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A Comparative study on ranging accuracy and interference robustness of LEO-PNT systems in urban and rural scenarios

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Abstract

While Global Navigation Satellite Systems (GNSS) have been the primary Positioning, Navigation, and Timing (PNT) solution since their advent, new technologies are being sought to address the limitations of GNSS. For the past few years, the strongest contender to offer global PNT solutions has been the use of Low Earth Orbit (LEO) satellites, not only to overcome the GNSS limitations but also to improve the positioning accuracy and coverage given the proliferation of new, more-demanding applications. The present work aims at shedding light on the LEO theoretically achievable positioning accuracy and interference robustness with respect to GNSS, depending on the choice of the carrier frequency, constellation design, hybridization with GNSS, and available satellite transmission power. The analysis uses a semi-analytical approach with 192,000 Monte Carlo runs, employing an in-house satellite constellation simulator to model 400 users across Europe operating in five representative outdoor scenarios, and for 480 different instances of satellite positions in time. This semi-analytical study provides the necessary insights to derive clear design takeaways depending on the choice of the aforementioned parameters. A moderate Effective Isotropic Radiated Power (EIRP) of 50 dBm is shown to be sufficient for achieving high accuracy outdoors, operating at the C-band in the urban scenarios where GNSS typically struggles. The most cost-effective hybrid LEO plus GNSS solutions come from the combination of 1) 'CentiSpace-like' plus BeiDou, and 2) 'Çelikbilek 1' plus GPS and Galileo, where LEO satellites drive performance in difficult environments while GNSS provides stability in nominal conditions. The findings suggest using the 'Çelikbilek 1' constellation with a 50 dBm EIRP at a 5 GHz carrier frequency or higher as the most effective system design.

Keywords LEO-PNT, Outdoor, Multipath, Interference, Hybrid LEO-GNSS positioning

Introduction

The space sector has been undergoing significant changes driven by the necessity of new revamped solutions that meet the requirements for unprecedented performance and lower complexity of space applications. These changes are further fueled by the decreasing costs caused by lower launch expenses, standardized subsystems, and further accelerated by the miniaturization of systems headed into space (Ojala & Baber, 2024). One main driver for these changes lies in the Position-Navigation-Timing (PNT) field, where Global Navigation Satellite Systems (GNSS) have been the de-facto provider since their adaptation for commercial use in the late 1980 s, given their world coverage, good accuracy in outdoor scenarios and relatively low burden on the receiver complexity. However, GNSS suffers from severe drawbacks that limit its usage in the more demanding PNT applications that come with the new space paradigm. These applications come in need of higher achievable accuracy, availability

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in indoor scenarios and/or the provision of PNT solutions in devices with limited resources, which GNSS systems have difficulties in handling. Furthermore, critical infrastructure has become increasingly reliant on GNSS (Goldstein & Kirschbaum, 2013; Falletti et al., 2018; Kaasalainen et al., 2021), and given the susceptibility of GNSS signals to be impaired by the presence of higher-powered interfering signals or intentional spoofers, new solutions are required to improve robustness towards these impairments and guarantee the sovereignty of this critical infrastructure.

These requirements have brought attention to the use of Low Earth Orbit (LEO) platforms as PNT providers with global coverage (Fabra et al., 2024). Inherently, due to LEO satellites operating at a lower orbit, the received power is greater than that of GNSS, which adds interference robustness since interferences will need to be more powerful to have the same damaging effect. Furthermore, a higher Carrier-to-Noise Ratio (C/N_0) also supports the challenge of higher accuracy positioning solutions, and might enable positioning in indoor scenarios given that the received power after infiltrating the building might still be enough to enable an accurate PNT solution (Foreman-Campins et al., 2025). In addition to higher-powered signals, LEO offers lower multipath impact due to a higher phase delay rate, which rises above the Delay-Lock-Loop (DLL) bandwidth for fast-changing multipath components (De Bast et al., 2023). Additionally, better satellite geometry might be achieved depending on the constellation design. In terms of the Precise Point Positioning (PPP) solution, LEO satellites may also offer faster convergence time due to their higher velocity (Li et al., 2024; Hong et al., 2023; Wang et al., 2022; Yang et al., 2022).

Important gains also lie on the carrier frequency choice and their corresponding one-sided bandwidth (B) allocation. Given that LEO satellites deliver stronger signals, the carrier frequency could be increased from that of GNSS because the higher path losses are compensated by the higher delivered power. Working at higher bands would entail a lower amount of unintentional interferences, higher allocated B (Eissfeller et al., 2024; Cerdeira et al., 2025), smaller antenna separation in receiver arrays and lower antenna cost. This combination of factors could enable effective beamforming techniques with a receiver array capable of solving the ever-present jamming and spoofing problem, while improving the achievable accuracy at the same time. Given these prospects, some companies and public entities are considering transmission at C-band (Anderson et al., 2024; Brown et al., 2023) or even Ku/Ka bands (Del Portillo et al., 2019; Neinavaie & Kassas, 2023). However, other entities do take the more conservative approach of operating at the GNSS bands (Kassas et al., 2023; Leclère et al., 2025), or even Ultra High Frequency (UHF)/ Very High Frequency (VHF) bands for indoor positioning with small satellites (Ries et al., 2023).

Furthermore, the transmission power might also be able to be alleviated and still provide the improved accuracy and robustness that entities are seeking for in next-generation satellite-based positioning systems.

Finally, as mentioned in Ojala and Baber (2024), the lower cost per LEO satellite unit increases the volume of deliveries to orbit, which also decreases cost per unit, and increases the overall resilience of the system. This opens the door to a wider range of actors in a sector historically limited to governmental projects and big companies.

In light of these possibilities, substantial efforts have been dedicated so far to researching the aspects of LEO-PNT systems, such as their signal design (Egea-Roca et al., 2021; Garcia-Molina et al., 2022; Hosseinian et al., 2021), the intricate orbit determination and clock error estimation (Allahvirdi-Zadeh et al., 2022; Chen et al., 2025; El-Mowafy et al., 2023; Ge et al., 2022), constellation optimisation (Çelikbilek et al., 2025; Marchionne et al., 2023), or opportunistic positioning from Non-Terrestrial Networks (NTN) LEO systems (Kassas et al., 2023; Stock et al., 2024; Stock et al., 2025; Trevlakis et al., 2023), among many others. Furthermore, extensive simulations have been run to analyse its potential use (Prol et al., 2024; Fabra et al., 2023).

Regarding the nature of this work, recent publications have shown simulated performance metrics for LEO systems operating at either outdoor (Marchionne et al., 2023) or indoor scenarios (Çelikbilek & Lohan, 2024; Foreman-Campins et al., 2025), and considering standalone LEO constellations or in combination with GNSS (Çelikbilek & Lohan, 2024; Ries et al., 2023), with (Yang et al., 2024) showing prospective LEO constellations as augmentation systems to BeiDou. The novelty in this work and the added value compared to the existing state-of-the-art lies on a few points: (1) assessing the impact on the positioning performance of the choice of carrier frequency, (2) evaluating the impact of the transmission power (and thereby of the satellite cost) on the LEO system performance, (3) proposing two gain metrics (one for positioning accuracy and one for interference robustness) and evaluating the actual gain brought by LEO satellites with respect to GNSS in these terms, and (4) summarizing concise take-aways that delve on the choice for these parameters. These contributions answer to the main objective of this work, which is to offer an exhaustive parameter-choice impact comparison on the performance of LEO-PNT systems operating outdoors.

To achieve this, we conduct an exhaustive simulation-based study. We evaluate the performance of numerous proposed standalone and hybrid LEO-GNSS constellations across five representative outdoor scenarios. Our analysis is specifically extended to include carrier frequencies in the L, C, and X bands, and Effective Isotropic Radiated Power (EIRP) values of 50 dBm or 67 dBm.

The remainder of this paper is organized as follows. Section 2 details the LEO-PNT system design and ranging error models used in this work. Section 3 describes the framework of the semi-analytical approach, including the performance metrics used to assess the standalone LEO and hybrid LEO-GNSS systems, the choices for the tested parameters, and the simulated outdoor scenarios. Section 4 presents and analyzes the simulation results, with key takeaways and design recommendations summarized in Sect. 4.3. Finally, Sect. 5 provides the conclusions of this work.

LEO-PNT system design

Space, ground and user segments

Most PNT systems are characterised by their space, ground, and user segments. The primary factors in their design impacting the user performance are described next:

- *Space segment:* The main factors on the LEO transmitter design impacting the user performance are (1) the constellation design, in terms of number of satellites, altitudes, planes, inclinations, and shells, (2) the satellite transmission power, (3) the carrier frequency (f_c), (4) the inclusion of an on-board GNSS receiver, (5) the transmission beamwidth, and (6) the one-sided signal bandwidth (B). The choice for the above-mentioned parameters (1) and (2) depends on the available constellation, number of satellites and allocated costs (launching, maintenance, de-orbiting, etc.), while the choice for parameters (3), (4), (5) and (6) will depend on the application requirements. Furthermore, parameter (6) also depends on parameter (3), since a higher B can be allocated at higher frequencies. This work considers various takes on the design of parameters (1) constellation type, (2) transmit power and (3) carrier frequency, which are explained in detail in Sect. 3, while the transmitted signal is considered to be broadband, mimicking the GNSS signals. As per parameter (4), this work considers that an on-board GNSS receiver is placed on the LEO satellite, due to its impact on the reduction of the LEO clock errors (Chen et al., 2025).
- *User segment*: The receiver performance is typically impacted by noise, multipath and interferences. One important factor is the elevation mask (θ_{el}) chosen at the receiver side, which will depend on the kind of signals that are being received: if the signals are broadband, then a similar θ_{el} to that of GNSS can be assumed in LEO, but if the aim is to use signals of opportunity coming from NTN LEO constellations, then the signals will be narrower and a higher θ_{el} will need to be considered. This work considers the LEO constellations transmitting broadband signals, and thus $\theta_{\mathrm{el}} = 10^o$ is assumed. As mentioned earlier, given that an on-board GNSS receiver on the LEO satellites is considered, the ground receiver will receive both the standard data for positioning and the estimations of the LEO clock error. While other error correction schemes exist, such as those that rely on having an uplink channel from the ground to the satellite, such architectures are not considered in this analysis.
- *Ground segment:* No considerations are taken on it in this work since its purpose is to monitor and control the satellites, and thus does not directly impact the user performance.

