

Cycle Slip Detection By Combining TECR And Reconstructed Doppler Integral Method

Sen Jiang^{a, *}, Chenglin Cai^b, Zijie Zhu^c

School of Automation and Electronic information, Xiangtan University, Xiangtan 411105, China

*. ^a Corresponding Author Email: 1120940600@qq.com, ^b chengcailin@126.com, ^c 851554108@qq.com

Abstract. Poor observation environment and other factors lead to the whole cycle slips of carrier phase observation value, which affects the positioning accuracy. There are detection loopholes in the traditional cycle slips detection methods, especially the small value cycle slips, equivalent cycle slips and special value cycle slips are difficult to detect. A method combining Total Electron Contents Rate (TECR) and Doppler Value Reconstruction is proposed to solve the deficiency of cycle slip detection. Based on Doppler observations and Doppler detection method, the Doppler observations are reconstructed. This method improves the accuracy of Doppler observations. The proposed method has been verified that the reconstructed Doppler observations can improve the detection accuracy of small cycle slips, and can accurately detect any large value, small value of 1 cycle, Both frequency equivalent cycle slips and special value cycle slips can be accurately detected.

Keywords: Reconstructed Doppler Integral, TECR, Cycle Slip Detection, Dual Frequency, Detection Accuracy.

1. Introduction

In order to achieve high accuracy positioning of the Global Navigation Satellite System (GNSS), the cycle slip values due to poor observation environment will have a great impact on the whole circumferential ambiguity solution [1] and the final positioning results if they are not repaired. Currently, the following methods are commonly used: literature [2] uses the high order difference method to obtain the data after the best-fit order difference for cycle slips detection; literature [3] extrapolates the carrier phase observation of the next epoch by fitting the carrier phase observation with a polynomial, and combines the Doppler method to detect the single-frequency cycle slips. In the literature [4], the Doppler observations are fitted and then the Doppler integration method is performed to detect the cycle slips. In [5], Doppler observations are smoothed with pseudorange observations and then differenced between ephemeris elements to detect dynamic single-frequency cycle slips, the shortcoming is that only cycle slips of about 3 cycles can be detected. The literature [6] improves the detection performance by estimating the threshold value of the cycle slips test through the inter-star single difference method. The literature [7] both combine MW method and ionospheric residual method to detect the equivalent cycle slips. The paper [8] proposes an altitude angle exponential filtering algorithm based on TurboEdit to detect the cycle slips, and the accuracy is affected by the satellite altitude angle. The ionospheric residual method [9] requires stable ionospheric variation during the sampling interval; TurboEdit method [10] uses a combination of dual-frequency pseudorange, so it is noisy and will not be detected at equivalent cycle slips of more than 6 cycles. And the separate dual-frequency cycle slips detection method cannot separate the cycle slips values generated by the respective frequency points.

A new method for combined detection of dual-frequency cycle slips is proposed to address various shortcomings of the traditional dual-frequency cycle slips detection method. In this paper, the method uses only carrier phase observations with high data accuracy to process the data, and uses the total electron content change rate (TECR) method [11] based on high sampling rate can effectively reduce the effect of ionospheric variations. Based on the Doppler detection cycle slips method, the Doppler observations are reconstructed to effectively improve the data accuracy of the Doppler values. Later, the two are combined to detect the cycle slips. Through the experimental analysis, it can be seen that

this method can accurately detect the position where the cycle slips is generated by joining the simulation, and can calculate the magnitude of the cycle slips value and separate the cycle slips of two frequency points by solving the equation, and it is very effective for the detection of small cycle slips, equal cycle slips and special value cycle slips.

2. Basic Method of Cycle Slip Detection

2.1 The TECR method

In a region of space, the rate of change of ionospheric electron content in a short period of time is relatively stable, so the rate of change of electron content can be used as a method of cycle slips detection, and the total ionospheric electron content can be calculated from the dual-frequency carrier phase observations Eq.

$$T_{EC}(i) = \frac{f_1^2[\lambda_1\phi_1^j(i) - \lambda_2\phi_2^j(i) + \lambda_2N_2^j - \lambda_1N_1^j - \varepsilon]}{40.3 * 10^{16}(\gamma - 1)} \quad (1)$$

Where $\gamma = \frac{f_1^2}{f_2^2}$ denotes the squared ratio of carrier frequency; superscript j denotes satellite prn number; i denotes ephemeris; f_1, f_2 are carrier frequency; λ_1, λ_2 are carrier wavelength; ϕ_1, ϕ_2 are carrier phase observation; N_1^j, N_2^j are whole-period ambiguity; ε is error term. Differentiation between calendar elements for $T_{EC}(i)$ yields the rate of change of the electron content at the epoch of $[i, i-1]$:

$$T_{ECR}(i) = \frac{T_{EC}(i) - T_{EC}(i-1)}{\Delta t} \quad (2)$$

where Δt is the time interval between calendar elements.

