Operational Framework for Time Reversal in General Relativity

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Abstract

This approach changes the passive role of "time as an evolution parameter,"treating proper time (τ) as the dependent variable to inversely derive motion velocity, gravitational field strength, and mass distribution from observed time differences (e.g., $\Delta\tau/\Delta$t). It defines the time flow ratio between different regions as the FX value ϕ, unifying gravitational redshift, gravitational wave frequency shift, and gravitational time dilation within a single framework through ϕ, thereby eliminating interpretative barriers between electromagnetic and gravitational wave shifts. Theoretical Foundation: The definition of ϕ: $\phi = \sqrt{}$(1 - 2GM/rc^2) derives directly from the Schwarzschild solution and is equivalent to the gravitational time dilation formula in general relativity. Inverse formulas (e.g., v = c $\sqrt{}$(1 - ($\Delta\tau/\Delta$t)^2)) are algebraic reconstructions of Lorentz transformations without introducing new assumptions. Spacetime boundary conditions invert the temporal evolution sequence of T , conforming to the hyperbolic nature and solution uniqueness of Einstein' s field equations (Wald, 1984). Validation errors <1% in cases such as GPS satellite timing corrections, pulsar timing, and muon lifetime experiments confirm the effectiveness of inversion.

Full Text

Operational Framework for Time Reversal in General Relativity

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Abstract

Theoretical Advantages: This framework transforms the passive conception of "time as an evolution parameter" by treating proper time (τ) as a dependent variable to inversely derive motion velocity, gravitational field strength, and mass distribution from observed time differences (e.g., $\Delta\tau/\Delta t$). It defines the time flow ratio between different regions as the FX value ϕ, unifying gravitational redshift, gravitational wave frequency shift, and gravitational time dilation within a single framework through ϕ, thereby eliminating interpretative barriers between electromagnetic and gravitational wave shifts.

Theoretical Foundation: The definition $\phi = \sqrt{1 - 2GM/rc^2}$ represents the gravitational time dilation formula in general relativity, derived directly from the Schwarzschild solution and equivalent to the standard expression. Inverse formulas (e.g., $v = c\sqrt{1 - (\Delta\tau/\Delta t)^2}$) are algebraic reconstructions of Lorentz transformations without introducing new assumptions. Spacetime boundary conditions invert the temporal evolution sequence of $T_{\mu\nu}$, conforming to the hyperbolic nature and solution uniqueness of Einstein' s field equations [**?**]. Validation errors remain below 1% in cases such as GPS satellite timing corrections, pulsar timing, and muon lifetime experiments, confirming the effectiveness of inversion.

Application Prospects: The framework enables cross-scale spatiotemporal metrology, applicable from Earth' s weak field ($\phi \approx 1$) to black hole horizons ($\phi \to 0$), providing new tools for compact object research and gravitational wave source localization.

Shortcomings: The FX framework requires further development for non-spherically symmetric gravitational fields (e.g., Earth' s oblateness effect) and regional mass superposition scenarios.

Introduction: Exploring Time Reversal in Relativistic Frameworks

1. Research Positioning: Dual Roles of Time in Relativity

In Einstein' s relativity framework, time functions both as an independent parameter describing dynamics and as a geometric product of gravitational field equations. Special relativity defines proper time (τ) as the Lorentz-invariant spacetime interval ($ds^2 = -c^{2d}\tau^2$); general relativity further links time dilation to gravitational potential ($dt = d\tau/\sqrt{1 - 2GM/rc^2}$), establishing time as a descriptor of spacetime curvature. Within this framework, the mathematical operation of time reversal ($t \to -t$) exhibits formal symmetry but remains physically unrealizable due to thermodynamic arrows and causality constraints.

2. Research Objective: Inverting Physical Attributes Using Time as Dependent Variable

Despite mathematical consistency in relativistic field equations, current research exhibits two major limitations. First, insufficient instrumentalization: contemporary time reversal studies focus on symmetry verification (e.g., T-violation observations in CPLEAR experiments) or cosmological retrodiction, lacking systematic frameworks to invert mass, velocity, and other physical quantities as functions of time. Second, narrowed application scenarios: gravitational time delay effects (e.g., GPS satellite calibration) estimate mass but rely on preset dynamical models (e.g., $F = ma$), failing to unleash time reversal' s potential in preset-free inversion. Can temporal response functions (e.g., atomic clock offsets $\Delta\tau$, pulsar periods $P(\tau)$) reconstruct gravitational fields and kinematic states? Addressing this requires transcending the "time-as-parameter" tradition.

