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Development of BeiDou Satellite-Based Augmentation System

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Abstract

China is developing its BeiDou Satellite-Based Augmentation System (BDSBAS) in accordance with international standards, and it has provided initial Single Frequency (SF) and Dual-Frequency Multi-Constellation (DFMC) services since July 2020. This paper gives a comprehensive introduction to BDSBAS from the aspects of its general design, system time datum, coordinate reference system and signal characteristics. The performance requirements and internationalization endeavors of BDSBAS also are presented. Additionally, the initial performance tests of BDSBAS SF service had been carried out based on the first two BDSBAS Geosynchronous Earth Orbit (GEO) satellites, including the quality of signal-in-space, and initial accuracy, integrity and availability. The results show that the characteristics of BDSBAS signal-in-space can well meet the requirements of the International Civil Aviation Organization (ICAO), and the initial performance of BDSBAS SF service can basically meet the requirements of Approach with Vertical guidance I (APV-I). Finally, before the application of BDSBAS services into civil aviation uses, testing and certification will be organized by the Civil Aviation Administration of China (CAAC) and carried out in three steps. In the future, China will continue to promote the development of BDSBAS in a steady manner in order to provide aviation integrity services compatible with the ICAO standards in China and the surrounding areas as soon as possible.

KEYWORDS
BDSBAS, BeiDou, CAT-I, DFMC, integrity, SBAS

1 | INTRODUCTION

The BeiDou Navigation Satellite System (BDS) was formally commissioned on July 31, 2020 (*Xinhua Net*, 2020). As an important part of BDS, the BeiDou Satellite-Based Augmentation System (BDSBAS) will provide Single-Frequency (SF) and Dual-Frequency Multi-Constellation (DFMC) services, in accordance with the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs). BDSBAS will serve users in China and surrounding areas and aim to achieve Approach with Vertical Guidance I (APV-I) and CAT-I precision approach capabilities (China Satellite Navigation Office (CSNO), December 2019a, 2019b).

China Satellite Navigation Office (CSNO), Civil Aviation Administration of China (CAAC) and China Satellite Navigation Project Center (CSNPC) are actively promoting the construction and application of BDSBAS in a joint effort. China has been carrying out BDSBAS system design and system demonstration, as well as tests and

verifications of SF SBAS technology, since 2012. Since 2015, DFMC SBAS technology tests and verifications have been carried out, and China has begun to select and construct ground monitoring stations and actively participate in the development of SBAS international standards. The first BDSBAS Geosynchronous Earth Orbit (GEO) satellite was successfully launched in November 2018, and BDSBAS system integration and testing have been underway since then (*Xinhua Net*, 2018).

Currently, the SBASs in service are the United States's Wide Area Augmentation System (WAAS), the European Union's European Geostationary Navigation Overlay System (EGNOS), Japanese MTSAT Satellite-based Augmentation System (MSAS) and Indian GPS Aided GEO Augmentation Navigation (GAGAN) (Shao et al., 2020). WAAS reached the full Localizer Performance with Vertical Guidance at 200 feet decision height (LPV-200) performance in 2014 and is in Phase 4 to establish a dual-frequency user capability while at the same time maintaining and sustaining the existing WAAS Legacy L1 service (Burns, 2016, 2019). After GPS L5 realizes Full Operational Capability (FOC) in late 2028, Federal Aviation Administration (FAA) plans are for a 24-month transition leading to a WAAS Dual Frequency Operations (DFO) FOC in 2030 (Thompson, 2020). EGNOS reached the LPV-200 performance in 2015, and the development of a new EGNOS system (EGNOS v3) is underway to implement DFMC SBAS with backward compatibility of current GPS L1 SBAS service (Châtre, 2019). And the European Organization for Civil Aviation Equipment (EUROCAE) and RTCA are jointly carrying out the modification of DFMC SBAS Minimum Operational Performance Standard (MOPS) (ED-259A) (Porfili, 2019). MSAS reached Non-Precision Approach (NPA) performance in 2007 and will reach LPV-200 performance in 2025 (Giho, 2016; Wada, 2019). GAGAN reached APV-I performance in 2015 and will provide LPV performance in the future (Airports Authority of India, 2016, 2019).

This paper introduces the latest progress of BDSBAS from the aspects of system composition, internationalization efforts, performance tests and testing processes. The current construction status and test results show that the progress of BDSBAS is very satisfactory and well in line with the expected plan. In the future, China will continue to steadily promote the development of BDSBAS to provide aviation integrity services compatible with the ICAO standards in China and the surrounding areas as soon as possible.

2 | OVERVIEW OF BDSBAS

This section mainly presents the composition of BDSBAS, including the space segment, ground segment and user
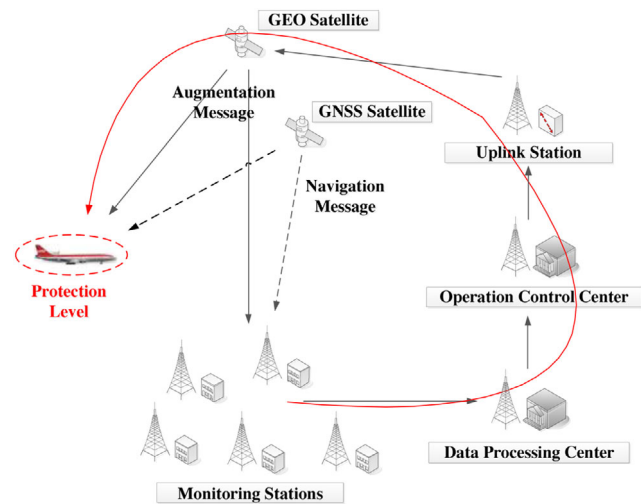
FIGURE 1 Architecture of BeiDou Satellite-Based Augmentation System (BDSBAS) [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

segment, the reference time and coordinate reference system, and the augmentation messages.

