A Novel Triple-Frequency Cycle Slip Detection and Correction Method for BDS

Ye Tian, Lixin Zhang and Qibing Xu

Abstract A novel triple-frequency cycle slip detection and correction method for BDS is proposed to detect and correct cycle slips when the ionosphere is active. Firstly, two sets of phase combinations whose sum equals zero are selected, and the corresponding pseudorange coefficients are obtained by the optimization algorithm, which effectively reduces the ionospheric amplification factor. Then, a set of phase combinations whose sum not equal to zero is adopted to reduce the condition number of coefficient matrices, meanwhile, the ionospheric delay variation between the epochs of this combination data is estimated and corrected. Thus, three linear independence sets of geometry-free and ionosphere-free pseudorange-phase combinations are constructed. Finally, the covariance matrix of the combined observations is obtained by employing observation error and ionospheric correct error, accordingly, the search space and objective function of cycle correction are constructed, which improves the correction accuracy. Based on BDS triple-frequency observations, the experiment results show that the proposed method possesses a good cycle slip detection and correction performance under active ionospheric situation.

Keywords BDS · Three-frequency cycle slip detection and correction
Geometry-free and ionosphere-free · Covariance matrix of observations

1 Introduction

Carrier phase observations are always used in precise GNSS applications and accurate carrier phase observation is the key to precise GNSS applications [1]. Due to interruption of the GNSS transmitted signal, low signal-to-noise ratio and some other reasons, a cycle slip presents a sudden jump of phase ambiguity by an integer number [2]. Detection and correction of cycle slips are necessary before the carrier

Y. Tian (✉) · L. Zhang · Q. Xu
Academy of Space Electrical Information Technology, Xi'an 710100, China
e-mail: tianye_504@163.com

J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2018 Proceedings*, Lecture Notes in Electrical Engineering 498,
https://doi.org/10.1007/978-981-13-0014-1_37

phases are used as high-precision measurements. At present, 3 or more than 3 carrier frequencies are used in GNSS, and it is a common and effective method to construct the multi-frequency linear combination observation for cycle slips detection and correction [2].

BDS has been able to provide triple-frequency signals. Cycle slip detection using multi-frequency BDS observations has been investigated for a long time. Based on the principle of ionospheric amplification factor and noise minimization, Ref. [3] selected the combination of geometric phase combination and pseudorange-phase combination to detect cycle slips. Reference [4] use wide-lane pseudorange-phase combinations with low ionosphere value as the first and second detectable amount, geometry-free phase combination with low ionosphere value as third detectable amount to detect cycle slip. Due to the current method is difficult to detect cycle slip when the ionosphere is active, a new triple-frequency TurboEdit method for weakening the ionosphere influence is proposed in Ref. [5]. Reference [6] selected two geometry-free phase combinations and one geometry-free pseudorange minus phase linear combination to detect and correct cycle slip in real time. In Ref. [7], a systematic study of BDS multi-frequency linear combination is carried out, and different optimal linear combinations are selected for long and short baselines. In Ref. [8], a robust polynomial adaptive algorithm is proposed for the small cycle of BDS GEOs at low elevation angles, which allows identification of such small cycle slips with high reliability. In above reference, Cycle slips detection and correction methods are studied in detail, but the method of Refs. [3–6] has a large condition number of coefficient matrix. The methods in the above reference don't fully consider the covariance of observations, which simplifies the search space and cause some correction errors.

In this paper, by choosing the two sets of coefficients in the group S_0 [7], the corresponding pseudorange coefficients are solved by using the optimization algorithm firstly. A set of coefficients is selected in the group S_1, meanwhile, the ionospheric delay variation is eliminated. Three sets of linearly independent, geometric-free ionospheric-free pseudorange-phase combinations are formed, which has better cycle slip detection capability. Through the covariance matrix of the combined observations, a corresponding search space is formed, and the correct cycle slip is searched under the influence of the weight coefficient to minimize the residual of the combined observation. Finally, the method is verified by the BDS triple-frequency data.

