

Assessment of the potential of LEO-PNT systems for improving positioning accuracy in urban environments

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Abstract: In recent years, there has been growing interest in the use of low Earth orbit (LEO) satellites for positioning, navigation, and timing (PNT) purposes. This article presents the results of simulations of two conceptual LEO-PNT constellations – S2-1 and S2-2 – based on parameters proposed by [Teng, et al. \(2023\)](#), which are an extension of the existing CentiSpace constellation. The aim of the study was to determine the impact of these constellations on positioning geometry accuracy (DOP coefficients) in open and obstructed horizon conditions, both in moderate (Poland, latitude = 51°) and low (Hong Kong, latitude = 22°) latitudes. The analysis was performed for different orbital inclination angles (31.5° and 79.1°) and based on GNSS data and simulated TLE files for LEO-PNT. The results showed that positioning based solely on LEO satellites is possible in open horizon conditions, while in urban environments the best results were achieved using hybrid GNSS+LEO constellations, which improved DOP factors by 3–14%. Constellations with higher orbital inclinations provided better coverage and accuracy in mid-latitude regions. Research confirms that the integration of LEO-PNT systems with GNSS can significantly improve the quality of positioning geometry, especially in difficult observation conditions, and that optimal orbit design and constellation density are key to achieving high positioning accuracy.

Keywords: GNSS, positioning, urban, LEO-PNT

1. Introduction

In recent years, with the growing interest in positioning, navigation, and timing using satellites in Low Earth Orbit (LEO), more and more research and simulations are being conducted to develop a LEO satellite system that will enable high-accuracy measurements independently, as well as support for current GNSS systems ([Prol, et al., 2024](#)). GNSS satellites are located at altitudes ranging from approximately 19,000 km (MEO) to as high as 36,000 km (GEO and IGSO). This causes their signals to become weaker as they travel the long distance to the receiver ([Prol, et al., 2022](#)). LEO satellites are located at an altitude of up to 2,000 km, which means they have higher speeds and better received signal power than GNSS satellites ([Teng, et al., 2023](#)). There are currently tens of thousands of satellites in LEO orbit, but only a small fraction of them are LEO-PNT (positioning, navigation, and timing) satellites, which are designed for positioning, navigation, and timing purposes. Most LEO satellites are designed to provide users with access



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to narrowband (e.g., Iridium) and broadband (e.g., Starlink) communications, IoT (Internet of Things) (e.g., Hiber), and Earth observation (e.g., ICEYE) (Morales Ferre, et al., 2020). The ESA FutureNAV LEO-PNT project is currently underway in Europe, with the aim of testing PNT technology from LEO orbit. As part of this program, two independent consortia have been working in parallel since 2024 to develop Pathfinder A and B satellite demonstrators. These small satellites are designed to test PNT services in the L and S bands, among others, including in the context of compatibility with 5G/6G networks and the IoT.

However, the first operational PNT systems from LEO orbit already exist worldwide. One example is Satelles which provides commercial PNT services via Iridium satellites. This system offers, among other things, time synchronization and navigation in environments with limited access to GNSS signals, such as inside buildings or environments subjected to spoofing or jamming. Other initiatives under development include the American Xona Space Systems and Trustpoint, the Chinese CentiSpace, as well as planned activities involving OneWeb and Geely (Geespace) (Le Priellec, et al., 2025). The rapid development of the space segment has led to a significant reduction in the costs associated with launching small satellites into orbit, their development, and maintenance. For example, the cost of launching a 6U CubeSat satellite (where 1U=10 cm $\times$ 10 cm $\times$ 10 cm) into orbit is approximately €300,000 (Prol, et al., 2022). Recent simulations of LEO-PNT satellite constellations are based on DOP coefficients or PPP positioning accuracy. The experiment conducted by Teng, et al. (2023) involved the use of two conceptual LEO-PNT constellations – S1 (close to polar and midlatitude orbits) and S2 (midlatitude and close to tropic orbits) – in conjunction with BDS-3 satellites. Both constellations were further divided into two sub-constellations shown in Table 1.

Table 1. Proposed parameters of the conceptual LEO-PNT constellations. Parameter symbols used in Table 1: P – number of orbital planes, S – number of satellites on the plane, F – relative phase parameter (0 – P-1), Δ_1 – longitude difference between the prograde orbital planes, I – inclination, Ω – right ascension of the ascending node, M_0 – mean anomaly, H – orbital altitude

Variables	S1		S2	
	Polar (S1-1)	Walker (S1-2)	Walker (S2-1)	Walker (S2-2)
P	9	6	6	10
S	12	12	9	12
F	–	2	4	8
Δ_1 (°)	21.2	–	–	–
I (°)	86.4	58.6	31.5	79.1
Ω (°)	0	10.9	0	12.1
M_0 (°)	0	4.4	0	64.2
H (km)	1300	900	1300	1000

