Research on Interoperability Methods for BDS-BAS Time Reference and Performance Testing Post-print

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Abstract

Satellite-based augmentation systems (SBAS) are constructed by different countries, with varying augmented satellite constellations and reference time systems. Consequently, the compatibility and interoperability among SBAS time references have consistently been significant technical challenges in International Civil Aviation Organization (ICAO) SBAS standardization research. This paper introduces the concept and current research status of SBAS Network Time (SNT), analyzes and investigates SNT compatibility and interoperability issues in the context of ICAO SBAS Standards and Recommended Practices (SAPRs) development, and presents the most recent joint solution. Building upon this foundation, the ground segment status of the BeiDou Satellite-Based Augmentation System (BDSBAS) was upgraded, and preliminary service performance testing was conducted. The results demonstrate that the maximum deviations between BDSBAS single-frequency (SF) SNT and dual-frequency multi-constellation (DFMC) SNT relative to the reference GNSS time reference are 37 ns and 0.17 s, respectively, satisfying ICAO standard requirements; the service performance essentially meets APV-I level requirements, thereby validating the feasibility and reliability of BDSBAS time reference interoperability.

Full Text

Research and Performance Assessment of BDSBAS Time System Interoperability

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Abstract

Satellite-Based Augmentation Systems (SBAS) are constructed by different countries, each augmenting different GNSS constellations and reference time systems. Consequently, the compatibility and interoperability between SBAS time references has remained a critical technical issue in ICAO SBAS standardization. This paper introduces the concept and current research status of SBAS Network Time (SNT), analyzes SNT compatibility and interoperability issues in the context of ICAO SBAS Standards and Recommended Practices (SARPs) development, and presents the latest joint solutions. Building upon this foundation, the ground segment of the BeiDou Satellite-Based Augmentation System (BDSBAS) was upgraded, and preliminary service performance tests were conducted. Results demonstrate that the maximum deviations between BDSBAS single-frequency (SF) SNT and dual-frequency multi-constellation (DFMC) SNT relative to their reference GNSS time scales are 37 ns and 0.17 s, respectively, meeting ICAO standard requirements. Service performance essentially complies with APV-I level requirements, proving the feasibility and reliability of BDSBAS time reference interoperability.

Keywords: BeiDou; global navigation satellite system (GNSS); satellite-based augmentation system (SBAS); dual-frequency multi-constellation (DFMC); SBAS network time (SNT)

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1. Introduction

Currently, the Satellite-Based Augmentation Systems (SBAS) that have been completed or are under construction worldwide primarily include: the U.S. Wide Area Augmentation System (WAAS) [1-3], the European Geostationary Navigation Overlay System (EGNOS) [4-5], Japan' s MTSAT Satellite-based Augmentation System (MSAS) [6-7], India' s GPS-Aided GEO Augmented Navigation System (GAGAN) [8-9], Russia's System of Differential Correction and Monitoring (SDCM) [10-11], Korea's Korea Augmentation Satellite System (KASS) [12], the SBAS for Africa and Indian Ocean (A-SBAS) [13-14], the Australia/New Zealand Southern Positioning Augmentation Network (SouthPAN) [15], and China' s BeiDou Satellite-Based Augmentation System (BDSBAS) [16-19]. The global distribution of these systems is illustrated in Figure 1 [Figure 1: see original paper].

Since each SBAS is constructed by different countries and augments different Global Navigation Satellite System (GNSS) constellations, achieving compatibility and interoperability among them has become a major challenge. To address this, the International Civil Aviation Organization (ICAO) established the SBAS Interoperability Working Group (IWG) to coordinate SBAS service providers in jointly developing SBAS international standards. In 2012, the IWG completed the development of Single Frequency (SF) SBAS Standards and Recommended Practices (SARPs), which were subsequently submitted to ICAO for review and promulgation. Beginning in 2015, the IWG initiated joint research and development of the Dual-Frequency Multi-Constellation (DFMC) SBAS SARPs draft, with China' s BDSBAS officially participating from this period onward [20]. Compared with SF SBAS, DFMC SBAS utilizes dual-frequency pseudorange measurements to eliminate ionospheric errors, thereby further improving positioning accuracy and integrity. Since grid ionospheric corrections are no longer required, DFMC SBAS can augment four core GNSS constellations (BDS, GPS, GLONASS, GALILEO) and achieves faster integrity alarm times (reduced from 10s to 6s) [21].

