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Low Earth Orbiter (LEO) Navigation Augmentation: Opportunities and Challenges

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Abstract: As China's Beidou satellite navigation system (Beidou system) achieves an initial global coverage, the low earth orbiter navigation augmentation (LEO-NA) technique has become a subject of significant research interest, since it is highly compatible with the Beidou system to improve global autonomous navigation precision and extend the application market of global navigation satellite systems (GNSSs). This study analyzes the demand for and status of the LEO-NA technique and focuses on the in-orbit validation of key techniques for the *Luojia-1A* satellite. It also studies the challenges faced in the case of the LEO-NA system, including interoperability of signal frequencies after navigation augmentation, integrated design of the communication and navigation signals, control and management of the LEO constellations, acquisition and tracking of the high-dynamic augmented signals, and integration with existing GNSSs. In consideration of the pressing demand for the LEO-NA techniques, the following suggestions are proposed, namely, enhancement of the LEO-NA system top-level design while focusing on the synergy of the LEO-NA and Beidou systems; promotion of the integration of the communication, navigation, and remote sensing functions; building of the space-based real-time service system in a stepwise and stratified manner; and planning and construction of the satellite project and the ground infrastructure in an integrated manner.

Keywords: Satellite navigation augmentation; low earth orbiter constellation; Beidou system; collaborative development; satellite–ground integration

1 Introduction

The Beidou-3 satellite navigation system has completed the core constellation deployment and possesses the capacity to provide multiple utilities, such as navigation and positioning services, satellite-based augmentation systems (SBASs), precision point positioning (PPP) services, regional short message communication (RSMC), and search and rescue (SAR) services, indicating that the Chinese Beidou satellite navigation (BDS) system is being upgraded from a regional navigation system to a global navigation service provider [1]. For domestic users, China has built a ground-based augmentation system (GBAS) and numerous monitoring stations for ship supervision, search and rescue operations, urban logistics distribution, coastal precision positioning services, shared bicycle supervision, and online car supervision. Subsequently, further improving the performance of the navigation and positioning services of the Beidou system and expanding the global market will be the challenges for China's satellite navigation industry.

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Currently, the navigation and positioning service faces multiple challenges that are difficult to solve with one particular navigation technology. Therefore, the new generation of positioning, navigation, and timing (PNT) systems needs to integrate multiple technologies, such as orbit diversity and non-satellite navigation [2] to enhance service capabilities. Parkinson et al. [3] proposed the protection, toughen, and augment (PTA) concept to overcome the vulnerability of the current GNSSs, including the SBAS, ground-based pseudolite, ranging, and enhanced Loran technologies. Yang et al. [2,4] proposed a comprehensive PNT system and resilient PNT system concepts, which consider the low earth orbiter navigation augmentation (LEO-NA) technology and multi-source navigation fusion technology as the core technologies. Li et al. [5,6] demonstrated the construction of a space-based real-time information system with air/space/ground integration, which combined communication, navigation, and remote sensing functions, and proposed LEO-NA technology assumptions. The five core services of the system are integration of the positioning, navigation, timing, remote sensing, and communication (PNTRC). On the one hand, navigation augmentation technologies can provide a high-precision spatial-temporal datum for low-orbit satellites; on the other hand, LEO-NA can provide real-time high-precision positioning services and improve the efficiency of communication and remote sensing services. When the LEO-NA technology is integrated into the Beidou system, cooperation is achieved to provide high-precision positioning service capabilities with high availability, high continuity, high integrity, and fast convergence worldwide.

Hence, this study examines the opportunities and challenges in the development of LEO-NA technology and researches requirement analysis, state-of-the-art analysis, in-orbit validation of key technologies, and future development suggestions for the development of Chinese satellite navigation industries.

