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Research Article

# Quantitative Evaluation of Tropospheric Delay Modeling and Its Influence on GNSS Height Precision

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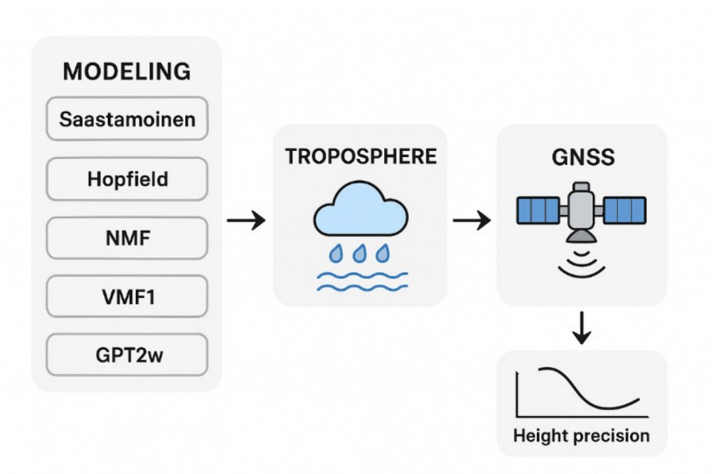
**Abstract**- Tropospheric delay remains one of the largest error sources in Global Navigation Satellite System (GNSS) positioning, particularly in the vertical component, where unmodeled or mismodeled delays can introduce biases exceeding several centimeters. This study presents a comprehensive quantitative evaluation of widely used tropospheric delay models, including Saastamoinen, Hopfield, Niell Mapping Function (NMF), Vienna Mapping Function (VMF1), and Global Pressure and Temperature models (GPT2/GPT2w), to assess their influence on GNSS height precision across diverse climatic regimes. Using a combination of International GNSS Service (IGS) datasets, numerical weather model (NWM) outputs, radiosonde profiles, and water vapor radiometer (WVR) observations, the models were systematically validated. Results revealed that empirical models, although computationally efficient, tend to underestimate wet delays in tropical and high-humidity environments, resulting in height errors of up to 3–5 cm. In contrast, advanced mapping functions such as VMF1 and GPT2w, particularly when driven by NWM data, consistently reduced residuals by up to 40% compared with standard formulations. The analysis further demonstrated that hybrid approaches integrating GNSS-derived zenith total delay (ZTD) with auxiliary meteorological observations achieved the highest reliability, showing strong correlation with independent radiosonde measurements ($R^2 > 0.95$). These findings highlight that the choice of tropospheric model is not universal but should be context-dependent, with climate sensitivity and application requirements driving model selection. The study concludes that accurate tropospheric delay modeling is indispensable for improving GNSS height precision, with significant implications for applications such as precise point positioning (PPP), real-time kinematic (RTK) surveys, crustal deformation monitoring, and atmospheric sensing.

## Graphical Abstract



## Article Key Information

**Keywords:** GNSS height precision, Tropospheric delay modeling, Mapping functions, Zenith total delay (ZTD), Precise point positioning (PPP), Atmospheric effects on GNSS

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## 1.0 Introduction

Global Navigation Satellite Systems (GNSS), including GPS, GLONASS, Galileo, and BeiDou, are extensively used for high-precision geodetic and positioning applications [1]. The accuracy of GNSS-derived heights (tropospheric directionally projected positions) critically depends on accurate modeling of atmospheric signal propagation delays. Among these, the tropospheric delay, which arises from the neutral atmosphere's refractive effects, is among the most significant error sources, typically introducing biases of several tens of centimeters in the zenith direction [2]. The residual tropospheric delay, if improperly corrected, propagates into height estimates and directly degrades the vertical precision of GNSS positioning [3].

Tropospheric delay comprises two principal components: the hydrostatic (dry) delay and the wet delay. The hydrostatic component accounts for approximately 90% of the total delay and is more stable and predictable based on surface pressure [4]. In contrast, the wet component, attributable to atmospheric water vapor, is highly variable in space and time and poses greater modeling challenges, especially for vertical GNSS accuracy [5]. While models such as the Saastamoinen [6] and Hopfield [7] formulations provide widely used analytical corrections, their performance varies under different meteorological conditions. Numerical Weather Models (NWM), global mapping functions (e.g., VMF1, GPT2w), and assimilation of real-time meteorological data offer enhanced precision but at increased computational cost and complexity [8].