2 BDS Triple-Frequency Cycle Slip Detection Method

BDS now has the service capabilities in the Asia Pacific region. Currently the satellites in orbits are able to broadcast triple-frequency navigation signals, respectively, B1: 1561.098 MHz, B2: 1207.14 MHz, B3: 1268.52 MHz. Generally, the frequencies are arranged in descending order, which the three frequencies f_1, f_2, f_3 correspond to B1, B3 and B2 respectively.

2.1 Cycle Slip Detections Using Triple-Frequency Geometric-Free Ionospheric-Free Pseudorange-Phase Combinations

The carrier phase observation in any frequency at epoch t_0 is expressed as:

$$\lambda_i\varphi_i(t_0) = \rho(t_0) + t_r(t_0) - t^s(t_0) + T(t_0) + \lambda_i N_i(t_0) - \eta_i I_1(t_0) + \lambda_i \varepsilon_{\varphi_i}(t_0) \quad (1)$$

where, λ is carrier wavelength, φ is carrier phase, ρ is satellite-to-receiver geometric distance, t_r is receiver clock error, t^s is satellite clock error, T is tropospheric delay, I_1 is ionospheric delay of the B1 carrier phase, N is integer ambiguity, η_i is ionosphere amplification factor, ε_φ is phase noise, subscripts i represent signals of different frequencies. Pseudorange at epoch t_0 is expressed as:

$$P_l(t_0) = \rho(t_0) + t_r(t_0) - t^s(t_0) + T(t_0) + \eta_l I_1(t_0) + \varepsilon_{P_l}(t_0) \quad (2)$$

where, ρ, t_r, t^s, T have the same meaning with (1), η_l is ionospheric amplification factor, ε_P is pseudorange noise, the subscript l represents different frequencies. Let the combination coefficients of the triple-frequency carrier phase be i, j, k and the combination coefficients of the triple-frequency pseudorange be l, m, n ($l, m, n \in R$, $l + m + n = 1$). The combination of the phase and pseudo-range of the triple-frequency is expressed as:

$$\begin{aligned} \lambda_{ijk}\varphi_{ijk} &= \lambda_{ijk}(i\varphi_1 + j\varphi_2 + k\varphi_3) \\ &= \rho + T + \lambda_{ijk}N_{ijk} - \eta_{ijk}I_1 + T + (\delta_s - \delta_r) + \lambda_{ijk}\varepsilon_{ijk} \end{aligned} \quad (3)$$

$$\begin{aligned} P_{lmn} &= lP_1 + mP_2 + nP_3 \\ &= \rho + T + \eta_{lmn}I_1 + T + (\delta_s - \delta_r) + \varepsilon_{lmn} \end{aligned} \quad (4)$$

where, the ionospheric amplification factors are:

$$\eta_{ijk} = \frac{\lambda_{ijk}}{\lambda_1}\left(i + j\frac{\lambda_2}{\lambda_1} + k\frac{\lambda_3}{\lambda_1}\right) \quad (5)$$

$$\eta_{lmn} = l + m\left(\frac{\lambda_2}{\lambda_1}\right)^2 + n\left(\frac{\lambda_3}{\lambda_1}\right)^2 \quad (6)$$

Here, the first-order ionospheric delay terms are mainly discussed. The influences of second-order terms and subsequent terms have little effect on the final result and can be ignored [9]. Differencing (3) and (4), the combined ambiguity of pseudorange-phase can be expressed as:

$$N_{lijk,lmn} = \varphi_{ijk} - \frac{P_{lmn}}{\lambda_{ijk}} + \eta_{ijk,lmn} I_1 + \varepsilon \quad (7)$$

$$\eta_{ijk,lmn} = (\eta_{ijk} + \eta_{lmn}) \big/ \lambda_{ijk} \quad (8)$$

where, $N_{ijk,lmn}$ is integer ambiguity, $\eta_{ijk,lmn}$ is ionospheric amplification factor and ε is noise. Difference (7) can be obtained difference of ambiguities between adjacent epochs, that is, the cycle slip detection value:

$$\Delta N_{ijk,lmn} = \Delta\phi_{ijk} - \frac{\Delta P_{lmn}}{\lambda_{ijk}} + \eta_{ijk,lmn} \Delta I_1 + \Delta\varepsilon' \quad (9)$$

