

The Vacuum Gravity Model (VGM): Metric-Free Scalar Framework for Gravitation and Inertia

Could gravitation, inertia, and time arise from measurable variations in the vacuum itself?

— **Vacuum Gravity Model (CE000)**—

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Abstract

We present the **Vacuum Gravity Model (VGM)**, a metric-free scalar framework in which gravitation, inertia, and time emerge from the dynamics of an observable vacuum field, the *cadence field* $A = \Phi/c^2$. The model replaces spacetime curvature by measurable variations of the vacuum’s inertial tension and reproduces exactly all first post-Newtonian (1PN) predictions of General Relativity: $\gamma = \beta = \sigma = 1$ within experimental precision. From a minimal variational principle, the Lagrangian density

$$\mathcal{L}_{\text{VGM}} = \frac{M^2}{2}(\partial_\mu A \partial^\mu A) - \frac{1}{2}m_A^2 A^2 - \frac{1}{4}\lambda_A A^4 + \alpha_m A \rho c^2,$$

defines a closed field equation linking the cadence amplitude to matter and light through a single metrological coupling $F_\Phi \sim 4\pi G/c^2$. Vacuum rigidity introduces an intrinsic length λ and propagation velocity c_A , supporting transverse (rigidity-wave) and longitudinal (cadence) modes with dispersion $\omega^2 = c_A^2 k^2 + m_A^2 c_A^4$. A Born-Infeld saturation at A_{max} regularizes high-field regimes and yields late-time cosmic acceleration without a cosmological constant. The full parameter set $\{\alpha_m, m_A, \lambda_A, c_A, H_\zeta\}$ maps directly to laboratory and cosmological observables, enabling explicit falsification via clock networks, light-time and deflection tests, interferometry, and redshift-drift surveys. VGM thus provides a unified, experimentally decidable representation of gravity and inertia as manifestations of the vacuum’s measurable rigidity and cadence, bridging metrology, gravitation, and cosmology without invoking spacetime curvature.

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Note to the Reader.

This paper belongs to the exploratory development of the *Vacuum Gravity Model (VGM)*, a scalar–inertial framework that investigates whether inertia, gravitation, and cosmic evolution can emerge from the dynamics of a structured vacuum field rather than from spacetime curvature.

The philosophical stance of this work follows the tradition of open theoretical inquiry pursued by the broader scientific community—ranging from scalar–tensor gravitation (Brans–Dicke), to emergent and superfluid vacuum analogies (Volovik, Afshordi, Verlinde), and to Born–Infeld and Machian approaches to inertia. In this spirit, the VGM does not aim to replace General Relativity, the Standard Model, or Quantum Field Theory, but to offer a complementary perspective that may highlight alternative pathways toward their unification.

The goal is not reiteration, but exploration: to examine whether the same observed phenomena might be understood through a different conceptual lens—one grounded in metrology, scalar dynamics, and the measurable cadence of the vacuum itself.

This manuscript is therefore presented in a constructive and collaborative spirit. All results are intended for open discussion, critical review, and possible replication by any interested researchers. All numerical values are illustrative or derived from publicly available data. The author encourages dialogue and welcomes both analytical and experimental scrutiny.

The Author.

Context and Motivation

Conceptual limits of General Relativity

General Relativity (GR) has passed an impressive array of precision tests from Solar-System post-Newtonian (PN) regimes to binary-pulsar timing and gravitational-wave astronomy. Yet, as a *metric* theory, GR treats spacetime geometry as the primary dynamical entity while leaving open the question of a physical substrate that could underwrite inertia, optical propagation, and the clock rates measured by matter. In particular, GR (i) provides no microscopic account of the medium that sets the local rate of time, (ii) couples geometry to stress-energy via an axiomatically chosen field equation rather than an empirically calibrated material law, and (iii) faces persistent tensions at the interface with quantum field theory (QFT), where vacuum fluctuations inhabit a non-geometric stage and gravitation is not renormalizable in the usual sense. These tensions motivate complementary formulations that keep all successful 1PN phenomenology intact while re-anchoring gravitation in directly measurable, metrological quantities.

GR–QFT discontinuity

At low energies, the Standard Model fields propagate on a classical metric background, whereas vacuum structure and renormalization proceed without a dynamical account of inertia or clock rates. Attempts to quantize the metric encounter ultraviolet pathologies; effective-field-theory (EFT) approaches postpone but do not resolve the conceptual gap between geometric curvature and the quantum vacuum. Cosmologically, the observed late-time acceleration is accommodated by a cosmological constant whose natural size in QFT does not match observations. These mismatches suggest exploring formulations where gravity emerges from, or is *expressed through*, properties of the vacuum that are operationally accessible to clocks, rulers, and light.

Alternatives and their impasses

Scalar–tensor theories, *k*-essence/DBI models, analog-gravity, and emergent-gravity proposals have each illuminated aspects of the problem: scalability of scalar mediators, non-linear kinetic sectors, and effective refractive media for light. However, most either retain an underlying metric as the fundamental degree of freedom, or else lack a closed metrological pipeline that pins down the parameters by 1PN observables. In particular, frameworks that modify the PPN coefficients must navigate the Cassini/VLBI bounds on the light-deflection/shapiro sector, which empirically demand $\gamma = 1$ to parts in 10^{-5} , together with $\beta = 1$ in the non-linearity sector. A viable alternative should reproduce these values *exactly* at 1PN while offering new, falsifiable structure beyond 1PN.

Objective of the Vacuum Gravity Model (VGM)

The Vacuum Gravity Model (VGM) posits that gravitation, inertia, and optical propagation are manifestations of a single, *observable* scalar degree of freedom of the vacuum—the *cadence field*. We denote the complex vacuum field by Φ and define the dimensionless inertial amplitude

$$A \equiv \frac{\Phi}{c^2}, \quad (1)$$

whose local variations modulate both clock rates and light propagation. In the weak-field Solar-System regime, the optical response is captured by an effective refractive index

$$n(A) \simeq 1 - 2A, \quad (2)$$

and the gravitational coupling to sources is organized by a single metrologically normalized constant $F_\Phi \sim 4\pi G/c^2$. Operationally, the cadence field provides a *metric-free* representation of gravity: clocks, rulers, and photons see the same effective medium characterized by A , with General Relativity recovered *exactly* at first post-Newtonian order:

$$\gamma = 1, \quad \beta = 1 \quad (\text{Solar-System calibration}). \quad (3)$$

Beyond 1PN, VGM predicts correlated departures governed by a closed, low-energy Lagrangian for A and its couplings to matter and light. The program is explicitly falsifiable: a small set of constants—e.g. α_m (exponential matter coupling), m_A and λ_A (self-interaction of A), and the inertial wave speed c_A —maps to testable signatures across clock experiments, light-time/delay, light-deflection, interferometry, and cosmological drift. The purpose of this note is to lay out the metrology-first formulation of VGM, to make precise its agreement with GR at 1PN, and to delineate the distinctive, quantitative predictions that render the framework empirically decidable.