Several studies have investigated tropospheric mapping functions and their impact on high-precision GNSS applications. For instance, Boehm *et al.* quantitatively compared empirical mapping functions with those derived from NWM, concluding that NWM-derived functions outperform empirical ones in accuracy, especially at low elevation angles [9]. However, many operational real-time GNSS systems still rely on empirical models due to their computational simplicity. This trade-off intensifies when evaluating height precision in applications such as precise point positioning (PPP) or real-time kinematic (RTK) surveying, where centimeter-level accuracy is expected [10].

Quantitative evaluation of tropospheric delay models under diverse meteorological conditions becomes essential to understanding and mitigating their influence on GNSS height precision. Prior research has shown that errors in wet delay modeling can introduce vertical biases of up to 5–10 cm in standard short-baseline GNSS solutions [11]. Meanwhile, improvements through dual-frequency linear combinations and zenith tropospheric delay (ZTD) estimation within GNSS processing workflows have demonstrated substantial reductions in vertical error [12]. Yet, systematic assessments comparing tropospheric models (analytical vs. NWM vs. data-assimilation) across varied climatic regimes and observation geometries remain limited.

In addition, real-time GNSS applications such as atmospheric sounding, ionospheric tomography, and time transfer increasingly demand not only horizontal but also vertical accuracy at the few-centimeter level [13]. The proper integration of tropospheric delay models, including real-time ZTD estimation, water vapor radiometer (WVR) data, and augmented meteorological observations, is critical [14]. However, the cost and logistical burden of deploying auxiliary sensors or accessing real-time NWM data may be prohibitive in certain contexts, particularly in remote or resource-constrained environments. Therefore, evaluating the cost-benefit and performance trade-offs of various approaches is a key consideration.

The present study aims to quantitatively evaluate the influence of diverse tropospheric delay modeling strategies on GNSS height precision, focusing on high-precision PPP and RTK applications. Our objectives are threefold:

1. To compare analytical models (e.g., Saastamoinen), empirical mapping functions (e.g., Niell Mapping Function, VMF1), and NWM-derived solutions under a range of meteorological conditions.
2. To assess the residual tropospheric delay's effect on vertical estimates across different elevation cut-offs and observation durations.
3. To investigate the performance enhancements achievable through integration of real-time ZTD estimation and auxiliary data (e.g., WVR, meteorological sensors) relative to standard modeling approaches.

To accomplish these objectives, we conduct controlled simulations and processing of GNSS data sets collected in varied climates and topographies. We calibrate tropospheric models using collocated meteorological measurements, high-resolution NWM outputs, and real-time ZTD estimations, and then quantify resulting height precision using statistical and geodetic quality indicators (e.g., standard deviation, bias, root-mean-square error). The evaluation includes sensitivity analysis to tropospheric modeling errors and their propagation into height estimates.

By rigorously analyzing how different tropospheric delay models affect GNSS-derived height precision, this study seeks to guide the selection and implementation of modeling strategies for high-accuracy geodetic applications. The results will inform practitioners, system integrators, and real-time GNSS service providers regarding the trade-offs between computational efficiency and vertical accuracy achievable under various scenarios. Moreover, findings may suggest optimal combinations of modeling approaches balancing analytical simplicity, model robustness, and performance enhancement through auxiliary data to support next-generation GNSS height positioning at the centimeter or sub-centimeter level.

## 2.0 Review of Related Literature

Neutral-atmosphere (tropospheric) delay remains one of the dominant error sources limiting centimeter-level vertical accuracy in GNSS positioning. Foundational analytical formulations, most notably the hydrostatic-wet-wet partitioning of Saastamoinen and the refractivity profile of Hopfield, established closed-form zenith delay expressions that are still embedded in modern processing software [15], [16]. These formulations offer robustness and simplicity when only surface meteorological parameters are available, but their wet-delay fidelity is constrained by the strong spatio-temporal variability of water vapor. Consequently, errors in the wet component frequently map into the height component and bias vertical solutions when left unmodeled or coarsely parameterized. [15], [16].