Assuming that the standard deviation of the carrier phase noise of triple-frequency is same as σ_ϕ and the standard deviation of the pseudorange noise at the triple-frequency is same as σ_P, then the standard deviation of ambiguity is (9):

$$\sigma_{\Delta N_{lmn,ijk}} = \sqrt{2}\sqrt{(i^2 + j^2 + k^2)\sigma_\phi^2 + (l^2 + m^2 + n^2)\sigma_P^2 \big/ \lambda_{ijk}^2} \quad (10)$$

Make three times the standard deviation of ambiguity estimation (confidence level of 99.7%) as the threshold of cycle slip judgment, and when the following formula holds, it is determined that cycle slip has occured.

$$i\Delta\phi_1 + j\Delta\phi_2 + k\Delta\phi_3 - \frac{l\Delta P_1 + m\Delta P_2 + n\Delta P_3}{\lambda_{ijk}} > 3\sigma_{\Delta N_{lmn,ijk}} \quad (11)$$

2.2 *Selection of Triple-Frequency Geometric-Free and Ionosphere-Free Pseudorange-Phase Coefficient*

From (7), (9), (11), when the change of ΔI_1 is large and the ionospheric amplification factor is large, the ionospheric amplification factor $\eta_{ijk,lmn}$ affect the result of the cycle slip detection. The standard deviation of the ambiguity estkimation $\sigma_{\Delta N_{lmn,ijk}}$ also has an impact on the accuracy of cycle slip detection. Therefore, it is necessary to select the appropriate parameters for pseudorange-phase combination to reduce the standard deviation of ambiguity estimation and the ionospheric amplification factor.

2.2.1 Method of Selecting Pseudorange-Phase Coefficient

From (5), (6), (8), the ionospheric amplification factor can be expressed as:

$$\eta_{ijk,lmn} = i\frac{1}{\lambda_1} + j\frac{\lambda_2}{\lambda_1^2} + k\frac{\lambda_3}{\lambda_1^2} + l\frac{1}{\lambda_{ijk}} + m\left(\frac{\lambda_2}{\lambda_1}\right)^2\frac{1}{\lambda_{ijk}} + n\left(\frac{\lambda_3}{\lambda_1}\right)^2\frac{1}{\lambda_{ijk}} \tag{12}$$

As can be seen from (10), when the phase coefficient is fixed, the smaller $l^2 + m^2 + n^2$ is, the smaller standard deviation of the ambiguity estimation. From the inequality $l^2 + m^2 + n^2 \geq 3lmn$ and $l + m + n = 1$, we can see when $l = m = n = 1/3$, $l^2 + m^2 + n^2$ has the minimum value, so let $l = m = n = 1/3$, we can get the smallest $\sigma_{\Delta N_{lmn,ijk}}$.

Although when $l = m = n = 1/3$, $\sigma_{\Delta N_{lmn,ijk}}$ has the minimum value, most of the references use this set of pseudorange coefficients. By analysing the Eq. (10) and the cycle slip correction processing, the influence of the ionosphere on the detection results is considerable. If the ionospheric delay can't be eliminated, the detection and correction of cycle slip will be affected. While the standard deviation of ambiguity estimation can be accurately corrected by search algorithm as long as the deviation is within a certain range. Therefore, the following optimization of pseudorange coefficients is given to further eliminate the ionospheric delay.

$$\begin{gathered}\min_{l,m,n}\left\|\eta_{ijk,lmn}\right\|_2^2 \\ s.t. \quad l + m + n = 1 \quad \sigma_{\Delta N_{lmn,ijk}} < \sigma_{\Delta N_{\min}} + \omega\end{gathered} \tag{13}$$

where, the phase coefficient is fixed and $\sigma_{\Delta N\_\min}$ is the result when $l = m = n = 1/3$. ω is used to limit the standard deviation of the ambiguity estimation, and being adjusted according to the pseudorange noise, the general empirical value is 0.001–0.01.

