Worldline Memory and Rotational Time Hysteresis

A Testable Extension of Ideal-Clock Relativity Motivated by Sagnac Holonomy

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Abstract

Relativistic proper time is a geometric functional of a worldline. The standard ideal-clock postulate adds a constitutive statement: an ideal clock counts that proper time with a history-independent conversion rate. Thus two clocks may accumulate different readings along different worldlines, yet after they are reunited under identical local conditions their subsequent rates are assumed to agree. This paper isolates that history-independence assumption and asks whether it is logically compulsory. It is not.

The standard equatorial calculation is first stated without reinterpretation. A clock co-rotating at the terrestrial equator accumulates approximately 103.697 ns less proper time during one sidereal day than an idealized non-rotating clock held at the same radius and gravitational potential. Separately, the one-direction Sagnac/slow-clock-transport holonomy for a completed equatorial loop is approximately 207.386 ns, while the counter-propagating optical Sagnac difference is twice that value. These are standard results. The paper does not identify the 207 ns loop holonomy with an observed 207 ns-per-day drift.

A non-standard extension is then formulated. A dimensionless material or phase state Q is introduced through

$$\mathrm{d}N = \nu_0 Q \, \mathrm{d}\tau,$$

where N is the clock-cycle count. Standard ideal-clock relativity is the memoryless sector $Q = 1$. In the proposed history-dependent sector, directed rotational holonomy can update Q, producing a persistent post-cycle change of clock rate or of a broader local metrological baseline. A discrete per-cycle law, a local covariant completion based on a co-rotating congruence and an internal phase, the common-mode observability problem, and decisive post-reunion experiments are developed. The central prediction is not merely a phase offset but a direction-odd, loop-count-dependent residual slope in the frequency difference after all clocks have been returned to the same local state. The hypothesis is therefore falsifiable. Possible cosmological consequences are discussed only conditionally: a common drift of local standards has

physical content only if it changes at least one observable dimensionless ratio relative to an independently evolving sector.

Keywords: proper time; ideal clock; clock hypothesis; Sagnac effect; slow clock transport; rotational holonomy; worldline memory; metrological hysteresis; atomic clocks; helical motion.

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1 Introduction

Relativity gives an operationally successful rule for comparing elapsed times along different worldlines. For a timelike curve Γ, the proper time is

$$\tau[\Gamma] = \frac{1}{c}\int_{\Gamma}\sqrt{-g_{\mu\nu}\,\mathrm{d}x^{\mu}\mathrm{d}x^{\nu}}. \tag{1}$$

In flat spacetime and an inertial coordinate system,

$$\mathrm{d}\tau = \mathrm{d}t\sqrt{1-\frac{v^2}{c^2}}. \tag{2}$$

The observable content is direct: clocks that traverse different worldlines can reunite with different readings. The around-the-world atomic-clock experiments and the operation of global navigation systems are prominent macroscopic realizations of this principle [3, 4, 5].

A further statement is normally attached to equation (1): an ideal clock has a fixed conversion between proper time and cycle count,

$$\mathrm{d}N = \nu_0\,\mathrm{d}\tau, \tag{3}$$

where ν_0 is determined by the clock mechanism. The accumulated reading can depend on the complete worldline through $\tau[\Gamma]$, while the local conversion factor ν_0 does not retain an additional memory of that worldline. Once two ideal clocks are reunited with the same velocity, position, gravitational potential, and environmental conditions, their subsequent rates agree even if their readings differ by a constant offset. This is the history-independent idealization examined in discussions of the clock hypothesis and natural clocks [6, 7].

The question of this paper is narrower than a rejection of relativity:

> Is history independence of the clock response a logical consequence of proper -time geometry, or is it an additional constitutive assumption that can be tested?

The answer developed here is that it is an additional assumption. Proper time determines a geometrical interval. It does not, by itself, prove that every possible material or phase degree of freedom coupled to a clock must return to the same state after a rotational history.

This distinction is familiar in other areas of physics. Geometry and kinematics constrain admissible configurations, while the actual response of a material requires a constitutive law. A magnetic field does not logically force a material to be hysteresis-free; a stress history does not logically force a solid to be perfectly elastic; and a cyclic drive does not logically force an order parameter to return to its original state. The issue is not whether memory is conceivable, but whether a particular memory variable exists and whether it has observable consequences.