Position estimation procedures

The estimation of the receiver position using GNSS signals has been typically done by means of pseudorange and/or carrier phase measurements. However, the lower altitude of LEO satellites opens the door to another approach, namely Doppler-based positioning (Levanon, 1998). A wide range of scientific contributions have been devoted to Doppler-based positioning, most importantly due to the limitations of pseudorange estimation that opportunistic LEO presents, since many LEO constellations not intended for positioning use signals that are not adequate for ranging (Psiaki, 2021), or they might not be equipped with high-precision clocks, which degrades pseudorange-based performance (Stock et al., 2024).

The work in Farhangian and Landry (2020) presented a software-defined receiver that retrieved Doppler measurements from Iridium-Next and Orbcomm constellations, effectively reaching a position solution with 100-meter level accuracy, with the works in Tan et al. (2019); Khalife and Kassas (2019) presenting similar results. The work in Morichi et al. (2024) showed the achievable positioning accuracy by comparing the Doppler measurements against pseudoranges. Particularly, Morichi et al. (2024) showed that the accuracy with Doppler measurements is only comparable to pseudoranges when the satellite altitude is around 160 km, but it decreases quickly as the altitude is increased. Similarly, the work in Morales-Ferre et al. (2020) showed that the achievable Doppler-based accuracy is typically about two orders of magnitude lower than the achievable accuracy via pseudorange-based positioning.

These evidences confirm that pseudorange-based positioning highly outperforms Doppler-based positioning, thus making the former the preferred choice for future dedicated LEO-PNT constellations. This premise becomes the cornerstone of the present work, which focuses on the ranging capabilities of future dedicated LEO-PNT systems.

Last but not least, pseudorange-based solutions are more commonly used in GNSS receivers due to their lower complexity compared to carrier-based methods. This significantly simplifies receiver design and allows future LEO-PNT receivers to share many synergies with existing GNSS architectures.

Ranging error modeling

Following the considerations in Sect. 2.1, the error modeling in LEO pseudorange estimation differs from that of a standard GNSS receiver. Their differences come mainly from the contrast orbit determination and clock error estimation errors, given that they will not be as precise as in GNSS.

In an interference-free scenario, the ranging error is usually characterised by the following equation (Reid et al., 2018):

$$\sigma_{\mathrm{UERE}} = \sqrt{\sigma^2_{\mathrm{IONO}} + \sigma^2_{\mathrm{TROPO}} + \sigma^2_{\mathrm{CLK}} + \sigma^2_{\mathrm{ORB}} + \sigma^2_{\mathrm{NOISE}}} \quad (1)$$

with UERE standing for User Equivalent Range Error, IONO stands for ionospheric errors, CLK stands for clock errors, ORB for orbital errors, NOISE for the background noise, and σ the notation for the standard deviation. The GNSS typical errors range from 0.4 to 1 m for the satellite clock and orbit, from 0.5 to 4 m for the ionosphere (Lohan & Borre, 2016), and are around 0.5 m for the troposphere and 0.5 m for the receiver noise (Borre et al., 2022). Notably, these values are applicable in the absence of external error corrections, such as those provided by Real-Time Kinematics (RTK) (Li et al., 2022) or PPP. This work does not consider these correction techniques, as the vast majority of GNSS receivers are low-cost and do not support them. Consequently, this typically results in a positioning accuracy on the few-meter level. If strong corrections were indeed applied, then σ_{UERE} would mostly depend on σ_{NOISE}, which can be reduced with a higher C/N_0 and/or B (Kay, 1993).

For the particular case of LEO satellites, the model in Eq. (1) can be kept since no non-negligible extra errors are brought by LEO signals in pseudorange estimation. For the ionospheric error, since the LEO constellations evaluated in this work mostly operate above the sublayers in the ionospheric layer that impact its error the most, namely the F-layer (Imad et al., 2023), the same error as in GNSS is considered, thus ranging from 0.5 to 4 m. The same GNSS error for the troposphere is also considered, and the same modeling for the noise error, using the 0.5 m error as a baseline to compute the LEO noise error, which will be lower because of the higher C/N_0 (and prospectively higher B). However, for the orbit determination and clock error, considering that LEO satellites have GNSS receivers on-board but clocks with less precision, and following El-Mowafy et al. (2023); Ge et al. (2022); Li et al. (2024); Wang et al. (2018); Yang and Song (2025); Critchley-Marrows et al. (2025), an average $\sigma_{\mathrm{CLK,ORB}} = 1.8$ m is found, and is considered herein.

The average value for the LEO and GNSS ionospheric errors and the GNSS clock and orbit determination error can be computed considering the choice of $\theta_{\mathrm{el}} = 10°$, following Lohan and Borre (2016). These values are presented in Table 1, and are the ones used in this work, along with the other previously-mentioned averaged errors.

Table 1 Values for the pseudorange error contributions considered in this work

Error source	σ_{IONO} (m)	σ_{TROPO} (m)	$\sigma_{\mathrm{CLK,\,ORB}}$ (m)	$\sigma_{\mathrm{NOISE\text{-}BL}}$ (m)
GNSS	2	0.5	0.8	0.5
LEO	2	0.5	1.8	0.5

Framework of the semi-analytical approach

This section is devoted to describe the considerations taken to analyse the performance of LEO satellites for the PNT solution. Mainly, this description encompasses the constellations that are tested, the metrics that are defined to assess their performance, and the definition of the user scenarios. With regards to the constellation design, the analysis is performed either using standalone LEO signals, using only the currently implemented constellations in GNSS, or using a hybrid combination of both LEO and GNSS constellations.

Most notably, the framework of analysis in this work deals with the features of the LEO-PNT system that render its performance, but not the manner in which this performance is achieved. For example, we analyse the performance of a hybrid GNSS plus LEO system, but we do not consider how the GNSS and LEO signals might be combined.

Standalone LEO-PNT

As in traditional GNSS systems, the performance of LEO-PNT systems will be driven by their achievable positioning accuracy and their showing in environments with aggravating signals, such as interferences, multipath or spoofing.

In this sense, the main metrics to evaluate the performance of the LEO-PNT system are the (C/N_0), the Geometric Dilution of Precision (GDOP), the Position Dilution of Precision (PDOP) and the coverage of the user, along with the impact of the additional errors presented in Sect. 2.3 on the positioning solution. The first is a measure of the received signal power, while the GDOP and PDOP are measures of the uniformity of the visible satellites' geometry in the sky. Given the diversity in the number of satellites and their altitude for the various LEO constellations proposed in the literature, it is also relevant to compute the coverage they provide as the percentage of users over time that have 4 or more satellites in-view.

Contribution due to error sources

To assess the importance of these metrics on the Three Dimensional (3D) positioning error ($\sigma_{\text{3D,LB}}$), the approximation in Reid et al. (2018) shown in Eq. (2) relates these terms and is used herein:

$$\sigma_{\text{3D,LB}} \approx \text{PDOP} \cdot \sigma_{\text{UERE}} \tag{2}$$

with σ_{UERE} the uncertainty in the ranging estimation as defined in Eq. (1), with the dependence on the C/N_0 as outlined previously.

The effect of the multipath on the correlation peak is mostly accounted for as an added jitter in the ranging measurements, and thus accounted for as a loss in C/N_0 degrading Eq. (2). The bias introduced by multipath strongly depends on the transmitted signal design, which cannot be assumed to be GNSS-like since many existing LEO constellations use different signaling formats and bandwidths. This is still a topic of research, and left as future work. In this sense, the results herein represent a lower bound on the achievable accuracy of LEO-PNT under various channel conditions, and is thus referred to as $\sigma_{\text{3D,LB}}$. This will in practice be increased by the displacement of the correlation peak caused by the presence of closely-delayed multipath signals.

Following the approximation in Eq. (2), the positioning accuracy gain that can be achieved by the standalone LEO constellations with respect to the existing GNSS counterparts can be obtained:

$$G_{\text{LEO}} = \frac{(\sigma_{\text{3D,LB}})_{\text{GNSS}}}{(\sigma_{\text{3D,LB}})_{\text{LEO}}} \approx \frac{\text{PDOP}_{\text{GNSS}}}{\text{PDOP}_{\text{LEO}}} \cdot \frac{(\sigma_{\text{UERE}})_{\text{GNSS}}}{(\sigma_{\text{UERE}})_{\text{LEO}}} \tag{3}$$

which describes the improvement on positioning accuracy that LEO satellites might bring. In the simulations, G_{LEO} is defined with respect to using a multiconstellation GNSS receiver that processes Global Positioning System (GPS) and Galileo satellite navigation system (Galileo) satellites. This metric strongly depends on whether the receiver has accurate error information brought by external reference stations, given their ability to reduce σ_{UERE}, but, as mentioned earlier, these are not accounted for in this work.

