Impact of Earth Orientation Parameter Prediction Errors on the Orbit Determination Accuracy of Beidou-3 Satellites (Postprint)

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Abstract

Earth orientation parameters (EOP) serve as the bridge for transformation between the Earth reference frame and the geocentric celestial reference frame, and constitute an indispensable parameter in the process of satellite precise orbit determination. Taking the EOP products provided by the International Earth Rotation Service (IERS) and the Shanghai Astronomical Observatory (SHAO) of the Chinese Academy of Sciences as examples, this study analyzes the relationship between orbit determination accuracy and EOP prediction errors under the BeiDou-3 regional network-only observation mode and the satellite-ground and inter-satellite joint observation mode. The research indicates that for products provided by IERS, their prediction errors have a relatively minor impact on the orbit determination accuracy of the regional station-only mode, but their prediction errors within 10 d can affect the orbit determination accuracy of the satellite-ground and inter-satellite joint mode to a decimeter-level extent. For products provided by SHAO, the orbit determination accuracy of both modes gradually degrades with increasing EOP prediction days. Additionally, the orbit determination accuracy under the satellite-ground and inter-satellite joint mode for different products is superior to that under the regional network-only monitoring mode, demonstrating that the incorporation of inter-satellite links can reduce the dependency of satellite orbit determination on EOP prediction errors. This research holds significant importance for the engineering implementation of satellite precise orbit determination under regional observation conditions.

Full Text

Influence of Earth Orientation Parameter Forecast Error on the Orbit Determination Accuracy of BeiDou-3 Satellites

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Abstract

Earth Orientation Parameters (EOP) serve as the critical link between the Earth reference frame and the geocentric celestial reference frame, representing indispensable parameters in the process of satellite precise orbit determination. This study analyzes the relationship between orbit determination accuracy and EOP forecast errors for BeiDou-3 under two distinct observation modes: regional network-only and satellite-ground-inter-satellite joint observation. Using EOP products from the International Earth Rotation Service (IERS) and the Shanghai Astronomical Observatory (SHAO), our findings reveal that IERS product forecast errors have minimal impact on regional station-only orbit determination accuracy, though their 10-day forecast errors can affect the satellite-ground-inter-satellite joint orbit determination mode at the decimeter level. For SHAO products, the orbit determination accuracy in both modes gradually degrades as the EOP forecast duration increases. Furthermore, the satellite-ground-inter-satellite joint determination mode consistently achieves higher accuracy than the regional network-only mode across all products, demonstrating that inter-satellite links can reduce dependence on EOP forecast errors. These results hold significant implications for implementing precise satellite orbit determination under regional observation conditions.

Keywords: Earth orientation parameters; satellite precise orbit determination; BeiDou-3 Navigation Satellite System

1 Introduction

When using Global Navigation Satellite Systems (GNSS) for positioning, users primarily rely on broadcast ephemerides and timing information transmitted by satellites to compute their own position, velocity, and time. The accuracy of satellite orbit parameters in broadcast ephemerides largely determines user positioning accuracy. The United States' Global Positioning System (GPS) and Europe's Galileo satellite navigation system achieve orbit determination through continuous observations from globally distributed monitoring stations. Their broadcast ephemeris orbit user range errors (URE) are 0.49 m and 0.14 m, respectively. To address the challenge that regional observation stations cannot observe satellites throughout entire orbital arcs, BeiDou-3 navigation satellites are equipped with Ka-band phased array antennas enabling inter-satellite observations. By jointly utilizing regional monitoring station data and inter-satellite link (ISL) observations, BeiDou-3 achieves significantly improved precise orbit determination with a broadcast ephemeris orbit URE of 0.09 m, surpassing both GPS and Galileo.