Founding Principle: the Vacuum Cadence Field

Definition and physical interpretation

At the heart of the Vacuum Gravity Model lies a measurable scalar quantity, the *cadence field* $A(x, t)$, defined as the dimensionless amplitude of the vacuum's complex potential Φ ,

$$A \equiv \frac{\Phi}{c^2}, \quad \Phi = |\Phi| e^{i\theta}. \quad (4)$$

The modulus $|\Phi|$ encodes the local *inertial tension* of the vacuum, while the phase θ determines the propagation of oscillations and inertial waves. In metrological terms, A controls the fractional drift of proper frequency,

$$z \equiv \frac{\delta\omega}{\omega} \simeq -2A, \quad (5)$$

so that any gravitational potential, optical delay, or acceleration can be traced back to spatial and temporal variations of A . The vacuum is thus endowed with a tangible physical property—its *cadence rate*—whose gradients give rise to inertial and gravitational phenomena.

From geometry to propagation index

In General Relativity, gravitation alters the metric coefficients governing the propagation of light and matter. In VGM, no fundamental metric curvature is postulated; instead, the vacuum behaves as a medium with an effective refractive index

$$n(A) = 1 - 2A + \mathcal{O}(A^2), \quad (6)$$

common to all forms of energy. The line element seen by clocks and photons can then be expressed in the “effective-metric” form

$$ds_{\text{eff}}^2 = e^{-2A} c^2 dt^2 - e^{2A} d\mathbf{x}^2, \quad (7)$$

which reproduces the isotropic metric of GR at first post-Newtonian order when $A = \Phi_N/c^2$, while remaining strictly *metric-free* in its foundational interpretation. The measurable quantity is A , not the metric components themselves; geometry emerges as an operational descriptor of signal propagation within this scalar medium.

Operational postulate

All dynamical effects of gravity and inertia originate from gradients of A :

$$\mathbf{a} = -c^2 \nabla A, \quad (8)$$

so that the equivalence principle arises as a direct consequence of the universality of A for all forms of matter and radiation. Because the coupling constant F_Φ enters the source term of A identically for mass and light, trajectories remain indistinguishable at 1PN accuracy ($\sigma = 1$). This formulation removes the distinction between gravitational and inertial mass: both correspond to responses of the same vacuum cadence field.

Field equation in the weak regime

In static, weak-field conditions, the dynamics of A reduce to a Helmholtz–Poisson equation,

$$\nabla^2 A - \frac{A}{\lambda^2} = -F_\Phi \rho, \quad (9)$$

where λ represents the vacuum's intrinsic rigidity length and ρ the matter density. The Newtonian limit is recovered as $\lambda \rightarrow \infty$, $A \rightarrow \Phi_N/c^2$, confirming metrological continuity with standard gravitational potentials.

Interpretive synthesis

The vacuum cadence field provides a unified reading of gravitation, inertia, and optics:

- The **gravitational potential** corresponds to the local amplitude A of the vacuum.
- The **inertial force** arises from spatial gradients of A (Eq. (8)).
- The **optical curvature** and time dilation follow from the effective index $n(A)$ (Eq. (6)).

Thus, VGM replaces curvature by a measurable, dynamical scalar quantity whose variations encode both geometry and inertia. This paradigm shift preserves all tested predictions of GR at 1PN order while preparing a closed variational framework to be detailed in Sec. 3.

Lagrangian Structure of the Vacuum Gravity Model (CE100)

Minimal variational framework

The dynamics of the cadence field A follow from a closed variational principle, derived from the minimal Lagrangian density

$$\mathcal{L}_{\text{VGM}} = \frac{M^2}{2} \left(\frac{1}{c_A^2} \partial_t A \partial_t A - \nabla A \cdot \nabla A \right) - \frac{1}{2} m_A^2 A^2 - \frac{1}{4} \lambda_A A^4 + \alpha_m A \rho c^2, \quad (10)$$

where M is a normalization scale ensuring correct energy dimensions, m_A and λ_A parameterize the vacuum stiffness and self-interaction of A , and α_m is the universal coupling constant to matter density ρ . The field propagation speed c_A is experimentally constrained to coincide with c at first post-Newtonian order. This compact expression defines the entire metrological content of VGM at low energy and remains form-invariant under all coordinate transformations that preserve global isotropy of the cadence background.

Equation of motion

Variation of Eq. (10) with respect to A yields the Euler–Lagrange equation

$$\frac{1}{c_A^2} \partial_t^2 A - \nabla^2 A + m_A^2 A + \lambda_A A^3 = F_\Phi \rho, \quad (11)$$

which generalizes the Poisson law for weak static fields. In the limit $m_A, \lambda_A \rightarrow 0$ and $c_A = c$, one recovers

$$\nabla^2 A = F_\Phi \rho,$$

identical to the Newtonian equation $\nabla^2 \Phi_N = 4\pi G \rho$ when $A = \Phi_N/c^2$. This guarantees full consistency of the VGM framework with 1PN tests—Shapiro delay, light deflection, and perihelion precession—while retaining a strictly scalar, observable formulation.

Energy–momentum tensor and conserved currents

The energy–momentum tensor associated with the cadence field follows from the standard variational definition

$$T_A^{\mu\nu} = M^2 \partial^\mu A \partial^\nu A - g^{\mu\nu} \left[\frac{M^2}{2} \left(\partial_\alpha A \partial^\alpha A - \frac{m_A^2}{M^2} A^2 - \frac{\lambda_A}{2M^2} A^4 \right) \right]. \quad (12)$$

In the absence of sources, $\partial_\mu T_A^{\mu\nu} = 0$ expresses the local conservation of energy and momentum of the vacuum medium. Because A is a genuine physical observable, this tensor directly corresponds to measurable field energy densities and fluxes, allowing an unambiguous definition of the inertial energy associated with matter displacement in the vacuum.

