Postprint: Research on Multipath Error Characteristics of Dual-Frequency Multi-Constellation BeiDou Satellite-Based Augmentation System

Authors: Dai Kaiyang, Shao Bo, Ding Qun, Shi Bin, Zhang Jian, Shao Bo

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Abstract

To verify the compliance of BeiDou Satellite Based Augmentation System (BDSBAS) multipath error characteristics with the Dual-Frequency Multi-Constellation (DFMC) Satellite Based Augmentation System multipath error model for international civil aviation, this study first examines navigation system signal features by comparing the frequency signal characteristics of BeiDou Navigation Satellite System (BDS), Global Positioning System (GPS), and Galileo satellite navigation system (GALILEO). Subsequently, based on the requirements of the DFMC BDSBAS multipath error model for international civil aviation, a verification methodology for DFMC BDSBAS multipath error characteristics is proposed. Finally, compliance is validated through aviation antenna group delay testing and measured data. The results demonstrate that: (1) the dual-frequency signal characteristics of BDS, GPS, and GALILEO are fundamentally consistent; (2) the aviation antenna employed in the testing meets the DO-373 antenna group delay characteristic requirements; and (3) the multipath error curves of BDS, GPS, and GALILEO show consistent variation trends, and the multipath error characteristics of the DFMC BDSBAS satisfy the International Civil Aviation Organization (ICAO) multipath model requirements.

Full Text

Research on Multi-path Error Characteristics of Dual-Frequency Multi-Constellation BeiDou Satellite-Based Augmentation System

Abstract

To verify the conformity of the multi-path error characteristics of the BeiDou Satellite-Based Augmentation System (BDSBAS) with the International Civil Aviation Organization (ICAO) dual-frequency multi-constellation (DFMC) satellite-based augmentation system multi-path error model, this study first compares the signal characteristics of BeiDou Navigation Satellite System (BDS), GPS, and Galileo satellite navigation system (GALILEO) frequency points from the perspective of navigation system signal features. Based on the ICAO DFMC SBAS multi-path error model requirements, a verification method for DFMC BDSBAS multi-path error characteristics is proposed. Finally, the conformity is verified through aviation antenna group delay tests and measured data. The results demonstrate that: (1) The dual-frequency signal characteristics of BDS, GPS, and GALILEO are basically consistent; (2) The aviation antenna used in the test meets the requirements of DO-373 standard aviation antenna group delay characteristics; (3) The variation trend of the multi-path error curve of BDS is basically consistent with that of GPS and GALILEO, and the multi-path error characteristics of DFMC BDSBAS meet the requirements of the ICAO multi-path model.

Keywords: BeiDou Satellite-Based Augmentation System; dual-frequency multi-constellation; RF signal characteristics; multi-path error; antenna group delay

1. Introduction

Satellite-Based Augmentation Systems (SBAS) can enhance the accuracy, continuity, and availability of basic satellite navigation systems, and provide timely warnings to users when the system is abnormal. Currently operational worldwide are the American Wide Area Augmentation System (WAAS), Japanese Multi-functional Satellite Augmentation System (MSAS), European Geostationary Navigation Overlay Service (EGNOS), and India's GPS Aided GEO Augmented Navigation (GAGAN). However, single-frequency (SF) SBAS has not yet achieved the service performance requirements for Category I precision approach due to ionospheric anomalies. To eliminate the impact of ionospheric anomalies on service performance and improve augmentation constellation service performance by utilizing the geometric layout of multiple satellite navigation systems, the ICAO SBAS Interoperability Working Group (IWG) is researching and developing DFMC SBAS Standards and Recommended Practices (SARPs) to achieve Category I precision approach performance requirements. DFMC SBAS represents the inevitable trend for future SBAS development.

China's BDSBAS officially began operation at the end of 2021, bringing new opportunities and challenges for the development of China's satellite navigation system, with continuous improvement in performance and accuracy. As the national 14th Five-Year Plan lists "BeiDou Going Global" as a key R&D task, China is actively participating in the formulation of ICAO DFMC SBAS standards. In the development of ICAO DFMC SBAS SARPs, both the BeiDou Navigation Satellite System as the object to be augmented and BDSBAS as the service provider have been incorporated into the DFMC SBAS SARPs, requiring verification of relevant content. Verification of DFMC BDSBAS multi-path error characteristics is a crucial component of this work.

