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Improvement of orbit determination accuracy for Beidou Navigation Satellite System with Two-way Satellite Time Frequency Transfer

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Abstract

The Beidou Navigation Satellite System (BDS) manages to estimate simultaneously the orbits and clock offsets of navigation satellites, using code and carrier phase measurements of a regional network within China. The satellite clock offsets are also directly measured with Two-way Satellite Time Frequency Transfer (TWSTFT). Satellite laser ranging (SLR) residuals and comparisons with the precise ephemeris indicate that the radial error of GEO satellites is much larger than that of IGSO and MEO satellites and that the BDS orbit accuracy is worse than GPS. In order to improve the orbit determination accuracy for BDS, a new orbit determination strategy is proposed, in which the satellite clock measurements from TWSTFT are fixed as known values, and only the orbits of the satellites are solved. However, a constant systematic error at the nanosecond level can be found in the clock measurements, which is obtained and then corrected by differencing the clock measurements and the clock estimates from orbit determination. The effectiveness of the new strategy is verified by a GPS regional network orbit determination experiment. With the IGS final clock products fixed, the orbit determination and prediction accuracy for GPS satellites improve by more than 50% and the 12-h prediction User Range Error (URE) is better than 0.12 m. By processing a 25-day of measurement from the BDS regional network, an optimal strategy for the satellite-clock-fixed orbit determination is identified. User Equivalent Ranging Error is reduced by 27.6% for GEO satellites, but no apparent reduction is found for IGSO/MEO satellites. The SLR residuals exhibit reductions by 59% and 32% for IGSO satellites but no reductions for GEO and MEO satellites.

Introduction

Global Navigation Satellite Systems (GNSSs) have changed our daily lives during the last few decades and are expected to benefit more people in the near future along with the new emerging systems. Beidou Navigation Satellite System (BDS), China's navigation satellite system, with the constellation consisting of 5 satellites in Geosynchronous Orbit

(GEO), 5 satellites in Inclined Geosynchronous Orbit (IGSO) and 4 satellites in Medium Orbit (MEO) by the time of March 1 2015, has been in operation and provides regional navigation services to users in the Asia-Pacific region. BDS is the third well-established navigation satellite system, following the GPS of the USA and the GLONASS of the Russia.

The satellite orbits and clock offsets determination is the key mission for the ground control segment of navigation satellite systems. The GPS satellite broadcast orbits and clocks are estimated in a state-space approach using measurements from a globally well-distributed network. After some minor and major updates, the orbit determination accuracy for GPS is greatly improved (Bertiger et al., 2010, Gruber, 2012). GLONASS finished its full constellation deployment by the end of 2011 and expanded its monitoring network (Kuzin et al., 2007, Revnivykh, 2012). From Revnivykh et al. (2012), the monitoring stations of GLONASS are mainly located within Russia's border. However, one should keep in mind that Russia has a wider territory than China.

In contrast to GPS and GLONASS, BDS has difficulties in the orbit and clock determination because of the different constellation and the limited ground tracking network. GEO satellites, the core component of the BDS regional constellation, play an important role in increasing the number of visible satellites and reducing Geometric Dilution Precision for navigation users within the Asia-pacific region. However, in the studies on orbit determination of BDS using measurements from the global network, the orbit accuracy of GEO satellites is much worse than those of IGSO and MEO satellites due to the static character and the poor observation geometry (Montenbruck et al., 2012, Steigenberger et al., 2013, Zhao et al., 2013b). Furthermore, only data from a regional monitoring network within mainland China are used for the BDS control segment. Thus, only 40% arc of the MEO satellites can be tracked (Zhou et al., 2013).

The largest dynamical error source for the navigation satellites orbit determination is the solar radiation pressure modeling error. Both analytical models (i.e. T20 or T30) and empirical models (i.e. ECOM) are well-established for the GPS satellites (Fliegel et al., 1992, Fliegel et al., 1996, Springer et al., 1999, Arnold et al., 2015) as well as for the GLONASS satellites (Ziebart et al., 2001). However, no commonly-recognized solar radiation pressure models intended for BDS are established and only models for GPS are applied in recent studies.

