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Real-time cycle slip correction for a single triple-frequency BDS receiver based on ionosphere-reduced virtual signals

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Abstract

Being an essential part of GNSS processing, cycle slip detection and repair has been intensively investigated. This paper develops an improved real-time cycle slip correction method based on three types of independent linear combinations of time-difference triple-frequency BDS observables. At first, one geometry-free pseudorange minus phase linear combination is selected as extra-wide lane (EWL) virtual signal and its cycle slips can be easily detected and repaired due to the long wavelength. Then, one geometry-free phase combination, treated as wide lane (WL) signal, is used to detect and repair cycle slips on WL combination based on fixed EWL ambiguity. Similarly, another one geometry-free phase combination is adopted to correct cycle slips on narrow lane (NL) signal. As a result of the short wavelength of NL combination, the residual ionospheric delay cannot be ignored and should be accurately estimated by the original observables. When the time-difference ambiguities of EWL, WL and NL signals are determined, the cycle slips on the original observables can be uniquely corrected by matrix operation. As the ionospheric delay plays a vital role in estimating ambiguities of combination signals, the second-order time-difference of ionospheric delay is used to detect the epoch with cycle slips and participate in estimating the time-difference ambiguity of NL signal. Considering that satellite elevation can be treated as quality factor of observables, we build a model to calculate the standard deviations of the selected combinations and 20° can be used as threshold value to correct cycle slips or not. The method has been tested on real 30 s triple-frequency BDS data with artificial cycle slips. Results show that the three-step method can detect and repair cycle slips correctly and effectively when the elevation is higher than 20°. While the elevation is lower than the threshold, the cycle slips should just be detected without repair to avoid miscalculation.

Keywords: BDS; Triple-frequency; Cycle slip correction; Real-time; Linear combination; Ionosphere-reduced

1. Introduction

The cycle slip, caused by the loss of lock in the carrier tracking loop, is a jump or interruption by an integer number in GNSS phase observables, which would degrade the accuracy and reliability of PNT services. Unfortunately, as a result of the large noise, presence of obstacles or interference signals, GNSS carrier observables usually contain cycle slip. Therefore, it should be detected and repaired, especially in precise positioning applications.

Over the past decades, a great number of algorithms had been proposed to detect and repair cycle slips (Bisnath and Langley 1997, Gao and Li 1999, Kim and Langley 1999). Although these methods have been proved effective and feasible in the practice, complex DD model should be established and two receivers are requisite to collect GNSS observations. In order to detect cycle slips easily, studies on a single receiver attracts more and more attention. Blewitt (1990) put forward the Turbo-Edit approach, which was

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developed for un-difference (UD) cycle slip detection and has been used in many GNSS positioning softwares. de Lacy et al. (2008) utilized Bayesian theory to deal with this problem, and numerical experiments on simulated and real data showed that the Bayesian approach was able to detect and correct cycle-slips based on UD GNSS observables. It should be noted, however, the basic assumption of these methods is that the observation errors remains stable, which means that rapid ionospheric delay may degrade the efficiency of these methods. Liu (2011) developed an automated cycle slip detection and repair method, which used the ionospheric total electron contents rate (TECR) and linear combination to determine the cycle slips on both L1 and L2 frequencies uniquely. Cai et al. (2013) also developed a new approach for cycle slip detection and repair using UD dual-frequency GPS carrier phase observables under high ionospheric condition. However, these methods have not taken the third frequency into account.

As the forthcoming GNSS systems have added additional frequencies, it is available to make new and optimal linear combination, which is favorable to fix ambiguities and detect cycle slips (Geng and Bock, 2013; Richert and El-Sheimy, 2007; de Lacy et al., 2012). Dai et al. (2009) developed a real-time algorithm, applying two geometry-free phase combinations along with LAMBDA technique (Teunissen, 1995), to detect and determine cycle slips for triple-frequency GPS data. However, this method might fail in the situation with low sampling observations. Zhao et al. (2015) presented a new real-time cycle slip detection and repair method based on three linear combination and the experiments showed that this method can effectively detect and repair cycle slip on triple-frequency observables in real time. Huang et al. (2015) employed two geometry-free phase combination and one geometry-free pseudorange minus phase linear combination to detect cycle slips, and then an effective search method based on LAMBDA and least squares minimum principle was applied to determine the cycle slips. Nevertheless, these methods assume that the observation errors remain unchanged and ignore the influence of the satellite motion to the quality of the observables.

