Overview of the Development of Low Earth Orbit Satellite Navigation Enhancement Technology

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Abstract

Low Earth Orbit (LEO) satellites, with their unique advantages in constellation and signal, are gradually gaining attention and favor in the world's satellite navigation field, and are expected to become a new increment in the development of the new generation of satellite navigation systems. With the low orbit constellations represented by the Starlink program in the United States becoming a new battlefield for global competition for space strategic resources, the development direction of satellite navigation enhancement is also gradually tilting towards the low orbit field, becoming a new growth and empowerment point for the next generation of satellite navigation. This article first introduces two major types of low orbit navigation enhancement technologies, namely information enhancement and signal enhancement; Summarized the current development status of global low orbit satellite navigation; Explained the key technologies for enhancing low orbit navigation; The focus was on discussing the new development opportunities brought by low orbit navigation enhancement technology for building a Global Navigation Satellite Systems (GNSS) global space-based monitoring network, providing global quasi real time high-precision services, and providing global high integrity monitoring services; Finally, the inspiration and suggestions for the development path of low orbit navigation enhancement technology were summarized.

Keywords: Low Earth Orbit Satellite Navigation Enhancement, LEO constellation, GNSS, navigation and positioning

1. Introduction

The Global Navigation Satellite System (GNSS) currently includes China's BeiDou Navigation Satellite System (BDS), the United States' Global Positioning System (GPS), and Russia's GLObal Navigation Satellite System, GLONASS) and the European Union's Galileo system, a total of more than 100 satellites are in orbit, providing global, all-weather, and high-precision services for all walks of life. For the satellite navigation system of medium and high orbit constellation, its satellite signal is very weak when it reaches the earth's surface from 20,000~30,000km space, and it is easy to be shielded and blocked in cities, canyons, jungles and other areas, and cannot serve the underground garage and other environments. At present, all major satellite navigation countries are aiming for higher service accuracy, more diverse functions, and more reliable services, and are starting to build a new generation of systems and a new round of competition.

With its unique advantages of constellation and signal, LEO satellite has gradually attracted the attention and favor of the world's satellite navigation field, and is expected to become a new increment in the development of a new generation of satellite navigation system. LEO satellites can enhance satellite navigation signals as an augmentation and supplement to GNSS (Global Navigation Satellite System); It can also be fused by the communication system and the navigation system to broadcast independent ranging signals to form a backup positioning and navigation capability. At present, in the field of international satellite navigation, the research and development and practice of how to apply low-orbit satellite technology to achieve PNT (positioning, navigation timing) enhancement, backup and supplement are in the ascendant. Iridium and GPS jointly developed and launched a new satellite timing and positioning service (STL), which has become a backup or supplement to the GPS system. The European Galileo system technical team is also actively promoting the research of Kepler system, through the low-orbit constellation composed of 4~6 low-orbit satellites, through the inter-satellite link to monitor and high-precision measurement of medium- and high-orbit satellites, so as to greatly improve the orbit determination accuracy of the Galileo constellation. In addition, the development of domestic low-orbit satellite technology was also in full swing during the same period. Under the promotion of relevant departments, large central enterprises, research institutes, and private enterprises, satellite in-orbit tests have been carried out in low-orbit satellite constellations such as Hongyan, space-ground integrated network, and micro-space.

2. Low-orbit navigation augmentation technology

Satellite navigation augmentation technology was first developed in the 90s of the 20th in response to the US GPS Selective Availability (SA) policy. Scholars have proposed a technology for differential processing between stations, which restores the C/A ranging code of GPS to the system design accuracy by eliminating the common measurement error between stations [1], [2], [3]. In the 21st century, with the abolition of the SA policy, the connotation of navigation augmentation technology has been further expanded, which refers to various technical solutions used to improve the service capability of satellite navigation systems.

As the low-orbit constellation represented by the Starlink program of the United States has become a new battlefield for the global competition for space strategic resources, the development direction of satellite navigation enhancement is also gradually inclined to the low-orbit field, which is becoming a new growth and empowerment point for the next generation of satellite navigation. The low-orbit satellite navigation augmentation technology can improve the accuracy, availability and integrity of satellite navigation and positioning, and it can be divided into two categories: information enhancement and signal enhancement according to the enhancement mode.

