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# Time synchronization of new-generation BDS satellites using inter-satellite link measurements

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## Abstract

Autonomous satellite navigation is based on the ability of a Global Navigation Satellite System (GNSS), such as Beidou, to estimate orbits and clock parameters onboard satellites using Inter-Satellite Link (ISL) measurements instead of tracking data from a ground monitoring network. This paper focuses on the time synchronization of new-generation Beidou Navigation Satellite System (BDS) satellites equipped with an ISL payload. Two modes of Ka-band ISL measurements, Time Division Multiple Access (TDMA) mode and the continuous link mode, were used onboard these BDS satellites. Using a mathematical formulation for each measurement mode along with a derivation of the satellite clock offsets, geometric ranges from the dual one-way measurements were introduced. Then, pseudoranges and clock offsets were evaluated for the new-generation BDS satellites. The evaluation shows that the ranging accuracies of TDMA ISL and the continuous link are approximately 4 cm and 1 cm (root mean square, RMS), respectively. Both lead to ISL clock offset residuals of less than 0.3 ns (RMS). For further validation, time synchronization between these satellites to a ground control station keeping the systematic time in BDT was conducted using L-band Two-way Satellite Time Frequency Transfer (TWSTFT). System errors in the ISL measurements were calibrated by comparing the derived clock offsets with the TWSTFT. The standard deviations of the estimated ISL system errors are less than 0.3 ns, and the calibrated ISL clock parameters are consistent with that of the L-band TWSTFT. For the regional BDS network, the addition of ISL measurements for medium orbit (MEO) BDS satellites increased the clock tracking coverage by more than 40% for each orbital revolution. As a result, the clock predicting error for the satellite M1S was improved from 3.59 to 0.86 ns (RMS), and the predicting error of the satellite M2S was improved from 1.94 to 0.57 ns (RMS), which is a significant improvement by a factor of 3–4.


## Introduction

Inter-Satellite Links (ISLs) are an important part of modern Global Navigation Satellite Systems (GNSSs) (Maine et al., 2003, Holmes and Raghavan, 2004, Avila-Rodriguez et al., 2007). The concept was first proposed to support autonomous satellite navigation, which provides the ability for GPS satellites to self-navigate by interactively using data from the rest of the constellation (Ananda et al., 1990). Starting from the BLOCK IIR series, GPS first implemented ISL beginning in 1997 (Rajan, 2002). GPS adopts an ultrahigh frequency (UHF) and frequency hopping spread spectrum system combined with a Time Division Multiple Access (TDMA) scheme (Rajan, 2002). The User Ranging Error (URE) of the BLOCK IIR autonomous orbits is better than 3 m after 75 days (Rajan, 2002). However, the UHF ISL ranging measurements have suffered from serious multipath and noise issues and have not been the optimal choice for new-generation GPS satellites (Rajan et al., 2003). Therefore, the Ka-band ISL was proposed to replace UHF ISL on GPS BLOCK III satellites (Maine et al., 2003). Ka-band ranging has a high accuracy and a strong resistance against interference. Inter-satellite link measurements are also used by the Iridium satellites for estimating clock offsets, with an accuracy of 200 ns (Pratt et al., 2012).

The Beidou Navigation Satellite System (BDS), China's navigation satellite system, finished its deployment of a hybrid constellation, including 5 satellites in Geosynchronous Orbit (GEO), 5 satellites in Inclined Geosynchronous Orbit (IGSO) and 4 satellites in Medium Orbit (MEO). The constellation began to provide regional navigation services to users in the Asia-Pacific region by the end of 2012. The Multi-GNSS Experiment (MGEX, Montenbruck et al., 2017) of the International GNSS Service (IGS, Dow et al., 2009) regularly provides precise orbits of BDS satellites using L-band code and carrier phase measurements from a globally distributed network. The radial accuracy of the precise orbits of the MGEX is better than 10.0 cm for MEO and about 10.0 cm for IGSO satellites in terms of overlap comparisons and Satellite Laser Ranging (SLR) validation (Montenbruck et al., 2017, Guo et al., 2017).

BDS adopts Multi-Satellite Precise Orbit Determination (MPOD) to estimate satellite orbits using L-band dual-frequency ionosphere-free code and carrier phase combination measurements from a regional network within China's borders (Zhou et al., 2011, Mao et al., 2011), whereas the clock offset determination and prediction are conducted by L-band Two-Way Satellite Time and Frequency Transfer (TWSTFT) (see Liu et al., 2009, Han et al., 2013, Zhou et al., 2016, Tang et al., 2016 for details). Time synchronization is realized between stations and satellites with a residual root mean square (RMS) of approximately 0.166 ns (Zhou et al., 2016). By fixing the clock offsets obtained from the TWSTFT during the process of orbital determination, the User Equivalent Ranging Error (UERE) of the BDS GEO satellites can be reduced by 27.6% (Tang et al., 2016), and the 4-h recovered orbit after orbital maneuvers achieves an approximately 0.71-m residual RMS error for the fit SLR data (Guo et al., 2015).

