Revisiting GPS-Derived Plate Kinematics: Evaluation of the Integration of Plate Motion Models in Terrestrial Reference Frames

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Abstract

Tectonic plate motion is a cornerstone of the physical theory of plate tectonics, yet our understanding of lithospheric kinematics increasingly depends on the framework in which measurements are interpreted. With the advent of satellite-based geodesy, particularly the Global Positioning System (GPS), direct measurement of Earth's surface dynamics has become possible with millimeter-level precision. However, integration of plate rotation models such as NNR-NUVEL-1A into terrestrial reference frames, particularly the International Terrestrial Reference Frame (ITRF), introduces a model-dependent bias that compromises the observational fidelity of crustal motion data. This paper critically examines the assumptions embedded in these physical frameworks, demonstrating how model-based corrections can obscure or distort the true Earth-fixed crustal motion. It is argued that tectonic behavior, as revealed through raw GPS measurements, is more complex and variable than the rigid-plate paradigm implies. A reevaluation of reference frame construction is proposed to better align geophysical observation with physical principles.

Keywords: GPS, ITRF, Plate Tectonics, Kinematics

1 Introduction

The motion of Earth's tectonic plates forms the theoretical foundation of modern Earth science. First proposed as continental drift by Alfred Wegener [1] and formalized into plate tectonic theory in the latter half of the 20th century [2, 3], this concept provides a macroscopic explanation for seismicity, mountain formation, and ocean basin evolution. Yet, the empirical verification of plate motion has only become feasible with the advent of high-precision geodetic technologies, especially GPS.

GPS measures station positions relative to an Earth-Centered Earth-Fixed (ECEF) reference frame, enabling direct observation of crustal motion independent of its underlying geodynamic causes. This observational capacity marks a significant shift from earlier reliance on geological models such as the No-Net-Rotation NUVEL-1A (NNR-NUVEL-1A), which estimate long-term plate velocities based on seafloor spreading and transform fault orientations [4].

Despite these advancements, many International Terrestrial Reference Frame (ITRF) realizations of the International Terrestrial Reference System (ITRS) continue to embed rigid plate motion models into GPS-derived velocity fields [5, 6, 7, 8, 9]. This fusion of model and measurement risks introducing bias into what should be a purely observational frame. This paper aims to disentangle these components, analyze the physical implications of their integration, and advocate for a measurement-first approach to geodynamic reference systems.

2 Conceptual Foundations of Tectonic Measurement Chains

2.1 Analog vs. Digital Geodetic Systems

Historically, analog systems provided the first estimates of Earth's geometry. Eratosthenes' ancient calculation of Earth's circumference, based on solar angle measurements, was a pioneering analog geodesic technique [10].

In contrast, modern digital systems leverage electromagnetic signals and atomic timing to precisely determine positions and distances across the Earth. Lunar Laser Ranging (LLR), initiated during the Apollo missions, employs high-precision laser pulses to measure the distance between Earth and the Moon, demonstrating how signal-based systems can resolve subtle orbital system properties [11]. GPS represents a further technological evolution, a space-based navigation and measurement network capable of resolving millimeter-level crustal displacements globally.

2.2 GPS as an Earth-Fixed Measurement Chain

GPS operates in ECEF coordinate frame that co-rotates with the planet, while its satellite orbits are modeled in an Earth-Centered Inertial (ECI) frame [12]. The transformation between these frames allows GPS to detect both secular and transient crustal motion, regardless of underlying dynamical causes.

Two conceptual models (Figure 1) describe how geodetic motion is interpreted:

- **Plate-Fixed Chains** assume that tectonic plates are rigid bodies. Measurements made within the same plate are expected to show negligible internal motion, and deviations are considered deformations.
- **Earth-Fixed Chains**, by contrast, make no assumptions about tectonic rigidity. All motion detected by GPS is treated as observational, whether due to tectonic activity, elastic rebound, volcanism, or anthropogenic effects.

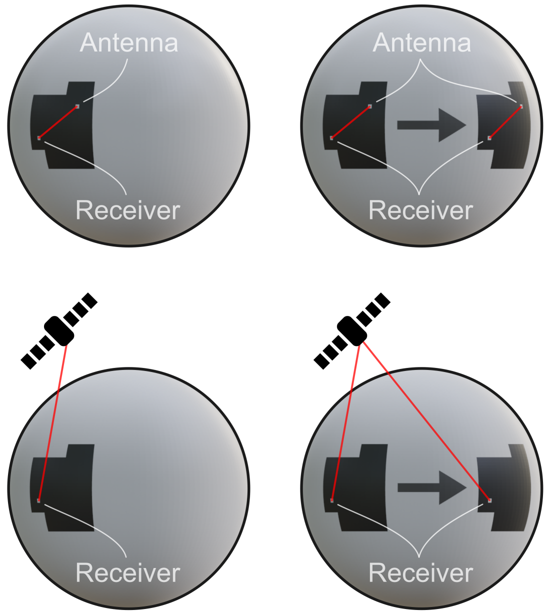

Figure 1: Plate-fixed (figure above) and Earth-fixed (figure below) measurement chains visualization. The geometry is not to scale; heights and distances are exaggerated for clarity.

