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REVIEW

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Advances in BeiDou Navigation Satellite System (BDS) and satellite navigation augmentation technologies

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Abstract

Several noteworthy breakthroughs have been made with the BeiDou Navigation Satellite System (BDS) and other global navigation satellite systems as well as the associated augmentation systems, such as the commissioning of the BDS-3 preliminary system and the successful launch of the first BDS-3 GEO satellite which carries the satellite-based augmentation payload. Presently, BDS can provide basic services globally, and its augmentation system is also being tested. This paper gives an overview of BDS and satellite navigation augmentation technologies. This overview is divided into four parts, which include the system segment technologies, satellite segment technologies, propagation segment technologies, and user segment technologies. In each part, these technologies are described from the perspectives of preliminary information, research progress, and summary. Moreover, the significance and progress of the BeiDou Satellite-based Augmentation System (BDSBAS), low earth orbit augmentation, and the national BeiDou ground-based augmentation system are presented, along with the airborne-based augmentation system. Furthermore, the conclusions and discussions covering popular topics for research, frontiers in research and development, achievements, and suggestions are listed for future research.

Keywords: BeiDou Navigation Satellite System, Satellite navigation augmentation systems, System segment technologies, Satellite segment technologies, Propagation segment technologies, User segment technologies

Introduction

GPS came into full operation in 1995, when Russia, Europe, and China subsequently put their satellite navigation systems into full use (Elliott and Christopher 2006). In recent years, China has been actively promoting the construction and development of the BeiDou Navigation Satellite System (BDS), and by the end of the year 2000 the construction of BDS-1 was complete and BDS-1 began to provide GPS services for China. The construction of BDS-2 was completed at the end of 2012, after which BDS-2 was utilized to provide service for regions all over the Asia–Pacific region. China is also working on applying its BDS to serve users all over the world. With the rapid development of BDS in all aspects, the chief designer of BDS, Yang Changfeng, announced the initial operation of BDS-3 at the state council information office of China in early 2019, and since this time BDS-3 has been officially providing global positioning, navigation, and timing services. Completion of the construction of BDS-3 is expected to occur around 2020, after which BDS-3 will be able to provide services to the world on a wider basis.

It is well known that the navigation service provided by GNSS covers use with bicycles, cars, and trains, which require adequate position accuracy. As GNSS is gradually applied to civil aviation, stricter requirements need to be satisfied for safe flight. In addition to accuracy, integrity is also emphasized for the safe navigation of aircraft. The civil aviation authority has produced the requirements for satellite navigation systems in terms of required navigation performance (RNP), including accuracy, integrity,

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continuity, and availability. These requirements in terms of accuracy and integrity (Guo et al. 2019) are illustrated in Fig. 1. The requirements for accuracy in civil aviation vary from the kilometer level to the meter level, for safety en-route and when carrying out CAT-III approaches, and the requirements for integrity risk probability lie between 10^{-4}/h and 10^{-9}/approach level.

The International Civil Aviation Organization (ICAO) has recommended specific GNSS requirements for different phases of flight (Anonymous 2006), which are listed in Table 1. The ICAO divides the satellite navigation augmentation systems into three categories: the Satellite-Based Augmentation System (SBAS), the Ground-Based Augmentation System (GBAS), and the Airborne-Based Augmentation System (ABAS). Generally speaking, as GBAS and SBAS are built with corresponding auxiliary facilities, they are also known as external augmentation systems. ABAS is built with an internal receiver or other airborne navigation sources and is hence also sometimes called the internal augmentation system.

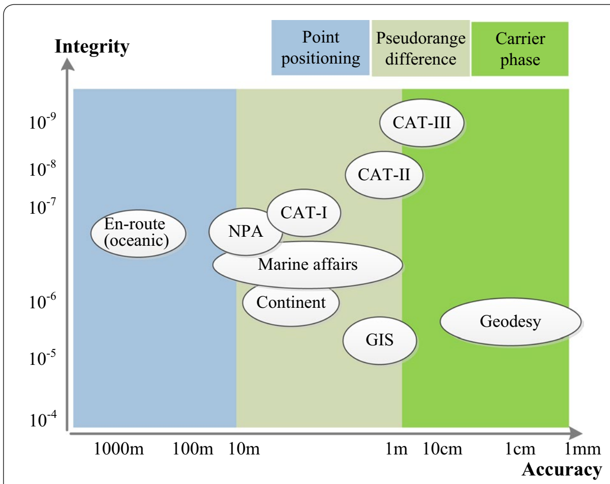

Fig. 1 Performance requirements in terms of accuracy and integrity

Satellite navigation augmentation technology is technology that can further improve the accuracy, integrity, continuity (Li et al. 2018), and availability of GNSS by generating augmentation information or adding a signal source. More specifically, satellite navigation augmentation technologies mainly include: satellite integrity monitoring and alarms, GNSS signal propagation technologies such as ionospheric propagation modeling, monitoring, and alarms, wide area integrity monitoring, local area integrity monitoring, GNSS differential correction, pseudolite augmentation, the design and implementation of the GNSS augmentation system, the analysis and verification of accuracy, integrity, continuity, availability, the accurate detection of faults and alarms, integrity risk modeling, anti-spoofing, and other augmentation technologies.

According to the principle of GNSS augmentation technologies, satellite navigation augmentation technology is divided into two categories: information augmentation technologies and signal augmentation technologies. For information augmentation technologies, the ground tracking network calculates GNSS signal error corrections and integrity information. The ground tracking network then broadcasts these data to users through the internet or satellite communication channels, and the user utilizes the received corrections and integrity information to process the GNSS signal received. For instance, the augmentation technology of GBAS is denoted information augmentation technology. Signal augmentation technologies refer to technology which provides additional ranging signals to complement

Table 1 ICAO GNSS requirements for different phases of flight

Typical operation	Accuracy (H,V)	Integrity		Continuity	Availability
		Integrity probability	Alert limit (H,V)		
En route	3700 m, –	$1–1 \times 10^{-7}$/h	3700 m, –	$1–10^{-4}$ to $1–10^{-8}$/h	0.99–0.99999
Terminal	740 m, –	$1–1 \times 10^{-7}$/h	1850 m, –	$1–10^{-4}$ to $1–10^{-8}$/h	0.99–0.99999
NPA	220 m, –	$1–1 \times 10^{-7}$/h	556 m, –	$1–10^{-4}$ to $1–10^{-8}$/h	0.99–0.99999
APV-I	16 m, 20 m	$1–2 \times 10^{-7}$/APCH	40 m, 50 m	$1–8 \times 10^{-6}$/15 s	0.99–0.99999
LPV	16 m, 20 m	$1–2 \times 10^{-7}$/APCH	40 m, 50 m	$1–8 \times 10^{-6}$/15 s	0.99–0.99999
LPV200	16 m, 4 m	$1–2 \times 10^{-7}$/APCH	40 m, 35 m	$1–8 \times 10^{-6}$/15 s	0.99–0.99999
APV-II	16 m, 8 m	$1–2 \times 10^{-7}$/APCH	40 m, 20 m	$1–8 \times 10^{-6}$/15 s	0.99–0.99999
CAT-I	16 m, 4–6 m	$1–2 \times 10^{-7}$/APCH	40 m, 10–15 m	$1–8 \times 10^{-6}$/15 s	0.99–0.99999
CAT-II/IIIA	6.9 m, 2.0 m	$1–2 \times 10^{-9}$/APCH	17.3 m, 5.3 m	$1–4 \times 10^{-6}$/15 s	0.99–0.99999
CAT-IIIB	6.1 m, 2.0 m	$1–2 \times 10^{-9}$/APCH	15.5 m, 5.2 m	$1–1 \times 10^{-7}$/15 s	0.99–0.99999

APCH APproaCH, *H* Horizontal, *V* Vertical those already provided by GNSS. Through the use of signal augmentation technologies, users can obtain accurate and reliable information concerning position in situations where GNSS cannot usually be used or does not work sufficiently (Ge et al. 2018; Wang et al. 2018a, b). For example, Low Earth Orbit (LEO) augmentation technology is a type of signal augmentation technology (Li et al. 2019a; Ma 2018; Reid et al. 2016). SBAS is a combination of information augmentation technologies and signal augmentation technologies, providing multiple augmentations including ranging signals, corrections, and integrity.

Satellite navigation augmentation technologies are of four types: system segment technologies, satellite segment technologies, propagation segment technologies, and user segment technologies. In this study, the theory and application of the augmentation technologies used in the BDS/GNSS augmentation systems are introduced with an emphasis on the theory and application of the BeiDou Satellite-Based Augmentation System (BDSBAS) and the National Beidou Ground-based Augmentation System (NBGAS). The popular topics in satellite navigation augmentation technologies are summarized from four perspectives. Through the introduction of the relevant technologies, the development status and trends in satellite navigation augmentation technologies are presented, providing a reference for future research.

System segment technologies

The system segment is the core of the GNSS augmentation system with the mission of monitoring GNSS satellites and generating differential corrections and integrity information over a wide area. System segment technologies are the key to the construction of GNSS augmentation systems and determine the service capability of GNSS augmentation systems. GNSS augmentation technologies used in system segments can be divided into two types: technology used in the SBAS system segment and technology used in the GBAS system segment.

Technologies of SBAS system segment

Preliminary information

SBAS system segments are mainly composed of monitor stations and master stations. Monitor stations receive and process signals from the GNSS and SBAS satellites (Parkinson et al. 1996). More specifically, monitor stations collect dual frequency code carriers and the pseudorange. The detection of cycle slip errors and repair can be implemented with dual frequency code carriers and the dual frequency carrier is used to smooth the dual frequency pseudorange, subsequently removing any ionospheric delay. Meteorological parameters are utilized to compute the tropospheric delay (SC-159 2013). The geometric range can be computed using the navigation message and the position of the monitor station. Common view time transfer is used to estimate the clock offset of the monitor station and the synchronized pseudorange (Chen et al. 2017; Tsai 1999). Finally, the monitor stations forward the resultant data to the master stations. Master stations generate differential corrections and integrity information with regard to each monitored satellite and each monitored ionosphere grid point (IGP). Differential corrections include long-term corrections, fast corrections, and ionospheric corrections. Long-term corrections and fast corrections are used to mitigate the slowly changing errors of the satellite clock-ephemeris and the rapidly changing errors of the satellite clock, respectively. Ionospheric corrections are used to revise the atmospheric delay and IGPs are used to deduce the pseudorange errors in the ionospheric pierce point. The accuracy of position provided by GNSS can be improved with differential corrections. Integrity Information includes the user differential range error (UDRE), clock-ephemeris covariance matrix, and the grid ionospheric vertical error (GIVE). UDRE is used to compute the integrity error bound for satellite clock-ephemeris errors and GIVE is used to compute the integrity error bound for ionospheric errors. Using GIVE and UDRE, the integrity protection levels of SBAS can be determined to analyze the probability of integrity. After generation by the master stations, the differential corrections and integrity information are quantified. All these data are packaged into SBAS messages and sent to navigation earth stations, as illustrated in Fig. 2. These stations then upload this augmentation information to SBAS satellites in space, and it is broadcast to users. The user receives the basic navigation signal from the GNSS satellite and the augmentation signal from the SBAS satellites, and thus determines location and information concerning safety.