2.1 | System architecture

BDSBAS is mainly composed of space segment, ground segment and user segment. The architecture of BDSBAS is illustrated in Figure 1 (Li & Shen, 2019).

2.1.1 | Space segment

The space segment consists of the three GEO satellites, which broadcast augmentation messages. These GEOs are planned to provide ranging capability; however, they aren't used as ranging sources now. All three GEOs have been successfully launched, with the coverage areas as shown in Figure 2.

The BDSBAS B1C signal will be compliant to the ICAO SBAS L1 standards, while BDSBAS B2a will be compliant to DFMC SBAS SARPs, which are under development. The signal characteristics of BDSBAS GEOs are shown in Table 1.

Following the concept of being compatible and interoperable with other SBASs, BDSBAS applied for "Final" pseudorandom noise codes (PRNs) of the three GEOs from the US Air Force's GPS PRN Coordination Office in August 2020. According to the PRN code assignments, PRN 130, 143 and 144 were assigned to the three BDSBAS GEOs, as shown in Table 2 (GPS PRN Coordination Office, 2020).
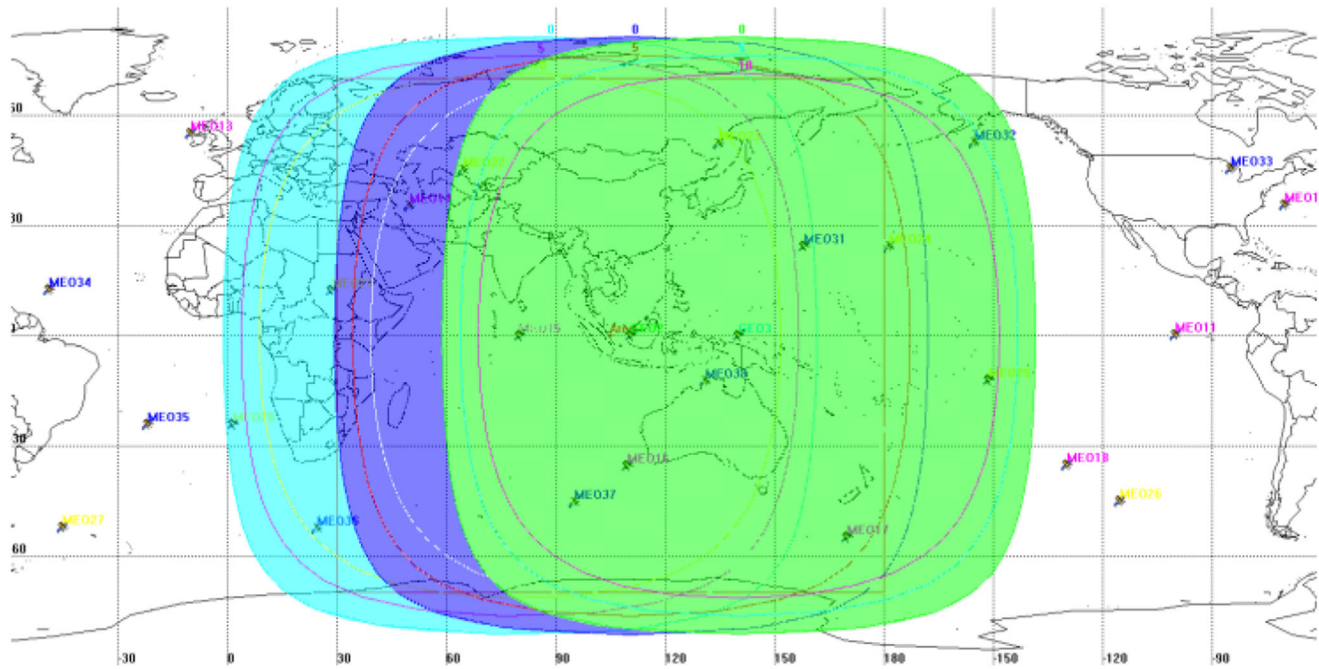
FIGURE 2 Signal coverage of BDSBAS [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

TABLE 1 Signal characteristics of BDSBAS GEOs (Li & Shen, 2019)

FRE	Signal component	Central FRE (MHz)	MODULATION	INFO rate (bps)	POWER allocation
B1	SBAS-B1C	1575.42	BPSK(1)	250	1/3
B2	SBAS-B2a_data	1176.45	BPSK(10)	250	1/3
	SBAS-B2a_pilot	1176.45		0	1/3

TABLE 2 The BDSBAS PRN codes and orbital slots

L1 C/A PRN Code Number	C/A			Satellite	Orbital Slot	Effective Through	Assignment Type
	G2 Delay (Chips)	Initial G2 Setting (Octal)	First 10 Chips (Octal)				
130	355	0341	1436	BDSBAS (GEO-1)	140E	Aug. 2030	Final
143	307	1312	0465	BDSBAS (GEO-3)	110.5E	Aug. 2030	Final
144	127	1060	0717	BDSBAS (GEO-2)	80E	Aug. 2030	Final

L5 PRN Code Number	XB Code Advance (Chips)		Initial XB Code State (Octal)		Satellite	Orbital Slot	Effective Through	Assignment Type
	I5	Q5	I5	Q5				
130	1224	1092	17754	12737	BDSBAS (GEO-1)	140E	Aug. 2030	Final
143	3745	8126	05474	15167	BDSBAS (GEO-3)	110.5E	Aug. 2030	Final
144	4723	7017	02275	16761	BDSBAS (GEO-2)	80E	Aug. 2030	Final

TABLE 3 The ground segment of BDSBAS

Station type	Number of stations
OCC	1
DPC	2
US	3
MS	30

2.1.2 | Ground segment

The ground segment consists of Operation Control Centers (OCCs), Data Processing Centers (DPCs), Uplink Stations, and Monitoring Stations (MSs) in China and overseas (Zhi, 2020b), as shown in Table 3.