While the United States and Europe have already obtained ICAO certification for their DFMC SBAS multi-path error characteristics, and Germany's Aerospace Center has conducted modeling analysis for GBAS using experimental data, China has not yet initiated work on DFMC BDSBAS multi-path error characteristics. Domestic scholars have not proposed specific solutions or approaches, making it urgent for BDSBAS to conduct relevant research. This paper investigates DFMC BDSBAS multi-path error characteristics, proposes verification methods and test procedures, and validates conformity through experiments, aiming to support the integration of BeiDou into the ICAO global satellite navigation framework and promote the national strategy of "BeiDou Going Global."

2. Satellite Navigation System Signal Characteristics

Signal characteristics are the primary factors to consider in performance design during GNSS construction. In early satellite navigation systems, BPSK modulation was widely applied due to its simple implementation. With GNSS development, factors such as spectral resource utilization and multi-path effects have become major considerations. Under the same frequency band, BOC modulation signals exhibit superior performance compared to traditional BPSK, enabling better spectral resource utilization among satellite navigation systems.

The dual-frequency signal characteristics of BDS, GPS, and GALILEO are shown in Table . At 1575.42 MHz, BDS B1C_{pilot}, GPS L1C/A, and GALILEO E1 all use BOC(1,1) or BPSK(1) modulation with a chip rate of 1.023 Mcps. At 1176.45 MHz, BDS B2a_{pilot}, GPS L5, and GALILEO E5a-Q all use BPSK(10) modulation with a chip rate of 10.23 Mcps. Since this study focuses on navigation satellite multi-path error characteristics and code length does not affect multi-path performance, the three systems exhibit basically consistent dual-frequency signal characteristics in terms of modulation mode and chip rate.

3. Verification Method Design for DFMC BDSBAS Multipath Error Characteristics

ICAO has two requirements for DFMC SBAS multi-path error characteristic verification:

1. The system multi-path error characteristics must meet the ICAO multipath error model envelope requirement. The multi-path error model is:

   $$MP\&AGDV = 0.4\exp(-El/0.34) \tag{1}$$

   where $MP\&AGDV$ is the standard deviation of DFMC SBAS multi-path error and El is the elevation angle.

2. The receiver antenna group delay must meet the Radio Technical Commission for Aeronautics (RTCA) DO-373 standard aviation antenna group delay characteristics envelope requirement. The standard aviation antenna group delay characteristic is:

   $$AGD \leq (1.5 + 0.021 \cdot El) \leq 0.65 \text{ ns} \tag{2}$$

   where AGD is the receiver antenna group delay.

Based on these requirements, this paper proposes a specific method and test procedure for verifying DFMC BDSBAS multi-path error characteristics.

3.1 Antenna Group Delay Test Procedure

The antenna group delay test is conducted in an anechoic chamber with the following steps:

1. Set up the test environment and connect all instruments. Use a level to calibrate the standard antenna and test antenna to ensure their vertical center lines coincide.
2. Calibrate the vector network analyzer at DFMC SBAS frequency points. For BDSBAS, test at B1C (1575.42 MHz) and B2a (1176.45 MHz).
3. Rotate the test aviation antenna one full circle, starting from 5° elevation angle, at azimuth angles $Az = 0°, 10°, 20°, 30°, ..., 330°, 340°, 350°$. Record the antenna group delay values $\Gamma(El, Az)$ output by the vector network analyzer.
4. Repeat step 3 for elevation angles $El = 5°, 10°, 15°, 20°, ..., 80°, 85°, 90°$ and record corresponding test data.

3.2 Data Processing Method

First, obtain the average value of the test aviation antenna group delay at $El = 85°$:

$$\bar{\Gamma}(85°) = \frac{1}{N} \sum_{Az=0°}^{350°} \Gamma(85°, Az)$$

Then calculate the maximum antenna group delay $\Gamma_{\max}(El)$ at each elevation angle:

$$\Gamma_{\max}(El) = \max_{Az}\{\Gamma(El, Az) - \bar{\Gamma}(85°)\}$$

Plot the curve of maximum antenna group delay versus elevation angle and verify whether it is enveloped by the DO-373 standard antenna group delay requirement curve.

For multi-path error characteristic verification: 1. Preprocess raw dual-frequency pseudo-range and carrier phase observations through data screening, cycle slip detection, and marking. Data screening removes observations with dual-frequency SNR < 28 dB-Hz. Outlier removal eliminates observations where dual-frequency pseudo-range differences exceed thresholds. Cycle slip detection uses geometry-free (GF) and Melbourne-Wübbena (MW) combinations. 2. Form ionosphere-free combinations of dual-frequency pseudo-range and carrier phase observations:

$$P_{IF} = \frac{f_1^2 \cdot P_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2}$$