Accurate description of satellite position and time in appropriate reference frames constitutes a fundamental prerequisite for GNSS to provide precise navigation and timing services. GNSS orbit product generation typically comprises three components: precise orbit determination, orbit prediction, and ephemeris parameter calculation. During precise orbit determination, corrections to various observation data are described in the BeiDou Coordinate System (BDCS), whose difference from the International Terrestrial Reference System (ITRS) is at the sub-centimeter level and thus negligible. Orbit integration and state transition matrix calculations are generally performed in the Geocentric Celestial Reference System (GCRS), while final ephemeris parameter calculation and user position/velocity solutions are conducted in BDCS. Consequently, the process from satellite orbit determination to user position solution involves multiple transformations between GCRS and ITRS. Therefore, accurately describing the relationship between these two reference systems represents a critical prerequisite for GNSS to provide high-precision orbit products.

Earth Orientation Parameters (EOP) are essential for transformations between terrestrial and celestial reference frames and for precise orbit determination. During precise orbit determination, EOP errors affect not only the coefficient matrix in observation equations but also satellite accelerations, thereby influencing state transition matrices and introducing systematic errors. These errors are not fully absorbed into orbit determination residuals and consequently impact orbit determination accuracy. EOP data updates involve delays exceeding one day, making real-time or near-real-time EOP unavailable for quasi-real-time satellite precise orbit determination. Since GNSS services require real-time capabilities ranging from seconds to hours, GNSS systems must rely on forecasted EOP data to maintain transformation accuracy between reference frames. Previous work by Dill et al. demonstrates that EOP forecast errors increase over time, affecting orbit determination accuracy. As GNSS precise orbit determination demands higher accuracy, research into high-precision EOP forecasting methods becomes increasingly important. Numerous studies have investigated EOP parameter forecast errors and models, overcoming many challenges in EOP prediction. However, research on the relationship between GNSS orbit determination accuracy and EOP forecast errors under different observation conditions remains limited, leaving the practical dependency of GNSS precise orbit determination on EOP unclear. This study examines BeiDou-3 under regional observation conditions to investigate the dependence of satellite precise orbit determination on forecasted EOP, which holds significant importance for engineering implementation.

We conducted our investigation using post-processed EOP data (IAU1980 nutation model) and observation data required for orbit determination from November 2021, along with EOP forecast data from September 3 to November 30, 2021. Section 2 introduces and analyzes EOP forecast errors from IERS and SHAO during November 2021. Section 3 describes the BeiDou-3 satellite orbit determination method using ground station observations only under regional network conditions and analyzes the relationship between orbit determination accuracy and forecast errors for both products. Section 4 presents the satellite-ground-inter-satellite joint orbit determination method incorporating ISL observations and analyzes the relationship between orbit determination accuracy and EOP forecast errors using inter-satellite observations from November 19-22, 2021.

2 Analysis of EOP Product Forecast Errors

Using IAU1976/1980 precession-nutation models recommended by IERS as an example, the forecast parameters required during satellite orbit integration and determination include nutation in longitude correction (Δ), nutation in obliquity correction (Δ), two components of Earth polar motion (xp, yp), and UT1-UTC. UT1-UTC is expressed in milliseconds and converted to angular units by multiplying with Earth's mean rotation rate.

Taking IERS products as an example, Figure 1 [Figure 1: see original paper] reveals that among all EOP parameters, UT1-UTC exhibits the largest forecast error, reaching 100 mas after 65 days. Polar motion parameters rank second, with forecast errors not exceeding 5 mas within 90 days. Nutation correction parameters show the smallest errors, remaining below 1 mas within 76 days.

Based on these considerations, Table 1 presents statistical results of maximum forecast errors for xp, yp, Δ , Δ , and UT1-UTC under different forecast durations in November 2021. Both Table 1 and Figure 1 indicate that SHAO's forecast errors for xp and yp are smaller than IERS within 7 days but larger beyond 7 days. SHAO's forecast errors for Δ and Δ are significantly larger than IERS; IERS forecast data for Δ and Δ terminates after day 77, with no data available beyond this period. SHAO's UT1-UTC forecast errors are essentially comparable to those of IERS.