The MSs are comprised of 27 domestic MSs evenly distributed in Beijing, Shanghai, Guangzhou, Xi'an, Changsha, and other places in China, and three overseas MSs in Kamchatka, Irkutsk, and Obninsk, which are all in Russia. Each monitoring station contains three multi-frequency and multi-mode monitoring receivers, meteorological equipment and a rubidium atomic clock. The MS monitors all visible navigation satellites, forms pseudorange and carrier observation data, and collects meteorological data with meteorological equipment. MS sends the data to the DPC every second.

Based on the received data, the DPC generates correction information (ionospheric correction, ephemeris correction and clock correction) and integrity information (User Differential Range Error, or UDRE; Grid Ionospheric Vertical Error, or GIVE; Dual Frequency Range Error, or DFRE; etc.), and sends this information to the OCC.

Then, the OCC generates augmentation messages according to the corresponding standard, and sends the messages to the Uplink Stations.

The Uplink Station uploads the messages to the BDSBAS GEO satellite. Each Uplink Station can inject up to three GEOs. And the GEO satellite broadcasts the messages to the users in China and surrounding areas.

2.1.3 | User segment

The user segment refers to BDSBAS terminals used in civil aviation, maritime, railway and other applications. The user uses the correction information from the messages to improve accuracy and the integrity information from the messages to calculate the protection level, which is used to determine whether the service can be used or not.

The SF user equipment satisfies the requirement of RTCA DO-229 (DO-229E, 2016), and China plans to add BDS to L1 SBAS Minimum Operational Performance Standards (MOPS) when the time is right.

The DFMC user equipment will satisfy the requirement of EUROCAE ED-259A (ED-259A (Draft) 2021; International Civil Air Organization DS2, 2019; Satellite-Based Augmentation Systems Interoperability Working Group, 2016b). Since the current version of the DFMC SBAS MOPS (EUROCAE ED-259) is limited to GPS and Galileo, China had submitted information papers of "Introduction of COMAC and our support to EUROCAE" and "Update on the BDS SARPs Validation," expressing its intention to join MOPS, which was supported by experts attending the meeting (Commercial Aircraft Corporation of China, Ltd., 2020a, 2020b).

2.2 | Reference time

The reference time of BDSBAS is BDS Time (BDT), and the leap second information is broadcast in the navigation message of BDS. BDT adopts the SI second as the basic unit. The origin of BDT is 00:00:00 on Jan. 1, 2006, of Coordinated Universal Time (UTC). BDT is aligned with UTC indirectly, and the deviation of BDT to UTC is maintained within 50 nanoseconds (modulo 1 second) (China Satellite Navigation Office, 2017). More specifically, BDT aligns with UTC (k) provided by China's National Time Service Center (NTSC), and UTC (k) aligns with UTC. BDT may steer to an intermediate frequency by adjustment after a period of time (usually more than 30 days), but the quantity of the adjustment does not exceed 5E-15 (Yang et al., 2019).

For the SF service of BDSBAS, the SBAS Network Time (SNT) is BDT+14s. The difference between SNT of BDS-BAS SF service and GPS Time is less than 50 nanoseconds. For the DFMC service of BDSBAS, the SNT is BDT.

2.3 | Coordinate reference system

BDSBAS uses the BeiDou Coordinate System (BDCS), which is in accordance with the specifications of the International Earth Rotation and Reference Systems Service (IERS). BDCS is defined as follows:

1. Definition of origin, orientation and scale. The origin is located at the Earth's center of mass. The Z-axis is the direction of the IERS Reference Pole (IRP). The X-axis is the intersection of the IERS Reference Meridian (IRM) and the plane passing through the origin and normal to the Z-axis. The Y-axis, together with Z-axis and X-axis, constitute a right-handed orthogonal coordinate system. The length unit is meter.
2. Definition of the BDCS Ellipsoid. The geometric center of the BDCS Ellipsoid coincides with the Earth's center

TABLE 4 Parameters of the BDCS Ellipsoid (China Satellite Navigation Office, 2017)

No.	Parameter	Definition
1	Semi-major axis	$a = 6{,}378{,}137.0$ m
2	Geocentric gravitational constant	$\mu = 3.986004418 \ast 10^{14}$ m^3/s^2
3	Flattening	$f = 1/298.257222101$
4	Earth's rotation rate	$\dot{\Omega}_e = 7.2921150 \ast 10^{-5}$ rad/s

of mass, and the rotational axis of the BDCS Ellipsoid is the Z-axis. The parameters of the BDCS Ellipsoid are shown in Table 4.

The BDCS and World Geodetic System 1984 (WGS 84) are both implementations of International Terrestrial Reference Frame (ITRF), and the difference between the two does not exceed 3 cm. The transformation parameters from BDCS to ITRF2014 are shown in Table 5.

2.4 | Augmentation message

2.4.1 | B1C augmentation message

The augmentation messages broadcast by the BDSBAS B1C are shown in Table 6, and these messages are used in the BDSBAS SF service.

Each message has bits, which consist of an 8 - bit part of a distributed preamble, a 6 - bit message type, a 212 - bit data field, and 24 bits of the Cyclic Redundancy Check (CRC) parity.

2.4.2 | B2a augmentation message

The augmentation messages broadcast by the BDSBAS B2a that are used in the BDSBAS DFMC service are shown in Table 7.

Defined as 250 bits, each message consists of a 4 - bit part of a distributed preamble, a 6 - bit message type, a 216 - bit data field, and 24 bits of CRC parity.

The receiver shall use a BOC (1, 1) replica for B1C-pilot signal and BPSK (10) replica for B2a-pilot signal. The satellite orbit and satellite clock shall be based on ephemeris in B-CNAV2 message on B2a (International Civil Air Organization DS2, 2019).

