Simulations using LEO-PNT systems: A Brief Survey

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***Abstract*— As the whole space segment of satellites in low Earth orbits (LEO) grows, simulations of positioning, navigation, and timing (PNT) through LEO satellites are needed to understand the possible gains that the upcoming satellite missions can offer to global navigation satellite systems (GNSS). The simulations do not only help to forecast the optimal GNSS future advancements, but also guide us on how to implement the most optimized PNT missions. In the most recent years, several simulation tools have focused on broadcast orbit models, precise orbit determination of LEO satellites, signal structure designs, atmospheric models, constellation optimization strategies, satellite clock implementations, and positioning integration with distinct sensors. In this work, we overview most of the latest developments found in the literature to define the status and challenges of LEO-PNT system simulations.**

Keywords—GNSS, LEO, PNT, Simulations, PPP, Signals of Opportunity, Dedicated signals

I. INTRODUCTION

To get a strategy of how to implement the upcoming LEO-PNT systems in the face of the large number of LEO satellites, simulations aiming at the optimum system design are essential. Most of the simulations so far have focused on how to define new broadcast orbit models [1], [2], [3], precise orbit determination [4], signal structure design [5], [6], [7], atmospheric models [8], [9], constellation optimization strategies to improve the GNSS convergence time [10], [11], [12], satellite clock estimations [13], and integration with distinct sensors [14]. These studies have focused on fragmented topics of a complete LEO-PNT system. In future implementations, the user, ground, and space segments must be bound together to fairly reproduce the system accuracy. While all these aspects will need to be considered in future LEO-PNT systems, a comprehensive overview of the latest results is needed. In this regard, we present a detailed overview of the main results obtained by the current simulations reported in the literature with respect to LEO-PNT systems. The latest developments of three types of PNT techniques are discussed: LEO as signals of opportunity (SoO), dedicated positioning signals on-board of LEO satellites, and LEO augmented by classic GNSS. Relevant considerations are explored to develop the ground-, space-, and user-segments of such simulation systems aiming to future developments of end-to-end simulation tools. The next three sections present our main findings from the literature review over several simulations and experimental results. The last section shows the conclusions.

II. SPACE SEGMENT

The space segment of any satellite-based navigation system is represented by satellites transmitting RF signals to users. This section overviews relevant characteristic to implement the LEO-PNT space segment.

A. Satellite Constelations

As part of the development of a new LEO-PNT system, the satellite constellation design is necessary to accomplish the requisites of the satellite mission. It refers to the simulation of several orbital parameters to analyze the expected coverage of the user. The orbital parameters include altitude, inclination, eccentricity, number of orbital planes, and number of satellites per plane. A few simulations of feasible LEO-PNT constellation designs have been conducted in the last years.

Prol et al. [15] performed simulations to find the minimum number of satellites and orbital planes to achieve a 4-fold coverage globally. The simulation considers all planes materialized with the same orbit inclination. They have found that altitudes around 500-1000 km are reasonable regions to deploy a LEO satellite, which requires around 10 to 20 orbital planes with inclinations ranging from 65° to 80°. These parameters provide a reasonable balance between path losses and drag forces from the Earth's attraction. In addition to the orbital parameters, the constellation topology given by the

Walker delta was found to be the most common for PNT. Further simulations are required to explore other options, such as the Street of Coverage, Draim Constellation, and Flower Constellation.

Ge et al. [10] analyzed how the number of LEO orbital planes, number of LEO satellites, and orbital inclination affect the precise point positioning (PPP) performance of a LEO-PNT system augmented by GNSS. The simulations were performed considering a Walker constellation with all LEO satellites placed at 1000 km. It was shown that the combination of three LEO constellations with different inclinations is more appropriate than single orbit inclinations to get a uniform distribution of the number of visible LEO satellites. With such considerations, an availability of 100% is achieved on a global scale if more than 180 LEO satellites are used. Additionally, 240 LEO satellites with orbital inclinations at 90°, 60°, and 35° was enough to provide one minute convergence time in PPP.