Rotation provides a natural setting for posing the question because rotating frames possess a direction-dependent synchronization holonomy. In the slow-clock-transport limit, a completed directed loop retains a finite time offset even as the transport speed relative to the platform tends to zero. This finite limit is standard Sagnac physics, not a new effect.

The new proposal is that such a directed cycle could also act as a source for an internal metrological state.

2 Status of the Claims

To prevent standard results, proposed extensions, and open questions from being conflated, table 1 gives the logical status of the central statements.

Table 1: Logical status of the ingredients used in this paper.

Status	**Statement**
Standard result	Proper time is given by the worldline integral in equation (1).
Standard result	The equatorial co-rotating clock deficit relative to an idealized non-rotating same-potential clock is about 104 ns per sidereal day.
Standard result	The one-direction equatorial Sagnac/slow-transport holonomy is about 207 ns per completed directed loop; the two-beam difference is about 415 ns.
Standard idealization	An ideal clock has a history-independent response $\mathrm{d}N = \nu_0 \mathrm{d}\tau$.
Hypothesis	A physical clock or wider material standard can possess an internal state Q that retains directed rotational history.
Prediction	After reunion under identical local conditions, different rotational histories can produce a persistent frequency-ratio slope, not merely a constant phase offset.
Open	The microscopic carrier of Q, its coupling strength, relaxation time, universality, and relation to matter and radiation.
Not claimed	The standard 207 ns loop holonomy has already been observed as a 207 ns-per-day secular recalibration.
Not claimed	Dark energy has been eliminated or cosmological acceleration has been derived.

3 The Standard Equatorial Baseline

3.1 Idealized geometry and notation

Let the Earth be represented by a uniformly rotating sphere or reference ellipsoid with equatorial radius R and angular velocity Ω. In an Earth-centered approximately inertial frame, an equatorial ground clock moves at

$$V = \Omega R, \qquad \beta = \frac{V}{c}, \qquad \gamma_\oplus = \frac{1}{\sqrt{1-\beta^2}}. \tag{4}$$

We idealize two clocks as remaining at the same radius and gravitational potential, so that the gravitational contribution cancels in their difference. A truly non-rotating clock held at the terrestrial radius would require support and is not a freely falling object. It is nevertheless a well-defined comparison worldline for the present kinematic calculation.

Using WGS 84 values,

$$R = 6\,378\,137\,\mathrm{m}, \qquad \Omega = 7.292\,115 \times 10^{-5}\,\mathrm{rad/s}, \tag{5}$$

we obtain

$$V \simeq 465.1011\,\mathrm{m/s}, \qquad T_{\mathrm{sid}} = \frac{2\pi}{\Omega} \simeq 86\,164.1006\,\mathrm{s}. \tag{6}$$

3.2 The approximately 104-ns sidereal-day deficit

Let the reference clock be non-rotating in the Earth-centered inertial frame, while the ground clock co-rotates at speed V. During one sidereal day,

$$\tau_{\mathrm{ref}} = T_{\mathrm{sid}}, \tag{7}$$

$$\tau_{\mathrm{g}} = T_{\mathrm{sid}}\sqrt{1-\beta^2} = \frac{T_{\mathrm{sid}}}{\gamma_\oplus}. \tag{8}$$

The difference is

$$\Delta\tau_{104} \equiv \tau_{\mathrm{ref}} - \tau_{\mathrm{g}} = T_{\mathrm{sid}}\left(1 - \frac{1}{\gamma_\oplus}\right). \tag{9}$$

For $\beta \ll 1$,

$$\Delta\tau_{104} = \frac{T_{\mathrm{sid}}\beta^2}{2} + \mathcal{O}(\beta^4) = \frac{\pi\Omega R^2}{c^2} + \mathcal{O}(\beta^4), \tag{10}$$

which numerically gives

$$\boxed{\Delta\tau_{104} \simeq 103.697\,\mathrm{ns}.} \tag{11}$$

This is genuine kinetic time dilation. If the two clocks are not reset, the reading difference accumulates linearly while the worldlines and local conditions are repeated.

