Postprint: Simulation Analysis and Quantitative Assessment of the Current Beidou Navigation Constellation

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Abstract

The BeiDou Satellite Navigation System (BDS) constitutes one of China' s critical infrastructure development projects. As the BeiDou-3 system deployment approaches its final stage, numerous navigation users continue to exhibit considerable interest in the current operational performance characteristics of the BDS. This study presents a simulation analysis and quantitative evaluation of the operational BeiDou navigation constellation as of May 2019, utilizing the Satellite Tool Kit (STK) software. The investigation encompasses geographically representative ground stations within China to evaluate regional BDS performance, alongside an assessment for high-dynamic users through simulation of a 700 km altitude Low Earth Orbit (LEO) Sun-synchronous satellite environment. Simulation results demonstrate that within Chinese territorial regions, the current BDS can already provide positioning services with accuracy superior to 10 meters, thereby possessing the capability to support national security operations with high-precision position information services. Furthermore, the current BeiDou navigation system can satisfy the navigation accuracy requirements of spacecraft under the Space Science Strategic Priority Program. The simulation results presented herein may serve as a data reference for comprehensive testing of the BeiDou navigation system.

Full Text

Simulation and Quantitative Assessment of the Current BeiDou Navigation Constellation

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Abstract

The BeiDou Satellite Navigation System represents a critical infrastructure project for China. As the BeiDou-3 system nears completion, numerous navigation users remain keenly interested in its interim navigation performance characteristics. This paper presents a simulation analysis and quantitative evaluation of the BeiDou navigation constellation as of May 2019, utilizing the Satellite Tool Kit (STK) software. The study selects geographically representative ground stations across China to assess regional BeiDou navigation performance, and additionally examines a 700 km altitude Low Earth Orbit (LEO) sun-synchronous satellite to evaluate navigation performance for high-dynamic spaceborne users. Simulation results demonstrate that within Chinese territory, the current BeiDou system can already provide positioning services with better than 10-meter accuracy, establishing its capability to support national security activities with high-precision location information. Furthermore, the current BeiDou navigation system can satisfy the positioning accuracy requirements of spacecraft under the Chinese Academy of Sciences' Space Science Strategic Priority Program. These simulation results offer valuable reference data for comprehensive testing of the BeiDou navigation system.

Keywords: BeiDou satellite navigation system; constellation; simulation; quantitative assessment; GDOP
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1 Introduction

The BeiDou Satellite Navigation System is an independently operated satellite navigation system and a vital infrastructure component for China. The BeiDou-1 experimental system, also known as the BeiDou Navigation Test System, employed active positioning using three geostationary satellites at approximately 36,000 km altitude—two operational satellites positioned at 80°E and 140°E, plus one on-orbit spare at 110.5°E. Completed by the end of 2000, BeiDou-1 provided regional navigation services to Chinese users with calibrated accuracy of 20 meters and uncalibrated accuracy of 100 meters. The BeiDou-2 regional system, comprising 14 satellites, was completed by the end of 2012 and offered two service types to the Asia-Pacific region: open service and authorized service. The open service provided free positioning, velocity measurement, and timing services with positioning accuracy of approximately 10 meters, timing accuracy of 50 nanoseconds, and velocity accuracy of 0.2 m/s. The authorized service delivered more secure positioning, velocity measurement, timing, and communication services along with system integrity information to authorized users.

The BeiDou-3 global system consists of 5 geostationary orbit satellites and 30 non-geostationary orbit satellites, with plans to establish a global BeiDou satellite navigation system around 2020, offering both open and authorized services globally. The open service will provide free positioning, velocity measurement,