The study reported geometric dilution of precision (GDOP) values of 0.92 for the combined BeiDou (BDS-3)+S1 configuration and 0.95 for the BDS-3+S2 configuration. Regarding 3D positioning performance, in relation to individual latitude zones (high, mid and low latitudes), the BDS-3 system alone exhibited an increase in error of approximately 11.6% when moving from high latitudes toward mid-latitudes, followed by a slight decrease of 2.27% from mid-latitudes to the equator. The decrease in error may be due to the fact that the BDS-3 constellation has satellites in geostationary orbit (GEO) with an inclination angle of 0°. When augmented with S1, positioning errors increased by 61.2% from high to mid-latitudes and by an additional 15.25% toward the equator. In contrast, the BDS-3+S2 combination showed a minor 0.47% reduction in

error from high to mid- latitudes, followed by a 50.0% increase from mid-latitudes to the equator. [Prol, et al. \(2024\)](#) proposed a constellation consisting of approximately 400 LEO satellites, at an altitude of 800 km, distributed across three orbital planes with inclination angles of 25°, 55°, and 85°. The GDOP coefficient was used as a measure of accuracy, which achieved very good values, below 2, worldwide with continuous visibility of at least 8 satellites. The quality of the constellation was also verified by simulating positioning using the PPP method. The observation collection time was 1 hour. For GPS satellites alone, the 3D PPP accuracy was 7.9 ± 4 cm (where mean is $\mu = 7.9$ cm and standard deviation is $\sigma = 4$ cm), for LEO satellites it was 6.3 ± 4 cm, and for GPS+LEO it was 3.7 ± 2 cm, which was an improvement of as much as 53% compared to the GPS constellation alone. [Alghisi, et al. \(2025a\)](#) analyzed the impact of integrating LEO satellites with existing GNSS systems to improve the performance of the PPP method in urban environments. The experiment used an Extended Kalman Filter (EKF), real observations from GNSS satellites, and a simulated environment with a 40-degree elevation mask. The evaluation metric was the time required to achieve a 2D error of ≤ 30 cm. The experiment showed that the hybrid GNSS + LEO system can reduce PPP convergence time by up to 80% in challenging urban conditions. The latest research ([Alghisi, et al., 2025b](#)) focused on analyzing the impact of integrating LEO satellites into the GNSS system on improving the accuracy and convergence time of the PPP method. The study compared the GNSS and GNSS+LEO constellations and used the PDOP index as a measure of geometry quality. Three scenarios were tested: open sky (5° elevation mask), built-up area (30°), narrow city streets (50°), and 10 sessions of varying lengths (2, 5, and 10 minutes) spread throughout the day were analyzed. The results of the study showed that for low elevation angles (5° and 30°), the PDOP improvement can be as high as over 93%, while for high elevation angles, the improvement ranges from about 2% (2-minute session) to 94% in a 10-minute session. The time required to achieve a PDOP of less than 1 also depends on the elevation angle and is lower for lower elevation angles.

There are also simulations conducted on satellites that are not used for LEO-PNT. The best of these is Starlink, which provides 100% coverage of the Earth and a GDOP coefficient below 2. The Kuiper constellation also achieved low GDOP values, but it does not provide full coverage. In the case of constellations used for IoT, Hiber provides good coverage of polar areas, while Myriota and Astrocast perform worse, also achieving high GDOP values. As for satellites designed for Earth observation, such as BlackSky or ICEYE, they may have low GDOP values locally, but they do not provide adequate coverage of the Earth ([Morales Ferre, et al., 2020](#)). Most current LEO satellites designed for telecommunications or Internet provision cannot be used for PNT, among other things because they do not meet the requirements for signal structure, clock accuracy, and geometry required for precise navigation ([Çelikkilek and Lohan, 2024](#)).

The lower quality transmitters or satellite clocks that LEO satellites are equipped with make determining the orbits of LEO satellites more difficult than is the case with GNSS satellites. Due to the large number of LEO satellites needed for precise positioning, it would be very expensive to use extremely accurate atomic clocks in each of these satellites ([Ge et al., 2021](#)). This is also due to the orbits of LEO satellites being much lower than those of MEO satellites (approx. 20,000 km for MEO and approx. 2,000 km for LEO). At lower orbital altitudes, there are stronger perturbations caused by higher atmospheric resistance and the stronger influence of the Earth's gravitational field ([Allahviridi-Zadeh, et al., 2021](#)). Due to the greater complexity of the forces acting on LEO satellites than on GNSS satellites, accurate determination of the LEO orbit requires the use of empirical force parameters to compensate for effects that are not fully described by the accepted force models ([Ge et al., 2021](#)). Additionally, low orbits of LEO satellites also mean that as many as 100 satellites are needed to globally cover the Earth's surface with LEO satellites, while in the case of MEO satellites, 10 times fewer satellites are needed ([Chobotov, 2002](#)).

In this paper, a simulation was carried out for the conceptual LEO-PNT constellations S2-1 Walker and S2-2 Walker, whose parameters were proposed by [Teng et al. \(2023\)](#). The choice of this particular constellation is related to: 1) it is extension to currently available and active CentiSpace constellation, 2) proposed constellation should provide significant increase of positioning quality in heavy urban environment. The study examined how these satellite constellations would perform in positioning under conditions with an unobstructed and an obstructed horizon. The analysis was conducted for constellations with low (31.5°) and high inclination angles (79.1°), using observation points in mid (51°) and low latitudes (22°). The measure of accuracy was the DOP coefficients.

2. Methodology

In our experiments we were testing whether in real urban conditions the geometry of GNSS solution, measured with DOP, will be significantly improved if receiver would observe GNSS and LEO-PNT satellites. Our case studies were based on the extension to currently working constellation CentiSpace proposed in [\(Teng, et al., 2023\)](#). File processing and all calculations were performed using scripts written in Python. Based on the information contained in Table 3, entitled “Hybrid constellation specific constellation configuration”, in article [\(Teng, et al., 2023\)](#) and in Table 1 in this paper, TLE (Two-Line Element) files were generated for two conceptual CentiSpace constellations – S2-1 Walker and S2-2 Walker.