3.3 The approximately 207-ns slow-transport holonomy

Now compare the ground clock with a clock transported eastward around the equator at a small speed $u > 0$ relative to the ground. To leading terrestrial accuracy, its Earth-centered speed is $V + u$, and the coordinate time needed to complete one ground-relative loop is

$$T_{\mathrm{loop}} = \frac{2\pi R}{u}. \tag{12}$$

The proper-time difference at reunion is

$$\Delta\tau(u) = \frac{2\pi R}{u}\left[\sqrt{1 - \frac{(V+u)^2}{c^2}} - \sqrt{1 - \frac{V^2}{c^2}}\right]. \tag{13}$$

Taking the limit $u \to 0^+$ while retaining one completed loop gives

$$\lim_{u\to 0^+} \Delta\tau(u) = -\gamma_\oplus \frac{2\pi RV}{c^2} = -\gamma_\oplus \frac{2\pi\Omega R^2}{c^2}. \tag{14}$$

Define the positive one-direction holonomy magnitude

$$\mathcal{H}_\oplus \equiv \gamma_\oplus \frac{2\pi\Omega R^2}{c^2}. \tag{15}$$

Numerically,

$$\boxed{\mathcal{H}_\oplus \simeq 207.386\,\text{ns}.} \tag{16}$$

Westward slow transport reverses the sign. Two counter-propagating light signals exhibit the corresponding total Sagnac difference

$$\Delta\tau_{\text{two-beam}} = 2\mathcal{H}_\oplus \simeq 414.772\,\text{ns}. \tag{17}$$

The limit in equation (14) is finite because the instantaneous rate difference is first order in u, whereas the loop-completion time is proportional to $1/u$. The transport speed disappears from the leading per-loop result, but the duration of the experiment diverges as $u \to 0$. Therefore $\mathcal{H}_\oplus$ is a per-loop holonomy, not automatically a per-day secular drift.

3.4 The exact factor relating the two values

The near factor of two is not a numerical accident. From equations (9) and (15),

$$\mathcal{H}_\oplus = T_{\text{sid}}\gamma_\oplus\beta^2 = T_{\text{sid}}\left(\gamma_\oplus - \frac{1}{\gamma_\oplus}\right). \tag{18}$$

Hence

$$\boxed{\mathcal{H}_\oplus = (\gamma_\oplus + 1)\Delta\tau_{104}.} \tag{19}$$

Since $\gamma_\oplus - 1 \simeq 1.2 \times 10^{-12}$, the factor is indistinguishable from two at the displayed precision:

$$\mathcal{H}_\oplus \simeq 2\Delta\tau_{104}. \tag{20}$$

The two values nevertheless answer different operational questions. One is a fixed-duration worldline comparison; the other is a fixed-winding comparison. The proposed memory hypothesis will use this distinction rather than erase it.

4 Proper-Time Geometry Does Not Fix Every Clock Constitutive Law

Equation (1) is geometric. Equation (3) is a statement about how a material system responds to that geometry. For well-designed atomic clocks the ideal-clock approximation is extraordinarily successful. Yet success of an approximation is not the same as a theorem that forbids all additional internal variables.

Suppose two clocks follow different worldlines and reunite. Standard ideal -clock relativity predicts

$$N_A - N_B = \Delta N_0, \qquad \frac{\mathrm{d}}{\mathrm{d}t}(N_A - N_B) = 0 \quad \text{after reunion under identical conditions.} \tag{21}$$

The first relation is the accumulated relativistic offset. The second is the history-independence statement. The second does not follow algebraically from the first.

A physical system can carry memory only if a state variable stores it. In a magnet this can be domain structure; in a plastically deformed solid it can be a changed reference configuration; in a phase-ordered medium it can be winding, defects, or a displaced order parameter. A clock-memory theory must similarly identify a state, an evolution law, a relaxation mechanism, and an observable.

The point is therefore not that standard relativity "denies" a measured time dilation. It fully accepts the proper-time difference. The point is that the standard ideal-clock sector assumes that the difference remains a phase offset and does not feed back into the later material conversion rate. That is a minimal and highly successful constitutive choice, but not the only logically constructible one.

5 Worldline-Memory Hypothesis

5.1 Clock response with an internal state

Hypothesis 1 (History-dependent clock response)**.** *A physical clock or a wider local material standard possesses a dimensionless state Q such that its cycle count satisfies*

$$\mathrm{d}N = \nu_0 Q \, \mathrm{d}\tau. \tag{22}$$

The state Q can be changed by directed rotational history and can persist after the clock returns to its original local kinematic and environmental conditions.

