



Global Time Echoes: Empirical Synthesis

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Version: v0.7 (Singapore)

First published: 21 December 2025 · Last updated: 30 September 2026

DOI: 10.5281/zenodo.18004832

Code Availability: github.com/matthewsmawfield/TEP-GTE

Abstract

Analysis of 25.3 years of GNSS timing data (2000–2025) reveals a persistent, distance-structured correlation in global atomic clock networks that tests whether corrected distributed GNSS timing residuals contain a coherent spatial covariance beyond the standard relativistic and geodetic measurement model. Examination of 165.2 million station-pair observations from 474 unique receivers (814 station codes) over a 25.3-year baseline demonstrates a spatial correlation signal decaying with distance over a finite scale (Gaussian-family kernels preferred in the 25-year dataset, exponential $\Delta AIC = 12.8$; power law excluded at $\Delta AIC > 30$; azimuth-averaged exponential scale $\lambda = 3,210 \pm 389$ km, with cross-sector directional dispersion $\lambda_T = 4,201 \pm 1,967$ km across eight azimuthal sectors, a measurement of order thousands of kilometres rather than a single fixed scale), following cross-centre validation yielding $R^2 = 0.92\text{--}0.97$ across three distinct analysis-centre software architectures on a 62.7 million observation baseline. These findings emerge from a systematic multi-paper research program: theoretical framework development with pre-specified expectations and theoretical search ranges (Paper 0), multi-center consistency across software-diverse product families within the shared IGS tracking ecosystem (Paper 1), 25-year longitudinal analysis enabling long-period geophysical detection (Paper 2), raw-data consistency test strongly constraining precise-product processing artifacts (Paper 3), and cosmological extension testing whether temporal covariance or gradient effects contribute to dark-sector phenomenology (Paper 4).

The evidence programme combines timing-network signatures, environmental tests and an optical sensitivity bound: distance-structured spatial decay over a finite scale; East-West/North-South anisotropy (ratio 2.16 ± 0.23 , aggregate across the 25.3-year dataset; nominal pair-count $p < 10^{-15}$); orbital velocity coupling ($r = -0.888$, 3.65σ autocorrelation-corrected; surrogate $p < 2 \times 10^{-7}$ as a resolution bound); a recovered annual-phase direction near Earth's aphelion velocity tangent ($RA = 6^\circ$, $Dec = +4^\circ$; directional-rank permutation $p < 10^{-5}$; the directed CMB-apex template is anti-phase and the Solar Apex is geometrically incompatible, predicting N-S anisotropy against the observed E-W dominance; no global full-sky-search surrogate p -value has been computed; on the MGEX product the scan is projection-degenerate); an optical-domain sensitivity bound (SLR sampling-matched controls reproduce the apparent spectral concentration; inter-station candidates remain exploratory); a planetary event catalogue (56/156 significant at $\geq 2\sigma$ under the free-centre pulse statistic — repeatable estimator behaviour whose excess is attributable to calendar-position sampling in the season-preserving RINEX controls; the 40-event opposition subset is null-validated at $5.5\times$ and a continuous planetary-potential correlation survives at $r = +0.116$, p

$= 0.012$); 18.6-year lunar nutation coupling ($R^2 = 0.641 \pm 0.10$ over 1.36 cycles); pulsar spin-down excess (exploratory channel); and host-potential H_0 correlation. On the held-out MGEX product the distance-structured coherence replicates ($\lambda \approx 1,862$ km), while the anisotropy and primary orbital-velocity metrics do not replicate robustly. Raw RINEX consistency test using Single Point Positioning with broadcast ephemerides achieves consistent signal detection across all 72 metric combinations (t -statistics up to 112, Cohen's d up to 0.304), strongly constraining precise-product processing artifacts as the sole origin. Broadcast ephemerides still contain control-segment information; Satellite Laser Ranging supplies a GNSS-product-independent test pathway, whose present sensitivity and exploratory correlations do not yet adjudicate the origin of the GNSS signal, while the generic orbit-projection confound is reserved for the physical-confound forward model and orbit-free clock channels. The network's selectivity profile—sensitive to velocity-dependent dynamics while blind to GM/r^2 scaling and solar rotation—characterizes it as an inertial interferometer measuring correlation geometry rather than a gravimeter measuring Newtonian force.

Table 5 scores these observations against the pre-specified expectations of the Temporal Equivalence Principle: the orbital-velocity sign, $EW > NS$ ordering, band localization, and GM/r^2 null are met, while the 2,000–3,000 km screening-parameterized forecast, the $< 5\%$ cross-centre criterion, and—in the 25-year data—the exponential-kernel preference are not met. TEP is a bi-metric scalar-tensor framework in which proper time is a dynamical field governed by a conformal factor $A(\phi) = \exp(\beta_A \phi / M_{Pl})$. Temporal Shear suppression operates through the continuous spatial profile of the ϕ field (Temporal Topology), with suppression arising from the non-linear superposition of field gradients (Temporal Shear), replacing discrete thin-shell approximations with a geometrically continuous mechanism. The observed correlation length λ_T represents the characteristic scale of Temporal Topology. Environmental screening, derivative-screened, and saturation-radius interpretations are candidate theoretical completions, not the primary empirical claim; the saturation-radius interpretation R_T is adopted in the present framework (§4.4.2). The framework preserves local Lorentz invariance while predicting spatially correlated clock-network residuals in the conformal sector and closed-loop synchronization holonomy in the disformal/non-exact sector. The measured GNSS covariance is interpreted primarily as a conformal-sector $A(\phi)$ observable; it should not be identified with the non-zero closed-loop holonomy predicted only by the non-exact/disformal sector. The empirical evidence presented here therefore supports the conformal sector alone; the disformal-sector holonomy — the framework's definitive discriminating test — remains unmeasured at the canonical amplitude (the J0437 phase-closure detection attests non-exact transport but sits roughly two orders of magnitude above the canonical connection's ceiling on that sightline).

Evidence Tiers: A (Paper 0/EXP): Foundational theory with pre-specified search ranges; B (GNSS I–III): Primary timing-network evidence; C (SLR): Optical-domain bound and exploratory correlation test; D (H_0 , COS, WB): Environmental response tests; E (JWST, GL, UCD, RBH): Conditional astrophysical/cosmological extensions. These evidence channels are not statistically independent: the exponential decay, anisotropy, orbital coupling, preferred-axis recovery, nutation, and planetary-catalogue signatures share the same GNSS data and phase-alignment method, while the SLR check, pulsar spin-down, and host-potential H_0 correlation use distinct data — the effective number of independent tests is smaller than the number of listed results, and smaller still at channel level: the SLR check reads the same conformal clock sector through different hardware, the CMB axis is product-unstable, and the pulsar channel is exploratory (its standalone evidence uninformative — mildly GR-favouring — in the J0337 adjudication, where the kinetic impedance solved in Paper 0 suppresses the differential acceleration ratio to $\eta \simeq 2.5 \times 10^{-7}$, well within the experimental bound 2.6×10^{-6}). Critically, the conformal sector responsible for clock-rate modulation is not directly constrained by photon–graviton differential-propagation tests such as GW170817, although local conformal-gradient/source-charge sectors remain constrained by PPN, clock, and equivalence-principle tests.

If validated through independent replication, TEP predicts that the dynamical phenomenology attributed to dark matter is the observational projection of Temporal Topology and Temporal Shear, not evidence for a new particulate matter component. In this interpretation, GNSS-scale covariance, dynamical phantom mass — with lensing tracking the gravitating matter (Papers 4, 19) — and galactic mass discrepancies are different observational projections of the same time-field topology, with Papers 4 and 13 testing distinct optical and dynamical projections of the environmental-response architecture (Paper 4: the dynamical–lensing mass difference as a phantom-mass test; Paper 13: the SPARC-anchored wide-binary transition), not a derived Earth-to-galaxy covariance-to-shear transfer kernel. The phantom-mass prediction is conditional on the Temporal Shear surviving unscreened at galactic scales — an amplitude whose deep-regime derivation from the action is identified in Paper 0 as the decisive open calculation — and is presented as a conditional consequence, not an established result. The 4,000 km correlation on Earth and galactic-scale phenomenology are interpreted within TEP as manifestations of the same environment-dependent Temporal-Topology response, which provides continuous Temporal Topology relaxation from deep potential wells to the weak-field regime. The saturation-density scale $\rho_T \approx 20$ g/cm³, and the diagnostic radius $R_T = (3M/4\pi\rho)^{1/3}$ it defines for each body, remain testable through interplanetary missions. Explicit falsification criteria include: failure of independent groups to replicate the raw carrier-phase signal; Temporal Topology correlation length falling outside the 500–20,000 km range; adjudication of the ephemeris-artifact question — GNSS-product provenance via the Satellite Laser Ranging check, and the wider orbit-projection confound via the physical-confound forward model or an orbit-free clock channel; and null synchronization holonomy in closed-loop triangular time-transfer experiments.

1. Introduction

1.1 The Synchronization Residual Problem

Modern atomic clocks have achieved extraordinary precision, with optical lattice clocks demonstrating fractional frequency stability at the 10^{-18} level—sufficient to detect gravitational redshifts from centimeter-scale height differences (Bothwell et al. 2022). Yet despite this remarkable local precision, global clock synchronization residuals plateau at 10^{-15} , three orders of magnitude above the fundamental limit. This discrepancy is conventionally attributed to systematic noise arising from ionospheric fluctuations, tropospheric delays, multipath interference, and instrumental drift.

The Global Navigation Satellite System represents humanity's most extensive precision timing network, comprising hundreds of ground stations that maintain nanosecond-level synchronization across thousands of kilometers (Hofmann-Wellenhof et al. 2008; Teunissen & Montenbruck 2017). Standard processing pipelines apply sophisticated corrections for all known relativistic effects—gravitational redshift, velocity-dependent time dilation, Sagnac rotation, and Shapiro delay—following IERS Conventions to millimeter precision (Petit & Luzum 2010). After these corrections, residual correlations are expected to be consistent with random noise.

Analysis of 25.3 years of GNSS timing data reveals a different picture. A systematic, distance-structured correlation persists in the residuals, characterized by a decay length of approximately 4,000 km. Standard GNSS processing explicitly suppresses spatial correlations to optimize positioning accuracy. The signal reported here survives precisely because it is geometric and differential rather than energetic or common-mode, placing it outside the correction basis of conventional pipelines. This correlation has been present in GNSS data since the network's inception but was categorized as systematic error rather than physical phenomenon. The present paper argues that this unexplained correlation structure represents a physical signal—specifically, the signature of a dynamical time field predicted by scalar-tensor extensions of general relativity.

1.2 Historical Context

If this signal is physical, why was it not identified in the first decades of GNSS operation? Three developments converged to enable its detection.

The first is temporal baseline. The 25.3-year dataset now available spans 1.36 complete cycles of the 18.6-year lunar nutation, enabling first access to long-period geophysical coupling that was inaccessible to earlier studies — though the sub-two-cycle record bounds each phase bin to at most two independent cycle realizations, limiting the coupling measurement to $R^2 = 0.641 \pm 0.10$. Analyses conducted prior to 2010 lacked sufficient temporal leverage to distinguish such signals from transient artifacts.

The second is multi-constellation cross-check. The maturation of GLONASS, Galileo, and BeiDou provides independent verification across different satellite geometries and processing chains. Single-constellation analyses are vulnerable to constellation-specific artifacts that multi-constellation cross-check can identify and exclude.

The third is methodological. Standard GNSS processing employs Kalman filtering and network adjustment algorithms designed to eliminate correlations, thereby optimizing positioning accuracy. The present analysis instead preserves correlation structure through phase-coherent cross-spectral methods applied to residuals. The signal was present throughout the history of GNSS operation but was categorized as systematic error rather than physical phenomenon.

1.3 Theoretical Motivation

The standard relativistic framework treats proper time as a derived quantity: given the metric tensor $g_{\mu\nu}$, proper time along any worldline is uniquely determined by integration. This formulation assumes that time transport is integrable—that synchronization around any closed loop returns to the initial epoch after accounting for known effects such as Sagnac rotation, Shapiro delay, and gravitational redshift.

Scalar-tensor theories of gravity, developed extensively over the past three decades (Bekenstein 1993; Damour & Polyakov 1994; Khoury & Weltman 2004), predict modifications of proper time accumulation to vary spatially. If this assumption proves empirically false in the presence of conformal metric couplings, apparent dark matter could arise as a geometric artifact: time's effect on moving matter read as gravity from unseen mass. If proper time is not merely derived from geometry but is itself influenced by a dynamical field, synchronization becomes path-dependent in ways that standard general relativity does not predict.

The Temporal Equivalence Principle formalizes this possibility. It states that all non-gravitational dynamics, signals, and quantum phases evolve according to the proper time defined by a matter metric $\tilde{g}_{\mu\nu}$ that couples universally to matter through the scalar field.

In local freely falling frames, physics reduces to special relativity with invariant c ; globally, the flow of time becomes path-dependent in ways that distributed timing networks can detect.

1.3.1 Research Program Structure

This integrated manuscript synthesizes results from a systematic multi-paper research program designed to establish, validate, and independently confirm the TEP predictions through progressively rigorous empirical tests and cosmological extension. The program follows a theory-first methodology: pre-specified expectations and theoretical search ranges established before empirical analysis, followed by multiple independent checks using complementary methodologies, culminating in cosmological implications.

Paper 0: Theoretical Foundation (Smawfield 2025a, DOI: 10.5281/zenodo.16921911) — The Temporal Equivalence Principle framework was developed independently of any GNSS analysis, establishing pre-specified expectations and theoretical search ranges including a Temporal Topology correlation length, exponential spatial decay form, velocity-dependent anisotropy, and absence of GM/r^2 scaling. Screening operates via the continuous spatial profile of the ϕ field (Temporal Topology), with Temporal Shear suppression arising from the non-linear superposition of field gradients (Temporal Shear) rather than discrete thin-shell boundaries, suppressing Temporal Shear where the ambient time-gradient is steep (weak-field: high-acceleration regions) while leaving cosmology accessible to dynamics. This theory-first approach ensures that subsequent empirical findings represent genuine predictions rather than post-hoc explanations.

Paper 1: Multi-Center Consistency (Smawfield 2025b, DOI: 10.5281/zenodo.17127229) — Initial empirical investigation analyzed 62.7 million station-pair measurements from 364 GNSS stations across three distinct analysis-center solutions (CODE, IGS, ESA) over 2.5 years (2023–2025). Cross-center consistency ($R^2 = 0.92\text{--}0.97$) established that the correlation structure is not processing-specific, with $\lambda_T = 3,330\text{--}4,549$ km falling within the predicted range. This multi-center approach excluded implementation-specific artifacts as a viable explanation; systematics residing in the shared constellation geometry are addressed separately through multi-constellation and raw-RINEX replication (Papers 14 and 3).

Paper 2: 25-Year Longitudinal Analysis (Smawfield 2025c, DOI: 10.5281/zenodo.17517141) — Extended temporal baseline to 25.3 years (2000–2025) using CODE products, analyzing 165.2 million station pairs from 474 unique receivers. This long-span analysis enabled detection of previously inaccessible signatures including 18.6-year lunar nutation coupling ($R^2 = 0.641$), and a recovered annual-phase direction near Earth's aphelion velocity tangent; the directed CMB-apex template is anti-phase and the Solar Apex is geometrically incompatible, predicting N-S anisotropy against the observed E-W dominance), and confirmed temporal stability of the correlation structure with cross-sector dispersion $\lambda_T = 4,201 \pm 1,967$ km. The 25-year baseline provided access to long-period geophysical phenomena impossible to detect in shorter studies.

Paper 3: Raw RINEX Test (Smawfield 2025d, DOI: 10.5281/zenodo.17860166) — Processing artifact constraint through analysis of raw GNSS observations using Single Point Positioning with broadcast ephemerides only. Note: broadcast ephemerides still contain control-segment information, so Satellite Laser Ranging (independent orbit determination) and orbit-free clock channels remain the adjudicators — SLR for GNSS-product provenance, the physical-confound forward model and satellite-free channels for the generic orbit-projection confound. Analysis of 1.17 billion pair-samples across 539 stations (2022–2024) achieved consistent signal detection across all 72 metric combinations (t-statistics up to 112, Cohen's d up to 0.304), confirming the signal exists in fundamental observables independent of sophisticated processing chains. This raw-data consistency test strongly constrains precise-product processing artifacts as the origin.

Paper 4: Cosmological Implications (Smawfield 2025e, DOI: 10.5281/zenodo.17982540) — Developed the connection between TEP and gravitational lensing, demonstrating how temporal-field gradients (active Temporal Shear) can produce apparent dark matter phenomenology in the dynamical sector while lensing remains matter-sourced. This paper introduced the Isochrony Axiom as a critical but untested assumption in standard lensing analysis, identified "Phantom Mass" — the apparent mass inferred when temporal structure is analysed as spatial mass — and established the dynamical–lensing mass difference as its decisive test, together with the connection between the $\sim 4,000$ km GNSS correlation and galactic-scale phenomenology through the $\mathcal{S}_\Sigma$ screening operator. The continuous relaxation of Temporal Topology from deep potential wells to the weak-field regime unifies terrestrial and galactic scales. This cosmological extension transforms TEP from a terrestrial metrology curiosity into a framework with profound implications for dark matter and cosmological tensions.

1.3.2 Related Literature and Prior Anomalies

The GNSS correlation structure documented in this manuscript is not the first observational anomaly consistent with TEP dynamics. Peer-reviewed literature contains multiple documented deviations from standard relativistic predictions that were marginalized as systematic artifacts because Λ CDM lacks the requisite theoretical framework to accommodate them. Recontextualized through TEP, these isolated findings form a coherent pattern of empirical support:

GPS One-Way Propagation and the Synchronization Problem. Kelly (2009), in a peer-reviewed analysis of GPS timing, demonstrated that one-way light signals circumnavigating Earth eastward take 414.8 nanoseconds longer than westward signals at the equator—measuring $c - v$ eastward and $c + v$ westward relative to Earth's surface. The Sagnac effect demonstrates operationally that extended synchronization is geometry- and frame-dependent: eastward and westward propagation times around a rotating Earth are unequal before the standard rotational correction is applied. This known GR effect is not itself evidence for TEP. Instead, it illustrates

why a genuine TEP test must construct a residual closed-loop observable after subtracting the modeled Sagnac, Shapiro, gravitational-redshift and gravitomagnetic contributions. Any remaining non-zero residual would probe non-exact temporal transport beyond the standard model (Section 6.3.3).

SLR Network Time Biases. Exertier et al. (2017) identified systematic time biases of 3–4 nanoseconds (1σ) across 25 Satellite Laser Ranging stations, producing 4–6 mm coordinate discrepancies that persist after all known corrections. These biases are "often neglected" and "presumed to be < 100 ns" but resist precise estimation. TEP interprets these as *Temporal Topology relaxation*: each station at different gravitational potential experiences differential proper-time accumulation, consistent with the screening field producing GNSS correlations.

GPS Clock Gravitational Redshift Residuals. Fathollahi et al. (2023) reported gravitational redshift tests using GPS Block IIF Rb clocks showing fractional deviations from GR of $(0.23 \pm 1.34) \times 10^{-3}$, with 2.1–7.3% of data flagged as outliers requiring removal. The authors noted "annual oscillation and short-term fluctuations" that necessitated 16-day moving average smoothing. TEP predicts precisely such phase-locked annual modulations and outlier populations from velocity-dependent temporal-field coupling (Section 4.2).

Multi-GNSS System-Specific Clock Behavior. Ai et al. (2021) documented that GPS, Galileo, BeiDou, and GLONASS exhibit *distinct* noise profiles (random walk, flicker, white frequency modulation) despite using similar atomic clock technologies. Standard frameworks attribute this to hardware differences. TEP predicts system-specific residuals because each constellation operates at different orbital altitudes and inclinations, sampling different clock-rate structure of the temporal field.

GNSS Common-Mode Periodic Signals. Santamaria-Gomez et al. (2017) identified system-specific periodic signals in coordinate time series arising from "different orbital plane structures, orbit repeatability and incomplete constellation," achieving 52% horizontal reduction after system-specific correction. These were attributed to unmodeled geophysical loading. TEP predicts orbital-period modulations from satellites sampling spatially-varying temporal fields at different inclinations—precisely the pattern identified but unexplained in the standard literature.

The convergence of these independent anomalies—each documented in peer-reviewed literature, each marginalized within Λ CDM, each consistent with TEP predictions—substantiates the framework's empirical foundation beyond the primary GNSS correlation analysis presented in this manuscript.