Interference robustness

In terms of the improvement on interference robustness that LEO systems may bring, the main impact that interferences have towards the positioning accuracy is in the loss of C/N_0, with the C/N_0 in the presence of interferences typically denoted as $(C/N_0)_{\text{eff}}$, and approximated as (Kaplan & Hegarty, 2006, Eq. 6.9):

$$(C/N_0)_{\text{eff}} = \left(\frac{1}{(C_s/N_0)} + \sum_{m=1}^{M} \frac{1}{\text{SIR}_m \cdot Q_m R_c} \right)^{-1} \tag{4}$$

where C_s/N_0 is the nominal C/N_0 (i.e. the C/N_0 when no interferences are present), R_c is the spreading code rate (e.g. 1.023 Mchips/s), M the number of interferences, Q the jamming resistance quality factor of the m-th interference and SIR_m the Signal-to-Interference ratio of the m-th interference.

Notably, as for the case of multipath, the interference robustness has a strong relation with the signal design. If we take a Continuous Wave (CW) interference whose tone is at $f = 0$, such that $Q = 1$, and assume for simplicity that the R_c for GNSS and LEO are the same, then the LEO improvement on interference robustness over GNSS simplifies to:

$$I_{\text{LEO}} = \frac{(C_s/N_0)_{\text{LEO}}}{(C_s/N_0)_{\text{GNSS}}} = \frac{\text{P}_{\text{LEO}}}{\text{P}_{\text{GNSS}}} \tag{5}$$

with P_{LEO} and P_{GNSS} the power of the received LEO and GNSS signals, respectively. Hence, we derive that the interference robustness for this generic case is solely dependent on the signal power, and thus the gain with respect to GNSS on their signal power ratio. Hence, a certain interference power affecting GNSS signals will have to be I_{LEO} times bigger to have the same detrimental effect on LEO signals. For other bandwidth limitations, the distinct R_c and signal spectra will need to be considered in the computation of I_{LEO}.

With the definition of G_{LEO} and I_{LEO}, alongside the C/N_0, GDOP, PDOP, coverage of the users and the $\sigma_{\text{3D,LB}}$, a first approach can be followed for analysing the performance of several standalone LEO constellations of interest. Such constellations comprise existing ones and some others under study, with specific optimised designs. Details about their constellation size, satellite altitude, number of shells, number of planes, number of satellites per plane, inclination and topology are provided in Table 2. The `Marchionne', `Çelikbilek'

Table 2 LEO standalone constellations considered in this work

Constellation	Number of satellites	Number of shells	Number of planes	Satellites per plane	Inclination(s) (°)	Topology	Satellite altitude(s) (km)
Marchionne 1	484	3	[1, 8, 8]	[44, 24, 31]	[0, 36, 80]	Walker-Delta	1250
Marchionne 2	326	3	[4, 6, 6]	[20, 20, 21]	[12, 50, 82]	Walker-Delta	1250
Marchionne 3	246	3	[2, 6, 6]	[18, 19, 16]	[6, 46, 82]	Walker-Delta	1250
Çelikbilek 1	382	3	[19, 3, 30]	[7, 33, 5]	[34, 86, 80]	Walker-Mixed	[1835, 1550, 1477]
Çelikbilek 2	404	3	[28, 11, 12]	[5, 12, 11]	[44, 86, 67]	Walker-Delta	[681, 1134, 914]
Çelikbilek 3	281	3	[11, 11, 10]	[12, 9, 5]	[34, 78, 80]	Walker-Mixed	[1790, 1462, 1286]
Iridium-like	66	1	6	11	86.4	Walker-Delta	780
OneWeb-like	648	1	18	36	86.4	Walker-Star	1200
Xona-like	258	2	[6, 12]	[11, 16]	[97, 53]	Walker-Star	1080
CentiSpace-like	190	3	[12, 3, 4]	[10, 10, 10]	[55, 87.4, 30]	Walker-Star	[975, 1100, 1100]

and `Xona-like' constellation configurations have been obtained from Marchionne et al. (2023), Çelikbilek et al. (2025), and Leclère et al. (2025), respectively.

Carrier frequency

As mentioned earlier, another point for analysis is the performance of LEO satellites depending on the carrier frequency of choice. In this work, the transmission of LEO signals either at 1.5, 5 or 10 GHz of carrier frequency are analysed. These values are chosen following the literature (Eissfeller et al., 2024; Soualle et al., 2024; Prol et al., 2024; Ries et al., 2023), which suggests operating at higher bands due to the extra power margin offered by working in lower orbits, and the gains in positioning accuracy and interference robustness mentioned previously.

Ku/Ka bands are not included in the analysis since they present rain attenuation values that are too strong (Eissfeller et al., 2024) and path losses that deem it impractical for the tested transmission power levels. Furthermore, systems operating at these bands usually have high gain receiver antennas that compensate the high path losses (Soualle et al., 2024). However, our work considers receivers with 0 dB gain, since our aim is to evaluate LEO-PNT for low-cost receivers.

Transmitted power

For the purpose of analysing the impact of the transmission power on the system performance, and given its relation to the satellite cost, two different EIRP values are simulated.

First, an EIRP of 50 dBm is considered, which is 4–5 dB lower than that of GPS (GPS, 2007). Being the EIRP the addition of the transmit power and the antenna gain, such a value could be achieved by using the antennas of GPS, such as the Joint Instrumentation Bus (JIB) antennas deployed in the recent GPS-III mission, which are monopoles with a gain around 13.5 dBi, as described in the Federal Communications Commission (FCC) filings (GPS, 2007). This gain is representative of a phased array that keeps a wide beamwidth for broadband transmission. Meanwhile, a simpler power amplifier than GPS could be employed, such as RFLambda's RP01G9GSPA. Another option to reach this EIRP would be to use antennas with 0 dBi gain, and use stronger power amplifiers such as Solid State Power Amplifiers (SSPA), like RFLambda's RFLUPA02G06GC-B or Qorvo's QPB0218. This EIRP value offers a good trade-off between performance and complexity, and is chosen for analysis due to its good performance for LEO satellites in all outdoor scenarios while operating at GNSS bands.

The second EIRP value that is tested is one of 67 dBm, which is representative of a high cost satellite, and is similar to the values described for NTN LEO systems such as Iridium-Next (Reid et al., 2020) or Amazon's Kuiper (2021). The reason for the choice of this value is to evaluate the performance of high-end LEO satellites, even if they present high transmitter complexity.

Other existing LEO systems normally use EIRP values that lie between the ones analysed in this work. For example, Starlink seems to be working with values between 57.6 and 63 dBm, depending on the channel conditions (Soualle et al., 2024), while Xona Space Systems satellites might be using an EIRP around 55 dBm, according to the power levels reported in Soualle et al. (2024), or around 49 dBm according to the ones reported in Leclère et al. (2025). Some other theoretical works have considered slightly lower values for LEO-PNT systems, such as 46 dBm (Ries et al., 2023) or around 44 dBm (Critchley-Marrows et al., 2025; Mayank et al., 2025).

Hybrid LEO-PNT and GNSS

Next, we move on to the case of having a PNT solution based on signals coming from both GNSS and LEO satellites. In this case, the same metrics are analysed as in standalone LEO satellites, but assessing the improvements in positioning accuracy brought by the addition of LEO satellites to the existing GNSS constellations.

For such a purpose, the metric in Eq. (3) is considered again, which is referred here as G_{HYB}. Since LEO and GNSS have two different models of σ_{UERE}, the computation of $\sigma_{\mathrm{3D,LB}}$ as denoted in Eq. (2) will imply a weighted average of the two σ_{UERE} models depending on the number of visible satellites of each constellation at each point in time.

In terms of interference robustness, we keep to the analysis in the previous section, given that it is based only on power and thus each constellation's interference robustness will be independent of each other.

The hybrid constellations that are considered in this work are outlined in Table 3. One of the points of this analysis is to compare various hybrid setups, depending on how many GNSS and LEO constellations might be available, in order to assess which of these combinations presents the best results. In this regard, we consider first the hybridisation of medium-sized LEO constellations 'Marchionne 2' and 'Çelikbilek 1' with GNSS. These two constellations are chosen following the analysis in Sect. 4.1, which shows that they present the best trade-off between number of satellites and overall performance of all standalone LEO constellations. We also consider the hybridisation of GNSS with small-sized LEO constellations 'Iridium-like' and 'CentiSpace-like'. The hybrid multi-shell configurations of 1 LEO + 1 GNSS, 1 LEO + 2 GNSS, 1 LEO + 4 GNSS, or 2 LEO constellations are evaluated through extensive simulations.

