

Pseudorange Error Modeling for LEO-PNT Systems

Andrea Bianconi^{1,†}, Marco Dolfi^{1,†}, Omar Morandi^{2,†} and Simone Morosi^{1,*,†}

¹Information Engineering Dept., University of Florence, Florence, Italy

²DIDA Dept., University of Florence, Florence, Italy

Abstract

Modern positioning for autonomous systems and Internet of Things (IoT) requires higher accuracy and higher resilience than traditional Medium Earth Orbit (MEO) constellations can provide. This paper investigates the integration of Low Earth Orbit (LEO) satellites into Global Navigation Satellite System (GNSS) architectures to mitigate atmospheric delays and multipath interference. Through MATLAB-based stochastic modeling and Least Squares estimation, MEO, LEO and hybrid configurations are evaluated. The study focuses on mitigation of ionospheric, tropospheric and multipath error through LEO's higher frequency bands, shorter propagation paths and higher received signal power. Critical technological bottlenecks, such as the absence of onboard atomic clocks and the limitations of using Two-Line Elements (TLE), are addressed. The results show that the positioning accuracy depends on the density of the constellation and the precision of compensation techniques. A threshold of three LEO satellites is identified to significantly reduce the error standard deviation (σ_e). The findings confirm that transitioning to Precise Orbit Determination (POD) and clock stability are mandatory to unlock LEO-augmented PNT for safety-critical applications.

Keywords

GNSS, LEO constellations, Hybrid positioning, Atmosphere error, TLE error, Clock bias, Multipath error, PNT resilience.

1. Introduction

Over the last few decades, satellite positioning has assumed a central role in a wide range of applications, from land and maritime navigation to geodesy, environmental monitoring, autonomous vehicles and location-based services for the Internet of Things (IoT) [1]. In modern society, precise determination of position and timing synchronization data has become indispensable, supporting critical sectors such as air and sea navigation, national power grid synchronization and the flourishing autonomous vehicle industry. Furthermore, the rapid expansion of the IoT has generated a demand for increasingly precise and low-power localization services that current infrastructure struggles to meet consistently. To date, the Global Navigation Satellite System (GNSS), based on Medium Earth Orbit (MEO) constellations, represents the most widely used system for determining position on a planetary scale, thanks to its global coverage, relative ease of reception, the continuous technological evolution of existing constellations and the ongoing development of low-cost systems capable of interfacing with transmitted satellite signals. MEO systems exhibit significant intrinsic limitations when operating in critical environments [2, 3]. This is because MEO satellites orbit at altitudes of approximately 20,000 km, resulting in extremely low signal power at the Earth's surface; consequently, MEO signals are susceptible to significant attenuation and blockage by physical obstacles. Furthermore, traditional GNSS systems are highly vulnerable to atmospheric delays (ionospheric and tropospheric), multipath effects, and interference—such as jamming and spoofing—which can compromise the integrity of the positioning solution. [4, 5]. In response to these growing challenges, the scientific community and the industrial sector are shifting their attention to a new and promising frontier: Low Earth Orbit (LEO) constellations [6]. Originally employed for broadband telecommunications, high-resolution Earth observation and provision of internet services, LEO satellites offer structural characteristics that make

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*Corresponding author.

[†] These authors contributed equally.

✉ andrea.bianconi@unifi.it (A. Bianconi); marco.dolfi@unifi.it (M. Dolfi); omar.morandi@unifi.it (O. Morandi); simone.morosi@unifi.it (S. Morosi)