According to the sum of the coefficients, the phase combination coefficients are classified [7]. Let $S = i + j + k$, S_x represent the combination of $i + j + k = \pm x$. In the following table, the appropriate phase combination coefficients are chosen in the group S_0 and S_1, and the corresponding pseudorange coefficients are calculated by using the above-mentioned pseudorange coefficients optimization algorithm, compared with the pseudorange coefficients given in [5] and [10], and also compared with the case $l = m = n = 1/3$. The standard deviations of the ambiguity estimation and ionospheric amplification factor are mainly compared. The subscript 1 represents the optimization method in this paper, the subscript 2 represents the method in the Refs. [5, 10], and the subscript 3 represents the case when $l = m = n = 1/3$. The pseudorange noise is 0.3 m and the phase noise is 0.01 cycle.

It can be seen from Table 1 that the proposed method can further reduce the ionospheric amplification factor. In the above table, the coefficients (0, 1, −1) and (1, −2, 1) are selected as the two sets of cycle slip detection combinations. In order to constitute three linear independent equations and reduce the condition number of the coefficient matrix, another set of phase coefficients are selected in the S_1

Table 1 The optimal combination in S_0 region

i	j	k	l	m	n	λ	η_1	η_2	η_3	$3\sigma_{\Delta N1}$	$3\sigma_{\Delta N2}$	$3\sigma_{\Delta N3}$
0	1	−1	0.020517	0.425042	0.554441	4.88	5.27×10^{-9}	-1.46×10^{-8}	0.04	0.1918	0.1918	0.1620
1	−2	1	0.750578	0.208140	0.041282	1.30	1.48×10^{-10}	2.56×10^{-8}	0.20	0.7726	0.7726	0.5762
1	−4	3	1.576600	0.035441	0.541159	2.76	-5.32×10^{-8}	4.30×10^{-5}	0.28	0.7975	0.7975	0.3427
1	−1	0	0.597330	0.254020	0.148650	1.02	1.77×10^{-8}	2.51×10^{-7}	0.16	0.8293	0.8293	0.7197
1	0	−1	0.497229	0.283998	0.218773	0.85	2.05×10^{-7}	-4.10×10^{-6}	0.13	0.9231	0.9231	0.8697
1	−5	4	3.597093	0.596986	2.000107	6.37	1.21×10^{-9}	-2.02×10^{-7}	0.32	0.8751	0.8751	0.2982
1	−6	5	11.786113	4.017404	8.768709	20.93	-5.26×10^{-9}	1.01×10^{-6}	0.36	0.9844	0.9844	0.3359

group. Subscript 1 represents the optimization method proposed in this paper, and subscript 2 is the case when $l = m = n = 1/3$.

It can be seen from Table 2 that although the optimized pseudorange coefficients can greatly reduce the ionospheric amplification factor, the standard deviation of the ambiguity estimation becomes very large. Therefore, the set of $l = m = n = 1/3$ is used for the S_1 group. (−4, 3, 2) is selected from S_1 group. This set of coefficient has longer wavelength, the standard deviation of ambiguity estimation is smaller. However, the ionospheric amplification factor of (−4, 3, 2) is larger, which needs to eliminate the influence of ionospheric delay.

2.2.2 Method of Eliminating Ionospheric Delay of S_1

To eliminate the ionospheric delay, we need to estimate the ionospheric delay variation between adjacent epochs at the B1 frequency. We can calculate ΔI_1 and its standard deviation using Eq. (14). There is no cycle slip in the phase observation [10].

$$\Delta I_1 = \frac{\lambda_i \Delta\varphi_i - \lambda_j \Delta\varphi_j}{\eta_j - \eta_i}, \sigma(\Delta I_1) = \frac{2\sigma_\varphi}{|\eta_j - \eta_i|} \tag{14}$$

When there are cycle slips in the phase observation, there is a difference ΔN between epochs. ΔN_i and ΔN_j between the frequencies can't offset each other, which have a greater impact on the ΔI_1 estimation. When three frequency exist the same cycle slip ΔN, the first two sets of coefficients can't detect the cycle slip. The ionospheric quadratic difference defined by (15) can be used to detect it. Due to the second epoch difference of the ionospheric delay is very smooth, if there is a large deviation, we can consider triple-frequency exist the same cycle slip.

$$\nabla\Delta I_1(\alpha) = \Delta I_1(\alpha) - \Delta I_1(\alpha - 1) \tag{15}$$