Based on real constellation designs, Morales Ferre and Lohan [16] run 10000 Monte Carlo simulations over the whole region of Europe to evaluate the benefits of merging medium Earth orbit (MEO) satellites, LEO satellites, and Internet of things (IoT) technologies in the PNT solution. The LEO constellations considered were the Amazon Kuiper (3236 satellites), BlackSky Global (60), Myriota (50), OneWeb (80), and Starlink (11927). They showed that LEO systems produce promising results as signals of opportunity to obtain low geometric dilution of precision (GDOP) values (<2). In particular, the Kuiper constellation was found to be the most promising among the studied ones in terms of GDOP and achievable positioning errors, as the Kuiper signals might be more suitable as signals of opportunity.

Zhang et al. [17] analyzed the positioning and GDOP performance of the Starlink LEO constellation. They computed the GDOP as well as the Beidou single point positioning, so they considered Starlink as a dedicated LEO-PNT system. Obvious regional differences were obtained in the GDOP values, with better performance in mid-latitudes. A GDOP of 0.7 was obtained within mid-latitude zones when using 1584 satellites. Additionally, the GDOP tended to be stable as the constellation reaches over 4000 satellites.

Liu et al. [18] conducted simulations to analyze the benefits that LEO constellations can bring to augment the Beidou satellite navigation system. Based on LEO constellations of 177 and 186 satellites at 1500 km altitude with diverse orbit inclinations, the global GDOP average was reduced from 2.4 to less than 1.1. The results also showed that, after 10 min of static positioning, both studied LEO constellations improved the positioning accuracy of the Beidou from the decimetre level to less than 5 cm, allowing a PPP convergence within less than 3.5 min.

Similar constellation designs were used/recommended by distinct authors. Li et al. [12] simulated the LEO constellation using 96 satellites distributed over 8 planes, with a single orbit plane tilted by an 86.4° inclination and placed at 900 km in altitude. Wang et al. [19] used several similar configurations. More et al. [20] analyzed that OneWeb and Starlink can bring potential improvements to the positioning performance in urban canyon environments. Morales Ferre et al. [5] found that LEO constellations with 55 to 1000 satellites placed around 500 to 700 km are necessary to bring relevant coverage to PNT. Summing up all these references, we can converge to the conclusion that hundreds (<1000) of LEO satellites placed at around 500-1500 km are necessary to provide PNT benefits to GNSS, in which the orbit inclination will define the regions with the highest coverage (i.e., higher orbit inclinations would allow a higher coverage towards the Poles).

B. Signal Structures

As discussed by Prol et al. [15], five main topics should be considered for the signal design: carrier frequency, modulation, channel coding, multiple access scheme, and beamforming scheme. Not many simulations have been conducted so far to define the most efficient carrier frequency, as it heavily depends regulatory aspects and the system cost (e.g., antenna design). We only highlight the study by Ma et al. [21], which proposes a feasible frequency scheme that combines the frequency bands L, S and C. In the following, the other four aspects are discussed.

Modulation: Prol et al. [15] showed the performance of 11 modulation schemes when simulating time and frequency measurements. It was found that any of the modulation schemes perform well with both time and frequency measurements. Phase modulations, e.g., binary phase-shift keying (BPSK), quadrature PSK (QPSK), or continuous phase modulation (CPM), behave better with delay/code-based measurements, while frequency modulations, e.g., multiple frequency-shift keying (MFSK), and Gaussian minimum shift keying (GMSK) behave better with frequency measurements. Low-order BPSK/QPSK or GMSK modulations were more appropriate for LEO-PNT than higher-order modulations, as high throughputs are not the main concern in LEO-PNT; also, the BPSK modulation was found to be the most suitable for time-based positioning due to its linearity and simplicity, while GMSK turned out to be the most suitable for Doppler-based positioning as it is more robust to Doppler errors. Advanced modulation schemes such as orthogonal time frequency space (OTFS) modulations [22], [23], [24], known to be highly robust to high Doppler shifts, were not studied in [15] and remain a topic of future investigation.

Channel Coding: A numerical comparison of four channel coding techniques, namely convolutional, Turbo, low-density parity-check (LDPC), and polar codes, was done in Prol et al. [15]. On one hand, convolutional coding was found to be the most suitable for LEO-PNT systems with low complexity at the receiver side. On the other hand, turbo coding was advisable for high-grade receivers, since higher-order channel codes offer better protection against channel errors, while they are more wasteful regarding the bandwidth resources.