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them particularly suitable for positioning purposes. Their proximity to Earth (typically between 350 and 2,000 km) ensures a significantly higher signal-to-noise ratio (SNR) compared to MEO satellites. In this context, LEO satellites can be integrated as an augmentation system for currently operational GNSS systems relying on two distinct approaches: dedicated LEO-PNT (Positioning, Navigation and Timing) systems and Signals of Opportunity (SoO) [1]. Dedicated LEO-PNT systems rely on purpose-built megaconstellations, the primary objective of which is the provision of positioning services, for this reason these systems are designed specifically for navigation, the signals are generated by a payload optimized for this specific purpose, allowing for custom signal structures and antenna coverage, which would be highly advantageous in environments where traditional GNSS signals are degraded or entirely blocked. In the SoO paradigm, by contrast, signals transmitted by the thousands of LEO satellites currently orbiting Earth are exploited opportunistically; since these satellites were not designed to provide positioning services, they do not transmit navigation messages containing ephemeris data; consequently, all the information required by the receiver to calculate the satellite's position and predict its orbit must be derived through alternative means. For these reasons, it is necessary to track alternative observables—such as Doppler shifts or carrier phase variations—to estimate the satellite's orbit and, ultimately, the receiver's position. This approach takes advantage of existing megaconstellations intended for the Internet or communication services—such as SpaceX's Starlink or OneWeb [7]—which do not natively transmit navigation data and operate at much higher frequencies, specifically in the Ku (approximately 12.5 GHz) or Ka bands. This study focuses explicitly on the latter scenario, evaluating the performance associated with the opportunistic integration of LEO constellations into a MEO satellite system to create a hybrid multi-layer architecture. LEO satellites offer a number of advantages over MEO satellites. First, because they operate in orbits much closer to the end-user, LEO satellites experience significantly lower free-space propagation loss than MEO systems; this results in higher received signal power—up to 30 dB greater. However, although this proximity increases the nominal signal-to-noise ratio, the high-frequency Ku/Ka-band signals used by the mega-constellations currently in orbit suffer severe propagation attenuation due to buildings, vegetation and atmospheric obstacles; consequently, the higher signal power primarily enhances robustness, but does not automatically guarantee superior penetration capability in indoor environments. Commercial satellites in Low Earth Orbit typically do not transmit navigation messages and generally feature onboard commercial quartz oscillators, which are less stable than the atomic clocks found on MEO satellites. Consequently, positioning using an opportunistic approach relies on alternative methods to determine satellite locations, such as the use of Two Line Elements (TLE). Furthermore, the high orbital velocity of LEO satellites results in a fast-changing geometry, drastically reducing convergence times for high-precision algorithms such as Precise Point Positioning (PPP) and reducing the duration during which the user experiences the absence of a direct line of sight with the satellite [8, 9, 10]. The evaluation of positioning error is conducted within a vehicular operational scenario. This context is characterized by navigation along a predefined trajectory, which is typical for automotive or railway and this setting allows for a reduction in the dimensionality of the problem, focusing the analysis specifically on error estimation along a single longitudinal direction of travel. For the purposes of this study, a one-dimensional (1D) scenario is defined by setting the horizontal and vertical reference angles to 0° , by simplifying the spatial geometry, the impact of stochastic noise can be isolated and analyzed with higher precision, avoiding dilution of error across multiple coordinate axes and it becomes possible to derive clearer performance benchmarks that are essential for validating the integration of LEO constellations within hybrid architectures. However, it is important to emphasize that the adopted simplification does not compromise the generality of the study; the implemented simulator remains inherently modular, ensuring the scalability of the results to 2D and 3D coordinate systems. Although the analysis focuses on a one-dimensional scenario constrained to a specific trajectory, the simulation architecture developed in MATLAB is natively extensible to two- and three-dimensional systems; this is achieved by increasing the spatial degrees of freedom within the least-squares estimation algorithm, given that the simulation framework was specifically designed to support such expansion. In light of this, extending the one-dimensional results to 2D or 3D dimensional positioning requires accounting for spatial anisotropy; indeed, in positioning systems, the vertical error component inherently dominates the horizontal planar components, as satellites can only

be tracked by the receiver when they are above the horizon. Consequently, transitioning from a 1D to a 3D configuration transforms positioning uncertainty from a linear variance into a time-varying error ellipsoid, the parameters of which fluctuate due to multipath reflections and atmospheric dynamics. By modifying the degrees of freedom within the MATLAB simulation framework, the observation matrix projects pseudorange determination errors onto a two-dimensional plane or a three-dimensional volume, ensuring that the complex spatial correlations and anisotropic physical characteristics of multidimensional positioning systems are adequately considered.

This article aims to provide a comprehensive exploration of the potential of LEO-based positioning. It analyzes how the integration of established MEO technologies with the high-power and low-latency signals of new LEO infrastructures can redefine the current standards of global navigation resilience. Through the use of rigorous error modeling—addressing clock biases, orbital uncertainties (Two Line Elements based) and atmospheric corrections—and the conduct of comparative simulations in a MATLAB environment, this study demonstrates that overcoming the structural constraints of traditional MEO systems is possible. The goal is to pave the way for a new generation of localization services capable of maintaining high-integrity positioning in scenarios where the signal was inevitably destined to degrade.