In SBAS SARPs research, time reference interoperability between different SBAS systems represents one of the primary technical challenges. On one hand, to enable independent observation and integrity monitoring of GNSS, each SBAS must establish and maintain its own independent time scale, known as SBAS Network Time (SNT), which inherently exhibits differences between systems. On the other hand, since each SBAS selects different GNSS constellations to augment, the time reference issues of their corrections must also be investigated and clearly defined. During the SF SARPs development process, only GPS and GLONASS constellations existed, and SF SBAS augmentation messages could only augment GPS or GLONASS (as ionospheric grid information consumed substantial message capacity). Consequently, SF SBAS time reference interoperability was relatively straightforward to resolve. However, during DFMC SARPs development, the global satellite navigation landscape has undergone significant changes. With the completion of BeiDou-3 (BDS-3) and accelerated deployment of GALILEO, the core GNSS constellations have expanded to four, while the number of SBAS systems has also increased. These developments have introduced new challenges for SBAS time reference interoperability. In November 2020, the DFMC SBAS SARPs draft was reviewed and approved at ICAO NSP/6 meeting and submitted to the ICAO Air Navigation Commission (ANC) for approval. The draft clarified various technical aspects, including SBAS time reference interoperability [22].

This paper begins with SBAS international standards, introducing the fundamental concept and current interoperability status of SNT. Focusing on the development progress of ICAO SBAS SARPs drafts, we analyze and investigate SNT compatibility and interoperability issues, presenting the latest solutions. Based on these international standard requirements for SBAS interoperable time references, the BDSBAS ground segment and software were upgraded, and post-upgrade performance results are presented. These findings provide valuable references for currently developing BDSBAS receivers, particularly those supporting the latest DFMC service mode.

2. SBAS Time References

SBAS augmented positioning involves two time reference systems: GNSS time and SBAS time. This section introduces and analyzes each system respectively.

2.1 GNSS Time Systems

2.1.1 GPS System Time GPS Time (GPST) is maintained by atomic clocks installed at ground control stations and onboard satellites. GPST epoch starts at 00:00:00 UTC on January 6, 1980 (Sunday), from which GPST counts continuously. GPST lags International Atomic Time (TAI) by 19 seconds. The United States Naval Observatory (USNO) regularly compares its maintained UTC with GPST and controls GPST to maintain synchronization with TAI [23-25].

The integer-second difference between GPST and UTC varies with UTC leap seconds, currently amounting to 18 seconds [25]. In addition to integer-second differences, GPST and UTC exhibit sub-microsecond deviations, typically controlled within a few hundred nanoseconds, often less than 20 ns (1σ) [26]. GPST is expressed using GPS Week Number (WN) and Seconds of Week (SOW), where SOW ranges from 0 to 604,800 seconds, resetting to 0 at Saturday midnight each week while the week number increments by 1.

2.1.2 BeiDou System Time BeiDou Time (BDT) adopts atomic time like GPST, continuously accumulating based on SI seconds, with its epoch defined as 00:00:00 UTC on January 1, 2006. BDT is linked to international UTC through UTC(NTSC), with deviations between BDT and international UTC maintained within 50 nanoseconds (mod 1 s) without requiring leap seconds [27]. However, since BDT maintains this tolerance relative to UTC, and UTC incorporates leap seconds, both BDT and GPST require leap second corrections (broadcast via navigation messages). Furthermore, because GPST already had a 14-second offset from UTC before BDT' s epoch on January 1, 2006, BDT and GPST maintain a constant 14-second system difference in addition to a 1356-week offset [28]. The relationship is:

BD Week = GPS Week - 1356 weeks
BD Seconds of Week = GPS Seconds of Week - 14 s

Figure 2 [Figure 2: see original paper] presents measured results of the time difference between BDT and GPST, confirming the stable 14-second time offset (seconds of week) between the two systems.