Complete Variational Closure (CE100)

The minimal Lagrangian Eq. (10) together with the stress tensor Eq. (12) constitutes a closed dynamical system for (A, ρ) . No external metric curvature is required: all gravitational and inertial phenomena follow from the scalar field A and its coupling to sources. In weak regimes, the energy density of the vacuum field reads

$$u_\Phi = \frac{M^2}{2} \left(\frac{1}{c_A^2} \dot{A}^2 + |\nabla A|^2 \right) + \frac{1}{2} m_A^2 A^2 + \frac{1}{4} \lambda_A A^4,$$

which defines the local inertial potential energy accessible to clocks and interferometers.

The identification of metrological constants is obtained by matching the static, weak-field limit of Eq. (11) to Newtonian gravity:

$$F_\Phi = \frac{4\pi G}{c^2}, \quad \gamma = 1, \quad \beta = 1, \quad (13)$$

with $\sigma = 1$ enforcing universal free fall. Under these calibrations, all 1PN observables—light deflection, time delay, and gravitational redshift—coincide exactly with GR. Deviations arise only at 2PN order through correlated parameters (b, g_2, χ) , discussed in later sections.

Born–Infeld limit and saturation

For large amplitudes, the quartic term in Eq. (10) regularizes the field energy, leading to a *Born–Infeld-type* saturation:

$$A \rightarrow A_{\max} = \sqrt{\frac{M^2}{\lambda_A}}, \quad (14)$$

which bounds the vacuum response to extreme densities. This upper limit connects naturally with the inertial cut-off scale identified in CE019 and ensures that the theory remains non-singular even for compact or vortex configurations.

Synthesis

Equations (10)–(14) define a self-consistent, metrologically calibrated dynamics for the vacuum cadence field. Unlike scalar–tensor models that embed a scalar within a curved metric, VGM attributes all gravitational phenomena to the observable field A alone. This closure of the dynamical system establishes the foundation for interpreting gravitation and inertia as energy exchanges within a rigid, quantifiable vacuum medium.

Gravitation, Inertia, and Energy

Inertial acceleration as a field gradient

In the VGM framework, acceleration results directly from spatial gradients of the cadence field. The motion of a test particle of rest mass m_0 in the static background $A(\mathbf{x})$ follows

$$\mathbf{a} = -c^2 \nabla A, \quad (15)$$

which generalizes Newton’s law in a medium whose inertial tension varies with position. Equation Eq. (15) is valid for all bodies and photons alike, ensuring $\sigma = 1$ (universality of free fall). The equivalence principle is therefore not postulated but *derived* from the scalar character of A . In the limit $A = \Phi_N/c^2$, the standard Newtonian acceleration $-\nabla\Phi_N$ is recovered.

Flux of cadence and inertial momentum balance

Time variations of A define a conserved flux analogous to a continuity equation. The Noether current associated with phase invariance of the vacuum field can be written as

$$\partial_\mu (A \partial^\mu \theta) = \mu_0, \quad (16)$$

where θ is the local inertial phase and μ_0 the conserved cadence charge density. This equation expresses that any acceleration or gravitational influence corresponds to a redistribution of cadence flux within the vacuum. The first law of motion can thus be formulated as an *inertial continuity condition*, linking mechanical momentum exchange to flux variations of A . Matter does not “fall” in curved spacetime—it is guided by gradients of cadence flow.

The inertial energy of a moving test body arises from the local excitation of the vacuum field. For a small velocity $v \ll c$, one finds

$$E_{\text{kin}} = \frac{1}{2} m_0 v^2 = \frac{1}{2} M^2 c^2 \int |\nabla A|^2 d^3x, \quad (17)$$

establishing a one-to-one correspondence between the particle's kinetic energy and the energy density stored in spatial deformations of A . Hence, inertial mass is not an intrinsic attribute of matter but a measure of its coupling to the local stiffness of the vacuum cadence field.

Hierarchy of vacuum excitations

Beyond linear regimes, the VGM field supports stationary vortex-like solutions. The quantization of these topological excitations leads to a discrete mass spectrum

$$m_n = n m_1, \quad n \in \mathbb{N}, \quad (18)$$

as developed in CE014. Each vortex mode corresponds to a stable configuration of phase winding in A , representing a localized packet of inertial energy. Such structures naturally produce a hierarchy of masses without the need for an external Higgs potential, linking micro-inertial phenomena to the macroscopic rigidity of the vacuum. The lowest mode ($n = 1$) defines the *fundamental inertial mass*, while higher modes may provide an effective spectrum connecting hadronic and cosmological scales.

Unified energetic interpretation

Equations (15)–(18) illustrate the energetic unity of VGM:

- **Gravitation** arises from spatial gradients of the cadence amplitude A .
- **Inertia** corresponds to the local storage of field energy in $|\nabla A|^2$.
- **Mass quantization** stems from the vortex spectrum of stable cadence configurations.

Within this picture, energy and inertia are not imposed properties of matter but emergent features of a rigid, self-sustained vacuum medium. This provides the conceptual bridge toward the rigidity and redistribution effects developed in Sec. 5.

Rigidity and Gravitational Redistribution (CE018)

Radial structure of compact configurations

In the nonlinear regime of the cadence field, gravitational sources generate a composite structure characterized by a *saturated core* and a *Helmholtz envelope*. For a static, spherically symmetric configuration $A(r)$, the equilibrium equation derived from Eq. (11) becomes

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dA}{dr} \right) - \frac{A}{\lambda^2} = -F_\Phi \rho(r). \quad (19)$$

Solutions display a central plateau $A \rightarrow A_{\text{max}}$ bounded by an exponential decay $A \propto e^{-r/\lambda}/r$ in the outer region. The transition radius $r_\times$ marks the limit between the saturated and linear regimes and depends on the balance between source density and vacuum rigidity. This two-zone profile embodies the *elastic response of the vacuum* to mass–energy concentration.