Information augmentation refers to a technical way to improve the accuracy and reliability of navigation and positioning by correcting the errors of satellite navigation and positioning systems. Information augmentation does not provide additional distance observations, only corrected information and integrity information to eliminate GNSS errors. Information augmentation usually requires a transmission channel that can broadcast the enhanced information to the user. According to the platform mode of enhanced information transmission, it can be divided into ground-based augmentation and satellite-based augmentation. Network RTK, satellite-based differential and other technologies are typical information augmentation systems.

Signal augmentation refers to the method of transmitting navigation signals through platforms other than navigation satellites, and users can also receive navigation signals from the navigation satellite system itself and other additional navigation signals, thereby improving the accuracy and usability of navigation and positioning. Signal enhancement typically requires a signal transmitter to provide the user with measurement information. The signal augmentation system provides observational measurements and can be used in conjunction with GNSS or independently. According to the position of the transmitting navigation signal platform, signal enhancement can also be divided into ground-based enhancement and satellite-based enhancement.

Information augmentation can improve GNSS positioning performance, but it is not effective in situations where GNSS signals are not received, such as indoors or in occluded environments. Signal enhancement can provide new observations and measurements, and can be used to compensate for scenarios where GNSS is powerless, such as under overpasses, urban canyons, etc., when the number of satellites may not be enough, and even for indoor areas where GNSS signals cannot reach, signal enhancement can also provide a solution.

3. Global development status of low-orbit satellite navigation

The construction of the next-generation Iridium satellite system in the United States was completed in 2019, and the new low-orbit satellite timing and positioning services provided by it have become an effective supplement and backup to GPS. The European Galileo technical team is also actively promoting the research of Kepler system, and 4~6 low-orbit satellites monitor and measure the operation of medium and high orbit satellites, so as to greatly improve the orbit determination accuracy of the system.

In order to improve the capabilities of the GPS system, the United States has integrated the development of the GPS system on the new generation of Iridium system [4], providing users with STL (Satellites Time and Location) service, which is provided by Satelles, which can backup and enhance the GPS capability.

The Iridium system was originally a global mobile communications system designed by the American company Motorola. It consists of 6 orbital planes, each with 11 satellites evenly distributed in each orbit, forming a complete constellation that can cover global regions including the polar regions. At the beginning of the design, it mainly provided users with satellite communication services, but due to the high cost of system construction and the cold reception of the market, the development of the Iridium system was relatively slow. In January 2019, the United States completed the launch and deployment of a new generation of Iridium satellite system. In addition to the communication service, the Iridium constellation can achieve positioning, navigation, and timing in indoor and canyon areas by providing STL services. STL service performance, positioning accuracy of 30~50 meters, timing accuracy of about 200ns, the original signal landing power is 300~2400 times stronger than the GPS L1 C/A code signal (24.8~33.8dB), indoor usability is greatly improved, and navigation availability and safety in complex terrain environment and complex electromagnetic environment are enhanced. With Iridium and GNSS receivers, STL services can be used to augment multi-GNSS navigation services, including GPS, and can also be used as a backup when signals are unavailable or inadequate.

In 2015, SpaceX proposed a plan to build Starlink, which will launch and deploy about 42,000 small satellites in low-earth orbit to achieve all-weather, low-latency high-speed Internet access services around the world. After the construction is completed, the Starlink constellation will undoubtedly be the best performing and largest low-orbit satellite constellation to date.

The European Galileo system technical team proposed to greatly enhance the capabilities of the Galileo system with the Kepler low-orbit system, which can enhance the integrity and accuracy of the Galileo system while reducing the dependence on the ground system. The technical core of the Kepler system is to use 4~6 low-orbit satellites to form a small-scale constellation, and laser inter-satellite link (ISL) to complete the existing constellation system. MEO satellites do not need to be equipped with atomic clocks, and all satellites are connected through laser inter-satellite links, so that navigation satellites can achieve direct synchronization at a very high precision level, and then further provide high-precision distance measurement instead of pseudorange for orbit determination, in order to obtain mm-level orbit determination accuracy and nm-level phase measurement accuracy, so as to achieve a significant increase in capabilities. At the same time, the system observes the navigation signals without ionospheric and tropospheric disturbances through the LEO satellite constellation, which can improve the integrity and accuracy of the MEO system. Under the Kepler system architecture, most of the survey and communication facilities of the ground operation and control system are no longer necessary, and only a small number of ground stations are required to maintain consistency with the earth's coordinate framework and the ability to control the system under special circumstances.

