Comparison between cycle slip detection methods based on dual-frequency observation data

Yuan Debao*, Ma Xu, Li meng, Liang Chen, Hou Xiaobo

College of Geoscience and Surveying Engineering, Surveying Engineering, China University of Mining & Technology, Beijing 100083, China

yuandb@cumtb.edu.cn

ABSTRACT. *Cycle slip detection, a key technique of carrier phase measurement, is essential to satellite positioning and navigation. In this paper, two cycle slip detection methods, namely, the ionosphere residual method and phase reduction pseudo range method, are subjected to a comparative analysis, revealing their similarities and differences and highlighting the importance of threshold in cycle slip detection. Then, the two methods were applied to detect the dual-frequency observation data of the GPS and China's BeiDou Navigation Satellite System (BDS). The results show that each method had its advantages and disadvantages in cycle slip detection, and performed differently in the detection of BDS data.*

RÉSUMÉ. *La détection de glissement de cycle, une technique clé de la mesure de la phase de la porteuse, est essentielle pour le positionnement et la navigation par satellite. Dans cet article, deux méthodes de détection de glissement de cycle, à savoir la méthode résiduelle d'ionosphère et la méthode de pseudo-plage de réduction de phase, sont soumises à une analyse comparative, révélant leurs similarités et leurs différences et soulignant l'importance du seuil dans la détection de glissement de cycle. Ensuite, les deux méthodes ont été appliquées pour détecter les données d'observation à double fréquence du GPS et du système chinois de navigation par satellite BeiDou (BDS). Les résultats montrent que chaque méthode présentait des avantages et des inconvénients en matière de détection de glissement de cycle et que des performances différentes ont été présentées dans la détection de données BDS.*

KEYWORDS: *BDS, cycle slip detection, ionosphere residual method, phase reduction pseudo range method, equation, threshold value, different type.*

MOTS-CLÉS: *BDS, détection de glissement de cycle, méthode résiduelle d'ionosphère, méthode de pseudo-plage de réduction de phase, équation, valeur de seuil, type différent.*

DOI:10.3166/I2M.17.357-367

1. Introduction

The BeiDou Navigation Satellite System (BDS) has completed the construction in the Asia-Pacific Region, On October 15, 2018, the 39th and 40th satellites were launched, and will expanding globally. Being an important process in the observation data prepossess of BDS, Cycle slip detection concerns the accuracy and precision of the subsequent essential factors like the integer ambiguity resolution. Nowadays, the cycle slip detection method research in China mostly on detecting the triple frequency combination of data for the cycle slip, and the there are few researches on the ordinary single or dual frequency ones. Influenced by the cost, triple frequency receivers' market share is relatively lower than the single or dual frequency ones. The Navigation signal of the BDS is similar but varies from that of GPS, thus, whether the traditional cycle slip detection method suitable for the GPS by the single or dual frequency will be feasible to the BDS needs to be verified by experiments (Chen *et al.*, 2010; Wang & Xu, 2017; Cai *et al.*, 2009).

The most popular methods on the cycle slip detection still as follows: Higher mode of difference, Polynomial fitting, Doppler integral (Cui *et al.*, 2017), Phase combination of pseudo range (Zhang & Yue, 2014), Polynomial fitting, Wavelet transform, and Kalman filtering together with the other ones deriving from them. Each of them will have its own limitations and characteristics. The features distinguishing BDS from GPS are bigger clock correction, louder pseudo range noise, and the C/A code rate of 2.046Mbit/s, P code rate of 10.23Mbit/s, the length of code C/A being 2046bit which doubles that from the GPS. Assumingly the deviation from the two codes elements alignment were 1/10 ~ 1/100 of their width, then the ranging accuracy for C/A is 1.47-14.7m, for P is 0.29-2.93m. Thus, the experiments are needed to explore the effectiveness of the application of cycle slip detection methods in the BDS cycle slip detection (Kadri & Mouss, 2017; Wei, 2017; Ham *et al.*, 2014; Acko *et al.*, 2015).