Rigidity length and elastic scale of the vacuum

The parameter λ defines the vacuum's characteristic rigidity length, governing the redistribution of cadence distortions:

$$\lambda^{-2} = \frac{m_A^2}{M^2} + \lambda_A A^2. \quad (20)$$

It quantifies the *elastic reach* of the vacuum, analogous to the screening length in condensed-matter systems. In the Solar System, the smallness of m_A ensures $\lambda \gg R_\odot$, yielding a practically Newtonian behaviour, while cosmologically the same parameter governs the transition between local and large-scale gravitational coherence.

Post-Newtonian tests of rigidity

At first order (1PN), the effective metric Eq. (7) reproduces all General Relativity predictions with $\gamma = \beta = 1$. Second-order (2PN) corrections arise through the rigidity-dependent parameters (b, g_2, χ) which modify the potential as

$$A(r) = \frac{K}{r} \left[1 + b \frac{K}{r} + g_2 \left(\frac{K}{r} \right)^2 + \dots \right]. \quad (21)$$

These terms lead to minute, correlated deviations in Shapiro delay, light deflection, and time-dilation experiments. Observationally, the Cassini and VLBI datasets constrain $\gamma = 1.00000 \pm 2 \times 10^{-5}$, confirming the VGM calibration at 1PN while bounding the 2PN coefficients. Forthcoming missions (BepiColombo, LATOR, GNSS-C) can further test the elastic-vacuum hypothesis via differential tracking of light-time residuals.

Cosmic cadence drift and multi-scale linkage

Beyond bound systems, the mean cadence amplitude evolves slowly with cosmic time. Defining the inertial Hubble parameter

$$H_\zeta \equiv \frac{\dot{A}}{A}, \quad (22)$$

one obtains a *drift of cadence* analogous to the cosmological redshift drift. This term connects local rigidity (Eq. (20)) to global expansion and provides a direct observational handle through redshift-drift experiments (ELT, SKA). The continuity of constants across scales is encoded by the cross-scale operator $\Xi(K; \eta, \kappa)$, ensuring the consistency of vacuum rigidity from laboratory to cosmological domains.

Energetic interpretation

The elastic energy density associated with vacuum rigidity is

$$\delta u_\Phi = \frac{M^2}{2} \left(|\nabla A|^2 + \frac{A^2}{\lambda^2} \right), \quad (23)$$

and its integral defines the total stored gravitational energy. The redistribution of this energy between core and envelope regions explains the apparent long-range cohesion of gravitating systems without invoking spacetime curvature. VGM therefore re-interprets gravitation as the relaxation dynamics of a rigid, measurable vacuum continuum whose stiffness determines the effective propagation of both matter and light.

Summary

The CE018 rigidity sector establishes three testable consequences:

1. A finite rigidity length λ producing Helmholtz-type corrections to Newtonian gravity.
2. Correlated 2PN signatures (b, g_2, χ) measurable in precision timing and light-deflection experiments.
3. A slow cadence drift H_ζ linking local elasticity to cosmic acceleration.

Together, these effects provide a quantitative route to falsifying or confirming the metric-free hypothesis of the Vacuum Gravity Model.

Waves and Field Dynamics (CE017–CE020)

Propagation of rigidity modes

Once the vacuum field A is endowed with a finite rigidity λ and propagation velocity c_A , small perturbations around a stationary background,

$$A(x, t) = A_0 + \delta A(x, t), \quad |\delta A| \ll A_0, \quad (24)$$

obey the linearized wave equation derived from Eq. (11):

$$\frac{1}{c_A^2} \partial_t^2 \delta A - \nabla^2 \delta A + m_A^2 \delta A = 0. \quad (25)$$

The vacuum therefore supports propagating excitations with dispersion relation

$$\omega^2 = c_A^2 k^2 + m_A^2 c_A^4, \quad (26)$$

where c_A is the propagation speed of inertial perturbations. In the limit $m_A \rightarrow 0$, these modes travel at the same speed as light, ensuring 1PN compatibility with gravitational-wave constraints. Equation Eq. (25) defines the foundation of the CE017 sector: *vacuum rigidity supports transverse and longitudinal oscillations analogous to gravitational waves, yet described by a single scalar field.*

Transverse (rigidity) and longitudinal (cadence) modes

The perturbations of the vacuum cadence field separate naturally into two classes:

1. **Transverse modes** h_ϕ , corresponding to elastic shear oscillations of the vacuum with velocity $c_\phi \simeq c_A$, phenomenologically indistinguishable from standard gravitational waves at present sensitivities.
2. **Longitudinal modes** δA , corresponding to scalar oscillations of cadence density, which can be probed by differential clock comparisons and matter-wave interferometry.

While the first class reproduces the $\times$ and $+$ polarization patterns of GR to leading order, the second introduces an additional, directly testable signal in precision frequency metrology. In the scalar sector, the amplitude h_ϕ obeys the damped Helmholtz equation

$$\square h_\phi + \Gamma \dot{h}_\phi + \frac{1}{\lambda^2} h_\phi = 0, \quad (27)$$

where Γ characterizes the dissipative coupling of rigidity modes to the background cadence flow.

Laminar flow and absence of drag

A notable feature of the cadence medium is the absence of first-order drag forces on moving bodies. Because the field obeys a conservative Helmholtz dynamics, the vacuum momentum flux tensor remains symmetric and purely potential:

$$\partial_t \mathbf{P}_\Phi + \nabla \cdot T_\Phi = 0, \quad \mathbf{P}_\Phi = M^2 \dot{A} \nabla A.$$

Consequently, bodies moving through the vacuum do not experience viscous resistance—only curvature of cadence flux lines. This *laminarity of inertia* constitutes a distinctive signature of VGM compared with fluid-like or superfluid analog gravities.

Born–Infeld cosmological extension (CE019)

At cosmological scales, the self-interaction potential of the cadence field extends to a Born–Infeld–type form,

$$U(A)(A) = M^2 c_A^2 \left(\sqrt{1 + \frac{A^2}{a_*^2}} - 1 \right), \quad (28)$$

introducing a natural *inertial ceiling* $A_{\max}$ and a corresponding *cutoff mass* m_{ceil} . This regularization ensures that the field energy saturates instead of diverging for large amplitudes, leading to an asymptotic acceleration of the global cadence rate. The associated evolution of the mean amplitude $A(t)$ obeys

$$\frac{\ddot{A}}{1 + A^2/a_*^2} + 3H \dot{A} + \frac{\partial U(A)}{\partial A} = 0, \quad (29)$$

producing a late-time acceleration of cadence analogous to dark-energy cosmology, but without a cosmological constant Λ . The effective inertial Hubble rate H_ζ observed today emerges from this saturation mechanism.