In 2019, the Russian State Space Corporation proposed to add 12 satellites to the existing "Messenger-D1M" low-orbit communication satellite constellation composed of 12 "Messenger-M" satellites, and launched three and six messenger satellites respectively at the end of 2019 and 2020, and launched a total of six satellites in two phases in 2021~2022, completing the networking of 24 messenger satellites. In 2019, Roscosmos also proposed to start building the "Messenger-2" low-orbit narrowband communications satellite constellation for the Internet of Things and mobile satellite communications in 2024, which is planned to consist of 28 satellites with an orbital altitude of 1,500km.

A number of domestic units have also carried out theoretical research, simulation calculation and in-orbit satellite verification of low-orbit satellite augmentation, and proposed corresponding constellation plans. Communication constellations such as "Hongyan" [5], "Hongyun" and "Space-Earth Integrated Information Network" all consider the needs of low-orbit satellite augmentation, and the micro-space and arrow brigade images focus on low-orbit high-precision enhancement. At the same time, the on-orbit technical tests of low-orbit test satellites such as "Hongyan Constellation Test Satellite", "Luojia-1", "Weili Space" and "Netcom-1" have accumulated experimental data for low-orbit satellite navigation signal enhancement technology and precision enhancement technology. At this stage, the "Nebula System" built by China is the second phase of the national satellite Internet project, which mainly provides communication and navigation services for civil and commercial users. Nebula Systems plans to launch 4 test satellites in September 2024, complete in-orbit verification in December 2024, complete the launch network of a total of 1,800 benchmark constellations by 2027, and complete the launch of a total of 3,600 constellations with an expanded configuration by 2030, with an orbital altitude of 508km, and its constellation configuration is shown in the figure below (Fig. 1).

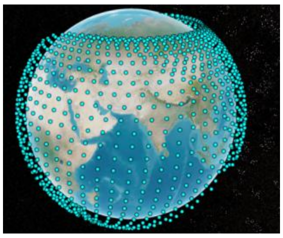

Fig. 1 Constellation diagram of the nebula system.

4. Key technologies for low-orbit navigation enhancement

The low-orbit navigation augmentation system [6] consists of three parts: the space segment, the ground segment and the user segment. The space segment is composed of dozens to hundreds of low-orbit satellites equipped with navigation enhancement payloads, and its main task is to broadcast navigation signals and enhanced information of high, medium and low-orbit navigation satellites to various users, and has the functions of forwarding satellites and navigation satellites. The ground segment includes a ground operation control system and a ground monitoring station to jointly complete the operation management and control of satellites in orbit, and the user segment includes various types of user terminals, modules, chips and supporting equipment. From the current concept stage to the actual operation of the business system in the future, a series of key technologies need to be broken through in the space segment, the ground segment and the user segment.

4.1. *Space Segments*

The design and optimization of constellation configuration is the primary problem that must be solved in the construction of space segment, which directly determines the cost, coverage performance, geometric strength and service capability of the augmentation system. The large number of low-earth orbit satellites is prone to multiple access interference, and due to the widespread use of L-band in multi-frequency GNSS, the signal in this band is becoming increasingly congested, and the problem of signal interference is becoming more and more serious. Therefore, it is necessary to design a new signal system with certain anti-interference performance, develop new navigation frequency bands (such as S-band and C-band), and study the technologies of spread-spectrum code optimization, signal modulation, capture and tracking, channel coding and multiplexing suitable for low-orbit navigation enhancement signals.

How to maximize the advantages of the low-orbit constellation itself, and realize the integration of navigation and communication is also the key. It is now possible to use mobile communication networks to broadcast GNSS augmentation messages. It can be considered that satellite navigation and mobile communications have achieved partial integration. Because the low-orbit navigation enhancement will mainly rely on the Internet constellation in the future to promote, the future will further strengthen the deep integration of navigation and communication at the information level and even the signal level, through the joint design of the navigation enhancement signal and the mobile communication signal, all the power of the navigation signal is allocated to the pilot component, which is conducive to the tracking, acquisition and ranging of the receiver, and the message data can be quickly broadcast through the low-orbit Internet communication.