After processing the observations before the i calendar element without cycle slips generated, the T_{ECR} value of the i calendar element is estimated by the T_{ECR} values of the $i-1$ calendar element and the $i-2$ calendar element with the following equation.

$$T_{ECR}(i) = T_{ECR}(i-1) + \dot{T}_{ECR}(i-1)\Delta t \quad (3)$$

$$\text{Where } \dot{T}_{ECR}(i-1) = \frac{T_{ECR}(i-1) - T_{ECR}(i-2)}{\Delta t} \quad (4)$$

Let the Cycle slips generated on carrier L_1 be $\Delta N_1(i), \Delta N_2(i)$, respectively, and set the detection value generated by the cycle slips to be calculated by the difference between the calculated and estimated values of T_{ECR} . Based on the above equation, the cycle slips detection value can be calculated as follows eq.

$$\lambda_1\Delta N_1(i) - \lambda_2\Delta N_2(i) = \frac{\lambda_1[\phi_1^j(i) - \phi_1^j(i-1)] - \lambda_2[\phi_2^j(i) - \phi_2^j(i-1)]}{f_1^2} - \dot{T}_{ECR}(i-1)\Delta t \quad (5)$$

Where $T_{ECR}(i)$ is represented by eq.(3); The error of the detection value is expressed as $\delta_1 = \pm\sqrt{(\lambda_1^2 + \lambda_2^2)\sigma_\phi^2}$. Take the threshold value of $3\delta_1$. If the detected value is less than the given threshold, it is considered as general error; if the detected value is greater than the threshold, it is considered as generating cycle slips.

This method only uses the carrier phase observation, so the error is very small and can detect small circumferential hops. The disadvantage is that the magnitude of the circumferential hop value cannot

be determined, the location of the circumferential hop ephemeris cannot be determined, and when $\Delta N_1 / \Delta N_2 = f_1 / f_2 = 77 / 60$, this method cannot detect the generation of cycle slips.

2.2 Methods for Reconstructing Doppler Integrals

Doppler observations are the result of receiver carrier loop measurements and are not affected by the environment. It can be detected by the relationship between the integration of the Doppler number over a short interval and the instantaneous rate of change of the carrier phase approximately equal to whether a cycle slips is generated, due to the large error in the direct use of the observations, the method of reconstructing the Doppler integration [12] is used to detect a dual-frequency cycle slips.

The reconstructed Doppler value f_d is calculated as:

$$f_d = \frac{(\overline{v_r} - \overline{v_s}) \cdot \overline{I}}{\lambda_r} \quad (6)$$

Where $\overline{v_r}$ is the receiver velocity vector; $\overline{v_s}$ is the satellite velocity vector; \overline{I} is the unit observation vector; the direction is pointed from the receiver to the satellite; λ_r is the reconstruction wavelength; and ‘.’ is the vector dot product.

$$L_1 = \varphi_1 + N_1 + c(\Delta t_r - \Delta t_s) / \lambda_1 + \Delta T_{rop} + \Delta ION_1 + \varepsilon_1 \quad (7)$$

$$L_2 = \varphi_2 + N_2 + c(\Delta t_r - \Delta t_s) / \lambda_2 + \Delta T_{rop} + \Delta ION_2 + \varepsilon_2 \quad (8)$$

Where φ_1 , φ_2 is the carrier phase observation; N_1 , N_2 is the whole-period ambiguity; c is the speed of light, Δt_r is the receiver clock difference; Δt_s is the satellite clock difference; λ_1 , λ_2 is the carrier wavelength; ΔT_{rop} is the tropospheric delay; ΔION_1 , ΔION_2 is the ionospheric delay; ε_1 , ε_2 is the other term error.