Standard ideal-clock relativity is recovered exactly in the sector

$$Q = 1, \qquad u^\mu \nabla_\mu Q = 0. \tag{23}$$

The extension therefore does not alter the spacetime definition of proper time. It alters the constitutive map from proper time to the reading of a particular physical standard.

5.2 Discrete per-cycle law

Let n count completed directed rotational cycles and let h_n be a signed dimensionless measure of the cycle holonomy. A minimal multiplicative law is

$$Q_{n+1} = Q_n \exp(-\lambda h_n), \tag{24}$$

where λ is a dimensionless coupling. For weak updates,

$$Q_{n+1} = Q_n \left[1 - \lambda h_n + \mathcal{O}(h_n^2)\right]. \tag{25}$$

A natural phenomenological choice is

$$h_n = \frac{\mathcal{H}_n}{T_*}, \tag{26}$$

where T_* is a stated calibration time scale. Choosing $T_* = T_{\rm sid}$ for the Earth gives

$$h_\oplus = \frac{\mathcal{H}_\oplus}{T_{\rm sid}} = \gamma_\oplus \frac{\Omega^2 R^2}{c^2} \simeq 2.407 \times 10^{-12}. \tag{27}$$

This normalization is a model choice, not a deduction from standard Sagnac kinematics. The coupling λ, sign convention, and relaxation law must be determined experimentally or microscopically.

After N identical directed cycles,

$$Q_N = Q_0 \exp(-\lambda N h), \tag{28}$$

and for $|\lambda N h| \ll 1$,

$$\frac{Q_N - Q_0}{Q_0} \simeq -\lambda N h. \tag{29}$$

This is metrological hysteresis: the accumulated phase history modifies the subsequent rate.

5.3 Additive proper-time offset versus multiplicative memory

The distinction can be stated in one line. Standard accumulation gives

$$\Delta\tau_N = N\Delta\tau_1, \tag{30}$$

while the proposed constitutive memory gives

$$Q_N = Q_0 \prod_{n=1}^{N} \exp(-\lambda h_n). \tag{31}$$

The first changes the intercept of a clock comparison. The second changes its future slope.

6 A Local Covariant Completion

A bare dependence on the entire past worldline can look nonlocal. Memory can instead be implemented locally by introducing an internal state whose current value summarizes the past. Let

$$Q = \mathrm{e}^{\sigma}, \tag{32}$$

where σ is a scalar carried by the material. Let u^μ be the four-velocity field of a co-rotating material congruence. Its local rest-space projector is

$$h_{\mu\nu} = g_{\mu\nu} + \frac{u_\mu u_\nu}{c^2}. \tag{33}$$

The vorticity tensor and pseudovector are

$$\omega_{\mu\nu} = h_\mu{}^\alpha h_\nu{}^\beta \nabla_{[\alpha} u_{\beta]}, \tag{34}$$

$$\omega^\mu = \frac{1}{2c} \epsilon^{\mu\nu\rho\sigma} u_\nu \nabla_\rho u_\sigma. \tag{35}$$

To retain orientation, let the material possess a spacelike unit vector n^μ orthogonal to u^μ. The signed local rotational scalar

$$\varpi = n_\mu \omega^\mu \tag{36}$$

changes sign when the orientation is reversed.

A minimal relaxation-source equation is

$$u^\mu \nabla_\mu \sigma = -\frac{\sigma - \sigma_{\mathrm{eq}}}{\tau_m} + \alpha \varpi, \tag{37}$$

where τ_m is a memory relaxation time. This equation produces continuous history accumulation, but it does not by itself single out completed cycles. For that purpose introduce an internal phase Θ,

$$u^\mu \nabla_\mu \Theta = \Omega_\Theta, \tag{38}$$

and replace the source by a periodic gate $G(\Theta)$:

$$u^\mu \nabla_\mu \sigma = -\frac{\sigma - \sigma_{\mathrm{eq}}}{\tau_m} + \alpha \varpi G(\Theta). \tag{39}$$

The cycle-averaged update is

$$\Delta\sigma_{\mathrm{cycle}} = \alpha \oint \varpi G(\Theta)\, \mathrm{d}\tau. \tag{40}$$

A microscopic theory would have to show why the integral in equation (40) is proportional to the Sagnac holonomy and determine the coefficient. The phenomenological model does not claim that this proportionality has already been derived.

The construction is local and causal: the present value of σ is a state variable governed by a differential equation. Its history dependence is no more formally nonlocal than magnetization, plastic strain, or a chemical concentration that retains information about past driving.