When any one of $\Delta N_{(0,1,-1)}$, $\Delta N_{(1,-2,1)}$, and $\nabla\Delta I_1(\alpha)$ exceeds threshold, it is determined that cycle slips have occurred. Therefore, ΔI_1 of the current epoch can't be calculated using Eq. (14) and can be corrected by the following equation.

$$\Delta I_1(\alpha) = \Delta I_1(\alpha - 1) + \nabla\Delta\bar{I}_1(\alpha - 1) \tag{16}$$

where $\nabla\Delta\bar{I}_1$ is the smoothed value of $\nabla\Delta I_1$ without cycle slips. The calculation equation is expressed as:

$$\nabla\Delta\bar{I}_1(\alpha) = \theta \cdot \nabla\Delta I_1(\alpha) + (1 - \theta) \cdot \nabla\Delta I_1(\alpha - 1) \tag{17}$$

θ is the weight factor. The ionospheric delay of the S_1 group coefficients (−4, 3, 2) can be corrected by using the calculated ΔI_1.

Table 2 The optimal combination in S_1 region

i	j	k	l	m	n	λ	η_1	η_2	$3\sigma_{\Delta N1}$	$3\sigma_{\Delta N2}$
−3	−3	7	149.196238	45.575365	104.620873	−7.71	2.18×10^{-8}	12.11	31.0028	0.3601
−4	4	1	152.981506	−46.031951	105.949556	8.14	-1.67×10^{-7}	11.71	29.9740	0.2599
−4	3	2	228.222347	65.007206	164.215140	−12.21	1.16×10^{-7}	11.75	30.0816	0.2363
−3	2	6	256.260891	−71.185352	184.075539	13.32	-7.02×10^{-9}	12.07	30.9075	0.3021
−3	0	4	39.898772	−11.431826	−27.466946	2.06	-1.22×10^{-7}	11.99	30.6957	0.4145

3 A New Cycle Slip Correction Method

Three pseudorange-phase combinations are used to construct cycle slip detection with geometry-free and ionosphere-free, and the above method is used to correct the ionospheric delay of S_1 group observations. The combined observations can be obtained from:

$$\mathbf{L} = \mathbf{C}\mathbf{L}' \tag{18}$$

$$\mathbf{C} = \begin{bmatrix} i_1 & j_1 & k_1 & \frac{-l_1}{\lambda_{i_1 j_1 k_1}} & \frac{-m_1}{\lambda_{i_1 j_1 k_1}} & \frac{-n_1}{\lambda_{i_1 j_1 k_1}} \\ i_2 & j_2 & k_2 & \frac{-l_2}{\lambda_{i_2 j_2 k_2}} & \frac{-m_2}{\lambda_{i_2 j_2 k_2}} & \frac{-n_2}{\lambda_{i_2 j_2 k_2}} \\ i_3 & j_3 & k_3 & \frac{-l_3}{\lambda_{i_3 j_3 k_3}} & \frac{-m_3}{\lambda_{i_3 j_3 k_3}} & \frac{-n_3}{\lambda_{i_3 j_3 k_3}} \end{bmatrix} \tag{19}$$

$$\mathbf{L}' = \begin{bmatrix} l_{\varphi_1} & l_{\varphi_2} & l_{\varphi_3} & l_{P_1} & l_{P_2} & l_{P_3} \end{bmatrix}^T \tag{20}$$

where, the phase coefficients (i_1, j_1, k_1) and (i_2, j_2, k_2) correspond to (0, 1, −1) and (1, −2, 1) in S_0 group, and the corresponding pseudorange coefficients are in Table 1. In this equation, The phase coefficient (i_3, j_3, k_3) corresponds to (−4, 3, 2) in S_1 group and the pseudorange coefficient is $l = m = n = 1/3$. l_{φ_i} and l_{P_i} are phase and pseudorange observations in $\mathbf{L}'$ respectively. The relationship between the combination coefficient and the cycle slip valuation is expressed as:

$$\mathbf{A}\mathbf{X} = \mathbf{L} \tag{21}$$

$$\mathbf{A} = \begin{bmatrix} i_1 & j_1 & k_1 \\ i_2 & j_2 & k_2 \\ i_3 & j_3 & k_3 \end{bmatrix} \mathbf{X} = \begin{bmatrix} \Delta N_1 & \Delta N_2 & \Delta N_3 \end{bmatrix}^T \tag{22}$$

