Yang et al. Satellite Navigation (2024) 5:11
https://doi.org/10.1186/s43020-024-00133-w

Satellite Navigation
https://satellite-navigation.springeropen.com/

ORIGINAL ARTICLE

Open Access

Demand and key technology for a LEO constellation as augmentation of satellite navigation systems

Yuanxi Yang[1,2*], Yue Mao[1,2], Xia Ren[1,2], Xiaolin Jia[1,2] and Bijiao Sun[1,2]

Abstract
A Low Earth Orbit (LEO) constellation augmenting satellite navigation is important in the future development of Global Navigation Satellite System (GNSS). GNSS augmented by LEO constellations can improve not only the accuracy of Positioning, Navigation, and Timing (PNT), but also the consistency and reliability of secure PNT system. This paper mainly analyzes the diverse demands of different PNT users for LEO augmented GNSS, including the precision demand in real-time, the availability demand in special areas, the navigation signal enhancement demand in complex electromagnetic environments, and the integrity demand with high security. Correspondingly, the possible contributions of LEO constellations to PNT performance are analyzed from multiple aspects. A particular attention is paid to the special PNT user requirements that cannot be fulfilled with existing GNSS, such as the PNT service demand in the polar regions and the onboard GNSS orbit determination demand of some LEO satellites. The key technologies to be considered in the constellation design, function realization, and payload development of the LEO-augmented navigation system are summarized.

Keywords Low earth orbit navigation constellation, Accuracy augmentation, Orbit determination, Integrity

Introduction

Low Earth Orbit (LEO) constellations have been widely used in many fields such as satellite-based internet, satellite communication, and remote sensing and shown a great potential. For the new generation of satellite navigation system, a LEO constellation augmented system will be a new development area.

The global Positioning, Navigation, and Timing (PNT) satellite systems provide important and fundamental supports for the construction of the information-based and intelligent society. In addition to free global PNT services, Chinese BeiDou Navigation Satellite System (NSS) also provides free global search and rescue service, satellite-based augmentation service for aviation safety, regional precise point positioning service, regional short message communication service, and global short message communication service for authorized users (Yang et al., 2020). However, the navigation signals of the Geostationary Orbit (GEO), Inclined Geosynchronous Orbit (IGSO), and Medium Earth Orbit (MEO) satellites are easy to be interfered due to the low received signal power (Yang & Xu, 2016a; Yang, 2019). The PNT service performance is relatively poor in the polar regions as the inclination angles of all MEO and IGSO satellites are 55° (Yang & Xu, 2016b). In other applications, like the inversion of ionosphere and other atmospheric elements, the accurate results can hardly be obtained due to the limited number of visible satellites in the zenith direction.

To improve the global performance of GNSS, a LEOs-augmented navigation system is a reasonable choice and

*Correspondence:
Yuanxi Yang
yuanxi_yang@163.com
[1] Xi'an Research Institute of Surveying and Mapping, Xi'an 710054, Shaanxi, China
[2] State National Key Laboratory of Geo-Information Engineering, Xi'an 710054, Shaanxi, China

an efficient way. Iridium NEXT of the United States can provide PNT service independently though the service ability is not that good with a positioning accuracy of 20–50 m and a timing accuracy of 200 ns (Joerger et al., 2010; Lu et al., 2023). Also, it can provide PNT service for indoor and valley users as the backup and enhancement of GPS (Joerger et al., 2010). Xona Space System in the United States started the "PULSAR" project by designing and experimenting the next generation of small LEO satelites (weighted less than 1000 kg) with the accurate PNT service, which will deliver the accuracy of 10 times better and the anti-interference ability of 100 times better than standard GNSS (Jason, 2023). The technical team of Europe Union's Galileo system is also dedicated to improving the system ability and promoting the Kepler system development a constellation consisting of 6 LEO and 24 MEO satellites with Inter-Satellite Links (ISLs) for ranging between the MEOs and LEOs to improve the Orbit Determination (OD) precision of MEOs, thereby improving the PNT performance (Giorgi et al., 2019; Glaser et al., 2020).

Chinese navigation experts and companies conducted extensive studies on LEO augmentation navigation constellations as well. Some scholars analyzed the contribution of different LEO augmentation navigation systems to the improvement of navigation and positioning accuracy, and many companies are developing or planning to develop commercial constellations (Gao et al., 2021; Jiang et al., 2021; Zhang & Ma, 2019). The Luojia-1 scientific experimental satellite launched in June 2018 can perform both the remote sensing and navigation augmentation function. Subsequently, the satellites that can be used for navigation augmentation, such as "Hongyan", "Hongyun", "Tianxiang-1" were launched. Some dedicated LEO satellite constellations have been designed, in which some "Centispace" satellites had been launched (Meng et al., 2022). The initial analysis shows that the pseudorange accuracies of Luojia-1 H1 and H2 augmentation signals are 0.7 m and 0.8 m, and the carrier phase accuracies are 2.8 mm and 2.6 mm, respectively. However, since the frequency ranges of H1 and H2 signals are different from all existing GNSS signals, special receiving antennas and receivers are required for signal acquisition (Wang et al., 2018). Up to now, China has more than 10 LEO augmentation navigation satellites in orbit, providing precious data and experience for experiment and verification.