2 Overview of the navigation augmentation techniques

2.1 Requirement analysis

2.1.1 Requirement of improving global positioning service performance

At present, the Beidou System can provide meter-level basic navigation services to global and SBAS and wide-area PPP services to China and surrounding areas. The current PPP is based on the mid-/high-orbit navigation satellites, which takes 30 minutes or longer to achieve a centimeter-level positioning due to the slow change of the geometric configuration between the satellite and the ground user. If the PPP service is augmented with the low-orbit satellites, the convergence time can be reduced to the order of several minutes [7]. Therefore, the Beidou system’s global navigation and positioning performance need to be augmented by the low-orbit satellites.

2.1.2 Requirement of improving the international competitiveness of the Beidou system

In the global navigation and positioning service market, the basic capabilities of the United States Global Positioning System (GPS), Russian Global Satellite Navigation System (GLONASS), European Galileo Satellite Navigation System (Galileo), and several regional navigation satellite systems (RNSS) are overlapped, and all these systems are engaged to improve their service capabilities to ultimately strengthen their international competitiveness. China is the third country to provide global navigation and positioning services after the United States and Russia. To participate in international competition and gain advantages, the Beidou System needs to improve its positioning accuracy, usability, continuity, reliability, anti-jamming capability, and integrity to leading the international standard. Navigation augmentation technology is a feasible solution for the Beidou system to improve the above requirements.

2.1.3 Requirement of extending the comprehensive PNT services

As a national infrastructure and an important strategic resource, the PNT service system needs the capabilities of air/space/ground/sea integration from multiple sources and heterogeneous navigation sources. Its performance measures include flexibility, toughness, and resistance to destruction. In the future, the PNT services will not be able to only rely on the Beidou system, it requires a backup solution with scattered resources and complementary capabilities. From the service perspective, the navigation augmentation system can be used as an extension, supplement, and backup of the Beidou system. It plays a key role in functional equivalence in extreme scenarios where the basic navigation service of the Beidou system cannot meet application requirements.

2.1.4 Requirement of building a PNTRC integrated space-based information services

From the perspective of China’s PNTRC construction, remote sensing and communication services need to be integrated with navigation augmentation services to achieve synergies [8]. Through the coordination and support of space-based information services, such as navigation, remote sensing, and communication, a real-time service system integrating spatial information acquisition, transmission, processing, command, and control can be constructed, and a new pattern of collaborative innovation in the spatial information industry can be formed. This is the urgent need and capability benchmark for China's leap from a large space country to a powerful space country.

2.2 State-of-the-art of LEO-NA techniques

The navigation augmentation technology is not an emerging concept and has a long development history. It refers to various technical solutions for improving the service capabilities of satellite navigation systems. The classification of existing satellite navigation augmentation systems is shown in Fig. 1. There are primarily two types: information-based and signal-based augmentation systems [9].