Research progress

Satellite navigation augmentation systems, especially SBAS, have been a popular topic for many years. Existing SBAS systems include the Wide Area augmentation System (WAAS) in the United States, the European Geostationary Navigation Overlay System (EGNOS) in Europe, the System of Differential Correction and Monitoring (SDCM) in Russia, BDSBAS in China, the Mtsat Satellite-based Augmentation System (MSAS) in Japan, and Gps-Aided Geo-Augmented Navigation (GAGAN) in India. WAAS has been in full use for 16 years, providing the LPV200 service. China successfully launched the GEO-1 satellite (SBAS PRN 130) on November 1, 2018. BDSBAS is still under construction, with three GEOs yet to be launched (Liu 2019). The BDSBAS signal has been broadcast since November 9, 2018 (Liu 2019). BDSBAS

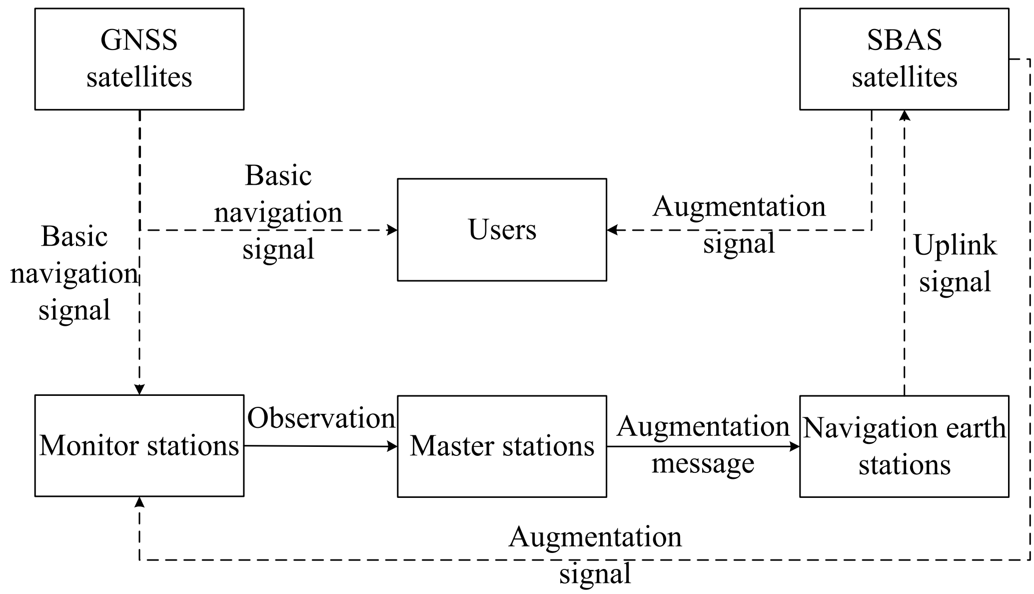

Fig. 2 Workflow of SBAS

is now broadcasting augmentation information to test the performance of SBAS. The augmentation information broadcast by BDSBAS does not conform to the service requirements for the Minimum Operational Performance Standards 229 of Radio Technical Commission for Aeronautics (RTCA MOPS 229); hence BDSBAS cannot yet provide services for civil aviation.

The goals surrounding the construction of BDSBAS are to perform wide area differential processing and integrity monitoring for BDS/GNSS satellites in China and its surrounding areas, broadcast augmentation messages via the B1C and B2a signals to users through the GEO satellites, and to improve the accuracy, integrity, continuity, and availability of the service. BDSBAS will initially suit the requirements of civil aviation users for APVI precision approach, ultimately reaching the level required for CAT-I precision approach. BDSBAS interoperates with WAAS, EGNOS, and other SBAS to provide information for the RTCA L1CA and RTCA DFMC interfaces. The BDSBAS satellites are located at 80°E, 110°E, and 140°E (Chen 2019; Guo et al. 2019; Liu 2019).

Few papers have been produced concerning BDSBAS. Chen Jinping, chief engineer of the Beijing Satellite Navigation Center, both designed and carried out preliminary testing on BDSBAS, producing a general design for BDSBAS including the system work mode, information processing mode, and analysis (Chen 2019), as shown in Fig. 3. The pseudorange and code phase of the monitor stations are returned to the information processing center at the master station in order to calculate the corrections necessary for the satellite, the ionospheric grid delay, and the corresponding information concerning integrity for use with multi-GNSS. Each monitor station is equipped with three independent receivers which are used for the calculation of differential corrections, integrity checks, and the backup of data. The master stations simultaneously process augmentation information for RTCA L1CA with the B1C signal and DFMC interfaces with the B2a signal. This information is then broadcasted by the GEO satellites.

BDSBAS uses the kinematics model and the dynamics model for orbit and clock correction, respectively. According to analysis of the regional monitoring network data, the accuracy of the corrections for orbit offset is similar to that of the corrections of the clock offset. Results show that the UDRE of BDS-3 is near to 0.4 m which is conservative compared with that of WAAS and EGNOS. The parameters UDRE and GIVE can provide the integrity confidences for the corresponding corrections. Degradation parameters are useful for guaranteeing service integrity on the rare occasions when SBAS users fail to receive differential corrections. BDSBAS monitor stations across China have been selected as users to analyze the performance of BDSBAS in terms of the position domain and the single point position accuracy of BDSBAS, which is similar to that of WAAS and EGNOS. However, the probability of integrity is lower for BDSBAS than it is for WAAS and EGNOS. BDSBAS will soon be able to provide RTCA L1CA, RTCA DFMC, and other protocol augmentation information (Chen 2019).

Dual frequency range error (DFRE) is a critical integrity parameter in DFMC SBAS, and the method used

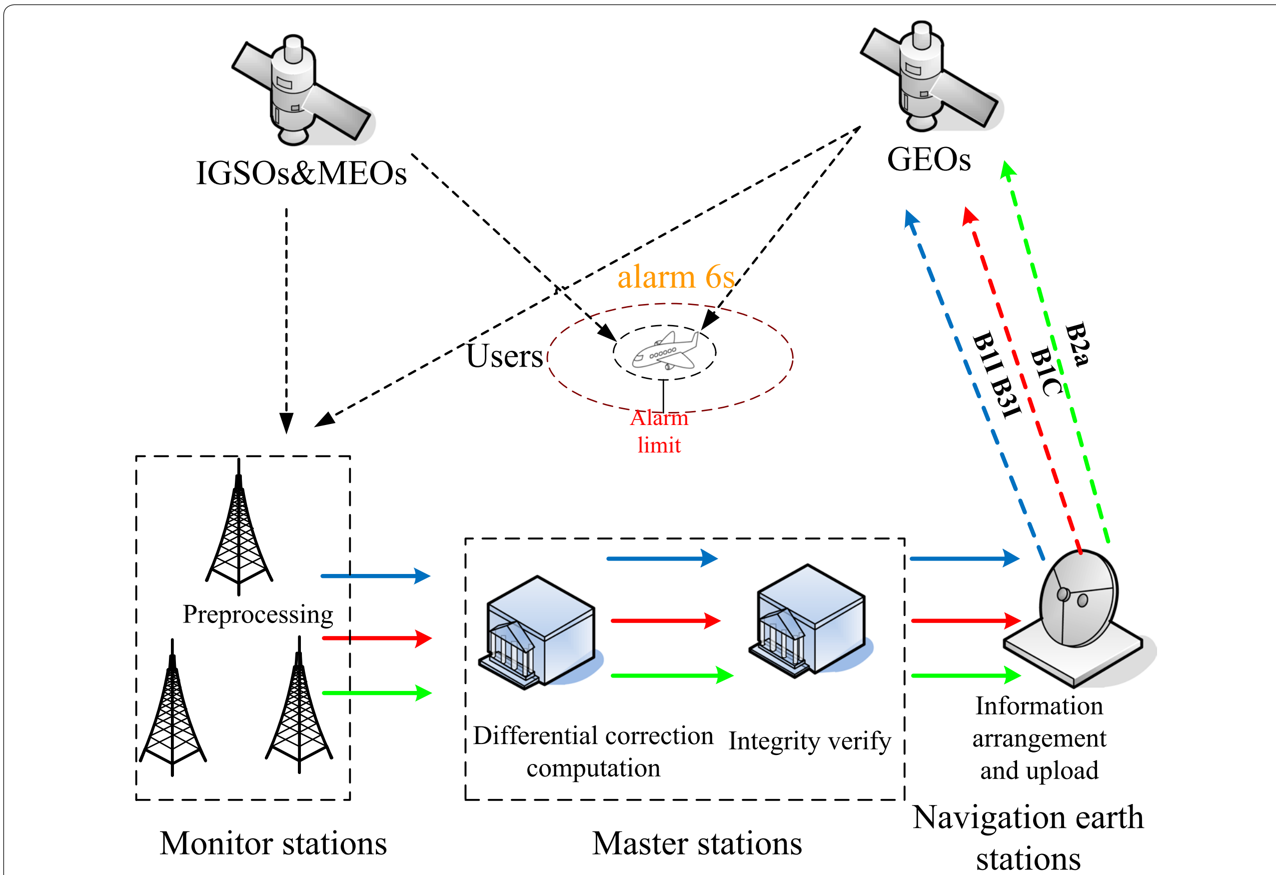

Fig. 3 BDSBAS operating process

to calculate DFRE has not yet been introduced in the relevant literature abroad. Shao Bo, an engineer at the 20th Research Institute of China Electronics Technology Group Corporation developed an integrity method for use with DFRE, using a projection method. The satellite clock-ephemeris covariance matrix is used to find the maximal projection direction, and the projection of the covariance matrix in this direction is defined as a DFRE which can form a bound for satellite correction error (Shao 2019; Shao et al. 2011).

The DFRE of BDS and GPS were solved and compared with the maximal corrected error using the observations made by the 24 monitor stations in China shown in Fig. 4. The DFRE, calculated using the projection method, can form an envelope for the maximal corrected error, which is suitable for monitoring the integrity of different constellations or types of satellites (Shao 2019; Shao et al. 2012). Results show that the DFRE solved with the projection method can bound the satellite correction error with a probability of 99.9%, and is suitable for use with different constellations or different kinds of satellites. After further validation, the method can be applied to the DFRE calculation of BDSBAS (Shao 2019; Shao et al. 2011).

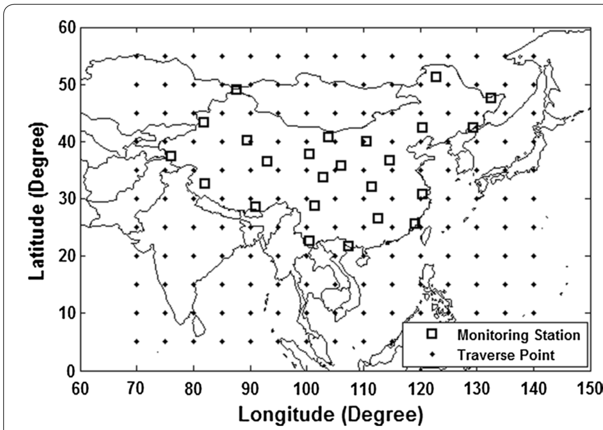

Fig. 4 Distribution of the selected monitor stations in China

In 2013, the China Aerospace Science and Technology Corporation Ltd signed a contract with the Algerian space agency regarding the Algerian communication satellite (Alcomsat-1). Alcomsat-1 utilizes a DFH-4 satellite and is equipped with 33 transponders, including the L1 and L5 navigation augmentation transponder payloads. The China Aerospace Science and Technology Corporation Ltd constructed a satellite augmentation system based on the Alcomsat-1, named Al-SBAS, in order to provide services for Algeria and the surrounding area. The Alcomsat-1 communications satellite was launched on December 11, 2017, and is located at 24.8° W in a geostationary orbit (Li 2019).

Compatible with ICAO standards and based on ALCOMSAT-1, the SBAS aims to improve the positioning accuracy and integrity in Algeria and the surrounding area, providing services for users in many fields such as surveying, transportation, aviation, railways, and the ocean (Li 2019), as seen in Fig. 5. The system collects GPS observations and solves GPS satellite ephemeris errors, clock errors, and ionospheric errors together with the corresponding integrity parameters in real-time, and broadcasts differential corrections and integrity information through GEO satellites with a high accuracy and a significant capability for integrity augmentation (Li 2019).