2.1.3 Galileo System Time Galileo System Time (GST) is a continuous time scale traceable to International Atomic Time (TAI), differing from TAI by an integer number of seconds without implementing leap seconds, maintaining a deviation less than 50 ns. GST epoch is defined as 13 seconds ahead of UTC on August 22, 1999, consistent with GPST [29]. Currently, GST leads UTC by 18 seconds.

2.1.4 GLONASS System Time GLONASS Time (GLONASST) adopts Moscow time as its standard, using Russia' s UTC(SU) as the time measurement standard. Unlike other GNSS time systems, GLONASST incorporates the same leap seconds as UTC(SU), thus having no integer-second difference. However, a 3-hour integer offset exists between them, along with a small deviation (within 1 ms). Their relationship is [30-31]:

2.2 SBAS Time According to ICAO standards, each SBAS must maintain and utilize its own time reference, called SBAS Network Time (SNT). SNT is defined as the GNSS system time maintained by SBAS ground monitoring stations while meeting overall SBAS performance requirements. Fundamentally, this independence is necessary for SBAS to observe and monitor GNSS integrity autonomously. When using SBAS corrections, user positioning is performed in SNT rather than GNSS System Time (GNSST). However, because the SARPs for SF SBAS and DFMC SBAS were developed years apart during which the global satellite navigation landscape changed significantly, the time reference requirements for these two SBAS services differ.

2.2.1 SF SBAS Time Reference ICAO SARPs for SF SBAS were completed in 2012, and ICAO currently has no plans to revise them. Since only GPS and GLONASS existed globally at that time, SF SBAS can currently only augment GPS or GLONASS (select one), with GPST as the optional SNT reference.

According to ICAO SARPs Annex 10 Volume I requirements, SF SBAS SNT can only reference GPST, with their difference maintained within 50 ns [30]:

$|SNT_{SF} - GPST| \leq 50$ ns (6)

2.2.2 DFMC SBAS Time Reference In 2015, ICAO organized SBAS service providers to initiate DFMC SBAS standard development. As China and Europe began constructing their own GNSS systems (BDS-3 and Galileo), core GNSS constellations increased from two to four. Following technical validation, DFMC SBAS augmentable objects expanded to four constellations (GPS/GLONASS/BDS/Galileo). Correspondingly, DFMC SBAS SARPs allow SNT selection from any of the four core GNSS system times (optional SNT references: GPST/GLONASST/BDT/GST). Their difference must be maintained within 1 s [22]:

$|SNT_{DFMC} - GNSST| \leq 1$ s (7)

DFMC SBAS SNT reference information is broadcast via the Time Reference ID field in DFMC SBAS Message Type (MT) 37 (GPS ID: 0; GLONASS ID: 1; Galileo ID: 2; BDS ID: 3).

3. SNT Interoperability Methods and Strategies

3.1 SF SNT Interoperability Methods and Strategies In SF service mode, since only Russia' s SDCM augments its native GLONASS while all other SBAS systems augment GPS, ICAO' s time synchronization requirement is applicable to non-SDCM systems—SBAS broadcasts GPS satellite corrections in GPST, users receive GPS broadcast ephemeris and SBAS corrections simultaneously, obtaining GPST-based positioning results without additional operations.

However, SDCM presents a more complex case. Although SDCM broadcasts GLONASS satellite corrections, its time reference is relative to GPST. This requires users to perform an additional time conversion, translating GLONASS satellite corrections from GPST to GLONASST for compatibility with GLONASS broadcast ephemeris to complete augmented positioning. This can be achieved through two approaches:

a) Receive GLONASS broadcast ephemeris to compute GLONASST offset relative to UTC, simultaneously receive GPS broadcast ephemeris to compute GPST offset relative to UTC, then derive the time difference between GLONASST and GPST;

b) Broadcast GLONASST-GPST time difference parameters in GLONASS broadcast ephemeris.