In terms of the configuration of satellite payloads, it is necessary to rely on the low-orbit Internet constellation platform, and select some satellites to achieve multiple uses of one satellite, and carry out scientific research such as navigation augmentation, remote sensing, satellite gravity, satellite altimetry, occultation detection, and satellite-based GNSS-R by carrying different payloads. Due to the low space ionizing radiation in the low-orbit region, commercial off-the-shelf (COTS) devices and chip-scale atomic clocks (CSACs) can be used to reduce costs.

4.2. *Ground Segments*

The ground operation control part also faces some challenges. Due to the special dynamic characteristics of low-orbit satellites, they are different from traditional medium- and high-orbit GNSS satellites in terms of fitting time, update frequency, and number of parameters of ephemeris and clock parameters. Compared with the basic navigation data, the effective time of the augmentation correction number is short and the timeliness is strong, which is divided into fast and slow correction parameters, and the parameter characteristics of the augmentation information must be analyzed, the relationship between the accuracy index of the fitting parameters and the broadcast delay is obtained, and the real-time requirements of each augmentation parameter are obtained. The low-orbit navigation message information and its orchestration mode, fast and slow message parameters and other information need to be redefined according to the reserved information bits, which mainly depends on the coordination between the system advertising capability and the real-time requirements of parameter broadcasting.

Low-orbit satellites have fast operating speed, short transit time, shortened information transmission time, and small ground coverage, so more ground injection stations or inter-satellite link communication are needed for message transmission. If inter-satellite communication is adopted, it should form a hybrid constellation with medium- and high-orbit satellites, and the optimal choice of communication mode between low-orbit satellites and medium- and high-orbit satellites is a problem to be demonstrated and solved. An important task in the ground segment is to establish and maintain the spatiotemporal datum of the low-orbit navigation augmentation constellation. The fusion and processing of GNSS and low-orbit augmented data needs to be completed under a high-precision and unified spatio-temporal framework. For the time system, it is necessary to give the time definition of the low-orbit navigation augmentation system, and carry out the establishment and maintenance of the system time, the internal time synchronization of the system, the time traceability and the time difference forecast. For the coordinate system, it is necessary to give the method of definition, implementation, update, maintenance and conversion of the coordinate system of the low-earth navigation augmentation system with other coordinate systems. The unification of space-time datums is inseparable from GNSS and low-orbit constellation precision orbit estimation clocks.

In order to obtain the real-time precision orbit of all low-orbit satellites, the ground main control station can adopt a variety of orbit determination strategies, including GNSS and low-orbit constellation joint precision orbit determination and orbit prediction under the condition of regional monitoring stations, orbit determination of low-orbit constellation using only the global tracking station network without relying on GNSS, inter-satellite link orbit determination, etc., due to the large number of satellites and the large amount of calculation, the single station observation arc is short, and there is an unstable and discontinuous situation of satellite entry and exit in local areas. Therefore, it is necessary to analyze and demonstrate the influence of different observed arc lengths on the orbit determination accuracy, and develop a high-efficiency distributed and parallel processing algorithm. The most difficult model of orbit determination and orbit prediction is the solar pressure model, which is mainly affected by the factors such as satellite platform and satellite attitude, and it is necessary to obtain the corresponding light pressure reflection coefficient for different types of low-orbit satellites, study the parameter change characteristics of the dynamic model based on the solar pressure reflection coefficient, and establish a high-precision mathematical model related to satellite attitude and solar position, so as to improve the accuracy of precision orbit determination and medium and long-term forecasting.

In terms of satellite-ground time maintenance and synchronization, due to the influence of factors such as power consumption, size, weight and cost of high-performance spaceborne atomic clocks, it is not suitable for the low-cost requirements of low-orbit satellites, and CASC or OCXO are generally used as substitutes for time maintenance. Or some satellites are equipped with high-performance atomic clocks, and the rest of the satellites achieve time synchronization through inter-satellite and satellite-to-ground communication.