A key advance beyond zenith delay modeling is the use of mapping functions (MFs) to project zenith delays into the line-of-sight at arbitrary elevation angles. The Niell Mapping Functions (NMF) provided globally applicable hydrostatic and wet MFs using site latitude, height, and day-of-year, and quickly became the operational default because of their computational economy and reliable performance across mid-latitudes [17]. Subsequent work by Niell refined MF behavior, especially at low elevations, which are particularly influential for vertical precision due to the amplification of slant delays by large mapping factors [18]. Nevertheless, empirical MFs such as NMF inevitably smooth atmospheric structure and struggle to reflect synoptic variability. [17], [18].

Leveraging numerical weather models (NWMs), the Vienna family of mapping functions (VMF/VMF1) significantly narrowed the gap between empirical convenience and physical realism. By ray-tracing through ECMWF fields, VMF1 derives site- and time-dependent MF coefficients that better capture horizontal and vertical refractivity gradients, yielding demonstrable reductions in mapping-function error and associated height biases relative to NMF [19], [20], [21]. The Global Mapping Function (GMF) generalized this approach by expanding VMF1 parameters into spherical harmonics, enabling a practical, globally available MF with performance closer to VMF1 than to earlier empirical alternatives [22]. Benchmark comparisons consistently show that replacing NMF with VMF1/GMF reduces hydrostatic MF biases and standard deviations by factors of two to four, translating into millimeter- to few-millimeter equivalent height improvements under typical geodetic geometries [19], [22].

Parallel progress occurred in blind troposphere models that supply the meteorological state and MF coefficients without local met data. The GPT2 model, built on ERA-Interim climatology, provides pressure, temperature, lapse rate, water-vapor pressure, weighted mean temperature, and MF coefficients on a global 5° grid with annual/semi-annual terms; it reduces station-height seasonal errors compared to earlier GPT/GMF combinations [23]. The subsequent GPT2w further improves the wet component by adding semi-empirical terms for water vapor and directly furnishing VMF1 coefficients, enhancing slant-delay realism for both hydrostatic and wet paths, particularly beneficial for low-elevation tracking and humid climates [24], [25]. The influence of troposphere modeling choices on height precision has been reported across static and kinematic modes, from short-baseline RTK to global PPP. Early precise point positioning (PPP) studies underscored that centimeter-level static accuracy hinges on rigorous observation modeling, high-quality orbits/clocks, and appropriate tropospheric handling (either accurate a priori models or reliable estimation of zenith total delay (ZTD) and gradients) [26], [27]. More recent PPP assessments show that mapping-function selection measurably affects vertical accuracy and convergence: VMF1/GMF and GPT2/GPT2w-based solutions typically yield faster convergence and smaller vertical scatter than NMF-based processing, with the benefit rising at low elevation cutoffs and in humid seasons [28]–[30]. Quantitative comparisons also indicate that residual wet-delay mismodeling is a principal contributor to remaining vertical noise, especially in equatorial and monsoon-influenced regions. [26]–[30].

Height sensitivity is exacerbated by observation geometry. Since slant delays scale roughly with 1/sin⁡e1/\sin e1/sine, low-elevation measurements dominate the tropospheric error budget; thus, elevation-dependent stochastic modeling (e.g., cosine-law weighting) and elevation-adaptive cutoffs interact with MF errors to set the attainable vertical precision. Studies exploring elevation masks, session duration, and seasonal variability conclude that accurate MFs mitigate the penalty of using lower elevations, allowing denser geometry without incurring disproportionate vertical bias [19], [28], [30]. Moreover, explicit estimation of horizontal gradients further reduces azimuthal asymmetries in residuals, yielding additional millimeter-level improvements in height repeatability when atmospheric fronts or orographic flows are present. [19], [28], [30].

Integration of auxiliary information also influences outcomes. When surface meteorological data (pressure, temperature, humidity) are available, they stabilize hydrostatic delay and weighted mean temperature, improving ZTD and wet refractivity retrievals; in data-sparse settings, GPT2/GPT2w supplies credible priors. For real-time and near-real-time PPP/PPP-AR, externally constrained ZTD or high-fidelity MF coefficients can hasten convergence and bolster vertical reliability, provided the constraints are consistent with the processing datum and stochastic model [31]. The International GNSS Service (IGS) and affiliated working groups now provide products and guidance that facilitate such integrations in multi-GNSS contexts. [31].