A reasonable and optimized constellation design is a prerequisite for a LEO augmentation navigation system. The constellation configuration at different altitudes (i.e. 500 km, 1000 km, 1500 km, and 2000 km) has been discussed to reduce the Geometry Dilution of Precision (GDOP) of global ground users to below 5 (Zhang et al., 2020). The DOP stabilities in different conditions of the time synchronization and non-synchronization between the LEO and BDS constellations are analyzed, and the result shows that the GDOP and Time Dilution of Precision (TDOP) values of ground, sea surface, and aviation users are improved obviously when the LEO time and BDS time are synchronized.

The signal design and ephemeris broadcasting are the foundation for realizing the LEO augmented navigation. It was pointed out that the conventional broadcast ephemeris with 16 parameters cannot fulfill the accuracy requirement of LEO satellites, and the singular point problem may occur especially for those with small eccentricity and small/large inclination angle (Meng et al., 2021). It was proposed that six third order harmonic terms could be added to the 16-parameter ephemeris (22 ephemeris parameters in total) to improve the accuracy and stability of ephemeris fitting and solve the singular point problem (Meng et al., 2021).

The methods of OD for LEO satellites are more flexible, and many research results have been achieved. The orbits of LEO augmentation satellites can be determined with the satellite-ground link, ISLs, and on-board GNSS measurements. The simulation experiment results show that the OD precision at centimeter level can be achieved with the optimized topology of inter satellite links (Ge et al., 2018; Li et al., 2019c). Some scholars compared the OD results of LEO satellites using different ground tracking networks with and without ISL observations, indicating that the orbit precisions determined by ground tracking networks at middle and low attitudes are better owing to the better observation geometry configuration. However, the geometry configuration requirement can be relaxed with the help of ISL observations (He et al., 2022). The joint OD of LEO and GNSS satellites with the ground tracking observations can improve the OD precision of both satellites (Geng et al., 2007; Zhao et al., 2017).

Another contribution of LEO constellation to the existing GNSS constellation is the Precise Point Positioning (PPP). Chinese scholars have conducted fruitful studies in this field and proved that the combination of LEO and existing GNSS constellations will significantly improve the accuracy of PPP and convergence time (Yang et al., 2022; Zhang & Ma, 2019; Li et al., 2019b; Hong et al., 2023).

This paper analyzes the demands of different users in the construction of the LEO augmented constellations. A particular attention is paid to the special user requirements for LEO augmentation navigation constellation that cannot be fulfilled with the existing GNSS.

Therefore, the availability of different LEO constellation configurations for different users is analyzed, and the potential key technologies for the construction of LEO augmentation systems are summarized.

Demands for LEO augmentation navigation satellites

(1) **GNSS precise positioning augmentation demand for LEO augmentation navigation satellites** The existing real-time positioning accuracy of GNSS is usually at the meter or decimeter level, fulfilling the requirements for most users. However, the positioning accauracy at centimeter or millimeter level and the timing accuracy at nanosecond level are also in high demand in the fields such as crustal deformation monitoring, real-time geological hazard monitoring and early warning, intelligent autonomous control, and sailing of unmanned vehicles (e.g. high precision time synchronization and positioning control of unmanned aerial vehicles, farmland information management and agricultural machinery operation of precision agriculture, safe operation and control of high speed rails, and automatic driving of automobiles). The application of LEO augmentation constellations will not only enable precise positioning at centimeter-level, navigation at decimeter-level, and timing at nanosecond level, but also improve the reliability of PNT services.

(2) **Availability demand for LEO navigation satellites in the polar regions The** existing GNSSs can have wide coverage with good geometry at low latitudes, but poor coverage at high latitudes, especially in the polar regions. Although a single navigation constellation, such as GPS and BDS, can cover the polar regions, the number of visible satellites is relatively small. In addition, the satellite elevation angle is usually low. For example, the largest elevation angle of BDS satellites is 55.12° for the polar users. For PNT users, it will lead to a poorer accuracy and even discontinuous service if only BDS constellation is applied, especially when a certain BDS satellite is in an unhealthy state.

(3) **Autonomous OD demand of other LEO constellations** LEO remote sensing satellites, LEO communication satellite, and other LEO sensing satellites usually employ on-board GNSS receivers to implement real-time kinematic OD to determine their own orbits with GNSS pesudorange measurements and broadcast ephemeris. However, it is difficult for one single GNSS constellation to satisfy the real-time and continuous OD requirement of LEO satellites, especially those in polar obits, as the visibility of a single GNSS system is usually not good enough. In actual LEO engineering applications, it happens sometimes that kinematic OD cannot be implemented due to the number of visible satellites is less than 4.