TABLE 6 Augmentation messages broadcast by BDSBAS B1C (China Satellite Navigation Office, 2020)

Augmentation message	Contents
0	Do not use this signal for safety application (for testing)
1	PRN mask assignments
2 to 5	Fast correction
6	Integrity information
7	Fast correction degradation factor
9	BDSBAS GEO navigation message
10	Degradation parameters
12	SBAS Network Time (SNT)/UTC offset parameters
17	Almanacs of BDSBAS GEO
18	Ionospheric grid point masks
24	Mixed fast corrections/long-term satellite error corrections
25	Long-term satellite error corrections
26	Ionospheric delay corrections
28	Clock-ephemeris covariance matrix message
63	Null message

TABLE 7 Augmentation messages broadcast by BDSBAS B2a (Satellite-Based Augmentation Systems Interoperability Working Group, 2016b)

Augmentation message	Contents
0	Do not use this signal for safety application (for testing)
31	PRN mask assignments
34, 35, 36	Integrity information
32	Satellite clock-ephemeris error corrections and covariance matrix
39	SBAS satellite clock, ephemeris and covariance matrix
40	
37	Degradation parameters and DFREI scale table
47	Almanacs of SBAS satellite
42	SNT/UTC offset parameters
63	Null message

TABLE 5 Transformation parameters from BDCS to ITRF2014

	Tx (mm)	Ty (mm)	Tz (mm)	Rx (mas)	Ry (mas)	Rz (mas)	Scal (ppb)
Estimation	−0.37	1.12	−0.55	0.01	−0.02	0.05	0.011
STD	0.74	0.74	0.74	0.03	0.03	0.04	0.012

TABLE 8 Performance requirements of BDSBAS

Items		BDSBAS	
		SF service	DFMC service
Planned service coverage		10°N~55°N; 75°E~135°E	10°N~55°N; 75°E~135°E
Augmentation constellation		BDS B1C (Future plan) GPS L1C/A	BDS B1C/B2a GPS L1C/A/L5 GALILEO E5a/E1 GLONASS L1/L3
Accuracy (95%)		H: Better than 16m V: Better than 20m	H: Better than 16m V: Better than 4m
Integrity	Time to alarm	10s	6s
	Integrity risk	2×10^{-7}/150s	2×10^{-7}/150s
	Alarm threshold	HAL: 40m	HAL: 40m
		VAL: 50m	VAL: 10m
Continuity		1-8 $\times 10^{-6}$/15s	1-8 $\times 10^{-6}$/15s
Availability		99%	99.9%

3 | PERFORMANCE REQUIREMENTS

The planned service coverage of BDSBAS is 10°N~55°N and 75°E~135°E. Right now, the service only covers the landmass of China. For SF service, GPS and BDS will be augmented, and the service performance will be APV-I. Although BDSBAS augments GPS only now, China plans to add BDS to ICAO L1 SBAS SARPs in the future. For DFMC service, BDS, GPS, Galileo and Globalnaya Navigazionnaya Sputnikovaya Sistema, or Global Navigation Satellite System (GLONASS) will be augmented, which will improve availability and provide robustness against single GNSS constellations (Satellite-Based Augmentation Systems Interoperability Working Group, 2016a), and the service performance will be CAT-I. Details of performance indicators are shown in Table 8.

4 | INTERNATIONALIZATION

4.1 | Radio frequency compatibility

Radio frequency signal compatibility and non-mutual-harm influence are the important basis of SBAS interoperability and joint integrity service for international aviation navigation. At present, under the ICAO framework, SBASs jointly carry out the study and formulation of DFMC standards. In the future, SBAS will provide single frequency SBAS service on BDS B1C band and DFMC SBAS service on BDS B2a band. Due to compliance with the requirements of signal power in ICAO and International Telecommunication Union (ITU) standards, the three BDSBAS

GEOs, which are located at 80E, 110.5E and 140E, will not cause significant interference to other GNSS systems and SBAS (the three BDSBAS GEOs as part of BDS have been reported together with the other BDS satellites at ITU). In fact, due to the limited transmitting and landing power, and the satellites being far from each other, the mutual interference brought by BDSBAS to other GNSS and SBAS is far less than their own self-interference.

Taking GPS and WAAS as examples, the intra-system interference between GPS/WAAS and inter-system interference between BDSBAS and GPS/WAAS are shown in Table 9. The results show that the reduction of carrier-to-noise ratio of GPS/WAAS L1 and L5 signals caused by BDSBAS B1C and B2a signals is extremely low, and generally far less than the reduction of carrier-to-noise radio caused by intra-system interference of GPS/WAAS. Thus, BDSBAS would not cause the degradation in performance of GPS/WAAS.

4.2 | Development of DFMC SBAS SARPs

During the 31st Satellite-Based Augmentation Systems Interoperability Working Group (SBAS IWG) meeting, China, the United States, the European Union, India, Japan, Russia, South Korea and other service providers co-signed the interface control document (ICD) and definition document of DFMC SBAS.