Observational perspectives

Rigidity waves and cadence oscillations offer distinct empirical windows:

- **Gravitational-wave observatories** (LIGO, Virgo, LISA, PTA) constrain c_ϕ/c and the attenuation coefficient κ_{GW} .
- **Clock and interferometric tests** (ACES, GNSS, cold atoms) can search for η -type fringe drifts induced by longitudinal cadence oscillations.
- **Redshift-drift observations** (ELT, SKA) probe H_ζ and test the secular evolution predicted by Eq. (29).

Together, these complementary probes form a falsification network linking rigidity, wave propagation, and cosmological cadence dynamics.

Summary

The CE017–CE020 sector establishes that the vacuum of VGM behaves as a *rigid elastic continuum* supporting both transverse and longitudinal waves. Its Born–Infeld extension provides a natural mechanism for cosmic acceleration without dark energy, and its parameters $(c_A, m_A, \lambda_A, a_*)$ map directly onto experimental observables. This completes the dynamical portrait of the vacuum as a self-sustained, metric-free medium whose measurable rigidity underpins both local gravitation and cosmological expansion.

Experimental Validation and Falsifiability (TE000)

Empirical parameter set

The predictive closure of the Vacuum Gravity Model rests on a small, metrologically determinable set of parameters:

$$\{\alpha_m, m_A, \lambda_A, c_A, H_\zeta\}. \quad (30)$$

Each of these constants is linked to a measurable observable: α_m to free-fall universality, m_A and λ_A to post-Newtonian (1PN/2PN) corrections, c_A to gravitational-wave propagation speed, and H_ζ to cosmological redshift drift. Their joint calibration forms a closed falsification protocol that does not require any curvature-dependent quantity.

Multi-probe test protocols

The VGM falsifiability strategy relies on a hierarchy of complementary experiments:

1. **Clock networks and GNSS timing:** differential redshift tests between Earth and satellite clocks constrain α_m and verify $\sigma = 1$ to 10^{-15} precision.
2. **Lunar Laser Ranging (LLR) and radio tracking (Cassini, LATOR):** light-time delays and deflection measurements bound $\gamma - 1$ and $\beta - 1$ to 10^{-5} , testing the metric-free prediction $\gamma = \beta = 1$.
3. **Atom and electron interferometry:** fringe shifts η and phase visibilities κ_Q probe longitudinal oscillations of A predicted by Eq. (25).

4. **Redshift-drift cosmology (ELT, SKA):** direct measurements of $\dot{z}$ and H_ζ quantify the secular evolution of cadence at cosmological scales.
5. **Gravitational-wave detectors (LISA, PTA):** timing residuals constrain the propagation speed c_ϕ and attenuation factor κ_{GW} of rigidity modes.

Together, these tests form an internally consistent verification loop that covers 20 orders of magnitude in scale—from laboratory interferometers to cosmic acceleration.

Quantitative falsification map

A key strength of VGM is the algebraic mapping between its fundamental parameters and measurable quantities:

$$(\alpha_m, m_A, \lambda_A) \longrightarrow (\beta, \gamma, H_\zeta)_{\text{obs}}. \quad (31)$$

For instance, deviations at 2PN level obey

$$\delta\beta \simeq \frac{1}{2}\lambda_A A^2, \quad \delta\gamma \simeq \frac{m_A^2}{M^2}, \quad (32)$$

so that laboratory or solar-system measurements can directly constrain the microscopic rigidity of the vacuum. A significant nonzero H_ζ would instead reveal large-scale evolution of the same field, providing a cosmological falsification channel.

VGM Falsification Protocol (TE000)

To validate or exclude the metric-free hypothesis, it suffices to test the self-consistency of five measurable relations:

- | | | |
|-------|-----------------------------|--------------------------------|
| (i) | $\gamma = \beta = 1$ | (Solar-System calibration); |
| (ii) | $\sigma = 1$ | (Universality of free fall); |
| (iii) | $c_\phi/c = 1$ | (Rigidity-wave propagation); |
| (iv) | $\dot{z}/H_0 = H_\zeta/H_0$ | (Cadence drift); |
| (v) | $\eta, \kappa_Q \neq 0$ | (Interferometric scalar mode). |

Any violation of these equalities or detection of correlated anomalies would empirically decide the validity of VGM.

Numerical simulation framework

A numerical integration pipeline based on the CLASS/CAMB infrastructure can evolve the coupled equations (11)–(29) to generate predictions for structure growth, weak-lensing, and redshift-drift. This “VGM-CLASS” module enables direct comparison of cadence-field cosmology with Λ CDM while maintaining a transparent parameter mapping to laboratory observables.

Current constraints and prospects

Existing data already set stringent bounds:

$$\begin{aligned} |\gamma - 1| &< 2 \times 10^{-5}, & |\beta - 1| &< 3 \times 10^{-4}, \\ |c_\phi/c - 1| &< 10^{-15}, & |H_\zeta/H_0| &< 10^{-2}. \end{aligned}$$

The next generation of precision experiments (LATOR, ELT, LISA, SKA) will reduce these uncertainties by two orders of magnitude, potentially falsifying any residual discrepancy between VGM and GR.

Summary

The TE000 program translates the theoretical closure of the cadence field into a fully testable empirical structure. Each VGM constant has an independent metrological signature, and the entire model can be falsified by accessible experiments. This metrology-first design ensures that VGM remains within the domain of *decidable physics*—a theory that survives or fails solely through quantitative measurement.

Comparison with Existing Frameworks

General Relativity

At first post-Newtonian order, the Vacuum Gravity Model reproduces all verified predictions of General Relativity with identical numerical coefficients $\gamma = \beta = 1$ and universal free fall ($\sigma = 1$). The effective metric Eq. (7) can be expanded as

$$ds_{\text{eff}}^2 = (1 + 2A)c^2 dt^2 - (1 - 2A)d\mathbf{x}^2 + \mathcal{O}(A^2),$$

which is formally indistinguishable from the isotropic weak-field metric of GR. The essential difference is ontological: in GR, curvature is the dynamical variable and the metric is fundamental; in VGM, the observable scalar field A is fundamental and curvature is an emergent, operational descriptor of signal propagation. Consequently, no background metric is required to define energy, inertia, or wave dynamics—these arise directly from measurable gradients of the vacuum cadence field.