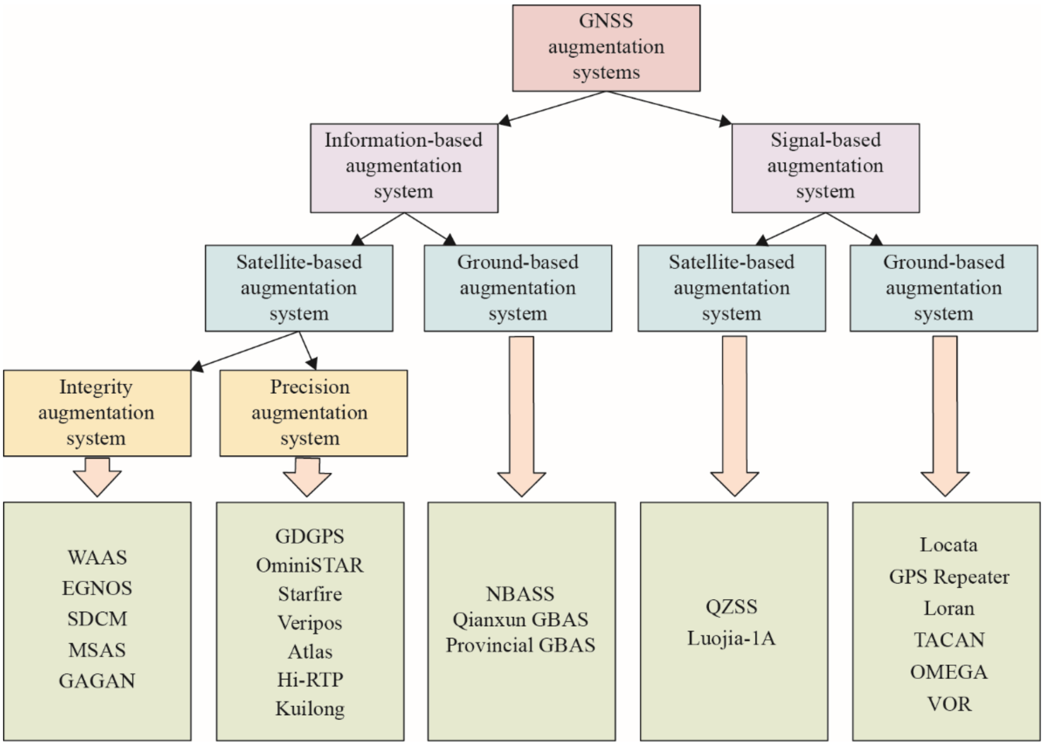

Fig. 1. Heritage of navigation augmentation systems and typical navigation augmentation systems [11–15].

Note: WAAS: Wide Area Augmentation System; EGNOS: European Geostationary Navigation Overlay Service; SDCM: Russian system of differential correction and monitoring; MSAS: Multi-Functional Satellite Augmentation System; BDSBAS: Beidou Satellite Based Augmentation System; GAGAN: The India GPS Aided GEO Augmentation Navigation; GDGPS: global differential GPS system; NBASS: The National Beidou Ground-based Augmentation Network; QZSS: Quasi-Zenith Satellite System; Loran: Long Range Navigation; TACAN: Tactical Air Navigation System; OMEGA: Very Long-Range VLF navigation system generating hyperbolic lines-of-position by phase difference measurements; VOR: The Very High-Frequency (VHF) Omnidirectional Range.

2.2.1 Information-based augmentation system

The information-based augmentation system (IAS) calculates the corrections or the integrity information through the ground monitoring station and broadcasts the correction data to users to improve the positioning accuracy or service integrity. The characteristic of IAS is that navigation and positioning still employ existing satellite navigation signals and the augmentation information is transmitted through space-based or ground-based communication links.

From the perspective of transmission methods for augmentation information, the IAS can be divided into ground-based and satellite-based augmentation. (1) The ground-based augmentation system (GBAS) uses the ground Internet, radio stations, or mobile communication networks to transmit the correction information, such as the National Beidou Ground-based Augmentation Network (NBASS) [10], Qianxun Ground-based Augmentation Network, and provincial-level Beidou ground-based augmentation networks. (2) The satellite-based augmentation systems (SBAS) broadcast the corrections to a wide area by leasing the communication satellite channels, and the correction data transmission does not depend on the ground communication facilities, so the coverage is wider [11]. At present, most SBAS provides global PPP services, which can achieve centimeter-level positioning accuracy (Table 1); but the PPP convergence often takes a long time if the regional augmentation information is not available. Furthermore, different SBAS service providers often require dedicated receivers, so the compatibility and interoperability of different systems are still challenging.

Table 1. Performance comparison between mainstream SBAS systems.

SBAS	Operator	Establishment (year)	Accuracy (cm)	Constellation	Convergence (min)
GDGPS	JPL	2000	10	G	–
OmniSTAR HP	OmniSTAR	–	10	GR	<35
Starfire	NavCom	2011	5	GR	–
CenterPoint RTX	Trimble	2011	10	GRBEQ	<15
Veripos APEX 5	Veripos	–	5 (H) 12 (V)	GRBEQ	–
ATLAS	Unistrong	2015	4	GRB	–
Hi-RTP	Hi-Target	2018	4	GRBE	<30

Note: G: GPS; R: GLONASS; B: BDS; E: Galileo; Q: QZSS.