Assuming that the altitudes of the polar LEO satellite are 500 km and 1000 km, the visibilities of BDS-3 constellation in the polar regions are analyzed. To receive observations as many as possible and to achieve better observation geometry, we set the observation elevation cutoff angle to be 1°. The visibility results are depicted in Fig. 1a and b, respectively, and the statistical results are shown in Table 1.

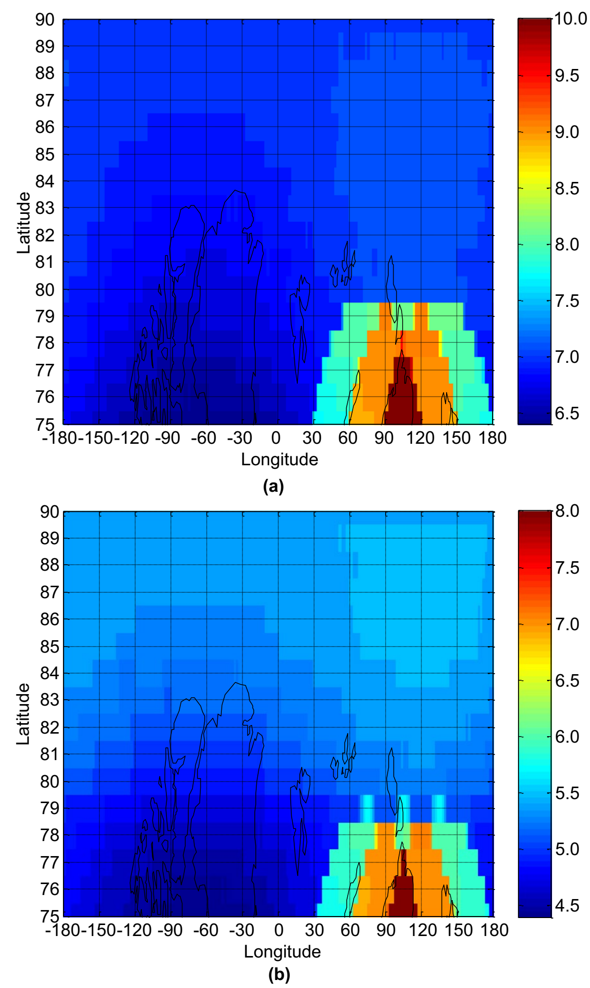

Fig. 1 **a** The average number of visible BDS satellites in the North Pole for LEO satellites at altitude of 500 km. **b** The average number of visible BDS satellites in the north pole for LEO satellites at altitude of 1000 km

Table 1 The visibility of BDS-3 in the polar region for LEO polar orbit satellites

Orbit altitude of the user	Elevation cutoff angle	North pole		
		AVE	MAX	MIN
500 km	1°	7.10	12	4
1000 km	1°	5.30	10	2

As shown in Fig. 1a, b and Table 1, the BDS-3 has service weakness when the user LEO satellites pass through the polar region. Only 4 and 2 BDS-3 satellites are visible under the most unfavorable conditions, which is unable to perform kinematic OD and will lead to the discontinuous OD result.

Thus, the LEO navigation constellation should consider the requirement of other LEO satellites which need to employ on-board GNSS kinematic OD to complement and augment the service of GNSS. For the on-board OD of the polar LEO satellites, it requires that the LEO augmentation navigation constellation has not only a higher orbit, but also a larger inclination angle to have a better observation configuration in high altitude regions.

(4) **Service demand for LEO satellite navigation constellation in complex electromagnetic environments** High-performance PNT services in complex electromagnetic environments require the satellite based PNT service with enhanced anti-interference and anti-spoofing ability. Thus, the enhancement of satellite signals is highly demanded. The landing power of B1, B2, and B3 signals of BDS is usually between − 152 dB and − 158 dB, 20 dB lower than the thermal noise of receivers (Liu and Lian, 2016). Therefore, both intentional and unintentional interference signals may lead to the disability of BDS PNT service. With a strong electromagnetic confrontation, it is more difficult for the normal service mode to work. For a lower orbit altitude, the landing power of LEO satellites will be significantly increased even if the signals are transmitted with the same power as BDS. However, with a high-intensity electromagnetic confrontation, signal power enhancement of lower than 20 dB can barely compensate the thermal noise of receivers, not to mention resisting the interference. Besides, the satellites having both communication and navigation functions may be interfered as well, as the navigation signal with stronger power may interfere the communication signal.

(5) **Ubiquitous integrity monitoring demand for the LEO navigation satellite** The term "ubiquitous integrity" here refers to the satellite PNT integrity and autonomous integrity of a wide range of needs, including secure PNT service in the fields like aviation, high speed railway, electric power, unmanned driving, and autonomous flight of drones. In most cases, only aviation sailing integrity is focused. Factually, the fields like manned spacecraft and high -speed rail operation need integrity information support as well. The integrity provided by a single GNSS system is not enough to satisfy all kinds of users' integrity requirements.