The ground segment of Al-SBAS is composed of 18 monitor stations in Algeria, a data processing center in Algiers, and an uplink station in Algiers. Signals that are supported include GPS, GLONASS, BDS, and GALILEO. The data processing center is used to perform local system redundancy, automatic switchover, autonomous state monitoring, and fast seamless recovery. The system collects data from GPS monitor stations to generate satellite corrections, ionospheric corrections, and integrity parameters, and then broadcasts these augmentation data through the GEO satellite Alcomsat-1 which is equipped with two way L1 and L5 navigation augmentation payloads (Li 2019).

The positioning accuracy of the single frequency and dual frequency services is at a sub-meter level. Follow-up plans include continuous operation, monitoring and evaluation of the L1 augmentation service, updating the L5 augmentation signal, BDS augmentation services, the issue of a signal-in-space ICD, and public services. AL-SBAS improves the positioning accuracy

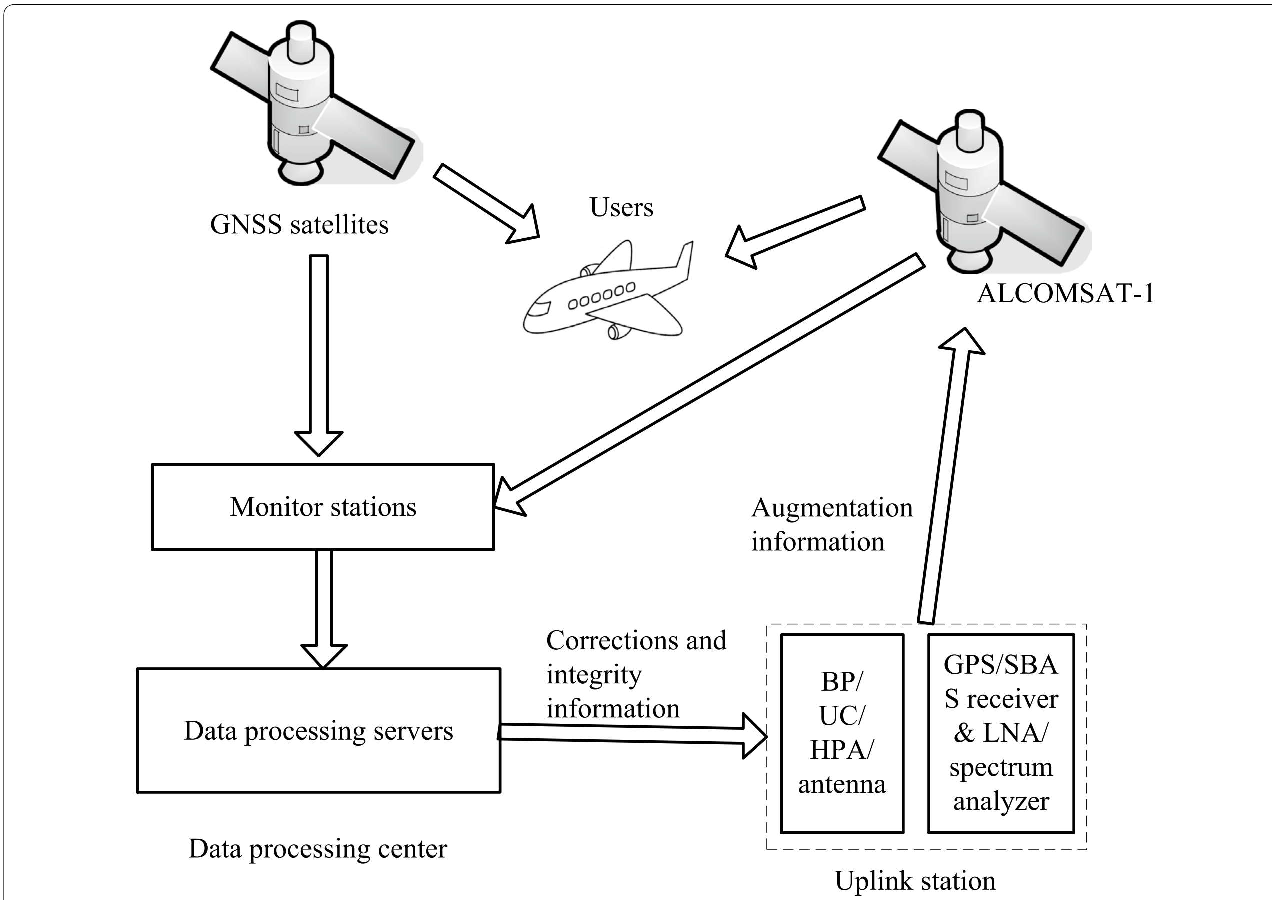

Fig. 5 Al-SBAS operating process based on ALCOMSAT-1

and integrity of GPS in the Algerian region. The construction and final testing of the ground monitor stations, data processing center, and the uplink station for AL-SBAS have been completed (Li 2019). The future prospects of Al-SBAS in Algeria and its surroundings are therefore promising.

The Wide Area Precise Positioning System (WAPPS) is a GNSS differential system for real-time high accuracy positioning and navigation as shown in Fig. 6. By referring to the work mode of SBAS, WAPPS broadcasts corrections by broadcasting from satellites and via the internet to ensure that users perform precise point position-ing (PPP) (Shen et al. 2019). With the advantages of the low density of stations, wide range of services, variation in services, and the simple user terminal, WAPPS is applied to marine transportation, surveying, and accuracy agriculture, among others. WAPPS provides services that are related to the safety, for which integrity with high accuracy in real-time can be obtained from the WAPPS signal produced by broadcasting satellites and the WAPPS service on the internet (Wang 2019e).

Similar to other differential systems such as SBAS and GBAS, integrity monitoring also needs to be performed for WAPPS. The performance of both the pseudorange and carrier correction is monitored to guarantee the service performance of PPP. The percentage of missed alerts is 10^{-3}, the percentage of false alerts is 10^{-5}, and the time taken to produce an alert is less than 10 s. WAPPS provides services using dual frequency ionosphere-free combination. Dual frequency ionosphere free combination can remove any ionospheric delay sufficiently, even when abnormal phenomena occur in the ionosphere. The carrier cycle slip and other abnormalities in the user segment need to be guaranteed by the receiver, which are not considered in the integrity monitoring of the system. WAPPS integrity fault modes can be divided into step faults and slow drift faults. All faults will affect the pseudorange, the carrier observation, and the positioning performance. Results reveal that in normal status, integrity monitoring can ensure the requirements for missed alerts and false alerts. When step faults or slow drift faults occur in the corrections, the alert has to be sent to a user within a short period of time. A slow drift rate of 0.1 m/s can be detected within 5 s with carrier phase monitoring (Wang 2019e).

An engineer at Space Star technology CO., Ltd recently predicted the service performance of single frequency BDSBAS and dual-frequency Multi-constellation (DFMC) SBAS in China without consideration of the

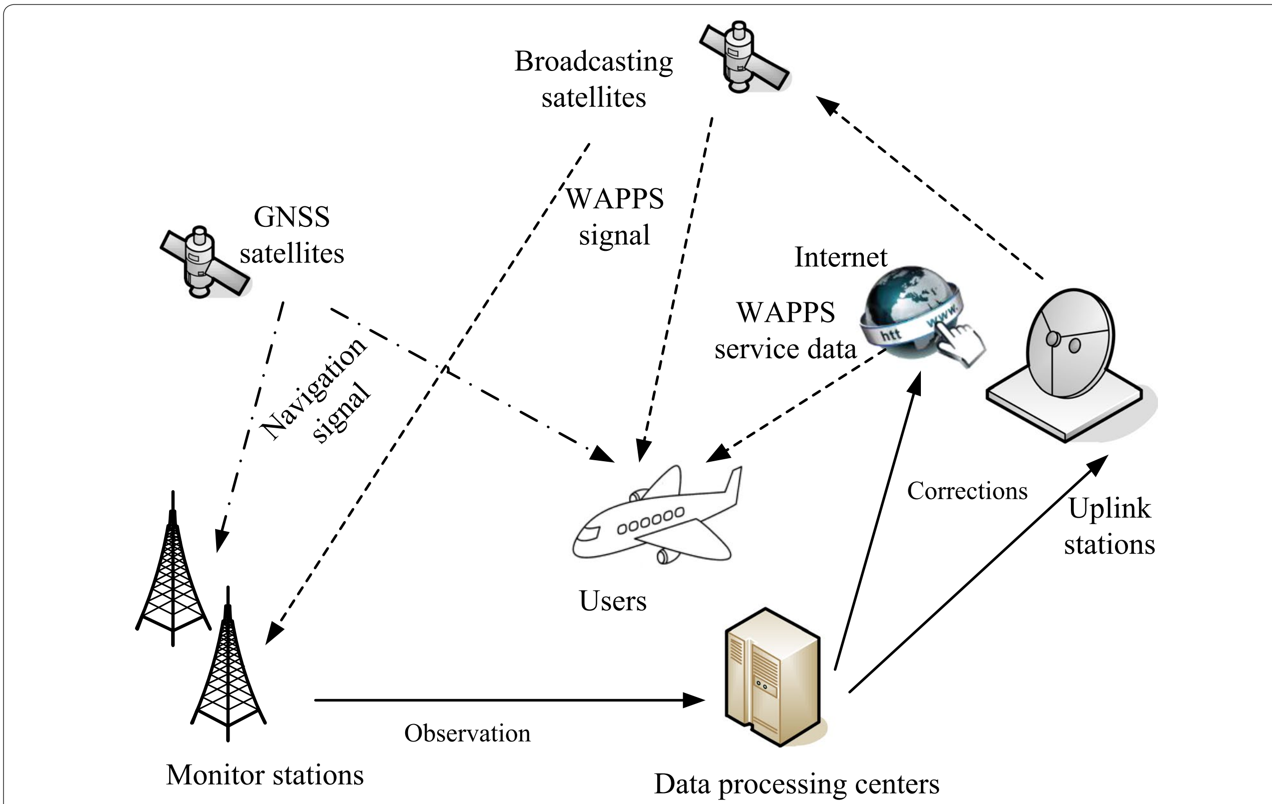

Fig. 6 Demonstration of the WAPPS operating process

broadcast of clock-ephemeris covariance matrix and augmentation information quantification (Chen et al. 2019). The results of this research are better than the BDSBAS performance derived from the general engineering community, which has led to many questions. Considerable work is needed to forecast the service performance of BDSBAS.

Summary

BDSBAS is still under construction. China successfully launched the first SBAS satellite and began broadcasting its augmentation signal last year. Two SBAS satellites still remain to be launched. Although BDSBAS has been broadcasting an augmentation signal for approximately 1 year, BDSBAS is still being tested and therefore cannot yet provide services for civil aviation.

Several studies have been carried out concerning the system segment of BDSBAS. The methods used for augmentation information are being developed from institute to university. Some scholars have given the design and preliminary analysis of BDSBAS the principle of differential correction and integrity parameters, and the service performance of BDSBAS. The algorithms used in the system segment of SBAS are significant for the construction of BDSBAS and are hence popular targets for research.

Technologies of GBAS system segment

Preliminary information

GBAS is a kind of differential GNSS (DGNSS) that is applied to aircraft for a precision approach. GBAS is able to provide CAT-I and higher level precision approach and landing guidance services for aircrafts equipped with the corresponding airborne equipment within the airspace of the terminal area of an airport (Geng 2019).