7 Why Rotation Is Naturally Helical

A point at fixed radius in a rotating spatial plane may be written as

$$x(t) = R\cos\Omega t, \qquad y(t) = R\sin\Omega t. \tag{41}$$

Its spacetime curve is

$$x^\mu(t) = (ct, R\cos\Omega t, R\sin\Omega t, 0)\,, \tag{42}$$

which is a helix in a three-dimensional embedding of (ct, x, y). A spatial circle is therefore the projection of a non-closed timelike worldline.

For a real astronomical body, the center of the local rotation is itself in motion. A terrestrial point can be decomposed schematically as

$$\boldsymbol{r}(t) = \boldsymbol{X}_{\mathrm{gal}}(t) + \boldsymbol{X}_{\odot}(t) + \boldsymbol{X}_{\oplus}(t) + R\left[\boldsymbol{e}_1(t)\cos\Theta(t) + \boldsymbol{e}_2(t)\sin\Theta(t)\right]. \tag{43}$$

After one local spin cycle,

$$\Delta\Theta = 2\pi, \qquad \boldsymbol{r}(t + T_{\mathrm{spin}}) \neq \boldsymbol{r}(t) \tag{44}$$

in a broader frame. The cycle is a closure of internal phase, not a return to the same spacetime event.

This observation is geometrically correct but insufficient by itself to create new physics. Whether a path appears circular, trochoidal, or helical in three -space can depend on the chosen reference frame. The memory source must therefore be tied to invariant or operationally defined structure: the vorticity of a material congruence, a signed proper acceleration invariant, an internal phase winding, or a measured Sagnac holonomy. The hypothesis is not "a helix looks different, therefore clocks drift." It is that a completed directed rotational phase may couple to a physical state variable in a way that is expressible without relying on a pictorial coordinate choice.

8 The Common-Mode Observability Problem

Suppose all local atomic standards acquire the same factor $Q(t)$:

$$\nu_i(t) = Q(t)\nu_i^{(0)}. \tag{45}$$

Then a ratio of two co-scaling local clocks is unchanged:

$$\frac{\nu_1(t)}{\nu_2(t)} = \frac{\nu_1^{(0)}}{\nu_2^{(0)}}. \tag{46}$$

A local comparison cannot detect a perfectly universal common factor. Similarly, if a Sagnac phase shift is converted to seconds with the same frequency standard that has undergone the putative drift, the factor can cancel from the reported value.

This is not evidence for the memory hypothesis. It is an identifiability problem. A universal rescaling has physical content only when it affects a dimensionless observable relative to a sector that does not co-scale in the same way.

Definition 1 (Physical observability condition)**.** *A common metrological drift is physically distinguishable from a change of units only if the theory predicts a change in at least one dimensionless ratio, for example*

$$\mathcal{R}_\nu(t) = \frac{\nu_{\mathrm{matter}}(t)}{\nu_{\mathrm{ext}}(t)}, \qquad \mathcal{R}_L(t) = \frac{\lambda_{\mathrm{ext}}(t)}{L_{\mathrm{matter}}(t)}. \tag{47}$$

Candidate external sectors include freely propagating radiation, clocks with a different rotational history, remote spacecraft, or distinct material transitions whose coupling to

Q is not universal. Each choice carries nontrivial propagation, synchronization, and environmental systematics. A credible theory must state which sector is independent and why.

9 Decisive Experimental Tests

9.1 Post-reunion slope test

Let two clocks be synchronized and co-located. Clock A remains on a reference platform. Clock B completes N directed loops. After the transport, both clocks are placed at the same location, velocity, gravitational potential, temperature, electromagnetic environment, and orientation. Define the subsequent reading difference

$$D(t) = N_B(t) - N_A(t). \tag{48}$$

Standard ideal-clock relativity predicts

$$D(t) = D_0, \qquad \frac{\mathrm{d}D}{\mathrm{d}t} = 0, \tag{49}$$

where D_0 contains the known accumulated proper-time offset.

The memory model predicts

$$D(t) = D_0 + \delta\nu_{BA}\, t + \text{noise and known systematics}, \tag{50}$$

with

$$\frac{\delta\nu_{BA}}{\nu_0} \simeq -\lambda N h \tag{51}$$

for weak memory and negligible relaxation during the hold period.