3 Impact of EOP Forecast Errors on Orbit Determination Accuracy Under Regional Station Observations

The orbit determination strategy under regional station observation conditions follows conventional GNSS satellite orbit determination approaches, as detailed in Table 2 . The geographical distribution of regional stations is shown in Figure

2 [Figure 2: see original paper].

This section conducts orbit determination experiments for BeiDou-3 satellites using EOP forecast parameters from both IERS and SHAO, along with BeiDou-3 ground station observation data, following the strategy outlined in Table 2. We analyze and statistically evaluate orbit determination residuals and accuracy under different EOP forecast durations. Orbit determination requires 4 days of EOP parameters. Since IERS products for Δ and Δ only provide 76-day forecasts before November 2021, results for IERS products with forecast durations of 77-90 days were not included. For periods beyond 77 days, calculations using IERS products employed Δ and Δ data from day 76.

Figure 3 [Figure 3: see original paper] illustrates the variation trends of pseudorange and phase residuals for Inclined Geosynchronous Orbit (IGSO) and Medium Earth Orbit (MEO) satellites as functions of EOP forecast duration. Comparison with Figure 1 reveals that within 90 days, phase and pseudorange residuals fluctuate within fixed ranges. When EOP forecast duration increases to 90 days, pseudorange residuals increase from 77.89 cm (SHAO) and 74.11 cm (IERS) to 80.11 cm (SHAO) and 74.76 cm (IERS), representing increases of only 2.9% (SHAO) and 0.9% (IERS). Phase residuals increase from 0.89 cm (SHAO) and 0.68 cm (IERS) to 1.09 cm (SHAO) and 0.72 cm (IERS), representing increases of 22.5% (SHAO) and 5.9% (IERS). These results demonstrate that EOP forecast errors have limited impact on both pseudorange and phase residuals.

Using post-processed EOP orbit determination results as a benchmark, we compared them with orbit determination results using different forecast durations to analyze radial errors (R), transverse-normal errors (TN, the vector sum of transverse error T and normal error N), and URE. URE is calculated using Equation (1):

$$URE = \sqrt{[\omega_R \cdot rms(R)]^2 + \omega_{TN}^2 \cdot [rms^2(T) + rms^2(N)]}$$

where $\omega R \; and \; \omega$\{TN\} are URE contribution factors with fixed values dependent on satellite orbital altitude: 0.992 and 0.088 for IGSO, and 0.981 and 0.136 for MEO, respectively.

Figure 4 [Figure 4: see original paper] presents orbit determination accuracy as a function of EOP forecast duration. Radial errors, transverse-normal errors, and orbital URE exhibit similar trends. For IERS products, orbit determination accuracy remains essentially unaffected by EOP forecast duration. However, for SHAO products, all three error metrics gradually increase with longer forecast durations. Additionally, when UT1-UTC and Δ , Δ undergo significant changes, orbit determination accuracy shows no substantial variation. Correlation analysis concludes that orbit determination accuracy is minimally affected by UT1-UTC and Δ , Δ , consistent with findings from related studies.

Figure 4 reveals that for IERS products, IGSO and MEO orbit errors remain essentially constant as EOP forecast duration increases. In contrast, for SHAO products, IGSO and MEO orbit determination accuracy degrades with longer forecast durations. When EOP forecast duration is 7 days, both IGSO and MEO orbital URE are below 0.6 m; when forecast duration reaches 90 days, IGSO and MEO orbital URE can increase to 1.30 m and 0.85 m, respectively.

These results indicate that using IERS products for EOP forecasting, regional station-only orbit determination accuracy remains unaffected by EOP forecast errors for considerable periods. However, using SHAO products, orbit determination accuracy degrades after a certain period. Additionally, for both IERS and SHAO products, as EOP forecast duration increases, IGSO orbit error variations are significantly larger than those of MEO, and IGSO errors consistently exceed MEO errors. This demonstrates that EOP forecast errors affect different satellite types differently, with greater impact on IGSO than MEO.

4 Impact of EOP Forecast Errors on Orbit Determination Accuracy with Inter-Satellite Link Support

Incorporating ISL observations, this study employs a satellite-ground-inter-satellite joint orbit determination strategy for BeiDou-3 precise orbit determination, as detailed in Table 2. The station data used are identical to those in Section 3.