The possible contribution of LEO augmentation navigation constellation

(1) A LEO augmentation navigation constellation usually consists of small satellites with light weight and low cost of satellite manufacturing and launching.

(2) LEO satellites have lower orbit altitude, less loss in signal-in-space transmitting, and stronger signal power than those at middle or high altitude (e.g. the landing power of Iridum satellite at an altitude of 780 km is 30 dB stronger than that of GPS), and thus have stronger penetrating and anti-interference capabilities, enabling a better availability in the strong confrontation environment and non-exposed space (Zhang and Ma, 2019; ENGE et al., 2012).

(3) The large amount of LEO satellites can provide PNT service with MEO and High Earth Orbit (HEO) navigation satellites together, thus significantly increasing the number of visible satellites, optimizing the observation geometry, and improving the service accuracy.

(4) A reasonably designed LEO constellation can optimize the geometric strength of PNT service for the users in the polar regions, improve the PNT service accuracy, and offset the disadvantages of GNSS satellites. If the LEO constellation appropriately increases the orbit altitude and orbit inclination angle, then the accuracy of the autonomous orbit determination of other LEO satellites using on-board GNSS can be increased as well.

As an example, a hybrid LEO augmentation constellation (shown in Fig. 2) is designed as follows. Walker 60/6/2 with the altitude of 1175 km and the inclination angle of 86.5° (close to the polar orbit); another Walker 108/12/6 with the altitude of 1150 km and the inclination angle of 50°. The DOP value and the visibility of this LEO and the BDS-3 constellations in the polar regions (latitude higher than 70°) are analyzed respectively, and the results are given in Tables 2 and 3.For the users in the

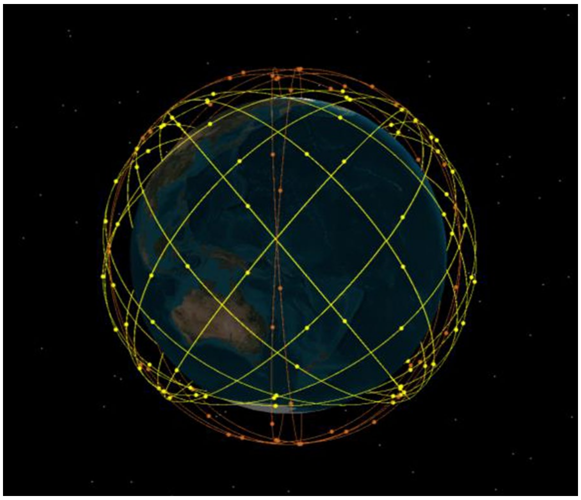

Fig. 2 The hybrid LEO augmentation constellation with Walker 60/6/2 and Walker 108/12/6

polar regions, LEO augmentation constellation can provide PNT service independently, with the visible satellite number larger than 7, the average DOP of 1.43, and the maximum DOP of 3.0. The service ability is comparable to that of BDS-3, or even slightly better. Assuming that the user range accuracy of LEO satellites is 1 m, the independent positioning accuracy with LEO-only is better than 3 m. If the BDS-3 and LEOs serve together, then at least 15 satellites can be observed, with the maximum PDOP value of 1.84, providing better visibility and observation geometry.

(5) LEO satellites have a more significant Doppler effect for ground users as they move relatively faster than MEO satellites, which can improve the velocity determination accuracy. Similarly, the functional correlation of the observations between epochs can be reduced, since the observation configuration of LEO constellation varies faster; as a result, the difficulty of stochastic model is reduced in PNT data processing.

(6) The combined orbit determination of LEO and GNSS constellation can improve both orbit determination precision, and then the PNT service ability (Zhao et al., 2017).

(7) The LEOs could be the augmentation of PPP if their correction parameters of the precise orbit and the satellite clock offsets are broadcast. The LEOs move faster than GNSSs with respect to the users providing better and rapid change in observation geometry for PPP. The augmentation performance has been analyzed with different simulated LEO constellations and positive results are achieved in PPP with both float resolution and fixed resolution (Zhang & Ma 2019; Ge et al., 2018; Yang et al., 2023; Li et al., 2019a). The convergence time of PPP with float resolution by using LEO and GPS constellations can be reduced by over 50% compared with GPS-only PPP, and the convergence time by using LEO and BDS constellations can be reduced from 30 to 1 min compared with that using BDS-only PPP (Ge et al., 2018; Li et al., 2019b; Su et al., 2019). The time to first fix of the fixed solution of the multi-GNSS PPP can be shortened by over 50% with a LEO constellation of 60 satellites and a better result can be achieved if more LEO satellites are applied (Li et al., 2019a). Besides, the LEO constellation could also augment the BDS PPP-B2b service and expand it from the regional to the global level if the LEOs are capable to broadcast the precise parameter corrections.

(8) The LEO augmentation navigation constellation could broadcast GNSS satellite-based augmentation corrections and integrity information like the three BDS GEO satellites, improving the reliability and security of the satellite-based augmentation service.