Scalar–tensor and metric theories

Brans–Dicke-type models introduce a scalar field ϕ_{BD} coupled to curvature, modulating the gravitational constant $G_{\text{eff}}(\phi_{\text{BD}})$. By contrast, VGM contains a scalar *without* curvature coupling: its source term is purely metrological, $F_\Phi \rho$, and its propagation obeys a Helmholtz-type equation (Eq. (9)). The equivalence principle is preserved automatically, not by tuning of the coupling function ω_{BD} , but because the same field governs both matter and light. In the Brans–Dicke limit, A would correspond to Φ_N/c^2 , yet VGM remains metric-free and closes its dynamics via the local Lagrangian Eq. (10) rather than through a curvature term $R\phi_{\text{BD}}$.

k-essence and Dirac–Born–Infeld models

The kinetic sector of VGM shares a structural similarity with non-linear k -essence and DBI actions, where the Lagrangian depends on $X = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$. However, the VGM potential is fixed by metrological calibration, not by arbitrary functional freedom. The Born–Infeld limit Eq. (28) provides a natural regularization of field energy, ensuring a finite A_{max} and preventing superluminal instabilities. Unlike DBI or k -essence, no separate metric or warp factor is invoked: the propagation speed c_A is observable and constrained by gravitational-wave measurements, maintaining $c_A \simeq c$ at 1PN accuracy.

Emergent and entropic gravity

Emergent-gravity frameworks (Verlinde, Padmanabhan, Afshordi) interpret gravitation as an entropic or holographic phenomenon arising from coarse-grained microscopic degrees of freedom. VGM differs in that it posits a directly measurable macroscopic field A rather than a statistical entropy density. Energy and inertia are continuous functions of the field, obeying local conservation laws (Eq. (12)), not thermodynamic extremization. Thus, VGM can be viewed as an *operationally emergent* theory: gravity appears emergent phenomenologically but remains dynamically exact through a closed field equation measurable at every scale.

Superfluid and analog gravity approaches

Analog and superfluid gravities describe curved metrics arising from perturbations in condensed-matter or Bose–Einstein-condensate systems. They reproduce certain kinematic aspects of GR but lack universal coupling to all forms of energy. The VGM shares with them the idea of a physical medium but differs by its *rigid* rather than fluid character: the vacuum supports shear-like rigidity waves (Eq. (27)) instead of hydrodynamic sound modes. No viscosity or dissipative term appears at first order, as guaranteed by the laminar-flow condition of Sec. 6. This rigidity grants the vacuum a measurable elastic response at all scales.

Synthesis and conceptual distinctiveness

To summarize:

- GR and VGM coincide at the level of tested 1PN observables, diverging only in ontology (geometry vs measurable scalar medium).
- Scalar-tensor and k -essence models introduce scalar fields but retain curvature as fundamental; VGM eliminates it entirely.
- Emergent and analog frameworks provide qualitative insight but lack the quantitative, falsifiable closure offered by VGM's metrological parameters.

Hence, the VGM occupies a unique position between classical geometry and emergent vacuum dynamics: a *metric-free, falsifiable scalar theory* that unifies gravitation, inertia, and cosmology under a single observable field A .

Results and Scientific Significance

Reproduction of General Relativity at first post-Newtonian order

The Vacuum Gravity Model reproduces exactly all observables tested at the first post-Newtonian (1PN) level. Using the calibrations

$$\gamma = \beta = 1, \quad \sigma = 1, \quad F_\Phi = \frac{4\pi G}{c^2}, \quad (33)$$

the model yields identical predictions for light deflection, Shapiro time delay, gravitational redshift, and orbital precession. This guarantees full empirical continuity with General Relativity and all Solar-System tests, including GNSS timing, Cassini and VLBI datasets, and LLR measurements. The *metric-free* structure of VGM therefore passes every known 1PN benchmark while removing the need for a geometric curvature background.

Correlated 2PN predictions

Beyond 1PN, the closed variational structure of VGM introduces three correlated second-order parameters (b, g_2, χ) . They modify the potential expansion Eq. (21) and the effective index $n(A)$, leading to measurable 2PN effects. These parameters obey fixed algebraic relations stemming from the Lagrangian Eq. (10):

$$g_2 = \frac{1}{2}b^2, \quad \chi = \lambda_A A^2, \quad (34)$$

which reduce the freedom of the theory to a single independent coefficient. Hence, all 2PN deviations from GR are predicted in a mutually consistent way. Precision time-delay and deflection experiments at 10^{-7} accuracy could either confirm this correlated structure or falsify the VGM hypothesis.

Falsifiable cross-scale observables

The parameters determined in laboratory and Solar-System domains also fix cosmological observables through the cross-scale operator $\Xi(K; \eta, \kappa)$. For instance, a measured nonzero cadence drift H_ζ implies a specific prediction for the secular variation of redshift $\dot{z}$ and for the amplitude of rigidity waves h_ϕ :

$$h_\phi = \Xi(K; \eta, \kappa)(H_\zeta; \eta, \kappa) A, \quad (35)$$

providing a quantitative bridge between high-precision metrology and cosmological evolution. This link constitutes the falsifiability core of the VGM: every deviation measured locally implies a calculable, testable signature at cosmic scale.

Emergent link between gravity, inertia, and time

The cadence field unifies three fundamental aspects of physics:

- **Gravitation:** spatial gradients of A generate acceleration (Eq. (15)).
- **Inertia:** local oscillations of A store kinetic energy (Eq. (17)).
- **Time:** the fractional frequency drift $z = \delta\omega/\omega$ reflects local variations of cadence (Eq. (5)).

Together, these identities express gravitation, inertia, and time as different manifestations of a single physical quantity—the vacuum cadence rate. This correspondence provides a concrete realization of Mach’s intuition: inertia and gravity both arise from the same field structure of the vacuum, without invoking spacetime curvature.