The ground control component is also responsible for low-orbit navigation, enhanced constellation management and satellite control. These include: the development of long-term and medium-term mission plans to ensure global coverage and continuity of signals; maintenance of the overall constellation of satellites; Sufficient replenishment of satellites as planned; Dealing with unexpected events and failed satellites to minimize their impact on services; Monitor and control the status of each satellite in all aspects, ensure the normal operation of the satellite and payload, and deal with some unexpected events when unexpected events occur; Plan and execute track scheduling, platform maintenance, etc.; Support on-orbit software maintenance.

4.3. *User Segments*

The enhancement of low-orbit navigation puts forward new requirements for the software and hardware equipment and data processing methods of ground users. Under the high dynamic conditions of low-orbit satellites, the receiver signal acquisition is more difficult, the Doppler search range is larger, and the acquisition speed is reduced. In a short period of time, the distance in the direction of the station satellite connection changes greatly, which makes the received signal strength change greatly, resulting in uneven changes in pseudorange noise, affecting the accuracy of code observations, and the RF front-end of the receiver must also change. At the same time, the acceleration in the direction of the station-satellite connection line will also change greatly, resulting in a large change in the carrier frequency and code phase, which is easy to cause signal lock-up, greater Doppler prediction uncertainty and shorter coherent integration time requirements, which brings challenges to the high-precision and stable tracking of signals. The number of low-orbit satellites is large, and the observation arc is short, and the satellite switching is frequent, so it is necessary to increase the number of channels, storage capacity, and microprocessor computing power of the receiver, and optimize the antenna unit and the receiving unit. For low-orbit navigation, S or C band enhancement signals may be used, and L+S or L+C integrated antennas need to be designed, and the corresponding RF, analog-to-digital conversion, baseband signal processing, capture, tracking, demodulation and other methods need to be adjusted.

In terms of data processing, more stringent quality control algorithms should be designed and developed to diagnose anomalies in satellite orbits and satellite clock products. Signal lock-up and frequent satellite handover may produce more cycle slips, while low-orbit satellites operate fast and the ionospheric changes between epochs are large, so traditional cycle slip detection algorithms such as the ionospheric residual method will no longer be applicable, and more effective algorithms need to be studied. The mathematical model of HFO satellite fusion positioning needs to be further refined, because the new navigation augmentation signal will introduce more deviations related to the system, orbit type, code type and frequency, etc., and the time and space characteristics of various deviations need to be carefully analyzed and modeled, and they should be corrected or estimated in subsequent data processing. In addition, the reasonable weighting of observations of multi-source heterogeneous constellations is also a problem that needs attention.

5. Opportunities presented by low-orbit navigation augmentation technology

Compared with medium- and high-orbit navigation satellites, including Beidou and GPS, low-orbit satellite navigation signals will bring new development opportunities for the construction of GNSS global space-based monitoring networks, the provision of global quasi-real-time high-precision services, and the provision of global high-integrity monitoring services due to their unique orbit and signal characteristics.

5.1. *LEO constellations and signals have unique advantages*

1) Low-orbit satellites have low orbits and small weights, and the cost of satellites and launches is low. Low-orbit satellites are lighter in weight and lower in orbit than medium- and high-orbit satellites, and can be

launched with multiple satellites with one arrow, and the cost of satellite research and development and rocket launch is lower.

2) The landing signal strength is higher, which can improve the positioning effect and improve the usability under the condition of occlusion

The orbital altitude of low-orbit satellites is generally about 1000km, and compared with medium- and high-orbit navigation satellites with an altitude of more than 20000km, the signal transmission path of low-orbit satellites is shorter, and the signal delay and power loss are smaller. To put it simply, if a low-orbit satellite and a medium- and high-orbit satellite transmit the same signal power, the signal power transmitted by the low-orbit satellite to the earth's surface will be 30dB (i.e., 1000 times) higher than that of the medium- and high-orbit satellite. Stronger landing signal power can improve the positioning effect in complex terrain environments and complex electromagnetic environments, and enhance anti-interference and anti-spoofing capabilities.