Differentiating between equations (7) and (8) yields:

$$\begin{aligned} \varphi_r(i) = & (\varphi_1 + N_1) - (\varphi_2 + N_2) + \Delta ION_1 - \Delta ION_2 \\ & + \varepsilon_1 - \varepsilon_2 + c(\Delta t_r - \Delta t_s) \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \end{aligned} \quad (9)$$

The difference between adjacent ephemerides of (9), the satellite clock difference and receiver clock difference are basically the same, and the ionospheric error changes in a short interval are very small and close to the same, resulting in:

$$\varphi_r(i+1) - \varphi_r(i) = \Delta N_1 - \Delta N_2 + \Delta \varepsilon_1 - \Delta \varepsilon_2 \quad (10)$$

From the Doppler value versus carrier phase: $\Delta N = \Delta \varphi - \int_t^{t+\Delta t} Dd_t + \varepsilon$. From the reconstructed Doppler value to detect the cycle slips, the detection value is expressed as follows:

$$\Delta N_1 - \Delta N_2 = \varphi_r(i+1) - \varphi_r(i) - \int_i^{i+1} f_d d_t \quad (11)$$

The error of the detection value is expressed as:

$$\pm \sqrt{2\sigma_\varphi^2 + 2\left(\frac{\Delta t}{2}\right)^2 \left(\frac{\sigma_f}{\lambda}\right)^2}$$

Where: σ_φ is the error size of the carrier phase observation; σ_f is the error size of the Doppler observation; Δt is the sampling time interval. When the detection value is greater than a given threshold, it is considered that the cycle slips occurs.

The method will be combined wavelength instead of the original wavelength, making the noise weakened, detection accuracy improved, but the drawback is that the occurrence of the equivalent of the Cycle slips $\Delta N_1 = \Delta N_2$ will not be detected.

2.3 Combined TECR method with reconstructed Doppler

For the TECR method can not determine the location of the Cycle slips and the special value of the Cycle slips can not be detected; Doppler integration method can not detect the equivalent Cycle slips; the combination of two detection methods, theoretically accurate detection of arbitrary value of the Cycle slips and determine the Cycle slips occurred in the calendar element.

At the same epoch moment, the two equations of (5) (11) are combined, because the right side of the equation is known, respectively set to a, b, there are:

$$\begin{cases} \lambda_1 \Delta N_1 - \lambda_2 \Delta N_2 = a \\ \Delta N_1 - \Delta N_2 = b \end{cases} \quad (12)$$

By solving the equation and then rounding to the nearest whole number, we can find the ΔN_1 , ΔN_2 ; and then subtract the original carrier phase observation from the calculated cycle slips value to fix the cycle slips.

3. Experimental Analysis

In order to verify the effectiveness of the cycle slips detection, static and dynamic data with a sampling interval of 1s and an observation duration of 600 epochs are used. According to the characteristics of the two methods, the simulated bounce values are added to the carrier phase values of two frequencies. The added cycle slips are shown in Table 1, and the special values of cycle slips are shown in the 250th and 350th epochs.

Table 1. Information Of Adding Cycle Slip In Simulation

epoch	Add cycle slips value(Cycle)	
	f_1	f_2
100	15	8
200	5	3
250	77	60
300	-3	-2
350	1	1
400	1	-1

Based on the MATLAB platform, two methods, TECR method and reconstructed Doppler integration method, were used to detect the joined Cycle slips, and the results are shown in Fig. 1, respectively.

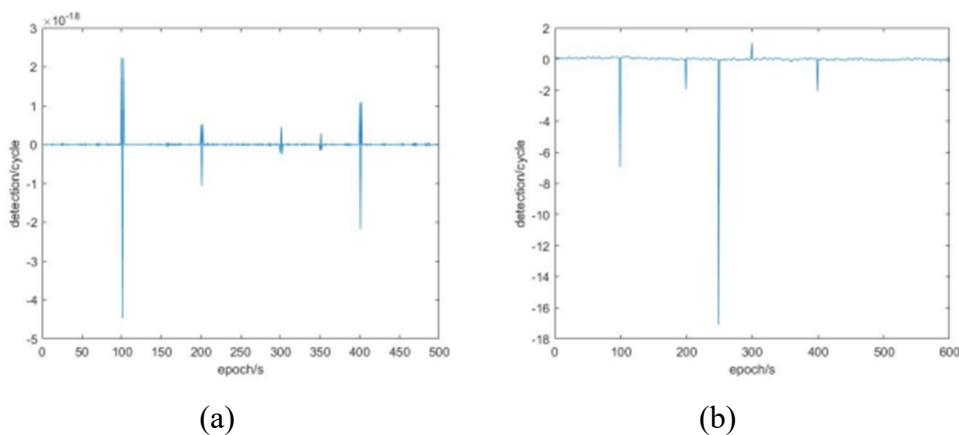


Figure 1. Cycle Slip Detection By TECR Method(a) And Cycle Slip Detection By Reconstructed Doppler Integral Method(b)

The single detection method found that the TECR method was unable to detect the cycle slips value of $\Delta N_1/\Delta N_2 = 77/60$ at the 250th epoch, and the Doppler integration method was unable to detect the cycle slips value of $\Delta N_1 = \Delta N_2$ at the 350th epoch.