In consideration of the correction contents, SBAS can be further divided into two types: integrity augmentation and accuracy augmentation. (1) The integrity augmentation system is primarily for the civil aviation industry. It is used to provide higher navigation integrity and can also improve the accuracy of navigation positioning to a certain extent (meter-level to sub-meter-level). (2) The precision augmentation system primarily broadcasts real-time precision orbit and clock products to support the precise positioning services; it also broadcasts information such as carrier phase fractional biases, regional ionosphere, and troposphere corrections to improve the precise positioning performance.

2.2.2 Signal-based augmentation system

In the signal-based augmentation system (SAS), the navigation augmentation sources can generate ranging signals, so users can combine positioning with existing GNSS signals. Therefore, SAS can improve the availability, reliability, and continuity of satellite navigation services. The SAS can be divided into a signal-based ground-based augmentation system (SBGBAS) and a signal-based satellite-based augmentation system (SBSBAS).

The SBGBAS can solve the positioning problems in challenging environments, such as urban canyons, open-pit mines, woods, indoor, underground spaces, and even underwater, which can effectively extend the service scope and application scenarios of satellite navigation systems. The Australian Locata system [16–18], as a ground pseudolite system, is a typical SBGBAS.

The SBSBAS uses non-navigation satellites to generate ranging signals and provides navigation services in cooperation with navigation satellite systems. A typical SBSBAS is the Japanese quasi-zenith satellite system (QZSS), which uses inclined geosynchronous orbit (IGSO) satellites for ranging signal broadcasting [19]. Due to the slow change of the station/satellite geometry, satellite positioning systems based on mid-high orbit navigation satellites have a long convergence time for precise positioning. The low-orbit satellite platform used as a navigation signal augmentation source has a unique advantage: The relative geometric relationship between the satellite and the ground changes rapidly, which assists in the rapid convergence of the precise positioning process.

3 Progress of LEO-NA techniques

In recent years, the innovative concepts and solutions for low-orbit communication constellations have consistently emerged. Both academia and industry have paid increasing attention to navigation augmentation systems relying on low-orbit satellite constellations. The LEO-NA satellite platform can provide both information and signal augmentation services. On the one hand, LEO-NA satellites can provide high-bandwidth, low-latency GNSS differential information augmentation services based on communication capabilities; on the other hand, LEO-NA satellites can effectively reduce the convergence time of the GNSS precision positioning. As a navigation signal augmentation source, it also improves navigation service availability and reliability. For the Beidou system, the LEO-NA satellites serve as mobile monitoring stations to improve the orbit determination accuracy of the Beidou GEO satellite, which avoids the globally distributed ground monitoring network [20,21]. Additionally, LEO-NA technology is also an important part of the resilient PNT framework [4] and the comprehensive PNT system [2].

3.1 Status of international progress

In earlier developments, a few researchers focused on researching and verifying the potential of LEO satellites for improving real-time kinematic (RTK) positioning performance [22]. In 2002, the Boeing Company proposed the high integrity GPS (iGPS) scheme, combining GPS with the Iridium constellation, which is essentially a low-earth or medium-orbit satellite navigation and timing system [23]. In 2007, the Boeing Company completed the iGPS anti-interference test, and the satisfactorily measured results contributed to the construction of the second-generation Iridium Next system.