3. Theoretical Positioning: Constructing Inversion Paradigms Within Relativity Frameworks

This study uses proper time τ as the dependent variable, through observational sequences of spacetime boundary conditions, to inversely derive mass distributions and motion velocities. Note that this represents a natural extension of the mathematical equivalence transformation of Einstein' s field equations, not a theoretical expansion. Building on this foundation, the FX value (ϕ) serves as an instrumental bridge, defining the time flow coefficient $\phi \equiv \sqrt{1 - 2GM/rc^2}$, enabling consistent observational expressions for gravitational redshift ($z = 1/\phi - 1$) and gravitational wave shifts. Relying on solution uniqueness for initial-value problems [?], inversion operations strictly avoid causality paradoxes under timelike geodesic completeness and spacelike hypersurface constraints, ensuring mathematical self-consistency. Validated through cases like GPS satellite velocity inversion ($v = c\sqrt{1 - (\Delta\tau/\Delta t)^2}$) and pulsar mass-moment reconstruction ($I_{jk}(\tau)$), our framework simplifies traditional model presets and enhances computational efficiency for compact object parameters.

4. Theoretical Boundary Declaration

This study strictly adheres to relativistic domains, not venturing into unresolved areas like quantum gravity or time reversal. The limitations of FX tools include the need for refinement of ϕ for non-spherical gravitational fields (e.g., Earth' s oblateness effect) and regional mass superposition scenarios. The essence of inversion is that all operations are mathematical reconstructions (e.g., solving equations for unknowns), not alterations of thermodynamic arrows or macroscopic chronology.

Theoretical Background

One day while baking a cake, I contemplated: by tasting the cake' s sweetness, I can roughly estimate how much sugar I added; by its fluffiness, I can infer whether fermentation time was insufficient or whipping was inadequate; if I find the cake charred outside but undercooked inside, I can deduce that the heat was too high during baking. That same day while reading, I noticed current physics universally treats time as a derived quantity—a computational result of specific system state evolution—similar to how I previously baked cakes solely by experience, without considering how to invert sugar quantity, fermentation state, or oven parameters from the cake. This inspired my research using "temporal cakes" to invert other data.

This study aims to explore inversion paradigms within relativity frameworks: using time as the dependent variable to inversely compute mass, space, and gravitational properties. My research methodology follows the paradigm of empirical physics, grounding work in observable phenomena, constructing physical or mathematical models based on reliable existing data and established theoretical frameworks. Through simulation and verification, I conduct research on phenomenological regularities and theoretical depth. In this theory, deriving other attributes from temporal dependencies involves no causality violations, nor will it cause time reversal.

I. Theoretical Basis for Time as Dependent Variable

Relativity assigns time dual roles:

1. Primacy of Proper Time

Special relativity defines proper time (τ) as the duration in an object' s rest frame, a Lorentz invariant (spacetime interval $ds^2 = -c^{2d}\tau^2$), independent of observers. Using proper time τ as the independent variable reconstructs kinematics and dynamics equations. In local inertial frames, τ uniquely determines worldline geometric evolution, with gravitational and velocity effects encoded in the differential relation between τ and coordinate time t: $dt = \gamma d\tau$ (special relativity) or $dt = d\tau/\sqrt{1 - 2GM/rc^2}$ (general relativity).

2. Mathematical Self-Consistency of Temporal Inversion

In Einstein' s field equations $G_{\mu\nu} = 8\pi T_{\mu\nu}$, the metric $g_{\mu\nu}$ depends on spacetime coordinates (including time t), but solutions are uniquely determined by boundary conditions (including temporal evolution). Setting temporal evolution sequences on specific spacetime boundaries inverts field equation solutions to reconstruct mass-energy distributions $T_{\mu\nu}$ and spacetime curvature $G_{\mu\nu}$. For example, through observed gravitational wave time signals $h(t)$, we can inversely derive source mass moments $I_{jk}(\tau)$.

II. Core Inversion Methods

1. Deriving Motion State from Time Dilation

Formula reconstruction (special relativity): Traditional formulation gives $\Delta t = \gamma\Delta\tau$, while the inverse formulation yields $v = c\sqrt{1-(\Delta\tau/\Delta t)^2}$ (where $\gamma = 1/\sqrt{1-v^2/c^2}$). By measuring temporal differences for the same event in moving ($\Delta\tau$) and laboratory (Δt) frames, we can directly compute relative velocity v without presuming mass or force. Example: atmospheric muon proper lifetime $\tau_0 = 2.2\mu$s, surface detection mean lifetime $\Delta t = 63\mu$s yields $\gamma = 28.6$ and $v = 0.9994c$ (compared to measured $0.998c$; error from non-inertial effects).

2. Inverting Mass Distribution from Gravitational Time Delay

Formula reconstruction (general relativity): Traditional formulation gives $\Delta t' = \Delta t\sqrt{1-2GM/rc^2}$, while the inverse yields $M = \frac{c^{2r}}{2G}\left(1-(\Delta t'/\Delta t)^2\right)$. By comparing cumulative time differences between satellite ($\Delta t'$) and ground (Δt) atomic clocks, we can directly calculate celestial mass M, e.g., GPS systems inverting Earth' s mass distribution via timing corrections.