Aviation GBAS consists of a ground segment and an airborne segment. The ground segment consists of a reference receiving subsystem, a ground processing subsystem, a maintenance management subsystem, and a VDB (very high frequency Data Broadcasting) subsystem. The airborne segment mainly refers to the multi-mode receiver (MMR). The reference receiving subsystem receives the ranging signal of the GNSS satellites and forwards it to the ground processing subsystem. The ground processing subsystem then generates the augmentation information for GBAS users. The maintenance management subsystem is used to ensure the normal work of the ground processing subsystem can detect any faults in the ground processing subsystem and send control commands to the ground processing subsystem. After receiving the augmentation information, the VDB subsystem transmits it to GBAS users, receiving the augmentation information from the MMR and calculating the location and the integrity information for the pilot. In detail, the ground processing subsystem generates the differential corrections for the visible satellite by combining observations from each reference receiver. The integrity information of the visible satellite or the navigation system is formed at the same time through the real-time monitoring of the navigation signal or the abnormality at the ground stations. The final approach segment (FAS) data, calibration, and integrity information are then transmitted through VDB to the airborne users, as illustrated in Fig. 7. The airborne user receives the augmentation information from the VDB subsystem and generates flight information which is displayed in the flight control instruments and display. As GBAS normally uses specialized reference stations that are located close to each other, which are always distributed around an airport, and the distance between the airborne users and the GBAS stations is close (less than 50 km), the errors between them are strongly correlated and GBAS can thus improve the positioning accuracy and integrity of the airborne users.

Research progress

GBAS is currently under development worldwide. The GBAS sls-3000 ground stations by Honeywell were installed at Malaga airport in Spain early in 2007. France conducted a signal-in-space verification of the CAT-I ground station for GBAS that was installed at Toulouse in 2006, and continuously monitors GBAS performance. As of 2009, the FAA has placed multiple CAT-I GBAS installations into service using the Honeywell SLS-4000 ground station. In 2017, the FAA began to carry out system design approval for the GAST-D system. However, the FAA had to suspend this project due to a lack of funding. In 2018, Japan finished the development and deployment of ground and airborne subsystem software for GBAS, and began to perform data collection and analysis. Japan plans to conduct air-ground experiments in 2019. In China, the China Electronics Technology Group Corporation is performing research and development on the GBAS Approach Service Type D (GAST-D), using its CAT-I GBAS products as a base.

China is also conducting research on NBGAS, using the BDS. NBGAS is a pivotal part of BDS. NBGAS uses an advanced system architecture, data processing system, and software to realize multiple mode positioning accuracy augmentation, utilizes various broadcasting means to broadcast augmented data products, and provides positioning with accuracy at the meter, decimeter, and centimeter level, or on the millimeter level after post-processing.

Geng Yongchao, a senior engineer at the CETC Northwest Group Co., LTD, developed GBAS for civil aviation,

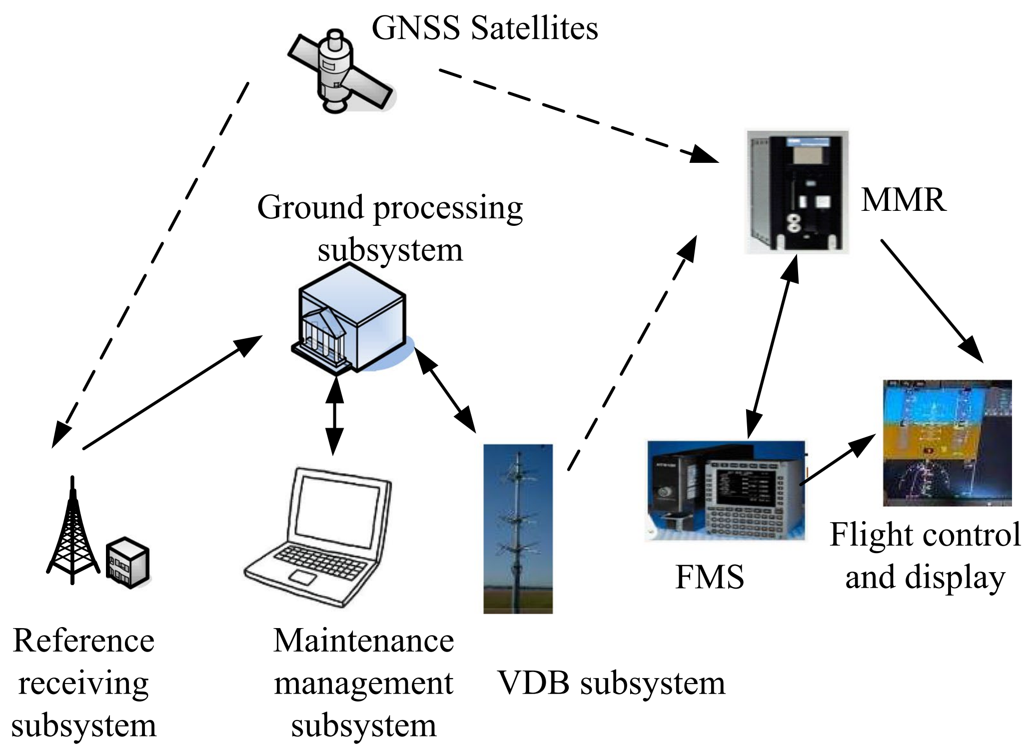

Fig. 7 Demonstration of aviation GBAS

including the concept of using GBAS for civil aviation, the civil aviation GBAS architecture, and progress in GBAS. The CETC Northwest Group Co., LTD has performed flight testing with inspection aircrafts. After performing a static check, a taxi check, GBAS reception, and a flight test, the group concluded that lgf-1a GBAS equipment can provide aircraft precision approach, automatic landing, and taxi guidance services under the current regulatory specifications (Geng 2019).

Cai Yi, a chief designer at the China Research & Development Academy of Machinery Equipment, developed NBGAS, with test equipment and a user terminal as shown in Fig. 8. NBGAS refers to the national BeiDou ground-based augmentation system which can provide service for ships, trains, and cars, etc. Unlike GBAS, which is designed to serve civil aviation, NBGAS is designed to provide a high precision positioning service for many areas. NBGAS focuses on the services of satellite broadcasting, digital radio, and mobile communication. NBGAS uses different wide reference stations (RSs) than GBAS, and pays significant amounts of attention to position accuracy. Obviously, NBGAS cannot support the current ICAO GBAS standards or provide service for civil aircrafts as does GBAS. NBGAS are composed of BeiDou augmentation RSs which are distributed all over China, data processing systems, data broadcasting systems, and user terminals. BeiDou wide area RSs and regional RSs collect the GNSS signals and forward these data to the corresponding data processing systems. NBGAS data processing systems include industrial data processing systems and national data processing systems, both of which output high accuracy real time (RT) products from the meter level to the millimeter level, which is sent to users through data broadcasting systems. Finally, users such as the cars drivers and pilots can obtain NBGAS services.

The real-time positioning accuracy for NBGAS was tested at the meter level, decimeter level, centimeter level, and post-processing millimeter level augmentation by Cai Yi. Results showed that the positioning accuracy of NBGAS meets or exceeds the design performance. According to the service capability tests for real-time positioning accuracy at the meter level to the post-processing millimeter level, the service capability of NBGAS's positioning accuracy meets and is superior to that indicated by the system design (Cai 2019).

Summary

With the rapid development and improvement of BDS, the system is being widely applied in many areas. As an important navigation system, the ground-based augmentation system has begun to provide services for all kinds

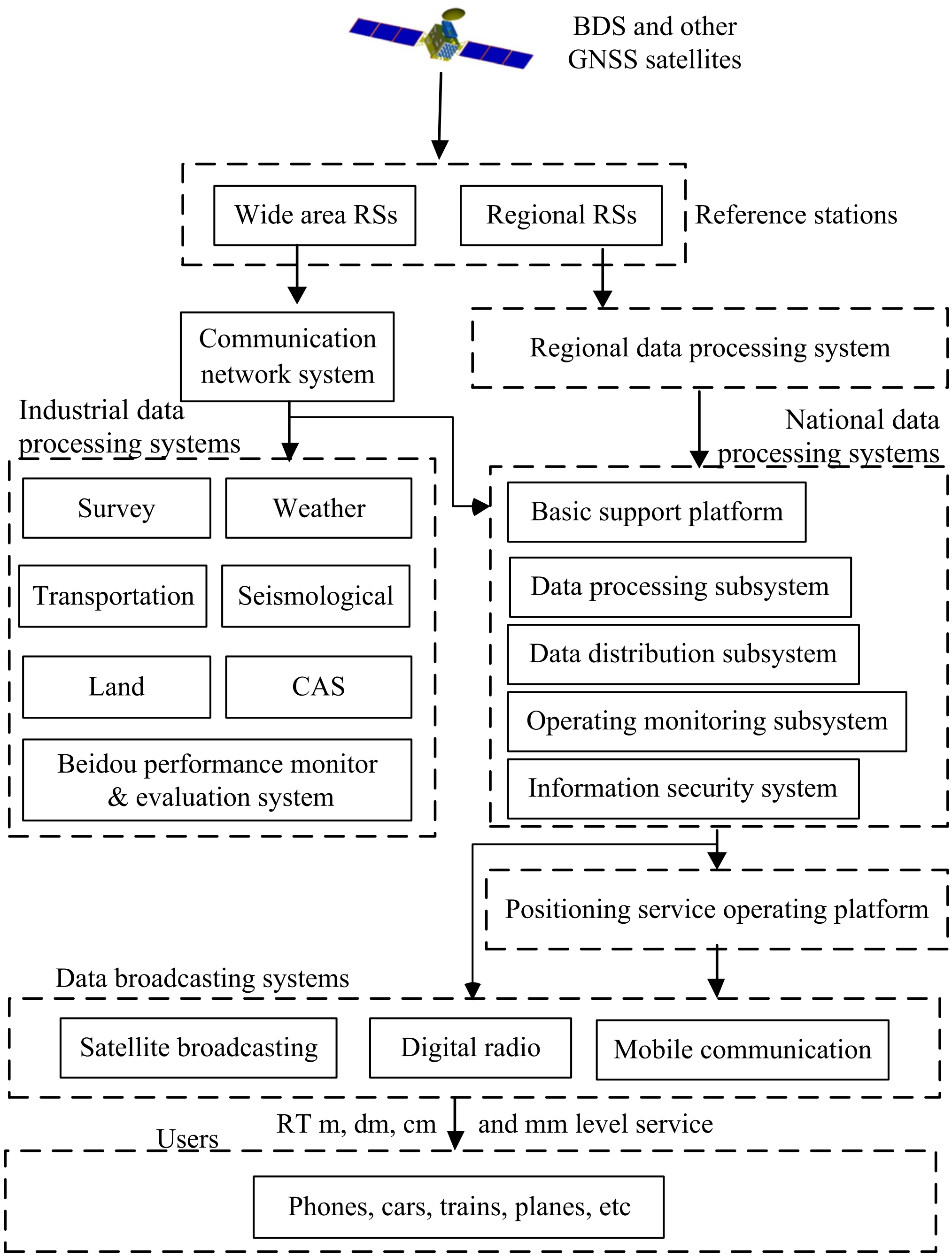

Fig. 8 Workflow of NBGAS

of users by combination with BDS. Three of the typical ground-based augmentation systems are under discussion: the civil aviation ground-based augmentation system, the Chinese ground-based augmentation system, and the national BeiDou ground-based augmentation system. The civil aviation ground-based augmentation system represents the traditional type of GBAS that is focused on civil aviation. The Chinese ground-based augmentation system represents the GBAS that is focused on aviation which was developed in China. The national BeiDou ground-based augmentation system refers to NBGAS, which provides service for trains and cars, etc. The Chinese ground-based augmentation system has passed technical reviews and system tests so far, and has reached the stage of verification flight. To implement the CAT II/III research, the first verification flight of the Chinese GBAS was performed in April 2019, and further GAST-D technical tests are being carried out during the second half of 2019 and into 2020. NBGAS officially started work in 2014 and provided real-time accuracy at the centimeter and the post-processing millimeter level in 2016. In 2017, NBGAS service performance specification version 1.0 was released and NBGAS began to undergo thorough testing in 2018. The augmentation for the real-time positioning accuracy at the meter level, decimeter level, centimeter level, and post-processing millimeter level of NBGAS was tested, with results indicating that the positioning accuracy of NBGAS either meets or exceeds the design performance. NBGAS can provide real time accuracy at the meter and decimeter level as of 2019.