In May 2016, the Iridium Corporation announced the launch of satellite time and location (STL) services. The Iridium system uses downlink channel beams to implement navigation-augmentation signals. Its satellite signal power has been increased by 25–30 dB, which significantly improved anti-interference ability. As reported [24,25], the public positioning accuracy of the Iridium STL service is 20–50 m, and the timing accuracy is about 200 ns; although the Iridium STL service is not comparable with GNSS positioning in terms of accuracy, its advantage lies in location certification and anti-interference capacity. With the introduction of a large-scale low-orbit communication constellation plan, international teams have completed simulation analysis of navigation augmentation service performance based on future broadband LEO constellations [26,27], but have not yet seen any low-orbit broadband communication constellation operators claim to provide navigation augmentation services.

3.2 Progress of LEO-NA research in China

3.2.1 Simulative study based on the Iridium and GNSS constellations

Chinese researchers provide a theoretical basis for the space-based GNSS signal monitoring using the simulated LEO constellations. The simulative research also treats the Iridium constellation as an independent navigation satellite system to analyze the navigation performance of combining the GNSS system and the LEO satellite constellation. The simulation focuses on analyzing the navigation performance indicators, such as the visible satellite number, dilution of precision (DOP), pseudo-range-based positioning accuracy, and integrity. Some researchers [28–30] studied the anti-interference, integrity, availability, and accuracy of the Iridium augmented GPS, which revealed the potential benefit of LEO augmentation. Researchers [31] also analyzed the anti-interference performance of the Beidou system based on LEO-NA technology, which indicates that the augmentation signal can tolerate an interference-to-signal ratio of about 50 dB and significantly improves the anti-interference ability of the system. The performance of the receiver autonomous integrity monitoring (RAIM) of the GPS and Beidou system receiver augmented by the Iridium system has also been studied [32].

3.2.2 Simulation analysis of accelerating PPP convergence in LEO constellation

With the development of PPP technology, low-orbit satellites are expected to solve the problem concerning slow PPP convergence. Existing research shows [33,34] that under the normal operation of GPS, GLONASS, GALILEO, and BDS global navigation systems, the first fixed time can be reduced from 7.1 min to 0.7 min with the support of 288 LEO-NA satellites. For the single BDS system, the PPP convergence time can also be reduced to three minutes, and the ambiguity fixed efficiency can be further improved. The contribution of LEO satellites to the PPP convergence time depends on the number of visible LEO satellites (Fig. 2). Additionally, the broadcast message parameters of LEO-NA satellites are also a research hotspot [27,35,36]. The orbital perturbations of the LEO satellites are more complicated than traditional navigation satellites. The existing navigation satellite broadcast ephemeris models cannot be directly applied to the ephemeris fitting of LEO satellites. Some scholars have proposed orbits with an extended state parameter to improve the LEO broadcast ephemeris model [35].

3.2.3 In-orbit verification of key LEO-NA technologies

After the Beidou system is put into operation, research on further improvement of the comprehensive performance of its navigation services is urgently required. Some universities, research institutes, and commercial companies in China attach high importance to the key technology research and in-orbit tests of the LEO-NA system; they hope to solve the engineering problem of LEO-NA technology through a technical verification and pave the way for construction of the LEO-NA system. Representative works include the Luojia-1A scientific experimental satellite developed by Wuhan University [37], the first experimental satellite of the *Hongyan* constellation constructed and operated by Dongfanghong Satellite Mobile Communication Co., Ltd. [38], and the successful launch of the Tianxiang-1A/B satellites by the China Electronics Technology Group for communication and LEO-NA in-orbit tests. These in-orbit tests reflect the substantial progress of China’s LEO-NA technology in key principles and system verification.

4 Key technologies validation based on the Luojia-1A satellite

In this study, we use the Luojia-1A satellite as an example to demonstrate the key technology development in

LEO-NA systems.