3 The International Terrestrial Reference Frame and Plate Motion Modeling

The ITRS is a global spatial reference system used for positioning, navigation, and geodetic science [13]. It is constructed from long-term space-geodetic observations, but often integrates plate motion models, most notably the NNR-NUVEL-1A model (Figure 2), to define station velocities.

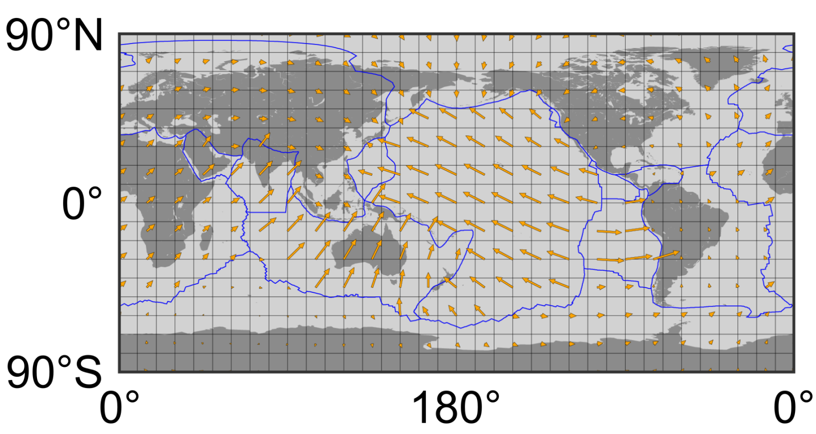

Figure 2: NNR-NUVEL-1A model. Maximum velocities are 104 mm/yr. Reproduced from [14].

While designed to align reference frames with plate tectonic theory, this practice raises a fundamental concern: model-derived velocities are superimposed onto observational data, distorting the true Earth-fixed motion. This compromises the scientific value of GPS as an independent observational tool.

3.1 Plate Motion Bias in ITRF

In ITRF constructions, station velocity vectors are modified using the following model-based expression [13]:

$$\vec{V}_0 = \vec{V}_{\text{plate}} + \vec{V}_r \tag{1}$$

where

- $\vec{V}_{\text{plate}}$: velocity from the NNR-NUVEL-1A plate rotation model,
- $\vec{V}_r$: residual velocity interpreted as deformation.

However, the residual $\vec{V}_r$ may actually represent the true Earth-fixed motion, while $\vec{V}_{\text{plate}}$ imposes theoretical assumptions. This model-driven distortion is implemented using a subroutine commonly referred to as `ABSMO_NUVEL` [13], which applies angular velocity vectors to update station positions.

A sample excerpt for the North America plate is shown below:

Plate Name	Ω_x [rad/Myr]	Ω_y [rad/Myr]	Ω_z [rad/Myr]
North America	0.000258	-0.003599	-0.000153

Table 1: Cartesian rotation vectors for the North America Plate from the NNR-NUVEL-1A model [13]

These rotation vectors define the motion of each plate around its respective Euler pole, a theoretical point on the globe about which the plate is assumed to rotate rigidly. While this spherical approximation is standard, it is important to note that the Earth is more accurately modeled as an oblate spheroid, and such simplifications may introduce further inaccuracies.

In practice, the station positions are updated by applying the modeled plate rotation through a subroutine `ABSMO_NUVEL`. The transformation equations are:

$$x = x_0 + \frac{(\Omega_y z_0 - \Omega_z y_0)(t - t_0)}{1{,}000{,}000} \tag{2}$$

$$y = y_0 + \frac{(\Omega_z x_0 - \Omega_x z_0)(t - t_0)}{1{,}000{,}000} \tag{3}$$

$$z = z_0 + \frac{(\Omega_x y_0 - \Omega_y x_0)(t - t_0)}{1{,}000{,}000} \tag{4}$$

where

- x, y, z: updated station coordinates,

- x_0, y_0, z_0: GPS-determined (Earth-fixed) coordinates,
- $\Omega_x, \Omega_y, \Omega_z$: cartesian rotation vector components,
- t: time of updated coordinates (in years),
- t_0: time of original GPS estimate (in years).

The scalar divisor of 1,000,000 reflects the conversion from radians per million years to radians per year.