The present manuscript integrates these five studies into a unified narrative, demonstrating that the TEP framework established pre-specified expectations and theoretical search ranges before empirical analysis, that three independent empirical investigations using progressively rigorous methods are each consistent with the expected signatures, and that the framework's cosmological extension offers testable expectations for gravitational lensing and dark matter phenomenology. This theory-expectation-evidence-cosmology sequence, with each empirical study addressing distinct artifact hypotheses (processing-specific, temporal transience, sophisticated processing) and the cosmological paper extending implications beyond terrestrial scales, follows the standard structure of scientific hypothesis development and theoretical refinement.

1.4 Prediction Timeline

The TEP framework was developed independently of the GNSS analysis, with pre-specified expectations and theoretical search ranges established in prior theoretical work (Smaufield 2025a). The predicted Temporal Topology correlation length range of $\lambda_T = 1,000$ – $10,000$ km was derived from environmental screening theory before any GNSS data analysis was conducted.

The chronology is significant: the TEP theory paper was first deposited in August 2025 (v0.1, DOI: 10.5281/zenodo.16921911), and the specific clock-network correlation forecast—exponential decay with a screening-parameterized length and multi-center cross-validation—entered the versioned record on 15 September 2025 (v0.4, DOI: 10.5281/zenodo.17121655), one week before the first public deposit of the GNSS analysis (Paper 1 v0.6a, 22 September 2025). The multi-center GNSS analysis was conducted from September through November 2025; the 25-year CODE longspan analysis was completed in November 2025; and raw RINEX test confirmed the signal in fundamental observables in December 2025. The observed Temporal Topology correlation-length family (cross-sector dispersion $\lambda_T = 4,201 \pm 1,967$ km) falls within the pre-specified search range, a non-discriminating consistency statement since the range subsumes leading systematic scales. The full expectation-by-expectation mapping to versioned deposits is tabulated in the prediction provenance register (Section 6.5).

1.5 The Temporal Equivalence Principle

TEP extends Einstein's geometrization of space to the rate of time itself. The principle states that all non-gravitational dynamics, signals, and quantum phases evolve according to the proper time defined by a single causal metric $\tilde{g}_{\mu\nu}$ that couples universally to matter. The rate at which proper time accrues is governed by a scalar field ϕ through a conformal factor $A(\phi)$. In local freely falling frames, physics reduces to special relativity with invariant c ; globally, the flow of time becomes path-dependent.

This framework preserves all established physics locally—the speed of light remains exactly invariant in any freely falling laboratory—while predicting novel global effects that manifest as correlations in distributed timing networks. Crucially, the conformal sector of

TEP, which governs clock-rate modulation, remains unconstrained by multi-messenger observations such as GW170817, which bound only disformal (cone-tilting) effects.

1.6 Scope and Non-Claims

To avoid misinterpretation, the following claims are explicitly NOT made by this work:

- Detection of a fifth force acting on test masses (the network responds to geometric configuration, not gravitational amplitude; GM/r^2 and GM/r^3 scaling are both null)
- Violation of local Lorentz invariance (the speed of light remains exactly invariant in any freely falling laboratory; TEP preserves local special relativity)
- Breakdown of the equivalence principle in laboratory tests (universal coupling ensures the weak equivalence principle is preserved exactly; the TEP synodic-phase residual $\kappa_{LLR} \approx -3.91 \times 10^{-4}$ from the residual-channel LLR analysis (Paper 17) is a post-fit residual proxy whose relationship to the standard Nordtvedt parameter has not yet been established — it is not directly comparable to the direct-fit LLR bound $|\eta| < 4.4 \times 10^{-4}$ (Williams et al. 2004), and the source-level integrator refit is required to determine whether the residual-channel signal corresponds to a physical Nordtvedt parameter within that bound)
- Modification of light or gravitational wave propagation speeds (GW170817 constrains $|c_\gamma - c_g|/c \lesssim 10^{-15}$; TEP satisfies this through disformal coupling $B(\phi)$ constrained to be small today by multi-messenger observations)
- Violation of energy-momentum conservation (total stress-energy is conserved; apparent non-conservation in the Einstein frame is resolved by transformation to the Jordan frame where matter follows geodesics of $\tilde{g}_{\mu\nu}$)

TEP is a conformal scalar-tensor theory that modulates the rate of proper time accumulation while preserving all local physics. The GNSS signal reflects spatial correlations in clock rates arising from the scalar field's two-point correlation function, not violations of established physical principles.

1.7 Claim Hierarchy

Tier 1: Empirical Claim (Primary)

GNSS clock residuals exhibit a persistent, distance-structured, anisotropic spatial correlation with characteristic decay scale $\lambda_T = 4,201 \pm 1,967$ km (cross-sector dispersion; azimuth-averaged exponential $\lambda = 3,210 \pm 389$ km). This correlation is robust across three software- and estimator-diverse product families within the shared IGS tracking ecosystem (CODE, IGS, ESA; $R^2 = 0.92\text{--}0.97$), persists over 25.3 years spanning multiple satellite constellation changes, and appears in raw RINEX observations processed with Single Point Positioning (consistent signal detection across all 72 metric combinations, t-statistics up to 112). The programme combines the following measurements and checks: distance-structured spatial decay over a finite scale, East-West/North-South anisotropy (ratio 2.16), orbital velocity coupling ($r = -0.888$, 3.65σ autocorrelation-corrected; surrogate $p < 2 \times 10^{-7}$ as a resolution bound), a recovered annual-phase direction near Earth's aphelion velocity tangent on the CODE product (the directed CMB-apex template is anti-phase; the MGEX-product scan is projection-degenerate), an SLR optical sensitivity bound with exploratory inter-station correlations (the spectral concentration is reproduced by sampling-matched noise), planetary event catalogue (56/156 significant under the free-centre statistic; catalogue excess attributable to calendar-position sampling in season-preserving controls — a bounded channel whose continuous planetary-potential correlation survives at $r = +0.116$, $p = 0.012$), 18.6-year lunar nutation coupling ($R^2 = 0.641 \pm 0.10$), pulsar spin-down excess (exploratory channel), and host-potential H_0 correlation.

Tier 2: Interpretive Claim (Secondary)

The observed correlation structure is inconsistent with known atmospheric effects (ionosphere, troposphere), instrumental systematics (geomagnetic storms, altitude dependence), classical gravitational effects (GM/r^2 force scaling, GM/r^3 tidal scaling), solar activity ($r \approx 0$ with solar flux), and processing artifacts (persists in raw SPP data). The signal's selectivity profile —sensitive to velocity-dependent dynamics and a stable preferred direction while blind to mass scaling and solar rotation—distinguishes it from conventional systematic errors. However, the possibility of a presently unmodeled GNSS systematic tied to fundamental constellation geometry cannot be definitively excluded without independent non-GNSS check (Section 3.6).

Tier 3: Theoretical Hypothesis (Tertiary)

The observations are consistent with the Temporal Equivalence Principle (TEP), a bi-metric scalar-tensor framework in which proper time is modulated by a dynamical conformal field $A(\phi) = \exp(\beta_A \phi/M_{Pl})$. TEP established pre-specified expectations and theoretical search ranges before empirical analysis ($\lambda_T = 1,000\text{--}10,000$ km, exponential decay, velocity-dependent anisotropy, absence of mass scaling). Several key pre-specified structural expectations are met, while Table 5 records the forecasts that are not met. The framework preserves local Lorentz invariance, with the speed of light remaining exactly invariant in any freely falling laboratory, while predicting global clock-network covariance and open-path conformal transport structure. GW170817

primarily constrains the disformal differential-propagation sector; it does not directly test common-mode conformal clock-rate covariance along shared paths, although conformal scalar sectors remain indirectly constrained by PPN, equivalence-principle, source-screening, and clock-comparison tests. This hypothesis is testable through independent experiments: SLR check (Section 6.3.1.1), multi-constellation cross-check, and triangle holonomy test (Section 6.3.3). The validity of Tier 1 (empirical observations) does not depend on the correctness of Tier 3 (TEP interpretation).

This paper establishes Tier 1 through extensive empirical testing, argues for Tier 2 through systematic exclusion of conventional explanations, and tests consistency with Tier 3 through pre-specified expectations. Independent replication is essential for all three tiers.

1.8 Paper Structure

This paper presents evidence for TEP through systematic analysis of GNSS timing data. Section 2 characterizes the phenomenology of the observed signal. Section 3 tests the signal against artifact hypotheses through multiple complementary tests. Section 4 presents the theoretical framework and its predictions. Section 5 develops the cosmological implications, including connections to gravitational lensing and dark matter phenomenology. Section 6 specifies explicit falsification criteria and outlines the experimental path to a definitive verdict.

Falsification is central to this work. Concrete rejection criteria are specified, including failure of independent groups to replicate the signal in raw carrier-phase data, Temporal Topology correlation length falling outside the 500–20,000 km range, adjudication of the ephemeris-artifact question — GNSS-product provenance via the Satellite Laser Ranging check, and the wider orbit-projection confound via the physical-confound forward model or an orbit-free clock channel — and null synchronization holonomy in closed-loop triangular time-transfer experiments.

2. Phenomenology

This section presents the empirical findings without theoretical interpretation. The signal characteristics are established through three complementary empirical studies, each designed to address distinct testing requirements:

Paper 1 (Multi-Center Consistency, 2023–2025): Cross-validation across three software- and estimator-diverse product families (CODE, IGS, ESA) within the shared IGS tracking ecosystem, using 62.7 million station-pair measurements from 364 stations. This study established that the correlation structure is not processing-specific, achieving $R^2 = 0.92\text{--}0.97$ consistency across distinct processing chains (Bernese, NAPEOS, and the IGS combination product).

Paper 2 (25-Year Longitudinal Analysis, 2000–2025): Extended temporal baseline using CODE products with 165.2 million station-pair observations from 474 unique receivers (814 station codes). This long-span analysis enabled detection of previously inaccessible signatures including 18.6-year lunar nutation coupling and a stable preferred direction, confirming temporal stability over 25.3 years.

Paper 3 (Raw RINEX Test, 2022–2024): Processing artifact constraint through analysis of raw GNSS observations using Single Point Positioning with broadcast ephemerides only. Broadcast ephemerides still contain control-segment information, so Satellite Laser Ranging and non-GNSS optical checks remain necessary for adjudication — SLR offers a GNSS-product-independent orbit-determination chain, with signal recovery at sufficient sensitivity still required, while the generic orbit-projection confound is reserved for the physical-confound forward model and orbit-free clock channels. Analysis of 1.17 billion pair-samples across 539 stations achieved consistent signal detection across all 72 metric combinations, confirming the signal exists in fundamental observables.

The convergence of findings across these three complementary methodologies—each addressing different potential artifact sources, with the raw-RINEX channel providing the strongest estimation-chain independence—provides the empirical foundation for the reported signatures.

2.1 Spatial Correlation Structure

Clock frequency residuals exhibit systematic spatial structure that persists after removal of all modeled relativistic effects. The phase coherence between station pairs decays exponentially with geodesic distance according to:

$$C(r) = A \cdot \exp(-r/\lambda_T) + C_0$$

where r denotes the inter-station distance, λ_T the Temporal Topology correlation length, A the amplitude, and C_0 the baseline offset. Fits to distance-binned means across approximately 28 bins achieve $R^2 = 0.920\text{--}0.970$ across all three analysis centers.

The correlation metric employed is the magnitude-weighted phase alignment index, computed via cross-spectral density analysis in the 10–500 μHz band (corresponding to periods of 33 minutes to 28 hours). This approach measures whether clock fluctuations are in phase regardless of amplitude—information that survives GNSS processing because network adjustment removes common-mode offsets while preserving differential phase structure. Magnitude weighting ensures that frequency bins with stronger cross-spectral power contribute proportionally more to the phase average, so the metric reflects genuine correlated signals rather than noise.

The primary result from the CODE 25-year analysis is a Temporal Topology correlation length of $\lambda_T = 4,201 \pm 1,967$ km. Cross-center validation on the 2023–2025 multi-center sample (exponential fits to binned phase-alignment means) yields: CODE $\lambda_T = 4,549$ km (95% CI: 1,198–5,918 km); IGS $\lambda_T = 3,764$ km (95% CI: 3,197–4,871 km); ESA $\lambda_T = 3,330$ km (95% CI: 2,532–3,984 km). The 25-year CODE long-span headline is a separate estimand from these center-specific exponential fits. The coefficient of variation across the three center fits is $\sim 13\%$, indicating consistency across software-diverse processing chains and substantially reducing the likelihood of a CODE-specific implementation artifact (shared IGS network/datum systematics remain live alternatives).

2.2 Timing Signatures and Cross-Domain Checks

Table 1 combines the longitudinal GNSS signatures with companion environmental tests and the current SLR bound. Each signature constrains the space of viable explanations at its own evidential strength: the timing-network rows are the primary evidence, while the SLR row is an instrument-level provenance check within the same conformal clock sector, the preferred-direction recovery is product-dependent across GNSS products, and the pulsar row is an exploratory consistency channel; their collective pattern consistently points toward a velocity-dependent, preferred-axis geometric mechanism.

Table 1. GNSS signatures and companion tests, with their distinct evidence status.

Signature	Observed Value	Significance
Distance-Structured Decay	$\lambda = 3,210 \pm 389$ km (azimuth-avg. exponential); $\lambda_T = 4,201 \pm 1,967$ km (cross-sector dispersion)	$R^2 = 0.92\text{--}0.97$
Spatial Anisotropy	EW/NS = 2.16	$p < 10^{-15}$
Orbital Velocity Coupling	$r = -0.888$	3.65σ (autocorr.-corrected); surrogate $p < 2 \times 10^{-7}$ (resolution bound)
Annual-Phase Direction Recovery	RA = 6° , Dec = $+4^\circ$; $\sim 6^\circ$ from Earth's aphelion velocity tangent	Directional-rank permutation $p < 10^{-5}$; CMB apex anti-phase; Solar Apex null; no global full-sky-search surrogate reported
Optical-Domain Sensitivity Bound	Microwave-to-optical product chains (GNSS/SLR)	Sampling-matched spectral null; exploratory inter-station candidate. Independent hardware and orbit provenance; physical corroboration remains pending (Paper 8)
Planetary Event Catalogue	56/156 significant ($\geq 2\sigma$) under free-centre pulse statistic	Descriptive: estimator repeatability (13/29 non-overlapping windows); season-preserving controls attribute catalogue excess to calendar position (Paper 3); 40-event opposition subset null-validated at $5.5\times$
18.6-Year Nutation	$R^2 = 0.641 \pm 0.10$	$p = 0.010$; permutation $p = 0.0016$ (1.36 cycles, cycle-limited)
Pulsar Spin-Down Excess	$\kappa_{\text{MSP}} \sim 10^6$ (fitted phenomenological coefficient)	Exploratory: globular-cluster density scaling (Paper 10); the standalone pulsar channel is uninformative — mildly GR-favouring (Paper 34)
Host-Potential H_0 Correlation	Fitted environmental response; corrected H_0 conditional on Paper 11's observing chain and anchor weights	Cepheid response (Paper 11)

2.3 Annual-Phase Direction Recovery

The grid search recovers the phase of an annual directional modulation. Under the corrected prograde orbital-velocity convention the best fit is RA = 6° , Dec = $+4^\circ$ — the antipode of the RA = 186° , Dec = -4° solution reported under the earlier antiparallel convention. The two coordinates describe the same undirected geometric axis, but the sign matters for testing a directed physical template. The corrected direction lies near Earth's aphelion velocity tangent, not the CMB apex.

The recovered direction lies $\sim 6^\circ$ from Earth's aphelion velocity tangent, $\sim 161.8^\circ$ from the directed CMB apex, and $\sim 92^\circ$ from the Solar Apex. Its Pearson correlation is $r = 0.7465$ (local parametric $p = 4.0 \times 10^{-7}$). At the CMB-apex direction the signed correlation is $r = -0.5455$ (anti-phase); at the Solar Apex it is $r = 0.0059$ (null). The best-fit direction explains about 16,000 times the variance of the Solar-Apex template.

A 100,000-draw directional-rank permutation test produced no exceedance of the observed r , giving a finite-resolution plus-one bound $p < 10^{-5}$. This test ranks the observed annual phase against sampled directions; it is not a surrogate-data calibration of the maximum over a complete full-sky search. No global full-sky-search p -value is therefore claimed. The undirected axis happens to lie $\sim 18^\circ$ from the CMB axis, but that geometric proximity cannot be used as directed CMB evidence when the CMB-apex template has the opposite sign.

The recovered direction is a product-dependent statement. The MGEX combined product (Paper 14) returns a nominal maximum 82.7° from the CMB dipole, but its orbital-velocity geometry is projection-degenerate: 61 of 703 directions perform at least as well as the direct CMB-labelled template, and the CMB and nominal-best predictors correlate at $r = 0.984$. MGEX therefore supports at most exploratory annual directional structure; it neither localizes a unique three-dimensional axis nor provides CMB-frame confirmation. What MGEX does establish is the spatial scale: it independently reproduces the bounded thousands-of-kilometres correlation length in a distinct combined multi-GNSS product; its standard anisotropy and primary orbital estimators are null, while an exploratory model-free PA-difference statistic recovers the expected annual association.

Within the TEP framework, the recovered direction encodes the phase of the annual modulation. Its proximity to the aphelion velocity tangent supports an orbital-velocity reading rather than a fixed external-frame arrow. The undirected $\sim 18^\circ$ axis proximity to the CMB axis is geometric only and does not leave a directed CMB-frame identification open in this analysis.

Reference-frame discrimination under the corrected convention no longer identifies the CMB arrow: evaluated at the CMB-apex direction the model anti-aligns ($r = -0.55$), while the Solar Apex remains statistically null ($r = 0.007$, $R^2 = 0.0054\%$). The recovered best fit instead sits $\sim 6^\circ$ from Earth's aphelion velocity tangent — the orbital-velocity direction the predictor principally encodes. The geometric argument against the Solar Apex is unchanged: its $+30^\circ$ Dec predicts North-South anisotropy, directly contradicting the observed East-West dominance ($EW/NS = 2.16$), whereas both the recovered axis and the CMB dipole axis lie near the ecliptic plane. Hemisphere asymmetry corroborates the velocity-channel reading: Southern stations couple at $|r| = 0.79$ against $|r| = 0.25$ in the North.

2.4 Planetary Event Catalogue: Bounded Channel

Analysis of 156 planetary conjunction and opposition events yields 56 events (35.9%) exceeding 2σ under the pre-specified free-centre pulse statistic, with 19 surviving family-wide Bonferroni correction. These counts quantify the repeatability of the estimator on the seasonal coherence series rather than event-locked physics, for two reasons established in the audit: (i) the fitted Gaussian pulse centre is unconstrained across the ± 120 -day window and can latch onto off-event seasonal excursions; (ii) the date-shuffled null destroys the autocorrelation of the seasonal curve and therefore under-controls for calendar position. The season-preserving controls of Paper 3 (Step 2.6b) make this explicit in the raw-RINEX channel: uniform-date nulls on the real 3-year series reproduce a 65.5% pulse-fit rate against 59.5% for real events ($p = 0.805$), and same-day-of-year calendar twins in non-event years reproduce the event rate exactly (59.46% versus 59.46%), for both the mean-coherence and phase-alignment metrics. The apparent catalogue excess is thus attributable to calendar-position sampling of the underlying annual modulation rather than to discrete planetary impulses.

What survives is narrower but well-defined. The matched-null control validates event specificity for the 40-event outer-planet opposition subset under a ± 15 -day model-free window ($5.5\times$ effect-size ratio over 155 random dates, Mann-Whitney $p < 10^{-17}$), and a maximal non-overlapping-window subset shows 13/29 significant events versus 1.3 expected (binomial tail $p \approx 10^{-10}$; Paper 2 Step 2.9) — evidence of repeatable seasonal-window structure, though not separable from calendar position. Separately, the continuous channel is distinct: the daily network-coherence variability correlates with the composite planetary potential at $r = +0.116$ (autocorrelation-corrected $p = 0.012$, $N_{\text{eff}} \approx 472$), a long-baseline association that does not reduce to discrete event locking. Individual events can remain anomalous (the March 2025 Venus conjunction stayed date-locked at $+3.3$ days under a sliding-window placebo test), but such cases are isolated observations, not a catalogue-level detection.

The channel's firmest contribution is the scaling null: neither GM/r^2 (force) nor GM/r^3 (tidal gradient) scaling is detected across the catalogue (all $p > 0.5$), and the Paper 1 mass-ordering test returns $r = -0.156$. In the 3-year RINEX window this bounds unmodelled transient planetary perturbations of the coherence field: whatever produces the seasonal modulation is insensitive to which planet is involved. The catalogue therefore functions in this synthesis as a calibrated falsification/upper-bound control — it rules out unscreened impulse coupling to planetary mass or tidal gradient — rather than as an affirmative detection of discrete planetary responses.