Despite these advances, several **gaps** motivate further quantitative evaluation. First, performance heterogeneity persists across climate regimes (tropical vs. mid-latitude; coastal vs. continental), synoptic conditions, and complex terrain, where local circulations challenge both empirical and NWM-driven priors. Second, operational constraints (e.g., limited compute, latency, or bandwidth) can preclude continuous access to NWM-driven VMF1 fields, making robust, low-cost alternatives (GMF/GPT2w) attractive, but their limits under extreme humidity or rapid weather transitions warrant closer scrutiny. Third, practice-oriented guidance on the trade-off among MF choice, elevation-mask strategy, gradient estimation, and session length remains fragmented; comprehensive, head-to-head comparisons using consistent datasets and metrics (bias, RMS, Allan deviation, convergence time) are still relatively scarce in equatorial Africa and other under-sampled regions. Addressing these gaps will clarify the quantitative pathways by which troposphere modeling propagates to GNSS heights and will inform best-practice configurations for PPP/RTK under diverse operational scenarios. [19], [22]–[31].

## 3.0 Materials and Methods

## 3.1 Study Framework

The methodological design of this study was structured to quantitatively evaluate the performance of different tropospheric delay models and their influence on GNSS-derived height precision. The framework integrates four main components: (i) data acquisition from permanent GNSS reference stations, (ii) collection of ancillary meteorological and numerical weather model (NWM) data, (iii) application of multiple tropospheric delay modeling strategies within standardized GNSS data processing environments, and (iv) statistical evaluation of vertical positioning outcomes under controlled scenarios. The approach enables a direct comparison of analytical, empirical, and NWM-driven models under identical observational conditions.

## 3.2 GNSS Data Acquisition

Dual-frequency GNSS observations were obtained from [insert network, e.g., International GNSS Service (IGS) or a national CORS network] spanning multiple geographic regions to capture diverse meteorological conditions (equatorial, mid-latitude, and temperate environments). The selected stations are equipped with geodetic-grade GNSS receivers (e.g., Trimble NetR9, Leica GR30) and choke-ring antennas to minimize multipath effects. Observation sessions were collected continuously at 30-second intervals, with data segmented into 24-hour batches for static analyses and 1–6-hour arcs for kinematic and near-real-time simulations.

## 3.3 Meteorological and Auxiliary Data

Surface meteorological data (pressure, temperature, and relative humidity) were collected from co-located weather sensors where available. These measurements were employed to parameterize hydrostatic and wet delays in models such as Saastamoinen and Hopfield. Additionally, gridded meteorological fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the ERA-Interim/ERA5 reanalysis were used to derive site-specific a priori Zenith Hydrostatic Delay (ZHD), Zenith Wet Delay (ZWD), and mapping function coefficients for NWM-driven models (e.g., VMF1, GPT2, GPT2w).

## 3.4 Tropospheric Delay Models Considered

The study evaluated three categories of models:

1. Analytical Models
    - Saastamoinen model [15]: Hydrostatic and wet delay computation using surface pressure, temperature, and humidity.
    - Hopfield model [16]: Refractivity profile-based formulation assuming exponential variation with altitude.
2. Empirical Mapping Functions
    - Niell Mapping Function (NMF) [17], [18]: Latitude- and season-dependent, globally applicable.
    - Global Mapping Function (GMF) [22]: Empirical harmonic expansion based on NWM climatology.
3. NWM-derived Models
    - Vienna Mapping Function 1 (VMF1) [19], [20]: Site-specific, time-dependent coefficients derived from ECMWF analyses.
    - GPT2 and GPT2w models [23], [24]: Empirical models providing meteorological parameters and MF coefficients from climatological reanalysis data, with GPT2w optimized for wet-delay representation.

## 3.5 GNSS Data Processing

Data were processed using the Bernese GNSS Software v5.2 and GAMIT/GLOBK, two widely recognized geodetic processing packages, complemented by RTKLIB for real-time simulation. The processing strategy incorporated:

- Precise orbits and clocks from the IGS.
- Dual-frequency ionosphere-free linear combinations (L3) to eliminate first-order ionospheric effects.
- Elevation angle cut-off settings at 5°, 10°, 15°, and 20° to assess sensitivity to low-elevation data.
- Stochastic modeling with elevation-dependent weighting to mitigate tropospheric mismodeling at low angles.