Table 3 The statistical results of visible satellites in the polar regions

Navigation constellation	Elevation cutoff angle	AVE	MAX	MIN
LEO navigation constellation	5°	9.20	14	7
BDS-3 constellation	5°	10.25	15	8
BDS-3 + LEO navigation constellation	5°	19.45	28	15

Table 2 The DOP values of navigation constellations in the polar regions

Navigation constellation	Elevation cutoff angle	PDOP		HDOP		VDOP	
		AVE	MAX	AVE	MAX	AVE	MAX
LEO navigation constellation	5°	1.68	3.18	0.86	1.56	1.43	3.00
BDS-3 constellation	5°	1.86	3.54	0.79	1.09	1.69	3.41
BDS-3 + LEO navigation constellation	5°	1.17	1.84	0.55	0.76	1.03	1.71

Moreover, combining the GNSS and LEO constellations to provide service for LEO, aviation, ground, and sea surface users will improve the autonomous integrity and decrease the false alarm rate. A better autonomous integrity of PNT service will be achieved if robust estimation is used (Yang et al., 2016c, d).

It must be pointed out that the LEO augmentation navigation constellation could not fulfill the availability and reliability requirements of the on-board orbit determination and time synchronization of other LEO perception satellites and communication satellites. We know that low-orbit satellites for different purposes have different space orbit designs. For the sake of generality, we only discuss the satellite visibility of low-orbit space users with orbital altitudes of 500 km and 1000 km in the polar region, respectively. For this reason, the LEO augmentation constellation (shown in Fig. 3) is designed as Walker 168/12/7 with the inclination angle of 86.5° and the altitude of 1500 km, slightly higher than those of the low-orbit user satellites. Two simulation schemes are performed.

Sc 1: LEO users at an altitude of 500 km to observe the LEO augmentation navigation constellation and LEO + BDS-3 constellation respectively;

LEO users at an altitude of 1,000 km to observe the LEO augmentation navigation constellation and LEO + BDS-3 constellation respectively.

The visibility results are listed in Table 4 and presented in Fig. 4.

The calculation results indicate that 168 LEO augmentation satellites at an altitude of 1500 km can meet the requirements for the on-board GNSS OD of the LEO

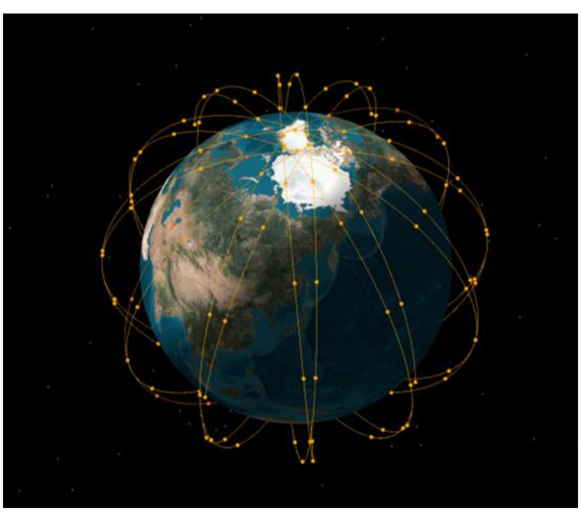

Fig. 3 Walker 168/12/7 of the LEO augmentation constellation

Table 4 The visibility of LEO users in different navigation constellations

Orbit altitude of the users	Navigation constellation	Statistical results		
		AVE	MAX	MIN
500 km	LEO navigation constellation	21.62	24	17
	LEO + BDS-3 navigation constellations	28.73	34	22
1000 km	LEO navigation constellation	4.58	12	0
	LEO + BDS-3 navigation constellations	9.87	19	3

user satellites at an altitude of 500 km, and at least 17 satellites are visible. For the LEO satellites at an altitude of 1000 km, there is still a possibility of no visible satellite at all. In addition, if only the kinematic OD orbit determination method is used, the discontinuity problem may occur in the joint orbit determination of LEO augmentation and BDS-3 constellations, as only 3 satellites can be observed in the most unfavorable conditions. The problem will be resolved if dynamic model information is involved in the Kalman filtering mode.

Key technologies for the construction of a LEO augmentation navigation constellation

According to the demands and the possible contributions, a well-designed and powerful LEO augmentation navigation constellation should be composed of large amount of miniaturized satellites that can be rapidly networked; it should upload cheap payloads to control the costs of the whole constellation; it should have reasonable constellation configuration to better compensate the coverage of current GNSSs and to provide better visibility for various users; it should have flexible signal system compatible to GNSS signals with better anti-interference capability; it should also have the autonomous operation capacity to reduce the burden of the ground control system. Then, the key technologies for the LEO augmentation navigation constellation can be concluded as follows.