TLE files have been generated for all satellites in both constellations for the period from March 31, 2025, at 12:00 p.m. to April 1, 2025, at 12:00 p.m., at 30-second intervals. Next, SP3 files provided by the CODE (Center of Orbit Determination in Europe) reference center (COD0MGXFIN) were obtained from the CDDIS service. These files contain the precise position of GNSS satellites during the period corresponding to the period for which TLE files were generated for LEO-PNT satellites. The position of GNSS satellites was calculated at 5-minute intervals. Therefore, using the Pandas library, linear interpolation of coordinates from the SP3 file to a 30-second interval was performed. In the next step, the satellite coordinates were transformed, starting with the conversion of Keplerian orbit parameters to the ECI (Earth-Centered Inertial) frame, followed by the transition from the ECI frame to the ECEF (Earth-Centered, Earth-Fixed) frame (for LEO-PNT satellites from TLE), and finally the transformation from ECEF to the local ENU (East, North, Up) frame (for TLE and SP3). Based on the coordinates in the ENU frame, the azimuth and elevation from the reference points to the satellites were calculated, and based on these, using elevation masks, DOP coefficients were calculated. The entire process described above is shown in the diagram in Figure 1.

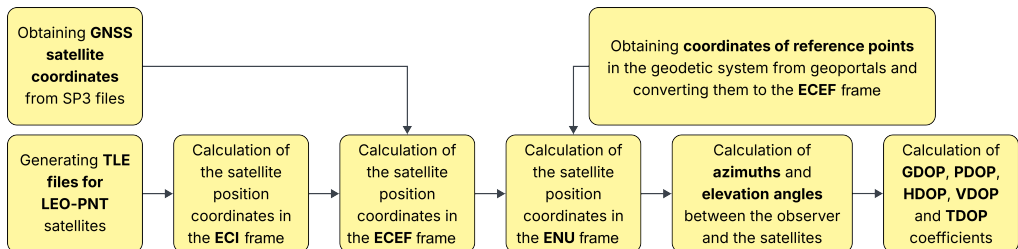


Fig. 1. Block diagram showing the steps taken to calculate the DOP coefficients, process starts with TLE for LEO-PNT satellites, goes through series of coordinates frame recalculation ending up with topocentric position for station and satellites. The process is concluded with DOP calculations

The SGP4 library (Rhodes, 2023) was used to calculate the ECI coordinates based on the Keplerian orbit parameters. The formulas to convert the ECI coordinates to the ECEF coordinates are described in Appendix 1.

3. Experiments setup

In order to test the impact of new constellation on positioning with standard MEO satellites and check potential for LEO only positioning in number of urban scenarios, following experiments were conducted:

1. Mid latitude (Poland, latitude = 51°): open horizon (IGS reference station WROC – Fig. 2), standard urban conditions (courtyard of UPWr building – Fig. 3), heavily obstructed (inner courtyard of Neony – Fig. 4);
2. Low latitude (Hong Kong, latitude = 22°): open horizon (IGS reference station HKSL – Fig. 5), standard urban conditions (down town Kowloon – Hong Kong 2 – Fig. 7), heavy urban conditions (Shau Kei high rise neighborhood – Hong Kong 1 – Fig. 6).

All figures are presented below.

All experiments were conducted for S2-1 (low inclination angle 31.5°) and S2-2 (high inclination angle 79.1°), with GNSS+S2-1 or GNSS+S2-2, as well as S2-1 and S2-2 only solution.