Faced with the problems of different constellation, regional network coverage and solar radiation pressure modeling errors, some studies on BDS orbit determination are conducted. A single satellite orbit determination experiment of GEO satellites using satellite laser ranging (SLR) and C-band transfer ranging data in combination was conducted in the early times. The orbit accuracy is better than 5 m and the radial accuracy of the 2-h predicted orbit is better than 0.5 m (Guo et al., 2010). However, that strategy cannot be applied to regular processing since SLR measurements may be affected by the weather condition and what is more, not all BDS satellites are equipped with the C-band transponders. With the deployment of the regional constellation, BDS adopts Multi-satellite precise orbit determination (MPOD) to estimate the satellite orbits and clock offsets simultaneously using L-band code and carrier phase measurements (Zhou et al., 2011, Mao et al., 2011). However, the satellite orbits are closely correlated with the satellites clock offsets due to the limited tracking network. And there are apparent periodic variations at the orbital frequency in the satellite clock estimates, which is most remarkable for the static GEO satellites (Zhou et al., 2011, Zhou et al., 2012, Zhou et al., 2013). Li et al. (2015) argued that the GEO orbit determination accuracy decreases during the spring and autumn equinox periods.

Zhao et al. (2013a) evaluated the BDS broadcast orbits accuracy with satellite laser ranging measurements and reported that the SLR residuals of C01 at the 70 cm level are much bigger than those of IGSO and MEO satellites. Montenbruck et al. (2015) compared the broadcast orbits with the final precise ephemerides from the Multi-GNSS experiment (MGEX, Montenbruck et al., 2013). The results indicate that the orbit accuracy for BDS IGSO and MEO satellites is better than the GEO satellites, and is at the same level with GLONASS, but is worse than the GPS satellites.

As only data from a regional monitoring network are used at the control segment of BDS, this work mainly focuses on the efforts to improve the BDS broadcast ephemerides accuracy. It seems possible to improve orbital accuracy and overcome the limitation of insufficient monitoring coverage with the assistance of the extra information on satellite clock.

Therefore, this work mainly focuses on the improvement of BDS orbit determination accuracy with TWSTFT. Two-way Time Frequency Transfer (TWSTFT) is a term to describe the technique for comparisons of remote time scales by exchange of timing signals between two ground stations via GEO satellites (Kirchner, 1999). However, TWSTFT in this text is used to describe the time comparison process between the ground station clocks and the on-board satellite clocks by comparing the uplink and downlink code measurements (Liu et al., 2009, Han et al., 2013). TWSTFT measures the on-board satellite clock offsets directly and the clock offsets measurements are free of the orbital errors, the station coordinates errors, the atmospheric propagation delay modeling errors and reflect the physical character variations of the satellite clocks. BDS also conducts a process to compare two ground station clocks by exchange of C-band timing signals via its GEO satellites: we refer to C-band TWSTFT in this text. The comparison of TWSTFT and C-band TWSTFT is made in Table 1.

The initial inspiration comes from Zhou et al. (2011). Zhou et al. (2011) reported that periodical variations are seen in the differences of the satellite clock estimates from MPOD and the TWSTFT satellite clock measurements. Since the TWSTFT clock measurements are free of the orbital errors, the periodical variations come from the clock estimates. And it is further pointed out in Zhou et al. (2011) that the clock differences series are quite similar with the SLR residuals. Thus, TWSTFT is used as a tool for the orbital accuracy evaluation in the same way as SLR (Zhou et al., 2011). He et al. (2014) accounted for the differences in orbit predication. Another strategy to improve the BDS orbit determination accuracy applied by Li et al. (2015) is to fix the satellite clock measurements as known values in orbit determination. But Li et al. (2015) applied this strategy only to the GEO satellites during the spring and autumnal equinox periods. No specific considerations for the systematic errors of TWSTFT or detailed analysis concerning the orbit accuracy improvement that new strategy brings to the whole constellation are found in Li et al. (2015). For this work, we propose a new satellite clock offsets fixed orbit determination strategy in which the systematic errors of TWSTFT are calibrated. As a result, the improvement of the orbit accuracy for all the BDS satellites is also discussed and is not limited to the GEO satellites.