The described procedure effectively superimposes model-derived plate motions onto observational GPS data. Critically, such a procedure introduces non-measured motion into the reference frame, thereby compromising the integrity of Earth-fixed tectonic velocity estimates. As a result, rather than representing purely observational outcomes, the ITRF station velocities are influenced, if not dominated, by theoretical assumptions built into the geological model.

4 Case Studies: ITRS Realizations and Model-Driven Artifacts

4.1 ITRF2000 and the Mischaracterization of Plate Motion

The ITRF2000 realization illustrates the drawbacks of embedding plate rotation models directly into geodetic reference frames (Figure 3). By aligning GPS-derived velocities to the NNR-NUVEL-1A model, the frame reinterprets Earth-fixed tectonic motion as deviation from an idealized rigid plate.

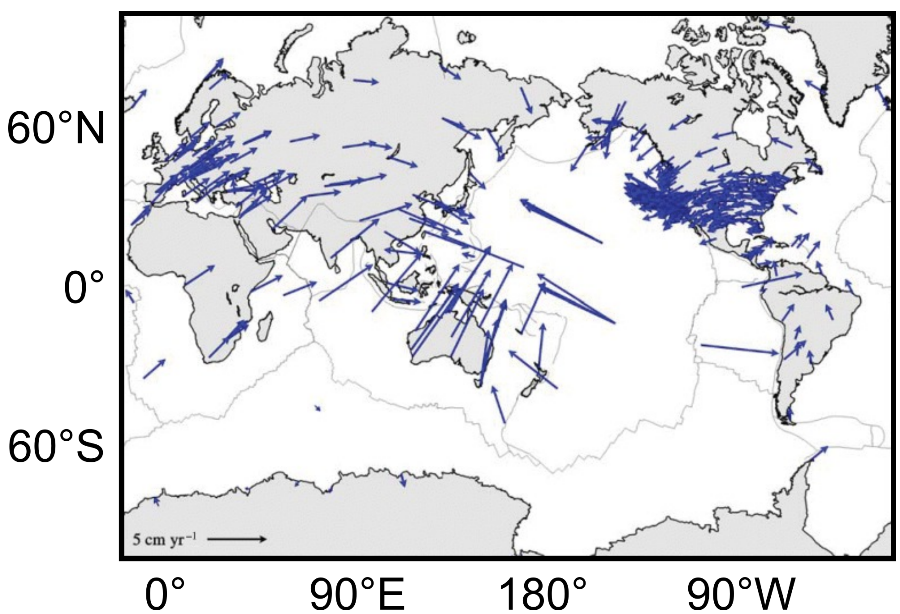

Figure 3: ITRF2000 global velocity field. Reproduced from [5].

When the plate model is removed, residual velocities expose substantial internal variability within Earth-fixed tectonic regions, challenging the assumption of plate rigidity and revealing a more complex crustal motion (Figure 4).

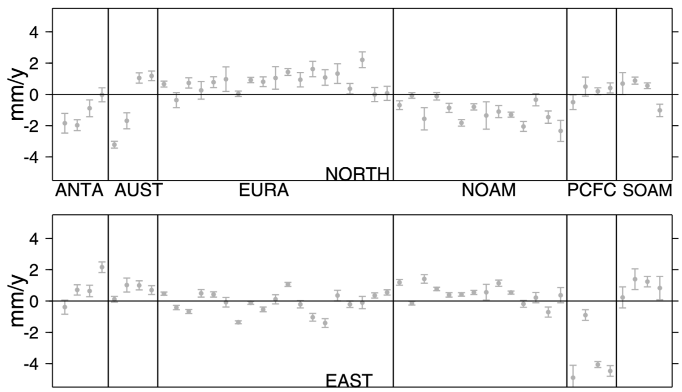

Figure 4: Residual velocities: differences between ITRF2000 velocities and NNR-NUVEL-1A model predictions for 49 core stations, expressed in mm/yr. Plate abbreviations: ANTA (Antarctica), AUST (Australia), EURA (Eurasia), NOAM (North America), PCFC (Pacific), and SOAM (South America). Residual velocities $\vec{V}_r$ are generally a few mm/yr, consistent with typical Earth-fixed tectonic motions. From [7].

4.2 The North America Reference Frame (NAREF)

The North America Reference Frame (NAREF) was developed to provide a stable regional frame for North America (Figure 5). However, like ITRF2000 and ITRF2005 (Figure 6), its reliance on the NNR-NUVEL-1A model introduces distortions in the representation of tectonic behavior [6].