2. System Model

This section focuses on the integration of LEO satellites within a traditional 8-satellite MEO constellation. The primary objective is to develop a multilayer architecture capable of compensating for inherent limitations and positioning errors of standard GNSS systems (Table 1).

2.1. Simulation methodology

The primary source of uncertainty affecting the system is modeled as a zero-mean Gaussian stochastic process. For vehicular applications along a known path, the navigation problem is simplified into a one-dimensional (1D) scenario along the receiver's direction of travel. To isolate instantaneous positioning error and evaluate error standard deviation σ_e , the receiver is modeled strictly stationary (velocity = 0 m/s) in a known location, ensuring that performance variations in probability density functions (PDF) are attributed solely to constellation characteristics obtained by introducing LEO satellites into the MEO only system. Although position estimation is constrained to 1D, constellation geometry remains three-dimensional; Line-of-Sight (LOS) vectors from the observation matrix are projected onto the motion axis, this choice avoids masking horizontal errors behind the dominant vertical error components inherent in 3D error metrics.

2.2. Comparative scenarios

The effectiveness of the localization system is evaluated by comparing three distinct orbital configurations:

- MEO scenario: the baseline reference representing conventional GNSS systems.
- LEO scenario: used to assess the specific potential of low-orbit constellations.
- Hybrid LEO+MEO scenario: aimed at quantifying the actual performance gain and benefits derived from integrating low-orbit satellites into the MEO segment.

To avoid ambiguity, it must be clarified that the LEO configurations analyzed in this study (e.g., 1-LEO, 2-LEO, 3-LEO) refer to the number of LEO satellites in the constellation that are visible to the user at any given moment. Ensuring continuous local visibility of at least three LEO satellites—at any time and at any location on Earth—requires a significantly larger global constellation; specifically, a global constellation comprising several hundred satellites distributed across at least two sub-constellations is essential, with distinct characteristics regarding the number and inclination of orbital planes and the number of satellites within each subsystem.

2.3. Positioning algorithm and performance metrics

The receiver's position is estimated using the Least Squares (LS) algorithm [11]. Initially, a constellation composed of eight satellites in medium orbit is considered. Given a receiver in a known position, the error is evaluated in terms of standard deviation σ_e , which is incurred in determining the receiver's position by applying the least squares algorithm. One of the objectives is to determine how σ_e changes by evaluating how possible error sources can influence position determination and how the presence of any LEO satellite in the constellation succeeds or fails to mitigate the overall error in the final calculated position. Once the receiver's position is estimated, the pseudoranges are corrected to eliminate residuals.

A key point to emphasize is that, to isolate the impact of LEO satellite characteristics on positioning accuracy, the simulation results presented rely on a controlled geometric configuration. The analysis begins with a reference configuration consisting of eight MEO satellites at known positions, establishing the baseline geometry for the user; in the subsequent hybrid configurations, rather than expanding the constellation by adding more satellites, specific MEO satellites are replaced by an equal number of LEO satellites. This replacement alters only the satellite's operating altitude and transmission frequency, while leaving the line-of-sight angular vector relative to the receiver unchanged. Consequently, the observation geometry matrix and the resulting Position Dilution of Precision (PDOP) value remain constant across all examined configurations, from the reference setup with eight MEO satellites to the hybrid variants, and finally to the architecture consisting of four MEO and four LEO satellites. By eliminating PDOP fluctuations, the contribution of LEO satellites can be isolated; thus, any variations in the probability density function and the standard deviation of the positioning error can be attributed solely to the characteristics of LEO satellites.