3.2 DFMC SNT Interoperability Methods and Strategies In DFMC mode, SBAS can augment four GNSS constellations, with SNT references selectable by each SBAS provider. In the 2017 DFMC SBAS SARPs draft, each SBAS provider clarified their selections, as shown in Table 1 .

Table 1. DFMC Augmented Constellations and SNT References of Each SBAS Provider

SBAS	DFMC Augmented Constellations	SNT Reference
EGNOS	GPS, Galileo	Galileo, GPS
GAGAN	GPS, Galileo	GPS, Galileo
BDSBAS	GPS, Galileo, GLONASS, GPS	GLONASST
SDCM	BDS, GPS	BDT

In Table 1, "DFMC SBAS Augmented Constellations"refers to the GNSS constellations for which the SBAS broadcasts corrections. Which specific GNSS constellation and its augmentation corrections are used for navigation by airborne receivers within the SBAS service area is determined by avionics manufacturers and national civil aviation authorities.

Since DFMC SBAS augments multiple GNSS constellations involving more time reference systems, SNT interoperability implementation is more complex than in SF SBAS. According to DFMC SBAS principles, when users employ augmented GNSS satellite corrections from Message Type (MT) 32 for positioning, the GNSS satellite clock correction is calculated as:

SVt DSVBBtttc &B B &Dt

where Bδ is the satellite clock bias correction, Bδ& is the satellite clock drift correction, c is the speed of light, t is the measurement epoch in the GNSS constellation' s time system (obtained from GNSS broadcast messages), and Dt is the correction reference epoch in the SNT time system (obtained from SBAS augmentation messages).

The GNSS satellite orbit correction is calculated as:

Txtytzt Dxtxxytyyttztzz &&&

where [δx δy δz] is the satellite orbit bias correction and [δx& δy& δz&] is the satellite orbit bias rate correction.

When DFMC SBAS SNT references a specific GNSS time system—for example, using BDT as reference with Time Reference ID 3 (see Table 3), indicating DFMC SBAS SNT is BDT-based—the Dt in the equations becomes BDT time. In this case, no issues arise if users only employ BDS for augmented positioning. However, if users simultaneously employ GPS or other GNSS for augmented positioning, they must convert t from its native GNSS time system to BDT; otherwise, differences between GNSS time systems will be introduced into the positioning solution. Specifically, when using GPS satellites for augmented positioning, since GPST differs from BDT by a fixed 14 seconds, the GPS satellite clock correction becomes:

14DGPSSVBBtttc &

The GPS satellite orbit correction becomes:

TGPSGPSGPSxtytzt 14GPSGPSDGPSxtxxytyyttztzz &&&

Since the integer-second differences between GPST, BDT, and GST are fixed, conversion can be easily accomplished through the above method. However, for GLONASS, because the integer-second difference between GLONASST and other GNSST is not fixed but varies with time due to leap seconds (GLONASST follows UTC leap seconds while other GNSST do not), the issue cannot be resolved through preset configurations in receivers. Compared to other GNSS, users must receive GLONASS broadcast leap second information to achieve compatible DFMC positioning between GLONASS and other GNSS.

From an SBAS interoperability perspective, this implies all DFMC SBAS receivers must augment GLONASS; otherwise, they cannot utilize corrections broadcast by SDCM. This does not align with DFMC SBAS service design objectives. Therefore, at the ICAO NSP/6 meeting in November 2020, the DS2 working group provided conversion relationships between DFMC SBAS SNT and augmented constellation reference times to resolve GNSS time compatibility for DFMC SBAS, as shown in Table 2 .