To develop the DFMC SBAS SARPs using the ICD and definition document of DFMC SBAS as input, DFMC SBAS DS2 sub-working group was established at the ICAO NSP meeting held in December 2016. China is one of the

TABLE 9 The interference between BDSBAS and GPS/WAAS*

Desired signal	Non-interfering condition	Intra-system interference of GPS/WAAS signals	Inter-system interference caused by BDSBAS signals
GPS L1C/A	43dB-Hz	38.747dB-Hz (4.253dB lower than 43dB-Hz)	38.668dB-Hz (0.079dB lower than 38.747dB-Hz)
GPS L1P(Y)	40dB-Hz	37.738dB-Hz (2.262 lower than 40dB-Hz)	37.720dB-Hz (0.018dB lower than 37.738 dB-Hz)
GPS L1M	43.5dB-Hz	40.914dB-Hz (2.586dB lower than 43.5dB-Hz)	40.914dB-Hz (0dB lower than 40.914dB-Hz)
GPS L1C	44.5dB-Hz	41.092dB-Hz (3.409dB lower than 44.5dB-Hz)	41.068dB-Hz (0.024dB lower than 41.092dB-Hz)
WAAS L1	43dB-Hz	42.615dB-Hz (0.385dB lower than 43dB-Hz)	42.467dB-Hz (0.148dB lower than 42.615dB-Hz)
GPS L5C	46.6dB-Hz	45.433dB-Hz (1.167dB lower than 46.6dB-Hz)	45.392dB-Hz (0.041dB lower than 45.433dB-Hz)
WAAS L5	44.5dB-Hz	44.431dB (0.069dB lower than 44.5dB-Hz)	44.390dB-Hz (0.041dB lower than 44.431dB-Hz)

*Note: 1) The power spectral density of noise is taken as -201.5dBW.

2) Reception loss is not considered.

3) GPS L1C is computed by MBOC modulation.

TABLE 10 SBAS service provider identifiers (DS2 SG, 2020)

Identifier	SBAS service provider
0	WAAS
1	EGNOS
2	MSAS
3	GAGAN
4	SDCM
5	BDSBAS
6	KASS
7	A-SBAS
8	SouthPAN
9 to 13	Spare
14 to 15	Reserved
16 to 31	Spare for additional SBAS L5 provider only

TABLE 11 UTC standard identifiers (DS2 SG, 2020)

Identifier	UTC standard
0	UTC as operated by the National Institute of Information and Communications Technology, Tokyo, Japan
1	UTC as operated by the U.S. National Institute of Standards and Technology
2	UTC as operated by the U.S. Naval Observatory
3	UTC as operated by the International Bureau of Weights and Measures
4	Reserved for UTC as operated by a European laboratory
5	UTC as operated by the National Time Service Center, Chinese Academy of Sciences
6	Reserved
7	UTC not provided
8 to 15	Reserved for DFMC SBAS only

members of DS2 sub-working group and continues to participate in the discussions and development of the DFMC SBAS SARPs.

During the ICAO DS2 meeting held in August 2017, China suggested BDSBAS as one of the SBAS service providers and "National Time Service Center, Chinese Academy of Sciences – UTC (NTSC)" as one of the UTC standard identifiers (Civil Aviation Administration of China, 2017). The two proposals were accepted by the ICAO DS2 and written into the DFMC SBAS SARPs during the DS2 meeting held in October 2017. The service provider identifier and UTC standard identifier of BDSBAS in the DFMC SBAS SARPs are shown in Table 10 and Table 11, respectively.

During the ICAO DS2 meetings held in February, April and November 2018, China submitted work papers about dual-frequency ranging signal, dual-frequency ranging mode, and augmented navigation message of BDS to the ICAO DS2.

During the 24th DS2 meeting held in April 2020, China proposed the Threat Model (TM) and Threat Space (TS) of BDS B1C and B2a signals by considering the BDS satellite payload characteristic, the ranging bias and differential error caused by the distortion signal. BDS B1C and B2a signals adopt the ICAO distortion model as the TM Frame,

TABLE 12 Threat space for BDS B1C and B2a signals

Signal	TM-A	TM-B	TM-C
BDS B1C	$-0.05 \leq \Delta \leq 0.05$ (chip)	$0.1 \leq \sigma \leq 20$ (Mnepers/s) $1.5 \leq fd \leq 18$ (MHz)	$-0.05 \leq \Delta \leq 0.05$ (chip) $0.1 \leq \sigma \leq 20$ (Mnepers/s) $1.5 \leq fd \leq 18$ (MHz)
BDS B2a	$-0.5 \leq \Delta \leq 0.5$ (chip)	$0.1 \leq \sigma \leq 18$ (Mnepers/s) $4 \leq fd \leq 18$ (MHz)	$-0.5 \leq \Delta \leq 0.5$ (chip) $0.1 \leq \sigma \leq 18$ (Mnepers/s) $4 \leq fd \leq 18$ (MHz)

and the TS is shown in Table 12 (Zhi, 2020d, 2020a). In response to the questions about the unicity of Issue of Data Ephemeris (IODE) and Issue of Data Clock (IODC), China explained that the IODE and IODC broadcast in B-CNAV1 and B-CNAV2 will not be repeated in one day for BDS satellites in healthy state, which can guarantee the unicity of IODE and IODC of B1C and B2a (Zhi, 2020c).

4.3 | Development of IALA standard

China continues to participate in the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) Engineering and Sustainability (ENG) meetings, and developed "ENG 10–14.3.3 IALA Guideline on SBAS Maritime Service" with 27 other countries at the 10th meeting, held in September 2019. This guideline is to identify aspects that maritime or coastal administrations may take into account when considering the use of SBAS on ships in their waters, and to describe all the elements of SBAS relevant to the maritime administrations (International Association of Lighthouse Authorities, 2019).

In the future, China will verify the performance of BDS-BAS for maritime during the development of BDSBAS. Also, China will track the development of IALA differential GNSS standard, and write BDSBAS in this standard at the right time.

5 | PERFORMANCE TEST

5.1 | Signal test

The ground test of the BDSBAS GEO-1 satellite was carried out in February 2018, and the ground tests of the BDSBAS GEO-2 and GEO-3 satellites were carried out in March and May 2019, respectively. According to the test results, the B1C and B2a RF characteristics of the three GEOs are shown in Table 13 and Table 14, respectively. The B1C RF characteristics indicate that the signal-in-space performance of GEO-1, GEO-2 and GEO-3 met the requirements of ICAO SARPs. The B2a RF characteristics show that the signal-in-space performance of GEO-1, GEO-2 and GEO-3

satisfy the requirements of the draft ICAO DFMC SBAS SARPs.