Multiple-Access: Among the multiple-access options, time division multiple access (TDMA) is not applicable because it requires non-continuous transmissions, which is not suitable for seamless and continuous positioning. Neither space division multiple access (SDMA) nor polarization division multiple access (PDMA) are applicable because a receiver should get transmissions from at least four satellites. Therefore, the main options are frequency division multiple access (FDMA) and code division multiple access (CDMA).

Alternatively, Sixin et al. [6] proposed a Doppler frequency-code phase division multiple access (DFCP-DMA). The idea was to exploit the high velocity of the LEO satellites and easy-to-distinguish LEO navigation signals by multiple combinations of different Doppler frequencies and code phases. Wang et al. [7] additionally proposed the idea of using several LEO satellites sharing the same pseudo random noise (PRN) code. As a result, their approach requires less receiver storage resources and receiver acquisition time than traditional PNR codes, which may be relevant for LEO constellations with a high number of LEO satellites.

Beamforming: Many beams will be supported at the satellite, ground, or both sides, due to the latest advances in multiple-input multiple-output (MIMO). Neinavaie and Kassas [25] described the possible beamforming strategies of Starlink LEO satellites, by applying a maximum likelihood (ML) estimation framework to the signal-to-noise ratio (SNR). This enables a potential future research direction in beam-based positioning by using the beam patterns as fingerprints to positioning solutions. However, not many simulations have been conducted so far in this direction.

It is worth highlighting the work carried out by Wang et al. [26]. They simulated several methods to integrate the navigation messages in the communication signals of the LEO satellites. The simulations considered the restrictions given by the Iridium signals and combined the TDMA and FDMA schemes with frequency access of 41.667 kHz and a total bandwidth of 10.5 MHz. The direct sequence spread spectrum (DSSS) and BPSK were considered for the navigation signal. Their analysis showed that the best balance between the navigation and communication performance was achieved when signal power rate was 15 dB. Under this power condition, they obtained the best pseudorange accuracy and bit error rate.

C. *Instruments*

As instruments in the space segment, we are considering the onboard equipment required to transmit RF signals and frequency standards to the users and the GNSS receivers/antenna for precise orbit determination (POD). The authors are not aware of simulations considering distinct instruments on-board the LEO satellites or their effect on the overall capacity of the system. Most studies have considered similar instruments used by GNSS in case of dedicated systems, and similar instruments to actual LEO constellations in case of opportunistic approaches. We have only found a very recent study [27] that discussed the impact of LEO satellite clocks for positioning applications. They proposed a new model for clock prediction, which can reduce the prediction errors in comparison to traditional polynomial models by 40%-70% in simulations and 5%-30% with real data. For ultra-stable oscillator (USO) clocks, short-term predictions of 1 minute resulted in a few centimeters of errors, while long-term predictions of 1h resulted in a few meters of errors. In case of oven-controlled crystal oscillator (OCXO), the 1h prediction could lead to errors of about 10 m.

III. GROUND SEGMENT

The ground segment is responsible for the maintenance of the navigation system. It processes the satellite orbits and generates all corrections and messages necessary to be transmitted to the users. This section mainly overview the studies concerned with precise orbit determination, ephemeris design, orbit prediction, and the required ground infrastructure.

A. *Precise Orbit Determination*

Precise orbit determination (POD) of LEO satellites is a well-established field. Many POD techniques were applied in the literature based on experimental data tracked by GRACE, CHAMP, HY-2A, GOCE, TOPEX/Poseidon, Swarm, and Jason-1 satellite missions [28]. Since real case scenarios were adopted by several authors and institutes, there is no need to analyze the simulation scenarios to draw further conclusions. An extensive literature review, for instance, was presented by Selvan et al. [28], demonstrating a clear trend for techniques using reduced-dynamic model, least-squares solvers, dual-frequency (DF) signals with undifferenced (UD) phase and code observations in post-processing mode. This technique is a prominent method for LEO precise orbit determination since it offers reasonable accuracy (from 1 to 10 cm) without extensive complexity. The best results were obtained by forming GNSS double-differences (DDs) with the on-board GNSS receivers and ground receivers. However, considerably higher complexity is required in the POD techniques when using DDs, in comparison to UDs, due to the necessity of simultaneous processing of multiple GNSS receivers by the user. A low accuracy was observed by the satellite laser ranging (SLR) techniques, with an average of 12 cm. This issue is relevant since the SLR solutions are usually considered as a reference for the POD validations. The possible justification was attributed to the lack of studies devoted to validating the SLR data itself.