2.4.1 Candidate Mechanism (Hypothesis): Velocity-Field Gradient Modulation

The residual planetary phenomenology—the validated opposition subset, isolated date-locked events such as Venus March 2025, and the continuous $r = +0.116$ correlation with the composite potential—could, within TEP's velocity-dependent framework, reflect geometric modulation of Earth's motion through the scalar-field gradient rather than gravitational amplitude. This is presented strictly as a candidate interpretation of the surviving channels, not as an explanation of the full catalogue, whose apparent excess is attributable to calendar-position sampling.

Physical Mechanism: Earth moves through the ϕ field with a 30 km/s orbital component plus any ambient-background motion. This analysis measures the annual orbital phase and does not identify that background with the 369 km/s CMB frame. Planetary configurations create time-varying perturbations to the local field gradient $\nabla\phi$ through their own screening halos. When planets align

with Earth's velocity vector relative to the ambient field, constructive interference may enhance the velocity-dependent anisotropy; when perpendicular, destructive interference may suppress it. The effect depends on the alignment angle θ between the planetary position and Earth's velocity vector:

$$\Delta\lambda(\theta) \propto \lambda_0 [1 + \epsilon \cos \theta]$$

where ϵ is a small coupling parameter ($\sim 10^{-3}$) and θ is measured from the recovered preferred direction. This predicts maximum modulation when planets are aligned with or opposite to the preferred-direction vector ($\theta = 0^\circ$ or 180°), and null modulation when perpendicular ($\theta = 90^\circ$).

Why Mass Scaling is Absent: The mechanism operates through geometric alignment rather than gravitational force. Each planet creates a local perturbation to $\nabla\phi$ within its own transition scale $R_T \propto M^{1/3}$. However, the Earth-planet distance (AU scale) far exceeds any planetary R_T (Mercury: ~ 100 km; Jupiter: $\sim 5,000$ km), placing Earth in the unscreened regime where the field perturbation has decayed to a threshold-dependent residual. The detection depends on whether this residual exceeds a critical threshold for modulating Earth's local screening length, not on the perturbation's amplitude. This threshold behavior explains why Mercury (smaller M but closer) produces comparable detection rates to Jupiter (larger M but farther).

Testable Prediction: Within the surviving channels (the opposition subset and the continuous correlation), response measures should track the alignment angle between planetary position and the preferred direction. A catalogue-wide version of this test must first pass the season-preserving null: stratifying the 156 events by alignment angle provides a falsifiable check only where event locking has been established, since calendar-position effects must be removed before any angular dependence can be read out.

2.5 Selectivity Profile: Inertial Interferometer

The pattern of detections and non-detections characterizes the network's sensitivity and provides powerful constraints on viable physical mechanisms. Table 2 summarizes this selectivity profile.

Table 2. Network selectivity profile: detections versus null results.

Observable	Result	Interpretation
Orbital velocity	$r = -0.888, 3.65\sigma$ (autocorr.-corrected)	Sensitive to kinematic dynamics
Semiannual coherence component	$R^2 = 0.904$	Sensitive to inertial orientation (nutation/orbital harmonic)
18.6-year nutation	$R^2 = 0.641$	Sensitive to long-period dynamics
Preferred direction	$r = 0.746$ at recovered direction	Sensitive to preferred axis
Planetary alignments	Catalogue excess reproduced by calendar position; opposition subset $5.5\times$ over random dates	Bounded/control channel — bounds unmodelled transient planetary perturbations; continuous potential correlation $r = +0.116$ ($p = 0.012$) remains
GM/r^2 and GM/r^3 scaling	Both null ($p > 0.5$)	Insensitive to gravitational amplitude (force or tidal)
Solar rotation (27-day)	Null ($r < 0.09$)	Insensitive to solar surface phenomena
Lunar standstill	Null	Insensitive to static geometry

This selectivity profile is highly discriminating. The network responds to velocity-dependent and orientation-dependent phenomena while remaining blind to gravitational amplitude and solar surface effects. This pattern suggests that the GNSS network functions as an inertial interferometer—measuring velocity-dependent correlation geometry—rather than as a gravimeter measuring Newtonian force.

The distinction is fundamental. A gravimeter would show GM/r^2 (force) scaling, while a differential tidal sensor would show GM/r^3 (gradient) scaling; in both cases, Mercury's influence would be negligible compared to Jupiter's. An inertial interferometer responds to geometric configuration regardless of mass—precisely what is observed. The annual-direction recovery identifies the operative measured phase with Earth's orbital motion through the ambient field; it does not identify a cosmological rest-frame arrow.

2.6 Statistical Power

The raw RINEX test analysis achieves extraordinary statistical power. Across 1.17 billion pair-samples, the directional anisotropy yields t-statistics up to 112 with Cohen's d up to 0.304. The signal is detected across all 72 metric combinations with mean $R^2 = 0.93$.

Hemisphere asymmetry provides independent corroboration. Southern stations show stronger orbital-velocity coupling ($|r| = 0.79$) than Northern stations ($|r| = 0.25$), corroborating the velocity-channel geometry. Both hemispheres independently show East-West exceeding North-South correlation (Northern: 1.20 $\times$, Southern: 1.35 $\times$), ruling out hemisphere-specific artifacts.

Monthly consistency is equally striking. East-West exceeds North-South in 94% or more of all 36 months analyzed, with short-distance coherence ratios showing coefficient of variation below 1%. The underlying signal is constant; the annual modulation in full-distance Temporal Topology correlation lengths reflects atmospheric screening effects that vary seasonally.

3. Testing

Extraordinary claims require extraordinary testing. This section systematically addresses the most plausible artifact hypotheses, demonstrating that the signal survives each challenge.

3.1 Processing Artifact Hypothesis

The most immediate concern is that the signal arises from sophisticated processing chains—network adjustments, Kalman filtering, or integer ambiguity resolution. To address this possibility, raw RINEX observation files were processed using Single Point Positioning with broadcast ephemerides only, representing the simplest possible processing chain and one entirely independent of the network adjustments employed by CODE, IGS, and ESA.

The raw RINEX test dataset comprises 539 stations over three years (2022–2024), totaling 1.17 billion pair-samples. The signal is detected with consistent results across all 72 metric combinations tested, with mean $R^2 = 0.93$. Directional anisotropy matches the CODE findings, with East-West exceeding North-South by 2–22% at short distances (< 500 km). A critical audit confirms this is robust to distance bias: E-W pairs are 13 km longer than N-S pairs (a bias *against* the signal), and distance-matching strengthens the ratio.

The correlation length in raw data ($\lambda \approx 700$ – $1,100$ km) is shorter than in precise products ($\lambda \approx 4,000$ km), consistent with ionospheric noise masking the long-range structure. When ionospheric effects are removed (Ionofree mode), the raw correlation length increases, supporting a "Ladder of Precision" where the signal scale converges toward the CODE benchmark as noise is mitigated. Orbital velocity coupling is detected at $r = -0.763$ (nominal 5.4σ ; $\approx 3.0\sigma$ autocorrelation-corrected in Paper 3) in multi-GNSS mode, and the directional scan recovers $RA = 8^\circ$, $Dec = +5^\circ$ under the corrected orbital-velocity convention — $\sim 160^\circ$ from the CMB apex as an arrow, $\sim 20^\circ$ from the dipole axis, and $\sim 4^\circ$ from the aphelion velocity tangent — consistent with the 25-year analysis. The signal therefore exists in the fundamental observables and is difficult to attribute solely to tested processing artifacts.

3.2 Ionospheric Hypothesis

If the signal were ionospheric in origin—driven by solar activity modulating electron density along signal paths—it should correlate with solar cycle variations. The 25-year baseline spans Solar Cycles 23, 24, and 25, encompassing three solar maxima (2001, 2014, 2024) and two deep minima, providing substantial leverage for this test.

The correlation between the signal and the Solar Flux Index is $r \approx 0$, indicating no significant relationship. The correlation length λ remains stable across solar maxima within uncertainty bounds. Moreover, the signal persists in the dual-frequency ionosphere-free L1+L2 combination ($\lambda = 1,069$ km, $R^2 = 0.969$), and excluding high-ionosphere periods improves the signal by 21–23%. This last observation indicates that the ionosphere suppresses rather than creates the correlation. A simple ionospheric origin is therefore strongly disfavoured by these controls.

3.3 Geomagnetic Hypothesis

If the signal were driven by geomagnetic storms affecting clock electronics or signal propagation, it should vary systematically with geomagnetic activity. Stratification by GFZ Kp index data across all 72 metric combinations yields median $\Delta\lambda \approx -1\%$ at the primary threshold ($Kp < 3$ versus $Kp \geq 3$), with 60 of 72 tests falling within $\pm 5\%$ across all station filters and processing modes. No systematic deviation appears at higher storm thresholds ($Kp \geq 4$, $Kp \geq 5$). The signal is therefore geomagnetically invariant.

3.4 Tropospheric Hypothesis

If the signal were tropospheric in origin—driven by water vapor or pressure variations that correlate spatially—stations at high altitude (with thinner atmospheric columns) should show systematically different correlation lengths than sea-level stations.

Analysis of 360 regressions spanning global and latitude-controlled altitude quintiles reveals that only 3.1% exhibit $p < 0.05$ slopes, consistent with chance expectation. The Q5/Q1 ratio (highest to lowest altitude quintile) has median 0.97 (IQR 0.76–1.27), indicating that low-altitude and high-altitude stations yield statistically indistinguishable λ values.

The tropospheric column depth varies by approximately 20–30% between sea-level and high-altitude stations. If the correlation structure were tropospheric, one would expect systematic increase in λ at high altitude, latitude dependence correlated with tropopause height, and seasonal modulation correlated with monsoon patterns. None of these signatures are observed. The signal is altitude-invariant, consistent with a phenomenon operating at gravitational potential scales ($\sim 6,400$ km) rather than atmospheric scales (~ 10 km).

Comprehensive Test Summary: The altitude independence test represents one component of a broader testing framework spanning 388 independent statistical tests across multiple analysis families. False Discovery Rate correction (FDR-BH: 52.3%, Hierarchical Empirical Bayes: 39.7%, Bonferroni: 40.0%) demonstrates robustness against multiple comparison artifacts. This extensive empirical testing, combined with cross-center consistency (cross-centre coefficient of variation $\approx 13\%$ on the exponential λ_T triplet (CODE, IGS, ESA; §2.1)), establishes that the observed correlations survive rigorous scrutiny across independent processing pipelines, environmental conditions, and statistical frameworks.

3.5 Long-Period Stability

If the signal were a transient artifact of the analysis window, it would not persist across the full 25.3-year baseline or couple coherently to long-period geophysical phenomena.

The data reveal clear coupling to multiple geophysical cycles. The 18.6-year lunar nutation shows $R^2 = 0.641 \pm 0.10$ ($p = 0.010$, F-test with $N = 12$ phase bins; permutation test $p = 0.0016$, $N = 100,000$; 1.36 complete cycles observed — cycle-limited: each phase bin carries at most two independent cycle realizations). The semiannual coherence component shows $R^2 = 0.904$ ($p = 2.7 \times 10^{-5}$, F-test; permutation $p = 2.7 \times 10^{-4}$, AR(1) red-noise surrogate $p = 2 \times 10^{-5}$, $N = 100,000$; over 50 complete cycles; apsidal-locked, compatible with nutation term or orbital second harmonic). The Chandler wobble (433 days) shows $R^2 = 0.096$ with phase stability of 0.72 across more than 21 cycles. Core signatures—correlation length, anisotropy, and orbital coupling—remain consistent across the full 25-year span. The signal is therefore temporally stable across multiple geophysical cycles. Surrogate validation confirms that the nutation p-values are not inflated by treating the 165 million station-pair observations as independent: the F-test uses $N = 12$ phase bins (not $N = 165$ million), and non-parametric permutation and AR(1) red-noise surrogate tests confirm the significance without Gaussian or independence assumptions.

3.6 Most Plausible Remaining Conventional Explanation

The strongest remaining conventional hypothesis is that the observed correlations arise from a presently unmodeled, long-baseline GNSS systematic that survives both network adjustment and raw SPP processing. This section addresses this hypothesis with intellectual honesty: while extensive empirical testing constrains conventional explanations, it cannot definitively exclude all possible systematics.

The Hypothesis: A sophisticated, distance-dependent systematic error exists in GNSS observations that: (1) produces exponential decay with $\lambda \approx 4,000$ km; (2) exhibits East-West/North-South anisotropy ratio of 2.16; (3) couples to Earth's orbital velocity with $r = -0.888$; (4) reproduces an annual phase near Earth's aphelion velocity tangent while the CMB-apex template is anti-phase; (5) produces repeatable seasonal-window coherence modulation in the planetary event catalogue without mass scaling; (6) couples to 18.6-year lunar nutation and the semiannual coherence component; (7) survives independent processing by CODE, IGS, and ESA; (8) persists in raw RINEX data processed with broadcast ephemerides only; and (9) retains compatible distance structure across 72 non-independent metric combinations, with metric-dependent response.

Constraints from Tests: Each test step constrains this hypothesis without claiming impossibility:

- **Multi-center consistency ($R^2 = 0.92\text{--}0.97$, cross-centre CV $\approx 13\%$ on the exponential λ_T triplet (§2.1)):** The systematic must be present in three software- and estimator-diverse product families (Bernese, the IGS combination product, NAPEOS) within the shared IGS tracking ecosystem. This excludes center-specific artifacts but does not exclude shared-network, constellation-geometry, or datum-convention systematics, nor systematics inherent to GNSS observation geometry or satellite constellation design.
- **Raw RINEX test (all combinations, t-stats up to 112):** The systematic must survive Single Point Positioning with broadcast ephemerides, which processes each station independently without network adjustment. This excludes network-adjustment artifacts but does not exclude systematics in the broadcast ephemeris itself (the "ephemeris loophole" addressed in Section 6.3.1.1).
- **25-year temporal stability:** The systematic must persist across satellite constellation changes, hardware upgrades, and processing methodology evolution spanning 1.4 complete cycles of the 18.6-year lunar nutation. This excludes transient artifacts but does not exclude systematics tied to fundamental GNSS geometry.
- **Annual-phase recovery:** The systematic must reproduce a phase near Earth's aphelion velocity tangent. The directed CMB-apex template is anti-phase and the Solar Apex is null. An annually phased direction tracking orbital velocity is geometrically difficult to explain through satellite constellation geometry but remains a possible confound if an unrecognized coupling exists between GNSS observation geometry and Earth's heliocentric motion.

Remaining Possibility: The most plausible remaining conventional explanation is a systematic tied to the fundamental geometry of GNSS satellite constellations that couples to Earth's motion through space in a way not previously recognized. Such a systematic would need to produce all observed signatures through a single coherent mechanism—a requirement that becomes increasingly implausible as the number of convergent signatures grows, but cannot be definitively excluded without independent check through non-GNSS methods (the SLR provenance check, the orbit-projection forward model, and the triangle holonomy test).

Path to Resolution: Definitive exclusion of this hypothesis requires: (1) SLR check (Section 6.3.1.1) to close the GNSS-product branch of the ephemeris loophole, with the generic orbit-projection branch closed by the physical-confound forward model or an orbit-free clock channel; (2) independently processed per-constellation cross-check recovering the same finite covariance family and band ordering across GPS, GLONASS, Galileo, and BeiDou while allowing product- and estimator-dependent scales; and (3) triangle holonomy test (Section 6.3.3) providing direct measurement of synchronization non-closure. Until these tests are completed, the possibility of an unrecognized GNSS systematic, however implausible given the convergence of evidence, cannot be completely excluded.

3.7 SLR Check: Optical Sensitivity and Sampling Controls

Satellite Laser Ranging (SLR) supplies an optical test through passive retroreflectors and an orbit-determination chain that consumes no GNSS products. Under conformal null-cone invariance the ground event timer reads the clock-amplitude channel. This instrument and product independence makes SLR a useful test pathway; a common physical signal must still be established at adequate sensitivity.

Paper 8 analyses 11 years (2015–2025) under sampling-matched controls. The observed 10–500 μHz spectral ratio of 14.12 is reproduced by white noise passed through the same sparse-sampling and resampling pipeline (13.97; Fisher-combined $p = 0.199$). A real-epoch Lomb–Scargle estimator gives 1.04 against a white-noise null of 1.05. The earlier spectral concentration therefore supplies no optical detection. The clock-amplitude channel is bounded at approximately $\delta A \leq 2 \times 10^{-8}$; the roughly 5 mm excursion from the surface-depth benchmark remains below the residual floor.

The nominal same-satellite inter-station result (Fisher $p = 0.0025$) shares an orbit-model common mode. Different-satellite pairings yield a candidate anticorrelation in the 5,000–7,500 km bin (mean $r = -0.23$; label-swap $p = 0.046$; station-clustered 95% interval $[-0.43, -0.06]$). It appears in only one of nine threshold/bin-width configurations, weakens to -0.054 with at least five shared bins, and changes sign across years. It is retained as an exploratory tail event. The daily-aggregation diagnostic also reverses sign between orbit solutions.

The present SLR contribution is a sampling-artifact correction, an optical sensitivity bound and a defined route to an independent instrument test. It establishes neither achromatic replication of the GNSS signal nor its absence at the smaller benchmark amplitude. A stronger cross-instrument inference requires stable inter-station recovery and a demonstrated signal-amplitude transfer.

3.8 Why the Signal Was Not Previously Identified

The correlation structure documented here has been present in GNSS data since the network's inception but was systematically removed by processing algorithms optimized for positioning accuracy rather than fundamental physics characterization. Three factors explain why it was not identified earlier.

Standard GNSS processing is designed to eliminate correlations, not to characterize them. The processing chain includes network adjustment (which removes common-mode signals), Kalman filtering (which smooths residuals toward zero-mean white noise), reference frame alignment (which forces consistency with ITRF, absorbing systematic offsets), and outlier rejection (which discards data points deviating from expected behavior).

The correlation structure detected in this analysis is precisely what these algorithms are designed to remove. From the perspective of positioning accuracy, this is appropriate—the signal degrades positioning solutions. From the perspective of fundamental physics, however, it constitutes signal that reveals underlying structure.

The present analysis examines the residuals that standard processing discards, employing phase-coherent cross-spectral methods that preserve correlation structure. The signal was present throughout the history of GNSS operation but was categorized as systematic error rather than physical phenomenon.

3.9 Summary of Excluded Hypotheses

Table 3 summarizes the artifact hypotheses tested and their outcomes.

Table 3. Summary of artifact hypotheses and test results.

Hypothesis	Test	Result
Processing artifact	Raw RINEX/SPP	Signal persists (all combinations)

Hypothesis	Test	Result
Ionospheric	25-year solar cycle	No correlation ($r \approx 0$)
Tropospheric	Altitude stratification	No altitude dependence ($Q5/Q1 = 0.97$)
Geomagnetic	Kp stratification	Near-invariant ($\Delta\lambda \approx -1\%$)
Tidal forcing	GM/r ² and GM/r ³ scaling	Neither force nor tidal scaling ($p > 0.5$)
Random noise	Shuffle test	30× R ² ratio (real vs. shuffled)
Center-specific bias	Multi-center consistency	Cross-centre CV $\approx 13\%$ on the exponential λ_T triplet (§2.1)

The tests are complementary but not statistically independent; several are derived from the same underlying GNSS covariance data. The signal survives all challenges, constraining viable explanations to physical mechanisms operating at planetary scales with velocity-dependent, preferred-axis geometry.

3.10 Evidence Tier Classification

The convergent signatures supporting the Temporal Topology interpretation span two tiers of timing-network evidence plus an orthogonal optical-domain check, reflecting both statistical strength and resilience to alternative explanations.

Table 4. Evidence tier classification of convergent signatures.