Scenarios under analysis

To reach the objective of the simulations of this work, which is to assess the performance of LEO constellations for users operating outdoors, five representative outdoor scenarios are chosen from the extensive *Quasi Deterministic Radio channel Generator* (QuaDRiGa) MATLAB library (Jaeckel et al., 2022), which follows the 3GPP specification in 3GPP (2018). These scenarios take the following path-loss models:

$$\mathrm{PL} = A\log_{10}(d_{3D}) + B + C\log_{10}(f_c) + D\log_{10}(\theta_{\mathrm{el}}) + \mathrm{PL}_{\mathrm{atm}} \tag{6}$$

Table 3 Hybrid constellations evaluated in this work

Constellation	Number of satellites	Number of shells	Satellite altitude(s) (km)
Marchionne 2 + GPS	356	4	[1250, 1250, 1250, 20200]
Marchionne 2 + GPS + Galileo	383	5	[1250, 1250, 1250, 20200, 23222]
Marchionne 2 + GPS + Galileo + BeiDou + Glonass	437	7	[1250, 1250, 1250, 20200, 23222, 21528, 19100]
Çelikbilek 1 + GPS	412	4	[1835, 1550, 1477, 20200]
Çelikbilek 1 + GPS + Galileo	439	5	[1835, 1550, 1477, 20200, 23222]
Marchionne 2 + Çelikbilek 1	708	6	[1250, 1250, 1250 1835, 1550, 1477]
CentiSpace-like + BeiDou	217	4	[975, 1100, 1100, 21528]
CentiSpace-like + GPS + Galileo + BeiDou + Glonass	301	7	[975, 1100, 1100, 20200, 23200, 21528, 19100]
Iridium-like + GPS	96	2	[780, 20200]
Iridium-like + GPS + Galileo + BeiDou + Glonass	177	5	[780, 20200, 23200, 21528, 19100]
CentiSpace-like + Iridium-like	256	4	[975, 1100, 1100, 780]
Iridium-like + Marchionne 2	516	4	[780, 1250, 1250, 1250]

with d_{3D} the distance between the satellite and the user, θ_{el} the elevation angle, and PL_{atm} the path losses caused by the atmosphere, comprising atmospheric absorption and cloud/fog attenuation, following the recommendation in International Telecommunication Union – Radiocommunication Sector (ITU-R) (2017). Meanwhile, $\{A, B, C, D\}$ represent the scenario-specific parameters, with A the 3D distance dependence on the path-loss, B the reference path-loss at 1 GHz, 1 m distance and 1 rad of elevation angle, C the frequency dependence on the path-loss and D the dependence on the elevation angle. Furthermore, PL_{atm} does not consider rain attenuation in our simulator, which would be around 0.2 dB at the L-band, 0.5 dB at C-band, and 2–3 dB at the X band (Eissfeller et al., 2024).

These parameters are configured as shown in Table 4, for the 5 scenarios at hand, following Jaeckel et al. (2022), and where the nominal scenario is understood as the one that only takes into account the Free-Space Path Losses (FSPL) (i.e. open-sky).

Meanwhile, 'O1' represents using Non-Line-of-Sight (NLoS) signals in an urban canyon, where GNSS typically struggles, 'O2' represents the same scenario but with a visible Line-of-Sight (LoS), while 'O3' and 'O4' are the equivalent of these scenarios for rural environments.

To properly assess the geometric impact on the performance and the offered coverage, the analysis considers service to 400 users uniformly distributed between latitudes of 30° and 75°, representative of users in Europe, China, or the US. The performance metrics are obtained for 480 different time instances separated 180 s between them to simulate the satellite passes for a total of 1 day. These are then simulated 5 times, one for each of the mentioned scenarios.

Numerical results

Following the framework in Sect. 3, the simulated performance results are presented in this Section. First, the C/N_0, GDOP, PDOP and coverage values are shown for all the standalone GNSS and LEO constellations considered in this work, depending on the carrier frequency of choice and the outdoor scenario at hand. Tables 5, 7, 9 and 10 show average values of these metrics excluding the best and worst 5% of all simulation points.

Table 4 QuaDRiGa scenarios considered in the present work

Outdoor scenario	*A*	*B*	*C*	*D*	PL_{atm}
O0: Nominal outdoor	20	32.5	20	0	No
O1: NLoS Urban	20.1	54.9	27.9	− 11	Yes
O2: LoS Urban	20	32.6	20	0	Yes
O3: NLoS Rural	20	47.5	22.8	− 8.3	Yes
O4: LoS Rural	20	32.5	20.1	0	Yes

LEO versus GNSS

Case #1: EIRP $= 50$ *dBm*

Table 5 presents the performance results for the case of a transmission EIRP of 50 dBm for the standalone constellations in Table 2. From them, it is readily apparent that the C/N_0 of LEO satellites surpasses that of GNSS for the case of a f_c of 1.5 GHz, while this gain is reduced for 5 GHz, where the C/N_0 values go down to the levels of GNSS. The case of having a 10 GHz carrier frequency shows somewhat poorer results to those of GNSS, which justifies the need for a higher satellite EIRP and/or bandwidth to achieve any gain in accuracy with respect to GNSS when operating in the X band. Hence, the lower complexity at this level of transmission EIRP can only really be achieved at the L or C bands.

For the C-band, we can assume that at least the same positioning accuracy as the L-band can be achieved, even if the C/N_0 values are lower, because of the higher available B. The delay estimation accuracy is lower bounded by the Cramér-Rao Lower Bound (CRLB), which inversely depends on the C/N_0 and on the squared-bandwidth (Kay, 1993). Increasing the carrier frequency by a factor K can allow, for example, the use of a bandwidth K times larger, which contributes in improving the CRLB by a factor K^2. However, increasing the carrier frequency by a factor K increases the free-space propagation losses by a factor K^2, thus reducing the C/N_0 and increasing the CRLB by the same amount. Overall, increasing the carrier frequency and thus increasing the bandwidth accordingly, can compensate the increased propagation losses, and thus preserve the same CRLB.

The higher number of visible satellites of most of the considered LEO constellations provides lower GDOP and PDOP values than GNSS, with 'Çelikbilek 1' and 'OneWeb-like' achieving the best values. Notably, the prior achieves a low GDOP with a considerably lower amount of satellites than the latter, because of its multi-shell configuration which distributes the satellites in various altitudes, inclinations, and topologies, as shown in Table 2. This design delivers a far better trade-off between GDOP and constellation size than 'OneWeb-like', which has all its satellites in one shell. From the rest of constellations, 'Çelikbilek 3' and 'Marchionne 2' also present a good trade-off between performance and constellation size, while the remaining constellations either do not present such a good trade-off or their performance is considerably worse. For example, 'Çelikbilek 2' has the same GDOP as 'Çelikbilek 3', though with an additional 123 satellites. It does improve

Table 5 Standalone constellations performance results, for a LEO EIRP = 50 dBm

Constellation	Fc (GHz)	C/N_0 (dB-Hz)					GDOP	PDOP	Coverage (%)
		O1	O2	O3	O4	O0/FSPL			
GPS	L1	21.0	44.7	28.2	45.1	45.2	2.1	1.9	100
Galileo	E1	20.5	44.2	27.6	44.6	44.7	2.3	2.0	100
BeiDou	B1I	20.5	44.0	27.6	44.3	44.5	2.2	2.0	100
GPS + Galileo	L1/E1	20.7	44.5	27.9	44.9	45.0	1.5	1.3	100
BeiDou + Galileo + GPS + Glonass	B1I/E1/L1	20.7	44.1	27.8	44.5	44.6	1.0	0.9	100
Marchionne 1	1.5	37.7	58.1	45.3	58.4	58.5	1.4	1.3	100
	5	22.9	47.4	33.3	47.8	47.9	1.4	1.3	100
	10	13.9	40.8	25.8	41.2	41.5	1.4	1.3	100
Marchionne 2	1.5	37.5	57.8	45.1	58.2	58.4	1.7	1.5	100
	5	22.9	47.4	33.2	47.7	47.8	1.7	1.5	100
	10	13.9	40.8	25.9	41.2	41.4	1.7	1.5	100
Marchionne 3	1.5	37.7	58.1	45.4	58.5	58.6	2.0	1.9	100
	5	23.0	47.5	33.3	47.9	48.0	2.0	1.9	100
	10	14.3	41.2	26.1	41.5	41.6	2.0	1.9	100
Çelikbilek 1	1.5	36.2	56.9	43.9	57.2	57.3	1.2	1.1	100
	5	21.5	46.3	31.9	46.6	46.7	1.2	1.1	100
	10	12.7	39.9	24.7	40.2	40.3	1.2	1.1	100
Çelikbilek 2	1.5	39.3	59.4	46.9	59.8	60.0	1.7	1.6	100
	5	24.7	48.9	35.0	49.2	49.4	1.7	1.6	100
	10	15.4	42.0	27.2	42.3	42.9	1.7	1.6	100
Çelikbilek 3	1.5	35.9	56.7	43.7	57.1	57.3	1.7	1.6	100
	5	21.4	46.3	31.8	46.7	46.8	1.7	1.6	100
	10	12.6	39.9	24.6	40.2	40.4	1.7	1.6	100
OneWeb-like	1.5	38.2	58.3	47.8	58.7	58.9	1.1	0.9	100
	5	23.6	47.9	33.9	48.2	48.3	1.1	0.9	100
	10	14.7	41.3	26.5	41.6	41.8	1.1	0.9	100
CentiSpace-like	1.5	38.7	59.0	46.4	59.3	59.5	3.8	3.5	98.3
	5	24.0	48.4	34.3	48.8	49.0	3.8	3.5	98.3
	10	15.1	42.0	27.0	42.3	42.6	3.8	3.5	98.3
Xona-like	1.5	38.8	59.0	46.4	59.4	59.5	2.3	2.1	100
	5	24.0	48.4	34.3	48.7	48.8	2.3	2.1	100
	10	14.9	41.7	26.8	42.0	42.4	2.3	2.1	100
Iridium-like	1.5	41.1	60.9	48.7	61.3	61.5	9.8	8.9	19.5
	5	26.3	50.2	36.5	50.6	50.7	9.8	8.9	19.5
	10	16.8	43.0	28.5	43.3	44.0	9.8	8.9	19.5

the C/N_0 by 2.8 dB, but we do not consider that this additional power margin justifies the extra cost. The 'Çelikbilek 2' and 'Çelikbilek 3' constellations have similar GDOP values because the design of the altitude and inclination of the shells of the prior was done to optimise the C/N_0, while for the latter it was done to optimise the GDOP.