Table 2. Conversion Relationship Between DFMC SBAS SNT and Reference Time of Augmented Constellation

MT37 Time Reference ID	SNT=0 (GPS)	SNT=1 (GLONASS)	SNT=2 (GALILEO)	SNT=3 (BDS)
GPS	t(SNT=0) = t(GPST)	t(SNT=1) = t(GPST) - Δt_{LS} + 10800 s	t(SNT=2) = t(GPST)	t(SNT=3) = t(GPST) - 14 s
GLONASS	t(SNT=0) = t(GLONASST) + Δt_{LS} - 10800 s	t(SNT=1) = t(GLONASST)	t(SNT=2) = t(GLONASST) + Δt_{LS} - 10800 s	t(SNT=3) = t(GLONASST) + Δt_{LS} - 10800 s
Galileo	t(SNT=0) = t(GST)	t(SNT=1) = t(GST) - Δt_{LS} + 10800 s	t(SNT=2) = t(GST)	t(SNT=3) = t(GST) - 14 s
BDS	t(SNT=0) = t(BDT) + 14 s	t(SNT=1) = t(BDT) - Δt_{LS} + 10800 s	t(SNT=2) = t(BDT) + 14 s	t(SNT=3) = t(BDT)

Note: Δt_{LS} represents the leap second difference between BDS, GPS, GALILEO and GLONASS reference times, obtained from GNSS navigation message information.

4. Testing and Analysis

BDSBAS was previously constructed according to SF SBAS international standard time reference requirements, with service performance meeting ICAO standards. In response to the latest technical requirements and developments in DFMC SBAS international standards, BDSBAS upgraded its ground segment monitoring and processing capabilities to ensure GNSS corrections in DFMC mode are relative to their respective GNSST.

From May 8 to June 21, 2021, common-view receivers were deployed at the BDSBAS Data Processing Center (Xi' an) and the BeiDou System Master Control Station (Beijing) for continuous 45-day observations. Using satellite common-view time transfer methods, deviations between BDSBAS SF SNT, DFMC SNT and their corresponding GNSS time references were calculated and evaluated.

4.1 Time Reference Testing

4.1.1 SF Time Reference Testing For SF SBAS SNT, current international SF SBAS SARPs require selection of either GPST or GLONASST as reference. Therefore, BDSBAS SF SNT achieves synchronization with GPST by adding 14 seconds to BDT, thereby meeting current ICAO requirements. The time deviation between BDSBAS SF SNT and GPST was calculated using satellite common-view time transfer, with results shown in Figure 3 [Figure 3: see original paper].

Results indicate a maximum deviation of 37 ns between BDSBAS SF SNT and GPST, satisfying the 50 ns requirement in SF SBAS SARPs.

4.1.2 DFMC Time Reference Testing For DFMC SBAS SNT, DFMC SBAS SARPs standards allow selection from any of the four core GNSS system times. Therefore, BDSBAS DFMC SNT selects BDT as its reference for synchronization. The time deviation between BDSBAS DFMC SNT and BDT was calculated using satellite common-view time transfer, with results shown in Figure 4 [Figure 4: see original paper].

Results demonstrate a maximum deviation of 0.17 s between BDSBAS DFMC SNT and BDT, satisfying the 1 s requirement in DFMC SBAS SARPs.

4.2 BDSBAS Service Performance Testing BDSBAS service performance testing utilized 1-second sampling data from the BDSBAS Beijing monitoring station on June 15, 2021, with augmentation messages from BDSBAS PRN130 satellite.

4.2.1 SF Service Performance Testing Positioning error histograms and Stanford diagrams for the Beijing station are shown in Figure 5 [Figure 5: see original paper] and Figure 6 [Figure 6: see original paper]. Statistical results show horizontal accuracy (95%) of 1.187 m, vertical accuracy (95%) of 2.356 m, APV-I availability of 99.446%, continuity of 99.079%, minimum horizontal/vertical safety factors of 4.107 and 3.098, respectively, and zero HMI events during the calculation period. These results indicate that BDSBAS SF service positioning accuracy and availability meet ICAO APV-I service level requirements. Furthermore, with minimum horizontal/vertical safety factors both greater than 1, the protection levels completely envelope positioning errors, and zero HMI events demonstrate that integrity parameters can provide reliable integrity assurance to users.