B. *Ephemeris Design*

After POD, the estimated solution needs to be sent to the PNT users by means of satellite ephemeris. In SoO approaches, two-line elements (TLEs) are typically used to describe the LEO orbit with rough approximations. In dedicated LEO-PNT systems, more sophisticated algorithms than TLE are necessary. In such cases, Keplerian ephemeris models are usually adopted.

Based on simulations, Xie et al. [3] developed several broadcast models using Keplerian elements and discussed that more complex orbital dynamics are required for LEO satellites than for MEO satellites. This is because they are much closer to the Earth than MEO and are affected to a greater extent by the gravity and atmospheric drag forces. The GPS broadcast ephemeris models, based on 16 coefficients, were not capable of describing these complex orbital dynamics. The use of the legacy 16 parameters in the Keplerian model provided a user range error of around 30 to 60 cm in LEO satellites at 400–1400 km altitudes. Therefore, the use of a larger number of coefficients for LEO satellites, rather than MEO, was suggested by the simulations, and they improved the solution considerably to better than 10 cm when using 22 number of coefficients.

Meng et al. [2] also developed broadcast models that considered more Keplerian elements than the usual legacy message, drawing similar conclusions as Xie et al. [3]. However, the model developed by Meng et al. [2] had the advantage to eliminate singularities caused by small inclinations and eccentricities. To this end, additional parameters were included, increasing the fitting accuracy. The best results with this method were obtained using 22 Keplerian parameters.

To identify an optimized number of Keplerian parameters, Guo et al. [1] improved the previous discussion based on harmonic analysis and considering the error of the orbit prediction. The optimized number of additional parameters to extend the GPS legacy ephemeris was found to be 21. The 21-parameter set achieved 87.3% fitting accuracy improvement in comparison to the GPS scheme. The fitting arc length was also examined, and the results indicated that 20 to 50 min in the fitting interval could meet a 10 cm accuracy. These results were obtained considering orbit altitudes higher than 500 km.

C. *Orbit Prediction*

A crucial aspect for the ephemeris creation is the availability of an accurate orbit prediction model. The end-user accuracy directly relies on the capacity to propagate the LEO orbit in time. Such highly accurate LEO-orbit prediction is a hard task, as the orbit prediction heavily depends on the correct description of several forces acting in the satellite. The main forces are: 1) Earth's gravity attraction; 2) third body attraction from Moon, Sun, Jupiter, Venus, and Mars; 3) solid and ocean tides; 4) solar radiation pressure; 5) atmospheric drag; 6) Earth's albedo; and 7) vehicle thrust. Additionally, some obstacles for accurate prediction arises due to the inherent limitations of the initial conditions (position and velocity at reference time) provided by POD. Table I summarizes the accuracy obtained by different studies in the orbit prediction of LEO satellites. As it can be seen, the accuracy mainly varies depending on the orbit altitude and the time window of the prediction. It is relevant to highlight that high accurate (<20 cm) orbit predictions exist for short arc lengths of 20 min.

TABLE I. ACCURACY OF A FEW LEO ORBIT PREDICTION TECHNIQUES.

Ref.	**Accuracy**	**Altitude**	**Prediction Time**
[29]	5-10 cm	500 km	20 min
[19]	0.2 m	700–800 km	6 h
[19]	0.6 m	500 km	6 h
[30]	~ 1-3 km	288 km	24 h
[31]	~ 20-50 km	460 km	7 days

D. *Ground Infrastructure*

The ground-segment infrastructure involves ground stations to perform the precise orbit determination, ephemeris computation, and clock corrections estimation, among other tasks. Just a few studies have focused on the best strategies to implement the ground segment for LEO-PNT systems. To the best of our knowledge, Çelikbilek et al. [32] and Prol et al. [15] presented a survey of several optimization techniques that can be applied to define the best number and location of the control stations. Since this issue is not specific to LEO satellites, the review was based on MEO and GEO satellite systems. The best metrics to optimize the whole system were found to be based on GDOP, scintillation fade depth, carrier to noise ratio, rain attenuation, and link outage probability. The above-mentioned studies identified the LSTM (long short-term memory) and NSGA-II (non-dominated sorting genetic algorithm) as good optimization methods to deploy the ground stations.