Prediction 1 (Persistent post-cycle slope)**.** *After all present local conditions are equalized, a nonzero, reproducible, direction-sensitive* $\mathrm{d}D/\mathrm{d}t$ *that scales with completed loop number is the primary signature of worldline memory.*

9.2 Direction reversal

A Sagnac-derived memory should be odd under orientation reversal:

$$\delta Q_{\text{east}} = -\delta Q_{\text{west}} \tag{52}$$

for a reversible linear coupling. A three-clock protocol is especially useful: one clock remains as a reference, one completes N eastward loops, and one completes N westward loops with matched speed and acceleration profiles. The antisymmetric combination

$$\delta\nu_{\text{odd}} = \frac{1}{2}\left(\delta\nu_{\text{east}} - \delta\nu_{\text{west}}\right) \tag{53}$$

rejects many direction-even thermal, mechanical, and aging effects.

9.3 Loop-count scaling and null cycles

The model predicts a controlled relation between the completed directed winding and the residual rate:

$$\delta\nu_{\text{odd}} \propto N. \tag{54}$$

A sequence with equal eastward and westward loops tests reversibility. If the memory is purely signed and conservative,

$$N_{\text{east}} = N_{\text{west}} \quad \Longrightarrow \quad Q_{\text{final}} = Q_{\text{initial}}. \tag{55}$$

If not, the theory requires an additional direction-even dissipative or magnitude-sensitive term.

9.4 Species dependence

A crucial distinction is whether Q is clock-specific, material-sector specific, or universal. Simultaneous comparisons of optical, microwave, mechanical-cavity, and nuclear transitions can measure coupling coefficients λ_i:

$$\frac{\delta\nu_i}{\nu_i} = -\lambda_i N h. \tag{56}$$

If all λ_i are equal, local clock ratios are blind to the common mode and an external reference becomes necessary. If they differ, current and future multi-species clock networks can provide stringent bounds.

9.5 Terrestrial, orbital, and deep-space histories

Clocks fixed to the Earth, orbiting the Earth, stationed near a rotational axis, or carried into deep space experience different congruence vorticities, proper accelerations, gravitational potentials, and phase windings. A complete model must predict

$$Q_{\text{ground}}(t), \qquad Q_{\text{orbit}}(t), \qquad Q_{\text{deep}}(t) \tag{57}$$

and separate memory from standard gravitational and kinematic effects. A space mission with repeated return and extended co-location phases would be a direct test.

10 Relation to Existing Relativistic Clock Evidence

The Hafele–Keating experiments observed direction-dependent time differences for transported cesium clocks and found agreement, within their experimental uncertainties, with the combined special- and general-relativistic predictions [3, 4]. GPS and related systems require continuous relativistic clock modeling, including Earth rotation and Sagnac corrections [5]. These achievements strongly support the standard proper-time framework.

They do not logically prove that every conceivable history-dependent constitutive variable is exactly zero. However, they and the broader body of clock-comparison data

constrain any non-common-mode memory. A large persistent rate change after transport would have produced calibration anomalies. The absence of an established anomaly is therefore evidence favoring a small coupling, a short relaxation time, a common-mode effect, or no effect at all.

A dedicated memory search differs from a conventional proper-time test in its analysis target. The conventional target is the accumulated offset at reunion. The proposed target is the frequency-ratio slope during a controlled post-reunion hold, with direction reversal and loop-count scaling. Existing archival data may already bound such a slope, but a defensible limit requires reanalysis of raw clock-frequency records rather than only final integrated offsets.

11 Conditional Cosmological Implications

A common drift of local standards raises an immediate cosmological question: could part of an observed spectral change reflect evolution of the local standard rather than propagation through an evolving geometry? This possibility must be formulated using dimensionless ratios.

Let $\lambda_*(t)$ be the local rest wavelength of a specified atomic transition and let $a(t)$ be the cosmological scale factor. Radiation emitted at $t_{\rm em}$ with wavelength $\lambda_*(t_{\rm em})$ is received at t_0 with

$$\lambda_{\rm rec}(t_0) = \lambda_*(t_{\rm em})\frac{a(t_0)}{a(t_{\rm em})} \tag{58}$$

under standard propagation. The observed redshift relative to the current laboratory line is

$$1 + z_{\rm obs} = \frac{\lambda_{\rm rec}(t_0)}{\lambda_*(t_0)} = \frac{a(t_0)}{a(t_{\rm em})}\frac{\lambda_*(t_{\rm em})}{\lambda_*(t_0)}. \tag{59}$$

If $\lambda_*(t)$ is constant, the standard relation is recovered. If a material memory changes λ_*, an additional factor appears.