2. Theory for cycle slip detection

2.1. Ionosphere residual method

Ionosphere residual method also known as No geometric phase combination method, the cycle slips are detected by the ionosphere residual from the dual frequency carrier phase measurement data to compose the detection quantity which will be applied for differences among the epochs. If the measurement noise and multipath effect were ruled out, the difference for the same epoch between the carrier phase measurements at two frequencies ought to be (Ma *et al.*, 2016):

$$\Phi_{gf}(t) = \lambda_1 \varphi_1(\mathrm{t}) - \lambda_2 \varphi_2(t) = \lambda_2 N_2 - \lambda_1 N_1 - \frac{A(t)}{f_1^2} + \frac{A(t)}{f_2^2} \tag{1}$$

In equation (1), λ_1, λ_2 above refer to the carrier wavelength of B_1 and B_2; $\varphi_1(\mathrm{t})$ $\varphi_2(t)$ refer to the observed value in carrier phrase of B_1 and B_2 at the given time t; N_1, N_2, refer to the carrier phrase ambiguity of B_1 and B_2; f_1, f_2 refer to the rate of B_1 and B_2. $A(t) = -40.3 \int_s N_e \, ds$, in which N_e refers to the electron density, s stands for transmission path. Divide λ_1 at both ends of the equation (1), and if no cycle slip occurs, the difference between epochs by $\frac{\Phi_{gf}}{\lambda_1}$ ought to be:

$$\triangle \Phi_{gf} = \frac{\Phi_{gf}(t+1)}{\lambda_1} - \frac{\Phi_{gf}(t)}{\lambda_1} = \varphi_1(t+1) - \varphi_1(\mathrm{t}) - \frac{f_1}{f_2}[\varphi_2(t+1) - \varphi_2(t)] = \Delta_{ion}(t+1) - \varDelta_{ion}(t) + \varepsilon \quad (2)$$

In equation (2), ε refers to the measurement noise, when the Ionosphere is relatively stable, $\triangle \Phi_{gf}$ the amplitude of variation should be on the small size around the value of zero. If the $\triangle \Phi_{gf}$ values jump abruptly, it indicates the observed value in carrier phrase of B_1 or B_2 may have the cycle slip at the time of t+1. It affects $\triangle \Phi_{gf}$:

$$\triangle \Phi_{gf} = \frac{f_1}{f_2}\Delta N_2 - \Delta N_1 + [\varDelta_{ion}(t+1) - \varDelta_{ion}(t)] + \varepsilon \approx \frac{f_1}{f_2}\varDelta N_2 - \varDelta N_1 = 1.29322\varDelta N_2 - \Delta N_1 \quad (3)$$

In equation (3), $\varDelta N_2$ and$\varDelta N_1$, refer to the cycle slips on the observed value in carrier phrase of B_1 and B_2. If the cycle slips caused $1.29322\varDelta N_2 - \varDelta N_1$ the result approaching zero or equaling to zero, then, the $\triangle \Phi_{gf}$ will become too small and the cycle slip could not be detected. Assumingly, the difference between the observed values in carrier phrase of B_1 or B_2, $m_\varphi = \pm 0.01$ Cycle, then, as to the cycle slip detected, the difference caused ought to be:

$$m_{\Delta N} = m_\varphi \cdot \sqrt{2 \times \left(1 + \frac{f_1^2}{f_2^2}\right)} = \pm 0.023 \text{ Cycle} \quad (4)$$

In equation (4), the limit is tripled inspection rate with the Root mean square error; the deadline difference is about ± 0.07 Cycle. Only if the cycle slips on the carriers wave of B_1 and B_2 making the ΔN no smaller than 0.07Cycle, they can be detected, otherwise, they cannot. Through the various combination of different ΔN, it was noticed that when the cycle slip is smaller than 4 Cycle, it will be easily detected by the method of Ionosphere residual, but when the number is bigger than 4, then the cycle slip will be multi-valued. Table 1 indicates the $\triangle \Phi_{gf}$ variation when the $\varDelta N_2$ and $\varDelta N_1$ are less than or equal to 4 Cycle.

It is shown in the above Table that when the cycle slip is less than the 4Cycle, the Ionosphere residual method can exactly detect the cycle slips. When there is any slip bigger than 4 Cycle in the cycle slips combinations, it will have the multi-values which lead to the resolving result from the special groups by the cycle slips inspection rate less than 0.07Cycle. Then, the combinations cannot be detected.

Table 1. The values of $\triangle \Phi_{gf}$ when the cycle slip is less than or equal to 4 Cycle