In terms of the smaller constellations 'Iridium-like' and 'CentiSpace-like', the latter reaches almost full coverage and GDOP and PDOP values worse than those of GNSS but still low enough to meet the accuracy requirements of some positioning applications. Meanwhile, 'Iridium-like' delivers the strongest C/N_0 values due to its closeness to Earth, although with a clearly limited 4-satellite coverage.

Finally, the GNSS constellations already achieve full coverage in outdoor scenarios, and thus the LEO constellations do not add value for this metric.

To continue the evaluation of the LEO constellations and be able to rank their performance, the next step is to compute the positioning error, given the simulated

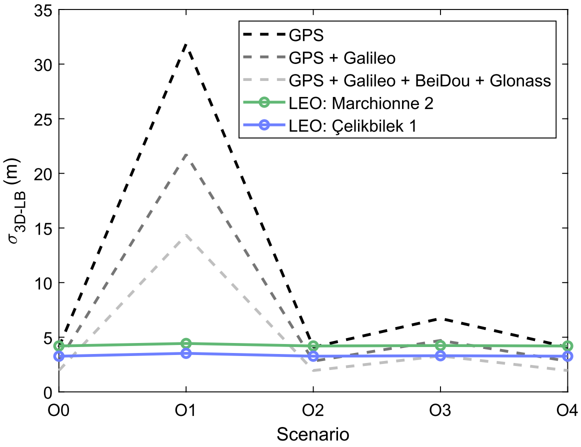

Fig. 1 Lower-bound positioning accuracy of GNSS and LEO systems in the outdoor scenarios in Table 4

results presented in Table 5. Following Eq. (2), the lower-bound positioning accuracy of LEO systems is presented in Table 6, and compared with that of GNSS in Fig. 1, for the case of $f_c = 1.5$ GHz. Notably, Fig. 1 can also be representative of the $f_c = 5$ GHz choice, if a larger bandwidth is allocated to compensate for the loss in C/N_0.

For the case of GNSS, the signals bring on a sufficiently low nominal C/N_0 that makes it frail to the conditions in scenarios ’O1’ and ’O3’, along with the potential presence of powerful interferences. Positioning accuracy is significantly degraded in the most taxing scenarios, being up to 7 times worse in ’O1’ than in the nominal case and up to 2.5 times worse in ’O3’. Even a multi-constellation GNSS receiver collecting signals from GPS, Galileo (GAL), BeiDou Navigation Satellite System (BDS), and GLONASS (GLO) fails to sufficiently reduce this inaccuracy. This demonstrates a clear need for the superior C/N_0 provided by LEO-PNT systems. Meanwhile, the $\sigma_{3D,LB}$ of LEO satellites is maintained to a low level in these challenging scenarios, given that their C/N_0 values are not sufficiently degraded to cause a strong decline in accuracy.

These results show that the EIRP of 50 dBm suffices to provide high enough C/N_0 values that do not deteriorate the $\sigma_{3D,LB}$ in the taxing ’O1’ and ’O3’ scenarios, when operating in the GNSS band.

Having estimated the $\sigma_{3D,LB}$ and with the obtained simulations for the C/N_0, the G_{LEO} from Eq. (3) is computed and shown in Table 6.

It is clear from these results that the constellations that optimise the geometry of their satellites fare better than those which optimise the C/N_0. For example, constellations ‘Çelikbilek 1’ and ‘Çelikbilek 2’ have a similar amount of satellites, yet the prior has far better G_{LEO} values since it was optimised for the best GDOP (Çelikbilek et al., 2025), while the latter was optimised for the best C/N_0 (Çelikbilek et al., 2025). The effect of a C/N_0 reduced by 2–3 dB makes little difference in terms of positioning accuracy in comparison to other constellations. Hence, when the goal is to achieve nominal outdoor positioning accuracy in challenging outdoor scenarios and the satellite works at an EIRP of 50 dBm, the best-performing LEO constellation will be the one that maximises the geometric uniformity.

For this reason, constellations ‘Çelikbilek 1’, ‘Çelikbilek 3’ and ‘Marchionne 2’ fare the best considering the amount of satellites they use, while ‘Çelikbilek 2’ fares the worst. The rest of the constellations fall between these two categories.

Table 6 Impact of using LEO constellations on positioning accuracy with respect to GPS+Galileo, for an EIRP of 50 dBm and an Fc of 1.5 GHz

	Scenario	Marchionne			Çelikbilek			OneWeb -like	CentiSpace -like	Xona -like	Iridium -like
		1	2	3	1	2	3				
$\sigma_{3D,LB}$ (m)	O0	3.4	4.2	5.0	3.3	4.2	4.2	2.5	9.5	5.7	24.0
	O1	3.6	4.4	5.3	3.5	4.4	4.6	2.6	9.9	6.0	24.6
	O2	3.4	4.2	5.0	3.3	4.2	4.2	2.5	9.5	5.7	24.0
	O3	3.4	4.2	5.1	3.3	4.2	4.3	2.5	9.6	5.8	24.1
	O4	3.4	4.2	5.0	3.3	4.2	4.2	2.5	9.5	5.7	24.0
G_{LEO}	O0	0.8	0.7	0.6	0.9	0.7	0.8	1.1	0.3	0.5	0.1
	O1	6.0	4.9	4.1	6.2	4.9	4.7	8.5	2.2	3.6	0.9
	O2	0.8	0.7	0.6	0.9	0.7	0.7	1.1	0.3	0.5	0.1
	O3	1.4	1.1	0.9	1.4	1.1	1.1	1.9	0.5	0.8	0.2
	O4	0.8	0.7	0.6	0.9	0.7	0.7	1.1	0.3	0.5	0.1

Table 7 Standalone constellations performance results, for a LEO EIRP = 67 dBm

Constellation	Fc (GHz)	C/N_0 (dB-Hz)					GDOP	PDOP	Coverage (%)
		O1	O2	O3	O4	O0/FSPL			
GPS	L1	21.0	44.7	28.2	45.1	45.2	2.1	1.9	100
Galileo	E1	20.5	44.2	27.6	44.6	44.7	2.3	2.0	100
BeiDou	B1I	20.5	44.0	27.6	44.3	44.5	2.2	2.0	100
GPS + Galileo	L1/E1	20.7	44.5	27.9	44.9	45.0	1.5	1.3	100
BeiDou + Galileo + GPS + Glonass	B1I/E1/L1	20.7	44.1	27.8	44.5	44.6	1.0	0.9	100
Marchionne 1	1.5	54.7	75.1	62.3	75.4	75.5	1.4	1.3	100
	5	39.9	64.4	50.3	64.8	64.9	1.4	1.3	100
	10	31.6	57.8	43.5	58.2	58.5	1.4	1.3	100
Marchionne 2	1.5	54.5	74.8	62.1	75.2	75.4	1.7	1.5	100
	5	39.9	64.4	50.2	64.7	64.8	1.7	1.5	100
	10	31.5	57.8	43.3	58.2	58.4	1.7	1.5	100
Marchionne 3	1.5	54.7	75.1	62.4	75.5	75.6	2.0	1.9	100
	5	40.0	64.5	50.3	64.9	65.0	2.0	1.9	100
	10	31.7	58.2	43.6	58.5	58.6	2.0	1.9	100
Çelikbilek 1	1.5	53.2	73.9	60.9	74.2	74.3	1.2	1.1	100
	5	38.5	63.3	48.9	63.6	63.7	1.2	1.1	100
	10	30.1	56.9	41.9	57.2	57.3	1.2	1.1	100
Çelikbilek 2	1.5	56.3	76.4	63.9	76.8	77.0	1.7	1.6	100
	5	41.7	65.9	52.0	66.2	66.4	1.7	1.6	100
	10	32.9	59.0	45.0	59.3	59.9	1.7	1.6	100
Çelikbilek 3	1.5	52.9	73.7	60.7	74.1	74.3	1.7	1.6	100
	5	38.4	63.3	48.8	63.7	63.8	1.7	1.6	100
	10	30.5	56.9	42.4	57.2	57.4	1.7	1.6	100
OneWeb-like	1.5	55.2	75.3	62.8	75.7	75.9	1.1	0.9	100
	5	40.6	64.9	50.9	65.2	65.3	1.1	0.9	100
	10	31.8	58.3	43.5	58.6	58.8	1.1	0.9	100
CentiSpace-like	1.5	55.7	76.0	63.4	76.4	76.5	3.8	3.5	98.3
	5	40.6	65.2	51.1	65.6	65.9	3.8	3.5	98.3
	10	32.0	58.8	43.8	59.1	59.5	3.8	3.5	98.3
Xona-like	1.5	55.8	76.0	63.4	76.4	76.5	2.3	2.1	100
	5	41.0	65.4	51.3	65.7	65.8	2.3	2.1	100
	10	32.6	58.7	44.6	59.0	59.4	2.3	2.1	100
Iridium-like	1.5	58.1	77.9	65.8	78.3	78.5	9.8	8.9	19.5
	5	43.3	67.2	53.5	67.6	67.7	9.8	8.9	19.5
	10	34.1	60.0	45.9	60.3	61.0	9.8	8.9	19.5

Case #2:* EIRP = 67 *dBm

Similar takeaways can be derived from the simulations using a satellite EIRP of 67 dBm, the results for which are shown in Table 7.