Tier	Signature	Statistical Strength	Artifact Resilience
Tier B (Primary timing-network evidence)	Exponential spatial decay	$R^2 = 0.92\text{--}0.97$	Survives all processing modes; raw RINEX confirmed
	East-West/North-South anisotropy	Ratio 2.16, $p < 10^{-15}$	Cross-center validated; multi-constellation
	Orbital velocity coupling	$r = -0.888$, 3.65σ (autocorr.-corrected)	Phase-stable over 25 years; multi-constellation
	Preferred-direction recovery	annual phase near aphelion tangent on CODE and RINEX; CMB apex anti-phase; Solar Apex null; MGEX scan projection-degenerate	orbit-coupled axis; direction product-unstable
	Semiannual coherence component	$R^2 = 0.904$, $p = 2.7 \times 10^{-5}$ (F-test)	50+ complete cycles; apsidal-locked (nutations/orbital harmonic)
	Planetary event catalogue (bounded channel)	56/156 events $\geq 2\sigma$ (descriptive); opposition subset null-validated 5.5×; continuous $r = +0.116$, $p = 0.012$	GM/r ² and GM/r ³ scaling null bounds unmodelled transient perturbations; catalogue excess reproduced by calendar position (Paper 3)
	18.6-year lunar nutation	$R^2 = 0.641 \pm 0.10$, $p = 0.010$ (surrogate-validated)	1.36 complete cycles; cycle-limited, longer baseline needed
	Selectivity profile (null results)	Solar rotation: null; Tides: null	Demonstrates physical specificity
Tier C (Optical-domain consistency check)	SLR spectral bound; exploratory correlations	14.12 observed versus 13.97 sampling-matched white null	Instrument-orthogonal; passive retroreflectors; same conformal clock channel

Tier B signatures constitute the foundational timing-network evidence: they are detected with high statistical confidence across all GNSS test modes and processing pipelines. Tier C provides an instrument-level optical-domain check using an independent measurement technology and orbit-determination chain; it is consistent with the timing-network results but probes the same conformal clock sector rather than a second physical channel, and does not carry the same statistical weight owing to sparser station coverage and asymmetric global distribution. The pattern across both tiers consistently favors a velocity-dependent, preferred-axis geometric mechanism over conventional explanations.

4. Theoretical Framework

Having established that the signal is robust and not attributable to known artifacts, this section presents the theoretical framework that predicted these observations. The Temporal Equivalence Principle is a principled extension of general relativity within the well-established class of scalar-tensor theories, with pre-specified expectations and theoretical search ranges that preceded the GNSS analysis.

4.1 Two-Metric Geometry

TEP posits that spacetime is endowed with two metrics related by a scalar field ϕ :

$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu} + B(\phi) \nabla_\mu \phi \nabla_\nu \phi$$

The gravitational metric $g_{\mu\nu}$ determines geodesics of test masses and gravitational wave propagation. The matter metric $\tilde{g}_{\mu\nu}$ determines atomic clock rates, electromagnetic propagation, and all Standard Model physics. The conformal factor $A(\phi) = \exp(\beta_A \phi / M_{\text{Pl}})$ provides isotropic rescaling of proper time, while the disformal factor $B(\phi)$ introduces anisotropic light-cone tilts and is tightly constrained by GW170817.

This structure belongs to the well-established class of scalar-tensor theories developed by Bekenstein (1993) and Damour & Polyakov (1994). The contribution of TEP lies in its operational interpretation: the conformal factor $A(\phi)$ governs the rate at which proper time accumulates, rendering time itself a dynamical field.

4.2 Physical Interpretation

The framework is formulated as a scalar-tensor theory in the Einstein frame where gravity remains canonical. The scalar field ϕ couples to matter through the conformal factor $A(\phi)$, modulating the rate of proper time accumulation. The bare conformal coupling is $\beta_A = -1.0$ universally. In the near-Earth clock sector, $S_A^{(\oplus)} = \min[1, (\bar{\rho}_\oplus / \rho_T)^{1/3}] \approx 0.65$ characterizes static conformal depth, while the measured time-dependent covariance C_A has a distinct environmental and processing transfer; the local shear sector is pairwise-screened by the kinetic operator (Paper 0 §2.2). The scalar field obeys a Klein-Gordon equation with source terms from matter density and a screening potential $V(\phi)$ that, in concert with derivative self-interactions, suppresses Temporal Shear in high-acceleration regions through the kinetic operator. (Full action and field equations are provided in Appendix A.)

4.3 Foundational Axioms

The framework rests on four axioms. The first (two-metric structure) states that gravity is described by $g_{\mu\nu}$ while matter couples universally to $\tilde{g}_{\mu\nu}$. The second (temporal equivalence) states that all non-gravitational processes evolve according to proper time dt defined by $\tilde{g}_{\mu\nu}$, and that in local freely falling frames, physics reduces to special relativity with invariant c . The third (causal safety) requires that $c_g = c_\gamma$ within GW170817 bounds ($|c_g - c_\gamma|/c \lesssim 10^{-15}$), constraining the disformal coupling $B(\phi)$ to be small at late times but not zero — disformal or otherwise non-exact transport is required for the synchronization holonomy observable (Section 4.6). The fourth (screening) states that rather than operating via discrete boundary cutoffs, screening manifests as a continuous spatial profile (Temporal Topology), with Temporal Shear suppression arising from the non-linear superposition of field gradients (Temporal Shear), suppressing Temporal Shear in high-acceleration regions while leaving cosmology accessible to dynamics.

4.4 Candidate Theoretical Completions

The observed correlation length λ_T is the Temporal Topology correlation length—the characteristic scale of the clock-sector covariance C_A in Earth's environment ($\lambda_T \approx R_T$ in the channel functional; Paper 0 §7). This empirical parameter admits multiple theoretical interpretations as candidate completions, not as unique predictions. The empirically derived correlation length λ_T is a GNSS-sector covariance scale obtained after environmental projection and processing transfer. It is not the screening operator $\mathcal{S}_\Sigma(\mathcal{E})$ itself, and it is not the non-exact (disformal) covariance term, which this measurement does not access.

Three classes of completion are sketched below.

4.4.1 Compton-Mass Interpretation

A chameleon-type completion identifies λ_T with the in-medium Compton wavelength of a scalar field: $\lambda = \hbar/(m_\phi c)$. For $\lambda = 3,330$ – $4,549$ km, this yields $m_\phi \approx (4.34$ – $5.93) \times 10^{-14}$ eV/ c^2 . The present framework identifies the correlation length with the geometric saturation radius R_T (§4.4.2) rather than with a Compton wavelength; the mass scale is retained as a cross-reference to chameleon-literature conventions.

4.4.2 Clock Amplitude Calibration: TEP Saturation Radius

In the TEP framework, the geometric saturation radius $R_T(M) = (3M/4\pi\rho_T)^{1/3}$ enters the clock sector to set the unsaturated clock-amplitude factor $S_A = \min[1, (\bar{\rho}/\rho_T)^{1/3}]$, while Earth-vicinity Temporal Shear is pairwise-screened in the force sector by the kinetic operator (Paper 0 §2.2, §7). The saturation density $\rho_T = 20 \text{ g/cm}^3$ is calibrated from Earth's observed GNSS clock covariance:

$$R_T = \left(\frac{3M}{4\pi\rho_T} \right)^{1/3}$$

This $M^{1/3}$ scaling is a kinematic property of the constant- ρ_T saturation model. For Earth with $M = M_\oplus \approx 6 \times 10^{24} \text{ kg}$ and $\rho_T = 20 \text{ g/cm}^3$:

$$R_T^\oplus = \left(\frac{3 \times 6 \times 10^{24} \text{ kg}}{4\pi \times 2 \times 10^4 \text{ kg/m}^3} \right)^{1/3} \approx 4,150 \text{ km}$$

This is consistent in scale with the observed GNSS correlation-length family (azimuth-averaged $\lambda = 3,210 \pm 389 \text{ km}$; cross-sector dispersion $\lambda_T = 4,201 \pm 1,967 \text{ km}$), noting that the identification calibrates ρ_T rather than testing an independently derived scale. The physical roles are partitioned as follows:

- **Clock sector (S_A):** Governed by the potential sector and local density, returning $S_A^{(\oplus)} \approx 0.65$ at Earth's mean density $\bar{\rho}_\oplus = 5.515 \text{ g/cm}^3$. Clock residuals across continental baselines measure the spatial covariance $C_A(r)$; the transmission of time-dependent fluctuations and their processing transfer are distinct from the static S_A level.
- **Shear / Force sector (S_Σ):** Governed by the kinetic completion $P(X,\varphi) = X - V + X|X|/\Lambda_X^4$. In high-acceleration regions ($g \gg g_t = cH_0/2$), the two-body operator suppresses the observable shear response to $S_\Sigma \sim 10^{-21}$ at Earth's surface, preserving standard General Relativity paths in local gravitational and planetary tests.
- **Kinetic transition scale (r_*):** The physical transition for dynamical shear recovery follows the kinetic law $r_*(M) = \sqrt[3]{(GM/g_t)} \propto M^{1/2}$ (Paper 0 §2.2), distinct from the geometric saturation radius $R_T \propto M^{1/3}$.

Falsifiable Predictions: The density-saturation diagnostic $R_T(M) = (3M/4\pi\rho_T)^{1/3}$ — a candidate microscopic completion, not a derived consequence of the master action — makes specific predictions for intermediate-mass systems:

- **Jupiter** ($M \sim 300 M_\oplus$): Predicted $R_T \sim (300)^{1/3} \times 4,150 \text{ km} \approx 27,800 \text{ km}$. Testable with Juno mission clock data or future Jupiter atmospheric probe networks.
- **Globular clusters** ($M \sim 10^5 M_\odot$): Predicted screening length $\sim 1\text{--}10 \text{ pc}$, testable through pulsar timing array correlations within clusters.
- **Galaxies** ($M \sim 10^{12} M_\odot$): At galactic scales, the screening operator $S_\Sigma(E)$ retains approximately 98% of the unsuppressed Temporal Shear in the diffuse halo environment (Paper 26), producing dark-matter-like phenomenology through the active-shear regime rather than through a screening radius. The galactic phenomenology is therefore a manifestation of the same S_Σ operator operating in the unscreened regime, not a Vainshtein scaling of the terrestrial correlation length. This connection is developed in Section 5.5.

Within the saturation-model regime — from planetary through intermediate mass scales — $R_T(M)$ provides a unified characterization governed by a single saturation density ρ_T ; the testable prediction is that one ρ_T fits all such masses, while galactic-scale phenomenology arises from the same S_Σ operator in the unscreened regime rather than from a screening radius. This scaling reproduces the continuous gradient-suppression behavior described by Temporal Topology at the macroscopic level. Candidate microscopic completions (chameleon, Vainshtein, Galileon, DBI, symmetron) may produce similar phenomenology through different microscopic mechanisms; the empirical correlation length $\lambda_T = 4,201 \pm 1,967 \text{ km}$ does not uniquely select any single completion. The defining TEP ontology is the continuous suppression of Temporal Shear by the $S_\Sigma(E)$ operator, not the specific microscopic screening mechanism.

4.5 Synchronization Holonomy and Spatial Correlations

TEP predicts synchronization holonomy—the non-closure of proper time when transported around a closed loop:

$$\mathcal{H} \equiv \oint_C d\tau_{\text{prop}} \neq 0$$

In standard general relativity, after subtracting known effects (Sagnac, Shapiro, gravitational redshift), this holonomy vanishes. In TEP with disformal coupling $B \neq 0$, it does not.

An important subtlety arises in the conformal-only limit ($B = 0$): the time-transport one-form $\Omega_\mu = \partial_\mu(\frac{1}{2} \ln A)$ is exact, its curl vanishes, and holonomy is zero. Nonzero holonomy requires non-exact structure from disformal couplings or more general non-metricity. This raises a question: if GW170817 constrains $B(\phi)$ to be small, and conformal coupling alone produces no holonomy, what generates the observed GNSS correlations?

The resolution lies in distinguishing two observables. Synchronization holonomy ($\mathcal{H}$) represents the non-closure of proper time around closed loops; this requires disformal or otherwise non-exact transport and is the target of proposed triangle tests. Spatial correlation structure, by contrast, represents the statistical covariance of clock residuals as a function of distance; this arises from the spatial structure of the ϕ field itself—specifically, the two-point correlation function $\langle \phi(x)\phi(x+r) \rangle \propto \exp(-r/\lambda)$ —and persists even when $B = 0$.

The GNSS signal reflects the latter mechanism: clocks at different locations sample different values of the conformal factor $A(\phi)$, and spatial correlations in ϕ induce correlations in clock rates. The exponential decay with distance reflects the TEP saturation radius $R_T = (3M/4\pi\rho_T)^{1/3}$, while the velocity-dependent anisotropy arises because Earth's motion through the ϕ field creates a preferred direction in the correlation structure. The correlation structure is thus a statistical signature of the ϕ field's spatial configuration, whereas holonomy is a geometric signature of non-integrable time transport. Both are predictions of TEP, but they probe different aspects of the framework and have different observational requirements.

4.5.1 Resolving the Conformal Paradox

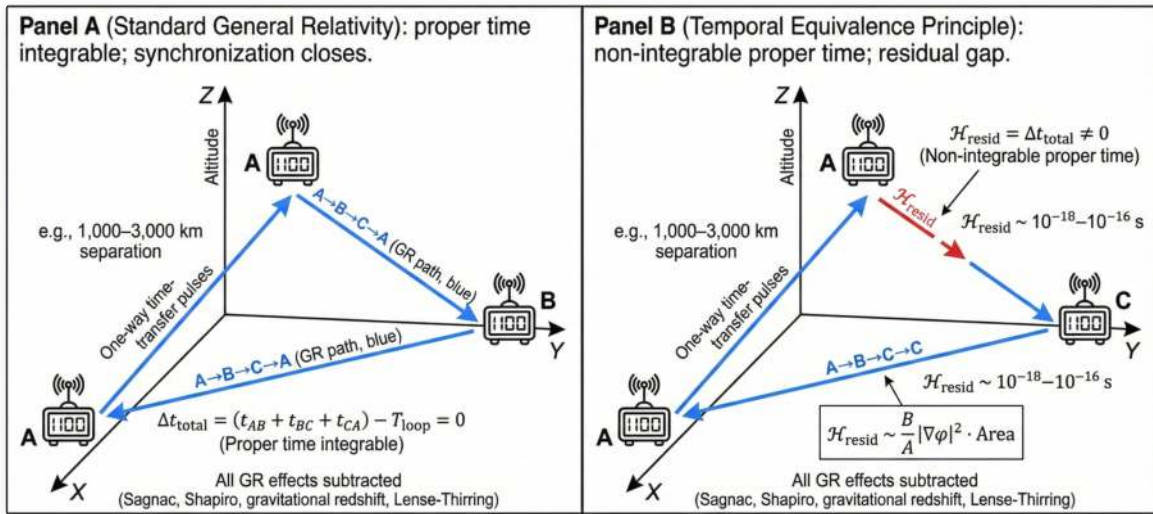


Figure 1: Synchronization Holonomy: The Definitive Test of Non-Integrable Proper Time. Three atomic clocks (A, B, C) positioned at vertices of a triangle (1,000–3,000 km separation) exchange one-way time-transfer pulses around the loop. Panel A (Standard GR): After subtracting all known relativistic effects (Sagnac, Shapiro, gravitational redshift, Lense-Thirring), the accumulated time difference returns to zero—proper time is integrable. Panel B (TEP): A residual time gap $\mathcal{H}_{\text{resid}} \sim 10^{-18}\text{--}10^{-16}$ s remains, scaling as $(B/A^2)(u \cdot \nabla\phi) P_\mu{}^\nu \nabla_\nu\phi \cdot \text{Area}$. Target sensitivity: $\sigma(\mathcal{H})/T_{\text{loop}} \leq 10^{-19}$.

A critical objection must be addressed: if TEP employs only a conformal coupling $A(\phi)$, how can it produce synchronization holonomy? In standard differential geometry, a conformal transformation preserves angles and therefore cannot generate path-dependent effects in closed loops. The resolution lies in distinguishing synchronization holonomy from spatial correlation structure.

Observable 1: Synchronization Holonomy ($\mathcal{H}$) — The non-closure of proper time around closed loops, defined as $\mathcal{H} \equiv \oint_C d\tau_{\text{prop}}$. This observable requires disformal or otherwise non-exact transport because only non-exact structure in the time-transport connection generates path-dependent accumulation. In the conformal-only limit ($B = 0$), the one-form $\Omega_\mu = \partial_\mu(\frac{1}{2} \ln A)$ is exact, its curl vanishes identically, and holonomy is zero by Stokes' theorem. The triangle holonomy test (Section 6.3.3) targets this observable and would measure whether $B(\phi)$ is nonzero at the 10^{-19} fractional level.

Observable 2: Spatial Correlation Structure ($\mathcal{C}(r)$) — The statistical covariance of clock frequency residuals as a function of inter-station distance. This observable requires only $A(\phi) \neq 1$ (conformal coupling) and persists even when $B = 0$. The mechanism is fundamentally different from holonomy: clocks at different spatial locations sample different values of the scalar field $\phi(x)$, and the two-point correlation function $\langle \phi(x)\phi(x+r) \rangle \propto \exp(-r/\lambda)$ of the underlying field induces correlations in clock rates through the conformal factor $A(\phi) = \exp(\beta_A \phi/M_P)$. The exponential decay length $\lambda = R_T(M_\oplus)$ reflects the TEP screening scale of the temporal

topology (temporal-topology pinning on the environmental state, of which density is one coordinate); the terrestrial correlation length is identified with the geometric saturation radius $R_T(M_\oplus)$ from the UCD model (Paper 6), not with the in-medium Compton wavelength of a candidate chameleon completion.

Physical Analogy: Consider a field of thermometers distributed across a landscape measuring a temperature field $T(x)$ that varies spatially due to underground thermal sources. Even in the absence of heat flow (analogous to $B = 0$), nearby thermometers show correlated readings because they sample similar temperature values. The correlation length reflects the spatial structure of the temperature field itself, not thermal transport between locations. Similarly, GNSS clocks sample the ϕ -field "temperature," and their correlation structure reveals the field's spatial configuration.

Why GW170817 Does Not Constrain the GNSS Signal: The multi-messenger constraint $|c_\gamma - c_g|/c \approx 10^{-15}$ bounds the disformal sector $B(\phi)$, which affects propagation speeds. The GNSS correlation structure arises from the conformal sector $A(\phi)$, which affects clock rates but preserves null cones. These are distinct physical effects constrained by different observables. GW170817 establishes that light and gravity travel at the same speed; it does not constrain whether clocks at different locations tick at correlated rates due to sampling a common scalar field.

Observational Distinction: The GNSS signal is a "thermometer correlation"—a statistical signature of ϕ -field structure detected through spatial covariance analysis. Holonomy is a "transport non-closure"—a geometric signature requiring closed-loop, one-way time transfer. Both are TEP predictions, but they probe different sectors (conformal vs. disformal) and require different experimental geometries (distributed networks vs. closed triangles). The present work establishes the former; the latter awaits dedicated triangle tests.

4.6 Prediction Comparison

TEP established pre-specified expectations and theoretical search ranges before the GNSS analysis was conducted: the framework was first deposited in August 2025 (Smawfield 2025a, v0.1) and the clock-network correlation forecast was versioned on 15 September 2025 (v0.4 §E), preceding the first public deposit of the GNSS analysis by one week (provenance register, Section 6.5). Table 5 compares these forecasts to observations.

Table 5. Comparison of TEP pre-specified expectations with GNSS observations.

Prediction	Forecast	Observed	Status
Correlation length (screening- parameterized forecast)	2,000–3,000 km	$3,210 \pm 389$ km (azimuth-averaged); IGS-final 3,330–4,549 km	Not met: observed scale lies above the band
Correlation length (search range)	1,000–10,000 km	$4,201 \pm 1,967$ km (sector dispersion)	Consistent; non-discriminating (range subsumes leading systematic scales)
Spatial decay form	Exponential; Gaussian-family preference would disfavour the screened-field reading (Paper 1, criterion iii)	Gaussian/squared-exponential preferred; exponential $\Delta AIC =$ $+12.8$; power law $\Delta AIC > 30$	Met in Paper 1; not met in the 25- year dataset
Multi-centre consistency	$< 5\%$ variation in fitted parameters	CV of $\lambda \approx 13\%$ across three centre exponential fits	Not met
Velocity-dependent anisotropy	Modulates with v/c	$r = -0.888$ (3.65σ , autocorr.- corrected)	Consistent in sign (pre-stated in Paper 1 v0.6a); coupling magnitude not derived in the current framework
Geometric alignment	EW $>$ NS in ecliptic frame	EW/NS = 2.16	Consistent
Broadband coupling	Not frequency-selective	Detected across 10–500 μHz	Consistent
Annual-phase direction recovery	Orbital-phase modulation	RA = 6° , Dec = $+4^\circ$; $\sim 6^\circ$ from aphelion velocity tangent; CMB apex anti-phase	Consistent with orbital-phase channel; no CMB-frame identification
GM/ r^2 and GM/ r^3 scaling	Both absent (filtered)	No force or tidal scaling ($p > 0.5$)	Null confirmed

The null prediction regarding GM/ r^2 scaling is particularly discriminating. Classical tidal forcing would produce mass-dependent signatures scaling with GM/ r^3 , with Mercury contributing far less than Jupiter. The observed absence of such scaling (all $p > 0.5$ across multiple metrics) persists across both CODE network-adjusted products and raw RINEX data processed with RTKLIB Single Point Positioning. Since SPP processes each station independently without network adjustment or common-mode filtering, the persistence of the null in SPP data rules out the hypothesis that the absence of mass scaling is merely a processing artifact. The TEP

coupling appears to be intrinsically geometric rather than energetic—responding to alignment configuration regardless of mass. Mercury (42.5% detection rate) produces comparable responses to Jupiter (34.8%) despite $\sim 10^6\times$ smaller gravitational influence, consistent with a threshold-dependent or alignment-driven mechanism rather than continuous force scaling.