where, the coefficient matrix $\mathbf{A}$ is reversible, and the cycle slip can be determined by $\mathbf{X} = \mathbf{A}^{-1}\mathbf{L}$. But for the first and second observations, in order to reduce ionospheric amplification factor, the standard deviation of ambiguity estimation is increased. Ambiguity estimation of the third detection amount is affected by the error of ionospheric delay estimation. Therefore, it is not easy to correct cycle slip by calculating $\mathbf{X} = \mathbf{A}^{-1}\mathbf{L}$ and rounding.

Assuming that the covariance matrix of the combined observation $\mathbf{L}$ is $\mathbf{Q}$ and the third combined observation is also affected by the variance of the ionospheric delay estimation, we consider it into the covariance matrix, then $\mathbf{Q}$ is defined as follows:

$$\mathbf{Q} = [\mathbf{C}\,\mathbf{e}_3]\mathbf{Q}_0[\mathbf{C}\,\mathbf{e}_3]^T \tag{23}$$

where $\mathbf{Q}_0 = diag(\sigma^2_{\varphi_1}, \sigma^2_{\varphi_2}, \sigma^2_{\varphi_3}, \sigma^2_{P_1}, \sigma^2_{P_2}, \sigma^2_{P_3}, \sigma^2_{\Delta I_1})$ $\mathbf{e}_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$, σ_{φ_i}, σ_{P_i}, $\sigma_{\Delta I_1}$ denote the standard deviation of phase and pseudorange and ionospheric correct error respectively. In order to determine the integer cycle slip $\mathbf{X}_N$, the corresponding search space is set up as:

$$(\mathbf{X}_N - \hat{\mathbf{X}})^T \mathbf{Q}^{-1} (\mathbf{X}_N - \hat{\mathbf{X}}) < \chi \tag{24}$$

The threshold χ is generally based on the observation noise. The target equation is expressed as:

$$(\mathbf{A}\mathbf{X}_N - \mathbf{L})^T \mathbf{Q}^{-1} (\mathbf{A}\mathbf{X}_N - \mathbf{L}) = \min \tag{25}$$

Under the influence of weight coefficient, the correct cycle slip minimizes the residuals of $\mathbf{A}\mathbf{X}_N$ and combined observations $\mathbf{L}$.

4 Experimental Analysis

The experiment adopts the data in JFNG observation station ($30°31'N, 114°29'E$) at a large magnetic storm on December 21, 2015, the satellite elevation cutoff angle is set to 15°. The geomagnetic Dst index from 0 to 6 h on that day was abnormal, indicating that a large magnetic storm occurred. Using the above method, the C04 satellite data (without cycle slips) are processed. As can be seen from Fig. 1, the large magnetic storms do not affect the detection value due to the elimination of the ionospheric effects.