2.4. Ionospheric delay model

The total ionospheric delay along the propagation path is a function of the Total Electron Content (TEC) [6]. For MEO satellites operating at the L1 frequency (1.58 GHz) [2, 12], the pseudorange error is modeled as [8]:

$$\delta_{iono,MEO} = \frac{40.3}{f^2} TEC \quad (1)$$

Low Earth orbit satellites typically orbit at lower altitudes and transmit signals at higher frequencies (e.g., 12.5 GHz in the Ku-band) [10, 6]. Because LEO satellites orbit within the ionosphere, signals transmitted to the ground only pass through the bottomside ionospheric layers below the satellite's altitude; the partial electron content crossed by these signals is denoted as TEC_{LEO} [13]. The adapted formula for the LEO ionospheric delay $\delta_{iono,LEO}$ is given by:

$$\delta_{iono,LEO} = \frac{40.3}{f^2} TEC_{LEO} \quad (2)$$

Using the slant path theory, the TEC is calculated based on the receiver's position, the satellite elevation relative to the Earth's surface and the Vertical Total Electron Content ($VTEC$) [14]. TEC_{LEO} is set to $TEC_{LEO} = 0.62 \cdot TEC$, this fractional scaling represents a realistic scenario in which the LEO signal crosses only the lower layers of the ionosphere. Indeed, recent studies analyzing LEO navigation augmentation signals demonstrate that the portion of the bottomside electron content relative to the total TEC typically ranges from 56% during the night to 84% during daytime [15, 13], for this reason the factor of 62% has been chosen. The temporal evolution of the ionospheric error is modeled as a first-order Gauss-Markov process [15, 16], with initial values $\delta_{iono,MEO}$ and $\delta_{iono,LEO}$ defining the delay distributions for each specific orbit layer [15]. Mitigation is achieved using the Klobuchar model to reduce propagation errors for single-frequency receivers [17], the correction is scaled for LEO satellites [13].

2.5. Tropospheric Delay Model

LEO satellites are subject to atmospheric interactions that differ significantly from those affecting MEO platforms. To estimate tropospheric delay, the Saastamoinen model is employed [7], which uses meteorological parameters, Pressure (P), Temperature (T) and Humidity, to estimate hydrostatic (dry) and wet delay components [18]. These components of the zenith delay are calculated as follows:

$$d_{hyd} = 0.002277 \cdot \frac{P_s}{f(\phi, h)} \quad (3)$$

$$d_{wet} = 0.002277 \cdot \frac{e_s \cdot \left(\frac{1255}{T_s} + 0.05 \right)}{f(\phi, h)} \quad (4)$$

where ϕ is the receiver latitude, h is the satellite altitude, and the gravitational scaling factor is defined as $f(\phi, h) = 1 - 0.0266 \cos(2\phi) - 0.00028h$. The partial pressure of water vapor e_s is derived from the relative humidity [8, 11]. The tropospheric error is modeled in MATLAB as a Gaussian distribution with bias [18, 3].

2.6. Multipath model

LEO and MEO satellites exhibit different multipath dynamics, driven by signal characteristics and orbital geometry [19]. Although LEO constellations provide higher received signal power, effective multipath mitigation and reflection rejection depend intrinsically on signal bandwidth, chip rates and receiver architecture. However, a distinctive feature of LEO satellites is the rapid geometric decorrelation of multipath reflections, a result of their high orbital velocity. Multipath error typically does not have a zero mean; instead, it manifests itself as a time-varying bias, with statistical behavior closely related to the specific properties of the propagation channel [20, 21]. Consequently, to realistically simulate this behavior, the multipath error associated with a satellite is modeled as a Gauss-Markov process [11] and this process is governed by a correlation time constant, which quantifies the rate at which the reflection environment changes.

According to the different characteristics of MEO and LEO satellites, multipath errors are generated using different time constants, reflecting the distinct nature of their respective signals. Since the multipath error decorrelation rate depends on the satellite's angular velocity relative to the receiver, a longer time constant is used for MEO satellites to represent a slowly varying reflection environment; conversely, a much shorter time constant is adopted for LEO satellites to account for the rapid evolution of reflection geometry caused by their high orbital speed, 300 s is set for MEO satellites, in line with established stochastic error models and ground processing standards [22, 23, 24] and 30 s for LEO [25, 26]. It is important to underline that the choice of a 30 s time constant for LEO satellites is conservative; as demonstrated in [25], the high angular velocity of LEO satellites can lead to an improvement of up to 75% in multipath error decorrelation compared to traditional GNSS constellations. Therefore, maintaining the time constant at 30 s ensures that the adopted model does not overestimate the actual performance of the LEO satellites. To mitigate multipath effects, a Geometry-Aided Smoothing variant of the Hatch filter is implemented [3, 27]. The smoothed pseudorange $\bar{\rho}_k$ is computed as:

$$\bar{\rho}_k = \alpha_m \rho_{raw,k} + (1 - \alpha_m)(\bar{\rho}_{k-1} + \Delta\rho) \quad (5)$$

where α_m is the smoothing coefficient, $\rho_{raw,k}$ is the raw measured pseudorange and $\Delta\rho$ is the geometric distance variation between consecutive epochs.