$\Delta N_1 \backslash \Delta N_2$	-4	-3	-2	-1	0	1	2	3	4
-4	-1.1729	0.1203	1.4136	2.7068	4.0000	5.2932	6.5864	7.8797	9.1729
-3	-2.1729	-0.8797	0.4136	1.7068	3.0000	4.2932	5.5864	6.8797	8.1729
-2	-3.1729	-1.8797	-0.5864	0.7068	2.0000	3.2932	4.5864	5.8797	7.1729
-1	-4.1729	-2.8797	-1.5864	-0.2932	1.0000	2.2932	3.5864	4.8797	6.1729
0	-5.1729	-3.8797	-2.5864	-1.2932	0.0000	1.2932	2.5864	3.8797	5.1729
1	-6.1729	-4.8797	-3.5864	-2.2932	-1.0000	0.2932	1.5864	2.8797	4.1729
2	-7.1729	-5.8797	-4.5864	-3.2932	-2.0000	-0.7068	0.5864	1.8797	3.1729
3	-8.1729	-6.8797	-5.5864	-4.2932	-3.0000	-1.7068	-0.4136	0.8797	2.1729
4	-9.1729	-7.8797	-6.5864	-5.2932	-4.0000	-2.7068	-1.4136	-0.1203	1.1729

2.2. Phrase reduction pseudo range method

This method requires not only the carrier phrase observation but also the pseudo range observation values. The observation equations for the single frequency pseudo range and carrier phrase measurement are (Li, 2016):

$$\mathrm{R} = \rho + \Delta I_R + \Delta m_R + \varepsilon_R \tag{5}$$

$$\lambda\varphi = \rho + \lambda \mathrm{N} + \Delta I_\varphi + \Delta m_\varphi + \varepsilon_\varphi \tag{6}$$

In equation (6), R, φ refer to the pseudo range observation value and the phrase observation value; λ stands for the wave length of the carrier; N refers to the integer ambiguity of carrier phase signals; ΔI_R, ΔI_φ refer to the ionosphere influence error respectively from the pseudo range and carrier phrase measurement; $\Delta m_R, \Delta m_\varphi$ refer to the multi-path effect influence error from the pseudo range and carrier phrase measurement; ε_R, ε_φ refer to the measure error from the pseudo range and carrier phrase measurement individually;

Subtract equation (5) and equation (6), and it comes to the following math formula on the ambiguity of whole cycle;

$$\mathrm{N} = \frac{1}{\lambda}[\lambda\varphi - R - \left(\Delta I_\varphi - \Delta I_R\right) - \left(\Delta m_\varphi - \Delta m_R\right) - (\varepsilon_\varphi - \varepsilon_R)] \tag{7}$$

Between the epochs, there is only slight change for the errors caused by the Ionosphere and multi-path effect. Thus, the application of the equation (7) for the difference among the epochs can eliminate the influence from the two factors while getting the approximate value of the cycle slip.

$$\Delta \mathrm{N} = \mathrm{N}(t_1) - \mathrm{N}(t_0) = \varphi(t_1) - \varphi(t_0) - \frac{1}{\lambda}[(R(t_1) - R(t_0))] \tag{8}$$

In equation (8), it is known that the p code precision in BDS is 0.293m; the wave length for B_1 and B_2 are 19.20cm and 24.83cm; Obtained by the law of error propagation: the Root mean square error of B_1 m $\approx$ 2.16Cycle, B_2 m $\approx$ 1.70Cycle, and because the parameters used merely include C/A fromB_1, P fromB_2, thus, taken the tripled Root mean square error as the threshold value, the weekly cycle slip threshold value of B_1 frequency is 6.48Cycles, meanwhile, 5.01Cycles for B_2. If the two threshold values were surpassed by the inspection rate, it means the cycle slip occurs in the observation data (Wu *et al.*, 2013).

3. Comparative analysis on the cycle slip detection by using the ionosphere residual method and phrase reduction pseudo range method

The data in the demonstration analysis were adopted from the two sets of dual frequency observation information separately taken from the zero o'clock but 30 seconds difference while sampling on the October 16th and 17th 2016 at WHU (Wu Han University). Since the observation begins at night, there is not much variation for the ionosphere. In total, 9 BDS satellites were observed and recorded, including C1, C2, C3, C4, C5, C6, C7, C8, C10. But some of them are not for day-night observation with long time suspension, hence, the paper only focuses on the other ones which could provide thorough information needed after the continuous observation. Both of the two methods were applied for the cycle slip detection during the two nights' observation and three results could be classified afterwards.

The three types of results are listed as follows:

1> Neither of the two methods worked

2> One of the two methods worked

3> Both methods worked.

Too many relating satellite images were involved in the whole process, but only some of representing ones were selected in this article.