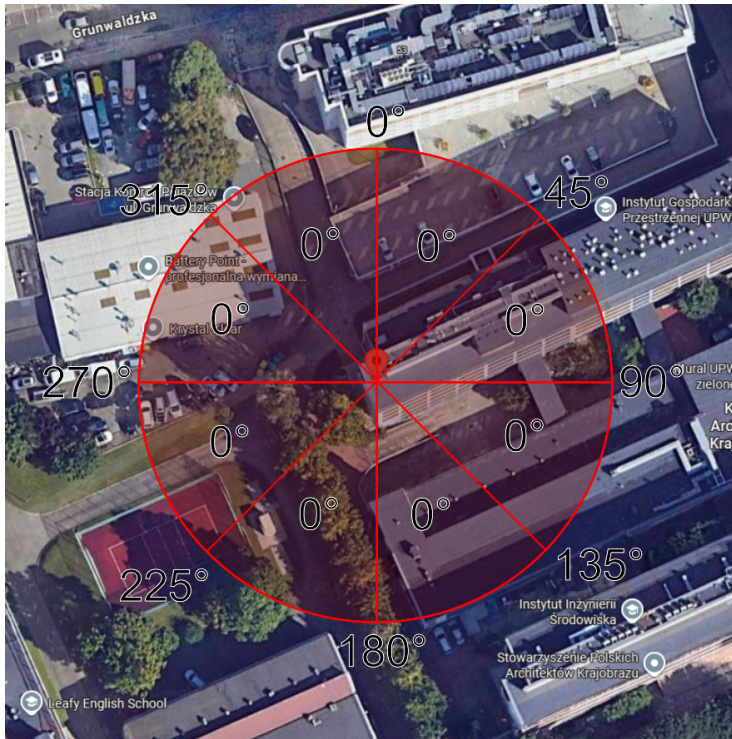


Fig. 2. Horizon obstruction for 45-degree azimuth intervals, for the WROC point

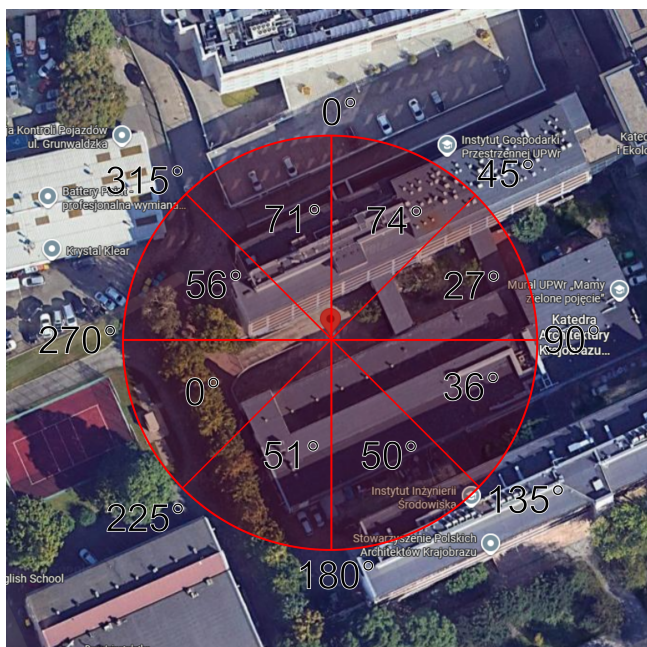


Fig. 3. Horizon obstruction for 45-degree azimuth intervals, for the UPWr point

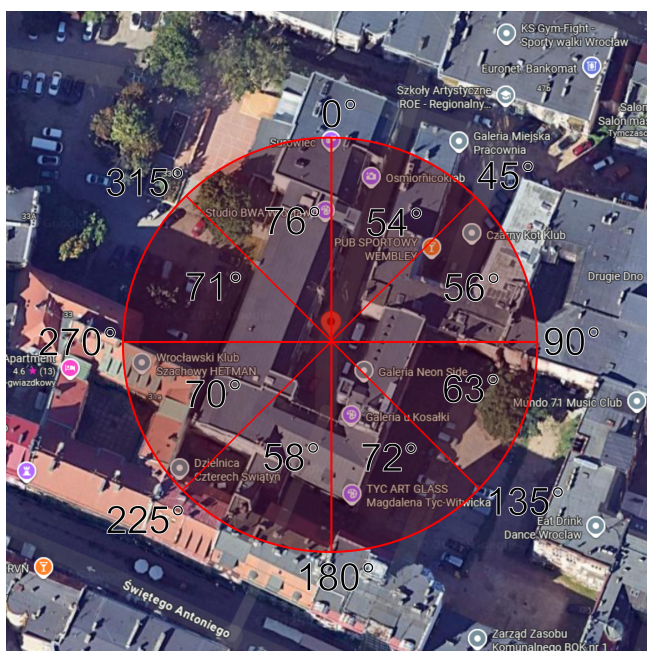


Fig. 4. Horizon obstruction for 45-degree azimuth intervals, for the Neonv point



Fig. 5. Horizon obstruction for 45-degree azimuth intervals, for the HKSL point

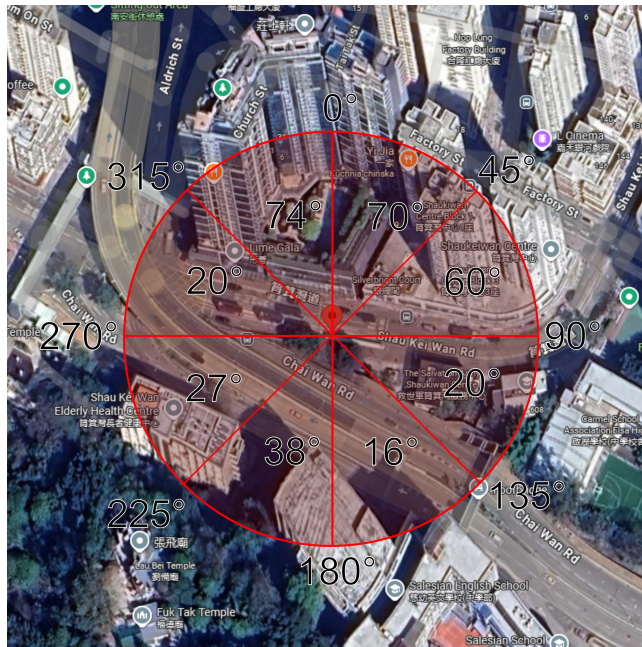


Fig. 6. Horizon obstruction for 45-degree azimuth intervals, for the Hong Kong 1 point