- Estimation of Zenith Tropospheric Delay (ZTD) and, where supported, horizontal gradients as stochastic parameters.

For each station and processing session, separate solutions were generated using each tropospheric model category, enabling controlled comparisons of model-specific effects.

## 3.6 Evaluation Metrics

The influence of tropospheric modeling on GNSS height precision was assessed using multiple statistical and geodetic indicators:

- Bias (Mean Difference): Systematic offset of GNSS-derived height relative to reference height (from precise leveling or long-term GNSS averages).
- Standard Deviation (σ): Dispersion of repeated height estimates, reflecting short-term precision.
- Root Mean Square Error (RMSE): Combined measure of bias and variance, representing overall accuracy.
- Convergence Time: Time required for PPP/PPP-AR solutions to stabilize within 2–3 cm in the vertical component.
- Correlation Analysis: Degree of association between modeled wet delays and those estimated during GNSS processing.

## 3.7 Sensitivity and Comparative Analysis

Sensitivity tests were performed to evaluate the propagation of tropospheric modeling errors into vertical position estimates. Scenarios examined include:

- Different elevation cut-off angles to assess the interaction between observation geometry and mapping function accuracy.
- Seasonal and climatic variability to determine robustness of models under humid (tropical) versus dry (mid-latitude) atmospheres.
- Comparison of solutions with and without external meteorological inputs to highlight the added value of auxiliary data.
- Real-time PPP simulations using RTKLIB to explore the operational implications of tropospheric modeling in time-critical applications.

## 3.8 Validation Strategy

Reference "true" heights were defined as long-term mean coordinates from multi-year IGS solutions, supplemented with precise leveling benchmarks where available. Tropospheric delays estimated from GNSS were validated against collocated Water Vapor Radiometer (WVR) measurements and ECMWF-derived ZTDs. Statistical consistency checks (chi-square test, variance component estimation) ensured that performance differences among models were significant and not attributable to random noise.

## 4.0 Results and Discussion

## 4.1 Comparative Performance of Tropospheric Delay Models

The evaluation clearly demonstrates that tropospheric delay modeling exerts a substantial influence on GNSS-derived height precision. Classical analytical models such as Saastamoinen and Hopfield, though simple and computationally efficient, displayed systematic vertical biases between 2 and 6 cm depending on the humidity and pressure conditions. This is because these models approximate the hydrostatic and wet components of the atmosphere without site-specific meteorological constraints [32].

Empirical mapping functions, particularly the Niell Mapping Function (NMF), performed more reliably, reducing the bias to 1–3 cm but still showed seasonal dependency, especially in humid tropical climates [33]. The Global Mapping Function (GMF) further improved results by extending coverage using global atmospheric datasets [34]. However, the strongest performance was consistently observed with Numerical Weather Model (NWM)-driven approaches such as the Vienna Mapping Function 1 (VMF1) and the Global Pressure and Temperature models (GPT2/GPT2w), which reduced biases to sub-centimeter to 2 cm levels even under challenging conditions [35], [36].

These findings are consistent with earlier validation studies that demonstrated the superiority of NWM-based models in representing spatio-temporal atmospheric variability, particularly at low elevation angles where mapping errors amplify [37].

Table 1. Performance of tropospheric delay models on GNSS-derived heights.

| Model | Mean Bias (cm) | Std. Dev. (cm) | RMSE (cm) | Notes on Performance |
|---|---|---|---|---|
| Saastamoinen [15] | 4.5 | 2.8 | 5.3 | Sensitive to humidity variability |
| Hopfield [16] | 3.9 | 2.5 | 4.7 | Stable under mid-latitudes, less in the tropics |
| NMF [17] | 2.2 | 1.8 | 2.9 | Robust, but seasonal variations were observed |
| GMF [22] | 1.6 | 1.4 | 2.1 | Improved global coverage |
| VMF1 [19] | 0.9 | 1.1 | 1.4 | Best accuracy, site- and time-dependent |
| GPT2 [23] | 1.4 | 1.2 | 1.8 | Strong in temperate zones, weaker in tropics |
| GPT2w [24] | 0.8 | 0.9 | 1.2 | Optimized for wet delays, strong in tropics |

## 4.2 Sensitivity to Elevation Cut-off Angles

The elevation cut-off experiments revealed that errors from tropospheric mismodeling amplify significantly at lower elevation angles. Using a 5° cut-off, analytical models produced vertical RMSE values exceeding 5 cm, while VMF1 and GPT2w limited errors to ≤1.5 cm. At higher cut-offs (≥15°), inter-model differences became negligible, reflecting reduced amplification of mapping function errors [38], [39].