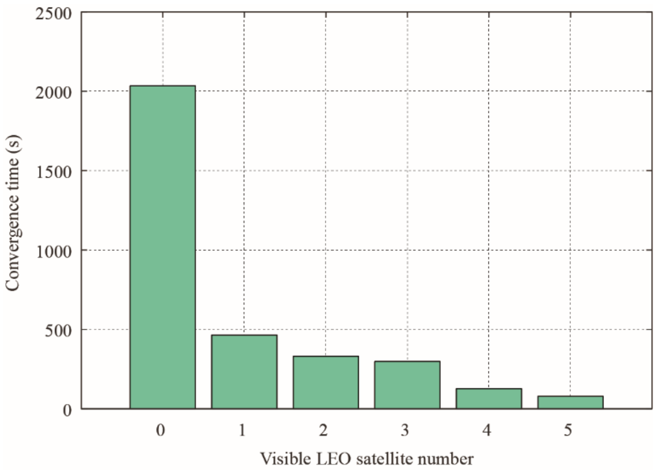

Fig. 2. Relationship between the precise positioning convergence time and visible LEO satellite number.

4.1 Satellite platform and navigation augmentation payload

The Luojia-1A scientific experimental satellite is primarily used to conduct the night-time light remote sensing and LEO-NA technology in-orbit tests (Fig. 3). The satellite is equipped with two sets of GPS/BDS receiving antennas, which can receive GPS and Beidou dual-constellation four-frequency observation data for in-orbit data processing, precision orbit, and calculation of clock information, and generate a dual-frequency ranging signal for broadcasting to the ground. The ground receiver simultaneously receives the ranging signals from GPS, Beidou, and Luojia-1A satellites and performs joint positioning to improve positioning performance, especially to reduce the PPP convergence time.

Fig. 3. Image of Luojia-1A scientific experimental satellite configuration.

The Luojia-1A satellite configured special navigation enhanced load for microsatellites has achieved breakthroughs in key technologies such as onboard signal isolation, on-board high-precision time maintenance, payload miniaturization, and low power consumption design. The ground-configured receiver prototype is newly developed and optimized based on the characteristics of the LEO-NA signal, which improves the acquisition sensitivity and tracking accuracy of low-orbit satellites, and can simultaneously capture and track GPS, Beidou navigation signals, and Luojia-1A navigation augmentation signals (Fig. 4).

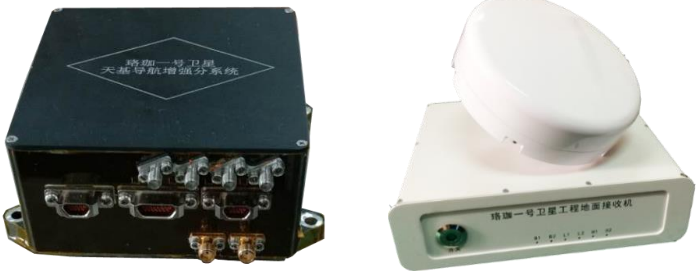

Fig. 4. LEO-NA payload (left) and ground receiver (right).

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4.2 In-orbit test results

The Luojia-1A scientific experimental satellite completed the in-orbit navigation augmentation technology test, and the ground receiver successfully captured and tracked the LEO-NA signal. The ground receivers were optimized to improve the carrier-to-noise ratio (C/N_0) of the navigation augmentation signal. The C/N_0 of the dual-frequency navigation augmentation signal is shown in Fig. 5, which reflects the continuous and stable tracking of the Luojia-1A dual-frequency navigation augmentation signal (H1 and H2 signals). During the test, the C/N_0 of the Luojia-1A satellite signal was always in the normal range, thus reflecting the technical feasibility of the Luojia-1A satellite LEO-NA solution. Furthermore, the evaluation of the dual-frequency signal of the Luojia-1A satellite shows that there is a significant correlation between the measurement accuracy of the pseudo-range and carrier phase of the navigation augmentation signal and the satellite elevation angle. The observation accuracy of the carrier phase signal also reached the millimeter-level, which is achieved using a low-cost crystal oscillator. The quality of the navigation augmentation signal of the Luojia-1A satellite meets the design expectation, and it has accumulated first-hand observation data and in-orbit test experience for China's LEO-NA technology [37,39].