5.2 | Initial performance test

The results shown in this paper were based on the BDSBAS SF service messages, by which only GPS was augmented, from November 27, 2019, to December 4, 2019. Using the observation measurements of International GNSS Monitoring & Assessment System (IGMAS) stations (bjf1: Beijing, sha1: Shanghai, and whu1: Wuhan) and the International GNSS Service (IGS) station (CHAN: Changchun), the accuracy, integrity and availability performance were tested. The performance test of DFMC service will be carried out later.

5.2.1 | Accuracy

Observation data, GNSS navigation messages, and BDSBAS augmentation messages are used to calculate positioning results and to evaluate the positioning accuracy as compared with the reference position. The results of accuracy are shown in Table 15, and the results satisfy the requirement of APV-I.

5.2.2 | Integrity

Integrity information from the BDSBAS augmentation messages is used to calculate the Horizontal Protection Level (HPL) and Vertical Protection Level (VPL), and integrity risk is determined based on the positioning error and protection level. (If the positioning error exceeds the protection level, then integrity risk occurs.)

The safety index is used to illustrate the integrity. The safety index is a metric that shows how well the protection levels are bounded by the observed error. The horizontal and vertical safety margin index is the ratio of HPL/HPE (Horizontal Position Error) and VPL/VPE (Vertical Position Error), respectively. If the minimal horizontal safety index and minimal vertical safety index are both greater than one, it indicates that no integrity risk occurs. The

TABLE 13 B1C RF characteristics of the BDSBAS GEO-1, GEO-2 and GEO-3

No.	Item	ICAO requirements	GEO-1 RF characteristics	GEO-2 RF characteristics	GEO-3 RF characteristics
1.	Carrier frequency	1575.42MHz	1575.42MHz	1575.42MHz	1575.42MH
2.	Spurious	≤ -40dBc	-56.66 dBc	-62.52 dBc	-58.34 dBc
3.	Modulation	BPSK (1) symbol rate 500sps code length 1,023 Chip rate 1.023Mchip/s	BPSK (1) symbol rate 500sps code length 1,023 Chip rate 1.023Mchip/s	BPSK (1) symbol rate 500sps code length 1,023 Chip rate 1.023Mchip/s	BPSK (1) symbol rate 500sps code length 1,023 Chip rate 1.023Mchip/s
4.	Phase noise	PLL of 10 Hz one-sided noise bandwidth is able to track the carrier with an accuracy of 0.1 radian	0.00578 rad	0.00630 rad	0.00598 rad
5.	Spectrum	At least 95% of the broadcast power will be contained within 12 MHz bandwidth	Band wide: ± 18.414MHz	Band wide: ± 18.414MHz	Band wide: ± 18.414MHz
6.	Frequency stability	<5e-11(1s~10s)	1.5e-12/1s	1.37e-12/1s	1.40e-12/1s
7.	Coherence of Code & Carrier	Short-term: < 0.15m	0.12m	0.08m	0.10m
		Long-term: < 0.19m	0.133m	0.09m	0.11m
		Long-term: <0.255m	0.16m	0.11m	0.15m
8.	Coherent of L1	Short-term: <0.2m Long-term: <0.255m	Short-term: 0.13m Long-term: 0.178m	Short-term: 0.04m Long-term: 0.078m	Short-term: 0.08m Long-term: 0.103m

TABLE 14 B2a RF characteristics of the BDSBAS GEO-1, GEO-2 and GEO-3

No.	Item	ICAO requirements	GEO-1 RF characteristics	GEO-2 RF characteristics	GEO-3 RF characteristics
1.	Carrier frequency	1176.45MHz	1176.45MHz	1176.45MHz	1176.45MHz
2.	Spurious	≤ -40dBc	-62.34 dBc	-54.38 dBc	-58.55 dBc
3.	Modulation	BPSK (10) symbol rate 500sps code length 10,230 Chip rate 10.23Mchip/s	BPSK (10) symbol rate 500sps code length 10,230 Chip rate 10.23Mchip/s	BPSK (10) symbol rate 500sps code length 10,230 Chip rate 10.23Mchip/s	BPSK (10) symbol rate 500sps code length 10,230 Chip rate 10.23Mchip/s
4.	Phase noise	PLL of 10 Hz one-sided noise bandwidth is able to track the carrier with an accuracy of 0.1 radian	0.00578 rad	0.00630 rad	0.00598rad
5.	Spectrum	At least 95% of the broadcast power will be contained within 3 dB bandwidth	Band wide: ± 35.805MHz	Band wide: ± 35.805MHz	Band wide: ± 35.805MHz
6.	Frequency stability	<6.7e-11(1s~10s)	5.2e-13/10s	4.77e-13/10s	4.9e-13/10s
7.	Coherence of Code & Carrier	Short-term: <0.2m	0.1m	0.09m	0.09m
		Long-term: <0.255m	0.16m	0.11m	0.15m
8.	Coherent of L5	Short-term: <0.2m Long-term: <0.255m	Short-term: 0.13m Long-term: 0.178m	Short-term: 0.04m Long-term: 0.078m	Short-term: 0.08m Long-term: 0.103m

TABLE 15 Initial test results of accuracy

Accuracy (95%)	bjf1		sha1		whu1		CHAN	
	H	**V**	**H**	**V**	**H**	**V**	**H**	**V**
BDSBAS	2.23m	3.83m	2.89m	3.89m	2.35m	3.85m	1.80m	2.70m

TABLE 16 Initial test results of safety index

Stations	Minimal horizontal safety index (min(HPL/HPE))	Minimal vertical safety index (min(VPL/VPE))
bjf1	3.29	2.90
sha1	1.65	1.45
whu1	1.90	5.00
CHAN	27.51	5.93

results of safety index are shown in Table 16. Both the minimal horizontal and minimum vertical safety index were greater than one; thus, no integrity risk happened during the test period, which satisfied the requirement of APV-I.