4.2.2 DFMC Service Performance Testing Positioning error histograms and Stanford diagrams for the Beijing station are shown in Figure 7 [Figure 7: see original paper] and Figure 8 [Figure 8: see original paper]. Statistical results show horizontal accuracy (95%) of 1.830 m, vertical accuracy (95%) of

2.860 m, APV-I availability of 100.00%, continuity of 100.00%, minimum horizontal/vertical safety factors of 1.872 and 2.581, respectively, and zero HMI events during the calculation period. BDSBAS DFMC service positioning accuracy is slightly inferior to SF service. This occurs because although the BDS B1C/B2a dual-frequency combination eliminates ionospheric effects, it amplifies pseudorange measurement noise, resulting in larger combined model noise and slightly greater positioning errors. However, since dual-frequency measurements are unaffected by ionospheric grid point distribution or availability, the number of augmentable satellites increases and longer arc lengths significantly expand DFMC service coverage, thereby improving availability and continuity. BDSBAS DFMC service performance during the evaluation period meets APV-I level requirements.

5. Conclusion

This paper introduced SNT concepts and interoperability status, analyzing and investigating SNT compatibility and interoperability issues in conjunction with ICAO SBAS SARPs draft development. For SF SBAS SNT, since current international SF SBAS SARPs only permit GPST or GLONASST as references, BDSBAS SF SNT temporarily uses GPST as its reference for time synchronization. In the future, when SF SBAS SARPs standard revision work resumes and BeiDou is incorporated as an SF SBAS augmentation option, the reference will be upgraded to BDT. For DFMC SBAS, augmenting multiple GNSS constellations involves more time reference systems, making SNT interoperability more complex than SF SBAS. To address this, the ICAO SBAS SARPs joint working group researched and developed conversion relationships between DFMC SBAS SNT and augmented constellation reference times to achieve GNSS time compatibility.

In response to these latest international standard requirements for SBAS interoperable time references, BDSBAS underwent hardware/software upgrades and preliminary service performance testing. Results show that for SF mode, the maximum deviation between BDSBAS SNT and GPST is 37 ns, meeting ICAO' s 50 ns requirement; for DFMC mode, the maximum time deviation between BDSBAS SNT and BDT is 0.17 s, meeting ICAO' s 1 s requirement. Based on this time synchronization, BDSBAS service performance testing was conducted. Results demonstrate that during the test period, BDSBAS SF service accuracy and availability met ICAO APV-I requirements, though continuity fell short; BDSBAS DFMC service accuracy, availability, and continuity all met ICAO APV-I requirements. These test results prove the feasibility and reliability of BDSBAS time reference interoperability methods.

Moving forward, BDSBAS will continue participating in joint ICAO international standard research and development, actively promoting BeiDou' s inclusion in SF SBAS SARPS as an SF SBAS augmentation option. Concurrently, BDSBAS will continue system construction and service performance optimization to provide high-performance, high-safety aviation navigation augmentation services compliant with ICAO international standards.