and timing within the service area with positioning accuracy of 10 meters, timing accuracy of 10 nanoseconds, and velocity accuracy of 0.2 m/s. By 2035, China aims to establish a more ubiquitous, integrated, and intelligent comprehensive space-time system [1]. Following preliminary key technology development, the BeiDou project has achieved breakthrough progress in recent years, with 45 satellites in orbit as of May 17, 2019 [2]. Both domestic and international users have expressed strong interest in BeiDou' s navigation service performance [3,4]. Domestic users, particularly spacecraft designers, often equip satellites with GPS/BeiDou dual-mode receivers or GNSS multi-mode receivers to enhance reliability in obtaining position information. Some spacecraft even incorporate specialized terminals for BeiDou's short-message communication service. Before BeiDou's global system provides effective service, domestic space system designs typically relied on single-mode navigation receivers with injected orbit data or USB tracking and control for position information [5]. Several spacecraft under the Chinese Academy of Sciences' Space Science Strategic Priority Program have considered expanded BeiDou application modes, representing potential space users of the BeiDou system. These space users are particularly concerned about the current navigation performance of BeiDou. This paper constructs a realistic operational scenario of the current BeiDou navigation constellation based on in-orbit satellite orbit data (approximately 40 valid satellites), and simulates the Geometric Dilution of Precision (GDOP) for both ground and space navigation users based on the current BeiDou system configuration. These results can serve as input constraints to validate the effectiveness of navigation application terminal designs for the Space Science Strategic Priority Program spacecraft.

[Figure 1: see original paper]

2 Constellation Construction and Navigation Performance Simulation

To meet the simulation verification needs of potential BeiDou users, we utilized internationally available space object orbit databases [9] to download orbit data for all current BeiDou navigation satellites and constructed a simulation scenario of the current BeiDou constellation using Satellite Tool Kits (STK) software. Based on this scenario, we selected key domestic regions as reference points and conducted simulation analysis and quantitative calculation of navigation performance for BeiDou users in these areas.

The distribution of selected domestic stations is shown in [Figure 2: see original paper], and the sub-satellite point distribution of in-orbit satellites used in this simulation is presented in [Figure 3: see original paper]. For the stations listed in [Figure 2: see original paper] and the in-orbit BeiDou satellites shown in [Figure 3: see original paper], we performed quantitative calculations of navigation performance for 19 target users considering a minimum ground elevation angle of 5 degrees. The simulation results are summarized in .

The GDOP values in exhibit several characteristics: (a) Lower latitude stations

show relatively smaller GDOP values, primarily due to the presence of multiple GEO satellites (zero inclination) in the BeiDou constellation, which provides better coverage for low-latitude regions; (b) Among all examined regions, the maximum GDOP values do not exceed 2.3; (c) For the examined LEO satellite at 700 km altitude in sun-synchronous orbit, the GDOP simulation yields an average value of 0.798954 and a maximum of 1.137430, indicating that LEO satellites experience relatively small geometric dilution of precision—an advantageous condition for navigation application terminals on Space Science Strategic Priority Program spacecraft.

[Figure 4: see original paper] through [Figure 13: see original paper] present daily GDOP variation curves for typical ground stations across China at one-minute sampling intervals. These figures demonstrate that the current BeiDou satellite navigation system can provide navigation and positioning services with GDOP no greater than 2.3 within Chinese territory. According to the BeiDou Open Service Performance Standard, the User Range Error (URE) for IGSO, MEO, and GEO satellites does not exceed 2.5 meters at 95% confidence level, ignoring single-frequency ionospheric delay model errors. Based on this, we can infer that the current BeiDou system can provide positioning services with approximately 5.75-meter accuracy in the regions examined in this study.

[Figure 14: see original paper] shows the daily GDOP variation for the LEO spacecraft. If the space signal accuracy of the BeiDou system for space users is approximately 1 meter, we can infer that the current BeiDou system can provide positioning accuracy of about 1.14 meters for LEO users. This accuracy meets the positioning requirements of the Space Science Strategic Priority Program scientific missions. By leveraging BeiDou positioning services together with GPS, spacecraft under the Space Science Strategic Priority Program can achieve redundancy in position information acquisition, effectively increasing system reliability and reducing dependence on injected orbit data, thereby decreasing the frequency of ground manual intervention during spacecraft long-term management.

3 Conclusion

Based on in-orbit BeiDou navigation satellite orbit data, we constructed a realistic operational scenario of the current BeiDou navigation constellation and simulated the geometric dilution of precision for both ground and LEO space users. The results indicate that the current BeiDou navigation system can satisfy the positioning accuracy requirements of spacecraft under the Space Science Strategic Priority Program. Moreover, within Chinese territory, the current BeiDou system can already provide positioning services with better than 10-meter accuracy, demonstrating its capability to support national security activities with high-precision location information services.

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