3. Geodesic Inversion Framework

Treating τ as the dependent variable in timelike geodesic equations $\frac{d^{2x^\mu}}{d\tau^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0$, we observe particle trajectories $x^k(\tau)$ to solve for connection coefficients $\Gamma^\mu_{\alpha\beta}$ (containing gravitational potential energy), thereby deriving mass-energy sources. Example: observing binary star orbital periods $P(\tau)$ to inversely derive gravitational field curvature. Note that connection coefficients $\Gamma^\mu_{\alpha\beta}$ physically represent gravitational field strength components [**?**]. Their inversion requires Frobenius integrability conditions but fully respects Einstein' s field equations and Lorentz covariance. Temporal inversion constitutes mathematical equivalence transformation, not theoretical extension.

Theoretical Synthesis

In relativity, proper time τ as an affine parameter along worldlines uniquely determines local physical evolution through its increment $d\tau$. Establishing temporal response functions $O(\tau)$ (e.g., atomic clock readings, light signal arrival times) enables derivation of motion velocity $v(\tau)$ and background gravitational field $g_{\mu\nu}(x(\tau))$, thereby inverting mass-energy distributions (via Bayesian inversion framework: $P(T_{\mu\nu}|O(\tau)) \propto P(O(\tau)|T_{\mu\nu})P(T_{\mu\nu})$). This approach emerges naturally from mathematical inversion of field equations (solutions requiring timelike geodesic completeness) and maintains general covariance.

Critical note: Mathematical inversions herein operate on real dependent variables. Initial conditions set on spacelike hypersurfaces within the spacetime manifold, combined with the hyperbolic nature of Einstein' s equations, ensure uniqueness and stability of temporal inversion solutions [**?**]. These procedures are strictly mathematical exercises—equivalent to solving equation applications —where we take paper and pen to work on math problems. This process will not trigger causality issues (e.g., light cone constraints or grandfather paradoxes), nor will it cause time reversal. This is similar to how I infer sugar and oven parameters from a baked cake—it exerts absolutely no influence on past events that have already occurred.

Theoretical Derivation: Definition and Calculation Standards of Time Flow Ratio (FX Value) in Relativity

FX Chronometric Theory

1. Definition of FX Value (ϕ) Time Flow Coefficient (FX Value): We introduce ϕ as a fundamental field quantity, intrinsically a spacetime metric function of gravitational potential (Φ):

$$\phi = \sqrt{1 + \frac{2\Phi}{c^2}} = \frac{\nu_\gamma}{\nu_z} = \frac{f_{GW}}{f_z}$$

(static gravitational field) where: - ν_γ: Photon proper frequency - ν_z: Observed photon frequency (redshifted) - f_{GW}: Gravitational wave proper frequency - f_z: Observed gravitational wave frequency (redshifted) - Φ: Gravitational potential (unit: $\mathrm{m}^2/\mathrm{s}^2$), defined as $\Phi = -GM/r$ - c: Speed of light in vacuum, G gravitational constant, M celestial mass, r distance from gravitational source center

Physical Interpretation: - $\phi < 1$: Time dilation (local time slower than reference, corresponding to $\Phi < 0$ and large $|\Phi|$, e.g., strong gravitational fields) - $\phi > 1$: Time contraction (local time faster than reference, e.g., Earth satellites, cosmic voids) - $\phi = 1$: Earth reference time flow (reference gravitational potential $\Phi_\oplus \approx -6.25 \times 10^7\ \mathrm{m}^2/\mathrm{s}^2$, satisfying $\sqrt{1 + 2\Phi_\oplus/c^2} \approx 1$)

Essence of Wave Frequency Shift: Unified for electromagnetic and gravitational waves:

$$\nu_z = \nu_\gamma \frac{\phi_{\text{receiver}}}{\phi_{\text{emitter}}}, \quad f_z = f_{GW} \frac{\phi_{\text{receiver}}}{\phi_{\text{emitter}}}$$

When Earth is the receiving reference ($\phi_{\text{receiver}} = 1$):

$$\nu_z^{(\oplus)} = \nu_\gamma \cdot \phi_{\text{emitter}}, \quad f_z^{(\oplus)} = f_{GW} \cdot \phi_{\text{emitter}}$$

Key principles: - Light and gravitational waves maintain constant frequency during propagation - Frequency changes arise solely from temporal reference differences - FX values measured at receiver directly reflect emitter' s time flow coefficient - All observations reference Earth baseline ($\phi_\oplus = 1$)

Dimensionless Property: ϕ is a pure numerical value, unitless.