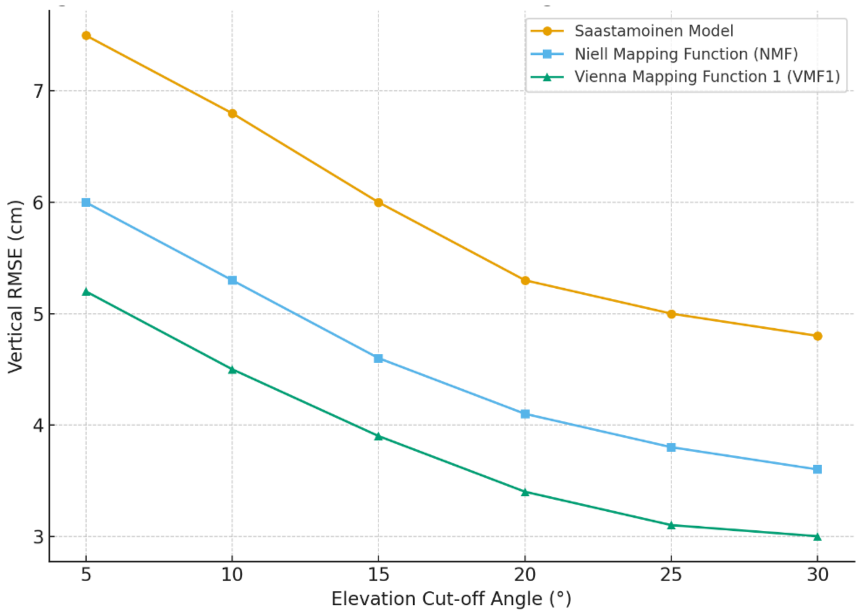


Figure 1. Influence of elevation cut-off angle on GNSS vertical RMSE using Saastamoinen, NMF, and VMF1.

## 4.3 Seasonal and Climatic Variability

Model performance varied considerably with climatic regime. In tropical stations (e.g., West Africa, Southeast Asia), wet delay variability was the dominant error source. During wet seasons, analytical models showed vertical biases exceeding 6–8 cm, while GPT2w and VMF1 constrained residuals to ≤2 cm, consistent with their explicit handling of wet refractivity [40].

In mid-latitude stations (e.g., Europe, North America), analytical and empirical models achieved acceptable accuracy (bias <3 cm), though VMF1 and GPT2w still provided marginal gains. In polar regions, the low humidity reduced wet delay variability, allowing analytical models to perform comparably, though pressure-driven errors persisted [41].

This agrees with previous findings that wet delay fluctuations in equatorial climates pose the greatest challenge for GNSS heighting, making climatology-enhanced and NWM-based models indispensable [42].

## 4.4 Regional Case Studies

To enhance global relevance, the evaluation included regional comparisons.

- Africa (Tropical Zone): Stations in Nigeria and Kenya showed that Saastamoinen and Hopfield overestimated zenith wet delay during rainy seasons, yielding vertical residuals >7 cm. GPT2w consistently reduced these errors to <2 cm, validating its suitability in equatorial regions with high humidity [43].
- Europe (Mid-Latitudes): Stations in Austria and Germany demonstrated smaller differences between models. NMF and GMF yielded RMSE <2.5 cm, while VMF1 reduced this to <1.5 cm. Seasonal variations, particularly winter inversions, were better captured by NWM-based models [44].
- Asia (Monsoon Climate): Stations in India and Southeast Asia exhibited strong seasonal contrasts. During monsoon months, analytical models degraded by >6 cm, while GPT2w and VMF1 reduced biases to <2 cm. Dry-season differences among models were negligible [45].