In summary, the development of GBAS in China has reached an early stage. The research of GBAS is considered significant, and has practical value in terms of aerospace missions in the future. The research into NBGAS with civil aviation has caught the attention of many researchers and is increasingly popular.

Satellite segment technologies

Satellite segment is the space part of the satellite navigation system and the key to constructing BDS/GNSS augmentation systems, which are composed of GNSS satellites and SBAS satellites. GNSS satellites mainly include GPS, GLONASS, Galileo, and BDS satellites, which are used to broadcast navigation messages and ranging signals, provide daily services for users all over the world, and play a pivotal part in daily life. SBAS satellites include the GEO and IGSO satellites which are used to transmit differential corrections and integrity information to civil aviation users and therefore have a significant effect on flight safety. Satellite segment technologies are therefore investigated and summarized in this paper.

Technologies of LEO satellite segment

Preliminary information

Signal augmentation technologies refer to the technology of signal extension which provides a signal source that is capable of transmitting ranging signals to expand and extend GNSS. Through signal augmentation technologies, users can obtain accurate and reliable locations in scenarios where GNSS cannot be used or does not work well (Ma 2018; Reid et al. 2016; Wang et al. 2018a). To overcome the vulnerability of the GNSS system from the perspective of availability, reliability, and anti-interference, some researchers both in China and abroad have proposed that LEO satellites broadcast a ranging signal to augment the performance of the satellite navigation system that is composed of Medium Earth Orbit (MEO) and High Earth Orbit (HEO) satellites. Therefore, LEO augmentation technologies are under development, attracting the attention of many researchers.

There are many advantages of using LEO satellites for satellite navigation signal augmentation in addition to the increase in visibility and the improvement to accuracy (Wang et al. 2018b), including the following: (1) Leo satellites move fast which helps to speed up the convergence of the accuracy positioning filter. Results show that the convergence time of precise point positioning is shortened from 30 to 1–2 min when using LEO; (2) As LEO satellites are at low altitude, the signal-in-space is stronger than that of the MEO or HEO satellites. (3) The range covered is larger than that of GBAS. (4) LEO satellites can provide global signal augmentation by constructing a global LEO satellite platform (Ma 2018; Reid et al. 2016).

Research progress

There are several companies which have proposed a plan to construct LEO satellites, such as SpaceX, the China Aerospace Science and Technology Corporation, and the China Aerospace Science and Industry Corporation (2018). On January 8, 2017, SpaceX adopted a ten-satellite solution to send the first 10 LEO satellites from the second generation of the Iridium plan into space. The LEO satellites made by Hongyan and Hongyun have entered the stage of research and development and the whole constellation will be completed in 2023.

Some academic research has also been conducted concerning LEO satellites. The Luojia-1A satellite that was developed by Wuhan University was successfully launched on June 2, 2018. The Luojia-1A satellite has the main function of providing precise measurements of orbit and timing, storing GNSS onboard observations and downloading to the ground, and LEO augmentation experiments. The Luojia-1A satellite was used to carry out experiments investigating the navigation signal augmentation based on the LEO satellite platform in China for the first time (Wang et al. 2018a).

The LEO augmentation system onboard the Luojia-1A satellite receives the dual frequency signal from BDS and GPS for real-time autonomous precise orbit determination and timing, and generates dual frequency ranging augmentation signals that are sent to the user on the ground as shown in Fig. 9. Users can simultaneously receive a dual frequency signal from BDS, GPS, and Luojia-1A in order to achieve the hybrid satellite constellation positioning of the HEO, MEO, and LEO satellites, improving the performance in navigation and positioning (Wang et al. 2018b). As the frequency of the

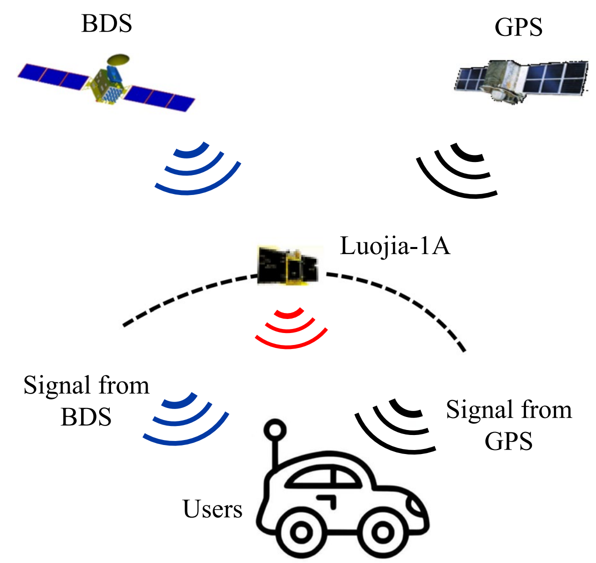

Fig. 9 Principle of the Luojia-1A augmentation system

augmentation signal from Luojia-1A is different from that of the existing GNSS signal, a modified receiver with specific receiving antenna is installed onto the equipment of a user to collect the signals from both GNSS and Luojia-1A. The signal augmentation experiments carried out with Luojia-1A reveal that the accuracy of the zero-baseline single difference signal reaches approximately 1 m and 4 mm for the code and carrier phase, respectively. The attenuation of the space signal from LEO satellites changes significantly during a single transit and the large variation in space signal loss needs to be compensated for by specially designed signal transmitting antennas such as the ISO-flux antennas. Conclusions can be drawn that the signal attenuation can be resolved by the antenna array through beam synthesis and that the ISO-flux radiation figure is then formed by the antenna array. The significant doppler and acceleration variation in the LEO signal provides both challenges and opportunities for receiver design. Balancing dynamics with code accuracy is still difficult (Wang et al. 2018a, 2019).

The LEO satellite moves faster than the MEO or HEO satellites. The phase center variation (PCV) of the satellite antenna observed by users changes rapidly, along with the azimuth and elevation angle. The PCV therefore needs to be measured at a higher sampling rate than the GNSS. PCV calibration also has to be conducted in order to improve the accuracy of the satellite antenna. Lei Wenying, an engineer at the China Academy of Space Technology (Xi'an) conducted research into LEO navigation augmentation to address this problem. For LEO navigation augmentation, the specifications of the PCV of the LEO satellite antenna at the decimeter level with precise point positioning are studied when PCV correction for the LEO satellite antenna is not required. This analysis can provide support and reference for the design of satellite antenna for LEO systems (Lei et al. 2019).

Considering the influence of broadcast ephemeris error on the orbital determination of LEO satellite-borne GPS, the theory of satellite-based augmentation is applied to the real time orbit determination of LEO satellite-borne GPS. At first, GPS real-time precise orbit determination is resolved with iGS, MGEX, and Unistrong data, and then high accuracy orbit and clock corrections are calculated using real-time precise orbit and clock offset. Finally, the LEO satellite is used to determine the accuracy of the correction parameters. The experimental observation of the satellite-borne GPS of the LEO satellites SWRAM A, B, and C is combined with the broadcast ephemeris and high precious ephemeris correction to determine the orbit. The accuracy of the real-time orbit determination of satellite-borne GPS assisted by state space representation can reach 10–15 cm. The real-time correction information for LEO satellites is quite useful for determining the orbit of satellite-borne GPS (Wang 2019c).

Summary

To further improve the performance of GNSS positioning, LEO augmentation technologies are proposed to provide more signal sources for users. With the advantages of fast movement and strong signal strength, the LEO augmentation technology has been widely focused by researchers. Wuhan University both launched the Luojia-1A satellite and performed the navigation signal augmentation experiment based on the LEO satellite platform for the first time in China. The phase center variation (PCV) of the satellite antenna is calibrated to improve the antenna accuracy of LEO satellites. Satellite corrections are used to improve the real-time orbit determination accuracy of LEO satellites for satellite-borne GPS. The research on LEO augmentation technologies has emerged rapidly and massively.

Technologies of GEO satellite segment

Preliminary information

GEO satellites tend to work as the information channel of the differential corrections and integrity information of SBAS, which are uploaded by navigation earth stations. GEO satellites receive SBAS augmentation data and transfer it to the ground user through a downlink. The GEO satellites of WAAS have been broadcasting WAAS messages for more than 15 years. However, details of the implementation of SBAS functions on the existing commercial GEO satellites are not public because they are proprietary to the satellite manufacturers and operators. It is therefore necessary to introduce more details of the GEO satellite segment.

Research progress

In China, some scholars begin to report on the BDSBAS GEO satellites in 2019. Liu Tianxiong, a research fellow at the China Academy of Space Technology, described the BDSBAS space segment. The BDSBAS PRN 130 was successfully launched on November 1, 2018 and the other two GEO satellites will be launched soon. The BDSBAS payload of the GEO satellite utilizes the processing transponder, as shown in Fig. 10. The augmentation signals from BDSBAS are generated by the mission navigation unit (MDU) which is composed of a navigational data unit and a navigational baseband. The process by which signals are broadcast by BDSBAS is the same as that of BDS RNSS. Navigation data is uploaded from the control segment. The receiver recovers the uplink navigation data and the navigation data is then transferred to the MDU on the BDSBAS payload via the 1553B bus. MDU generates the navigation message and the augmentation signal which is broadcast by the B1, B2, and B3 array antenna. The augmentation signal and RNSS signal are broadcast through the same RF link (Liu 2019).

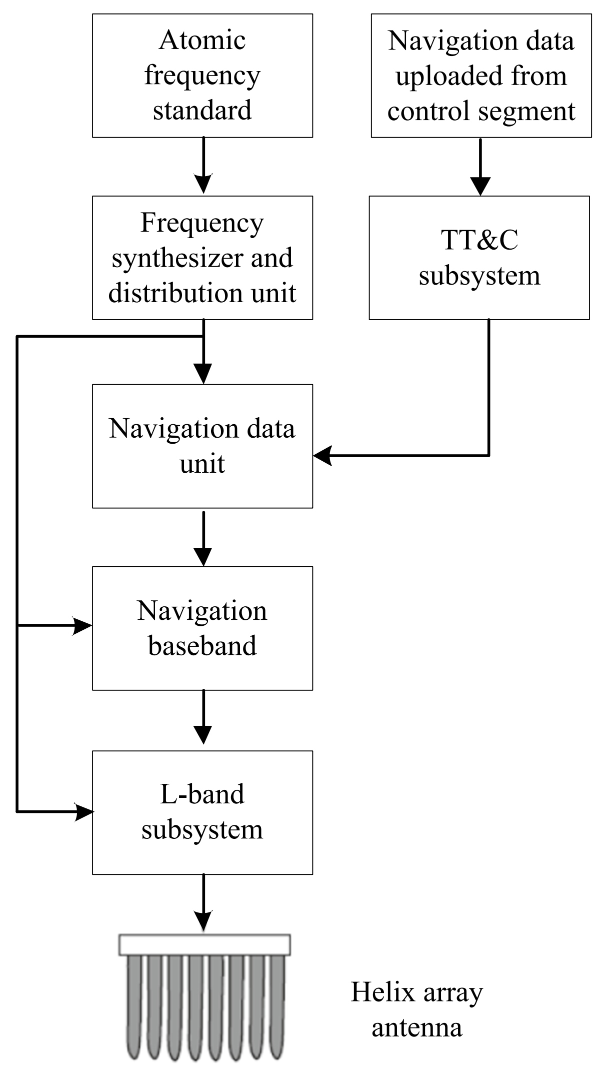

Fig. 10 Design of the BDSBAS GEO payload

Tests show that the radio frequency characteristics of both the single frequency service and the dual frequency multi-constellation service meet the requirements of RTCA MOPS 229 and ICAO SBAS ICD. The GEO-2 and GEO-3 satellite of BDS-3 will be launched in the near future. BDSBAS will initially provide the APV-I service, and finally the CAT-I service for civil aviation in China.

