

# 4. Non-destructive code/result/manuscript verification
python scripts/reproduce.py --verify-only

# Results are stored in results/outputs and the gate ledger in EVIDENCE_STATUS.md
```

Sealed-Envelope Ex-Ante Verification (Step 174)

The cryptographic sealed-envelope protocol is independently auditable. The replay suite re-derives every seal origin from the archived Gram matrices and reruns the full falsification battery:

```
# Replay all 24 sealed-envelope origins + falsification battery
# (~60-90 min; re-derives every seal's eigendecomposition and the full
#  lambda x lead x epoch-position lattice from the archived Grams)
python scripts/steps/step_174_sealed_envelope_prediction.py

# Verify a live sealed envelope: SHA-256 integrity, then score every
# post-seal window against the committed frozen weights
python scripts/live/sealed_envelope_verifier.py --verify

# Retrospective N-window walk-forward backtest under the sealed protocol
python scripts/live/sealed_envelope_verifier.py --backtest 8

# Live watch mode: score each new post-seal window as it is solved;
# --seal-every mints a fresh envelope per window and --anchor appends
# each seal's digest to the hash-chained anchors.log provenance record
python scripts/live/sealed_envelope_verifier.py --watch 60 --seal-every --anchor

# Verify every envelope against all post-seal windows (lead-decay ladder)
python scripts/live/sealed_envelope_verifier.py --verify-all

# Verify the 122-link hash-chained anchor log and full 7,262-pair lattice audit
python scripts/live/anchor_chain_status.py
python scripts/live/sealed_lattice_audit.py

# Re-run the satellite-scale reconciliation (Step 178), CMB-axis cluster
# robustness (Step 179), clean-origin prospective preregistration (Step 180),
# and 65-day European optical-fibre clock network reanalysis (Step 181)
python scripts/steps/step_178_satellite_scale_reconciliation.py
python scripts/steps/step_179_axis_robustness.py
python scripts/steps/step_180_prospective_preregistration.py
python scripts/steps/step_181_european_optical_fiber_2023.py
```

Each sealed envelope in `data/ppp_live/sealed_envelopes/` stores the seal timestamp, the cutoff window identity, the member Gram list, the frozen weight archive, and its SHA-256 digest; `verification_log.json` appends every scored post-seal window with the recomputed digest, so any alteration of the committed weights invalidates the chain. The append-only `anchors.log` hash-

chains every seal's digest to its predecessor (anchor_sha256 = SHA-256(prev ‖ weights ‖ utc)), producing an externally publishable timestamped provenance record. Because archived Grams are built on each member window's own holdout, the reported one-step skill is additionally bounded by the resubstitution, strict-future epoch-slice, 3,600/7,200 s embargo, and zero-overlap clean-origin controls tabulated in Section 3.9.

System Requirements

Component	Minimum	Recommended
Python	3.10	3.11+
RAM	4 GB	8 GB
Disk	20 GB	30 GB
RTKLIB	2.4.3	2.4.3 b34+

Open Science Statement

This work is a preprint and is open to community review, ideas, and collaboration. All analysis code, configuration files, and manuscripts are open source. Feedback and contributions to further test these results are welcome.

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Contact

For questions, comments, or collaboration opportunities regarding this work, please contact:

Matthew Lukin Smawfield
✉*matthewsmawfield@gmail.com*