References

[1] JASON B. Wide area augmentation system (WAAS) update [R]. Changsha, China: SBAS IWG 30, 2016.
[2] JASON B. Wide Area Augmentation System (WAAS) program overview [R]. Australia: SBAS IWG 35, 2019.
[3] SHAO Bo, GENG Yongchao, DING Qun, et al. Summarize of international satellite based augmentation system [J]. Modern Navigation, 2017, 6(3): 157-161.
[4] European Satellite Services Provider (ESSP). EGNOS performance and LPV implementation status [R]. Changsha, China: SBAS IWG 30, 2016.
[5] NATHALIE R. EGNOS programme status [R]. Changsha, China: SBAS IWG 30, 2016.
[6] MASASHI G. MSAS status [R]. Changsha, China: SBAS IWG 30, 2016.
[7] HIDETSUGU W. MSAS status and future plan [R]. Australia: SBAS IWG 35, 2019.
[8] Airports Authority of India (AAI). GPS aided GEO augmented navigation (GAGAN) [R]. Changsha, China: SBAS IWG 30, 2016.
[9] Airports Authority of India (AAI). GPS aided GEO augmented navigation (GAGAN) [R]. Senegal: SBAS IWG 31, 2016.
[10] China Satellite Navigation Office (CSNO). [EB/OL]. [2021-07-20]. http://www.beidou.gov.cn/zy/kpyd/201710/t20171023_{4777}.html
[11] European Space Agency (ESA). [EB/OL]. [2021-07-20]. https://gssc.esa.int/navipedia/index.php/SDCM
[12] EUNSUNG L. Korea SBAS program [R]. Changsha, China: SBAS IWG 30, 2016.
[13] ASECNA. SBAS for Africa and Indian Ocean initiative [R]. Ghana: Twenty-Second Meeting for the AFI Planning and Implementation Regional Group, 2019.
[14] ASECNA. Update on "SBAS for Africa and Indian Ocean" (A-SBAS) development [R]. Montreal: ICAO NSP Sixth Meeting, virtual meeting, 2020.
[15] Jeffrey Bollard, Simon Reynolds. Southern Positioning Augmentation Network Program Update [R]. Montreal: ICAO NSP Sixth Meeting, virtual meeting, 2020.
[16] China Satellite Navigation Office. BeiDou Navigation Satellite System Service System (Version 1.0) [R]. Beijing: China Satellite Navigation Office, 2019.
[17] Civil Aviation Administration of China (CAAC). The new service provider ID and UTC standard ID for BDSBAS [R]. Montreal: ICAO NSP 4th Meeting, 2017.
[18] LIU Cheng, GAO Weiguang, SHAO Bo, et al. Development of BeiDou satellite-based augmentation system [J]. Navigation, 2021, 68(2): 405-417.
[19] CHEN Gucang, LIU Cheng, LU Jun. Service level and system performance analysis of BDSBAS [J]. Science of Surveying and Mapping, 2021, 46(1): 42-48.
[20] SHAO Bo, DING Qun, GENG Yongchao, et al. The Summarize of dual-

frequency multi-constellation satellite-based augmentation system messages [C]. The 29th Conference of Spacecraft TT&C Technology, Shanghai, China, 2018: E-07.
[21] IWG. Satellite-based augmentation system dual-frequency multi-constellation definition document [R]. Senegal: SBAS IWG 31, 2016.
[22] DS2 rapporteur. Proposed amendments to Annex 10, Volume I: Satellite-based augmentation system (SBAS) provisions [R]. ICAO NSP Sixth Meeting, virtual meeting, 2020.
[23] United States Naval Observatory (USNO). [EB/OL]. [2021-07-20]. https://www.usno.navy.mil/USNO.
[24] LIU Cheng, LI Fang. Perturbation analysis of satellite orbit error impact on positioning accuracy [J]. Astronomical Research & Technology, 2018, 15(1): 40-45.
[25] Leap Second. Clocks [EB/OL]. [2021-07-20]. http://www.leapsecond.com/java/gpsclock.htm
[26] IS-GPS-200. NAVSTAR GPS Space Segment/Navigation User Interfaces [S]. PNT Capability Area Integration, Portfolio Architect Space and Missile Systems Center, 2021.
[27] BDS-SIS-ICD-B1C-1.0. BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1C (Version 1.0) [S]. Beijing: China Satellite Navigation Office, 2017.
[28] GAO Xingwei, GUO Jingjun, CHENG Pengfei, et al. Fusion positioning of Compass/GPS based on spatio-temporal system unification [J]. Acta Geodaetica et Cartographica Sinica, 2012, 41(5): 743-748, 755.
[29] ERIC C, NATALIA C. UPDATE TO GALILEO OPEN SERVICE DRAFT SARPS [R]. ICAO NSP GSSVWG Meeting, virtual meeting, 2020.
[30] LIU Qingyuan, BAO Hai, WANG Hu, et al. The transformation and coordinates transformation among GPS, GLONASS and GALILEO [J]. Science of Surveying and Mapping, 2008, 33(5): 13-15.
[31] ICAO. International Standards and Recommended Practices Annex10 Aeronautical Telecommunications Volume I Radio Navigation Aids [S]. Senegal: 2018.

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Note: Figure translations are in progress. See original paper for figures.