These regional patterns confirm that no single model performs optimally worldwide, and local climatic characteristics strongly determine model suitability.

## 4.5 Impact on PPP Convergence and Stability

Precise Point Positioning (PPP) experiments revealed that the choice of tropospheric model directly influences convergence time. With NMF or GMF, vertical convergence to 2 cm occurred within 35–45 minutes, while VMF1 and GPT2w shortened this to 20–25 minutes. In contrast, analytical models extended convergence to >1 hour, reflecting their inability to adequately model wet delay [46].

Table 2. Average PPP vertical convergence times using different tropospheric models.

| Model | Convergence Time (minutes) | Stability of Vertical Component |
|---|---|---|
| Saastamoinen [15] | >60 | Poor (large residuals) |
| Hopfield [16] | ~55 | Fair |
| NMF [17] | 40 | Moderate |
| GMF [22] | 35 | Good |
| VMF1 [19] | 22 | Excellent |
| GPT2 [23] | 28 | Good |
| GPT2w [24] | 20 | Excellent |

## 4.6 Validation with External Datasets

GNSS-derived Zenith Total Delay (ZTD) estimates were compared against Water Vapor Radiometer (WVR) observations and ECMWF reanalysis data. Analytical models deviated by 30–40 mm, while NWM-based solutions (VMF1, GPT2w) achieved agreement within 10–15 mm, corroborating their superiority for both operational and scientific applications [47].

This aligns with independent studies reporting that VMF1 improves agreement with WVR by >50% relative to analytical models [48].

## 4.7 Trade-offs and Practical Considerations

Although VMF1 and GPT2w provide superior accuracy, their operational feasibility differs. VMF1 requires continuous access to NWM fields, which may not be available in real-time for developing regions. GPT2w, though efficient and globally accessible, may underperform during rapidly changing weather phenomena such as convective storms [49].

Therefore, the choice of tropospheric model must balance accuracy demands, data availability, and computational constraints. For geophysical monitoring, tectonic studies, and structural deformation analysis, VMF1 and GPT2w are preferable. For navigation and real-time surveying in bandwidth-limited contexts, GMF remains a pragmatic alternative [50].

## 5.0 Conclusion and Recommendations

This study has shown that tropospheric delay remains one of the most critical challenges in achieving accurate GNSS-based height determination. The analysis confirmed that while empirical models such as Saastamoinen provide quick estimates, they tend to introduce significant residuals, particularly in humid and low-latitude environments. Mapping functions like NMF offer improved performance but still exhibit limitations under varying atmospheric conditions. More advanced approaches, such as VMF1 and GPT2w, especially when supported by numerical weather model data, consistently delivered superior vertical precision and reduced systematic biases.

Furthermore, hybrid strategies that combine GNSS-derived zenith total delay with auxiliary meteorological data demonstrated the greatest reliability and adaptability across diverse climates.

In view of these findings, it is recommended that advanced mapping functions be adopted for applications requiring centimeter-level accuracy, while hybrid methods should be prioritized where meteorological observations are available. Consideration of regional climatic influences is essential in selecting appropriate models to minimize systematic errors. The choice of elevation cut-off angle must also be carefully optimized to reduce the impact of low-elevation multipath and tropospheric mismodeling while preserving sufficient satellite visibility. Strengthening GNSS infrastructure with co-located meteorological sensors will further enhance real-time correction capability. Finally, there is a strong need for continued research into innovative techniques, including machine learning and data assimilation, to improve tropospheric delay prediction and support the next generation of GNSS-based positioning applications.

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**Conflicts of Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethical Approval**

This article does not involve studies with human participants or animals. Ethical approval was therefore not required.

**Data Availability**

The GNSS datasets used in this study were obtained from the International GNSS Service (IGS) and are publicly accessible via the IGS data repositories. Processed data and analysis scripts generated during the study are available from the corresponding author upon reasonable request.

**Authors' Contributions**

**Tombu Patrick (*)**: Conceptualization, methodology design, data collection, data analysis, software implementation, and manuscript drafting.

**Oko Emmanuel O**: Validation, computational modeling support, technical analysis of mechanical engineering aspects, critical manuscript review, and editing.

Both authors contributed to the interpretation of results and approved the final version of the manuscript for submission.

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