A study completely focused on the LEO ground segment was developed by Yang et al. [13]. They proposed a real-time estimation approach of LEO satellite clocks based on ground tracking stations. A LEO constellation of 168 satellites was simulated with two inclination planes (50° and 85°) at around 810 km altitude. The ground segment, established with 15 ground stations over the region of China, was enough to provide quick convergence for the LEO satellite clocks due to the rapid LEO satellite motion. An average accuracy of 0.71 ns was obtained. However, the estimated LEO satellite clocks still performed slightly worse in PPP than that with the precise clock. It was recommended to perform clock estimations using joint observations from ground and onboard receivers to further improve the accuracy of the LEO satellite clock.

IV. USER SEGMENT

The user segment mainly deals with the instruments and techniques applied by the users. This section hence discusses the receivers and results found in the literature regarding to the user's perspective. First, we discuss the possible receiver's architectures and then, we present the results/simulations using SoO and dedicated/ augmented signals.

A. *Receiver Architectures*

A general satellite-based PNT receiver contain antennas, radio front end, analog to digital converter (ADC), baseband processor, navigation data block, and interface to the user. Other detailed points differ depending on the user's application. In the following, we organize them in SoO or dedicated receivers.

SoO user receivers are usually made of a software defined radio (SDR) and an altimeter. In the case of a receiver proposed by Khalife et al. [33], the setup was made of a fast Fourier transform (FFT), individual phase lock loop, Kalman filters, and a QPSK modulation scheme, resulting in the Doppler-shift estimates of the Orbcomm signals. Based on simulations, 11 m positioning accuracy was achieved with 25 LEO satellites. In case of experimental results using 2 Orbcomm satellites, the proposed receiver provided an accuracy of 360 m when tracking for 1 minute period. An extended version of this receiver was proposed by Kassas et al. [35]. Additional elements were an inertial measurement unit (IMU) and GNSS receiver to facilitate the positioning solution. As this setup was more applicable for dynamic than static users, they applied it to extract an unmanned aerial vehicle (UAV) trajectory. A similar setup was developed by Khalife et al. [36]. They used a SDR and altimeter to process Starlink signals. However, an additional downconverter was included as the commercial SDR was designed to process low carrier frequencies. Additionally, the Starlink signal structure was unknown at that moment (proprietary information), requiring characterization on the user receiver to extract positioning. The experimental results with six Starlink satellites showed a horizontal positioning error of 7.7 m with known receiver altitude. Another dynamic user setup was proposed by Benzerrouk et al. [37] and focused on an aircraft trajectory using Iridium signals. A universal software radio peripheral (USRP) was used to sample the Iridium signals and to compute range rates. Combined with an IMU position, velocity, and attitude, a navigation filter was applied and the aircraft trajectory was estimated with an accuracy level between 200 to 1000 m.

In case of dedicated systems, no LEO-PNT constellation has been deployed yet. It is therefore hard to define the receiver requirements since it depends on the unknown frequency and content of navigation message. Nevertheless, Wang et al. [14] examined a Kalman filter method that considered simulated LEO dedicated signals together with 5G ranging signal, IMU, and GNSS. A closed-loop correction was used as the final output of the integrated navigation, which reduced errors in the linearization. The results showed that including LEO dedicated signals and 5G improves the positioning accuracy of the original INS/GNSS solutions by an order of magnitude.

B. Positioning with Signals of Opportunity

Many simulations and real-case scenarios have been studied with the SoO techniques. The Geometric Dilution of Precision (GDOP) analysis presented by Psiaki [34] indicates that an absolute position accuracy of 1 to 5 meters may be achievable in SoO if the Doppler-shift or range-rate precision is in the order 0.01 m/sec. When carrying out the positioning solution with simulated or real measurements, the accuracy is reduced. A summary of the main studies is presented in Table II, where all of them are based on the measurements given by the Doppler effect or rate of the pseudorange.

TABLE II. ACCURACY OF SOO TECHNIQUES.