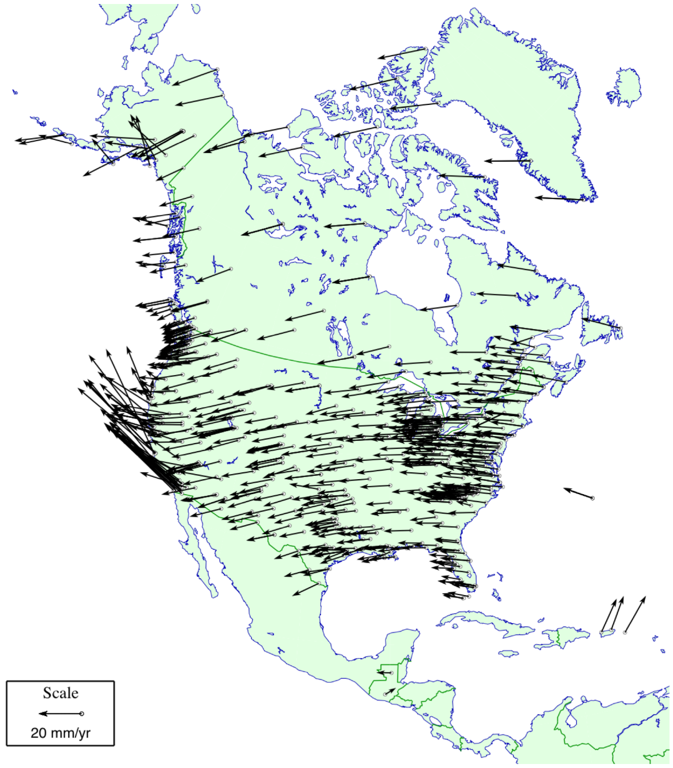

Figure 5: Horizontal velocities from the NAREF cumulative solution. From [6].

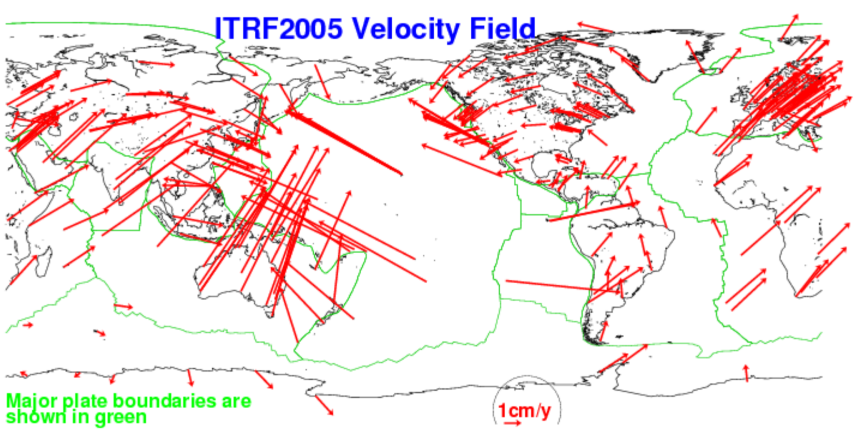

Figure 6: ITRF2005 global velocity field, showing strong similarity to ITRF2000 due to shared alignment with NNR-NUVEL-1A. From [9].

When the model-based corrections are removed, internal deformation becomes evident across the North American continent (Figure 7), indicating that the continent does not act as a single rigid body [6]. This observation fundamentally challenges a core tenet of classical plate tectonics [2, 3].

Figure 7: NAREF horizontal velocities after removal of NNR-NUVEL-1A model influence. Internal deformation is clearly visible, undermining assumptions of rigid plate behavior. From [6].

5 Discussion

The incorporation of geological models such as NNR-NUVEL-1A [4] into GPS-based reference frames creates a hybrid system that blends empirical measurements with theoretical assumptions [5, 6, 7, 8, 9]. While intended to stabilize geodetic products, this approach undermines the diagnostic power of GPS observations.

From a physics perspective, this is problematic: observational reference frames should be derived solely from measured data, free from imposed theoretical constraints. Empirical evidence from GPS consistently reveals complex, localized crustal deformation [6, 7]—contradicting the oversimplified rigid-plate assumptions embedded in models like NNR-NUVEL-1A. A more robust, data-driven approach is needed to accurately model Earth's dynamic behavior.

6 Conclusions

Modern satellite geodesy provides unprecedented insight into Earth's kinematics. However, the utility of GPS observations is compromised when reference frames are shaped by geological models. This paper has demonstrated that incorporating NNR-NUVEL-1A into ITRS realizations biases interpretations of crustal motion and obscures the true nature of Earth's tectonic behavior.

The development of purely observational, Earth-fixed reference frames that reflect the full complexity of crustal dynamics as revealed by GNSS (Global Navigation Satellite Systems) is advocated. A physics-based, measurement-first framework is essential for accurately testing and advancing tectonic theories.

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