3) The low-orbit satellite runs fast, accelerates the high-precision positioning convergence time, and provides a better user experience

The geometric configuration of the satellite constellation in medium and high orbit changes slowly, and the correlation between the observation equations between adjacent epochs is too strong, so it takes a long time to estimate and separate various errors when estimating positioning parameters, so as to fix the carrier phase ambiguity and achieve precise positioning. Therefore, the convergence time of traditional high-precision positioning is generally 15 minutes ~ 30 minutes.

However, the time for low-orbit satellites to orbit the earth is much smaller than that of medium- and high-orbit satellites, and the trajectories of low-orbit satellites in the same period of time are longer and the geometric configuration changes rapidly. Theoretically, the operation of a low-orbit satellite for 1 minute is equivalent to the geometric change of the current medium-orbit satellite for 20 minutes. The orbital characteristics of low-orbit satellites help to accelerate the convergence time of high-precision positioning, reaching 1 minute convergence, and the user experience is more excellent (Fig. 2).

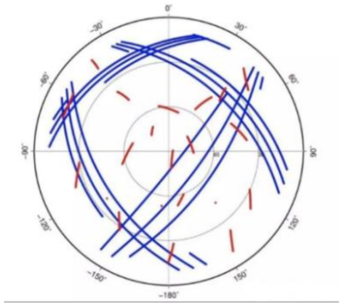

Fig. 2 Trajectories trajectories of low-orbit and medium-high orbit satellites in the same time (red is the trajectory of medium- and high-orbit satellites, and blue is the trajectory of low-orbit satellites).

4) Higher information rate, more precise correction information can be broadcast

Due to the increase of landing signal power, the LEO enhanced signal can carry a higher information rate or a larger signal bandwidth, and can be used as an broadcast channel for satellite navigation basic messages and differential correction messages.

5) The terminal is miniaturized, integrated, low power consumption, and easy for users to use

The improvement of low-orbit enhanced signal power is conducive to the use of smaller terminal equipment by ground users; At the same time, when used as a communication, ground users can be normally received by low-orbit satellites with a smaller signal power.

5.2. *Establish a GNSS global space-based monitoring network*

Generally speaking, GNSS requires global distribution of ground monitoring stations for observation support, and the United States, Russia, and Europe basically adopt the approach of global station construction to meet the requirements of global continuous observation. Most of the GPS monitoring stations in the United States are located near the equator, including five monitoring stations in Colorado, Diego Garcia, Ascension, Cavagalin, and Hawaii. Russia has a large east-west span, which can basically solve the global observation problem of the GLONASS system; The European Galileo system can be used to establish stations in overseas colonies and achieve global observations. At present, China's Beidou system is mainly based on domestic station construction, and realizes global observation and operation support through inter-satellite links.

Based on the low-orbit satellite constellation, it can help build a GNSS global space-based monitoring network.

1) Achieve high-quality global monitoring of satellite navigation signals

Compared with the ground monitoring network, the observation of navigation signals by low-orbit satellites has the characteristics of less influence by ionosphere and troposphere, long tracking arc, more coverage times, and less influence of multipath effect. As a high-precision space-based monitoring station of GNSS, low-orbit satellites can greatly improve the observation geometry, weaken the correlation between tangential orbit and phase ambiguity, improve the accuracy of navigation satellite orbit and clock error, and effectively make up for the shortcomings of ground-based monitoring network in space coverage, so as to achieve global high-quality monitoring.

2) It can effectively improve the accuracy of satellite orbit determination

By selecting 30 navigation satellites, the orbit determination capabilities of only ground monitoring stations, low-orbit satellite-based monitoring and ground joint monitoring were simulated and analyzed. Only the ground monitoring station carries out orbit determination, and the space signal accuracy is about 0.3 meters, and the space-based monitoring station composed of 12 low-orbit satellites has a signal accuracy of about 0.1 meters. Preliminary analysis shows that the ground-based and space-based joint monitoring and orbit determination based on the low-orbit constellation can improve the orbit determination accuracy of the constellation by more than one times.

5.3. *Provide global quasi-real-time high-precision services*

1) Diversification of high-precision positioning service providers and hierarchical service models

At present, high-precision positioning services (precision single-point positioning, PPP) mainly include commercial PPP services and PPP services embedded in satellite navigation systems.