4.7 Why Existing Tests Do Not Directly Test the Target TEP Observables

Existing precision tests probe different observables than TEP's primary signatures, as summarized in Table 6.

Table 6. Why existing precision tests do not constrain TEP.

Test	Observable	Reason TEP Is Unconstrained
GW170817	$ c_\gamma - c_g /c$	Constrains disformal $B(\phi)$, not conformal $A(\phi)$
Cassini (PPN- γ)	Two-way Shapiro delay	Reciprocity-even; does not bound loop holonomy; samples screened solar-vicinity regime
Resonator MM/KT	Closed-path anisotropy	Even-parity; blind to one-way non-reciprocity
GPS operation	Internal consistency	Uses explicit GR+Sagnac modeling; verifies model
Clock redshift tests	Pairwise comparisons	Confirms GR locally; closed loops required

The critical distinction is that existing tests probe two-way or pairwise measurements, whereas TEP's holonomy is a closed-loop, one-way observable to which these tests are structurally blind. Two-way measurements probe reciprocal paths where holonomy cancels by symmetry; pairwise clock comparisons measure local potential differences but cannot detect non-integrability, which requires closed loops. TEP effects are therefore structurally invisible to these geometries, explaining why decades of precision tests found nothing amiss while the signal was present in GNSS residuals.

Operational Measurement Protocol: What Existing Tests Probe

The distinction between observables that constrain TEP and those that do not can be formalized through the synchronization holonomy (after GR subtraction), where σ is the time-transport one-form whose line integral equals the calibrated proper-time increment along a leg:

$$\mathcal{H}_{\text{resid}} = \oint_{\partial\Sigma} (\tilde{\sigma} - \sigma_{\text{GR}}) = \iint_{\Sigma} (\tilde{F} - F_{\text{GR}})$$

This represents the loop non-closure of time transport built from measured proper times (in time units; right-hand rule on Σ). It is gauge and synchronization-invariant and vanishes in standard relativity and in the conformal-only limit of TEP. GR subtraction includes Sagnac, Lense-Thirring gravito-magnetic effects, Shapiro delay, and gravitational redshift, with ITRF ephemerides and TT/TDB standards.

How flagship constraints map to $\mathcal{H}_{\text{resid}}$:

- GW170817 (GW-EM coincidence): $|c_\gamma - c_g|/c \lesssim 10^{-15}$ constrains global cone splits. In TEP, late-time conformal coupling preserves null cones, so electromagnetic and gravitational waves share causal structure; small disformal tilts today are allowed. This is a boundary condition, not a loop-holonomy test.
- Cassini (PPN- γ): Two-way Doppler/Shapiro is reciprocity-even; it calibrates σ_{GR} to subtract but does not bound $\mathcal{H}_{\text{resid}}$. The measurement was performed during solar conjunction, sampling the Sun's deep potential well—the screened regime where the source-charge sector S_Σ is suppressed. The bound therefore applies to the solar-vicinity environment, not to the dilute regimes where Temporal Shear recovers.
- Resonator MM/KT tests: Cavities bound closed-path, even-parity (two-way sums) anisotropy at 10^{-17} – 10^{-18} , yet are blind to odd-parity (direction-reversing one-way differences) non-reciprocity and loop non-closure—the ingredients of $\mathcal{H}_{\text{resid}}$.
- GPS operation: Network self-consistency uses explicit GR+Sagnac modeling and largely two-way/common-view calibration. This verifies internal consistency under the assumed GR model; it is not a direction-reversing one-way loop-closure null.
- Clock redshift and pairwise $A \leftrightarrow B$ tests: Exquisitely confirm GR locally; only closed loops ($A \rightarrow B \rightarrow C \rightarrow A$ with direction reversal) can reveal non-integrability captured by $\mathcal{H}_{\text{resid}}$.

Why classical tests can be null while $\mathcal{H}_{\text{resid}} \neq 0$: (1) Conformal null-cone invariance implies no large GW-EM kinematic delays (consistent with GW170817). (2) If $\partial_t \phi = 0$ over loop timescale and gradients are conservative, there is no first-order one-way anisotropy. Along a fixed path, forward and backward times cancel at order $(B, \nabla \phi)$; leading effects are second order or require time dependence and kinematics. Thus two-way and closed-path nulls can hold while a loop-holonomy test remains sensitive.

Experimental falsifier (primary endpoints): Run a closed-loop, one-way time-transfer (and/or portable-clock) test and report: (1) Leg-wise antisymmetry: $\Delta t_{AB} = t_{AB} - t_{BA}$ (and optionally $\Xi_{AB} \equiv (t_{AB} - t_{BA})/(t_{AB} + t_{BA})$). (2) Loop holonomy $\mathcal{H}_{\text{resid}}$ after subtracting GR (Sagnac/gravito-magnetic/Shapiro). Use triangle/quadrilateral geometries with direction reversal; extend with interplanetary one-way links and multi-species clock networks.

4.7.1 Compatibility with Binary Pulsar Timing and Lunar Laser Ranging

Two high-precision tests warrant explicit discussion: binary pulsar timing (PSR J0737-3039, testing GR to 0.05%) and Lunar Laser Ranging (testing the equivalence principle to 10^{-13}). Both are compatible with TEP through screening and universal coupling.

Binary Pulsar Timing: The Hulse-Taylor pulsar PSR B1913+16 and the double pulsar PSR J0737-3039 provide exquisite tests of general relativity through orbital decay measurements. The observed orbital period derivatives match GR predictions to better than 0.05%, constraining deviations in the strong-field regime. TEP compatibility requires that scalar field effects are screened in the vicinity of neutron stars.

The TEP saturation radius for a neutron star ($M \sim 1.4 M_{\odot}$) is:

$$R_T^{\text{NS}} = \left(\frac{3M_{\text{NS}}}{4\pi\rho_T} \right)^{1/3} \sim 3.2 \times 10^5 \text{ km}$$

This saturation radius far exceeds the neutron star radius ($R_{\text{NS}} \sim 10 \text{ km}$). Binary pulsar timing, however, probes the gravitational sector (metric $g_{\mu\nu}$), not the clock sector (metric $\tilde{g}_{\mu\nu}$). The scalar field's effect on $g_{\mu\nu}$ is second-order in the coupling, proportional to $(\nabla\phi)^2/c^4$, which at orbital distances ($a \sim 10^6 \text{ km}$) from a $1.4 M_{\odot}$ neutron star gives a fractional effect below 10^{-30} — far below the 0.05% observational precision of binary pulsar tests. The two-metric structure allows the gravitational dynamics to remain GR-like while clock rates exhibit conformal modulation—these are distinct observables probing different sectors of the theory. Binary pulsar insensitivity to the conformal coupling that generates GNSS correlations is therefore a consequence of the two-metric structure, not of the screening radius.

Critically, pulsar timing measures orbital dynamics (gravitational sector, metric $g_{\mu\nu}$), not clock correlations (matter sector, metric $\tilde{g}_{\mu\nu}$). The two-metric structure allows the gravitational dynamics to remain GR-like while clock rates exhibit conformal modulation—these are distinct observables probing different sectors of the theory.

Lunar Laser Ranging: LLR measures the Earth-Moon distance to millimeter precision, testing the equivalence principle through the Nordtvedt parameter η . The current bound $\eta < 4.4 \times 10^{-4}$ constrains deviations from the strong equivalence principle. TEP satisfies this constraint through universal coupling: the conformal factor $A(\phi)$ couples identically to all matter fields, preserving the equivalence principle in the matter frame.

The key distinction is between weak and strong equivalence principles. The weak EP (universality of free fall for test masses) is preserved exactly in TEP because all matter couples to the same metric $\tilde{g}_{\mu\nu}$. The strong EP (self-gravitating bodies fall identically to test masses) can show deviations in scalar-tensor theories through composition-dependent couplings. However, TEP's universal conformal coupling ensures that the Nordtvedt parameter:

$$\eta = 4\beta_{\text{PPN}} - \gamma - 3$$

remains within observational bounds. The PPN nonlinearity parameter β_{PPN} is driven to its GR value $\beta_{\text{PPN}} \rightarrow 1$ by the TEP screening operator, where the pairwise response is suppressed by the kinetic operator ($S_{\Sigma}(g_{\text{lunar}}) \approx 1.6 \times 10^{-14}$; Paper 0 §2.2). With $\gamma \approx 1$ (Cassini constraint), the predicted Nordtvedt parameter is well below the LLR bound. The predicted metric deviation applies to the gravitational sector, preserving the Strong Equivalence Principle. The $\sim 10^{-4}$ synodic-phase anomaly reported in Paper 17 is an empirical matter-frame clock residual (κ_{LLR}), not a classical Nordtvedt metric violation.

Furthermore, the Earth-Moon separation lies in the deeply suppressed regime of the pairwise Temporal-Topology response $\mathcal{S}_{\text{eff}}(s)$: the scalar-mediated Earth-Moon differential acceleration is suppressed by pairwise response factors of order 2.5×10^{-14} relative to the unsuppressed coupling (Paper 0, screening operator), comfortably below the LLR bound. The suppression acts on the shear sector ($\mathcal{S}_{\Sigma}$) — the geodesic and force projection — while each body's clock-amplitude coupling ($\mathcal{S}_A$) remains unsuppressed. The combination of universal coupling and sector-separated screening ensures LLR compatibility while preserving the GNSS clock-covariance signal in the terrestrial environment.

4.8 Relation to Established Scalar-Tensor Theory

In the canonical non-screened limit, TEP shares structural similarities with scalar-tensor theories, but its physical realization is defined by the non-canonical kinetic sector $P(X, \phi) = X - V + X|X|/\Lambda_X^4$ and universal matter-metric coupling. In the limit $B = 0$, $V = 0$, $\Lambda_X \rightarrow \infty$, TEP with $A(\phi) = \exp(\beta_A \phi/M_{\text{Pl}})$ reduces to Brans-Dicke gravity in the Jordan frame, with the coupling β_A related to the Brans-Dicke parameter ω_{BD} . However, the full TEP framework requires disformal or otherwise non-exact transport for the synchronization holonomy observable (Section 4.6); the $B = 0$ case is a limiting benchmark, not the operative theory. In the master TEP framework, screening is realized through the non-canonical kinetic operator, separating the conformal clock response S_A from the environmental source-charge projection S_Σ (Paper 0 §2.2). TEP's environmental screening operates through kinetic derivative self-interactions rather than density-dependent mass. The two-metric structure is philosophically similar to Bekenstein's TeVeS, though TEP is more minimal, employing only a scalar field rather than scalar plus vector.

The novelty of TEP lies not in the field theory but in the observational interpretation—specifically, the recognition that conformal coupling creates spatial correlations in clock rates that standard GNSS processing preserves while filtering amplitude information.

4.9 The Processing Filter Mechanism

A critical insight explains both why the signal was missed for three decades and why it survives in the data. Standard GNSS processing is designed to optimize positioning accuracy by removing correlations, not to characterize them. The processing chain includes network adjustment (which removes common-mode signals), Kalman filtering (which smooths residuals toward zero-mean white noise), reference frame alignment (which forces consistency with ITRF, absorbing systematic offsets), and outlier rejection (which discards data points deviating from expected behavior).

This architecture creates a natural filter: energetic (common-mode) signals are suppressed while geometric (differential) signals are preserved. Classical gravitational effects manifest as common-mode offsets—all clocks in a region experience similar tidal acceleration—and are therefore filtered. The TEP signal, by contrast, manifests as differential phase structure—the correlation between clock pairs depends on their geometric relationship—and is therefore preserved.

This mechanism implies: GM/r^2 scaling should be absent in processed data because it is common-mode, while geometric signatures (anisotropy, preferred-direction structure) should survive because they are differential. The observations are consistent with both expectations. The processing filter is not a bug but a feature: it explains why the signal was categorized as systematic error rather than physical phenomenon, and why it can now be detected by examining the residuals that standard processing discards.

4.9.1 Mathematical Demonstration of Filter Selectivity

The processing filter mechanism can be demonstrated mathematically by decomposing clock residuals into common-mode and differential components. Consider a network of N stations with clock residuals $\delta t_i(t)$ after initial processing. Standard GNSS processing applies a datum constraint that forces residuals to have zero spatial mean, removing common-mode offsets. In Fourier space, this constraint eliminates the $k = 0$ (monopole) component while preserving all $k \neq 0$ (dipole, quadrupole, and higher) components that have zero spatial mean.

Classical gravitational effects manifest as either GM/r^2 (force) or GM/r^3 (tidal gradient) scaling. Tidal effects are $k \approx 2$ (quadrupole) in spherical harmonic decomposition. However, standard GNSS processing explicitly models and subtracts known tidal terms (solid Earth tides, ocean loading, pole tide) using IERS conventions with sub-millimeter precision. The datum constraint removes residual common-mode offsets, while explicit tidal modeling eliminates the structured quadrupole components.

The TEP signal survives not merely because it is differential ($k \neq 0$), but because it represents an unmodeled scalar correlation function with exponential spatial form $C(r) \propto \exp(-r/\lambda)$. This functional form does not match the spherical harmonic basis (Y_{lm}) used in standard tidal modeling. Tidal corrections are parameterized as sums of spherical harmonics with known frequencies (diurnal, semidiurnal, long-period); the TEP correlation is a distance-dependent phase coherence that is not decomposable into the standard tidal basis. The processing removes what it models (tidal harmonics) but preserves what it does not model (exponential distance correlations in phase space).

The TEP correlation structure manifests as phase coherence between station pairs. The analysis uses cross-spectral methods that are invariant under common-mode amplitude rescaling because they depend only on relative phases, not absolute amplitudes. The datum constraint removes monopole amplitude information but preserves the phase structure encoded in higher-order spatial modes. The exponential decay $C(r) \propto \exp(-r/\lambda)$ reflects the two-point correlation function of the underlying ϕ field, which has nonzero spatial gradients and therefore survives network adjustment. (Detailed mathematical formulation is provided in Appendix B.)

Expectation Verification: This mathematical framework yields two testable expectations, both consistent with observations:

- **Null Prediction:** Classical gravitational effects (GM/r^2 force and GM/r^3 tidal gradient) should be absent in processed data because they are predominantly $k = 0$ and $k \approx 0$ (long-wavelength) modes that the datum constraint removes. Observed: Neither GM/r^2 nor GM/r^3 scaling detected (all $p > 0.5$).
- **Positive Prediction:** Geometric anisotropy (EW/NS ratio) should survive because it represents a $k \neq 0$ quadrupole moment with zero spatial mean but nonzero phase structure. Observed: EW/NS = 2.16 detected at $p < 10^{-15}$.

The persistence of both predictions in raw RINEX data processed with Single Point Positioning (which applies no network adjustment) confirms that the filter mechanism is a property of the signal's spatial structure, not an artifact of CODE/IGS processing algorithms.

4.10 Systematic Error Budget for Triangle Test

For the proposed triangle holonomy test to achieve definitive discrimination, systematic errors must be controlled below the target sensitivity of 10^{-19} fractional. Table 7 presents the error budget.

Table 7. Systematic error budget for the triangle holonomy test.

Systematic	Mitigation	Residual
Sagnac (Earth rotation)	IERS Earth orientation parameters	$\leq 10^{-21}$
Shapiro (GR potentials)	Precise ephemerides + atmospheric models	$\leq 3 \times 10^{-20}$
Troposphere/ionosphere	Dual-frequency + water vapor radiometry	$\leq 5 \times 10^{-20}$
Fiber dispersion	Bidirectional calibration + thermal control	$\leq 5 \times 10^{-20}$
Link noise + clock instability	Optical clocks + day averaging	$\leq 3 \times 10^{-19}$
Total budget		$\leq 1 \times 10^{-19}$

For parameters saturating current bounds, the predicted signal is $H/T_{\text{loop}} \sim 10^{-16}\text{--}10^{-18}$. The error budget demonstrates that a definitive test is achievable with current technology.

5. Consistency with Cosmological Phenomenology

Epistemic Status

The following section does not constitute an independent detection of cosmological effects. Instead, it addresses the question: if the terrestrial clock correlations reported in Sections 2–4 arise from a conformally coupled scalar field (whether screened via continuous gradient flattening or derivative completions), then what are the necessary consequences for astrophysical observations that already exist? The empirical GNSS result stands independently of the validity of this extension.

This section examines how the same scalar field producing $\lambda \approx 4,000$ km correlations on Earth bears on gravitational lensing observables. The optical channels bounded in the tested Paper 19 configuration are scalar backreaction at $\kappa_\phi \sim 10^{-5}$ for the SN Refsdal benchmark and the disformal transport term; the dynamical discriminant is the dynamical–lensing mass difference produced by active Temporal Shear. A source-independent CDM-free lensing potential remains a separate calculation. The framework yields testable expectations that may provide discriminators between particulate dark matter and conformal time-field interpretations at astrophysical scales.

Within the TEP framework, the same Temporal Topology field ϕ that modulates clock correlations on Earth structures the temporal response of matter across cosmological distances. The canonical TEP transition scale $R_T = (3M/4\pi\rho_T)^{1/3}$, set by the environmental screening density ρ_T , connects terrestrial and astrophysical scales. The measured GNSS correlation-length family (azimuth-averaged $\lambda = 3,210 \pm 389$ km; cross-sector dispersion $\lambda_T = 4,201 \pm 1,967$ km) is interpreted as a characteristic empirical scale of the clock-sector covariance C_A in Earth's environment, compared with the Earth-calibrated R_T scale (Paper 0 §7). At galactic scales, the distinct shear response can be active in low-acceleration environments where $S_\Sigma \approx 0.98$. The galactic ~ 50 kpc phenomenology concerns that weak-field dynamical regime, not an extrapolation of the GNSS covariance length or a common screening radius. The terrestrial and galactic observations are interpreted within the same environmental-response architecture; Papers 4 and 13 test distinct optical and dynamical projections of that architecture. Paper 4 identifies the dynamical–lensing mass difference as the phantom-mass consistency test; Paper 13 reports a SPARC-anchored wide-binary transition at $R_s \approx 2,646 \pm 182$ AU. Neither supplies a derived quantitative mapping from terrestrial C_A to galactic shear.

5.1 GW170817 Constraints

The simultaneous detection of gravitational waves (GW170817) and gamma rays (GRB 170817A) from a binary neutron star merger at approximately 40 Mpc is widely cited as constraining modified gravity theories. The signals arrived within $\Delta t = 1.74 \pm 0.05$ seconds after traveling some 130 million years, yielding:

$$\frac{|c_\gamma - c_g|}{c} \lesssim 10^{-15}$$

This constraint is often interpreted as ruling out theories in which light and gravity propagate differently. However, this interpretation conflates two distinct effects that must be carefully distinguished.

The disformal sector $B(\phi)$ tilts light cones, causing $c_\gamma \neq c_g$, and is indeed tightly constrained by GW170817. The conformal sector $A(\phi)$, by contrast, rescales proper time isotropically: photons and gravitational waves share the same null geodesic and experience identical time dilation. Because both messengers originated from the same coordinate and traversed the same path through the scalar field, any conformal time dilation is common-mode and cancels in the differential measurement. GW170817 therefore constrains cone tilting but remains blind to clock-rate modulation. The dark matter phenomenology in TEP arises from the Temporal Shear acting on matter trajectories — the channel to which multi-messenger tests and static image-plane geometry are both blind — rather than from null-ray deflection, which the conformal sector leaves unmodified.

This can be seen explicitly in the conformal metric limit ($B = 0$):

$$ds^2 = A^2(\phi)g_{\mu\nu}dx^\mu dx^\nu = 0$$

Since $A(\phi)$ is an overall prefactor, the null condition $ds^2 = 0$ is identical for both the matter metric $\tilde{g}_{\mu\nu}$ (governing photons) and the gravitational metric $g_{\mu\nu}$ (governing gravitational waves). Their null cones coincide exactly: $c_\gamma = c_g = c$ locally. The conformal factor therefore produces no direct same-path propagation delay; its observable effect is carried by proper-time and clock-rate mapping, while differential cone propagation belongs to the disformal sector.