$$\phi_{IF} = \frac{f_1^2 \cdot \phi_1 - f_2^2 \cdot \phi_2}{f_1^2 - f_2^2}$$

where f_1, f_2 are the frequencies and P_{IF}, ϕ_{IF} are the ionosphere-free combined pseudo-range and carrier phase. 3. Generate Code Minus Carrier (CMC) observations that contain only multi-path error and high-frequency noise:

$$CMC(i) = P_{IF}(i) - \phi_{IF}(i)$$

4. Eliminate integer ambiguity effects using cycle slip markers and apply smoothing filter to reduce high-frequency noise:

$$\overline{CMC}(i) = \frac{1}{T} \sum_{k=i-T/2}^{i+T/2} CMC(k)$$

where $T = 100$ s is the filter time window. 5. Group the final multi-path error sequence by elevation angle intervals, calculate the standard deviation for each group, and plot the multi-path error standard deviation versus elevation angle characteristic curve. Verify whether this curve is enveloped by the ICAO DFMC SBAS multi-path error model curve.

4. Experimental Validation

Based on the verification procedure, experiments were conducted using a NovAtel G5Ant-743AT1-A2 aviation antenna for group delay measurement. Field tests were performed in Xi'an Caotang with the antenna mounted above a 1.2 m diameter aluminum plate to simulate aircraft skin multi-path environment. A Septentrio PolaRx5 receiver collected 30 days of raw observation data at 1 Hz sampling rate with 5° satellite cut-off elevation angle for BDS B1C/B2a, GPS L1C/A/L5, and GALILEO E1/E5a signals.

4.1 Antenna Group Delay Measurement

The antenna group delay test setup in the anechoic chamber is shown in [Figure 2: see original paper]. The measured maximum antenna group delay versus elevation angle for the G5Ant-743AT1-A2 antenna at 1575.42 MHz and 1176.45 MHz is shown in [Figure 3: see original paper], [Figure 4: see original paper], and [Figure 5: see original paper]. The black dashed line represents the DO-373 antenna group delay envelope, while the blue solid line shows the measured maximum antenna group delay curve at each elevation angle. The results demonstrate that the measured antenna group delay is enveloped by the standard curve, meeting DO-373 requirements.

4.2 Multi-path Error Characteristic Verification

The processed dual-frequency ionosphere-free combined multi-path error characteristic curves are shown in [Figure 6: see original paper] and [Figure 7: see original paper]. The red curve represents the ICAO DFMC SBAS multi-path error model envelope, while the pink and green curves show the calculated dual-frequency multi-path error characteristics for BDS, GPS, and GALILEO. The variation trends of the three systems' multi-path error characteristic curves are basically consistent and enveloped by the ICAO multi-path error model, confirming that DFMC BDSBAS multi-path error characteristics meet ICAO requirements.

5. Conclusion

This paper first compared the signal characteristics of BDS, GPS, and GALILEO, then proposed a verification method and test procedure for DFMC BDSBAS multi-path error characteristics based on ICAO DFMC SBAS multi-path error model requirements. Experimental validation using raw dual-frequency observation data confirmed that BDS dual-frequency multi-path error characteristics are consistent with GPS and GALILEO and meet ICAO DFMC SBAS multi-path model envelope requirements. This study provides specific research methods and test procedures for DFMC BDSBAS multi-path error characteristic analysis, supporting the integration of BeiDou into the ICAO global satellite navigation framework and promoting the national strategy of "BeiDou Going Global."

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Author Information

Dai Kaiyang[1],[2],, Ding Qun[1], Zhang Jian[1], Shao Bo[1], Shi Bin[1]

[1] The 20th Research Institute of China Electronics Technology Group Corporation, Xi'an 710068, China
[2] Shaanxi Key Laboratory of Integrated and Intelligent Navigation, Xi'an 710068, China

Abstract: In order to verify the conformity of the multi-path error characteristics of the BeiDou Satellite-Based Augmentation System with the ICAO

Dual-Frequency Multi-Constellation Satellite-Based Augmentation System multi-path error model, this paper compares the signal characteristics of BDS, GPS, and Galileo systems, proposes a DFMC BDSBAS multi-path error characteristic verification method based on ICAO DFMC SBAS multi-path model requirements, and verifies its conformity through aviation antenna group delay test and measured data. The results show that: (1) Dual-frequency signal characteristics of BDS, GPS, and GALILEO are basically consistent; (2) The aerial antenna used in the test meets the requirements of DO-373 antenna group delay characteristics; (3) The change trend of multi-path error curve of BDS is basically consistent with that of GPS and GALILEO. The multi-path error characteristics of DFMC BDSBAS meet the requirements of multi-path model of ICAO.

Keywords: BDSBAS; DFMC; radio frequency signal characteristics; multi-path error; antenna group delay

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