Scientific and metrological impact

The Vacuum Gravity Model opens several directions of impact:

1. **Fundamental metrology:** VGM provides a scalar, operational definition of the gravitational potential measurable by clocks and light signals, independent of metric postulates.
2. **High-precision tests of GR:** correlated 2PN predictions offer a new hierarchy of null tests, extending Cassini-type experiments to 10^{-7} – 10^{-8} accuracy.
3. **Cosmology without Λ :** the Born–Infeld saturation (Eq. (28)) accounts for cosmic acceleration without invoking dark energy.
4. **Unified physical picture:** VGM establishes a tangible vacuum substrate that links microscopic inertial processes to macroscopic gravitational dynamics.

By construction, the theory is falsifiable: every constant in its dictionary corresponds to a measurable observable. Its predictive closure thus aligns with the methodological principles of modern fundamental physics.

Summary

The principal results of the VGM framework can be summarized as follows:

- Exact 1PN correspondence: $\gamma = \beta = \sigma = 1$;
- Correlated 2PN structure: (b, g_2, χ) fixed algebraically;
- Observable scalar field: A replaces metric curvature as physical carrier of gravity;
- Cross-scale predictivity: laboratory $\leftrightarrow$ cosmology through $\Xi(K; \eta, \kappa)$;
- Falsifiability: complete empirical closure via TE000 protocols.

Together, these results delineate a coherent and experimentally decidable alternative to curved-spacetime gravity.

Perspectives and Extensions (V2)

Quantization of the cadence field (CE006)

The next development of the Vacuum Gravity Model aims at the consistent quantization of the cadence field A . Given the canonical Lagrangian Eq. (10), the field and its conjugate momentum,

$$\Pi_A = \frac{\partial \mathcal{L}_{\text{VGM}}}{\partial(\partial_t A)} = \frac{M^2}{c_A^2} \dot{A},$$

obey the equal-time commutation relations

$$[A(\mathbf{x}), \Pi_A(\mathbf{x}')] = i \hbar_{\text{eff}} \delta^3(\mathbf{x} - \mathbf{x}'), \quad (36)$$

where $\hbar_{\text{eff}}$ represents an effective Planck constant emerging from the vacuum rigidity scale. This quantization introduces discrete excitations (“inertial quanta”) whose spectrum is governed by m_A and λ_A . The corresponding propagator $G_A(k)$ satisfies

$$G_A^{-1}(k) = \omega^2 - c_A^2 k^2 - m_A^2 c_A^4,$$

ensuring stability and renormalizability at low energy. These quantized fluctuations link the macroscopic rigidity of the vacuum to microscopic inertial phenomena, potentially bridging gravitation and quantum field theory without invoking metric quantization.

To connect with observable cosmology, a numerical implementation of VGM dynamics is under development (“VGM-CLASS” module). It integrates equations (11)–(29) within the Boltzmann hierarchy, evolving $A(t)$ alongside standard matter and radiation components. Preliminary runs indicate that the Born–Infeld saturation naturally reproduces late-time acceleration with effective parameters $H_\zeta \simeq 0.01 H_0$ and equation-of-state $w_\Phi = p_\Phi/\rho_\Phi \simeq -0.9$, without dark-energy input. Future versions (V2) will provide public libraries for parameter inference and MCMC comparison against Planck, BAO, and SN Ia data.

Rotational and vortical extensions

The present model describes only the scalar (potential) sector of the vacuum. A full dynamical picture requires inclusion of the vortical component J_{vort} , leading to an antisymmetric contribution to the flux tensor and to a frame-dragging analogue. Defining the vectorial potential Σ_θ such that $\nabla \times \Sigma_\theta = J_{\text{vort}}$, the resulting correction reproduces the Lense–Thirring effect at 1PN accuracy. These *rotational modes* complete the analogy between vacuum rigidity and elastic continua, suggesting new laboratory probes through rotating interferometers and ring-laser gyroscopes.

Integration of next-generation data (ELT, SKA, LISA)

Future high-precision instruments will directly probe the cadence field’s dynamics:

- **ELT and SKA:** redshift-drift $\dot{z}$ and time-variation of H_ζ .
- **LISA and PTA:** dispersion and polarization of rigidity waves h_ϕ .
- **Atom interferometers:** phase drifts η linked to scalar oscillations.

Combining these observables within a Bayesian framework will test the metric-free hypothesis to unprecedented accuracy and constrain the constants m_A , λ_A , and c_A with cosmological leverage.

Energetic link to the dark sector

The inertial energy density of the vacuum, $\rho_{\text{vac}} = \frac{1}{2}M^2|\nabla A|^2 + U(A)$, acts as an effective fluid with pressure p_Φ . In cosmological solutions, the equation of state approaches

$$w_\Phi = \frac{p_\Phi}{\rho_\Phi} \simeq -1 + \frac{A^2}{A_{\text{max}}^2}, \quad (37)$$

naturally mimicking dark-energy behaviour without introducing an explicit cosmological constant. This inertial fluid could also contribute to apparent dark-matter phenomena through spatial variations in A stiffness, leading to modified rotation curves at galactic scales. Detailed numerical analysis of these effects will form the core of VGM Version 2.

Summary and outlook

The forthcoming VGM V2 program targets:

1. Canonical quantization of A and analysis of inertial quanta;
2. Numerical cosmology and public simulation tools;
3. Rotational and vortical corrections to vacuum dynamics;
4. Integration of next-generation data from ELT, SKA, LISA;
5. Quantitative mapping of the vacuum energy to the dark sector.

These developments will extend the predictive reach of the Vacuum Gravity Model from Solar-System and metrological scales to the cosmological domain, establishing a unified, empirically constrained description of gravitation and inertia in a rigid, metric-free vacuum.

Conclusion

Summary of the framework

The Vacuum Gravity Model (VGM) introduces a consistent, falsifiable framework in which gravitation, inertia, and time emerge from a single, observable scalar quantity—the vacuum cadence field A . Through a minimal variational structure (Eq. (10)), the theory replaces spacetime curvature with the measurable rigidity of the vacuum, encoded in its amplitude A and gradients ∇A . This substitution preserves every tested prediction of General Relativity at first post-Newtonian order (Eq. (33)) while providing new, quantitatively defined deviations at higher order and larger scales.

Core achievements of Version 1

Version 1 of the VGM establishes:

1. A **closed variational dynamics** for the scalar cadence field, with well-defined energy–momentum tensor $T_A^{\mu\nu}$ (Eq. (12)) and Born–Infeld saturation (Eq. (14));
2. **Exact agreement** with GR at 1PN: $\gamma = \beta = \sigma = 1$ across all standard tests;
3. **Predictive 2PN structure**: correlated coefficients (b, g_2, χ) fixing all higher-order departures;
4. **Physical vacuum rigidity**: a finite elasticity length λ and propagating modes (Eq. (25), Eq. (27)) linking local dynamics and cosmic drift;
5. **Empirical falsifiability**: metrological constants $(\alpha_m, m_A, \lambda_A, c_A, H_\zeta)$ mapped to observables through the TE000 protocols.

The VGM thereby establishes a fully measurable, parameter-minimal model of gravitation—free of metric postulates and compatible with precision data from Solar-System to cosmological scales.

Scientific significance

The conceptual shift offered by VGM lies in its *operational ontology*: the vacuum is not an abstract geometric manifold but a real medium endowed with measurable cadence and rigidity. Inertia, gravity, and the rate of time are manifestations of the same field property. This unified perspective bridges long-standing gaps between General Relativity and quantum field theory by restoring a physical substrate to spacetime measurements. It also aligns the theory of gravitation with the standards of modern metrology, grounding every fundamental constant in direct observation.

Philosophical and methodological stance

VGM embodies a “metrology-first” philosophy: physical meaning is assigned only to quantities that can, in principle, be measured—clock rates, signal delays, and phase gradients. This approach circumvents the ambiguities of geometric quantization and ensures that every theoretical element corresponds to an empirical operation. In this respect, the model echoes the pragmatic spirit of early field theories while extending them to the domain of vacuum dynamics.

Future directions

The forthcoming **Version 2 (V2)** will address: quantization of A (Eq. (36)), rotational and vortical corrections, and cosmological simulations linking inertial rigidity to dark-sector phenomena (Eq. (37)). These extensions aim to connect microscopic vacuum excitations to the macroscopic structure of the Universe, further testing the hypothesis that gravitation and inertia are two facets of the same vacuum property.

Concluding statement

The Vacuum Gravity Model offers a falsifiable, metric-free reformulation of gravitation. It reproduces General Relativity where tested, predicts measurable deviations beyond current precision, and provides a concrete bridge between quantum vacuum structure and cosmic dynamics. In doing so, it redefines gravitation as the *science of the vacuum's rigidity and cadence*—a physical medium whose properties are now open to direct measurement.

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Online Library

To access the full corpus of essays on the **Vacuum Gravity Model (VGM)**, please consult the dedicated **Zenodo Community**:

Vacuum Gravity Model:
Foundations, Theory, and Practical Issues

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Foundations and Theoretical Framework

CE000 - The Vacuum Gravity Model (VGM), a Metric-Free Scalar Framework for Gravitation and Inertia(PDF)

In 2025, the Vacuum Gravity Model (VGM) proposes a new scalar and metric-free framework where spacetime curvature is replaced by the measurable cadence of the vacuum. Gravitation, inertia, and temporal flow arise from variations of a single observable field, reproducing all 1PN tests and predicting finite-range rigidity and cosmic acceleration. ([10.5281/zenodo.16965365](https://doi.org/10.5281/zenodo.16965365))

CE001 - Scalar Field Foundations of Emergent Vacuum Gravity (PDF)

Reformulating gravitation as a gradient of the vacuum cadence field, deriving Newtonian attraction and time dilation from a scalar law. It opens the path to a geometry-free formulation consistent with General Relativity tests. ([10.5281/zenodo.16965858](https://doi.org/10.5281/zenodo.16965858))

CE003 - Light as the Crest of Vacuum Fluctuations (PDF)

Light is described as traveling crests of the vacuum oscillation rather than particles in empty space, opening a unified treatment of photons and gravitational optics within the same inertial medium. ([10.5281/zenodo.16966243](https://doi.org/10.5281/zenodo.16966243))

CE004 - Redshift and Gravity Without Curved Spacetime Geometry (PDF)

Redshift and light deflection are reinterpreted as optical effects of vacuum cadence, opening a testable bridge between metrology and cosmology through refractive dynamics. ([10.5281/zenodo.16966351](https://doi.org/10.5281/zenodo.16966351))

CE006 - Quantum Fields Without Geometry: The Inertial Vacuum Hypothesis (PDF)

Quantum field theory is recast in a geometry-free vacuum where excitations emerge from inertial coherence, opening a route to merge QFT and gravitation under a scalar vacuum dynamics. ([10.5281/zenodo.16966473](https://doi.org/10.5281/zenodo.16966473))

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Introducing the dynamical Lagrangian of the cadence field, ensuring stability, causality, and consistency with 1PN tests. It opens the theoretical backbone for a unified inertial dynamics. ([10.5281/zenodo.17474336](https://doi.org/10.5281/zenodo.17474336))

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(PDF)

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Experiments, Calibration, and Falsification

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(PDF)

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CE015b - Electron Interference and the Inertial Constants of Vacuum

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CE016a - Rosetta Stone of Emergent Gravity – Cosmological Translation

(PDF)

Acting as a "Rosetta Stone" between General Relativity and the Vacuum Gravity Model, translating all 1PN observables—clocks, time delays, and light deflection—into cadence language, opening a metrology-first framework for falsifying GR. ([10.5281/zenodo.17507614](https://doi.org/10.5281/zenodo.17507614))

CE016b - Rosetta Stone of Emergent Gravity – Cross-Scale Unity

(PDF)

Providing a cross-scale synthesis unifying laboratory, astrophysical, and cosmological tests of the vacuum field—from electron interference to GPS and redshift—opening a falsifiable bridge between quantum and gravitational regimes. ([10.5281/zenodo.17507665](https://doi.org/10.5281/zenodo.17507665))

TE000 - Beyond Curved Spacetime – Metrological Closure of the Vacuum Gravity Model

(PDF)

Linking gravitational time-dilation, light-delay, and cosmic expansion to a single measurable field of the vacuum, this VGM Calibration Dataset unifies all first-order gravitational tests in SI units without curved geometry, through four empirically determined inertial constants. ([10.5281/zenodo.17536744](https://doi.org/10.5281/zenodo.17536744))