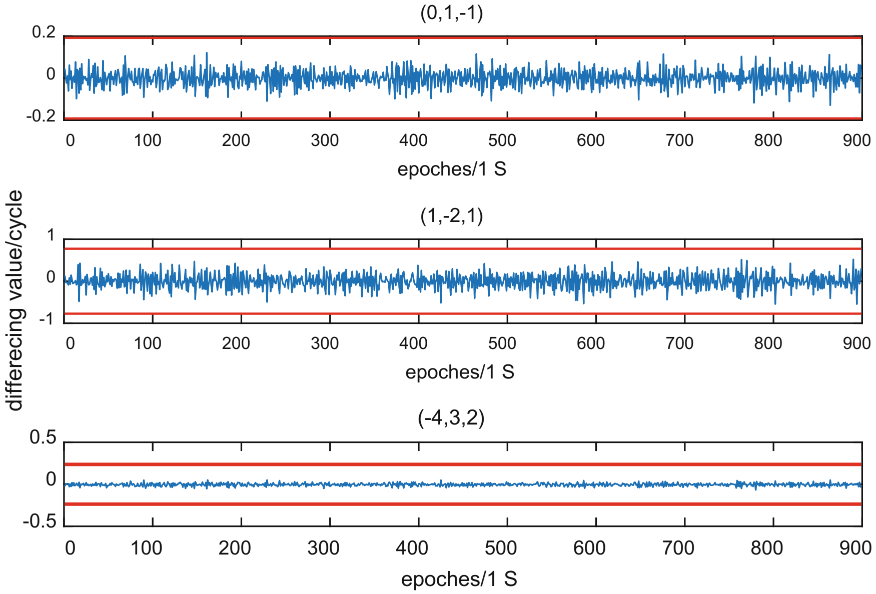

Fig. 1 Detection of three groups when no cycle slips occur

Figure 2 shows the results of four sets of special cycle slips. The special cycle slips include the cycle slips which are not sensitive to each set of coefficients and the small jumps which occur simultaneously in triple-frequency. As can be seen from Fig. 2, when a group of coefficients is not sensitive to the cycle slips, other coefficients can detect cycle slip. For $\Delta N_1 = \Delta N_2 = \Delta N_3 = 1$ this type of cycle slip, coefficients in S_1 group can be detected.

In order to further verify the performance of this cycle slip detection and correction method, different cycle slips combinations are added in different epochs of carrier phase observations of C08 and C12 satellites, including small cycle slips, large cycle slips and special cycle slips. As can be seen from Table 3, this method eliminates the effect of the ionospheric delay between epochs and can detect and correct the cycle slip. When some cycle slips occur, it is not correct to use the $\mathbf{X} = \mathbf{A}^{-1}\mathbf{L}$ directly to get the cycle slips. Using the method mentioned in this paper to search the optimal value in a certain region can avoid the problems caused by pseudorange, phase and ionospheric repair errors.