Ref.	**Accuracy**	**User**	**Aid**
[33]	11.38 m	Static	TLE
[35]	10.5 m	Dynamic	IMU, Altimeter
[36]	7.7 m	Static	TLE, Altimeter
[38]	132 m	Static	TLE
[39]	168 m	Static	TLE, Altimeter
[37]	200-1000 m	Dynamic	TLE, IMU
[40]	100 m	Dynamic, Static	AoA

We can see varied results among the SoO techniques, with accuracies ranging from 7 m to 1000 m. These differences are mainly related to the techniques applied, the environment surrounding the receiver, and the tracked constellation. Common to almost all techniques is the necessity of TLE files due to the lack of a navigation message. The TLEs are valid for 24 hours, but they are not very accurate. Although possible, the receiver position determination without accessing a navigation message is still a topic of continuous research. Another common limitation is the lack of satellite clocks. The technique therefore usually requires time-free solutions, which causes severe degradation in the final accuracy. It is important to mention that SoO techniques are often aided by IMU and altimeters to help the solver. However, even with the help of external instruments, the accuracy is still far from what is achievable by high-accurate GNSS techniques. The best obtained accuracy of 7.7 m is linked to the usage of precise measurements (carrier phase) and the high satellite coverage given by the Starlink constellation.

C. Positioning with Dedicated Signals

In the most recent years, several simulations were performed considering dedicated LEO signals as alternative or complementary to GNSS, often referred to LeGNSS. They are briefly discussed below.

In the simulations developed by Li et al. [41], the feasibility of LeGNSS was investigated for providing real-time PPP services based on BeiDou, GPS, and sixty-six satellites of the Iridium satellite constellations. Global averages of GDOP and signal-in-space ranging error (SISRE) were investigated, concluding that centimeter level could be achieved by the end-user in outdoor scenarios.

Ge et al. [10] also explored the potential of LeGNSS to the end users. Based on simulations of 240 LEO satellites with orbital inclinations at 90°, 60°, and 35°, one minute convergence time was achieved in PPP on a global scale when merging GNSS and LEO satellites. The main conclusions in Ge et al. [10] promoted the idea of using inclination combinations of LEO constellations to improve the PPP performance at a global scale. It was recommended to use more precise optimization metrics in the future work, and to consider the effects of LEO orbit errors and clock precision to analyze the LeGNSS PPP performance.

Yang et al. [13] presented a method to estimate LEO satellite clocks based on simulated observations of 15 ground tracking stations. A LEO constellation containing 168 satellites was simulated and the estimated LEO clocks in real-time were used to evaluate the PPP. The performance of LeGNSS PPP solutions with the estimated satellite clocks accelerated the PPP convergence time in comparison to using only GPS, or GPS plus Beidou, by around 30%, to 60%. An interesting point to notice is that the LEO satellites did not improve the number of visible satellites and PDOP as remarkably as Beidou satellites did; however, the fast LEO geometry change was capable to accelerate the PPP convergence more substantially than Beidou system.

In some of the most recent LEO-PNT simulations to our knowledge, Ge et al. [11] presented a comprehensive review of the status of LeGNSS. Several analyses were presented applying PPP with distinct LEO constellations. Assuming a PPP convergence time with a 10-cm threshold, they found that the convergence can be shortened to 1 minute if appropriate LEO constellations were deployed and used together with GNSS measurements. This improvement was justified due to the fast geometric change brought by LEO satellites.

The last study presented here was developed by Li et al. [12]. The LeGNSS simulation environment was designed with

Beidou, GPS, and 96 simulated LEO satellites in polar orbit at 900 km in altitude. A distinction in comparison to previous studies was related to the consideration of various challenging environments, including the blocking of satellite signals, cycle slips, and signal multipaths. In their study, an instantaneous fixing of the ambiguities was achieved in environments free of cycle slips. When multipath effects were considered, the time for LeGNSS fixing was about 3 minutes.

V. CONCLUSIONS

Based on the review presented in this work over several simulation-based and real-case scenarios, we can conclude that standalone SoO provides lower accuracy than GNSS, while dedicated LEO-PNT systems can bring relevant gains compared to the current GNSS solutions, mainly when used together with GNSS. Perhaps, the upcoming mega-constellations can improve the overall accuracy of SoO, but it is not yet clear how to implement such a system. In case of dedicated systems, the system implementation requires dedicated instruments, such as antennas and onboard clocks. The current simulations also need to further improve the binding between all the LEO-PNT segments. However, although the simulations have limitations in representing a realistic scenario, it is clear that the fast geometry variation of the LEO orbits can provide faster convergence time in dedicated PPP solutions. Also, LEO-PNT solutions using code measurements have not been studied much so far, even though it could provide more accurate positioning results in a broader set of scenarios than Doppler-based positioning.

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