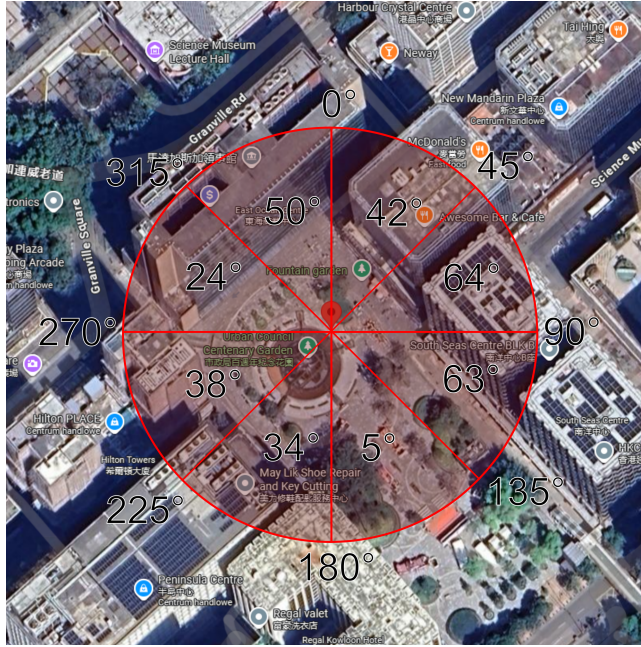


Fig. 7. Horizon obstruction for 45-degree azimuth intervals, for the Hong Kong 2 point

4. Data

Satellite positions were determined every 5 minutes over the course of one day. The SP3 files obtained cover days 90 and 91 of the year 2025, which corresponds to March 31 and April 1. The study also uses TLE files generated using a script written in Python. Each TLE file relates to a different CentiSpace satellite. The TLE file is divided into 30-second epochs, each containing three lines of information. The title line contains the name of the satellite. Line 1 contains information such as the satellite catalog number, the epoch for which the information was obtained, and the first and second derivatives of the mean motion. Line 2 contains Keplerian orbit parameters, including the inclination angle (i), right ascension (Ω) of the ascending node, eccentricity (e), argument of perigee (ω), mean anomaly (M_0), and mean motion (n). As shown in Table 1, in the case of the S2-1 constellation, there are 6 orbital planes, with 9 satellites in each plane. There are 54 satellites in total in the S2-1 constellation. The angular separation between satellites in a single orbit is 40° , which, for an orbit altitude of 1,300 km, gives an arc distance between satellites of approximately 5,350 km. The S2-2 constellation has 10 orbital planes with 12 satellites on each. In total, the S2-2 constellation has 120 satellites. The angular separation between satellites in the same orbit is 30° , while the arc distance for an orbit altitude of 1,000 km is approximately 3,860 km. The last data obtained for the study were the distances to buildings and their heights in order to simulate horizon obstruction. For reference points located in Poland, these data were obtained by measuring buildings in LOD1 standard on an online geoportal (https://dev.info-solutions.pl/dut_test/#/home). For points located in Hong Kong, horizon obstruction was calculated based on sky plots generated in GNSS Realistic Urban Multiagent Simulator (RUMS) software (Zhang, et al., 2021).

5. Results

This section is devoted to the analysis of DOP coefficients and the average number of visible satellites in each scenario. The results for the CentiSpace satellites are presented in Table 2.

Table 2. Median DOP values for both CentiSpace S2 constellations, relative to different observation points. The color scale from red to green indicates DOP values from highest to lowest

Reference	Constellation	CentiSpace satellites (mean)	GDOP	PDOP	VDOP	HDOP	TDOP
WROC	S2-1	2.74	19.93	19.76	19.57	2.98	2.67
WROC	S2-2	10.68	1.99	1.91	1.76	0.71	0.56
UPWr	S2-1	0.41	–	–	–	–	–
UPWr	S2-2	1.35	–	–	–	–	–
Neony	S2-1	0.00	–	–	–	–	–
Neony	S2-2	0.15	–	–	–	–	–
HKSL	S2-1	5.90	2.58	2.43	2.15	1.22	0.85
HKSL	S2-2	5.98	3.48	3.32	3.11	1.21	0.94
Hong Kong 1	S2-1	1.34	–	–	–	–	–
Hong Kong 1	S2-2	0.85	–	–	–	–	–
Hong Kong 2	S2-1	1.40	–	–	–	–	–
Hong Kong 2	S2-2	0.89	–	–	–	–	–

In the case of CentiSpace satellites, both constellations – S2-1 and S2-2 – had the minimum required number of 4 visible satellites only for the open horizon points – WROC and HKSL. For WROC points, for the S2-1 constellation, the average number of visible satellites was 2.74, and for S2-2 it was 10.68. The greater number of visible satellites in the S2-2 constellation may be due to the fact that the satellites in this constellation are in orbits with an inclination angle of 79.1° , while the inclination angle of the S2-1 constellation satellites is 31.5° . The WROC station is located at a latitude of approximately 51° . For the HKSL point, both for the S2-1 and S2-2 constellations, the average number of visible satellites is approximately 6. In the case of the WROC point, for the S2-1 constellation, the GDOP, PDOP, and VDOP coefficients are approximately 20. The HDOP and TDOP coefficients are 2.98 and 2.67, respectively. In the case of the S2-2 constellation, the GDOP, PDOP, and VDOP coefficients are much lower than for S2-1, at 1.99, 1.91, and 1.76, respectively. HDOP and TDOP are 0.71 and 0.56, respectively. The difference in the values of GDOP, PDOP, and VDOP coefficients is over 90%, and for HDOP and TDOP it is 76-79%. For the HKSL point, the GDOP, PDOP, and VDOP coefficients range from 2 to 2.5 for the S2-1 constellation and from 3 to 3.5 for the S2-2 constellation. The HDOP and TDOP coefficients are approximately 1 for both constellations. Table 3 shows the results for GNSS.