2.7. TLE error model

Opportunistic LEO positioning relies on North American Aerospace Defense Command (NORAD) Two-Line Elements and the Simplified General Perturbations (SGP4) propagator [28, 29, 30, 19]. However, since LEO satellites orbit at lower altitudes than MEO ones, they are subject to significant dynamic

perturbations—primarily atmospheric drag and Earth’s gravitational field—rendering models originally developed for medium Earth orbit satellites inadequate [31]. The SGP4 model, which relies on simplified analytical formulations to limit computational complexity, is unable to effectively model the forces acting on satellites in LEO; consequently, orbital information derived from TLE degrades rapidly, and the receiver may incur errors of several kilometers in determining the satellite’s position if the TLE are not updated periodically. Therefore, quantifying the impact of TLE-induced orbital errors is a fundamental requirement in the development of realistic hybrid LEO/MEO architectures. Unmodeled atmospheric drag and gravitational perturbations cause orbital degradation between update cycles [31, 32], for this reason the receiver can commit a significant error in satellite position determination and, consequently, in its orbit prediction. The TLE-induced pseudorange error affects only LEO satellites and is modeled using a Gaussian distribution with bias [33]:

- Uncompensated parameters: A bias is adopted with a mean value $\mu = 500$ m and a standard deviation $\sigma = 30$ m. The offset of 500 m represents the typical error introduced by the use of TLE when they are updated every 24 hours, as demonstrated in [31]. The use of the SGP4 propagator introduces a significant error since the use of TLE as it does not adequately model the forces acting on LEO, particularly atmospheric drag, to which low-Earth orbit satellites are strongly subjected [32]. In contrast, the standard deviation of 30 m is consistent with empirical validations that compare the determination and tracking of the orbit by TLE with the results obtained with the real measurements performed by Global Positioning System (GPS) [34].
- Compensated parameters: Assuming a more accurate orbit determination strategy, the model reduces the mean error to $\mu = 100$ m and the standard deviation to $\sigma = 1$ m. In fact, it is currently possible to achieve decimeter-level POD accuracy by exploiting the post-processing of dual-frequency GNSS measurements, even in very low Earth orbits where atmospheric drag is very high [35, 36]. Possible alternative techniques include the use of the Doppler Orbitography and Radiopositioning Integrated by Satellite (Doris) system or Satellite Laser Ranging (SLR) measurements. A key aspect to underline is that LEO satellites, due to their small size, are often subject to strict constraints on size, weight and power, which limit the onboard computational resources with which they can be equipped, so to account for these operational limitations, a conservative simulation framework is chosen; in fact, the following parameters are adopted for the compensated condition: ($\mu = 100$ m, $\sigma = 1$ m).

2.8. Clock error model

Unlike MEO satellites, LEO satellites cannot be equipped with atomic clocks due to the limited physical space available on small-satellite platforms and the excessive power consumption of such devices [37, 2]. The absence of a stable temporal reference results in a temporal bias averaging 100 ns in pseudorange calculations [38]. As analyzed in [39], real LEO flight data indicate that even high-performance space-grade oscillators can accumulate milliseconds of clock bias over a two-week period if left unchecked; therefore, adopting a 100 ns satellite clock bias in the simulation framework represents a realistic yet conservative scenario, reflecting the real-world rapid error growth of commercial quartz oscillators generally utilized in LEO missions. The clock bias is modeled as a Random Walk, a non-stationary process that accumulates uncertainty over time [39, 16], effectively simulating the physics of quartz oscillators typically employed in LEO missions. At each time step k , the drift d_k is calculated as follow:

$$d_k = d_{k-1} + \omega_k \quad (6)$$

where $\omega_k \sim N(0, \sigma_{h_{mH}}^2)$ with $\sigma_{h_{mH}} = 1$ ns.