This section conducts orbit determination experiments for BeiDou-3 satellites using EOP forecast parameters from IERS and SHAO, along with inter-satellite link observation data from November 19-22, 2021, and BeiDou-3 ground station observations, following the strategy in Table 2. Orbit determination residuals and accuracy were analyzed using the same methodology as Section 3.

Orbit determination residual results are shown in Figure 5 [Figure 5: see original paper]. Pseudorange and phase residual variation trends are consistent with those from orbit determination without inter-satellite observations. As EOP forecast duration increases to 90 days, pseudorange residuals change from 83.26 cm (SHAO) and 82.90 cm (IERS) to 85.64 cm (SHAO) and 83.70 cm (IERS), representing increases of 2.9% (SHAO) and 1.0% (IERS). Phase residuals change from 1.02 cm (SHAO) and 0.97 cm (IERS) to 1.59 cm (SHAO) and 1.09 cm (IERS), representing increases of 55.9% (SHAO) and 12.4% (IERS). Inter-satellite pseudorange residuals change from 8.25 cm (SHAO) and 8.20 cm (IERS) to 8.62 cm (SHAO) and 8.27 cm (IERS), representing increases of 4.5% (SHAO) and 0.9% (IERS).

These results demonstrate that in satellite-ground-inter-satellite joint orbit determination, EOP forecast errors have minimal impact on residuals for IERS products. For SHAO products, EOP forecast errors exert relatively greater influence on phase residuals but relatively minor influence on pseudorange and inter-satellite pseudorange residuals.

Figure 6 [Figure 6: see original paper] shows that for IERS products, orbit errors gradually increase during the first 10 days, then fluctuate within a 0.2-0.4 m range. For SHAO products, orbit determination accuracy degrades with longer forecast durations. When EOP forecast duration is 7 days, both IGSO and MEO orbital URE are below 0.3 m; when forecast duration reaches 90 days, IGSO and MEO orbital URE can increase to 0.78 m and 0.57 m, respectively.

These results indicate that using IERS products for forecasting, satellite-ground-inter-satellite joint orbit determination accuracy remains better than 0.5 m within 90 days. However, using SHAO products, orbit determination accuracy gradually degrades with longer forecast durations. Both products exhibit the same differential impact on IGSO and MEO satellites as observed in regional station mode. For IERS products, IGSO and MEO are affected equally, while for SHAO products, forecast errors affect IGSO more significantly than MEO.

5 Summary and Outlook

By applying EOP parameters from IERS and SHAO to BeiDou-3 satellite precise orbit determination and analyzing the relationship between orbit determination accuracy and EOP forecast errors under regional network and satellite-ground-inter-satellite joint observation modes, we conclude that both IERS and SHAO EOP products meet BeiDou-3 precise orbit determination requirements. For IERS products, orbit errors remain essentially constant as EOP forecast duration increases. For SHAO products, satellite orbit determination errors gradually increase as EOP forecast errors grow. Additionally, EOP forecast errors affect different satellite types differently, with greater impact on IGSO than MEO. The incorporation of inter-satellite links can reduce satellite orbit determination dependence on EOP forecast errors.

Based on experimental results, Table 3 presents the maximum EOP forecast duration requirements for achieving different orbit accuracy levels under both determination modes. For typical phase users requiring centimeter-to-decimeter-level service accuracy, using EOP forecasts within 2-3 days satisfies orbit determination accuracy requirements with URE below 10 cm. For typical pseudorange users requiring decimeter-to-meter-level service accuracy, using EOP forecasts within 90 days satisfies orbit determination accuracy requirements with URE below 1 m. These results demonstrate that inter-satellite links not only effectively improve satellite orbit determination accuracy but also reduce dependence on EOP parameter accuracy. These conclusions offer valuable references for stable satellite operation engineering, autonomous navigation, and theoretical development of space-based future space-time reference systems.

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