5.2 The Isochrony Axiom and Observational Degeneracy

Standard gravitational lensing analysis assumes that all photons in a lensed image represent a synchronous snapshot of the source. This Isochrony Axiom—the assumption that differential time delays arise solely from geometric path length differences (Fermat potential), not from temporal-field gradients along the paths—is implicit in the lens equation and has never been empirically tested at the precision required to distinguish these scenarios.

Within the TEP framework, this axiom would generically fail in the presence of conformal metric couplings. Photons themselves accumulate no proper time ($d\tau_\gamma = 0$) and conformal factors produce no additional same-path propagation delay; what varies is the matter-clock rate. Signals emitted from regions sampling different temporal-field values $\phi(x)$ are referenced to matter clocks that accumulate proper time at different rates, so the measured source-to-observer timing relation contains the standard geometric/Fermat delay together with the source- and observer-clock mapping determined by the temporal field — an endpoint and reconstruction contribution, not an additional conformal photon transit delay. For an evolving source, the resulting differential emission-time structure can survive into the reconstructed image, creating an observational degeneracy with particulate dark matter under standard analysis assumptions:

Consider two interpretations of the same Fermat potential surface. Under the standard interpretation, which assumes isochrony, an Einstein ring with apparent convergence κ_{obs} exceeding baryonic mass implies a dark matter halo with $M_{\text{DM}} = M_{\text{obs}} - M_{\text{baryons}}$. Under the TEP interpretation, which rejects isochrony, the observed image is a temporal composite: photons arriving simultaneously left the source at different epochs. For evolving sources, this temporal depth projects onto the image plane as apparent spatial distortion—apparent mass that does not correspond to matter. The channel is bounded: it vanishes identically for static sources and is limited to $\lesssim 10^{-7}$ in shear for galaxy sources by the ratio of differential delay to source-evolution time (Paper 4), so it cannot account for the static-source lensing excess.

The degeneracy is therefore bounded and source-dependent, not a free reinterpretation: for static sources the two frameworks make different predictions, with the TEP dark-sector signature living in the dynamical sector — the dynamical–lensing mass difference — rather than in the lensed image itself.

5.3 Phantom Mass

Within a two-metric framework where the Isochrony Axiom breaks down, a mechanism for apparent dark matter emerges naturally. Phantom Mass is the observational projection of dynamical temporal geometry: spatial variation of the conformal time field changes the source–lens–observer temporal mapping and the proper-time histories of the emitting regions that different image paths sample. Standard isochronous reconstruction maps this temporal structure onto an apparent spatial mass distribution. Genuine cone-tilting propagation terms belong to the disformal sector. Phantom mass has two routes: this reconstruction channel, which requires an

evolving source and vanishes for static sources, and the dynamical channel — the Temporal Shear's direct effect on matter trajectories — which carries the dark-sector claim and is tested by the dynamical–lensing mass difference (Papers 4, 19).

For an evolving source, this temporal-structure difference creates a temporal composite image: photons arriving simultaneously at the detector left the source at different epochs. Standard lens reconstruction, which assumes isochrony, interprets this temporal smearing as spatial distortion—apparent mass that does not exist.

The amplification matrix in TEP decomposes as:

$$\mathcal{A}_{ij} = \underbrace{\mathcal{A}_{ij}^{\text{GR}}}_{\text{Baryonic}} + \underbrace{\mathcal{A}_{ij}^{(g[\phi],\text{static})}}_{\text{bounded optical}} + \underbrace{\mathcal{A}_{ij}^{(\text{dyn})}}_{\text{Shear Noise}}$$

Standard analyses attribute the sum of the first two terms to total mass. TEP identifies the second term as a bounded optical contribution — scalar backreaction on the Einstein-frame metric ($\kappa_\phi \approx 4 \times 10^{-5}$, $\sim 2 \times 10^3$ below dark-matter level) plus the disformal null-cone tilt ($\lesssim \frac{1}{5}$ of the Refsdal residual under the measured deprojection; Paper 19, Steps 61–63) — rather than particulate matter. Phantom mass itself is not an amplification-matrix term: it enters the dynamical sector, and the dynamical–lensing mass difference is its observable signature.

5.3.1 Static versus Dynamic Time Delays

Observed strong-lens time delays (day-to-month scale, e.g., SN Refsdal $\Delta t \sim 1$ year between images) are set by the propagated Fermat structure; the halo-scale temporal field enters the inference not through the measured delay itself but through the reconstructed lens model. The distinction resolves through two complementary mechanisms.

Mechanism 1: Static versus Dynamic Decomposition — The amplification matrix decomposition (Equation above) separates temporal effects into distinct components with different observational signatures:

- **Static Temporal Structure ($\mathcal{A}^{(g[\phi],\text{static})}$):** The scalar's gravitational backreaction on $g_{\mu\nu}$ contributes real, structured curvature on halo scales — bounded at $\kappa_\phi \sim 10^{-5}$, about 2×10^3 below dark-matter level (Paper 19, Step 61) — a smooth field on the image plane whose Hessian an isochronous reconstruction absorbs into the inferred convergence κ , with the mean level entering the mass-sheet normalization. The conformal clock-transfer map $\Delta\tilde{\tau}(\theta) = c^{-1} \int (A(\phi) - 1) d\ell$ is the companion reconstruction-space field the lens model would misassign to convergence or delay calibration; it carries no propagated photon content: null cones are conformally invariant and the Temporal Shear one-form is exact, so the open-path integral is endpoint-determined and the exact static-conformal inter-image residual is 0.0 d (Paper 19, step_56).
- **Source-evolution response ($\mathcal{A}^{(\text{dyn})}$):** The gradient of the delay field $\nabla(\Delta\tilde{\tau})$ creates differential emission-time structure that depends on the ray's impact parameter and the source's evolutionary state. This is an endpoint-sector effect — it acts on the moving source's own clock/emission mapping (the temporal-composite response of Paper 4), not on photon propagation, so it inherits neither the conformal exact-one-form cancellation nor the disformal ≤ 0.2 s bound. For transient sources with variability timescale t_{var} , the dynamic contribution scales as $\Delta\tau_{\text{dynamic}} \sim \nabla(\Delta\tilde{\tau}) \times v_{\text{source}} \times t_{\text{var}}$, where v_{source} is the source's proper motion or internal velocity field.

Observational Consequence: Time delays measured between multiple images of transient events (supernovae, AGN flares) are governed by the propagating carriers: the standard Fermat potential plus the disformal multipath deformation, bounded by GW170817 to ≤ 0.2 s per 2 Mpc halo path — far below any measured lens delay. The halo-scale temporal-depth field contributes no propagated delay residual; its observable imprint enters instead through the mass reconstruction, where the unmodeled image-plane structure is absorbed as convergence.

Mechanism 2: Screening Locality — The Temporal Topology field ϕ varies significantly only within the region where Temporal Shear is non-negligible, bounded roughly by the TEP transition scale $R_T \sim 100$ kpc around the lens galaxy, where the environmental screening operator $S_\Sigma(\mathcal{E})$ transitions from the suppressed to the unscreened regime. Beyond this radius, Temporal Topology flattens to its cosmological value, $\phi \rightarrow \phi_0$, and temporal-structure signatures cease accumulating. The integration path for the temporal-depth scale is therefore limited to the halo depth $L_{\text{halo}} \sim 2$ Mpc (the physical extent of the dark matter halo), not the full cosmological distance $D_L \sim \text{Gpc}$ to the source. This locality ensures that the static temporal-depth scale remains far smaller than the cosmological light-travel time $D_L/c \sim 10^9$ years.

$$\Delta\tau_{\text{depth}} \sim \frac{\epsilon}{2} \frac{L_{\text{halo}}}{c} \quad (\text{not } \frac{D_L}{c} \sim 10^9 \text{ years})$$

Testable Expectation for Time-Delay Cosmography: TEP implies a systematic offset in H_0 measurements from time-delay cosmography, but through the mass-inference channel, not the image plane. The unmodelled temporal field enters neither the delay numerator — the propagated conformal residual is zero — nor the reconstructed potential: the scalar-backreaction and disformal image-plane channels are bounded far below dark-matter level (Paper 19, Steps 56, 61, 63), so no phantom convergence is available to inflate $\Delta\Phi$. What the temporal field modifies is the *dynamical* input by which the mass-sheet degeneracy may be broken: TDCOSMO-style analyses anchor the lens model with the galaxy's stellar velocity dispersion. Paper 4 identifies a dynamical–lensing mass difference as a test of active Temporal Shear; Paper 19 evaluates delay-blind implied phantom fractions in several lenses. Neither result derives a universal conversion from the source-screening fraction S_Σ to a stellar-dynamical mass bias and then to a fitted H_0 shift. In particular, the PPN photon–source product $\alpha_0\alpha_{\text{eff}}$ does not by itself establish the two-matter-body dynamical response at a lens aperture.

The kinematic apertures of galaxy-scale lenses probe accelerations of order 10^{-9} – 10^{-8} m/s², above the transition scale $g_t \approx 3.4 \times 10^{-10}$ m/s². A time-delay prediction therefore requires the pairwise shear response, the stellar-orbit projection and a lens-model mass-sheet refit for each system. A numerical H_0 offset cannot be inferred solely from the aperture screening factor; the delay-blind contrasts in Paper 19 are empirical tests of the proposed phantom-mass interpretation of the delay residual rather than a calibrated correction to H0LiCOW.

Falsification Test: If TEP is correct, time-delay cosmography measurements should show systematic residuals correlated with the acceleration at the lens's kinematic aperture relative to g_t , after controlling for halo mass, velocity dispersion and mass-model systematics. Analysis of the H0LiCOW and TDCOSMO samples stratified by a_{ap}/g_t should reveal this correlation if the phantom-mass channel is operative; a clean null across lenses whose apertures approach g_t would bound the channel. A first pass already exists in Paper 19's delay-blind phantom-mass analysis (step_60): implied phantom fractions are positive across all non-zero contrasts — $\lambda = +8.7 \pm 2.6\%$ (Refsdal SX:S1), $+9.1 \pm 5.8\%$ (Encore), $+9.5 \pm 4.8\%$ (H0pe AB), with a archived diagonal-weight mean fractional delay residual of $+7.8 \pm 2.0\%$ ($\chi^2 = 2.06/3$ dof; not a covariance-calibrated phantom-mass detection) — marginally above the mundane κ_{ext} floor and in the predicted sign, though not yet σ_v -stratified.

5.4 The Variability-Mass Correlation

A critical discriminator between TEP and standard dark matter emerges from the dynamic term in the amplification matrix. Because the stochastic shear contribution depends on source proper motion μ_s through the delay gradient, the inferred lens mass should correlate with source variability timescale. Physical lens mass is source-independent in the standard model, but source variability and time delays can also bias standard reconstructions. The discriminant is therefore the residual beyond that baseline, not the existence of a variability correlation alone (Paper 4, Regime II).

Specifically, lenses observed through rapidly variable sources (AGN, quasars) should show systematically different mass reconstructions than the same lenses observed through slowly evolving sources (elliptical galaxies). The amplitude and sign require the measured source variability, ordinary Fermat delays and reconstruction transfer; no universal percentage mass offset is supplied by the existing temporal-composite calculation.

This test can be performed with existing data from HST strong-lens archives and SDSS quasar lenses. A null result bounds the response at the achieved sensitivity; exclusion requires that sensitivity to reach the specified source-dependent prediction. A positive correlation must be tested against source selection, ordinary delay/variability effects and reconstruction systematics before it can discriminate TEP.

5.5 Cross-Scale Dynamics: Saturation vs. Kinetic Transitions

The TEP framework connects terrestrial timing phenomenology with astrophysical and galactic dynamics through two distinct, mathematically grounded scales:

- **The Clock Sector (Geometric Saturation Scale R_T):** For macroscopic bodies of saturation density $\rho_T \approx 20$ g/cm³, the geometric saturation radius follows $R_T(M) = (3M/4\pi\rho_T)^{1/3} \propto M^{1/3}$. Calibrated through Earth's GNSS clock-covariance correlation length ($R_T(M_\oplus) \approx 4,150$ km; Paper 6), this scale fixes the unsaturated clock-amplitude factor $S_A = \min[1, (\rho/\rho_T)^{1/3}] \approx 0.65$ for Earth. It characterizes static clock-sector depth; the measured GNSS covariance $C_A(r)$ and its dynamic environmental and processing transfer are distinct from this static S_A level.
- **The Force / Shear Sector (Kinetic Transition Scale r_*):** For geodesic kinematics, orbital dynamics, and rotation curves, the master kinetic action $P(X,\phi) = X - V + X|X|/\Lambda_X^4$ derives the two-body transition scale directly from first principles:

$$r_*(M) = \sqrt{\frac{GM}{g_t}} \propto M^{1/2}$$

where $g_t = cH_0/(2|\beta_A|) \approx 3.4 \times 10^{-10} \text{ m/s}^2$ with $\Lambda_X = \sqrt{(M_{\text{Pl}} H_0)} \approx 1.9 \text{ meV}$ (Paper 0 §2.2). In high-acceleration regimes ($g \gg g_t$), the kinetic operator suppresses the observable Temporal Shear to $\mathcal{S}_\Sigma \ll 10^{-5}$ (satisfying Cassini and Solar-System ephemeris bounds), while in low-acceleration regimes ($g \ll g_t$) the shear recovers unsuppressed ($\mathcal{S}_\Sigma \rightarrow 1$).

Galactic dark-matter-like phenomenology does *not* represent an $M^{1/3}$ screening radius extrapolated across 15 orders of magnitude. Active Temporal Shear supplies extra matter acceleration, with a threefold unscreened dynamical enhancement under the unit-term branch and mass-inference assumptions of Paper 0 §7. Flat outer rotation curves and baryonic Tully–Fisher scaling are instead obtained in the alternative low-gradient realization already derived and evaluated against SPARC (Paper 6, Steps 10–13). The field-wide-binary transition $R_s \approx 2,646 \text{ AU}$ (Paper 13) tests the pairwise recovery profile; it is not itself a derivation of the galactic outer force law. These results retain their branch and calibration provenance within the common matter-coupling architecture; the two kinetic realizations have not yet been shown to be a single action across local, binary and galactic regimes (Paper 0 §7). Table 8 distinguishes the corresponding responses.

Table 8. Comparison of clock-saturation and kinetic-transition regimes across scales.

Physical Regime	Governing Scale	Scaling Law	Observational Channel	Typical Domain
Clock Sector (Saturation)	$R_T = (3M/4\pi\rho_T)^{1/3}$	$R_T \propto M^{1/3}$	Static conformal-depth calibration (S_A); clock covariance (C_A) measured separately	Planetary bodies: Earth ($R_T \approx 4,150 \text{ km}$)
Kinetic Shear Sector (Two-Body)	$r_* = \sqrt{(GM/g_t)}$	$r_* \propto M^{1/2}$	Geodesics, wide-binary orbital velocity excess	Wide binaries ($R_s \approx 2,646 \text{ AU}$ at $1.24 M_\odot$)
Galactic Halo Regime	Low acceleration ($g \ll g_t$)	Baseline recovery or declared low-gradient realization	Dynamical phantom mass (baseline ceiling 3 under Paper 0 §7); flat-tail rotation curves and BTFR in Paper 6's low-gradient branch	Galactic halos ($r \sim 10\text{--}50 \text{ kpc}$)

This clean bifurcation separates the compact-body clock-amplitude response (S_A) from the dynamical field-gradient recovery (r_*), eliminating the vulnerability of treating GNSS correlation lengths as universal screening thresholds.

5.6 Environmental Cepheid Response and the Hubble Tension

Local distance-ladder measurements and CMB inferences yield different values of H_0 . Paper 11 tests whether an environment-dependent Cepheid response contributes to this discrepancy; its corrected distance-ladder value is conditional on the fitted response and the observing-chain model, not a direct clock-period prediction.

5.6.1 Cepheids as Environmental Clocks

Cepheid pulsation periods are governed by stellar-envelope dynamics in local matter-frame proper time. A direct conformal period shift from host potential alone does not reproduce the measured environmental response after the full matter-frame observing chain is imposed: the bare core-to-disk clock-ratio contribution is bounded well below the fitted Cepheid coefficient (Paper 11, Step 61). Paper 11 instead tests a period-dependent amplitude-sector response with an inferred stellar transport weight; its absolute normalization from a common stellar and ambient-field solution remains outstanding.

5.6.2 Empirical Detection of the Bias

Analysis of the SH0ES Cepheid sample (Paper 11), stratified by host-galaxy potential depth $u_\phi = V_{\text{rot}}/\sqrt{2}$ (a TEP-independent kinematic proxy reconstructed from pinned HyperLEDA rotation velocities), reveals a positive correlation between potential depth and derived H_0 — an environmental ordering tested by Paper 11's revised amplitude-sector response, not a detection of the bare clock-ratio mechanism. Split at the sample median ($u_\phi = 114.6 \text{ km/s}$), the deep-potential subsample yields $H_0 = 68.49 \pm 3.21 \text{ km/s/Mpc}$ against $66.99 \pm 2.50 \text{ km/s/Mpc}$ for the shallow-potential subsample (full host-distance covariance propagated), and the continuous endpoint response $\Gamma_X = (1.156 \pm 0.958) \times 10^7 \text{ km/s/Mpc}$ (1.2σ at the canonical $\sigma_v = 250 \text{ km/s}$ convention; 2.0σ at the $\sigma_v = 150 \text{ km/s}$ sensitivity variant) returns a positive sign in all 37 leave-one-host-out refits. The constraint on κ_{Cep} is set by this environmental slope—a statistic orthogonal to the mean offset that defines the tension—and the procedure is falsifiable on the same data: a flat or opposite-sign slope admits no coefficient that reconciles the corrected value with the early-universe baseline. Two channels outside the Hubble-flow fit provide additional, differently controlled checks rather than a calibration of the absolute response. The Cepheid–TRGB differential on the matched hosts—regressing $\mu_{\text{Cep}} - \mu_{\text{TRGB}}$ against the same environmental coordinate, independent of redshift information—returns $\kappa_{\text{Cep}} = (0.32 \pm 0.39) \times 10^6 \text{ mag}$, a consistent point estimate at presently low significance; and the internal radial P–L gradient within the LMC ($+0.0284 \pm 0.0086 \text{ mag}$, 3.3σ , robust to period and colour matching) propagates through the fitted transfer to the same order of response.

Under Paper 11's fitted environmental response and adopted anchor weights, the model-conditioned correction yields:

$$H_0 = 66.65 \pm 1.58 \text{ km/s/Mpc}$$

The Cepheid host-potential correlation is an empirical environmental result, while its causal normalization remains model-dependent. Paper 11 finds that the bare conformal core-to-disk clock ratio cannot supply the fitted response; the revised amplitude-sector, period-dependent carrier has an inferred transport weight but awaits an absolute stellar/ambient-field normalization. Its corrected local $H_0 = 66.65 \pm 1.58 \text{ km/s/Mpc}$ agrees with the companion TEP-CMB value $66.70 \pm 0.58 \text{ km/s/Mpc}$ at 0.03σ within the framework, not as an independent confirmation of the mechanism. The joint-ladder bookkeeping assigns the fitted response predominantly to the endpoint distance-modulus channel rather than propagation along the Hubble-flow leg (Paper 11, Appendix C.4). The environmental host-level slope is modest at the canonical velocity-scatter convention, and host-uniform shifts can be absorbed into latent distance moduli; the within-host period-coupled term provides a more identifiable test. The corrected value is therefore a conditional inference, not an established resolution of the Hubble tension.

5.7 Observational Predictions

TEP yields testable expectations for existing and near-future observations, summarized in Table 9.

Table 9. Observational predictions of TEP.

Observable	TEP Prediction	Dataset
Lensed quasar time delays	Systematic residuals correlated with halo mass	H0LiCOW, TDCOSMO
Galaxy rotation curves	$r_* \propto M^{1/2}$ fixes the kinetic transition, not outer flatness; the flat-tail/BTFR prediction is evaluated under Paper 6's low-gradient branch. Geometric saturation remains $R_T \propto M^{1/3}$.	SPARC, THINGS
Weak lensing S_8	No universal sign fixed by the source-dependent covariance channel; the implemented HC posterior is above DES-Y3/KiDS-1000 and is a live diagnostic	DES, KiDS, HSC vs. Planck
Strong lens mass-variability	Source-dependent reconstruction residual; amplitude set by the measured transfer	SLACS, BELLS
FRB lensing residuals	Achromatic delays 0.1–10 ms	CHIME/FRB repeaters

These predictions are falsifiable within 2–5 years using archival data and ongoing surveys. A single null result does not exclude TEP, but a pattern of null results across all five observables would constitute strong evidence against the framework.