The main commercial services are the Global Differential GPS (GDGPS) system for satellite orbit determination, scientific research and high-end commercial services from the Jet Propulsion Laboratory (JPL) in the United States, the StarFire system from Navcom, the OmniSTAR system and RTX system from Trimble, the StarFix/SeaStar system from Fugro, and the C-Nav system from Oceaneering International. Hexagon's Veripos system and TerraStar system include meter-level, decimeter-level, centimeter-level and other service capabilities.

In recent years, with the increasing demand for high-precision applications in the industry and the public, Galileo in Europe, QZSS in Japan and Beidou in China have also designed and provided PPP services embedded in satellite navigation systems. Galileo provides free PPP services based on E6B signals, with an advertising rate of 500bps, and enhances the GPS and Galileo systems to achieve decimeter-level positioning. QZSS precision positioning is divided into two categories: sub-meter level enhanced service (SLAS) and centimeter-level enhanced service (CLAS), both of which are free services, which are provided by L1 and L6 signals respectively, of which the CLAS service broadcast rate reaches 2000bps, which can enhance the four major GNSS and QZSS five systems at the same time. China's Beidou system uses GEO satellites to provide high-precision positioning free services to users in China and surrounding areas, with a broadcast frequency of B2b and a rate of 500bps, to achieve real-time decimeter-level and post-event centimeter-level positioning.

2) The precision enhancement of low-earth orbit satellites has the characteristics of fast convergence, which can improve the high-precision user experience

At present, the PPP service provided by GNSS through medium and high orbit satellites usually has a convergence time of 15~30 minutes due to its slow orbit change. Although Japan's QZSS system uses PPP-RTK technology to shorten the convergence time of PPP services to less than 1 minute, it requires the support of a large number of highly dense ground monitoring stations, and thousands of monitoring stations need to be built within the territory of Japan alone. The low-orbit satellite has the ability of global GNSS high-precision monitoring, and the geometric change is large, which is easy to achieve high-precision positioning and rapid convergence. Relevant studies show that after the integration of low-orbit satellite constellation, the convergence time of satellite navigation system PPP service can be shortened to less than 1 minute, and users can obtain high-precision services in quasi-real-time.

5.4. *Provide global high integrity monitoring services*

1) At present, each satellite-based augmentation system mainly provides regional integrity services

Integrity service refers to the timely warning to users when navigation satellites fail and risks, so as to improve the user's ability to use safety, which is particularly important for users involved in life safety such as civil aviation.

At present, the satellite-based augmentation systems (SBAS) mainly include the FAA Wide Area Augmentation System (WAAS), the European

Geostationary Satellite Navigation Overlay Service (EGNOS), China's Beidou Satellite-based Augmentation System (BDSBAS), the Russian Differential Correction and Monitoring System (SDCM), the Japanese Multifunctional Satellite Augmentation System (MSAS), the Indian GPS-assisted Geostationary Orbit Augmentation and Navigation System (GAGAN), the South Korean Satellite Augmentation System (KASS), etc. The differential correction number is broadcast, and the GNSS accuracy and integrity of a certain area are enhanced. The coverage of each system is shown in the figure belo w (Fig. 3).

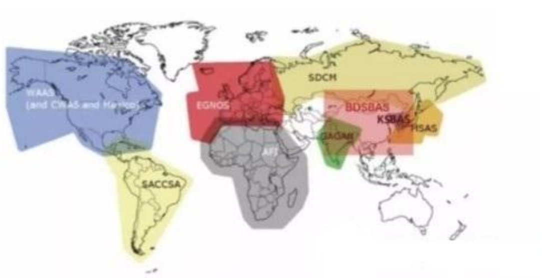

Fig. 3 SBAS Service Providers and Coverage

2) Higher-quality space-based integrity monitoring capabilities

Through the GNSS global space-based monitoring network of the low-orbit constellation, the space-based monitoring of the integrity of navigation satellites can be realized, and the orbital characteristics of the low-orbit constellation make it not affected by the ionosphere and troposphere, and the multipath impact is smaller than that on the ground, which can improve the monitoring ability of the integrity of navigation satellites.

3) Integrity alarm information can be broadcast to the world

In the future, user demand for SBAS services will not only be satisfied with the region, but will be expanded globally. The global coverage of the LEO constellation gives it a natural ability to broadcast global integrity services.