(1) **The constellation design technology** The design of LEO augmentation navigation constellation should mostly consider the coverage weakness of current GNSSs and meet the new requirements of multiple special users for PNT services (such as polar users and LEO satellite users), and reduce the load burden of users in applying the satellite PNT services in specific areas. On this basis, the constellation scale should be as reasonable as possible to reduce the operation and maintenance burden of the system and save the cost of construction.

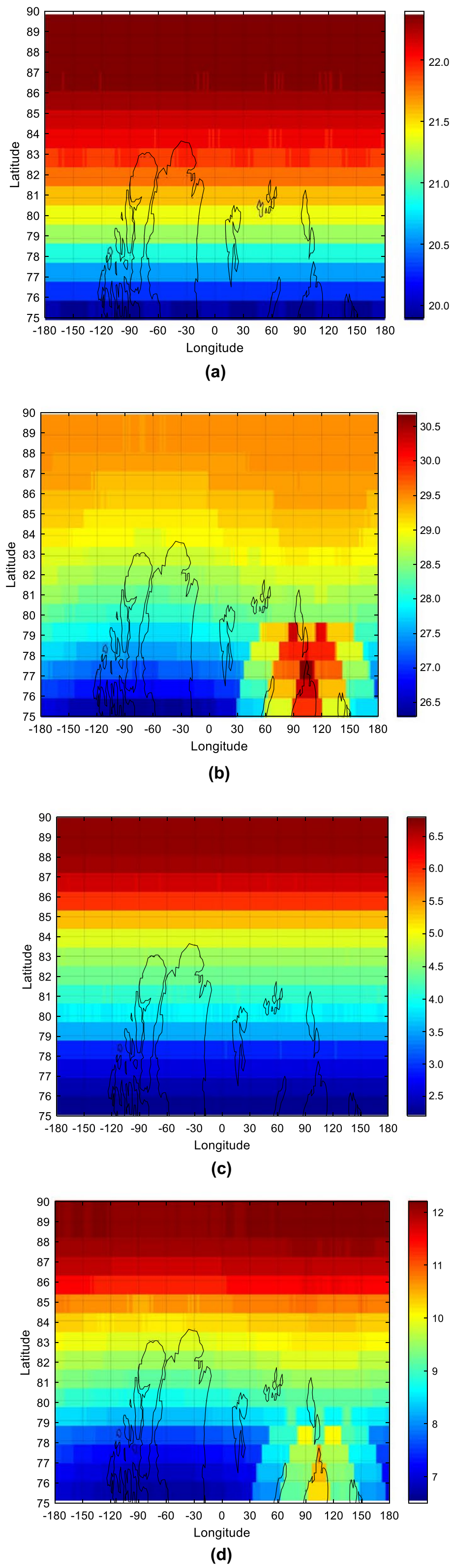

Fig. 4 **a** The average number of visible LEOs in the North Pole for LEOs at altitude of 500 km. **b** The average number of visible LEOs and BDS in the North Pole for LEOs at altitude of 500 km. **c** The average number of visible LEOs in the North Pole for LEOs at altitude of 1000 km. **d** The average number of visible LEOs and BDS in the North Pole for LEOs at altitude of 1000 km

(2) **The compatibility and interoperability technology for LEO, MEO, and HEO navigation satellite signals** The signal compatibility and interoperability technologies involve the signal frequency selection, signal modulation mode, transmitting power, etc. The design of LEO, MEO and HEO signals should meet the requirement of compatibility and interoperability to make sure that the signals will not interfere with each other and be easily for users to receive and process. To adapt to the requirement in special periods, the problem of adaptive transformation of signal modulation mode and the difficulty of software defined frequency must be solved for navigation satellites. Besides, the navigation signal should also consider the electromagnetic compatibility with other on-board radio devices especially for multi-function LEO constellations.

(3) **The signal power enhancement technology for LEO navigation satellites** The signal power enhancement capability of the existing MEO navigation satellites is usually 8–15 dB higher than the original signal due to the limitation of orbit altitude (Zhang et al., 2023). In a complex electromagnetic environment, satellite-based navigation signals usually need to be enhanced by more than 30 dB. Then, the LEOs could be a reasonable selection, since it has stronger landing power than the MEOs attached with stronger power enhancement capability in nature (Zhang and Ma, 2019). This technology aims not only to realize stronger power enhancement capability, but also to solve the resilient and rapid signal enhancement in a special period, special area, and special electromagnetic environment.

(4) **Autonomous operation technology for LEO augmentation navigation satellites** According to the existing simulation analysis and constellation construction plan, the LEO navigation constellation usually consists of dozens or even hundreds of LEO satellites distributed in different altitudes and planes. It's impossible to operate such a large constellation with limited ground-based resources, especially with only regional ground tracking systems. Then, it is necessary to solve the problems of autonomous orbit determination, autonomous timekeeping and timing for a large LEO constella-

tion, and the challenges of autonomous Telemetry, Tracking and Commanding (TT&C) of the large constellation.