5.8 Connection to Cosmological Tensions

TEP offers potential resolution to persistent tensions in precision cosmology.

Regarding the H_0 tension: time-delay cosmography assumes standard GR time transport. If TEP's temporal structure contributes to lens delays, the inferred H_0 would be biased, potentially explaining why independent time-delay lensing measurements falsely agree with the uncorrected distance ladder, rather than tracking the true CMB value.

Regarding the S_8 tension: galaxy sources can carry additional source-dependent reconstruction covariance absent from the CMB source-evolution channel. Paper 4 bounds this temporal-composite contribution far below the percent-level mean-amplitude discrepancy; it does not explain the observed S_8 offset. The TEP-HC weak-lensing comparison is a live tension under a CDM-containing likelihood, not a CDM-free resolution. A CDM-free prediction of the source-independent CMB and galaxy lensing potentials remains required.

The source-class dependence is a bounded prediction to test against ordinary reconstruction and selection effects; it is not a demonstrated explanation of the mean S_8 discrepancy or CMB deflection.

5.9 Relation to Λ CDM

The standard Λ CDM cosmological model fits observational data with remarkable precision. This framework attributes gravitational lensing anomalies to cold dark matter particles and explains cosmological structure formation through hierarchical assembly of particulate halos. Λ CDM is empirically successful and theoretically well-motivated.

TEP treats Λ CDM as the successful control reconstruction, not as the final ontology. In the TEP interpretation, particulate dark matter and dark energy are not fundamental ingredients; they are effective labels produced when temporal shear, temporal topology, and screening structure are compressed into an isochronous FLRW reconstruction. The key distinction is therefore ontological, while many current static-source observables remain operationally degenerate:

- **Λ CDM interpretation:** Gravitational lensing mass reconstructions directly measure matter distribution. Excess convergence beyond baryonic mass indicates particulate dark matter with density profile $\rho_{\text{DM}}(r)$. The cosmological constant or dark-energy sector supplies late-time acceleration. The Isochrony Axiom (all photons in an image represent a synchronous snapshot) is implicitly assumed and never tested.
- **TEP interpretation:** Gravitational lensing mass reconstructions measure the effective Fermat potential, sourced by the true gravitating mass — null curves are conformally invariant (Paper 0, Appendix A2), so the conformal sector contributes neither deflection nor propagated delay, and static image-plane geometry is identical to GR. Temporal structure enters instead through the measurement chain: source- and observer-clock mappings, and for evolving sources the emission-time structure folded into reconstruction (bounded at $\leq 10^{-7}$ in shear for galaxy sources; Paper 4). The dark-sector signature is the dynamical–lensing mass difference — the phantom mass appearing in dynamics where the Temporal Shear is active — while apparent dark energy arises from reconstructing non-integrable temporal transport as a global acceleration term.

Both frameworks fit existing lensing data because they make identical predictions for static sources: the conformal sector supplies no propagated content, and the bounded channels — scalar backreaction and disformal transport — sit far below the lensing excess (Paper 19). The degeneracy is broken by observations that probe temporal structure or dynamical inference:

- **Lensed fast radio bursts:** Λ CDM predicts achromatic residuals (after plasma correction) consistent with zero. TEP predicts achromatic residuals at the 0.1–10 ms level arising from the disformal transport sector — the bounded non-exact channel, not conformal path accumulation (Section 5.4).
- **Variable source lensing:** Λ CDM predicts inferred lens mass is independent of source variability timescale. TEP predicts systematic correlation between inferred mass and source variability, with AGN showing higher apparent mass than elliptical galaxies for the same lens (Section 5.4).
- **CMB vs. galaxy lensing S_8 :** Λ CDM predicts convergence of CMB-inferred and galaxy-inferred S_8 as systematics are controlled. TEP's bounded source-evolution channel predicts survey-dependent covariance, but not the observed mean offset; the implemented Paper 18 posterior lies above DES-Y3/KiDS-1000 under a CDM-containing likelihood, so the current difference is a live tension rather than an established TEP explanation.

The frameworks compete at the level of ontology. Λ CDM remains the default control model given its theoretical maturity and empirical success, but TEP denies that the dark sector is fundamental. TEP becomes distinguishable through specific tests designed to probe temporal structure in lensing observations. Independent of the cosmological extension, the terrestrial GNSS correlation structure documented in Sections 2–4 requires explanation within any framework.

Falsification asymmetry: Null results in the tests above would exclude the tested temporal-field replacement channel while leaving Λ CDM intact as the control reconstruction. Positive results would force a reinterpretation of dark matter phenomenology in the tested regime and would count directly against dark-sector ontology. The full TEP claim that dark matter and dark energy are non-fundamental still requires consistency across clusters, CMB lensing, structure formation, and late-time distance probes.

6. Falsification and Experimental Program

A theory that cannot be falsified is not science. TEP makes specific, testable predictions with explicit null-result thresholds. This section specifies the criteria that would exclude the framework and outlines the experimental path to a definitive verdict.

6.1 Explicit Falsification Criteria

The TEP framework is falsified if any of the following observations are confirmed:

Tier 1: Terrestrial Falsification (GNSS Signal)

- **Independent replication failure:** Independent research groups fail to reproduce exponential decay ($\lambda_T \approx 3,000\text{--}5,000$ km) using either raw carrier-phase observables (RINEX data with Single Point Positioning) or independent clock solutions (CLK files from CODE, IGS, ESA, or JPL). This would exclude the entire GNSS evidence base.

- **Correlation length out of bounds:** Independently replicated correlation length falls outside $\lambda_T = 500\text{--}20,000$ km range. This would exclude the TEP prediction of $\lambda_T \sim 4,000$ km based on the relaxation of Temporal Topology from Earth's potential well.
- **Ephemeris loophole confirmed:** The ephemeris question splits into two layers with different adjudicators. (i) *GNSS-product provenance:* Satellite Laser Ranging (SLR) residuals show no low-frequency spectral concentration or distance-structured daily-aggregation signal when analyzed using sampling-matched methods and demonstrated sensitivity to the predicted optical counterpart. Only a null at that sensitivity can exclude the specified common-clock transfer. The present spectral null alone does not establish a GNSS-product origin (Section 6.3.1.1). (ii) *Generic orbit-projection confound:* a positive SLR result cannot by itself exclude the wider hypothesis that any satellite-range observable inherits distance-structured residuals from its own orbit-determination chain; adjudicating that layer requires the physical-confound forward model (the orbit/product-error projection kernel) or an orbit-free clock channel such as terrestrial fiber-link or transportable-clock comparisons, which carry no satellite content at all.

Tier 2: Synchronization Holonomy (Direct Test)

- **Null holonomy at high precision:** Closed-loop one-way time-transfer around triangular geometry (1,000–3,000 km legs) yields null synchronization holonomy $\mathcal{H}/T_{\text{loop}} < 10^{-19}$ after subtracting all known relativistic effects (Sagnac, Shapiro, gravitational redshift, Lense-Thirring). This would constrain disformal coupling $B(\phi)$ below cosmologically interesting levels and exclude the non-integrable proper time prediction (Section 6.3.3).

Tier 3: Cosmological Falsification (Source-Dependence Channel)

- **CMB-Galaxy source covariance:** Next-generation surveys (CMB-S4 + LSST) showing no systematic dependence on source redshift or variability would exclude the bounded temporal-composite reconstruction channel. The current S_8 offset is a diagnostic to be confronted, not a predicted correspondence.

Framework Scope: Tier 1 tests the GNSS evidence base, Tier 2 tests the synchronization-holonomy mechanism, and Tier 3 tests the bounded weak-lensing source-dependence channel. Failure of a single Tier 1 criterion is sufficient to exclude the GNSS evidence base; a null Tier 3 result constrains that channel without deciding the dynamical sector.

6.2 Consequences of Failed Replication

If independent groups cannot replicate the raw RINEX signal, this would indicate one of several possibilities: a subtle processing artifact specific to the present pipeline that was not identified, a statistical fluctuation in the particular dataset selection, or an unidentified systematic in the cross-spectral analysis method.

In such a scenario, TEP would lose its primary empirical support. The theoretical framework would remain mathematically consistent but empirically unmotivated, and the cosmological predictions would become untestable speculation. This outcome would represent the scientific method working as intended.

6.3 Three-Tier Experimental Strategy

TEP can be confirmed or excluded through a coordinated experimental program organized by urgency and discriminating power.

6.3.1 Tier 1: Immediate Replication

The most urgent priority is independent replication. If independent research groups cannot replicate the raw RINEX signal, the GNSS evidence base is excluded and TEP loses its primary empirical support.

Required tests include independent clock analysis using either raw carrier-phase data (RINEX files with SPP processing) or processed clock solutions (CLK files from independent analysis centers), multi-constellation cross-check (verifying that the signal appears identically in GPS, GLONASS, Galileo, and BeiDou), and cross-center consistency (confirming CODE/IGS/ESA/JPL agreement

with $CV < 20\%$). Both RINEX and CLK approaches provide valid replication pathways; the key requirement is independence from the original analysis pipeline.

These tests can be performed by any institution with GNSS processing capability, including IGS, NIST, PTB, SYRTE, and JPL. The publicly available data (both raw RINEX observations and processed CLK solutions) enable independent verification of the $\lambda_T \approx 4,000$ km exponential decay, and the analysis can be completed in weeks using standard GNSS processing tools.

6.3.1.1 Addressing the Ephemeris Loophole

A legitimate concern exists regarding the Single Point Positioning test: SPP relies on broadcast ephemerides generated by control segments using network adjustments. If the artifact originates in the broadcast orbit determination, SPP would reproduce rather than eliminate it. This represents a potential systematic loophole requiring independent check.

Satellite Laser Ranging (SLR) provides the adjudicating test at the product level, within a precisely stated scope. SLR is a purely geometric, optical measurement independent of the GNSS microwave clock and ephemeris loop: its satellites are passive retroreflectors, and its orbits are determined from the laser ranges themselves — a processing chain wholly disjoint from the GNSS broadcast and precise products in which an ephemeris artifact would have to live. Within the conformal channel, however, the SLR residual probes the same endpoint-clock sector as GNSS: the ground event timer is itself a clock, so a physical clock-rate field enters both observables at co-located sites. The test therefore discriminates provenance rather than sector: correlation structure present in SLR cannot originate in the GNSS products, while structure absent at demonstrated sensitivity supports a GNSS-product artifact.

Proposed Tier 1.5 Test: Correlate GNSS clock residuals with SLR range residuals for co-located or nearby stations. The International Laser Ranging Service (ILRS) operates approximately 40 SLR stations globally, with several co-located with IGS GNSS stations. Analysis would proceed as follows: (1) Extract SLR range residuals after precise orbit determination; (2) Compute cross-correlation between SLR residuals and GNSS clock residuals for station pairs as a function of distance; (3) Test whether the exponential decay structure ($\lambda_T \approx 4,000$ km) appears in SLR data.

Expected Outcome: If TEP is correct and the signal reflects physical clock-rate modulation, SLR residuals should show distance-structured correlations because the laser round-trip time depends on both the satellite orbit and the ground station clock. If the signal is a GNSS-product artifact, SLR residuals (which use independent orbit determination) should show no correlation structure. Two qualifications bound the verdict: the SLR measurement must reach the demonstrated sensitivity for the GNSS-scale correlation before a null excludes the physical reading, and an SLR-positive outcome remains degenerate with the satellite-generic orbit-projection confound — orbit-determination errors imprint spatially structured residuals on any satellite-range observable. The differing orbit geometry of the two systems (GNSS in medium Earth orbit, LAGEOS-class targets in low Earth orbit) makes the correlation scale itself diagnostic: a common λ_T across independent orbit-determination chains indicates station-level rather than product-level origin. Final closure of the generic confound rests with the physical-confound forward model or the orbit-free channel above. The test can be performed with existing ILRS data.

6.3.2 Tier 2: Direct Holonomy Test

The triangle holonomy test provides the most direct discrimination between TEP and artifact hypotheses by measuring synchronization non-closure via closed-loop, multi-leg, one-way time-transfer. The proposed geometry involves two ground stations separated by 1,000–3,000 km plus a MEO satellite. The target sensitivity is $\sigma(H)/T_{\text{loop}} \leq 10^{-19}$ after averaging, with a signal forecast of $H/T_{\text{loop}} \sim 10^{-16}$ – 10^{-18} for parameters saturating current bounds. This test requires a dedicated mission.

6.3.3 Tier 3: Cosmological Testing

CMB-S4 combined with LSST weak lensing would test for source-dependent kinematic noise. The discriminator is covariance with source redshift and variability, not a universal 3–5% downward shift: the bounded Paper 4 temporal-composite channel is below the observed mean S_8 discrepancy, while the implemented Paper 18 posterior lies above the DES-Y3/KiDS-1000 central values under a Λ CDM-containing likelihood. The current S_8 difference is therefore a live diagnostic and falsification target, not a demonstrated TEP correspondence. Absence of the predicted source-class covariance at Stage-IV precision would exclude this kinematic-noise channel.

6.4 Path to Resolution

Table 10 summarizes the experimental program and its decision structure.

Table 10. Three-tier experimental program for TEP testing.

Tier	Test	Null-Result Threshold	What It Would Exclude
Tier 1	Raw carrier-phase replication	Signal absent	Entire GNSS evidence base
	Multi-constellation cross-check	Different λ across constellations	Universal coupling

Tier	Test	Null-Result Threshold	What It Would Exclude
	SLR ephemeris check (GNSS-product provenance)	No correlation in SLR residuals at demonstrated sensitivity	Physical-clock origin; the generic orbit-projection confound is excluded separately by the forward-model / orbit-free test
Tier 2	Triangle holonomy test	Null $< 10^{-19}$	Holonomy mechanism
Tier 3	CMB-S4 + LSST source covariance	No redshift/variability dependence	Temporal-composite reconstruction

Tier 1 tests determine whether TEP survives as a viable hypothesis. If all three Tier 1 tests confirm the signal, Tier 2 tests discriminate among mechanisms. Tier 3 tests probe the cosmological regime. A definitive verdict—confirmation or exclusion—is achievable through this coordinated program.

6.5 Prediction Provenance Register

The pre-specification claim is anchored to the immutable, timestamped version record of the public Zenodo deposits rather than asserted. Each tested expectation is mapped below to the earliest versioned manuscript section containing it, with deposit timestamps (UTC) and version DOIs that are independently checkable through the Zenodo API. All framework-level and pre-analysis entries precede the first public deposit of the GNSS analysis (Paper 1 v0.6-alpha, deposited 2025-09-22); the register is distributed as a machine-readable artifact (`results/prediction_provenance.json`) so that the ordering can be verified without trusting this manuscript.

Table 11. Prediction provenance register: each tested expectation mapped to its earliest versioned statement. Deposit timestamps are immutable per version DOI.

Tested expectation	Earliest versioned statement	Deposit (UTC)	Version DOI
Distance-correlated clock-network residuals (observable class; cross-spectral estimator, 3-D distance binning, multi-center cross-validation)	Paper 0 v0.4 (Marseille), §E Phase I	2025-09-15	10.5281/zenodo.17121655
Exponential spatial decay, $C(r) = A \exp(-r/\lambda) + C_0$	Paper 0 v0.4 (Marseille), §E Phase I; restated pre-analysis in Paper 1 v0.6α §1.2	2025-09-15	10.5281/zenodo.17121655
Correlation-length forecast, screening-parameterized $\lambda \sim 2,000\text{--}3,000$ km; stated search range $\lambda = 1,000\text{--}10,000$ km	Paper 0 v0.4 (Marseille), §E forecast; Paper 1 v0.6α §1.2 search range	2025-09-15 / 2025-09-22	10.5281/zenodo.17121655; 10.5281/zenodo.17174802
Multi-center parameter consistency (< 5% variation)	Paper 0 v0.4 (Marseille), §E forecast	2025-09-15	10.5281/zenodo.17121655
Velocity-dependent coupling: EW/NS anisotropy anticorrelates with Earth's orbital speed (negative sign)	Paper 1 v0.6α (Jaipur), §3.6, stated as the TEP expectation before the reported result; framework basis in velocity-dependent time transport, Paper 0 v0.1	2025-09-22 (framework 2025-08-21)	10.5281/zenodo.17174802; 10.5281/zenodo.16921912
Directional anisotropy of the correlation field	Paper 1 v0.6α (Jaipur), §3.2, carried as a critical TEP test; the ecliptic EW>NS ordering (2.16) is the measured outcome	2025-09-22	10.5281/zenodo.17174802
Achromatic universality (coupling not frequency-selective)	Paper 0 v0.1 (Guyana), axiom A4 universal coupling	2025-08-21	10.5281/zenodo.16921912
Absence of GM/r^2 and GM/r^3 scaling in clock correlations (selectivity profile)	Paper 0 v0.1 (Guyana), axioms A1–A4: conformal clock-sector coupling is not a fifth-force channel	2025-08-21	10.5281/zenodo.16921912
Annual orbital-phase directional structure	Paper 0 v0.1+ permits a background direction; the measurement recovers a phase near Earth's aphelion velocity tangent. It does not identify the directed CMB rest frame.	2025-08-21	10.5281/zenodo.16921912

Two entries are deliberately flagged as measured identifications rather than pre-specified values: the ecliptic ordering of the anisotropy and the preferred-axis direction. What was fixed in advance is the observable class, the estimator, the functional decay

form, the correlation-length forecast and search range, the cross-center consistency criterion, the sign of the orbital-velocity coupling, and the sector-level selectivity. Of these, the screening-parameterized correlation-length forecast, the $< 5\%$ cross-centre criterion and the exponential-kernel criterion were not met in full (Table 5). The discriminative weight therefore rests on the orbital-velocity sign, band localization, the $EW > NS$ ordering and the sector-level selectivity.

7. Conclusions

This paper presents empirical evidence for a persistent, distance-structured correlation in global atomic clock networks that probes an empirically untested assumption of general relativity: whether distributed proper-time rates contain a coherent spatial covariance beyond the standard relativistic model.

7.1 Summary of Findings

This integrated manuscript synthesizes results from a systematic research program that establishes, tests, and corroborates Temporal Equivalence Principle predictions through progressively rigorous empirical tests and cosmological extension. The convergence of evidence across seven domains—theoretical prediction (Paper 0), multi-center microwave consistency (Paper 1), 25-year longitudinal stability (Paper 2), raw RINEX test (Paper 3), optical SLR check (Paper 8), pulsar timing (Paper 10), and Cepheid environmental-response test (Paper 11)—provides an empirical foundation for TEP. The domains are not all channel-independent, and the audited strengths differ: the GNSS entries are the primary timing-network evidence; SLR supplies an optical bound and an exploratory correlation test within the same conformal clock sector; and the pulsar channel is exploratory, its standalone evidence uninformative rather than confirmatory.

The theoretical framework (Paper 0) supplied the search range and structural expectations tested by the GNSS programme. Distance structure and orbital coupling are recovered across several GNSS products and the raw-RINEX estimation chain. The optical SLR analysis (Paper 8) contributes a sampling-matched spectral null and sensitivity bound; its inter-station candidates remain exploratory. Its independent hardware and orbit provenance provide a future cross-instrument discriminator once a common signal is measured at adequate sensitivity.

Paper 11 tests an environment-dependent Cepheid response and reports a conditional corrected value $H_0 = 66.65 \pm 1.58 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Agreement with the companion TEP-CMB value is internal to the framework. The canonical joint host-level response is about 1.1σ , while the within-host period term is 2.57σ in the joint fit with host-assignment permutation $p = 0.0125$. The period–density relation motivates a carrier with an inferred transport weight; its absolute response normalization remains to be derived from a common stellar and ambient-field solution. These empirical tests constrain that physical completion.

The evidence programme combines timing-network signatures, environmental tests and an optical sensitivity bound: (1) distance-structured spatial decay over a finite scale (azimuth-averaged $\lambda \approx 3,210 \text{ km}$), (2) spatial anisotropy ($EW/NS = 2.16$), (3) orbital velocity coupling ($r = -0.888$, 3.65σ autocorrelation-corrected; surrogate $p < 2 \times 10^{-7}$ as a resolution bound), (4) an annual-phase direction near Earth's aphelion velocity tangent on the CODE and RINEX products (CMB apex anti-phase; Solar Apex null; MGEX scan projection-degenerate), (5) an optical SLR bound and exploratory inter-station test, (6) a planetary event catalogue functioning as a bounded control channel (catalogue excess attributable to calendar-position sampling; opposition subset null-validated; continuous potential correlation $r = +0.116$, $p = 0.012$), (7) 18.6-year nutation coupling, (8) pulsar spin-down excess (exploratory), and (9) host-potential H_0 correlation. The signal survives all challenges across solar cycles, geomagnetic storms, altitude, and software-diverse processing chains—systematically excluding conventional artifact explanations.