Wang Binghao, a Ph.D. candidate at the Information Engineering University introduced the influence of the GEO orbit error fluctuation on the BDS Wide Area Differential Service (WADS). Fluctuation is found frequently in GEO orbit errors. The fluctuation in the cross component of the GEO orbit errors is similar to a sinusoidal waveform. The fluctuation in the BDS GEO orbit error of the broadcast ephemeris degrades the BDS WADS PPP performance. With accurate estimation and correction of the fluctuation, the fluctuation can be effectively smoothed, and the performance of WADS PPP can be improved. After correction, the effective range of the zone correction can be further expanded (Wang 2019a).

Summary

GEO satellites are usually used as an information channel for differential corrections and the integrity information of SBAS. In China, a few scholars began to introduce BDSBAS GEO satellites in 2019. The BDSBAS GEO-1 satellite (SBAS PRN 130) was successfully launched on November 1, 2018 and the other two GEO satellites will be launched in the near future. The BDSBAS signal was broadcast from November 9, 2018. Research on the SBAS satellite segment is still popular.

Propagation segment technologies

The propagation segment is the path of the information interaction taken between the satellite and the ground. The propagation segment technology mainly includes tropospheric delay estimation technologies, ionospheric delay estimation technologies, and the multipath mitigation technologies that will be introduced later.

Technologies of tropospheric delay estimation

The troposphere is located at the bottom of the atmosphere; the top of troposphere lies at approximately 40 km above the ground. When the GNSS signal passes through the troposphere, the signal propagation time is prolonged leading to tropospheric delay. Tropospheric delay is an error source that affects the performance of GNSS. In order to service users with the high accuracy requirements of GNSS, it is necessary to accurately estimate the tropospheric delay. Unlike signal propagation in the ionosphere, the speed and direction of propagation do not change in the troposphere. The propagation velocity of a GNSS signal in the troposphere is only related to the meteorological conditions. Tropospheric delay is therefore usually determined using the empirical weather model (Elliott and Christopher 2006).

Tropospheric delay of SBAS is split into two parts and takes the form (SC-159 2013):

$$\mathrm{TC}_i = -\left(d_{hyd}^2 + d_{wet}^2\right) \cdot m(\theta) \tag{1}$$

where the variables d_{hyd}, d_{wet} denote the estimated range delays for a satellite at an elevation angle of 90°, caused by atmospheric gases in hydrostatic equilibrium and water vapor, respectively. The variable θ denotes the mapping function used to scale the delays to the actual satellite elevation angle $m(\theta)$. The two variables d_{hyd}, d_{wet} are a function of the meteorological parameters which can be calculated via linear interpolation (SC-159 2013).

The tropospheric delay for GBAS is estimated by (SC-159 2004):

$$\mathrm{TC}(\theta) = \mathrm{N}_R h_0 \frac{10^{-6}}{\sqrt{0.002 + \sin^2\theta}} \left(1 - e^{\frac{\Lambda h}{h_0}}\right) \tag{2}$$

where the variables $\mathrm{N}_R, \Lambda h, h_0$ denote the refractivity index transmitted by the ground subsystem, the difference in altitude between the airborne and the ground subsystems, and the troposphere scale height transmitted by the ground subsystem, respectively (SC-159 2013).

The meteorological phenomena in the troposphere are complex, and the value for tropospheric delay changes with different seasons and latitudes. The tropospheric delay can be estimated via the empirical weather model by using the corresponding meteorological parameters.

Technologies of ionospheric delay estimation

Preliminary information

The ionosphere is an important atmospheric layer in the space environment of the Earth. Atmospheric molecules in the ionosphere are decomposed into atmospheric ions and electrons under the influence of light from the Sun (Elliott and Christopher). When the GNSS signal passes through the ionosphere, which is filled with electrons, its propagation speed and direction will change, and the signal propagation time is prolonged. This phenomenon is known as ionospheric delay, which is an error source that can affect the performance of GNSS, especially single frequency GNSS. Ionospheric delay is the biggest source of error in signal propagation and the multipath effect is a complex phenomenon in signal propagation. To service users with the high accuracy requirements of GNSS, it is necessary to accurately estimate ionospheric delay. The estimation of ionospheric delay is not straightforward, especially when ionosphere storms and scintillation occurs.

Research progress

Some research has attempted to determine ionospheric delay for satellite navigation users. For single frequency GNSS users, the Klobuchar model is commonly adopted to estimate ionospheric delay using eight parameters; ionospheric delay can be eliminated by approximately 60% using this method (Elliott and Christopher 2006) In the Klobuchar model, the ionospheric delay between midnight and early morning is described by a constant and the ionospheric delay during the day is described by the sum of half the cosine function and the constant. With the increasing requirements of users in terms of accuracy, the Klobuchar model is no longer considered competent for high accuracy applications. Yaqi Peng from the Beijing Institute of Technology established an error prediction model for Klobuchar ionospheric delay based on the Takagi–Sugeno fuzzy neural network (TS-FNN). TS-FNN combines neural networks and the TS fuzzy theory which reveals an ability for self-learning, parallel processing, and processing uncertain information. The TS-FNN-based Klobuchar model has good fitting ability and prediction effects on the Klobuchar ionospheric delay error. Using this model to provide compensation for ionospheric delay, the error can be reduced by approximately 20% relative to the error after application of the Klobuchar method, which is of great significance for improving navigation positioning accuracy (Peng et al. 2019).

The SBAS master stations collect the information concerning the ionospheric pierce points (IPPs) and adopt either the Kriging method (Blanch 2002, 2003) or the inverse distance weighted (IDW) method (Prasad and Sarma 2004) to determine the grid ionospheric vertical delay (GIVD) and GIVE at each IGP. The augmentation information of GIVD and GIVE is broadcast to users through the SBAS GEO satellites. For SF SBAS users, the grid Ionospheric correction method (GIM) is used to provide augmentation information. The ionospheric error can be mitigated by approximately 75–80% using this method (Elliott and Christopher 2006). GIM is used by WAAS users, for which the ionospheric augmentation

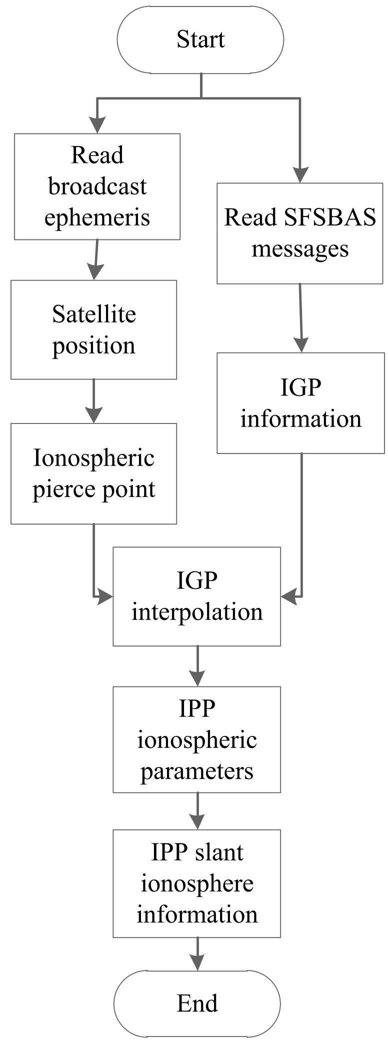

Fig. 11 Process of grid ionospheric correction method for single frequency SBAS users

information is provided by IGPs and broadcast by messages of type 18 and 26. The IPP is determined according to the intersection between the ionospheric thin shell and the imaginary line between user and satellite. The IGPs nearest the IPP is used to obtain the ionospheric augmentation information by triangular or rectangular interpolation. The corresponding ionospheric pseudorange error is corrected using the augmentation information from the IPP (SC-159 2013). The process of GIM is as shown in Fig. 11.

The correction of ionospheric delay and the integrity monitoring of the ionosphere are the main problems in the construction of SBAS. Compared with America and Europe, China spans a significant number of latitudes with complex ionospheric characteristics. The ionospheric characteristics of China have yet to be analyzed. From the point of view of space weather, in addition to ionospheric scintillation (Crane 1977) and ionospheric storms (Buonsanto 1999), solar radio burst (SRB) events are also important phenomena that impact GNSS application. SRB events tend to generate instantaneous wideband radio noise, causing degradation of GPS signals and increasing the ionospheric delay, as shown in Fig. 12, where SID denotes a sudden ionospheric disturbance. As shown in Fig. 12, large amounts of Radio irradiation, high energy particles, and plasma clouds are ejected during a solar burst event, posing a potential threat to GNSS applications. SRBs radiate strong electromagnetic noise. If this electromagnetic radiation covers the working band of GNSS and is strong enough, it can inflict radio frequency (RF) like interference on GNSS receivers (Liu et al. 2019). The effect of solar radio bursts on GNSS receivers is essentially an electromagnetic interference. The solar radio burst interference is directional to the GNSS receiver, injecting interfering energy at the solar zenith angle of the receiver position (Liu et al. 2019).

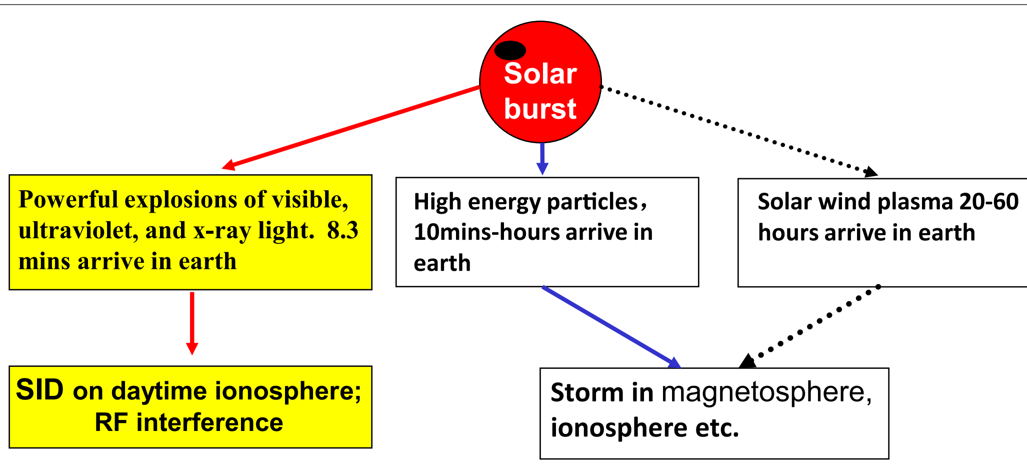

Fig. 12 Impacts of solar burst (Liu et al. 2019)