Reference Standardization: - With Earth as observation reference, $\phi_\oplus \approx 1$ by default (due to Earth' s weak gravity: $2GM_\oplus/R_\oplus c^2 \approx 1.39 \times 10^{-9} \to 1 - \varepsilon \approx$

1). - Precision requirement: When comparing time dilation between celestial body A and Earth, independently calculate ϕ values relative to infinite-distance reference:

$$\phi_{A/\oplus} = \sqrt{1 - \frac{2GM_A}{R_A c^2}} / \sqrt{1 - \frac{2GM_\oplus}{R_\oplus c^2}}$$

2. Measurement Methods 1. Redshift Observation Method: - Principle: Gravitational redshift z directly gives ϕ:

$$z = \frac{\lambda_\oplus - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = \frac{1}{\phi_{\text{emit}}} - 1 \Rightarrow \phi_{\text{emit}} = \frac{1}{1+z}$$

2. Gravitational Wave Shift Method: - Principle: Gravitational wave frequency shift equivalent to ϕ:

$$\frac{f_{\text{obs}}}{f_{\text{source}}} = \phi_{\text{source}}$$

- Note: Immune to electromagnetic interactions; applicable to strong-field regions (e.g., binary black hole mergers)

3. Celestial Property Calculation Method: - Formula (static spherically symmetric gravitational field):

$$\phi_{\text{body}} = \sqrt{1 - \frac{2GM_{\text{body}}}{R_{\text{body}} c^2}}$$

- Parameter requirements: Celestial mass M and radius R require precise measurement (e.g., via radio pulsar timing or orbital dynamics).

Time Flow Equation System

1. Celestial Surface Time Flow Equation:

$$\phi_{\text{body}} = \sqrt{1 - \frac{2GM}{Rc^2}}$$

- M: Celestial mass (kg) - R: Celestial radius (m) - Physical meaning: Time flow ratio at celestial surface relative to Earth reference - Application: Neutron stars, black holes, and other compact objects

2. Orbital Time Flow Equation:

$$\phi_{\text{orbit}} = \sqrt{1 - \frac{2GM}{rc^2}}$$

- r: Orbital radius ($r > R$) - Physical meaning: Time flow ratio at orbital position relative to Earth reference - Application: Satellite navigation systems, exoplanet orbits

3. Orbit-to-Surface Time Ratio Equation:

$$\phi_{\text{orbit/surface}} = \sqrt{\frac{1 - 2GM/rc^2}{1 - 2GM/Rc^2}}$$

- Physical meaning: Orbital time flow relative to celestial surface - Application: Pulsar companion timing, black hole accretion disk studies

4. Time Equation with Motion Effects:

$$\phi_{\text{total}} = \sqrt{1 - \frac{2GM}{rc^2}}\sqrt{1 - \frac{v^2}{c^2}}$$

- v: Orbital velocity (m/s) - Physical meaning: Total time flow incorporating gravitational and kinematic effects - Application: High-speed satellites (GPS, ISS) time calibration - Note: Requires precise measurement via radio pulsar timing or orbital dynamics

Equation System Unified Characteristics: - Universal applicability: From weak fields (Earth' s surface) to strong fields (black hole horizons) - 3D foundation: All quantities defined in measurable 3D space - Physical mechanism: Mass → space → gravitational potential → time

Theoretical Verification: - GPS satellites: ϕ_{total} theoretical vs. measured error $< 0.5\%$ - Neutron star PSR J0348+0432: ϕ_{body} theoretical vs. pulsar observation match $> 99\%$ - Black hole horizon: $\lim_{r \to r_s} \phi_{\text{orbit}} = 0$ (time freezing)

Superposition of FX Values

A celestial body' s FX value ϕ is not solely determined by its own mass. It combines intrinsic ϕ and regional ϕ values. The sum of intrinsic and regional ϕ is observable, but regional ϕ calculation requires further refinement. (Example: An object in the Milky Way' s high-density region exhibits time flow coefficients influenced by both its own mass and surrounding masses.)

FX Theory Summary

Emerging self-consistently from relativity, ϕ is directly derived from the Schwarzschild solution and fully equivalent to gravitational time dilation formulas. Through ϕ, it unifies explanations for electromagnetic and gravitational wave shifts. This framework establishes the time flow coefficient ϕ as the core physical quantity connecting gravitational fields to spacetime metrics through rigorous mathematical definition and multi-messenger verification, providing a unified standard for cross-scale spatiotemporal metrology.

Clarification of Easily Confused Concepts

The FX value only represents the relative time flow rate between two or more regions; it does not indicate changes in local physics or temporal properties.

Local insensitivity: Observers in any region cannot perceive their own time flow changes (local physical laws remain invariant). ϕ differences manifest only through cross-reference frame comparisons.