In this case, the C/N_0 of LEO satellites is outstandingly higher than that of GNSS for a f_c of 1.5 GHz, and continues to have a strong gain for 5 GHz, similar to that of a satellite with an EIRP of 50 dBm working at 1.5 GHz. This EIRP level unlocks the 10 GHz band, where LEO satellites still have 10–15 dB gain in C/N_0 with respect to GNSS, depending on the scenario and the constellation.

Most importantly, the improvements in positioning accuracy with respect to using an EIRP of 50 dBm are scarce. While the accuracy in the more taxing scenarios 'O1' and 'O3' reaches the nominal accuracy, they are still bounded by the sources of error described in Eq. (1), and thus hardly provide any gain. Hence, the extra complexity and cost in the satellite brought by the use of elements that might put forward such a powerful signal are not justified. Nonetheless, such an assumption cannot be taken for indoor scenarios or applications with needs for very accurate PNT that do use some external error correction.

Using 'Iridium-like' in open-sky with a $f_c = 1.5$ GHz and an EIRP of 67 dBm gives a $C/N_0 = 78.5$ dB-Hz, which is similar to that divulged in Reid et al. (2020), where the Satelles Satellite Time and Location (STL) PNT service component integrated in the Iridium-Next signal was used to retrieve a C/N_0 around 80 dB-Hz. This further validates the suitability of the analysis in our work, with the small discrepancy possibly coming from the different user latitude used in Reid et al. (2020) and/or a slightly higher EIRP value used by Iridium-Next satellites. The results in this work are also validated with other analytical studies that simulate dedicated LEO-PNT systems, with the works in Soualle et al. (2024); Eissfeller et al. (2024) presenting similar results for the open-sky scenario, when corrected for the EIRP, carrier frequency and satellite altitude used in each work.

The amount at which either of the two EIRP values are sufficient to provide services when GNSS is in denial-of-service because of the presence of interferences is evaluated through the I_{LEO} metric, the results of which are presented in Table 8. The I_{LEO} is relatively low for an EIRP of 50 dBm, particularly in the higher frequencies, where no additional robustness is observed. Nonetheless, given that a higher B will be available at higher frequencies, and given the dependence of the $(C/N_0)_{\text{eff}}$ on the B through the R_c term, as pointed out in Eq. (4), it can be assumed that the robustness observed for 1.5 GHz can be maintained for the rest of the evaluated carrier frequencies. In this sense, the choice of EIRP depends on the application requirements and the profile of the interferences, but clearly both cases of EIRP provide an important layer of security that GNSS does not have.

The evaluation of the level at which strong EIRP transmission values are needed or not, or, in other words, the power of the interferences that would significantly degrade the positioning accuracy for a certain EIRP, is left as future work, given the strong dependance on the LEO signal design depicted in Eq. (4).

Hybrid LEO-GNSS

Following the comparison between LEO standalone constellations, we now take a look at the performance of the hybrid LEO-GNSS constellations described in Table 3.

Case #1: EIRP = 50 *dBm*

Taking first the case of LEO satellites transmitting at an EIRP of 50 dBm, Table 9 extends the previous results for the considered hybrid configurations. These results show improved GDOP and PDOP values for the 'Marchionne 2' combinations with GNSS with respect to either of their standalone counterparts. For the case of the 'Çelikbilek 1' constellation, even if its standalone GDOP and PDOP values are already substantially lower than those of GNSS, combining it with GNSS still brings a solid improvement, such that the G_{HYB} of 'Çelikbilek + GPS + GAL' is similar to adding both 'Çelikbilek 1' and 'Marchionne 2' together.

These results also show that using two medium-sized, multi-shell and optimised LEO constellations may not prove to be better than using a single bigger constellation, such as 'OneWeb-like'. The latter has a similar PDOP and a higher C/N_0 than the 2 medium-sized LEO combination, while operating with 50 fewer satellites. This is notable because the constellation 'OneWeb-like' is not multi-shell, it has fewer satellites with lower altitude, and no further optimisation has been done in its design aside from making it a Walker Star constellation.

Next, we take a look at the gain in linear scale (G_{HYB}) that these configurations bring with respect to the standalone GNSS constellations, as defined by Eq. (3). Figure 2 showcases the G_{HYB} for medium-sized LEO constellations combined with various GNSS constellations, for the five outdoor scenarios, and for the case of $f_c = 1.5$ GHz.

Table 8 Impact of using LEO constellations on interference robustness with respect to GNSS, for scenario O0 and assuming equal *B*

	EIRP (dBm)	Fc (GHz)	Marchionne			Çelikbilek			OneWeb -like	CentiSpace -like	Xona -like	Iridium -like
			1	2	3	1	2	3				
I_{LEO} (dB)	50	1.5	13.4	13.4	13.5	12.3	14.9	12.2	13.8	13.6	14.3	16.4
		5	2.8	2.7	2.9	1.6	4.3	1.6	3.2	3.0	3.7	5.6
		10	−3.6	−3.7	−3.5	−4.8	−2.5	−4.7	−3.3	−3.4	−2.7	−1.1
	67	1.5	30.4	30.3	30.5	29.2	32.9	29.2	30.8	30.6	31.4	33.4
		5	19.8	19.7	19.9	18.6	21.3	18.6	20.2	20.0	20.7	22.6
		10	13.4	13.3	13.5	12.2	14.5	12.3	13.7	13.6	14.3	15.9

Table 9 Hybrid constellations performance results, for an EIRP = 50 dBm

Constellation	**LEO Fc (GHz)**	**C/N$_0$ (dB-Hz)**					**GDOP**	**PDOP**	**Coverage (%)**
		O1	**O2**	**O3**	**O4**	**O0/FSPL**			
Hybrid configurations with medium-sized LEO constellations									
Marchionne 2 + GPS	1.5	31.5	53.6	39.6	54.0	54.1	1.2	1.1	100
	5	22.2	47.0	32.6	47.3	47.4	1.2	1.1	100
	10	16.5	42.8	52.1	43.2	43.5	1.2	1.1	100
Marchionne 2 + GPS + Galileo	1.5	28.1	51.3	36.5	51.7	51.8	1.0	0.9	100
	5	21.6	46.6	32.6	47.0	47.1	1.0	0.9	100
	10	17.6	43.8	54.4	44.2	44.4	1.0	0.9	100
Marchionne 2 + GPS + Galileo + BeiDou + Glonass	1.5	26.1	50.0	34.6	50.4	50.5	0.8	0.7	100
	5	23.1	47.1	32.6	47.4	47.5	0.8	0.7	100
	10	19.0	45.0	28.2	45.4	45.6	0.8	0.7	100
Çelikbilek 1 + GPS	1.5	33.1	54.8	41.2	55.2	55.3	1.0	0.9	100
	5	19.9	46.4	31.9	46.8	47.0	1.0	0.9	100
	10	18.9	41.6	50.1	42.0	42.3	1.0	0.9	100
Çelikbilek 1 + GPS + Galileo	1.5	30.5	53.1	38.8	53.4	53.4	0.9	0.8	100
	5	21.2	46.4	31.9	46.8	46.9	0.9	0.8	100
	10	16.0	42.4	52.9	42.8	43.1	0.9	0.8	100
Marchionne 2 + Çelikbilek 1	1.5	37.8	58.0	45.8	58.3	58.7	1.0	0.9	100
	5	23.3	47.3	33.5	47.6	48.1	1.0	0.9	100
	10	14.2	41.1	26.0	41.4	41.7	1.0	0.9	100
Hybrid configurations with small-sized LEO constellations									
CentiSpace-like + BeiDou	1.5	31.4	50.9	36.5	51.3	51.4	1.5	1.4	100
	5	22.7	46.0	30.8	46.4	46.5	1.5	1.4	100
	10	20.2	43.2	27.4	43.6	43.7	1.5	1.4	100
CentiSpace-like + GPS + Galileo + BeiDou + Glonass	1.5	23.3	48.1	32.2	48.5	48.6	0.9	0.8	100
	5	21.4	46.8	30.7	47.2	47.3	0.9	0.8	100
	10	20.0	45.8	29.5	46.2	46.3	0.9	0.8	100
CentiSpace-like + Iridium-like	1.5	44.0	64.3	51.6	64.6	64.6	2.7	2.5	100
	5	28.8	53.3	39.2	53.6	53.9	2.7	2.5	100
	10	20.0	46.8	31.8	47.1	47.5	2.7	2.5	100
Iridium-like + GPS	1.5	26.1	47.5	32.0	47.9	48.0	1.8	1.6	100
	5	22.3	45.6	29.8	46.0	46.1	1.8	1.6	100
	10	20.9	44.6	28.5	45.0	45.1	1.8	1.6	100
Iridium-like + GPS + Galileo + BeiDou + Glonass	1.5	22.3	47.3	31.0	47.7	47.8	1.0	0.9	100
	5	22.0	47.1	30.8	47.5	47.6	1.0	0.9	100
	10	21.6	47.0	30.7	47.4	47.5	1.0	0.9	100
Iridium-like + Marchionne 2	1.5	40.9	61.1	48.5	61.5	61.6	1.6	1.5	100
	5	26.1	50.5	36.4	50.8	51.0	1.6	1.5	100
	10	17.1	43.8	28.9	44.1	44.5	1.6	1.5	100