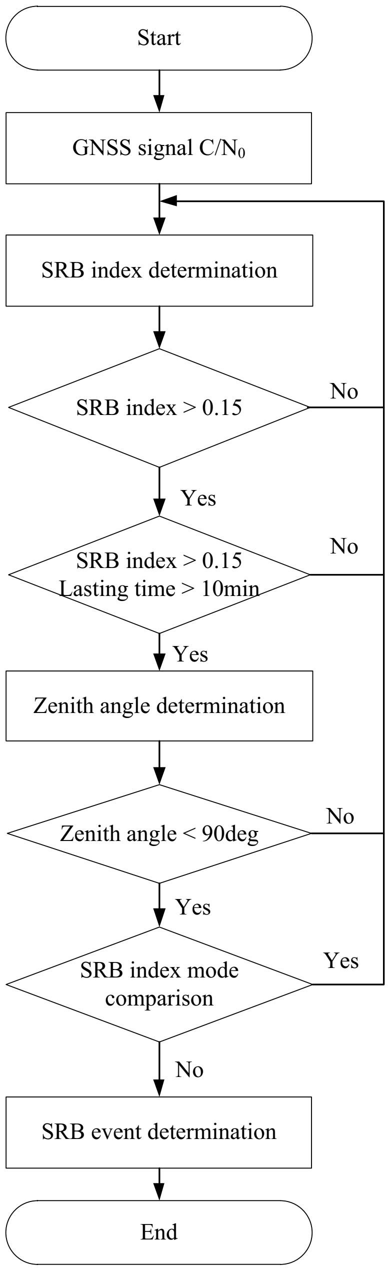

Fig. 13 Method of discovering a possible SRB event

Possible SRB events therefore need to be predicted. Liu Dun, a research fellow from the 22nd Research Institute, CETC developed a method that could be used to find possible SRB events, as shown in in Fig. 13. Like the ionospheric amplitude scintillation index S4 that is used to measure the degree of variation in amplitude, a SRB event is determined by a SRB Index (SRBI), the period for which an event is expected to last, and the zenith angle. The SRBI is defined as (Liu et al. 2019)

$$\mathrm{SRBI} = \sqrt{\frac{\sum_{i=1}^{N}\left(\frac{C}{N_0}\right)_i^2 - \left(\sum_{i=1}^{N}\left(\frac{C}{N_0}\right)_i\right)^2}{\left(\sum_{i=1}^{N}\left(\frac{C}{N_0}\right)_i\right)^2}} \quad (3)$$

where $\frac{C}{N_0}$ represents the de-trended carrier-to-noise ratio of the GNSS signal and N is the number of data in a period of time. After SRB events are discovered, analysis of the GNSS signal fading model for the SRB event is carried out. Results show that only strong SRB events that cover the L band with high intensity (40,000 solar flux units (SFU), $\mathrm{SFU}=10^{-22}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$) will seriously interfere with GNSS. A solar burst will affect GNSS receivers located in daytime areas instantaneously. There are some factors that could degrade the model performance: saturation in the fading depth, the quality of the GNSS measurement, SRB events of less intensity, and sites at low incidental angles (Liu et al. 2019).

For dual frequency users, ionospheric delay can be calculated via the dual frequency signal directly and the ionospheric error can be removed by up to 95%. The user with a dual frequency receiver can still pick up the dual frequency signal. This is because ionospheric delay can be taken as approximately inversely proportional to the square of the frequency. According to the relationship between the dual frequency and the pseudorange, the pseudorange after revision by ionospheric delay estimation can be expressed as a linear combination of the dual frequency pseudoranges (Elliott and Christopher 2006).

Summary

Ionospheric delay is the focus of research in many countries at present. Each country faces problems when constructing SBAS and GBAS, or in applying GNSS to other areas. Two phenomena, namely ionospheric storms and ionospheric scintillations, affect the performance of GNSS and the augmentation systems. Ionospheric scintillation can cause signal loss at the receiver and ionospheric storms can badly affect the performance of SBAS. Recently, solar radio burst events that can lead to ionospheric scintillation are taken as factors that can impact GNSS application.

China is still constructing its BDSBAS and civil aviation GBAS. As the ionosphere in southern China is relatively active, the ionospheric characteristics of southern China need to be studied further.

Technologies of multipath mitigation

In the field of wireless communications, the term multipath refers to the propagation of radio signals from a transmitter through multiple paths to a receiver. The scattering of electric waves by the atmosphere, the reflection and refraction of the ionosphere by radio waves, and the reflection of electric waves by surface objects such as mountains and buildings all cause multipath effects.

GNSS provides a good outdoor positioning service; however its service performance degrades noticeably indoors. The multipath effect is a problem in indoor positioning. To provide indoor positioning, pseudolite is introduced. Pseudolite systems such as Locata are developed with the installation of a transmitter above the ground which can transmit signals similar to that of GPS. The receiver of the pseudolite system receives this signal, determines the distance between the transmitter and receiver, and takes this location as the user's position. Pseudolite systems work in the same manner as local GPS. Pseudolite systems face many difficulties because of the complicated structures of many buildings and the changeable environments during indoor positioning. The multipath effect is a complex phenomenon of signal propagation and is always one of the main factors affecting the accuracy of pseudolite positioning (Wang 2019d). Using antenna arrays to generate strong directional signals as an advanced multipath suppression method can be applied to indoor positioning, which generates a high gain in the direction of the arrival of the direct signal and attenuates interfering signals from other directions, suppressing the multipath signal (Wang 2019d). Wang Xinyi from Southeast University conducted research on the indoor pseudolite signal propagation effect with multipath statistical modeling. A pseudolite array antenna structure and a pseudolite array indoor positioning algorithm are developed for a pseudolite signal system. Results reveal that the lobes of the two array-type pseudolite antennas are denser than that of isotropic antenna, the energy can be gathered more at the side lobes relative to the main lobe, and the radiation range is relatively larger. The two array antenna gain radiation from the direction of the arrival of a signal if the power carried by the signals is high enough, up to -40 dB, and the interference signal is thus attenuated, providing a solution for the remote pseudolite transmission link (Wang 2019d).

The multipath effect still needs to be considered and mitigated against for receiver positioning, especially for indoor application. The multipath effect is quite complex, and it is difficult to find an appropriate model to describe multipath characteristics. The multipath effect therefore has great potential for further research.

User segment technologies

Satellite navigation systems are established to provide positioning and navigation services for users. User segment technologies are key in the application of Satellite navigation systems. The General user can determine their location and positioning domain parameters by receiving a GNSS signal. Civil aviation users require more information or signals to improve the accuracy, integrity, continuity and availability of the GNSS in order to reach aviation standards. Satellite navigation augmentation systems are constructed to provide more information and signals for users.

With the development and improvement of various satellite navigation systems, the number of satellites in the view of the user is increasing significantly, and the geometric structure of the satellites in the view of the user has been improved. If all visible satellites are used for positioning, redundant signal sources increase the signal processing burden of the receiver and it will be difficult to implement real-time positioning. Therefore, it is necessary to develop user segment technology to find an optimal performance for users. In this section, user segment technologies are divided into two parts: ABAS user technologies and other user technologies.

ABAS user technologies

Preliminary information

ABAS users mainly include Airborne Autonomous Integrity Monitoring (AAIM), Receiver Autonomous Integrity Monitoring (RAIM), and Advanced Receiver Autonomous Integrity Monitoring (ARAIM). AAIM usually combines an inertial navigation unit with a barometric altimeter or radio altimeter for integrity monitoring and performance improvement. RAIM utilizes the redundant observation of the receiver for integrity monitoring. RAIM is one of the important means by which integrity can be ensured, and its fault detection is autonomously performed by the airborne receiver (Zhang et al. 2019). RAIM compares the observation of each GNSS satellite with other available satellite observations so that faulty satellites are detected by the currently available satellites. RAIM is commonly used for auxiliary navigation in the en route and terminal area and supports horizontal navigation in the approach phase (Wang and Yang 2019; Wang et al. 2017a). Based on the multi-frequency multi-constellation navigation source, ARAIM is an integrity monitoring method combined with an integrity support message that is provided by the ground monitor station to achieve the vertical navigation performance of LPV200. ARAIM is an upgraded version of RAIM.

Research progress

The initial operation of BDS-3 at was announced at the state council information office of China in early 2019, and BDS can provide basic navigation services globally. As the applications for which BDS can be used increase, investigation surrounding RAIM has become more popular.

Fault detection and exclusion is a pivotal part of RAIM. The consistency check on satellite observation is performed and the test statistic is compared with the detection threshold to identify the specific faults. The existing integrity monitoring algorithms do not take into account the impact of the navigation signal itself on integrity monitoring. As the baseband signal can be used to capture information that is not used for integrity monitoring during the tracking process, the signal-to-noise ratio and the related peaks from the process of acquiring and tracking are used to adjust the asymptotic covariance matrix and then construct the test statistic. The baseband signal-based algorithm for autonomous integrity monitoring reveals a high fault detection rate and a high sensitivity. Nevertheless, the stability of this method is lower than the weighted least squares methods (Wang and Yang 2019).

Most of the BDS RAIM algorithms are designed for BDS-2. These algorithms are based on false alarms and missed detection and are not suitable for integrity and continuity, and hence the detection threshold needs to be updated according to the features of BDS-3 and applied to the receivers of BDS-3. Usually, the performance of RAIM algorithms is closely related to constellation geometry, the observation quality, and the number of visible satellites. Compared with BDS-2, BDS-3 shows better geometry, better code rates, and more abundant frequencies. A RAIM method in the situation that the missed detection probability is allocated to each visible satellite is taken as a solution for BDS-3 receivers. Compared with traditional methods, this RAIM method, which is based on the equal allocation of missed detection probability, reveals less integrity risk, and provides better protection levels and higher availability (Zhang et al. 2019).

Since the GNSS signal is susceptible to high-rise building barriers, electromagnetic interference, and geomagnetic interference, the performance of GNSS is affected by those factors. The single epoch parity vector is adopted to construct a test statistic with which the large pseudorange deviation faults can be detected. The normalized and post-normalized constructive test statistic is used to detect the fault of a slowly varying pseudorange deviation. The loop detection of a single epoch to multi-epoch parity vector using a sliding window can detect small stepped faults and small gradual faults. In detail, the observation from the satellite is obtained and each epoch observation parity vector is determined. The current test statistic and detection threshold is then constructed. Finally, the test statistics and detection thresholds are compared to detect faults. The cumulative improvement algorithm of the parity vector sliding window detects the faults of isolated satellites in a timely manner and guarantees the accuracy and reliability of satellite navigation systems (Li et al. 2019b).

Summary

As BDS provides services for global users, some research has been carried out with RAIM to improve the performance of the user domain positioning. RAIM can be applied to the fault detection during different phases of flight and provide real-time integrity monitoring of GNSS. On this basis, some work has been conducted to apply RAIM to the BDS-3 receivers. BDS-3 receiver autonomous integrity monitoring is a popular topic at present. More research on AAIM and ARIAM with the BDS-3 navigation system is expected to be carried out in the near future.

Other user technologies

With the globalization of the BDS-3 satellite system and the construction of BDSBAS, there has also been some research carried out investigating other user technologies.

The processing center of GBAS has adopted the technology of Precise Point Positioning (PPP) ambiguity resolution (AR) to deduce the carrier phase integer ambiguities of the virtual reference station (VRS) (Xu et al. 2019). Subsequently, the carrier phase without ambiguities in VRS is broadcast to users. Based on this, a VRS-based rapid PPP integer ambiguity resolution is assisted using RTK technology to determine integer ambiguity. By performing single difference RTK between the rover station and the VRS, single difference ambiguities between the two can be solved. Considering that the observation of a VRS carrier phase does not include the phase ambiguities, the single difference ambiguities can be taken as the non-difference phase ambiguities of the rover station. The single difference ambiguities can be fixed like RTK and PPP AR can be performed at the rover station. The performance of PPP is improved with high convergence accuracy (Xu et al. 2019).