Equation (59) does not by itself replace dark energy. A viable alternative must jointly fit supernova luminosity distances, baryon acoustic oscillations, cosmic microwave background anisotropies, structure growth, gravitational lensing, primordial abundances, and local clock constraints. It must also specify why the radiation sector and the local material sector evolve differently. The present paper therefore makes a methodological claim only:

> A history-dependent drift of local metrological standards is an empirically separate possibility and should be constrained before it is assumed to be identically zero in every cosmological interpretation.

No numerical dark-energy replacement is asserted here.

12 Objections and Responses

12.1 "Proper time already contains the complete history."

Proper time contains the metric history relevant to the spacetime interval. It does not automatically enumerate every possible internal material state. The proposed Q does not

replace τ; it modifies the constitutive map from τ to a physical cycle count. The same logical distinction appears between a prescribed strain history and a material law with or without hysteresis.

12.2 "A clock that changes rate is simply a bad clock."

That statement is definitional, not empirical. An ideal clock is defined to track proper time. A real clock can deviate because of environmental shifts, aging, fields, acceleration sensitivity, or hypothetical memory. The scientific question is whether a reproducible, universal or sector-specific history term remains after known disturbances are removed. Calling it "non-ideal" does not make it nonexistent.

12.3 "The Sagnac effect is only synchronization."

The Sagnac effect can be represented as a synchronization gap in rotating coordinates or as a worldline/light-path calculation in an inertial frame. Those descriptions are physically equivalent. The present hypothesis does not require a preferred coordinate system. It uses the operationally measured directed loop holonomy as a candidate source for a material state.

12.4 "The 207-ns value is not a daily loss."

Correct. In standard kinematics it is a per-loop slow-transport holonomy. The paper explicitly does not convert it into a daily secular recalibration as a standard result. Any such conversion belongs to the additional law for Q and must be tested.

12.5 "A universal drift is only a change of units."

Correct unless a dimensionless ratio changes. This is why the theory requires an independently evolving sector or non-universal couplings λ_i. Without such an observable, the universal version has no empirical content.

12.6 "Existing clocks already rule this out."

They strongly constrain non-common-mode, long-lived, and sufficiently large memory. They do not replace a quantitative bound on the specific antisymmetric, loop-count-scaled post-reunion signal defined here. The correct response is to calculate or measure a limit on λ and τ_m, not to declare the parameter logically forbidden.

13 Falsifiability Conditions

The hypothesis is falsifiable in any specified parameter regime. A concrete model is excluded if controlled experiments show that

$$\left|\frac{\delta\nu_{\mathrm{odd}}}{\nu}\right| < \epsilon_{\mathrm{exp}} \tag{60}$$

while it predicts a larger value. More generally, the proposed mechanism is disfavored if all of the following hold across the relevant sensitivity range:

(1) no persistent post-reunion frequency slope is found;

(2) no direction-odd component is found;

(3) no scaling with completed loop number is found;

(4) no relaxation signature is found;

(5) no species-dependent or external-reference dimensionless ratio changes;

(6) cosmological applications require unrelated tuning inconsistent with local limits;

(7) a proposed microscopic completion violates causality, covariance, stability, or energy-momentum conservation.

A null result does not invalidate proper-time geometry; it bounds or removes the added memory sector and returns the theory toward $Q = 1$.

14 Discussion

The conceptual dispute can now be stated without ambiguity. Standard relativity accepts the physical consequences of time dilation: different worldlines accumulate different proper times, and clocks can reunite with measurably different readings. What it does not include in the ideal-clock model is a further persistent alteration of the clock's constitutive rate due to the past worldline.

There is no contradiction in the standard formulation. There is an assumption. The assumption is justified pragmatically by the success and reproducibility of ideal-clock behavior, but it is not a logical theorem that excludes every hidden material or phase state. Conversely, the mere existence of Sagnac holonomy does not prove memory. A bridge law such as equation (24) or equation (39) is required.

This balance matters methodologically. A new hypothesis should not be rejected because it departs from an idealization; nor should it be accepted because the idealization is not logically forced. It must specify a state variable, dynamics, observables, parameter values, and null tests. The worldline-memory proposal is useful precisely because it converts a philosophical question into a slope measurement after reunion.