For GNSS, as seen in Table 3, for the WROC point, all DOP values are below 1, and the average number of visible satellites is above 47. For HKSL, the results are very similar, with differences in DOP coefficients in the order of hundredths. The average number of satellites for the HKSL point is above 51. For the UPWr, Hong Kong 1, and Hong Kong 2 points, the GDOP and PDOP values range from approximately 1.5 to approximately 2. The remaining values range from approximately 0.8 to 1.4 approximately. The average number of visible GNSS satellites is above 17 for the UPWr and Hong Kong 1 points and above 21 for the Hong Kong 2 point. The Neony

point, i.e. the point with the greatest horizon coverage, is characterized by high DOP coefficients. GDOP is above 30, PDOP, VDOP, and TDOP are above 20, and HDOP is 8. The average number of visible satellites is only 4.69. Table 4 shows the results for GNSS+CentiSpace.

Table 3. Median DOP values for GNSS constellation, relative to different observation points. The color scale from red to green indicates DOP values from highest to lowest

Reference	Constellation	GNSS satellites (mean)	GDOP	PDOP	VDOP	HDOP	TDOP
WROC	GNSS	47.11	0.68	0.62	0.51	0.36	0.28
UPWr	GNSS	17.10	1.87	1.67	1.13	1.19	0.83
Neony	GNSS	4.69	38.66	28.50	26.57	8.00	25.92
HKSL	GNSS	51.26	0.66	0.60	0.48	0.35	0.28
Hong Kong 1	GNSS	17.62	2.08	1.74	1.37	1.01	1.12
Hong Kong 2	GNSS	21.74	1.75	1.47	1.19	0.84	0.94

Table 4. Median DOP values for both CentiSpace S2 constellations together with GNSS constellation, relative to different observation points. The color scale from red to green indicates DOP values from highest to lowest

Reference	Constellation	GNSS satellites (mean)	CentiSpace satellites (mean)	GDOP	PDOP	VDOP	HDOP	TDOP
WROC	GNSS+S2-1	47.11	2.74	0.64	0.59	0.48	0.34	0.25
WROC	GNSS+S2-2		10.68	0.61	0.56	0.46	0.32	0.24
UPWr	GNSS+S2-1	17.10	0.41	1.79	1.61	1.07	1.18	0.77
UPWr	GNSS+S2-2		1.35	1.73	1.56	1.04	1.14	0.75
Neony	GNSS+S2-1	4.69	0.00	38.66	28.50	26.57	8.00	25.92
Neony	GNSS+S2-2		0.15	36.43	26.73	25.22	7.22	24.62
HKSL	GNSS+S2-1	51.26	5.90	0.62	0.56	0.45	0.33	0.26
HKSL	GNSS+S2-2		5.98	0.61	0.55	0.45	0.33	0.25
Hong Kong 1	GNSS+S2-1	17.62	1.34	1.92	1.62	1.28	0.94	1.03
Hong Kong 1	GNSS+S2-2		0.85	1.97	1.65	1.31	0.96	1.07
Hong Kong 2	GNSS+S2-1	21.74	1.40	1.67	1.41	1.14	0.80	0.89
Hong Kong 2	GNSS+S2-2		0.89	1.69	1.43	1.15	0.82	0.91

In the case of the GNSS+CentiSpace combination, for the WROC point, for the S2-1 constellation, a reduction in DOP values of approximately 5–8% can be observed compared to the use of the GNSS constellation alone. For the S2-2 constellation, the improvement in DOP values is 9–14%. Again, for the HKSL point, the differences compared to the WROC point are minimal, so the percentage results do not differ noticeably. For the Neony point, in the case of the S2-1 constellation, there is no improvement in DOP values due to the insufficient number of visible CentiSpace satellites. For the S2-2 constellation, the improvement is 5–10%. For Hong Kong 1 and the S2-1 constellation, the DOP improvement is 7–8%, and for the S2-2 constellation, it is 4–5%. For Hong Kong 2 and the S2-1 constellation, the DOP improvement is also 4–5%, and for the S2-2 constellation, it is approximately 3%.

6. Discussion

Based on the above research, it can be concluded that LEO only positioning is possible in open horizon (Table 2), but the performance depends on the alignment between locations of station and satellite inclination, for S2-1 in WROC station quality is rather poor (GDOP over 19), whereas for S2-2 in WROC station quality is much better with GDOP (almost 2), similar to obstructed case (UPWr) with MEO satellites only (Table 3). However, for the HKSL station, good results can be observed for both the S2-1 (GDOP near 2) and S2-2 constellations (GDOP near 3). This may be due to the fact that the HKSL station is located below (latitude 22°) the inclination angles of both constellations (inclination angle 31.5° for S2-1 and 79.1° for S2-2). Any other point was not able to observe sufficient number of LEO satellites (at least 4). Prol, et al. (2024) reported that for 400 satellites constellation on 3 different inclination orbits, GDOP would be lower than 2 globally, in our study such quality is also visible in case of open horizon station, but with lower number of satellites (S2-1 54 and S2-2 120). However, this is latitude dependent and our study has limited geographic scope.