After the comparison between the original Doppler observations and the reconstructed Doppler values in this paper, the reconstructed Doppler values are more accurate for the detection of small cycle slips, so small hops are added to the simulations, and the added hops are shown in Table 2 and the experimental results are shown in Figure 2(a)(b).

Table 2. Compare The Original / Reconstructed Doppler Simulation And Add Cycle Slip Information

epoch	Add cycle slips value(Cycle)	
	f_1	f_2
100	-1	-2
200	2	1
250	2	3
300	-1	-2
400	1	3

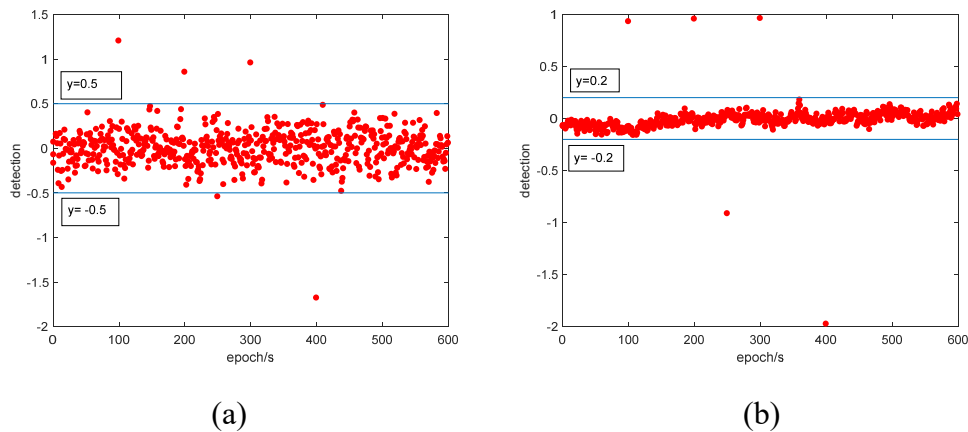


Figure 2. Comparison of original Doppler observations(a) and reconstructed Doppler values(b) for cycle slips detection experimental results

The results shows that if the original Doppler value is used, the detection of the cycle slips at the 250th epoch is influenced by the selection of the threshold, if the threshold is too large or too small, the cycle slips will not be detected or will be misjudged in the front and back epochs. If the reconstructed Doppler value is used to detect the cycle slips, the threshold of the selected area can be approximately 0.3 cycles smaller than the original Doppler value, which can avoid this problem. This comparison shows that the reconstructed Doppler value has the advantage of less noise than the original Doppler value, and is more accurate for detecting small values of cycle slips.

Finally, the combined method proposed in this paper is used to conduct receiver static detection experiments and receiver dynamic detection table 1 cycle slips experiments, the experimental detection results are shown in Figure 3(a) and Figure 3(b), respectively.

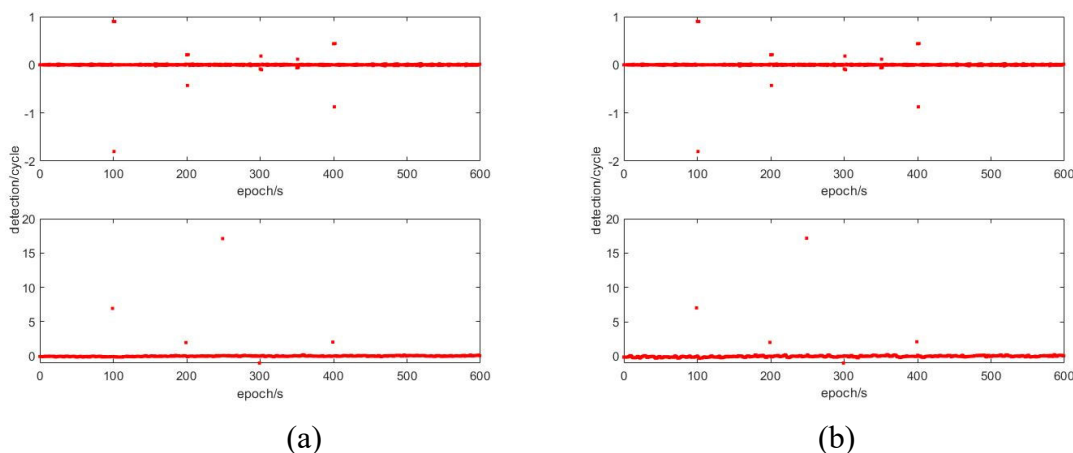


Figure 3. Experimental results of combined static(a) and dynamic(b) methods to detect cycle slips

The test threshold is set to 3 times the error, and the experimental results show that the joint detection of the two methods can detect every joined simulated Cycle slips, and there is no missed detection and wrong detection. Then, by substituting the ephemeral points, the values of the corresponding frequency hops can be calculated by the equation. Finally, the original carrier phase observation value is added to the calculated hop value to fix the cycle slips.