To visualize the relationship between HPL/HPE and VPL/VPE, the Stanford Plots of CHAN are shown in Figures 3 and 4. Based on the two figures, no points appeared in the Missing Information (MI) and Hazardous Missing Information (HMI) areas, which means no integrity risk occurred.

5.2.3 | Availability

The availability test analyzes the percentage of time that BDSBAS can provide the aircraft with available service within its service scope, and the initial results are shown in Table 17. It uses the HPL and VPL obtained from the integrity test to compare with the Horizontal Alarm Limit (HAL) and Vertical Alarm Limit (VAL) of the corresponding flight phase, and the percentage of time that the Protection Level (PL) is lower than the Alert Limit (AL) is considered as the availability.
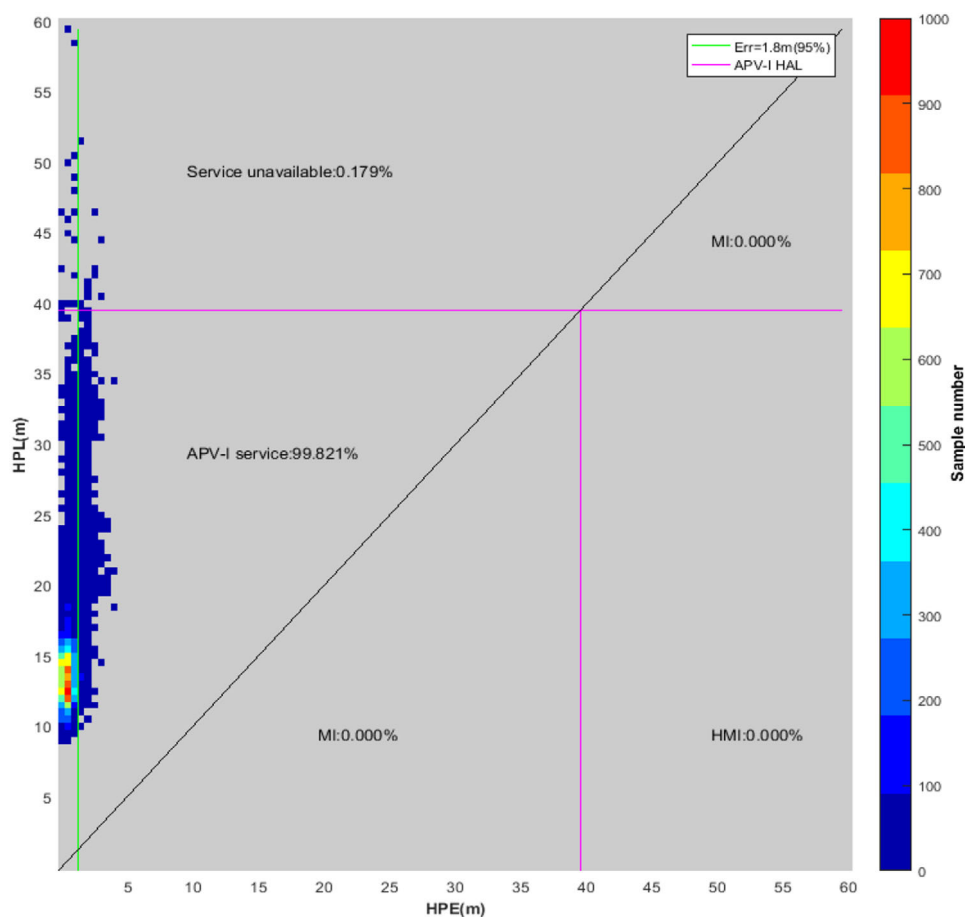

FIGURE 3 HPL/HPE Stanford Plot of CHAN station [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]
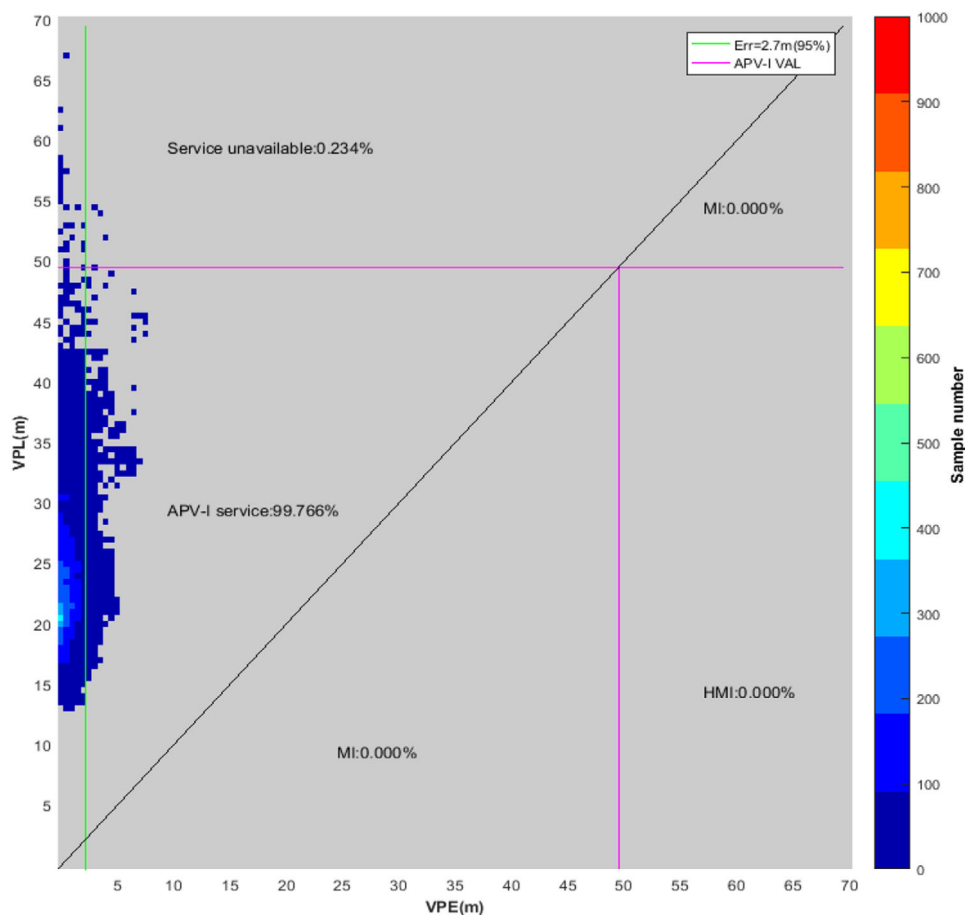
FIGURE 4 VPL/VPE Stanford Plot of CHAN station [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