7.2 Theoretical Interpretation

These observations match the predictions of the Temporal Equivalence Principle, a bi-metric framework in which proper time is a dynamical field. TEP established pre-specified expectations and theoretically motivated search ranges—including correlation length range, exponential decay, velocity-dependent anisotropy, and absence of GM/r^2 (force) and GM/r^3 (tidal) scaling—consistent with the observed data. The theory paper was published in August 2025 with these predictions; the GNSS analysis was conducted from September through December 2025.

The framework preserves local Lorentz invariance, with the speed of light remaining exactly invariant in any freely falling laboratory, while predicting global clock-network covariance and open-path conformal transport structure. GW170817 primarily constrains the disformal differential-propagation sector; it does not directly test common-mode conformal clock-rate covariance along shared paths, although conformal scalar sectors remain indirectly constrained by PPN, equivalence-principle, source-screening, and clock-comparison tests.

7.2a Predicted vs Fitted Coefficients across Probes

Probe	Predicted in advance (sign/shape/ordering)	Fitted (amplitude)	Coefficient
GNSS λ (Papers 1–3, 14)	Exponential decay; EW>NS polarity; orbital-velocity sign	Decay length (metric- and product-dependent, 1,862–4,549 km on the precise-product family)	λ_T
Cepheid H_0 (Paper 11)	Sign of potential-depth correlation	Response amplitude	$\kappa_{\text{Cep}} = (0.266 \pm 0.239) \times 10^6 \text{ mag (multi-block)} / (0.452 \pm 0.220) \times 10^6 \text{ mag (redshift-only)}$; theory benchmark $\kappa_{\text{canonical}} = 0.96 \times 10^6$
MSP spin-down (Paper 10)	Suppression direction vs Newtonian; field-binary null	Response amplitude	$\kappa_{\text{MSP}} \sim 10^6$
LLR (Paper 17)	Synodic phase; sideband structure	$\kappa_{\text{LLR}} = -3.91 \times 10^{-4}$	κ_{LLR} (Solar-System ORC)
Wide binaries (Paper 13)	Transition existence; environmental ordering (high- $ Z < \text{midplane } R_s$)	$\alpha_{\text{sat}} = 0.366$; $R_s = 2646 \text{ AU}$	$\alpha_{\text{sat}}, M_{\text{screen}}$
Flybys (Paper 15)	Candidate clock-sector reduction artifact in clock-carrying links (Paper 0 §2.2; physical shear pairwise-screened)	Intermittent signature; candidate attribution in non-coherent links	Clock-sector artifact
Refsdal (Paper 19)	Residual sign (6/7, 7/7 blind)	Amplitude underpredicted; kernel open	Transfer kernel

TEP's amplitudes are currently measured, not predicted: each sector carries its own Observable Response Coefficient, and deriving their hierarchy from a single coupling function $A(\phi)$ with continuous Temporal Topology screening is the framework's central open theoretical problem. Two quantitative coincidences mark the target: κ_{Cep} and κ_{MSP} independently land at $\sim 10^6$, and the saturation scale satisfies $\rho_T \approx \alpha^{\{4/3\}} m_{\text{ec}}^3 / h^3 \approx 12\%$ (equivalently $\Lambda \approx \alpha^{\{1/3\}} m_{\text{ec}}^2$, 3%) with no derivation yet selecting either exponent. A completion that predicts both, or falsifiably fails to, is the program's next theoretical milestone.

7.3 Cosmological Implications

If validated through independent replication, TEP predicts that the phenomenology attributed to dark matter in the dynamical sector is the observational projection of Temporal Topology and Temporal Shear, not evidence for a new particulate matter component. In this interpretation, GNSS-scale covariance and galactic dynamical mass discrepancies are different observational projections of the same time-field topology, with Papers 4 and 13 testing distinct optical and dynamical projections of the same environmental-response architecture (Paper 4: matter-sourced deflection and a dynamical–lensing phantom-mass test; Paper 13: a SPARC-anchored wide-binary transition at $R_s \approx 2,646 \pm 182 \text{ AU}$), without a derived quantitative terrestrial-covariance-to-galactic-shear transfer. Conformal shear acts on matter trajectories without directly changing null paths at fixed $g_{\mu\nu}$; scalar stress can still curve that metric, and the absolute lensing potential remains a separate required CDM-free test (Paper 19). The $\mathcal{S}_{\Sigma}(E)$ screening operator provides continuous Temporal Topology relaxation from deep potential wells to the weak-field regime: at the terrestrial scale, the density-saturation diagnostic gives $R_T(M_{\oplus}) \approx 4,150 \text{ km}$ — Earth, whose mean density lies below ρ_T , sits in the partially active regime, while at galactic scales the operator retains approximately 98% of the unsuppressed Temporal Shear in the diffuse halo environment (Paper 26), producing dark-matter-like phenomenology through the active-shear regime rather than through a screening radius. The $\sim 4,000 \text{ km}$ GNSS correlation and the $\sim 50 \text{ kpc}$ galactic phenomenology are therefore manifestations of the same environment-dependent Temporal-Topology response operating in different density regimes, not a single $M^{1/3}$ scaling across 15 orders of magnitude.

The framework offers a conditional environmental-response account of the H_0 discrepancy and a source-dependent covariance diagnostic for weak lensing; it does not presently supply the mean S_g offset or a CDM-free lensing potential.

7.4 The Path Forward

Independent replication is essential. The critical next steps are: raw carrier-phase analysis by independent research groups using the publicly available benchmark dataset; multi-constellation testing across GLONASS, Galileo, and BeiDou to verify universal coupling; lensed FRB timing to probe achromatic residuals at millisecond precision; and triangle holonomy tests to directly measure synchronization non-closure. It is stated plainly that the disformal-sector holonomy — the framework's definitive discriminating test — remains unmeasured at the canonical amplitude: the J0437 phase-closure detection (Paper 16) attests loop-ordered non-factorizability but sits roughly two orders of magnitude above the canonical disformal connection's ceiling on that sightline, so it is a non-exact-transport signature rather than a measured holonomy amplitude; the empirical evidence assembled here supports the

conformal-sector spatial correlation alone. A definitive verdict—confirmation or exclusion—is achievable through the coordinated experimental program outlined in Section 6.

7.5 Concluding Remarks

The correlation structure documented in this paper is statistically robust and matches the predictions of a principled theoretical framework grounded in established scalar-tensor gravity. Whether it ultimately reflects new physics or reveals subtle systematics yet to be identified, the signal demands explanation.

For three decades, standard GNSS processing systematically removed a $\sim 4,000$ km correlation as part of routine noise filtering. The algorithms were designed to optimize positioning accuracy rather than to characterize fundamental physics. The correlation structure reported here was present in the residuals but categorized as systematic error rather than physical phenomenon.

If confirmed through independent replication, the implications extend to cosmology. The Isochrony Axiom—the assumption that all photons in a lensed image represent a synchronous snapshot—has never been empirically tested. If this axiom fails in the presence of conformal metric couplings, apparent dark matter arises in the dynamical sector as a geometric artifact: the Temporal Shear's effect on matter trajectories projected onto a Newtonian mass model. The artifact does not extend to photon paths — null curves are conformally invariant — so its spatial-sector signature is the dynamical–lensing mass difference — the phantom mass appearing only in dynamics — rather than a second apparent mass in lensing (Paper 19).

Einstein established that simultaneity is relative. The TEP framework suggests that simultaneity may be generally non-integrable—that the rate of proper time accumulation is itself a dynamical field. The speed of light remains exactly invariant locally, but global synchronization becomes path-dependent.

The $\sim 4,000$ km correlation on Earth (cross-sector mean and directional dispersion $\lambda_T = 4,201 \pm 1,967$ km — an order-of-magnitude measurement) and the ~ 50 kpc dark-matter-attributed dynamical phenomenology in galaxies are interpreted within TEP as manifestations of the same environment-dependent Temporal-Topology response, pending independent replication, completion-dependent transfer calculations, and lensing–dynamics consistency (Paper 19), connected by the continuous relaxation of Temporal Topology from deep potential wells to the weak-field regime. The $M^{1/3}$ scaling appearing in some candidate completions remains testable through interplanetary missions and pulsar timing arrays, but it is not the primary empirical claim. This hypothesis is falsifiable through the experimental program outlined in Section 6. Independent replication is essential, and the data and analysis code are publicly available. The community is invited to verify, challenge, or refute these findings.

Data and Code Availability

All analysis code, processed data products, and raw RINEX processing pipelines are publicly available:

- Multi-center and 25-year CODE analysis: github.com/matthewsmawfield/TEP-GNSS
- Raw RINEX test: github.com/matthewsmawfield/TEP-GNSS-RINEX
- Benchmark dataset: A simplified CSV file containing binned residuals versus distance for the 25-year period, available for theorists who wish to fit models without processing raw GNSS data: [TEP-GNSS/benchmark](https://github.com/matthewsmawfield/TEP-GNSS-benchmark)

Acknowledgments

The author expresses gratitude to the International GNSS Service (IGS), the Center for Orbit Determination in Europe (CODE), the European Space Agency (ESA), and NASA's Crustal Dynamics Data Information System (CDDIS). This analysis was possible because these organizations have championed the principles of open science, making decades of high-precision timing data freely available to the global research community. The GFZ Helmholtz Centre Potsdam is acknowledged for providing geomagnetic Kp indices.

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Data Availability & Reproducibility

This work follows open-science practices. This synthesis paper integrates results from a systematic multi-paper research program. All primary analysis code and data are available in the referenced repositories.

Repository & Code

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

This synthesis manuscript integrates findings from Papers 1–4. Primary analysis repositories:

TEP Research Program Structure

Paper	Repository	Download Size
Paper 1: GNSS Analysis	TEP-GNSS	~50 MB (benchmark data)
Paper 2: 25-Year Longspan	TEP-GNSS-II	~100 MB
Paper 3: Raw RINEX	TEP-GNSS-RINEX	~5 GB (RINEX files)
Paper 4: Gravitational Lensing	TEP-GL	N/A (theoretical)
Paper 8: Satellite Laser Ranging	TEP-SLR	~200 MB (normal-point data)

Primary Data Sources

- **CDF Data:** CODE analysis center clock products (2000–2025)
- **IGS Data:** International GNSS Service clock products
- **ESA Data:** European Space Agency navigation support products
- **RINEX Files:** Raw observation files from IGS stations

Prediction Provenance

The dated prediction register of Section 6.5 is distributed as a machine-readable artifact, `results/prediction_provenance.json`, recording each tested expectation's earliest versioned statement with its version DOI and immutable deposit timestamp. The ordering is independently verifiable against the public Zenodo version records under the concept DOIs listed there (Paper 0: 10.5281/zenodo.16921911; Paper 1: 10.5281/zenodo.17127229).

Reproduction Instructions

```
# Clone this synthesis repository
git clone https://github.com/matthewsmawfield/TEP-GTE.git
cd TEP-GTE

# Build manuscript
cd site
npm install
npm run build
```

Software Versions

- **Node.js** 16+

Appendix A: Mathematical Formalism

A.1 Full Action

The canonical low-kinetic benchmark of the TEP action (Paper 0, §2.2) is formulated in the Einstein frame where gravity is canonical:

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} K(\phi) g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + S_{\text{matter}}[\psi, \tilde{g}_{\mu\nu}, \phi]$$

where M_{Pl} is the reduced Planck mass, R is the Ricci scalar, $K(\phi)$ is the kinetic function (absorbable by a field redefinition; the operative screening realization is the noncanonical $P(X, \phi) = X - V(\phi) + X|X|/\Lambda_X^4$), $V(\phi)$ is the screening potential, and S_{matter} is the matter action in the Jordan frame with coupling to the matter metric $\tilde{g}_{\mu\nu}$.

A.2 Field Equations

Variation with respect to the gravitational metric yields the Einstein equations:

$$G_{\mu\nu} = \frac{1}{M_{\text{Pl}}^2} \left[T_{\mu\nu}^{(\phi)} + T_{\mu\nu}^{(\text{matt})} \right]$$

where the scalar field stress-energy tensor is:

$$T_{\mu\nu}^{(\phi)} = K(\phi) \partial_\mu \phi \partial_\nu \phi - g_{\mu\nu} \left[\frac{1}{2} K(\phi) g^{\rho\sigma} \partial_\rho \phi \partial_\sigma \phi + V(\phi) \right]$$

Variation with respect to the scalar field yields:

$$\nabla_\mu [K(\phi) \nabla^\mu \phi] - \frac{\partial K}{\partial \phi} \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{\partial V}{\partial \phi} = -\alpha(\phi) T + S_{\text{disf}}$$

where $\alpha(\phi) \equiv d \ln A/d\phi = \beta_A/M_{\text{Pl}}$ is the conformal coupling strength (for $A(\phi) = \exp(\beta_A \phi/M_{\text{Pl}})$), T is the trace of the matter stress-energy tensor in the Jordan frame, and S_{disf} contains disformal source terms proportional to $B(\phi)$.

A.3 Candidate Microscopic Completions and Nonlinear Screening

Candidate Completion (Historical Provenance): This appendix presents an illustrative candidate completion (cubic Galileon derivative screening) that exhibits the $(\beta_A M/M_{\text{Pl}} \Lambda^3)^{1/3}$ transition scale. In the current TEP master architecture (Paper 0 §2.2), environmental screening is derived from the non-canonical kinetic operator $P(X, \phi) = X - V + X|X|/\Lambda_X^4$.

The following derivation illustrates one candidate microscopic completion (cubic Galileon) that realizes the continuous gradient suppression described as Temporal Shear in Section 4; it is not required for the empirical results.

One candidate completion invokes cubic Galileon terms in the action to generate nonlinear screening:

$$S_{\text{Galileon}} = \int d^4x \sqrt{-g} \left[\frac{c_3}{\Lambda^3} (\partial\phi)^2 \square\phi \right]$$

where Λ is the strong-coupling scale (an energy scale, $[M]$ in natural units $c = \hbar = 1$) and c_3 is a dimensionless coefficient of order unity. With the canonical scalar field normalization (ϕ has mass dimension 1) and the TEP source term $(\beta_A/M_{\text{Pl}})T$, the nonlinear term becomes important when:

$$\frac{|\nabla\phi|^2}{\Lambda^3} \sim 1$$

The Vainshtein radius, inside which nonlinear effects dominate, is (in natural units $c = \hbar = 1$):

$$r_V = \left(\frac{\beta_A M}{M_{\text{Pl}} \Lambda^3} \right)^{1/3}$$

where β_A is the conformal coupling, $M_{\text{Pl}} = \sqrt{(\hbar c/G)}$ is the Planck mass, and Λ is the strong-coupling energy scale. Restoring SI units:

$$r_V = \left(\frac{\beta_A M (\hbar c)^3}{M_{\text{Pl}} \Lambda^3} \right)^{1/3} = \left(\frac{\beta_A M}{M_{\text{Pl}}} \right)^{1/3} \frac{\hbar c}{\Lambda}$$

The factor $\beta_A M/M_{\text{Pl}}$ supplies the dimensionless source strength; $(\hbar c/\Lambda)^3$ supplies the length scale cubed. The bare expression $(GM/\Lambda^3)^{1/3}$ sometimes quoted in the Galileon literature is a shorthand that suppresses the β_A/M_{Pl} coupling and implicitly assumes natural units with a specific field normalization; it is dimensionally incomplete as written.

For a spherically symmetric source of mass M , the scalar field profile in the Vainshtein regime ($r < r_V$) is:

$$\phi(r) \sim \frac{\beta_A M_{\text{Pl}}}{M_{\text{Pl}}^2} \frac{GM}{r} \left(\frac{r}{r_V} \right)^3$$

This suppresses the Temporal Shear by a factor of $(r/r_V)^3$ inside the screening radius, reconciling weak-field cosmological behavior with strong-field solar system constraints. Other completions (e.g., chameleon mechanisms, symmetry-breaking potentials) may produce similar phenomenology.

A.4 Conservation Laws

The total stress-energy tensor is conserved:

$$\nabla_\mu \left[T_{(\phi)}^{\mu\nu} + T_{(\text{matt})}^{\mu\nu} \right] = 0$$

However, the matter stress-energy alone is not conserved in the Einstein frame:

$$\nabla_\mu T_{(\text{matt})}^{\mu\nu} = \alpha(\phi) T \nabla^\nu \phi + \text{disformal terms}$$

This apparent violation is resolved by transforming to the Jordan frame, where matter follows geodesics of $\tilde{g}_{\mu\nu}$ and energy-momentum is conserved with respect to the matter-frame covariant derivative.

Appendix B: Processing Filter Mathematical Formulation

B.1 Network Adjustment Constraint

Standard GNSS processing applies a datum constraint that forces residuals to have zero spatial mean:

$$\delta t_i^{\text{adj}} = \delta t_i - \frac{1}{N} \sum_{j=1}^N \delta t_j$$

This constraint preserves zero-mean residuals while removing any common-mode offset.

B.2 Fourier Decomposition

Decompose the TEP signal into spatial Fourier modes characterized by wavevector $\mathbf{k}$:

$$\delta t_i^{\text{TEP}} = \sum_{\mathbf{k}} A_{\mathbf{k}} e^{i\mathbf{k} \cdot \mathbf{r}_i}$$

where $\mathbf{r}_i$ is the position of station i . The network adjustment removes the $\mathbf{k} = 0$ (monopole) component:

$$A_{\mathbf{k}=0}^{\text{adj}} = A_{\mathbf{k}=0} - \frac{1}{N} \sum_j A_{\mathbf{k}=0} = 0$$

but preserves all $\mathbf{k} \neq 0$ (dipole, quadrupole, and higher) components that have zero spatial mean.

B.3 Cross-Spectral Density

The TEP correlation structure manifests as phase coherence between station pairs, quantified by the cross-spectral density:

$$C_{ij}(\omega) = \langle \tilde{\delta t}_i(\omega) \tilde{\delta t}_j^*(\omega) \rangle$$

where tildes denote Fourier transforms and angle brackets denote ensemble averaging.

B.4 Phase Alignment Index

The magnitude-weighted phase alignment index extracts the phase relationship:

$$\Phi_{ij} = \frac{\sum_{\omega} |C_{ij}(\omega)| \cos[\arg C_{ij}(\omega)]}{\sum_{\omega} |C_{ij}(\omega)|}$$

This metric is invariant under common-mode amplitude rescaling because it depends only on relative phases, not absolute amplitudes. The datum constraint removes $A_{\mathbf{k}=0}$ (amplitude information) but preserves the phase structure encoded in the $\mathbf{k} \neq 0$ components.

B.5 Exponential Correlation Function

The exponential decay $C(r) \propto \exp(-r/\lambda)$ reflects the two-point correlation function of the underlying ϕ field:

$$\langle \phi(\mathbf{x}) \phi(\mathbf{x}') \rangle = \phi_0^2 \exp\left(-\frac{|\mathbf{x} - \mathbf{x}'|}{\lambda}\right)$$

where $\lambda = R_T(M_{\oplus})$ is the geometric saturation radius (§4.4.2); under the mass-completion interpretation this would correspond to the Compton wavelength $\lambda = \hbar/(m_{\phi}c)$. This correlation function has nonzero spatial gradients ($\mathbf{k} \neq 0$ in Fourier space) and therefore survives network adjustment, which only removes the $\mathbf{k} = 0$ component.

B.6 Tidal vs. TEP Signal Discrimination

Classical tidal effects are parameterized as sums of spherical harmonics $Y_{lm}(\theta, \varphi)$ with known frequencies:

$$\delta t_{\text{tidal}}(t, \mathbf{r}) = \sum_{l,m,n} A_{lmn} Y_{lm}(\theta, \phi) \cos(\omega_n t + \phi_n)$$

where ω_n are tidal frequencies (diurnal, semidiurnal, long-period). Standard GNSS processing explicitly models and subtracts these terms using IERS conventions.

The TEP correlation is a distance-dependent phase coherence:

$$C_{\text{TEP}}(r_{ij}) = A_0 \exp(-r_{ij}/\lambda)$$

This functional form is not decomposable into the standard tidal spherical harmonic basis. The processing removes what it models (tidal harmonics) but preserves what it does not model (exponential distance correlations in phase space).