In this paper, an improved method for real-time cycle slip correction is proposed based on linear combinations of triple-frequency BDS observables. At first, as there are great deal of linear combinations for three frequency data, we put forward two improved criterions to select optimal linear combinations. Then, a geometry-free pseudorange minus phase linear combination is selected to detect the EWL cycle slip, whilst two geometry-free phase combinations are selected to decrease the number of sensitive cycle slip groups and detect the WL and NL cycle slips. Considering the ionospheric delay keeps stable within short interval, the second-order time-difference of ionospheric delay is utilized to recognize the epoch with cycle slips and is also conducive to estimate the time-difference ambiguity of NL signal. In addition, as the satellite elevation can be available to reflect the observation accuracy, simulations and real data have been used to indicate the AR success rates, and then the threshold value of elevation has been determined to ensure the reliability of this correction method.

In the following, we introduce the observation model and linear combinations of triple-frequency GNSS data and then draw up the principles to select the optimal linear combinations. Then, BDS triple-frequency data with simulated cycle slips are used to test the effectiveness of the proposed method.

2. Formation of ionosphere-reduced GNSS signals

2.1. Pseudorange and carrier-phase equations

The observation equations for triple frequency phase and pseudorange measurements have been discussed in Feng and Rizos (2005). Ignoring the second order ionospheric effects, the simplified code and carrier-phase observation models for one BDS satellite can be expressed as (Eueler and Goad, 1991)

$$\begin{cases} P_i = \rho + \frac{f_1^2}{f_i^2} I + h_{pi} + \varepsilon_p \\ \Phi_i = \rho - \frac{f_1^2}{f_i^2} I - \lambda_i N_i + h_{\Phi i} + \varepsilon_\Phi \end{cases} \tag{1}$$

where the subscript $i = (1, 2, 3)$ refers to the three signals of BDS, f is signal frequency, and h is the hardware delay. P and Φ denote the code and phase measurements in meters, and ρ denotes the distance between the phase center of satellite and receiver antenna, which includes the tropospheric errors, the receiver and satellite clock errors. The ionospheric delay on the B1 signal is denoted by I in meters. λ denotes carrier wavelength and N denotes integer ambiguity. ε_p and ε_Φ denote the pseudorange and phase noise, respectively.

2.2. Triple-frequency BDS combination equations

With the BDS B1, B2 and B3 signals, the linear combination of three frequencies can be expressed as (Feng, 2008)

$$\begin{cases} P_{(a,b,c)} = \frac{a \cdot f_1 \cdot P_1 + b \cdot f_2 \cdot P_2 + c \cdot f_3 \cdot P_3}{a \cdot f_1 + b \cdot f_2 + c \cdot f_3} \\ \Phi_{(i,j,k)} = \frac{i \cdot f_1 \cdot \Phi_1 + j \cdot f_2 + \Phi_2 + k \cdot f_3 \cdot \Phi_3}{i \cdot f_1 + j \cdot f_2 + k \cdot f_3} \end{cases} \tag{2}$$

where a, b, c, i, j, k are integer coefficients. Then the frequency, wavelength and integer ambiguity of the linear combination can be expressed as:

$$\begin{cases} f_{(i,j,k)} = i \cdot f_1 + j \cdot f_2 + k \cdot f_3 \\ \lambda_{(i,j,k)} = C / f_{(i,j,k)} \\ N_{(i,j,k)} = i \cdot N_1 + j \cdot N_2 + k \cdot N_3 \end{cases} \tag{3}$$

where C is the speed of radio waves in vacuum.

According to Eqs. (1) and (3), the virtual pseudorange and phase signals can be expressed as: