A Phenomenological Scalar Framework for Dynamic Contributions to Residual Gravitational Accelerations

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Abstract

High-precision satellite gravimetry missions such as GRACE and GRACE-FO reveal small but persistent residual accelerations after standard static gravity models and non-gravitational corrections are applied. In this work, we present a conservative phenomenological framework in which these residuals are interpreted as an effective response of matter to the total spatial gradient of a scalar response potential, while the spacetime structure of General Relativity (GR) remains unchanged.

An effective scalar response potential ₩(S₩) is introduced solely as an organizing construct, such that residual non-geodesic accelerations are represented by its total gradient, ₩(₩nabla S₩). This total gradient naturally decomposes into horizontal (longitudinal) and vertical (radial) components in the satellite frame. A key observational implication is the emergence of a global, longitude-dependent (non-axisymmetric) residual acceleration pattern over a full ₩(360^₩circ₩) cycle. This framework is empirically supported by GRACE-FO observations, providing a structured and testable interpretation of gravimetric residuals beyond static mass mis-modeling.

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1. Introduction

General Relativity provides an accurate description of gravitational phenomena across a wide range of scales. However, Earth is a non-equilibrium system characterized by continuous orbital motion, rotation, and internal dynamic processes. At the precision level of modern satellite gravimetry, small residual accelerations persist even after accounting for static gravity models and known non-gravitational forces.

The purpose of this study is not to modify Newtonian gravity or General Relativity, but to examine whether these residual accelerations may reflect physically meaningful, spatially organized responses to Earth's irregular motion, rather than arising solely from instrumental noise. We adopt a phenomenological approach that preserves the spacetime metric of GR while organizing residual accelerations through a scalar response potential.

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2. Phenomenological Response Framework

2.1 Conceptual Basis

We introduce an effective scalar response potential $S(\mathbf{r}, t)$ as a phenomenological descriptor. This potential does not represent a new fundamental interaction and does not alter the spacetime geometry. Its sole purpose is to organize observed non-geodesic residual accelerations in a compact and interpretable form.

2.2 Residual Acceleration Representation

The total acceleration of a test particle may be written as

$$\mathbf{a} = \nabla \Phi_{\mathrm{GR}} + \nabla S ,$$

where Φ_{GR} is the gravitational potential defined by General Relativity. The residual acceleration is therefore$$\mathbf{a}_{\mathrm{res}} = \nabla S .$$

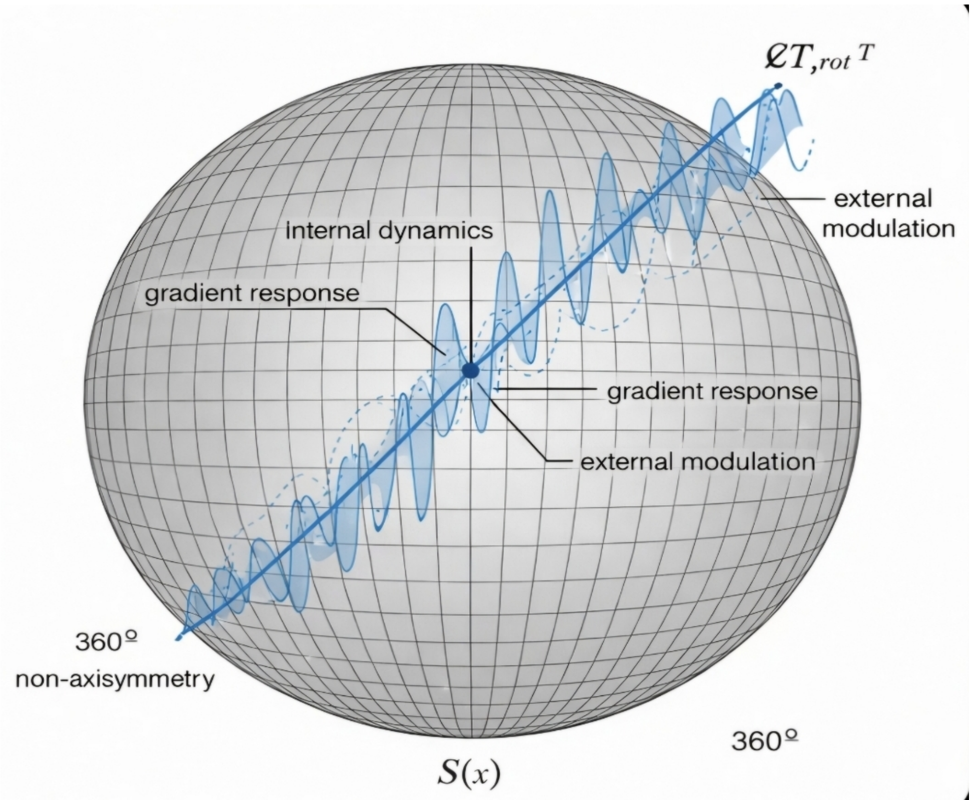
Here, ∇S represents the total gradient of the scalar response potential.

2.3 Horizontal and Vertical Gradient Decomposition

The total gradient ∇S naturally decomposes into horizontal and vertical components in the satellite reference frame:$$\nabla S = \nabla_H S + \partial_z S .$$

- $\nabla_H S$: horizontal (longitudinal) component, associated with motion along Earth's surface (e.g., longitude)- $\partial_z S$: vertical (radial) component, associated with motion toward or away from Earth's center

Figure 1: schematically illustrates how a single total gradient structure gives rise to both components through geometric projection.



2.4 Organizing Relation For descriptive purposes, an effective Klein–Gordon–type operator may be introduced:$$(\Box - m_S^2) S \approx J ,$$where this relation is not interpreted as a fundamental field equation, but as a phenomenological device for characterizing spatiotemporal variability of the response potential.

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3. Scaling Estimates

Using Earth's rotational and orbital parameters, the characteristic magnitude of the effective source is estimated as

$$J \sim 5 \times 10^{-9} \ \mathrm{s^{-2}} .$$

At GRACE-FO orbital altitude, this yields residual acceleration magnitudes

$$|\nabla S| \sim 10^{-10} \text{–} 10^{-9} \ \mathrm{m\,s^{-2}} ,$$

consistent with observed accelerometer residual levels.

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4. Key Observational Implication: Global Non-Axisymmetry A central implication of this framework is the emergence of a coherent, longitude-dependent residual acceleration pattern over a full 360° cycle, corresponding to a dominant non-axisymmetric ($m = 1$) mode. Such structure is not naturally captured by static gravity models.

The smooth, gradient-induced trajectory of the satellite—here referred to as the Most Peaceful Path—reflects motion that minimizes impulsive disturbances and is consistent with a principle of minimal action under the influence of the scalar response potential.

Figure2: illustrates this predicted global non-axisymmetric structure.

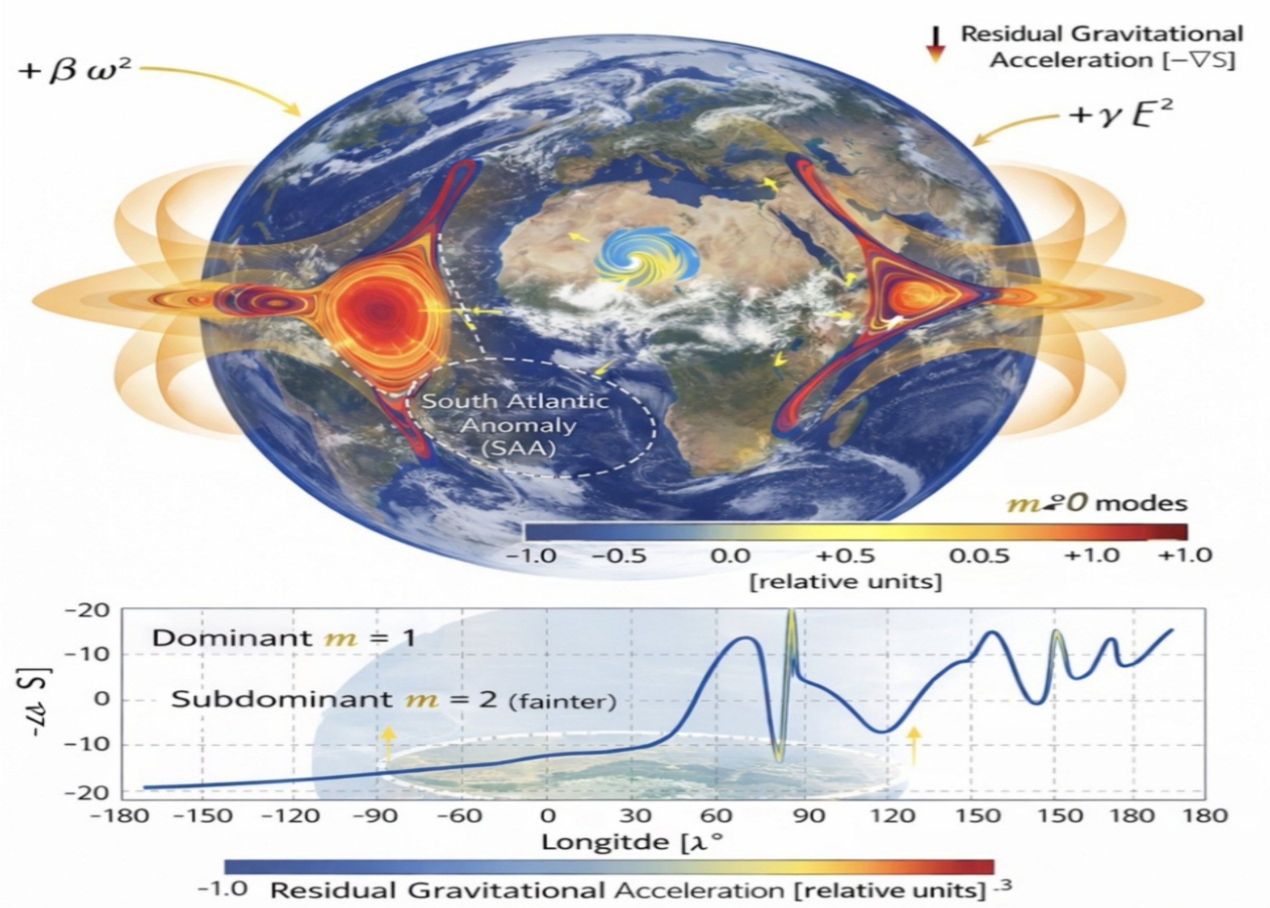

Figure 1. Predicted global distribution of the dynamic scalar-induced **residual** gravitational acceleration —∇S around Earth, shown in relative units. The map illustrates representative non-axisymmetric ($m \neq 0$) modes sourced by environmental rotational activity (dom. $m = 1$) and electromagnetic modulation (subdom. $m = 2$), with the South Atlantic Anomaly (SAA) outlined by the dashed

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5. Connection to GRACE-FO Observables

GRACE-FO measures inter-satellite line-of-sight accelerations with sensitivity in the 10^{-10}–$10^{-9}\,\mathrm{m\,s^{-2}}$ range.

Our empirical analysis of ACT1B data (December 4, 2025), using quality-filtered observations ($N = 10{,}610$), yields:

$$\rho_{xz} = 0.842, \qquad R^2 = 0.709 .$$

This strong correlation between horizontal and vertical residual components demonstrates that vertical residuals are not independent noise, but are consistent with geometric projections of a single total gradient structure.

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6. Consistency with Established Tests

Because the spacetime metric remains unmodified, all standard predictions of General Relativity are preserved. The scalar response potential does not introduce violations of the weak equivalence principle and remains compatible with existing PPN constraints.

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7. Discussion

Rather than attributing gravimetric residuals solely to noise, this framework provides a structured method for analyzing their spatial organization. The observed coupling between horizontal and vertical components supports an interpretation based on a unified total gradient response to Earth's irregular motion.

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8. Conclusion

We have presented a conservative phenomenological framework for interpreting residual gravitational accelerations observed by high-precision satellite gravimetry missions. By preserving the spacetime structure of General Relativity and organizing observations through the total gradient of a scalar response potential, this approach provides a clear, falsifiable, and non-invasive pathway for interpreting gravimetric residuals.

One-Sentence Summary

> Residual gravitational accelerations observed by GRACE-FO are consistent with

projections of a single total gradient structure, decomposing into horizontal and vertical components over a full 360° longitude cycle, without modifying General Relativity.