3.1. Neither of the two methods worked

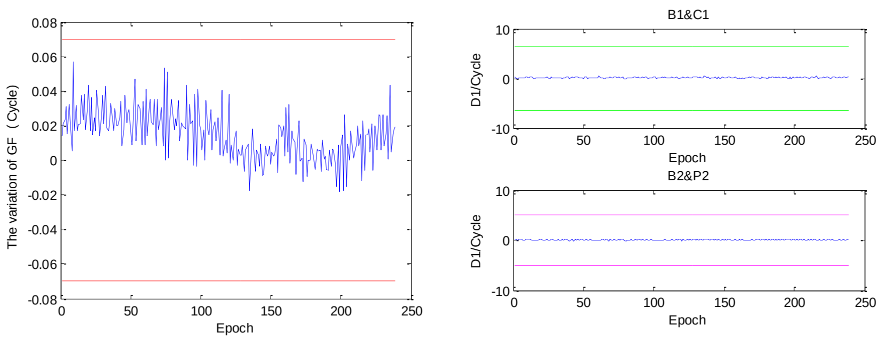

Figure 1. C2 processing results by the ionosphere residual method (L) and the phrase reduction pseudo range method (R) on 16/10/2016

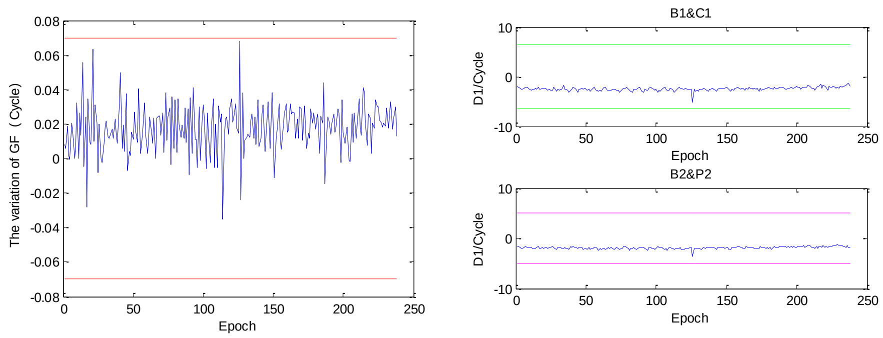

Figure 2. C8 processing results by the ionosphere residual method (L) and the phrase reduction pseudo range method (R) on 17/10/2016

Firstly, the outcome shown in the picture indicating there is none cycle slip detected.

Neither of the two methods work because either of the inspection rates surpassed the threshold value. Hereon, only Fig.1 and Fig.2 are taken as the illustration examples. From the comparison results in the Fig.1, it illustrates that when there is no cycle slip occurring, the inspection rates in both methods are not changing much, and the processing results of the two have some consistency as to the fluctuation track to a certain degree. Moreover, considering the details from C8 on the 17th in the Fig.2, we could conclude that both of them fluctuated greatly while approaching 125 epochs yet still lower than the thresholds.

3.2. One of the two methods worked

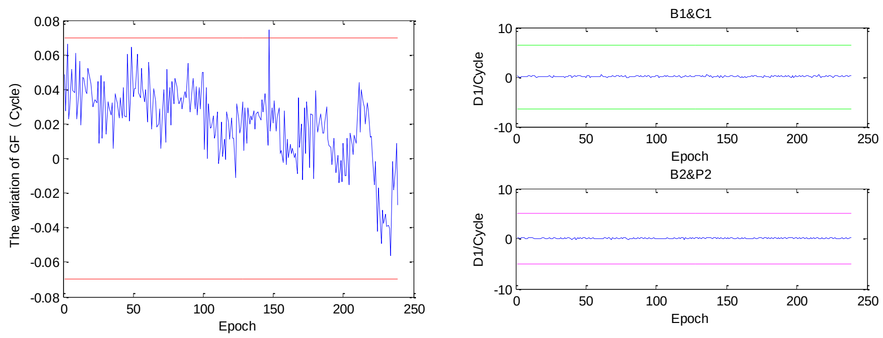

Figure 3. C1 processing results by the ionosphere residual method (L) and the phrase reduction pseudo range method (R) on 16/10/2016

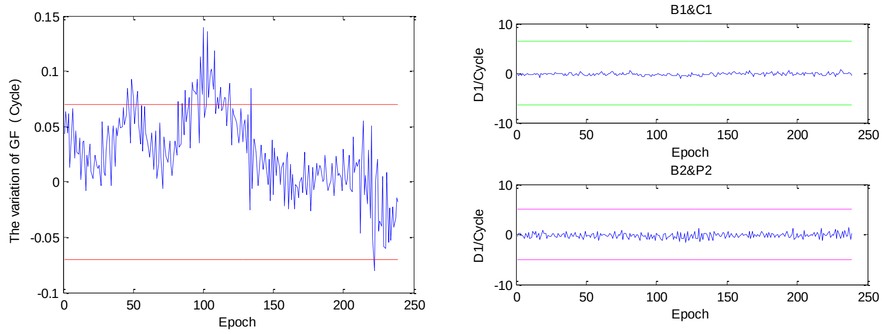

Figure 4. C4 processing results by the ionosphere residual method (L) and the phrase reduction pseudo range method (R) on 16/10/2016

Theoretically, Ionosphere residual Method is better than the single frequency Phrase Reduction Pseudo Range Method regarding the minor cycle slip detection. The followings are some of the typical results after processing.