(5) **The key payload miniaturization and multi-payload sharing technology** Satellite miniaturization and low power consumption are necessary for the large-scale constellation construction. The LEO navigation constellation must break through the technology of multiple PNT functions with a small satellite platform to control the construction cost of the whole constellation, which is also the premise to realize the rapid networking capability through ride-sharing missions.

Conclusions

The construction of a LEO augmentation navigation system is an important component of a national comprehensive PNT and secure PNT system. Different kinds of PNT users have different demands for LEO navigation enhancement, and the special demands of particular user groups must be taken into consideration. It should be realized that the LEO augmentation constellation improves not only the accuracy, continuity, and availability of PNT service, but also its reliability, integrity, and safety. The orbit altitude and inclination angle should be increased to fulfill the requirements of polar users and some other LEO users. The LEO navigation satellite constellation should have anti-interference and anti-spoofing capabilities to improve the security of PNT service in a complex electromagnetic environment. With many satellites, the LEO navigation constellation must possess the capabilities of autonomous OD and autonomous TT&C.

Acknowledgements
Not applicable.

Author contributions
YXY proposed the idea and wrote the manuscript. YM performed the experimental analyses. XR, XLJ, and BJS contributed to the analysis of the result and helped improve the manuscript. The final manuscript has been read and approved by all authors.

Funding
This work was funded by the National Natural Science Foundation of China (Grant No. 42388102; No. 41931076), the National Key Research and Development Program of China (Grant No. 2020YFB0505800) and the Laoshan Laboratory (Grant No. LSKJ202205101).

Availability of data and materials
The simulated data will be made available on reasonable request.

Declarations

Competing interests
Yuanxi Yang is an editorial board member for Satellite Navigation and was not involved in the editorial review or decision to publish this article. All authors declare that they have no competing interests.

Received: 21 January 2024 Accepted: 19 March 2024
Published online: 29 April 2024

References

Enge, P., Ferrell, B., Bennett, J., Whelan, D., Gutt, G., & Lawrence, D. (2021). Orbital diversity for satellite navigation. ‖Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2012). *Nashville, TN: ION, 2012*, 3834–3846.

Gao, W. G., Zhang, G., Liu, C., Lu, J., Wang, W., Chen, Y., Li, M., & Lu, F. R. (2021). Research and simulation of LEO-based navigation augmentation. *Science Sin-Physics, Mechanic & Astronomy, 51*, 019506.

Ge, H. B., Li, B. F., Ge, M. R., Zang, N., Nie, L., Shen, Y. Z., & Schuch, H. (2018). Initial assessment of precise point positioning with LEO enhanced global navigation satellite systems (LeGNSS). *Remote Sensing, 10*(7), 984.

Geng, J. H., Shi, C., Zhao, Q. L., & Liu, J. (2007). GPS precision orbit determination from combined ground and space-borne data. *Geomatics and Information Science of Wuhan University, 32*(10), 906–909.

Giorgi, G., Kroese, B., & Michalak, G. (2019). Future GNSS constellations with optical inter-satellite links. Preliminary space segment analyses. 2019 IEEE Aerospace Conference. *Big Sky, MT, USA, 2019*, 1–13.

Glaser, S., Michalak, G., Männel, B., König, R., Neumayer, K. H., & Schuh, H. (2020). Reference system origin and scale realization within the future GNSS constellation "Kepler." *Journal of Geodesy, 94*, 117.

He, X. C., Hugentobler, U., Schlicht, A., Nie, Y. F., & Duan, B. B. (2022). Precise orbit determination for a large LEO constellation with inter-satellite links and the measurements from different ground networks: A simulation study. *Satellite Navigation, 3*, 22.

Hong, J., Tu, R., Zhang, P. F., Zhang, R., Han, J. Q., Fan, L. H., Wang, S. Y., & Lu, X. C. (2023). GNSS rapid precise point positioning enhanced by low Earth orbit satellites. *Satellite Navigation, 4*, 11.

Hou, Z. W., Yi, X. Q., Zhang, Y. H., Kuang, Y. H. Y., & Zhao, Y. (2019). Satellite-ground link planning for LEO satellite navigation augmentation networks. *IEEE Access, 7*, 98715–98724.

Jason, R. (2023). Xona to test GPS-alternative demo satellite with customer [EB/OL] [2023–10–10]. https://spacenews.com/xona-to-test-gps-alternative-demo-satellite-with-customer/

Jiang, X. D., Chen, X., Ma, M. S., Wang, Y., Hou, R. T., & Yang, Z. J. (2021). Comparative evaluation of navigation enhancement performance of typical LEO satellite systems. *GNSS World of China, 46*(2), 49–55.

Joerger, M., Gratton, L., Pervan, B., & Cohen, C. E. (2010). Analysis of iridium-augmented GPS for floating carrier phase positioning. *Navigation, 57*(2), 137–160.

Li, X. X., Jiang, Z. H., Ma, F. J., Lv, H. B., Yuan, Y. Q., & Li, X. (2019c). LEO precise orbit determination with inter-satellite links. *Remote Sensing, 11*, 2117.