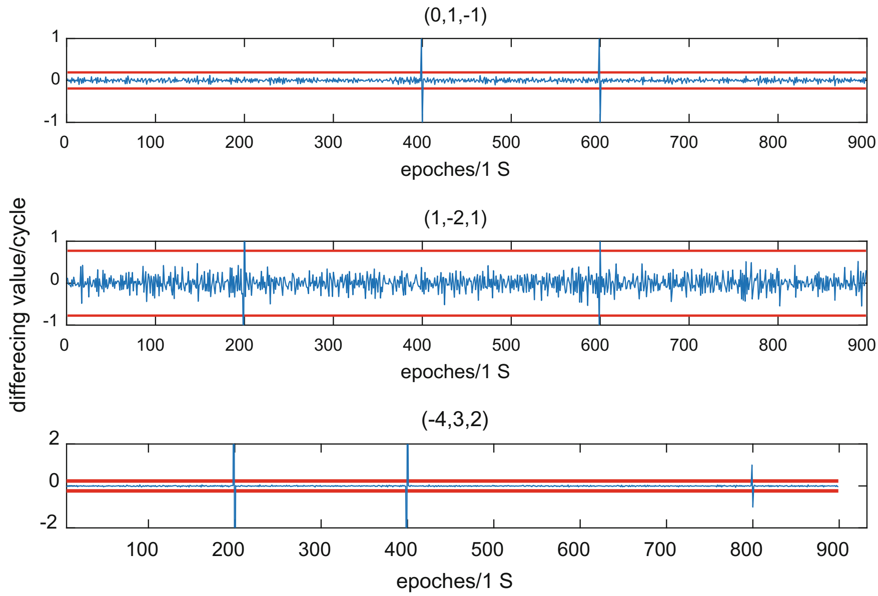

Fig. 2 Detection of three groups when special cycle slips occur

Table 3 Cycle slips detection and correct results

Satellite number	Epochs	Simulation cycle slips	$\Delta N_{(0,1,-1)}$	$\Delta N_{(1,-2,1)}$	$\Delta N_{(-4,3,2)}$	$\mathbf{A}^{-1}\mathbf{L}$	$\Vert\mathbf{A}\mathbf{X}_N-\mathbf{L}\Vert^2_{\mathbf{Q}^{-1}}$	Search results	$\min\Vert\mathbf{A}\mathbf{X}_N-\mathbf{L}\Vert^2_{\mathbf{Q}^{-1}}$
	60	(1, 0, 0)	−0.0262	0.7700	−3.9892	(0, −1, −1)	0.3517	(1, 0, 0)	0.0130
	150	(1, 1, 1)	0.0630	0.2749	0.9843	(2, 2, 2)	0.3675	(1, 1, 1)	0.0185
C08	310	(−3, 2, 1)	1.0037	−6.0796	19.9819	(−3, 2, 1)	0.0014	(−3, 2, 1)	0.0014
	420	(2, 2, 1)	1.0444	−1.0967	−0.0224	(2, 2, 1)	0.0022	(2, 2, 1)	0.0022
	550	(5, 8, 7)	1.0654	−4.0397	17.9885	(5, 8, 7)	0.0006	(5, 8, 7)	0.0006
	80	(0, 1, 1)	−0.0353	−1.2825	4.9998	(−2, 0, 0)	3.1367	(0, 1, 1)	0.0189
	170	(−1, −1, −1)	0.0515	0.0098	−1.0296	(−1, −1, −1)	0.0004	(−1, −1, −1)	0.0004
C12	350	(−1, 0, 1)	−0.9696	−0.0630	6.0065	(0, 0, 1)	5.5673	(−1, 0, 1)	0.0008
	460	(2, 1, 1)	−1.0415	2.1533	−1.0123	(2, 1, 2)	0.0064	(2, 1, 1)	0.0064
	600	(2, 5, 2)	3.0066	−6.0911	10.9947	(2, 5, 2)	0.0019	(2, 5, 2)	0.0019

5 Conclusions

A new triple-frequency cycle slip detection and correction method for BDS is proposed when the ionosphere is active. Firstly, two sets of phase combinations are selected from group S_0, and the corresponding pseudorange coefficients are obtained by the optimization algorithm, which effectively reduces the ionospheric amplification factor. Then, a set of phase combinations is selected from group S_1 to reduce the condition number of coefficient matrices, meanwhile, the ionospheric delay variation between the epochs of this combination data is estimated and corrected. Thus, three linear independence sets of geometry-free and ionosphere-free pseudorange-phase combinations are constructed. Finally, the covariance matrix of the combined observations is obtained by using observation and ionospheric correct error, which is employed to establish searching space. Under the influence of weight coefficient, the correct cycle slip is searched to minimize the residual of the combined observation. At last, the performance of proposed method is verified by BDS triple-frequency data. When the ionosphere is active, this method possesses a good cycle slip detection and correction performance.

References

1. Zhang X, Zeng Q, He J, Kang C (2017) Improving TurboEdit real-time cycle slip detection by the construction of threshold model. Geomatics and Information Science of Wuhan Univers 42(3):285–292
2. Cocarf M, Bourgon S, Kamali O et al (2008) A systematic investigation of optimal carrier-phase combinations for modernized triple-frequency GPS. J Geodesy 82(9):555–564
3. Huang L, Song L, WANG Y et al (2012) BeiDou triple-frequency geometry-free phase combination for cycle-slip detection and correction. Acta Geodaet Cartographica Sinica 41 (5):763–768
4. Yao Y, Gao J, Wang J et al (2014) Real-time detection and repair for compass triple-frequency carrier phase observations. J China Univer Min Technol 43(6):1140–1148
5. Huang L, Zhai G, Ouyang Y, et al (2015) Triple-frequency TurboEdit cycle-slip processing method of weakening ionospheric activity. Acta Geodaet Cartographica Sinica 44(8):840–847
6. Huang L, Lu Z, Zhai G et al (2015) A New Triple-frequency cycle slip detecting algorithm validated with BDS data. GPS Solutions 20(4):1–9
7. Zhang XH, He XY (2015) BDS triple-frequency carrier-phase linear combination models and their characteristics. Sci China Earth Sci 58(6):896–905
8. Ju B, Gu D, Chang X et al (2017) Enhanced cycle slip detection method for dual-frequency BeiDou GEO carrier phase observations. Gps Solutions 1–12
9. Banville S, Langley RB (2013) Mitigating the impact of ionospheric cycle slips in GNSS observations. J Geodesy 87(2):179–193
10. Wang X, Liu W, Li B et al (2016) Detection and repair of cycle slips for undifferenced bds triple-frequency observations. J Nat Univ Defense Technol 38(3):12–18