4. Conclusions

In this paper, we propose a combined TECR and reconstructed Doppler integration method to detect and repair the cycle-slip values of the carrier phase observation data, which makes the localization results more accurate, in view of the shortcomings of the traditional cycle-slip detection method that cannot determine the location of cycle slips occurrence and separate the cycle slips of two frequency points:

(1) In this paper, the experimental method has been developed to accurately detect any value of the hop, and to determine the ephemeris from which the hop is generated, separate the two frequency points and calculate the hop value. (2) The TECR method is not affected by the difference between the satellite and receiver clocks and the geometric distance between the ground and the star, and the reconstructed Doppler value method improves the detection accuracy of the original Doppler observations. (3) Although the method in this paper is applicable to any cycle slips value, the shortcoming is that the cycle slips generated by all epochs cannot be repaired at the same time, but the cycle slips value of the previous epoch needs to be repaired before the detection of the next epoch.

References

- [1] Jiao Weidong, Bili Gebate. Integer ambiguity resolution and cycle slip detection of Beidou satellite navigation system. *Journal of Civil Aviation University of China*. 2018, pp. 1-5.
- [2] Chen Chaangxin, Lin Xu, Cheng Lin, et al. A Cycle Slip Detection and Repair Method for Real-time Single Frequency. *Proceedings of the 13th Annual China Satellite Navigation Conference*. BeiJing, 2022, pp. 151-156.
- [3] Zhao Songke, Fu Wentao, Ruan Lanjun. Detection and repair of dual frequency differential cycle slip. *Journal of Guilin University of Electronic Technology*, 2021, pp. 490-493.
- [4] Zhang Xi, Cai Chenglin, Tang Zhenhui, et al. A Method of Detecting and Repairing Cycle-slip Based on Doppler Improved BDS Single-frequency Observations. *Acta Astronomica Sinica*. 2017, pp. 40-46.
- [5] Yang Kaichun, Lv Zhi ping, Li Linyang, et al. Kinematic single-frequency cycle slip detection of Doppler integration method. *Geomatics and Information Science of Wuhan University*. 2022, pp. 1-18.

- [6] Chen Meng, Li Jiangwen, Chen Xingyu, et al. A New Cycle Slip Detection Based on MW and Improved Ionosphere Residual Method. *Gnss World of China*. 2016, pp. 39-42.
- [7] Fan Sijie, Chen Guanxu, Liu Yanxiong, et al. Cycle-Slip Detection Methods for Dual-frequency Undifference Data at Low Elevation Angle. *Geomatics and Information Science of Wuhan University*. 2016, pp. 310-315.
- [8] Zhang Chenxi, Dang Yamin, Xue Shuqiang, et al. An improved BDS cycle slip detection method based on TurboEdit. *Science of Surveying and Mapping*. 2021, pp. 47-64.
- [9] Liang Lingfeng, Li Kezhao, Tian Chendong. Improved turboEdit cycle slip detection and repair method based on LM-BP algorithm. In: Yang, C., Xie, J. (eds) *China Satellite Navigation Conference Proceedings. Lecture Notes in Electrical Engineering*, Vol. 910, 2022.
- [10] Maria Clara Lacy, Mirko Reguzzoni, Fernando Sansò. Real-time cycle slip detection in triple-frequency GNSS. *GPS Solutions*, Vol. 16, 2012, pp. 353-362.
- [11] Cui Jianguyong, Chen Mingjian, Lei Nana. Cycle Slip Detection Method based on the Ionosphere Total Electron Content Rate. *Gnss World of China*. Vol. 37, 2012, pp. 37-52.
- [12] Cai Chenlin, Shen Wenbo, Zeng Wuling, et al. Detect and repair cycle-slip by reconstruction Doppler integral algorithm and STPIR. *Acta Geodaetica et Cartographica Sinica*. Vol. 50, 2021, pp. 160-168.