Li, X., Li, X. X., Ma, F. J., Yuan, Y. Q., Zhang, K. K., Zhou, F., & Zhang, X. H. (2019a). Improved PPP ambiguity resolution with the assistance of multiple LEO constellations and signals. *Remote Sensing, 11*(4), 408.

Li, X. X., Ma, F. J., Li, X., Lv, H. B., Bian, L., Jiang, Z. H., & Zhang, X. H. (2019b). LEO constellation-augmented multi-GNSS for rapid PPP convergence. *Journal of Geodesy, 93*, 749–764.

Liu, X. B., & Lian, C. M. (2016). The design and realization of anti-inference technology for BDS navigation terminal. *Digital Technology & Application, 6*, 2.

Lu, J., Guo, X., & Su, C. (2020). Global capabilities of BeiDou navigation satellite system. *Satellite Navigation, 1*(1), 27.

Lu, J., Su, C. G., Lv, F. R., Jiang, K., Yang, X. H., & Tang, C. P. (2023). Analysis of navigation augmentation techniques and capabilities based on low earth orbit constellation. *Spacecraft Engineering, 32*(04), 1–11.

Meng, L. D., Chen, J. P., Wang, J. X., & Zhang, Y. Z. (2021). Broadcast ephemerides for LEO augmentation satellites based on nonsingular elements. *GPS Solutions, 25*, 129.

Meng, Y. S., Yan, T., Bian, L., Wang, Y., & Tian, Y. (2022). LEO broadband satellite constellations based global navigation augmentation: Opportunity and challenge. *Navigation Positioning & Timing, 9*(01), 12–24.

Su, M. D., Su, X., Zhao, Q. L., & Liu, J. N. (2019). BeiDou augmented navigation from low Earth orbit satellites. *Sensors, 19*(1), 198.

Wang, L., Chen, R. Z., Li, D. R., Zhang, G., Shen, X., Yu, B. G., Wu, C. L., Xie, S., Zhang, P., Li, M., & Pan, Y. J. (2018). Initial assessment of the LEO based navigation signal augmentation system from Luojia-1A satellite. *Sensors (basel), 18*(11), 3919.

Yang, Y. X. (2016c). Concepts of comprehensive PNT and related key technologies. *Acta Geodaetica Et Cartographic Sinica, 45*(5), 505–510.
Yang, Y. X. (2019). Resilient PNT concept frame. *Journal of Geodesy and Geoinformation Science, 2*(3), 1–7.
Yang, Y. X., Ding, Q., Gao, W. G., Li, J. L., Sun, B. J., & Xu, Y. Y. (2022). Principle and performance of BDSBAS and PPP-B2b of BDS-3. *Satellite Navigation, 3*(1), 5.
Yang, Y. X., Liu, L., Li, J. L., Yang, Y. F., Zhang, T. Q., Mao, Y., Sun, B. J., & Xia, R. (2021). Featured services and performance of BDS-3. *Science Bulletin, 66*(20), 2135–2143.
Yang, Y. X., Lu, M. Q., & Han, C. H. (2016d). Some Notes on Interoperability of GNSS. *Acta Geodaetica Et Cartographic Sinica, 45*(3), 253–259.
Yang, Y. X., Mao, Y., & Sun, B. J. (2020). Basic performance and future developments of BeiDou global navigation satellite system. *Satellite Navigation, 1*, 1–8.
Yang, Y. X., Ren, X., Jia, X. L., & Sun, B. J. (2023). Development trends of the national secure PNT system based on BDS. *Science China Earth Sciences, 66*(5), 929–938.
Yang, Y. X., & Xu, J. (2016a). Navigation performance of Beidou in polar area. *Geomatics and Information Science of Wuhan University, 41*(1), 15–20.
Yang, Y. X., & Xu, J. Y. (2016b). GNSS receiver autonomous integrity monitoring (RAIM) algorithm based on robust estimation. *Geodesy and Geodynamics, 7*(2), 117–123.
Zhang, P. C., Huang, X. M., Hou, L. Y., Li, J. Y., & Ou, G. (2023). Compatibility analysis on low-orbit navigation power enhancement signals. *Journal of Navigation and Positioning, 11*(3), 119–124.
Zhang, X. H., & Ma, F. J. (2019). Review of the development of LEO navigation-augmented GNSS. *Acta Geodaetica Et Cartographica Sinica, 48*, 1073–1087.
Zhang, Y., Li, Z. S., Li, R., Wang, Z. Y., Yuan, H., & Song, J. H. (2020). Orbital design of LEO navigation constellations and assessment of their augmentation to BDS. *Advances in Space Research, 66*(8), 1911–1923.
Zhao, Q. L., Wang, C., Guo, J., Yang, G. L., Ma, H. Y., & Liu, J. N. (2017). Enhanced orbit determination for BeiDou satellites with FengYun-3C onboard GNSS data. *GPS Solutions, 21*, 1179–1190.

Publisher's Note