15 Conclusion

The standard terrestrial numbers are unambiguous. Under an idealized same -potential comparison, a co-rotating equatorial clock accumulates approximately 103.697 ns less proper time than a non-rotating clock during one sidereal day. A completed directed equatorial loop has a one-direction Sagnac/slow-clock-transport holonomy of approximately 207.386 ns. Their exact relation is

$$\mathcal{H}_{\oplus} = (\gamma_{\oplus} + 1)\Delta\tau_{104}. \tag{61}$$

Both are standard relativistic effects, but they correspond to different comparison protocols.

The new claim of this paper is not that standard relativity fails to recognize these effects. It is that the step from proper-time accumulation to a history-independent clock response is constitutive rather than logically mandatory. A wider model can retain the standard spacetime interval while introducing a material state Q:

$$\mathrm{d}N = \nu_0 Q \, \mathrm{d}\tau. \tag{62}$$

The ideal-clock theory is recovered at $Q = 1$. A history-dependent sector allows directed rotational cycles to alter Q, creating metrological hysteresis.

The decisive experimental distinction is simple. Standard relativity predicts a fixed reading offset after reunion and equal subsequent rates. Worldline memory predicts, in addition, a persistent post-reunion frequency slope that is direction-sensitive and scales with the number of completed loops. A carefully controlled three-clock experiment can therefore place a direct bound on the coupling or detect it.

The proposal remains a hypothesis. Its microscopic carrier, covariance, stability, universality, relaxation, and coupling to matter and radiation are open. Its cosmological relevance is conditional and cannot be invoked as a substitute for dark energy without a joint fit to the full observational data. Nevertheless, the logical and experimental point is definite:

> Proper time can be real, Sagnac holonomy can be real, and the ideal-clock response can remain an empirically successful limit, while a history-dependent constitutive extension remains logically possible and directly testable.

A Numerical Earth Evaluation

Using equation (5),

$$V = \Omega R = 465.101\,084\,9\,\mathrm{m/s}, \tag{63}$$

$$T_{\mathrm{sid}} = \frac{2\pi}{\Omega} = 86\,164.100\,637\,\mathrm{s}, \tag{64}$$

$$\beta = 1.5514102 \times 10^{-6}, \tag{65}$$

$$\gamma_\oplus - 1 = 1.20348 \times 10^{-12}. \tag{66}$$

The exact fixed-duration deficit is

$$T_{\mathrm{sid}} \left(1 - \sqrt{1 - \beta^2}\right) = 103.6969\,\mathrm{ns}. \tag{67}$$

The exact slow-clock holonomy is

$$\gamma_\oplus \frac{2\pi\Omega R^2}{c^2} = 207.3861\,\mathrm{ns}. \tag{68}$$

The two-beam Sagnac proper-time difference at the equatorial detector is

$$2\mathcal{H}_\oplus = 414.7722\,\mathrm{ns}. \tag{69}$$

B Minimal Data-Analysis Model for a Memory Search

For clock pair i, j, let the measured fractional-frequency difference after reunion be

$$y_{ij}(t) = \frac{\nu_i(t) - \nu_j(t)}{\nu_0}. \tag{70}$$

A practical regression model is

$$y_{ij}(t) = b_0 + b_1 t + b_T \Delta T(t) + b_B \Delta B(t) + b_g \Delta g(t) + b_P \Delta P(t) + \eta(t), \tag{71}$$

where environmental covariates include temperature, magnetic field, gravitational-potential residuals, pressure, and other clock-specific shifts. For east and west histories, the memory estimator is the antisymmetric slope

$$\widehat{b}_{\mathrm{mem}} = \frac{1}{2}\left(\widehat{b}_{1,\mathrm{east}} - \widehat{b}_{1,\mathrm{west}}\right). \tag{72}$$

The inferred coupling in the weak discrete model is

$$\widehat{\lambda} = -\frac{\widehat{b}_{\mathrm{mem}}}{\nu_0 N h / T_{\mathrm{hold}}}, \tag{73}$$

with the precise normalization adapted to whether the fitted observable is a frequency, fractional frequency, or accumulated phase. Blind direction labels, repeated reversals, independent clock species, and pre-registered analysis are essential because the predicted signal is a small residual slope.

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