Obviously, the more obstructed horizon the higher DOP parameters (Table 3 and Table 4), even in very difficult obstructed location (Neony) there are at least 4 satellites visible, it is worth to note that only S2-2 constellation has positive impact on the geometry of positioning solution in such a harsh conditions (improvement by up to 10%). Alghisi, et al. (2025a) conducted an experiment with GNSS and LEO PPP positioning, for 50° cut off angle reported improvement in PDOP was from 24 to 1.4, in our case the improvement is much smaller 28.5 to 26.7, which is likely a result of two factors: 1) LEO constellation has 8 orbital planes in 89° inclination, and 11 orbital planes on 55° inclination all together 263 satellites, 2) in case our horizon obstructions range from 54° to 76° . It demonstrates the importance of number of satellites and orbital planes to conduct observations in urban canyons as well as calls for more realistic simulations of LEO-PNT performance.

We did not observe impact on the DOP geometry larger than 14% (WROC S2-2 – Table 4), unlike reported by Alghisi, et al. (2025a) demonstrate many folds of difference (1 to 0.01), and closer to results reported by Teng, et al. (2023) who is demonstrating impact on the order of 10 to 50% depending on the location. Similarly, non PNT LEO constellations (such as Starlink, ICEYE, Astrocast) reported by Morales Ferre, et al. (2020), have GDOP varying from 0.5 to 1000000 and mean values ranging from 0.5 to 34, which is similar to what we achieved.

7. Conclusion

Impact of LEO-PNT was reported on the level of 3–14% on the DOP modulated by latitude, inclination angle and number of satellites. Realistic obstructions based on modelling of buildings results in limiting access to LEO satellites. This confirms that hybrid GNSS+LEO constellations can enhance geometry and positioning accuracy, especially under open-sky conditions. The study revealed that horizon obstruction caused by urban environments significantly limits the number of visible LEO satellites, reducing their standalone usefulness. Open-horizon locations allow for LEO- only positioning, while urban canyons or heavily obstructed areas benefit more from hybrid constellations. Performance varied between constellations S2-1 (31.5° inclination) and S2-2 (79.1° inclination). Results showed that higher-inclination constellations offer broader coverage and better DOP values in mid-latitude regions. This highlights the importance of orbit design optimization to balance global coverage and urban performance. The obtained improvements are consistent with earlier findings (Teng, et al., 2023; Alghisi, et al., 2025a), though smaller in magnitude due to a limited number of satellites and realistic obstruction modeling. This underlines the importance of constellation density and geometry in achieving high-accuracy LEO-PNT performance.

To extend this research, it would be valuable to:

1. Further research should include areas with diverse geographical conditions – from polar regions, through mid-latitudes, to equatorial regions. This will allow for a comprehensive assessment of the impact of latitude on satellite geometry quality (DOP), signal availability, and positioning stability.
2. The next step should be to conduct advanced simulations covering constellations with a larger number of satellites, various orbital heights, and different inclination angles. Such an analysis will allow the optimal orbit configuration to be determined in order to achieve a compromise between global coverage and efficiency in urban environments.
3. In order to increase the reliability of the results obtained, it is necessary to compare the simulation results with actual measurements from operating LEO constellations, e.g., CentiSpace S1 or similar demonstration systems.
4. An important direction for further work is the integration of LEO-PNT and GNSS constellations with inertial navigation systems (IMU) and additional sensors, such as odometers. Simulations and experimental tests of hybrid systems will allow us to assess the possibilities of compensating for signal loss and determine the optimal way to integrate data from different sources in order to obtain a stable and precise navigation solution.

Author contributions

Conceptualization: M.J.W., W.R.; methodology: M.J.W., W.R.; formal analysis and investigation: M.J.W.; writing – original draft preparation: M.J.W.; writing – review and editing: M.J.W., W.R.; supervision: W.R.

Data availability statement

The data used in this work are available for download from the Crustal Dynamics Data Information System website (<https://cddis.gsfc.nasa.gov/archive/gnss/products/>). The module used to calculate the DOP coefficients is available as part of the script <https://github.com/makuchs/LEO-satellites-simulation-for-GNSS-tomography> (mode: constellation). The 3D building models were obtained from <https://digitwins4peds.eu> project.

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1. Appendix

Julian Date Calculation

For a given UTC date and time:

$$JD = [365.25 \cdot (Y' + 4716)] + [30.6001 \cdot (M' + 1)] + D - 1524.5 + B, \quad (1)$$

where:

$$\begin{aligned} Y' &= Y - 1 \quad \text{if } M \leq 2, \text{ otherwise } Y' = Y, \\ M' &= M + 12 \quad \text{if } M \leq 2, \text{ otherwise } M' = M, \\ D &= d + h/24 + m/1440 + s/86400 - \text{day with fractional part from hours, minutes, and seconds,} \\ A &= Y'/100, \\ B &= 2 - A + A/4 - \text{Gregorian calendar correction,} \\ Y, M, d, h, m, s &= \text{year, month, day, hour, minute, second (in UTC).} \end{aligned}$$

Greenwich Mean Sidereal Time (GMST)

First, compute the number of Julian centuries since J2000.0:

$$T = \frac{JD - 2451545.0}{36525}. \quad (2)$$

GMST in degrees:

$$\begin{aligned} \text{GMST}_{\text{deg}} = & 280.46061837 + 360.98564736629 \cdot (\text{JD} - 2451545.0) \\ & + 0.000387933 \cdot T^2 - \frac{T^3}{38710000}. \end{aligned} \quad (3)$$

Normalize to the range 0–360:

$$\text{GMST}_{\text{deg}} = \text{GMST}_{\text{deg}} \text{ modulo } 360. \quad (4)$$

Convert to radians:

$$\theta = \frac{\pi}{180} \cdot \text{GMST}_{\text{deg}}, \quad (5)$$

where θ is the Earth rotation angle at the given UTC moment.