In all scenarios, the combination of 'Marchionne 2' and GNSS produces a higher gain G_{HYB} than their standalone counterparts, and the LEO constellations bring the highest gain in the most complex scenarios. However, it is noticeable that, in scenarios 'O0', 'O2' and 'O4', the gain of hybridising Marchionne 2+GNSS with respect to Marchionne 2 is substantial, and higher than for scenarios 'O1', 'O3', such that the contribution of GNSS is highest in the less-complex scenarios. This shows a dependance of this gain both on the scenario and the constellation. If we compare 'Marchionne 2 + GPS' to the highest accuracy between both standalone 'Marchionne 2' and GPS, the combination brings between 5 and 49% gain depending on the scenario. Specifically, this gain is lowest for scenarios 'O1' and 'O3', which shows that GPS is contributing less to the

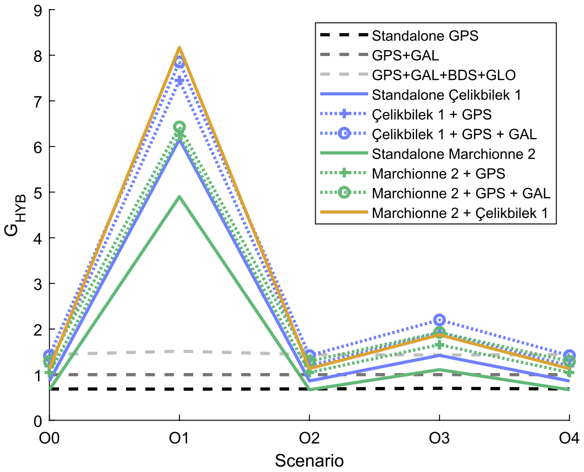

Fig. 2 Gain in the lower-bound positioning accuracy with respect to GPS+Galileo for hybrid combinations of medium-sized LEO and GNSS

solution. Adding Galileo increases these values to between 29 and 73%. The strongest improvement comes from scenario 'O3', where GNSS has a sufficiently high C/N_0 to contribute to the solution, but still benefits substantially from the addition LEO constellation.

Meanwhile, for 'Çelikbilek 1 + GPS' the gain is between 19 and 35%, and adding Galileo increases these values to between 27 and 54%. Interestingly, these results have lower variance between scenarios than for 'Marchionne 2' + GNSS.

In hybrid combinations of any two constellations, the G_{HYB} might be driven by one of the two constellations, or by a combination of them. For example, in a hybrid configuration of a very small LEO constellation with GNSS, the driver of the performance will be the latter, since the low amount of LEO satellites will do little to improve G_{HYB}. In this sense, one can compute how much the constellations add to G_{HYB} by comparing it to their standalone gains. If G_{HYB} is close to the gain of any of the constellations forming the hybrid setup, then that constellation will be driving the performance. Otherwise, if G_{HYB} is substantially bigger than the gain of each standalone constellation forming the hybrid setup, then all constellations will drive the performance. The better outcome is the latter, particularly considering that GNSS is already deployed. The more cost-effective solution will be that where G_{HYB} is equally higher than both the standalone gain of the LEO constellation and the GNSS constellation. Hence, depending on the scenarios at hand and the hybridisation setup, there will be a 'sweet spot' of LEO constellation design that provides the more cost-effective solution.

In this sense, for the 'Marchionne 2' + GNSS configurations, the GNSS satellites drive the performance in the simpler scenarios, while the LEO satellites drive it for taxing scenarios or with higher presence of interfering signals, thus proving that these hybrid configurations are useful in providing a secure and robust solution for all outdoor scenarios.

When taking a look at the combination of 'Çelikbilek 1' with GNSS, the contribution of the GNSS satellites to G_{HYB} is lower than for 'Marchionne 2', although it is still high. This is because the geometric uniformity of 'Çelikbilek 1' is better than for 'Marchionne 2', such that hybridising it with GNSS brings less improvement. By inference, the hybridisation of larger LEO constellations such as 'OneWeb-like' with GNSS will produce little gain with respect to the standalone large LEO constellation. However, since the variance of G_{HYB} between scenarios is lower for 'Çelikbilek 1' + GNSS than for 'Marchionne 2' + GNSS, the prior is the more cost-effective solution, and 'Çelikbilek 1 + GPS + GAL' is better than 'Çelikbilek 1 + GPS'.

Producing the same experiment with the combination of small LEO constellations with GNSS gives the output shown in Fig. 3. For small-sized LEO constellations, the G_{HYB} in scenarios 'O0', 'O2', and 'O4' is actually very close to the gain of GNSS constellations, while for scenarios 'O1' and 'O3' it is a combination of both constellations. Hence, the addition of small-sized LEO constellations to GNSS only serves some purpose in the challenging scenarios. Notably, while the the hybridisation of 'Iridium-like' with GNSS provides some improvements in accuracy, 'CentiSpace-like' combined with BeiDou or with 4 GNSS is closer to the cost-effective 'sweet spot', and shows that the design of 'CentiSpace-like' with BeiDou might follow this logic. For the most challenging scenario 'O1', combining 'CentiSpace-like+BDS' brings a 153% improvement over 'CentiSpace-like'.

Furthermore, joining two small-sized LEO constellations proves to be useful to improve the coverage, but with little improvement in the positioning accuracy, except for scenario 'O1'. Finally, adding a small-sized constellation to a medium-sized one also shows little gain with respect to just using the medium-sized one.

Case #2: EIRP $= 67$ *dBm*

Similar conclusions can be taken from using an EIRP of 67 dBm, with the results presented in Table 10, since the main factor impacting $\sigma_{\mathrm{3D,LB}}$ and thus G_{HYB} is actually the geometry and not so much the C/N_0, as long as the C/N_0 is sufficiently high to overcome the losses in complex scenarios.

However, while the G_{HYB} does decrease for an EIRP of 50 dBm when operating at 5 GHz, it actually increases

Table 10 Hybrid constellations performance results, for an EIRP = 67 dBm

Constellation	LEO Fc (GHz)	C/N_0 (dB-Hz)					GDOP	PDOP	Coverage (%)
		O1	O2	O3	O4	O0/FSPL			
Hybrid configurations with medium-sized LEO Constellations									
Marchionne 2 + GPS	1.5	41.9	64.1	50.0	64.4	64.4	1.2	1.1	100
	5	31.8	56.6	41.6	57.0	57.6	1.2	1.1	100
	10	26.5	52.8	37.3	53.2	53.5	1.2	1.1	100
Marchionne 2 + GPS + Galileo	1.5	35.2	58.4	43.6	58.8	58.9	1.0	0.9	100
	5	28.7	53.8	38.3	54.1	54.2	1.0	0.9	100
	10	24.5	50.6	34.8	51.0	51.3	1.0	0.9	100
Marchionne 2 + GPS + Galileo + Beidou + Glonass	1.5	30.2	54.3	38.8	54.7	54.8	0.8	0.7	100
	5	26.3	51.4	35.6	51.8	51.9	0.8	0.7	100
	10	23.8	49.6	33.6	50.0	50.2	0.8	0.7	100
Çelikbilek 1 + GPS	1.5	45.8	67.6	53.9	67.9	67.9	1.0	0.9	100
	5	34.2	59.2	44.3	59.5	59.6	1.0	0.9	100
	10	27.1	53.9	38.4	54.3	54.6	1.0	0.9	100
Çelikbilek 1 + GPS + Galileo	1.5	40.2	62.7	48.4	63.1	63.2	0.9	0.8	100
	5	31.0	56.1	40.9	56.5	56.7	0.9	0.8	100
	10	25.6	52.1	36.4	52.5	52.8	0.9	0.8	100
Marchionne 2 + Çelikbilek 1	1.5	53.6	74.3	61.4	74.6	74.7	1.0	0.9	100
	5	39.3	63.5	48.3	63.7	64.1	1.0	0.9	100
	10	30.7	57.1	41.9	57.4	57.7	1.0	0.9	100
Hybrid configurations with small-sized LEO Constellations									
CentiSpace-like + BeiDou	1.5	41.6	58.7	44.4	59.0	59.1	1.5	1.4	100
	5	32.7	53.8	38.8	54.2	54.3	1.5	1.4	100
	10	27.5	50.8	35.4	51.2	51.3	1.5	1.4	100
CentiSpace-like + GPS + Galileo + BeiDou + Glonass	1.5	25.2	50.0	34.0	50.4	50.5	0.9	0.8	100
	5	23.5	48.8	32.6	49.2	49.3	0.9	0.8	100
	10	22.3	47.9	31.6	48.3	48.5	0.9	0.8	100
CentiSpace-like + Iridium-like	1.5	55.9	76.2	63.5	76.5	76.5	2.7	2.5	100
	5	40.7	65.1	51.0	65.5	65.8	2.7	2.5	100
	10	31.9	58.6	43.7	59.0	59.4	2.7	2.5	100
Iridium-like + GPS	1.5	30.6	50.6	35.1	51.0	51.2	1.8	1.6	100
	5	26.7	48.7	32.9	49.1	49.2	1.8	1.6	100
	10	24.4	47.5	31.6	47.9	48.0	1.8	1.6	100
Iridium-like + GPS + Galileo + BeiDou + Glonass	1.5	22.1	47.3	31.0	47.7	47.8	1.0	0.9	100
	5	21.8	47.1	30.8	47.5	47.6	1.0	0.9	100
	10	21.6	47.0	30.7	47.4	47.5	1.0	0.9	100
Iridium-like + Marchionne 2	1.5	55.3	75.6	62.9	75.9	75.9	1.6	1.5	100
	5	40.1	64.5	50.5	64.9	65.2	1.6	1.5	100
	10	31.3	58.1	43.1	58.4	58.8	1.6	1.5	100