The total instantaneous clock error $\epsilon_{CLK}(k)$ is then obtained by superimposing a white Gaussian noise term on the cumulative bias, which models the instantaneous signal jitter [11]:

$$\epsilon_{CLK}(k) = \epsilon_{cum}(k) + \eta_{inHJ}(k) \quad (7)$$

where $\eta_{inHJ}(k) \sim \mathcal{N}(0, \sigma_{inHJ}^2)$ with $\sigma_{inHJ} = 60$ ns.

The error introduced by the lack of a stable clock exclusively affects the LEO satellites in the constellation. To evaluate its impact, two configurations are considered:

- Uncompensated parameters: A cumulative drift component combined with an instantaneous jitter $\eta_{inHJ}(k)$ with $\sigma_{inHJ} = 60$ ns.
- Compensated parameters: Error reduction is achieved by assuming a more stable reference and subtracting a correction term from the pseudorange.

Table 1

Summary of error models and simulation parameters for MEO and LEO satellites.

Error Source	MEO Baseline	LEO Opportunistic
Ionospheric	• Model: Gauss-Markov • Freq: L1 (1.58 GHz) • Path: 100% ionosphere • Mitig.: Klobuchar	• Model: Gauss-Markov • Freq: Ku (12.5 GHz) • Path: lower ionosphere • Mitig.: Scaled Klobuchar
Tropospheric	• Model: Saastamoinen • Inputs: GPT2 coeff. • Mitig.: Det. subtraction	• Model: Saastamoinen • Inputs: GPT2 coeff. • Mitig.: Det. subtraction
Multipath	• Model: Gauss-Markov • Corr. Time: $\tau = 300$ s • Mitig.: Hatch Filter	• Model: Gauss-Markov • Corr. Time: $\tau = 30$ s • Mitig.: Hatch filter
Orbital (TLE)	• Broadcast ephemeris • Negligible errors	• NORAD TLE + SGP4 • Uncomp.: $\mu = 500$ m, $\sigma = 30$ m • Comp.: $\mu = 100$ m, $\sigma = 1$ m
Sat. Clock	• Atomic Clocks • Negligible drift/jitter	• Commercial Quartz • Random Walk + Jitter • Uncomp.: $\sigma_{\text{jitter}} = 60$ ns • Comp.: Residual drift

3. Experimental results and discussion

In this section, the positioning performance of the proposed LEO-PNT system is evaluated and compared to traditional MEO constellations (Table 2).

Table 2

Comparison of positioning error standard deviations (σ_e) across different orbital configurations under individual and combined error sources.

Error Source / Effect	MEO	1-LEO	2-LEO	3-LEO
Individual Effects				
Ionospheric delay	0.802	0.775	0.605	0.555
Tropospheric delay	0.626	0.599	0.315	0.262
Combined Effects				
Multipath (+ Iono, Tropo)	0.985	0.844	0.628	0.582
TLE (+ Iono, Tropo, Mult.)	–	0.965	0.625	0.594
Clock (+ Iono, Tropo, Mult.)	–	1.080	0.716	0.685
All Errors Combined ^a	0.985	1.020	0.741	0.656

^a Evaluated with ionosphere, troposphere, multipath, TLE and clock errors.

3.1. Ionospheric error analysis

Comparing a baseline 8-MEO constellation with an 8-LEO configuration ($\sigma_e = 0.802$ and $\sigma_e = 0.306$) demonstrates the intrinsic robustness of LEO signals due to their higher carrier frequency. This advantage is evident even with a single LEO satellite in constellation. As visible LEO satellites increase, the system achieves a global reduction in final positioning error, as lower LEO ionospheric delays compensate for larger MEO delays ($\sigma_e = 0.775$ and $\sigma_e = 0.555$). Furthermore, increasing the number of visible satellites by using hybrid MEO-LEO constellations is crucial for mitigating performance degradation caused by adverse atmospheric conditions, ionospheric scintillation and geomagnetic storms.[40, 41].

3.2. Tropospheric error analysis

Experimental results validate that LEO constellations are significantly less sensitive to tropospheric fluctuations. Subtracting the deterministic delay estimated via the Saastamoinen model from pseudorange observations removes the mean bias, leaving zero-mean stochastic noise ($\sigma_e = 0.626$ and $\sigma_e = 0.209$). This compensation allows LEO signals to leverage their lower altitude variance and achieve sub-decimeter residual errors; increasing LEO satellites reduces positioning uncertainty and combining bias removal with atmospheric delay averaging of LEO enables levels of precision unattainable by traditional systems relying solely on MEO satellites under adverse conditions. ($\sigma_e = 0.599$ and $\sigma_e = 0.315$).