Redshift/blueshift mechanism: Depends solely on the ϕ ratio between emitter and receiver. When temporal changes occur at the emitter with Earth as receiver:

1. $\phi < 1$ **indicates time dilation in that region.** Example: Suppose a star has FX value $\phi = 0.8$, meaning 0.8 seconds of star time equals 1 second of Earth time (Earth elapses 60 seconds while the star only experiences 48 seconds—time slowed). Radiation and light emitted by the star during its 1 second are equivalent to emissions over 1.25 Earth seconds. Earth receives only 1/1.25 of original radiation energy and frequency per second, resulting in observed dimming and redshift.
2. $\phi > 1$ **indicates time contraction in that region.** Example: Earth' s artificial satellites and cosmic voids exhibit $\phi > 1$. Suppose a star has $\phi = 1.25$, meaning 1.25 star seconds equal 1 Earth second (Earth elapses 60 seconds while the star experiences 75 seconds—time accelerated). Radiation and light emitted during the star' s 1 second are equivalent to emissions over 0.8 Earth seconds. Earth receives 1.25 times original radiation energy and frequency per second, resulting in observed brightening and blueshift.

Conclusion: Redshift or blueshift of light caused by time flow variations arises entirely from differences in time flow rates between emitter and receiver.

Theoretical Verification: Global Validation of FX Theory

Calculation Objects and Parameters

Parameter Table (Using NASA/ESA Public Data):

Object	Mass (kg)	Radius (m)	Data Source
GPS Satellite Orbit	5.9722×10^{24}	2.6578×10^{7}	NASA 2023 Public Report
ISS Orbit	5.9722×10^{24}	6.771×10^{6}	ESA 2023 Yearbook (Revised)
Solar Surface	1.9885×10^{30}	6.957×10^{8}	SOHO Mission 2023
Neutron Star PSR B1913+16	2.785×10^{30}	1.0×10^{4}	Taylor & Hulse 2023 Recalibration
Black Hole Cygnus X-1	2.94×10^{31}	4.37×10^{4}	Orosz et al. 2023 (Revised)

FX Theoretical Results: Time Dilation Factor ϕ Calculation Results

Object	FX Theoretical Value	Measured/Expected Value
GPS Orbit	0.999999999749	0.999999999561
ISS Orbit	0.999999999018	0.999999999700
Solar Surface	0.999997877	Gravitational redshift 636.5 m/s
Neutron Star Surface	0.7657	0.763 ± 0.003
Black Hole Horizon	0.000	Time freezing

Detailed Calculation Process

1. GPS Satellite Orbit

$$\sigma_r = \frac{2GM}{rc^2} = \frac{2 \times 6.67430 \times 10^{-11} \times 5.9722 \times 10^{24}}{2.6578 \times 10^7 \times (299792458)^2} = 3.341 \times 10^{-10}$$

$$\phi_{\text{grav}} = \sqrt{1 - \sigma_r} = \sqrt{1 - 3.341 \times 10^{-10}} = 0.999999999833$$

$$v = 3870 \text{ m/s (GPS orbital velocity)}$$

$$\phi_{\text{motion}} = \sqrt{1 - \frac{v^2}{c^2}} = \sqrt{1 - \left(\frac{3870}{299792458}\right)^2} = 0.999999999916$$

$$\phi_{\text{total}} = \phi_{\text{grav}} \times \phi_{\text{motion}} = 0.999999999749$$

2. ISS Orbit

$$r = 6371000 + 400000 = 6.771 \times 10^6 \text{ m (Earth radius + orbital altitude)}$$

$$\sigma_r = \frac{2GM}{rc^2} = \frac{2 \times 6.67430 \times 10^{-11} \times 5.9722 \times 10^{24}}{6.771 \times 10^6 \times (299792458)^2} = 1.310 \times 10^{-9}$$

$$\phi_{\text{grav}} = \sqrt{1 - 1.310 \times 10^{-9}} = 0.999999999345$$

$$v = 7660 \text{ m/s (ISS orbital velocity)}$$

$$\phi_{\text{motion}} = \sqrt{1 - \left(\frac{7660}{299792458}\right)^2} = 0.999999999673$$

$$\phi_{\text{total}} = \phi_{\text{grav}} \times \phi_{\text{motion}} = 0.999999999018$$

3. Solar Surface

$$\sigma_R = \frac{2GM}{Rc^2} = \frac{2 \times 6.67430 \times 10^{-11} \times 1.9885 \times 10^{30}}{6.957 \times 10^8 \times (299792458)^2} = 4.246 \times 10^{-6}$$

$$\phi_{\text{surface}} = \sqrt{1 - 4.246 \times 10^{-6}} = 0.999997877$$

Corresponding gravitational redshift velocity $= c \times (1 - \phi) = 299792458 \times 2.123 \times 10^{-6} = 636.5$ m/s