As a promising field, unmanned aerial vehicle (UAV) delivery presents the advantages of low cost and high flexibility and has thus been adopted by logistics companies. The key issues for UAV delivery include accuracy, safety, and efficiency. However, the restrictions and regulations of low air navigation for small aircraft such as drones remain to be determined or has not been released. A UAV navigation monitoring requirements (UNMR) framework based on the required navigation performance (RNP) has been designed for accuracy and integrity monitoring in UAV delivery (Cheng 2019). Taking into account navigation system errors (NSEs), flight technical errors (FTEs), and path definition errors (PDEs), the total system errors (TSEs) of UNMR have been defined (Cheng 2019). To optimize the UNMR framework, it is essential to model all the aforementioned errors where those errors need to be associated with their factors in order to consider the accuracy and reliability. The reliable en-route width and vertical separation design can be determined based on the refined framework. A TSE model has been designed for the UAV en-route, and the impact of the wind model and the operating performance for the UAV FTE have been analyzed. The sensitivity analysis of the horizontal and vertical TSE has been carried out with various wind models and different flight scenarios. The TSE model will be a benefit for the design of UAV flight routes and formulation of the operating manual (Cheng 2019).

With GNSS widely applied to many fields, it is necessary to analyze the instantaneous availability of GNSS in a local area. Existing availability researches are mainly focused on long-term fault monitoring and the availability of the GNSS constellation; they pay little attention to the availability for local instantaneous situations. Gao Xi from Beihang University investigated the availability of the global navigation signal to the local area navigation signal and the regional instantaneous availability on satellite navigation systems was analyzed and evaluated (Gao et al. 2019; Wang et al. 2017b). The signal availability under the impact of power anomalies and related peak distortions is presented. Based on this, the number of visible satellites and position dilution of precision (PDOP) are analyzed for a service area. The theory of local instantaneous availability evaluation is developed and of great significance to the availability evaluation of GNSS (Gao et al. 2019; Wang et al. 2017b).

As GNSS is used in all kinds of applications, the navigation metrics of accuracy, availability, continuity, and integrity are closely scrutinized. When GNSS is used for autonomous applications in planes, trains, and automobiles, some problems need to be considered. Automation means that significant amounts of trust in GPS/GNSS systems for use with automobiles and railways is critical. With high levels of trust, GNSS can also aid navigation at the lane level. However, because of multipath and radio frequency interference (RFI), major challenges occur. The major challenge in using GNSS safely is integrity. A 10 m integrity bound is achievable with a system similar to aviation and PPP may be good enough for a 1 m level. High integrity GNSS for use with trains and automobiles is an upcoming requirement and the major challenges to satisfy this goal are radio frequency interference and multipath effects (Sher 2019).

The flow of air traffic has increased dramatically with the rapid development of civil aviation, and flight safety has become increasingly important. As a solution, the Automatic Dependent Surveillance-Broadcast (ADS-B) is proposed to guarantee flight safety. ADS-B can provide air–air and ground-air surveillance to improve flight safety and thus ADS-B is widely used in civil aviation transportation and flight training processes. ADS-B will become the mainstream monitoring technology in the future according to plans by the CAACs. Currently, the GNSS navigation data, whose accuracy and reliability need to be improved, is indispensable to ADS-B. To provide the navigation performance required for ADS-B, the CORS differential ground-based augmentation positioning based on BDS-3 can be adopted to produce accurate position data. The new ADSB system can perform stably with accuracy at the decimeter level or even the centimeter level reliably, which can provide support for the performance optimization and airworthiness industrialization of the current ADS-B. BDS is currently applied to general aviation navigation and surveillance and provides navigational services for many airports and airlines (Yang 2019).

General aviation refers to all aviation activities other than military aviation and public air transportation. Those activities include operations in industry, agriculture, forestry, fisheries, construction, disaster relief, meteorological detection, marine monitoring, scientific experiments, sports, education and training, medical and health care, flight in culture, etc. (Wang 2019b). Under the support of the government, general aviation ushers in new opportunities. General aviation navigation and surveillance technology has become a popular topic from the following perspectives (Wang 2019b): (1) General aviation aircraft navigation and surveillance systems based on multi-network convergence; (2) Distributed network data sharing technology for general aviation aircraft navigation surveillance; (3) BeiDou short message information coding and compression technology; (4) Multi-network fusion portable airborne navigation surveillance integrated devices; and (5) BeiDou general aviation navigation surveillance application. A number of technical problems in the navigation surveillance of low altitude airspace navigation vehicles that restricted the development of navigation technology have been solved. BeiDou general aviation navigation surveillance can provide communication, navigation, and surveillance with the multi-network integration of satellites, airspace, and the land, and provides remarkable economic and social benefits. The engineering application of BeiDou general aviation navigation surveillance covers flight monitoring, flight test, plant protection with UAVs, and the measurement of the temperature of nuclear power plant seawater with UAVs (Wang 2019b).

It is a national strategy to develop an integrated positioning, navigation, and timing (PNT) system based on the BDS which can be used to provide service all over China. However, in the challenging situations of high buildings, the indoors, 3D transportation, shopping mall, and underground development, the precise positioning requirements cannot be met. To address this problem, cooperative real-time positioning (CRP) technology is proposed as a technology that can provide intelligent navigation and positioning for public application. CRP is a technology based on BDS and multiple positioning resources to obtain high precision positioning either separately or jointly to provide accurate, rapid, and ubiquitous location-based services to mass users through augmentation technologies such as information augmentation, signal augmentation multiple-source fusion, and location sharing (Lou 2019). CRP is focused on multisource collaboration, station-network collaboration, cloud-end collaboration, and end–end collaboration. To build a cooperative real-time positioning service platform, the database of a high precision beacon and fingerprint is built in the main areas of more than 200 large scale shopping malls or transportation hubs (such as airports and railway stations) in the major cities of China. This platform responds to the requests of 50 billion collaborative positionings each day. Three systems are utilized: the GNSS real-time high precision cloud processing system, the A-BDS/GNSS location service system, and the multi-source location data collaborative processing system (Deng et al. 2018; Lou 2019). The integrated PNT systems are developed based on BDS and the collaborative precision positioning that is based on the cloud platform has made great progress (Deng et al. 2018) and been applied to many fields such as public users, intelligent transportation, and UAVs (Deng et al. 2018).

The application of BDS/GNSS has been explored from many different perspectives to provide solutions for application of the BDS/GNSS augmentation system.

As the globalization of BDS continues, BDS/GNSS augmentation technologies have been applied to many areas and scholars from different companies are providing BDS for use in everyday life. BDS and BDSBAS can be used in aerospace, maritime affairs, transportation, and agriculture, among others. BDS/GNSS technologies, together with their augmentation technologies, are therefore a promising industry.

Conclusions and discussions

Satellite navigation augmentation technologies are an important part of satellite navigation systems and a popular topic for research in the field of satellite navigation technology. This paper comprehensively discusses satellite navigation augmentation technologies and shares the latest academic achievements of those fields. It aims at promoting cooperation among scholars at home and abroad, helping researchers to understand the progress and requirements of satellite augmentation technology from different perspectives. In detail, system segment technologies, satellite segment technologies, propagation segment technologies, and user segment technologies are described to introduce the theory and application of BDS/GNSS augmentation technologies. Each section gives a short summary of the corresponding technology. The theory and application of satellite navigation augmentation technology involves many aspects of GNSS, not only including the construction of BDSBAS and NBGAS, but also covering the application of those systems. Through these technologies, the status and trend of the development of BDS/GNSS augmentation technologies can be summarized as follows.

Popular topics for research

This paper focuses on the technology and applications of BDS/GNSS augmentation technologies, covering satellite based augmentation systems, LEO augmentation systems, ground-based augmentation systems, ionospheric technologies, aviation applications, and UAV applications for GNSS, satellite autonomous integrity monitoring and integrity onboard testing, and user integrity technologies. These include:

(1) The construction, testing, and verification of the BeiDou satellite-based augmentation system and the Algerian AL-SBAS. The BeiDou satellite-based augmentation system and the Algerian AL-SBAS were developed to provide a safe service for civil aviation. It is necessary to promote the construction, testing, and verification of these SBASs and apply them to civilian aircraft before the receiver of another SBASs dominates the Chinese civil aircraft market.

(2) The national BeiDou ground-based augmentation system and its application. The national BeiDou ground-based augmentation system is an important part of the BeiDou satellite navigation system which was developed to service all kinds of fields in China. After the system test of the national BeiDou ground-based augmentation system in 2018, it will be able to provide position services at the meter and even the decimeter-level. The national BeiDou ground-based augmentation system and its application are highly significant for engineering applications.

(3) GNSS receiver autonomous integrity monitoring. China is promoting its BDS-3 to service many kinds of industries. The receiver autonomous integrity monitoring for BDS-3 is proposed to serve in civil aviation. It is a pivotal action to provide navigation

information to Chinese aircraft with BDS-3. GNSS receiver autonomous integrity monitoring is a popular topic in China at present.

Research and development frontiers

There are two aspects in research and development frontiers. The collaborative precision positioning based on the cloud platform has presented great progress and been applied to many fields, such as intelligent transportation and unmanned aerial vehicles. With four collaborations (multi-source, station network, cloud-end, and end–end), collaborative precision positioning plays a key role in both national strategies and livelihoods. Combined with a public location-based service, intelligent transportation, new artificial intelligence, and the next generation communication network, collaborative precision positioning becomes the academic frontier for positioning, navigation, and timing. On the other hand, LEO augmentation has received much attention. With the advantages of a great signal strength, a short delay between satellite and user, and the fast satellite geometry variation, LEO satellites are used to provide more signals in service areas. The design and distribution of the LEO constellation, navigation signal analysis, and the phase center variation calibration has come into the focus of researchers.

Achievements

This paper mainly discusses the key technology used in satellite navigation augmentation systems in China. There have been many achievements in BDS, which mainly include the following:

(1) The BeiDou satellite-based augmentation system and Algerian AL-SBAS are the latest achievements of the Chinese satellite-based augmentation system, for which provide preliminary test results have been provided, revealing the great progress made by Chinese researchers in overcoming the difficulties in the development of satellite systems.

(2) The monitor stations of the national BeiDou ground based augmentation system have been distributed all over China and the construction of the national BeiDou ground-based augmentation system is basically finished. The system can provide preliminary experimental results for most of China. According to the results of the national BeiDou ground-based augmentation system for the real-time positioning accuracy at the meter level, decimeter level, centimeter level, and post-processing millimeter level, the service capability of the national BeiDou ground-based augmentation system for positioning accuracy satisfies, and is superior to, the design indicators.

(3) The civil aviation ground-based augmentation system has completed both flight inspections and testing, and the certification scheme for civil aviation ground-based augmentation system has been issued which suggests the rapid development of the Chinese civil aviation ground-based augmentation system. The equipment Lgf-1a of the civil aviation ground-based augmentation system is capable of providing aircraft with information concerning precision approach, automatic landing, and taxi guidance services which suit the requirements of the current regulatory specifications.

Suggestions

The development of satellite navigation augmentation technologies in China is still in its early stages. Much attention has centered on the design of augmentation systems, integrity monitoring and alarms, anti-spoof solutions, and the improvement of receiver performance. China has to promote the construction and application of the BDS augmentation systems in order to reach the progress level of America and Europe.

Overall, BDS, BDSBAS, and NGBAS are approaching the state of full operation. With the continuous improvement seen in the performance of BDS, this system can be quickly applied to high-end users such as civil aviation, promoting the globalization of BDS.

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Authors' contributions
Conceptualization: RL, JC, SF, DW and LD; Methodology: RL and EW; Writing original draft: SZ and EW; Editing: EW, SF and RL; Review: RL, JC, SF, DW and LD. All authors read and approved the final manuscript.

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