6. Enlightenment and suggestions on the technical path for the enhanced development of low-orbit navigation

In view of the good development prospects of the low-orbit satellite low-orbit navigation augmentation system, the number of low-orbit satellite navigation systems currently planned has exceeded the number of GNSS systems. Each system has different ways to implement navigation enhancements. In the future, the field of low-orbit satellite navigation will face fierce competition, which puts forward high requirements for the construction speed and service level of China's low-orbit satellite navigation system. Foreign low-orbit satellite navigation systems have begun to have service capabilities and have been applied in specific industries and scenarios. At present, most of China's domestic low-orbit satellite navigation systems are in the stage of demonstration and in-orbit verification, and there is still a gap between technology and management and formal service provision.

In view of the construction cost and technical difficulty of the system, the current low-orbit satellite navigation system is mainly enhanced, supplemented by backup mode, and the navigation performance can be improved and backed up with fewer satellites. The enhancement mode adopts the mode of "information + signal enhancement", and comprehensively improves the service capability of the system by a variety of means. Considering the cost and technical risks of system construction, the LEO satellite independent navigation system is still in the stage of academic and technical research, and has the potential to be built simultaneously with the deployment of the giant LEO constellation.

Based on the research on the construction status of low-orbit satellite constellation at home and abroad, combined with China's national conditions, the development route of domestic low-orbit satellite navigation system is proposed.

1) For space segments

Step 1: Achieve single-weight coverage of the earth through 60~150 low-orbit satellites. Low-orbit satellites can be special navigation satellites, or low-orbit communication and remote sensing satellites equipped with standardized navigation enhancement payloads. At present, this stage of construction has been started, and a number of units have put forward construction plans in response.

Step 2: Dual coverage of the earth through 150~250 low-orbit satellites, with independent positioning capabilities, can be used as a supplementary backup system for GNSS. At the same time, it is capable of joint service with GNSS.

Step 3: More than 400 low-orbit satellites achieve multiple coverage of the earth, and the satellites do not rely on the use of low-cost on-board atomic clocks, intelligent large-scale operation and maintenance and other key technologies, reducing system construction and operating costs.

2) For the ground segment

The ground section mainly includes GNSS/low-orbit monitoring stations, GNSS/low-orbit data processing centers, and other data transmission and business control and other reuse with existing ground facilities. The construction of ground stations makes full use of existing resources, and realizes 10 domestic monitoring stations through new or renovated ones, realizes high-precision pseudo-code and carrier phase measurement and collection, and supports high-precision orbit determination and clock deviation determination.

3) For user segments

According to the number of visible Beidou satellites and low-orbit satellites, the terminal adopts the integrated design of conduction, comprehensively collects observation information, independently selects the positioning and calculation method, and supports multi-source fusion positioning, and the solution modes include GNSS independent positioning, low-orbit independent positioning, GNSS and low-orbit combined positioning, and auxiliary Beidou positioning in complex electromagnetic environment.

7. Conclusion

With the full completion of the four major navigation systems, the major countries in satellite navigation applications are also planning and deploying the development of a new generation of navigation systems, and actively looking for new capabilities to grow. With its advantages of high signal power, large geometric dynamics and strong anti-interference ability, the low-orbit constellation can form information enhancement and signal enhancement for GNSS on a global scale, and comprehensively improve the accuracy, integrity, continuity and availability of satellite navigation systems, which will bring new development opportunities for the construction of GNSS global space-based monitoring network, global quasi-real-time high-precision services and global high-integrity monitoring services. It is expected to solve the problems of global coverage, low landing power, long initialization time and low reliability of the current augmented system, and serve high-value security users such as power grids, banks, securities, and military in the future, as well as real-time precision positioning users represented by autonomous driving and drones. With the development of 5G/6G technology, the establishment of mobile communication networks in the air, space, ground and sea, and the improvement of the processing capacity of mobile terminals such as smart phones, the enhancement of low-orbit navigation is finally expected to enter thousands of households and realize mass application. The enhancement of low-orbit navigation will also be an important part of China's comprehensive PNT system. The integration of various satellites with different orbits will bring new changes and new developments to the world's satellite navigation, and the low-orbit constellation will become a new increment in the development of a new generation of satellite navigation systems because of its unique advantages.

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