The Luojia-1A satellite navigation augmentation experiment has made progress in numerous aspects, including the payload design, signal design, key components selection and performance evaluation, LEO-NA receiver design, signal monitoring and evaluation, and LEO-NA data processing. It has provided an experience for future LEO-NA system development.

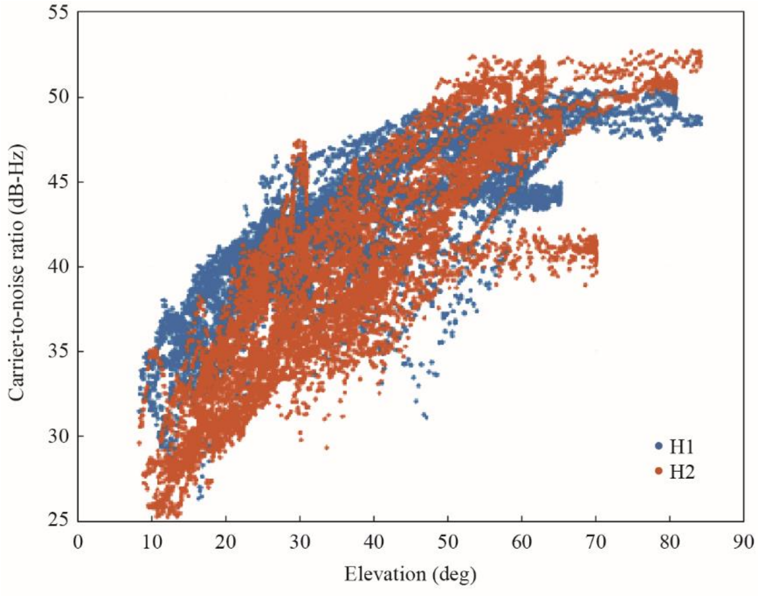

Fig. 5. C/N_0 of Luojia-1A navigation augmentation signals.

5 Challenges of LEO-NA technique

At present, LEO-NA technology research is still in the proof-of-concept and technical research phase. Although some key technologies have made breakthroughs, they still face several technical challenges in terms of improving the technical system, system development, and operation.

5.1 Compatible interoperability for navigation augmentation frequencies

At first, there are no available frequency resources in the L-band for navigation augmentation. Therefore, the LEO-NA system must consider the compatibility and interoperability with the existing satellite navigation system signals, including frequency band selection, signal power control, receiving signal power control, out-of-band signal suppression, spurious suppression, intermodulation interference control, satellite signal reception, and isolation, thereby ensuring that while providing LEO-NA services, it will not interfere with the normal use of existing satellite navigation systems.

5.2 Integrated design of communication and navigation signals

The integration of navigation and communication at the signal level is the primary trend to solve the shortage of navigation signal spectrum resources, signal power augmentation, and limited high-bandwidth information transmission. However, the communication and navigation communication links have significant differences in their needs and technical approaches. Technical research is required to promote the fusion of navigation and communication applications. Communication signals usually use multiple multiplexing methods such as space-division multiplexing, time-division multiplexing, frequency division multiplexing, and code division multiplexing to maximize the effective communication bandwidth and point-to-point services; while navigation signals prefer a complex communications protocol to achieve high-precision navigation and positioning services.

5.3 Error modeling of navigation augmentation signals

For the error source modeling of LEO-NA signals, the current methods for modeling errors in GNSS signals cannot be simply applied, and further research should be performed. When compared with the navigation augmentation load, components, and space environment of GNSS satellites, those of LEO satellites are different, which results in different hardware delay time-varying characteristics of navigation augmentation signals. Moreover, the LEO-NA system’s space-time reference maintenance method, motion characteristics, and atmospheric delay characteristics on the signal propagation path are all different from the current GNSS signals.