Rotation Matrix from ECI to ECEF

Rotation about the Z-axis by angle θ :

$$R = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (6)$$

Position Transformation

$$r_{\text{ECEF}} = R \cdot r_{\text{ECI}} \quad (7)$$

where:

$r_{\text{ECI}} = [x, y, z]^T$ – position vector in ECI frame,
 $r_{\text{ECEF}} = [x', y', z']^T$ – position vector in ECEF frame.

Velocity Correction for Earth Rotation

Earth angular velocity vector:

$$\vec{\omega} = \begin{bmatrix} 0 \\ 0 \\ \omega_{\text{Earth}} \end{bmatrix}, \quad (8)$$

where $\omega_{\text{Earth}} = 7.2921150 \cdot 10^{-5}$ rad/s.

Velocity due to Earth's rotation:

$$v_{\text{rot}} = \vec{\omega} \cdot r_{\text{ECEF}} \quad (9)$$

Velocity Transformation

$$v_{ECEF} = R \cdot v_{ECI} + v_{rot}, \quad (10)$$

where:

$v_{ECI} = [v_x, v_y, v_z]^T$ – velocity in ECI frame,
 v_{ECEF} – velocity in ECEF frame.

The observer's position, i.e. the coordinates of the reference points, was also transformed to the ECEF system, but from the geodetic system.

Constant values used:

$a = 6378137.0$ m – equatorial radius,

$f = 1/298.257223563$ – Earth's flattening,

$e^2 = f/(2 - f)$ – first eccentricity squared.

Geodetic to ECEF

Given geodetic coordinates: latitude ϕ (degrees), longitude λ (degrees), and ellipsoidal height h (meters).

Convert angles to radians first:

$$\varphi_{rad} = \varphi \cdot \frac{\pi}{180}, \quad \lambda_{rad} = \lambda \cdot \frac{\pi}{180}. \quad (11)$$

Compute the prime vertical radius of curvature N :

$$N(\varphi) = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}}. \quad (12)$$

Then the ECEF coordinates are:

$$x = (N(\varphi) + h) \cos \varphi \cos \lambda, \quad (13)$$

$$y = (N(\varphi) + h) \cos \varphi \sin \lambda, \quad (14)$$

$$z = (N(\varphi)(1 - e^2) + h) \sin \varphi. \quad (15)$$

This returns $r_{ECEF} = [x, y, z]^T$.

Then the satellite coordinates were calculated in the local ENU system, related to the observer's position.

Local ENU coordinates

Given a target ECEF position r_{ECEF} and the observer position r_{obs} , form the displacement vector from observer to target:

$$\Delta_r = r_{ECEF} - r_{obs}, \quad (16)$$

where r_{obs} is observer position in ECEF coordinates transformed from geodetic coordinates $(\varphi_o, \lambda_o, h_o)$.

The ENU coordinates are obtained by rotating Δ_r into the local tangent frame at the observer. Using φ_o, λ_o in radians, the rotation matrix R_{ENU} is

$$R_{\text{ENU}} = \begin{bmatrix} -\sin \lambda_o & \cos \lambda_o & 0 \\ -\sin \varphi_o \cos \lambda_o & -\sin \varphi_o \sin \lambda_o & \cos \varphi_o \\ \cos \varphi_o \cos \lambda_o & \cos \varphi_o \sin \lambda_o & \sin \varphi_o \end{bmatrix}. \quad (17)$$

Then

$$\begin{bmatrix} E \\ N \\ U \end{bmatrix} = R_{\text{ENU}} \Delta_r, \quad (18)$$

where E points east, N points north, U points up (away from the ellipsoid normal).

Given the ENU coordinates, the azimuth and elevation angle between the observer and each satellite were calculated.

$$\text{azimuth} = \arctan\left(\frac{E}{N}\right) \text{ modulo } 360. \quad (19)$$

Azimuth defined as the angle measured clockwise from North toward East.

$$\text{elevation} = \arcsin\left(\frac{U}{\sqrt{E^2 + N^2 + U^2}}\right). \quad (20)$$

Elevation angle defined as the angle above the local horizon.

Finally, having calculated the ENU coordinates and the azimuths and elevation angles between the observer and the satellites, the DOP coefficients were calculated.

Geometry Matrix

For each satellite at ENU position, the distance from the observer was calculated:

$$r = \sqrt{E^2 + N^2 + U^2}. \quad (21)$$

Normalized the vector and added an additional column for the receiver clock bias:

$$h_i = \left[\frac{E}{r}, \frac{N}{r}, \frac{U}{r}, 1 \right]. \quad (22)$$

The geometry matrix H has dimensions $m \times 4$, where m is the number of satellites.

Covariance Matrix

$$Q = (H^T H)^{-1}. \quad (23)$$

This is the covariance matrix of the least-squares position estimate (up to a scale factor related to measurement noise).

DOP values

DOP values are derived from the diagonal elements of Q . The formulas used to calculate the DOP coefficients are found in (Kaplan and Hegarty, 2017) and are marked with numbers 11.16, 11.22, 11.23, 11.24, 11.25.