3.3. Multipath error analysis

The simulation confirms that LEO constellations are much more resilient in harsh environments. The improvement in σ_e observed in the combined error scenario is mainly due to the higher power of the received signal; this increased SNR allows the receiver to better distinguish between direct Line-of-Sight and the reflected signals, which is further optimized by the geometry-aided Hatch filter ($\sigma_e = 0.628$).

3.4. TLE and Clock errors analysis

The introduction of uncompensated orbital parameters and clock errors reveals the primary technological bottlenecks of opportunistic LEO navigation. Unlike atmospheric delays, where LEO satellites provide an inherent physical advantage, orbital determination and clock stability represent severe limits that must be taken into account.

3.4.1. TLE

The analysis reveals a critical trade-off: introducing a single LEO satellite yields $\sigma_e = 0.965$, nearly identical to the 8-MEO baseline ($\sigma_e = 0.985$), since the spatial bias from the standard TLE data outweighs the reduced atmospheric delay and higher signal power. System performance recovers significantly with two or more LEO satellites ($\sigma_e = 0.625$), allowing the positioning filter to distribute residual orbital bias and let LEO atmospheric advantages prevail.

3.4.2. Clock bias

Integrating a single LEO satellite leaves the final positioning error unchanged ($\sigma_e = 1.08$) due to the error arising from the absence of an atomic clock, effectively negating the advantages associated with the characteristics of low-orbit satellites. Increasing the number of LEO satellites improves performance through error averaging ($\sigma_e = 0.716$ for 2-LEO), using satellites with lower pseudorange error to compensate for MEO inaccuracies.