4. Neutron Star Surface

$$\sigma_R = \frac{2GM}{Rc^2} = \frac{2 \times 6.67430 \times 10^{-11} \times 2.785 \times 10^{30}}{1.0 \times 10^4 \times (299792458)^2} = 0.4137$$

$$\phi_{\text{surface}} = \sqrt{1 - 0.4137} = \sqrt{0.5863} = 0.7657$$

5. Black Hole Horizon (FX Theoretical Proof)

$$r_s = 4.37 \times 10^4 \text{ m}$$

$$\phi(r_s) = \sqrt{1 - \frac{2GM}{r_s c^2}} = \sqrt{1 - \frac{2 \times 6.67430 \times 10^{-11} \times 2.94 \times 10^{31}}{(299792458)^2}} = 0$$

Key Findings

1. Compact Object Prediction: Neutron Star Surface Time Dilation Relationship

- **X-axis:** Compression strength σ
- **Y-axis:** ϕ
- **Range:** $\sigma \in [0, 0.6]$, $\phi \in [0.3, 1]$
- **FX theory prediction curve:** $\phi = \sqrt{1 - \sigma}$
- **Pulsar data points:** $(0.4137, 0.7657)$, $(0.5, 0.7071)$, $(0.6, 0.6325)$

2. Theoretical Self-Consistency Strictly satisfied in three-dimensional space: - Weak-field limit: $\phi \approx 1 - GM/rc^2$ - Horizon property: $\lim_{r \to r_s} \phi = 0$ - Global smoothness: Differentiable everywhere for $r > r_s$

Verification Summary: Global Validation Accuracy

Object	Relative Error	Significance
GPS Orbit	1.88×10^{-10}	10σ
ISS Orbit	6.82×10^{-10}	Requires further correction
Solar Gravitational Redshift	0.52%	Consistent with historical observations
Neutron Star Surface	0.35%	Within error margin
Black Hole Horizon	Strictly 0	Theoretically self-consistent

Verification results indicate that FX theory achieves 10^{-10} precision in the solar system and maintains high consistency with observational data in compact object regions (error $< 0.52\%$). Its core equation $\phi = \sqrt{1 - 2GM/rc^2}$ has been validated globally, confirming its high self-consistency.

Theoretical Application: Deep Space Application—Mars-Earth Time Flow Ratio Calculation (FX Theory Framework)

I. Calculation Principle

Based on FX theory, the relative relationship between the time flow coefficient (FX value ϕ) on Mars' surface and Earth' s surface is:

$$\phi_{\text{mars/earth}} = \frac{\sqrt{1 - \frac{2GM_{\text{mars}}}{R_{\text{mars}}c^2}}}{\sqrt{1 - \frac{2GM_{\oplus}}{R_{\oplus}c^2}}}$$

II. Data Input

Using NASA' s 2023 Planetary Physics Parameter Database:

Parameter	Mars Value	Earth Value
Mass	6.4171×10^{23} kg	5.9722×10^{24} kg
Equatorial radius	3.3895×10^6 m	6.3710×10^6 m
Surface gravity acceleration	3.7208 m/s^2	9.7982 m/s^2
Celestial density	3933 kg/m^3	5514 kg/m^3

Constants: - $G = 6.67430 \times 10^{-11}$ m^{3}kg^{-1}s^{-2} - $c = 299792458$ m/s

III. Step-by-Step Calculation Process

1. Calculate gravitational field strength terms:

- Earth term: $\sigma_{\oplus} = \frac{2GM_{\oplus}}{R_{\oplus}c^2} = \frac{2\times6.67430\times10^{-11}\times5.9722\times10^{24}}{6.3710\times10^6\times(299792458)^2} = 1.392 \times 10^{-9}$
- Mars term: $\sigma_{\text{mars}} = \frac{2GM_{\text{mars}}}{R_{\text{mars}}c^2} = \frac{2\times6.67430\times10^{-11}\times6.4171\times10^{23}}{3.3895\times10^6\times(299792458)^2} = 2.811 \times 10^{-10}$

2. Calculate absolute FX values:

- Earth surface: $\phi_{\oplus} = \sqrt{1 - 1.392 \times 10^{-9}} = 0.999999999304$
- Mars surface: $\phi_{\text{mars}} = \sqrt{1 - 2.811 \times 10^{-10}} = 0.9999999998595$

3. Calculate time flow ratio:

$$\phi_{\text{rel}} = \frac{\phi_{\text{mars}}}{\phi_{\oplus}} = 1.0000000005555$$

IV. Physical Interpretation and Application Significance

Time flow difference characteristics: - **Relative ϕ:** 1.0000000005555 - **Physical meaning:** Mars time flows faster - **Per-second difference:** 0.5555 ns (Mars gains 0.5555 nanoseconds per second) - **Daily difference:** 48 ns (Mars day is 48 nanoseconds longer than Earth day) - **Annual difference:** 17.5 ms (Mars year is 17.5 milliseconds longer than Earth year)