for an EIRP of 67 dBm from 1.5 GHz, given that the ionospheric error would be lower and the C/N_0 is high enough to keep the noise error component low, showing that the highest G_{HYB} of all the tested configurations comes from using an EIRP of 67 dBm and an f_c of 5 GHz.

System design takeaways

The previous standalone LEO performance results bring us to some system design takeaways, which are summarised next:

- The best choice of a constellation relies heavily on the demands of the PNT applications for which they are designed, but, in general terms, the constellations

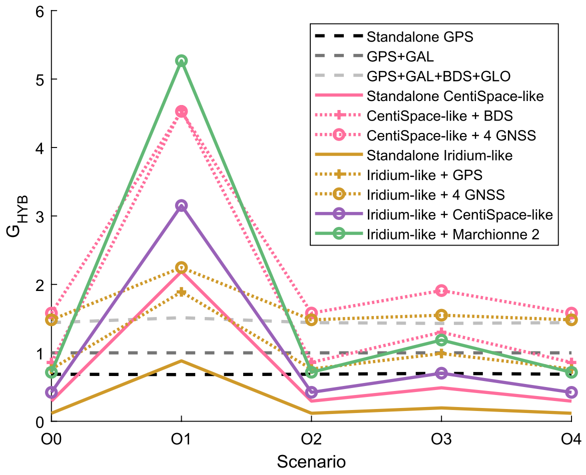

Fig. 3 Gain in the lower-bound positioning accuracy with respect to GPS+Galileo for hybrid combinations of small-sized LEO and GNSS

‘Marchionne 2’ and ‘Çelikbilek 1’ offer the best trade-offs in performance and size compared to the other considered LEO constellations. Since they operate with 326 and 382 satellites, respectively, both these constellations achieve considerably lower GDOP and PDOP values than the GNSS standalone constellations, along with a much stronger C/N_0. The ‘Çelikbilek 1’ constellation, whose constellation optimisation criterion sought to minimise the GDOP, provides the best positioning accuracy for medium-sized constellations, and is surpassed only by ‘OneWeb-like’, which is a much bigger-sized constellation.

- In this work, we have analysed the performance of LEO satellites in outdoor scenarios considering receivers that do not have accurate error information brought by techniques such as RTK or PPP. Considering that the various constellations analysed in this work have been optimised for different purposes, the conclusion on them is that, for rural and urban outdoor scenarios, those that optimise a uniform geometry of their satellites instead of the C/N_0 are a better choice to provide the best positioning accuracy.
- Following the previous takeaway, having a satellite EIRP of 50 dBm suffices to provide good positioning accuracy in all the evaluated outdoor scenarios. Having analysed also the case of an EIRP of 67 dBm, which is closer to the values reported by Iridium-Next and Amazon Kuiper, the gain in using such a value is little when there are no error corrections, while the satellite cost needs to be heavily increased to accommodate such EIRP values. Whether this is also the case for indoor scenarios or not is left as future work.
- The analysis in this work shows that the higher power of LEO signals does enable the choice for higher carrier frequencies, such as those in the C band, whose gain will come from the ability of allocating a higher bandwidth, a reduction in receiver antenna size and array separation, and a lower amount of interferences. Hence, this analysis shows that the interference and spoofing problem in PNT could be strongly alleviated with a transmission f_c of 5 GHz and an EIRP of 50 dBm, as long as a higher B is allocated. For the massive bandwidths used by the commercial NTN constellations, some external error correction would need to be done in order to make an effective use of this bandwidth for improved positioning accuracy, since then the σ_{UERE} in Eq. (1) would mostly depend on σ_{NOISE}, where the higher B has a stronger impact.
- The smaller-sized constellation ‘CentiSpace-like’ manages to achieve decent GDOP values (though worse than GNSS) and presents a stronger robustness to interference than GNSS, making it viable for applications with moderate accuracy requirements. The constellation ‘Iridium-like’ is insufficient for positioning.

In addition, the takeaways for a hybrid LEO-GNSS system are presented next:

- The design of a medium-sized constellation such as ‘Marchionne 2’ or ‘Çelikbilek 1’ with an EIRP of 50 dBm bodes well in combination with currently existing GNSS constellations, given that the LEO satellites drive the positioning accuracy in challenging scenarios while GNSS drives it in close to nominal scenarios, but with the G_{HYB} improving substantially in all scenarios with respect to the gain of their standalone counterparts.
- The combination of a small-sized LEO constellation with GNSS proves to be only useful in the more taxing scenarios where a higher C/N_0 is needed, since the added contribution of the LEO satellites to the positioning accuracy is little in the close-to nominal scenarios.
- Following the two previous takeaways, and considering the scenarios at hand, the cost-effective ’sweet spot’ LEO constellation design to hybridise with GNSS (that is, the one that has a similar G_{HYB} with respect to the standalone GNSS constellations and LEO constellations in all scenarios) lies in the medium-sized constellations, such as ‘Marchionne 2’ or ‘Çelikbilek 1’. These constellations present the

best combination with GNSS, given that GNSS drives the performance in scenarios 'O0', 'O2' and 'O4', while LEO drives it in 'O1' and 'O3', but still with substantial gain in all scenarios from both LEO and GNSS constellations with respect to their standalone counterparts. The most cost-effective combination is 'Çelikbilek 1 + GPS + Galileo', while 'CentiSpace-like + BDS' presents the best results for a lower-cost LEO-GNSS combination.

- The combination of 2 medium-sized LEO constellations might perform worse than one single bigger constellation, even if the combination has a bigger amount of satellites and a better geometric optimisation given by multiple shells, as shown by the obtained values for 'Marchionne 2 + Çelikbilek 2' in Table 9, compared to the 'OneWeb-like' values in Table 5.

Conclusions

In conclusion, this work has presented the capabilities of LEO satellites in terms of positioning accuracy and interference robustness, and its gain in comparison to the GNSS solution, for receivers with no external error corrections operating in various representative rural and urban outdoor scenarios. This analysis has been carried out by assessing the positioning performance as a function of the transmission power, carrier frequency and the constellation design, for 480 different instances of time, for 400 users uniformly distributed within Europe, and for 12 standalone LEO or GNSS constellations, as well as for 12 hybrid constellations, simulating LEO, GNSS, and LEO-GNSS constellations.

From the analysis focused on the 12 standalone constellations, the medium-sized LEO constellations designed to optimise the geometric uniformity in the sky represent the best trade-off between performance and complexity. One example of such medium-sized LEO constellation reaching good trade-offs between the considered performance metrics is the constellation 'Çelikbilek 1', which showed the best solution among the considered cases. Moreover, we found that the minimum tested EIRP of 50 dBm suffices to achieve close-to nominal accuracy in the simulated scenarios, and the gains of having a stronger EIRP are scarce in outdoor scenarios, which shows that the LEO satellites' EIRP can indeed be decreased compared to the one used by GNSS systems and still keep the improvements brought by LEO satellites. With respect to the choice of carrier frequency, our studies in outdoor scenarios show that carrier frequencies up to 5 GHz can be safely used without any significant performance losses, given that a bigger B can be allocated at higher frequency bands. Hence, the best trade-off between cost and performance would be to use the 'Çelikbilek 1' constellation with an EIRP of 50 dBm and a carrier frequency of 5 GHz.

For hybridised constellations, we have found the combinations that deliver the best cost-effectiveness considering that GNSS is already deployed, by analysing their gain with respect to their standalone counterparts in all tested scenarios. In this regard, the more cost-effective solution would be a medium-sized LEO constellation combined with GNSS, where both systems contribute roughly equally to the positioning accuracy, such as 'Çelikbilek 1' + GPS + Galileo. The small-sized 'CentiSpace-like' combined with the BDS system also poses an excellent cost-effective solution. Nonetheless, the high positioning accuracy reached by some bigger LEO constellations cannot be matched by a combination of a medium-sized LEO constellation and GNSS, even when combined with all the available GNSS systems. Hence, very accurate PNT solutions may only be achieved with the deployment of bigger LEO constellations, even if their performance is not greatly enhanced by combining them with GNSS with respect to the standalone LEO version, and are thus not so cost-effective.

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Data availability
Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Competing interest
The authors declare that they have no competing interest.

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