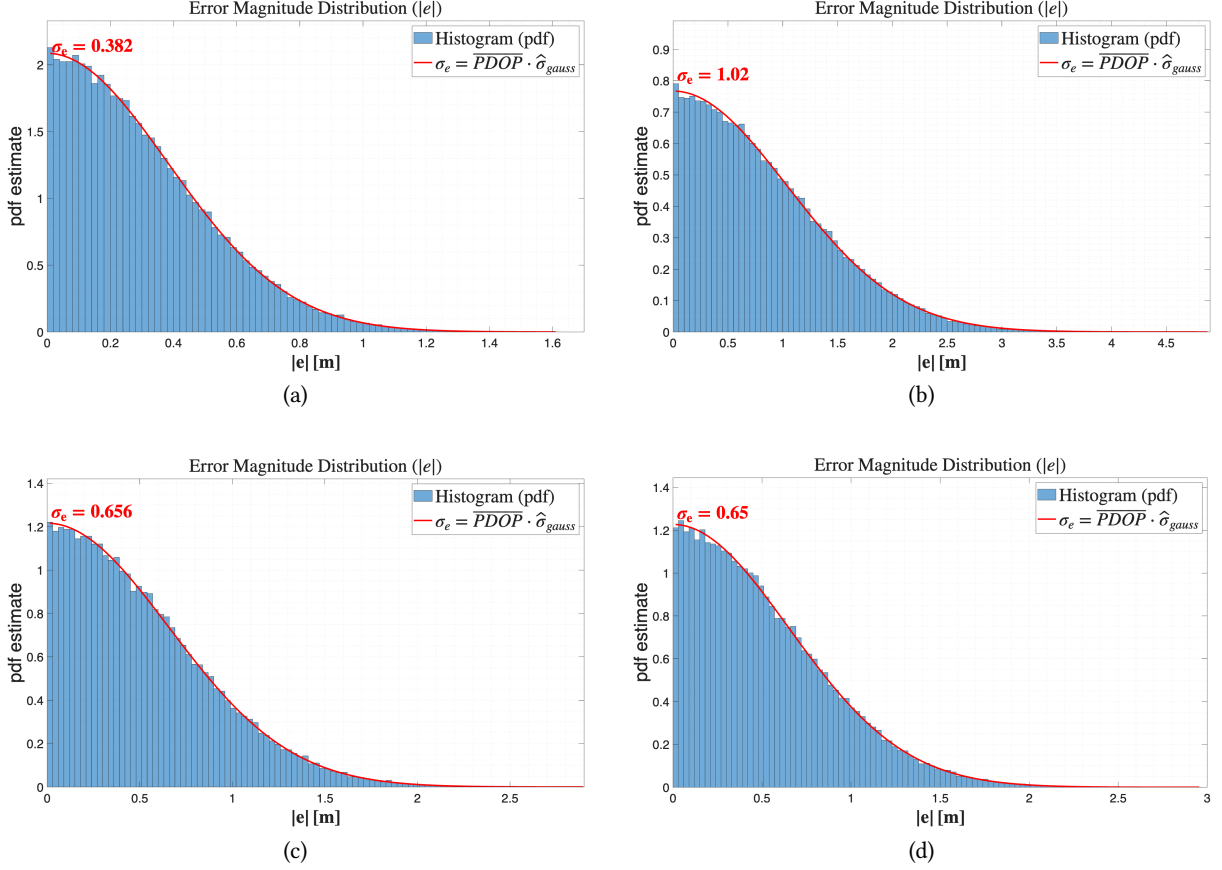


Figure 1: Positioning error PDFs for the cumulative error scenario (atmospheric, multipath, TLE and clock errors): (a) 8-LEO ($\sigma_e = 0.382$), (b) 7-MEO and 1-LEO ($\sigma_e = 1.020$), (c) 5-MEO and 3-LEO ($\sigma_e = 0.656$) and (d) 4-MEO and 4-LEO ($\sigma_e = 0.650$).

3.4.3. Cumulative TLE and clock errors

Analyzing cumulative clock bias and TLE uncertainty confirms that hybrid architectures require a threshold LEO density to suppress cumulative error variance. A single LEO satellite does not show a significant gain ($\sigma_e = 1.020$, Fig. 1(b)). Scaling to 3-LEO reduces σ_e to 0.656 (Fig. 1(c)), achieving a performance gain of 35%, while 4-LEO produces $\sigma_e = 0.650$ (Fig. 1(d)).

4. Conclusions

The results of this study demonstrate that integrating LEO satellites into existing MEO-based GNSS constellations is a viable strategy to improve global positioning performance; however, the actual benefit can only be realized by overcoming outstanding technological challenges.

The simulation results indicate that replacing MEO satellites with LEO nodes does not automatically lead to an improvement in ground positioning error; indeed, the analysis identifies a critical threshold: the integration of three LEO satellites represents an optimal compromise between system complexity and positioning accuracy. Increasing the number of LEO satellites beyond this value yields diminishing returns, as the performance gains are negated by the constellation's increased computational and management complexity. A key finding of this study is that the intrinsic advantages of LEO platforms regarding link budgets are largely nullified by the absence of atomic-grade frequency references and high-precision orbit determination systems. Specifically:

- **Clock stability:** The reliance on quartz oscillators introduces a non-stationary drift that, if uncompensated, significantly degrades the user position solution.

- Orbital ephemeris propagation: TLE-based ephemeris propagation is insufficient for high-precision PNT applications. Replacing TLE with advanced Precise Orbit Determination algorithms is mandatory to exploit the LEO constellation's potential.

A significant methodological aspect of this work is the adoption of a one-dimensional vehicular scenario for performance evaluation. This approach provides a controlled environment to isolate stochastic error components and validate model performance; however, although the analysis is limited to a single dimension, the simulator's modular architecture ensures that the analytical results remain inherently scalable to 2D and 3D coordinate systems for any real-world trajectory.

The path toward an autonomous LEO-based PNT system—as well as a hybrid GNSS/LEO architecture—is inextricably linked to resolving the aforementioned critical issues regarding clocks and TLE data. Future implementations must prioritize the miniaturization of atomic clocks and the adoption of advanced real-time orbit estimation techniques; such technological measures are crucial not only for enhancing accuracy but also for ensuring system integrity, keeping residual errors within the confidence limits required for safety-critical applications. This work provides the analytical foundation for future developments in fields where highly resilient and high-precision positioning—such as autonomous driving and smart city infrastructure—demands performance levels currently unattainable by standalone GPS architectures.

Declaration on Generative AI

During the preparation of this work, the authors used Google Translate for translation assistance and Google Gemini for grammar, spelling and syntactic corrections. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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