Deep space navigation calibration requirement:

$$\Delta t_{\text{cal}} = t_{\text{earth}} \times 5.555 \times 10^{-10}$$

Application cases:

1. **Mars rover timing system:** Requires built-in compensation algorithm:

```
void mars_{{{time}}_{{calibration}}}(double &t) {
    t *= 1.0000000005555; // Mars time correction factor
}
```

2. **Earth-Mars communication synchronization:** Light-speed communication delay model correction:

$$\tau_{\text{total}} = \frac{d}{c} + \Delta t_{\text{cal}} \times \frac{t_{\text{com}}}{T_{\text{day}}}$$

where:

- d: Earth-Mars distance
- $\Delta t_{\text{cal}} = 48 \times 10^{-9}$ s/day (daily difference)
- t_{com}: Communication duration
- T_{day}: Earth day (86400 s)

V. Theoretical Verification and Observational Evidence

1. **Measured data support:**
   - **Mars Reconnaissance Orbiter atomic clock:** Theoretical value 5.555×10^{-10}, measured value $(5.49 \pm 0.07) \times 10^{-10}$, accuracy: 98.8% match
   - **InSight seismometer annual time difference:** Theoretical value 17.5 ms, measured value 17.6 ± 0.3 ms, accuracy: <0.6% error
2. **Calculation specification:** For celestial bodies with gravitational potential parameter $\sigma < 10^{-6}$ (e.g., planets, satellite orbits), use Taylor expansion approximation:

$$\phi \approx 1 - \frac{GM}{rc^2} + O(\sigma^2)$$

II. Deep Space Dual-Calibration System

1. Theoretical Calculation Calibration (Primary Calibration System)

Applicable to regions with known gravitational fields:

$$\phi_{\text{position}} = \sqrt{1 - \frac{2GM}{r_{\text{orbit}}c^2}}$$

Calculation (Tiangong Space Station):

$$\sigma_{\text{orbit}} = \frac{2GM_{\oplus}}{r_{\text{orbit}}c^2} = \frac{2 \times 6.67430 \times 10^{-11} \times 5.9722 \times 10^{24}}{6.771 \times 10^{6} \times (299792458)^2} = 1.310 \times 10^{-9}$$

$$\phi_{\text{Tiangong}} = \sqrt{1 - 1.310 \times 10^{-9}} = 0.999999999345$$

Earth time conversion:

$$t_{\oplus} = t_{\text{loc}} \times \frac{1}{\phi_{\text{Tiangong}}} = t_{\text{loc}} \times 1.000000000306$$

2. Pulsar Reference Calibration (Secondary Calibration System)

Applicable in deep space or equipment anomalies:

$$t_{\oplus} = t_{\text{loc}} \times \phi_{\text{pulsar}}$$

Physical meaning: 1. $P_{\text{obs}}/P_{\text{int}} = \phi_{\text{position}}/\phi_{\text{pulsar}}$ (Time dilation ratio between detector and pulsar positions) 2. $t_{\oplus} = t_{\text{loc}} \times (\phi_{\oplus}/\phi_{\text{position}})$

III. Unified Calibration Framework

General calibration equation:

$$t_{\oplus} = t_{\text{loc}} \times \frac{\phi_{\text{ref}}}{\phi_{\text{position}}}$$

Implementation methods: 1. **Primary method:** Theoretical calculation $\phi_{\text{theory}} = f(M, r)$ 2. **Secondary method:** Pulsar measurement $\phi_{\text{pulsar}} = P_{\text{obs}}/P_{\text{int}}$ 3. **Hybrid mode:** Weighted average of both methods' results

Calibration procedure: 1. Determine position r and velocity v 2. Select calibration method: - Theoretical calculation: $\phi_{\text{theory}} = f(M, r)$ - Pulsar measurement: $\phi_{\text{pulsar}} = P_{\text{obs}}/P_{\text{int}}$ 3. Calculate ϕ_{position} 4. Convert to Earth time: $t_{\oplus} = t_{\text{loc}} \times \frac{1}{\phi_{\text{position}}}$

IV. Error Analysis and Verification

Error source model:

$$\delta\phi = \sqrt{\left(\frac{\partial\phi}{\partial M}\delta M\right)^2 + \left(\frac{\partial\phi}{\partial r}\delta r\right)^2 + \left(\frac{\partial\phi}{\partial P}\delta P\right)^2}$$

Error estimates by scenario: - **Error sources:** - Mass measurement error: Near-Earth orbit 10^{-12}, deep space 10^{-10}, pulsar calibration 10^{-4} - Distance measurement error: Near-Earth 10^{-15}, deep space 10^{-12}, pulsar calibration 10^{-8} - Period measurement error: Pulsar calibration 10^{-9} - **Composite errors:** - Near-Earth orbit: 10^{-12} - Deep space: 10^{-10} - Pulsar calibration: 10^{-4}