TABLE 17 Initial test results of availability

Stations	Availability
bjf1	99.82%
sha1	93.78%
whu1	99.70%
CHAN	99.67%

From Table 17, the results of availability satisfied the requirement of APV-I except sha1. There are no overseas MSs at the east of sha1; therefore, the number of ionospheric pierce points that can be used is low. Due to the lack of ionospheric pierce points on the east of sha1, the availability of station "sha1" is worse than the other three stations located inland.

6 | PROCESS OF TESTING AND CERTIFICATION

BDSBAS testing and certification consist of three stages: technical review, test verification and test operation, and the process is shown in Figure 5.
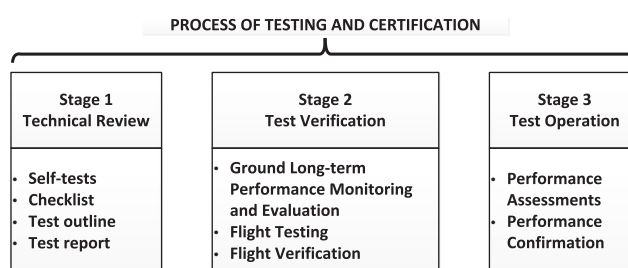

FIGURE 5 Process of testing and certification

6.1 | Technical review

During the technical review, the auditee (BDSBAS construction unit) shall carry out self-tests and provide the standard compliance checklist and corresponding test outline/test report to the auditor (organized or designated by the Civil Aviation Administration of China (CAAC)). In addition to the textual review, the auditor will conduct witness verification of some review contents.

6.2 | Test verification

During the test verification, the auditee shall carry out service performance evaluation for a long time (about two or three years) in accordance with the requirements of the ICAO SARPs for SBAS space signals and the requirements of the BDSBAS Performance Standard, and provide quarterly evaluation reports to the auditor. During this period, the auditor will conduct ground long-term performance monitoring and evaluation, flight testing, and flight verification.

The ground long-term performance monitoring and evaluation will be performed in accordance with the requirements of Section 3.2 of Chapter III of ICAO Doc. 8071 (5th edition), including GNSS interference monitoring, GEO interference monitoring, performance evaluation and data content inspection, interface monitoring with the operating unit, etc.

The flight testing will be performed in accordance with the requirements of Section 3.3 of Chapter III of ICAO Doc. 8071 (5th edition), and the implementing agency will be the CAAC Flight Inspection Center (CFIC). The flight tests will be carried out in Sanya, Kunming, Lhasa, Urumqi, Xi'an, Harbin and Shanghai.

The flight verification includes repeated flight verification of the en route, terminal area, departure and approach phase using a transport aircraft; under the premise of establishing visual conditions and ensuring flight safety, it should follow the BDSBAS service signal guidance and implement en route and terminal flight procedures to verify the performance of BDSBAS service signals.

6.3 | Test operation

The test operation is a transition period before entering the formal service status of BDSBAS. During this period, the BDSBAS operator will provide comprehensive service signals in accordance with formal operational requirements, strengthen monitoring of signal quality and system operating status, and regularly conduct corresponding operational performance assessments. The BDSBAS operator shall also regularly conduct service performance assessments in accordance with the requirements of ICAO SARPS and the BDSBAS Performance Standard, and provide a quarterly assessment report to the auditor (CAAC).

Under the premise of ensuring safety margins, civil aviation will study and formulate corresponding flight procedures and operating standards, use BDSBAS signals for navigation under actual operating environmental conditions, and strengthen user-side monitoring of actual navigation performance and service signals. Simultaneously, civil aviation will also carry out training of crew members and related operators, approve the operating conditions of aircraft operators, confirm the actual performance of the BDSBAS service in the actual operating environment, and accumulate experience for formal operations.

The auditor may extend the test operation time according to the feedback of problems during the test operation until the system ensures that it can meet the civil aviation operation safety requirements.

7 | SUMMARY

China is constructing the BDSBAS in accordance with international standards and plans to provide SF and DFMC services. BDSBAS is mainly comprised of three segments: the space segment, the ground segment and the user segment. The reference time of BDSBAS is BDT, and the coordinate reference of BDSBAS is BDCS.

Following the concept of being compatible and interoperable with other SBASs, China had applied for PRNs for the three GEOs from the US Air Force GPS Directorate, and obtained SBAS service provider identity from ICAO.

The BDSBAS signals have been broadcasted since Nov. 9, 2018, and the on-orbit test and ground test have been carried out. The results show that the characteristics of signal-in-space met the requirements of ICAO, and the performance of SF service basically meets the requirements of APV-I.

According to the plan, BDSBAS has provided initial service from July 2020. However, before BDSBAS is applied to civil aviation users, CAAC will organize the testing and certification, the process of which will be carried out in three steps. It is foreseeable that BDSBAS will provide formal service in 2023.

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