The paper is organized as follows. First, BDS orbit determination, TWSTFT and the comparison of the satellite clock estimates and measurements are introduced briefly in Section 2. And then a satellite-clock-fixed GPS regional network orbit determination experiment is conducted in Section 3 to verify its effectiveness. Section 4 presents the satellite-clock-fixed BDS orbit determination experiment and its analysis. Finally, conclusion and discussion are given in Section 5.

Section snippets

BDS orbit determination and Two-way Satellite Time Frequency Transfer

The Multi-satellite orbit determination estimates the satellite orbits and the clock offsets simultaneously. The satellite clock offsets are also measured by TWSTFT, which is free of the satellite orbital dynamic information. Both orbit determination and TWSTFT give the satellite clock offsets relative to BDT, the time reference for BDS, which is related to the UTC through UTC (NTSC) with offsets within 100 ns (see CSNO, 2013). As a prerequisite, the orbit determination process, TWSTFT and…

GPS regional orbit determination experiment

Zhou et al. (2010) reported that the 24-h prediction URE is better than 0.58 m for GPS satellites with the so-called “two-step” approach based on the measurements from a Chinese regional network. In order to verify the effectiveness of our proposal, measurements from 6 IGS tracking stations in the mainland China (Beijing, Shanghai, Wulumuqi, Wuhan, Changchun and Lasa) are used to conduct standard orbit determination (POD strategy) and satellite-clock-fixed orbit determination (POD^+ strategy)....

Satellite clock fixed BDS orbit determination

The details on the standard orbit determination are completely introduced in Zhou et al. (2011). A complete comparison of both strategies of BDS is made in this section for the time period November 27–December 21 of 2014.

In the proposed satellite clock fixed orbit determination strategy, the clock measurements, treated as satellite-ground clock offsets ground truth, are fixed in pseudoranges observations so pseudoranges observations may be treated as range observations.

Before these clock…

Conclusion and discussion

Limited by the different constellation, the regional network coverage and solar radiation pressure modeling deficiency, the broadcast orbit errors of BDS are larger than GPS and the broadcast orbit errors of GEO satellites are larger than the IGSO and MEO satellites. In order to improve the BDS orbit accuracy, a new strategy for the satellite clock measurements fixed orbit determination is proposed. The proposal is first verified by a GPS regional orbit determination experiment. With the IGS…

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2023, Advances in Space Research

> *Citation Excerpt :*
> …As an alternative or complement to OISL, ground-space oriented OTWL measurements (Schlicht et al., 2019; Marz et al., 2021) can be used as well. Two-way ranging additionally supports this GNSS system with accurate time transfer by an optical measurement LTT (Laser Time Transfer; Meng et al., 2013) and a two-way microwave technique TWSTFT (Two-way Satellite Time Frequency Transfer; Tang et al., 2016). Ranging and time transfer techniques like the pulsed one-way/two-way European Laser Timing (ELT; Schreiber et al., 2010) or T2L2 (Time Transfer by Laser Link; Samain et al., 2014) are also able to achieve 1 mm ranging and time transfer precision (Marz et al. 2021).…

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…Observations to anchor stations (ground–satellite links) use the same communication and measurement system as the ISLs; however, unlike the ISL observations, they should be corrected for tropospheric delays (Ren et al., 2019). The BDS orbits and clock offsets are estimated simultaneously (Tang et al., 2016). The European Space Agency (ESA) conducted exploratory projects in the frame of the General Studies Programme (GSP).…

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