In accordance with the construction plan, the system is designed to provide global coverage by approximately 2020. Starting in March 2015, five new-generation BDS satellites, including 2 satellites in IGSO and 3 satellites in MEO, have been launched to validate key technologies for the global service of the future BDS (see Table 1). One mission of the new-generation satellites is to test Ka-band ISLs and autonomous satellite navigation.

The new-generation BDS satellites are equipped with ISL payloads, which observe other satellites and ground anchor stations with Ka-Band single-frequency pseudo-code ranging measurements. Since only one-to-one inter-satellite or satellite-to-ground measurements can be simultaneously realized using Ka-band measurements, two modes of Ka-band inter-satellite ranging and communication measurements, TDMA and continuous link, have been investigated using new-generation BDS satellites (see Table 1).

This study concentrated on a feasibility analysis and accuracy assessment of the time synchronization of the new-generation BDS satellites with inter-satellite links. The global system of BDS requires MEO satellites to gain global coverage for navigation signals and services. However, for several reasons, the global BDS system is still using its regional network to obtain orbital information and clock offsets for the satellites, and the regional network's effective tracking coverage for MEO satellites is less than 40%. With the support of relative inter-satellite clock offsets, the clock offsets of out-of-view satellites can also be obtained, thus lengthening the tracking coverage of MEO satellites. The broadcast orbits and clock parameters are then uploaded to in-view satellites and transmitted to target satellites via inter-satellite communication. The equipment time delay error is the key error source that limits the clock offset accuracy, which is usually validated and calibrated by data adjustment. Experiments with real data from new-generation BDS satellites show that inter-satellite ranging measurements suffer from system errors caused by the payload time delay, which strongly affects the applications of ISL measurements for inter-satellite time synchronization and for improvements in the orbital determination accuracy. A new system error calibration method for the TDMA ISL payload is proposed and was validated in this study as well.

The remainder of this paper is organized as follows. In Section 2, the inter-satellite link and the ISL ranging measurement processing principles for the TDMA and continuous link are introduced. In Section 3, the characteristics of the ISL ranging measurements are described. The clock offsets from the ISL measurements are also compared with the L-band TWSTFT results. A system error calibration for the TDMA payload is proposed, and in Section 4, we conduct time synchronization of the new-generation BDS satellites supported by the ISL and an accuracy analysis. Conclusions and discussions are provided in Section 5.

## Section snippets

### Inter-satellite link of the new-generation BDS satellites

The two modes of the inter-satellite link, the TDMA and continuous link, were both established using dual one-way pseudo-code measurements. In this section, the observation equations and the measurement process are introduced. More technical details on ISL please see Han et al. (2013).

For the TDMA system, each satellite was assigned a 1.5-s time slot and operated in link pairs. For each time slot, there are several link-pair satellites simultaneously ranging with each other. Each satellite uses …

### Evaluation of the inter-satellite link measurements

From Eq. (5), the relative clock offset measurements of the pair links can be calculated. In this section, the ranging measurements of the TDMA mode and the continuous link mode are analyzed and compared.

Regular time synchronization of the BDS satellites to a ground control station based on the system time in BDT is conducted using L-band TWSTFT (Liu et al., 2009, Han et al., 2013, Zhou et al., 2016), following the basic principles described below.

Both satellite S and station G separately…

### Time synchronization experiments and results

In this section, the clock offset determination is conducted combining clock offsets obtained from L-band TWSTFT and Ka-band ISL of four satellites during the period from Apr 7 to Apr 20 of 2016. The system error of ISL payload is estimated. The anchor station is included in the system error estimation for comparison. The combined clock offsets are compared with L-band clock offsets to evaluate the accuracy of combined clock offsets.…

### Conclusions and discussion

In our algorithm, dual one-way ISL ranging measurements of new-generation BDS satellites, including TDMA and continuous link, were processed to separately obtain the clock offsets and geometrical distances. The TDMA ISL mode and continuous link mode were compared with each other: the ranging accuracies were approximately 4 cm and 1 cm (RMS), respectively, and the clock offset accuracy was approximately 0.3 ns (RMS) for both modes.

The TDMA inter-satellite relative clock offsets were used to…

## Acknowledgements

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2024, Measurement: Journal of the International Measurement Confederation

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Improved method for BDS-3 satellite clock parameterization in the broadcast ephemeris, real-time service (RTS) and IGS final products

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>
> …The application of the linear or quadratic polynomial in the broadcast ephemeris benefits from its good performance in short-term (e.g., 1 h, 2 h and 3 h) satellite clock correction modeling and extrapolating [23,29]. The BDS broadcast ephemeris is generated using L-band two-way satellite time–frequency transfer (TWSTFT) [10,30,19,16] and differs from other GNSSs. Yang et al. [24] shows that BDS-3 satellite clock correction in the broadcast ephemeris exhibits poor self-consistency and the improved method is necessary for improving the signal-in-space accuracy.…

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