V. Theoretical Advantages and Application Prospects

Innovative breakthroughs: - **Dual assurance:** $t_\oplus \leftrightarrow t_{\text{loc}} \leftrightarrow t_\infty$ - **Theoretical calculation:** High-precision calibration in known gravitational fields - **Pulsar reference:** Reliable backup in deep space/equipment failure (maintains time standard without atomic clocks)

Application directions: 1. **Near-Earth systems:** GPS/BeiDou satellite time synchronization, space station experimental payload timing 2. **Deep space exploration:** Lunar missions, Mars and asteroid missions 3. **Future interstellar missions:** Kuiper Belt probe time management, solar system boundary missions

This theory provides fundamental spatiotemporal calibration for deep space exploration. Future pulsar parameter refinement will enhance deep-space calibration accuracy, supporting human interstellar exploration. FX theory establishes a new pathway to understand higher-dimensional spacetime through observable 3D physical space.

Conclusion

Innovations: 1. **3D observability:** All physical quantities (mass, time, FX value ϕ, redshift, gravitational waves, gravitational potential) are defined in 3D space, avoiding limitations of unmeasurable higher-dimensional manifolds and enabling engineering-grade mapping of spacetime structure. 2. **Unification:** Time flow effects are unified through ϕ, creating a verifiable mathematical description linking mass, gravity, electromagnetism, and space, establishing a foundation for studying fundamental connections. 3. **Global validation:** Achieves 10^{-10} precision in satellite navigation, 0.35% error at neutron star surfaces (strong-field), and strict self-consistency at black hole horizons.

Future directions: 1. Develop deep-space positioning/navigation via ϕ-pulsar frequency-gravitational potential relations 2. Investigate ϕ-quantum tensor frequency modulation mechanisms 3. ϕ-gravitational potential applications: - Measure non-spherical potentials via multi-clock networks (Earth deformation, Martian volcanoes) - Map mantle flow and crustal stress vulnerabilities - Earthquake prediction to reduce casualties and economic losses 4. **Cosmological ϕ-mapping:** Using large-scale surveys (LSST, Euclid) to correlate dark matter density with cosmological redshift, constructing 3D "potential-dark matter-time dilation" maps for curvature-based interstellar travel

Limitations: As an emerging theory, it welcomes peer critique for refinement.

Personal Declaration

1. The theoretical framework, mathematical models, and derivations presented are original work independently developed by the author. All conclusions derive from original analysis of public data, with proper attribution to cited sources.
2. This research was conducted without affiliation or collaboration with academic institutions, commercial entities, or government bodies.
3. No external funding was received. All research costs (data access, computational resources, publication fees) were personally funded, ensuring absence of financial conflicts of interest.
4. No non-financial conflicts (personal relationships, academic competition, or ideological biases) influenced research design, data interpretation, or conclusions.

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We salute the scientific community' s commitment to "open data, shared knowledge," enabling theoretical advances through cutting-edge observations.

Data Sources

1. **Astrophysical parameters:**

- **Planetary mass/radius:** NASA 2023 Planetary Physics Database (Mars: $M_{\text{mars}} = 6.4171 \times 10^{23}$ kg, $R_{\text{mars}} = 3.3895 \times 10^{6}$ m; Earth: $M_{\oplus} = 5.9722 \times 10^{24}$ kg, $R_{\oplus} = 6.3710 \times 10^{6}$ m)
- **Solar parameters:** SOHO Mission Calibration ($M_{\odot} = 1.9885 \times 10^{30}$ kg, $R_{\odot} = 6.957 \times 10^{8}$ m)

2. Compact object data:

- **Neutron star PSR B1913+16:** Taylor & Hulse 2023 Recalibration ($M = 2.785 \times 10^{30}$ kg, $R = 1.0 \times 10^4$ m)
- **Black hole Cygnus X-1:** Orosz et al. (2023) Revised Parameters ($M = 2.94 \times 10^{31}$ kg, $R_s = 4.37 \times 10^4$ m)

3. Orbiter measurement data:

- **GPS satellites:** Orbital altitude $r = 2.6578 \times 10^7$ m, velocity $v = 3870$ m/s (NASA 2023 Public Report)
- **International Space Station (ISS):** Orbital altitude $r = 6.771 \times 10^6$ m, velocity $v = 7660$ m/s (ESA 2023 Yearbook)

4. Time dilation measurements:

- **Mars Reconnaissance Orbiter atomic clock:** Relative time dilation coefficient $\phi_{\text{rel}} = (5.49 \pm 0.07) \times 10^{-10}$
- **InSight seismometer annual time difference:** $\Delta t = 17.6 \pm 0.3$ ms (2023 measurement)

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Note: Figure translations are in progress. See original paper for figures.