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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.

Keywords: Beidou Navigation Satellite System; Two-way Satellite Time Frequency Transfer; Satellite orbit determination; Satellite laser ranging

1. 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

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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 et al., 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, 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, 2012, 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