5.4 Operation and control of LEO satellite constellation

Future LEO-NA constellation plans are all large constellations with hundreds of satellites, and inter-satellite communication links need to be established between the in-orbit plane and inter-orbit plane satellites, leading to an extremely complicated constellation management scheme. At present, the operational low-orbit communication constellations, such as the Iridium and Globalstar constellations, only have dozens of satellites, and the constellation management is relatively simple. Therefore, there is an urgent need to build a long-term continuous operation, robust satellite measurement and control mechanism, and performance evaluation system. Through technical research on the constellation maintenance, fault recovery, resource scheduling, load balancing, and ground station optimization, a constellation for large-scale low-orbit communication with the capacity to meet the needs of ground operations management should be formed.

5.5 LEO satellite high dynamic navigation augmentation signal acquisition and tracking

The LEO satellite platform is close to the ground and travels at high speed, which makes the Doppler change and acceleration change range of the satellite navigation signal in the line of sight (LOS) larger than the medium and high orbit satellites. In the design of the LEO-NA ground receiver, attention is required for the acquisition sensitivity of highly dynamic navigation signals, and multiple approaches have been adopted to maintain and improve the key signal tracking accuracy factor [39,40].

5.6 Integration and collaboration with the Beidou system

The LEO-NA system is not only an expansion and augmentation of the existing Beidou system but also a backup and supplement of its navigation function. Therefore, the LEO satellite will play a dual role as *user* and *signal source* in the future integrated navigation system. Because of the large scale of the LEO constellation, the complex inter-satellite link, and the short time window for transit measurement and control, the integrated architecture optimization design between the LEO-NA and Beidou systems should be further developed to achieve high-quality compatibility and interoperability, unified space-time reference. The satellite-ground interface is unified, while taking into account the independent maintenance capabilities of the respective constellations.

6 Suggestions

Through the construction and operation of the Beidou system, China has earned rich experience in satellite navigation system development and trained professional teams. The LEO-NA technology is an important development trend for the Beidou system to further improve the navigation service performance and expand the global market by overtaking the performance aspects. Spearheaded by the key technological breakthroughs achieved by the Luojia-1A scientific experimental satellite, China’s research in the field of LEO-NA technology has made significant progress. Focusing on the engineering construction and efficient operation of related systems in the future, the LEO-NA technology field still faces numerous technical and engineering challenges. Therefore, this article proposes development suggestions for the construction of LEO-NA systems in China.

(1) Strengthening of the top-level design of the system and fully exploiting the existing resources, dealing with the misalignment relationship between the LEO-NA and Beidou systems, and focusing on the synergies between the two systems. As a large-scale low-orbit constellation, the LEO-NA system involves the design of complex inter-satellite links. It is advisable to make full use of and draw on China's existing research and development resources for satellite platforms and space information payloads to optimally, efficiently, and collaboratively solve the system construction issues.

(2) Promotion of the integration of communication, navigation, and remote sensing functions, and construction of the PNTRC system incrementally. The coordinated development of China's communications, navigation, and remote sensing technologies is required to build a low-orbit constellation with multi-purpose satellites and multi-satellite networking, which can save on constellation construction costs and spectrum resources and improve comprehensive service capabilities. Considering the large scale and complexity of the low-orbit constellation, it is recommended to draw on the successful experience of the Beidou system construction and construct the PNTRC system in a step-by-step manner according to the different needs of communication, navigation, and remote sensing functions for space orbits, satellite platforms, and business models to build a multi-level, multi-mode mixed constellation, thereby maximizing the effectiveness of the collaborative operation.

(3) Unified planning of satellite engineering and ground infrastructure, and integration of space segments and ground facility construction. Through the integration of top-level architecture, planning, and design, undesirable situations and possibilities can be avoided where ground measurement, operation control stations, and information gateways become the "bottlenecks" impeding the performance of large systems. Focus should be placed on adopting and exploiting new technologies such as cloud computing, big data, and 5G mobile communications, optimizing system architecture, expanding service scope, and improving the overall PNTRC system performance.

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