Fig.3 and Fig.4 show that the cycle slips were detected by the Ionosphere residual Method instead of the other which testified the better detecting ability of it for minor cycle slips than the Phrase Reduction Pseudo Range Method.

However, it is abnormal that another option different from the description above from the observation to the C10 on the 16th of October, 2016.

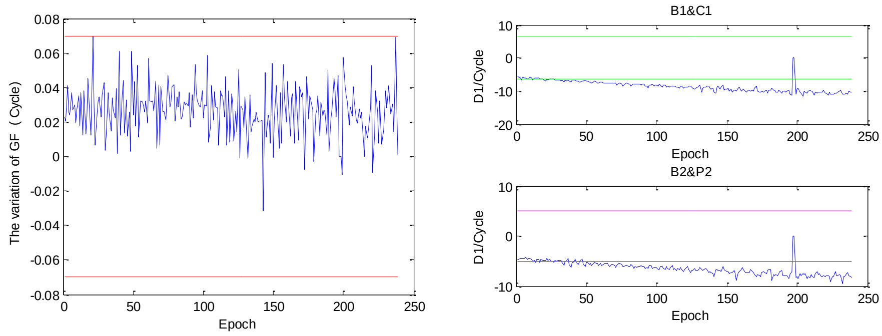

Figure 5. C10 processing results by the ionosphere residual method (L) and the phrase reduction pseudo range method (R) on 16/10/2016

In Fig.5, there are a few points in the Ionosphere residual Method that the inspection rates are approaching the threshold but never surpassed, while, almost all the inspection rates in the Phrase Reduction Pseudo Range Method have surpassed the threshold. It can be concluded that for the cycle slip bigger than 4 Cycle detecting, the Phrase Reduction Pseudo Range Method works more effectively, and the

Ionosphere residual Method got influenced by the dual frequency cycle slip combinations while detecting the large scaled cycle slips.

3.3. Both methods worked

The processing results from C7 on the 16th and C4 on the 17th are used for the demonstration analysis.

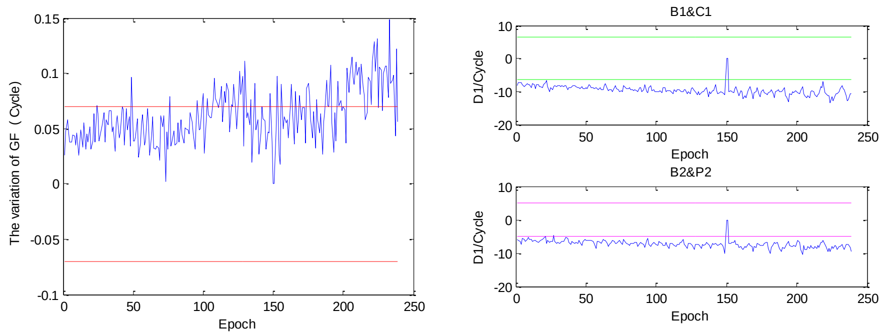

Figure 6. C7 processing results by the ionosphere residual method (L) and the phrase reduction pseudo range method (R) on 16/10/2016

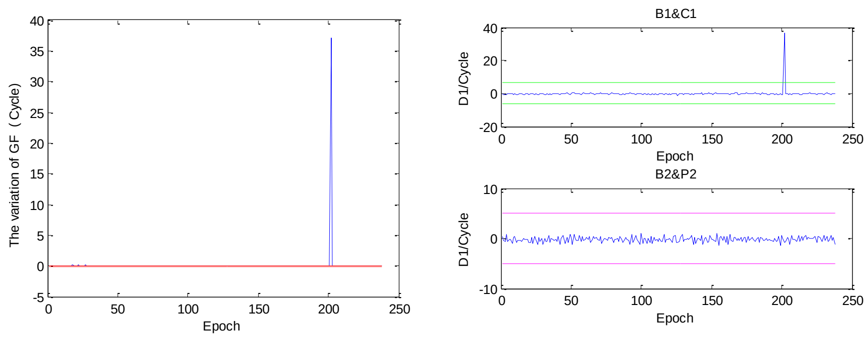

Figure 7. C4 processing results by the ionosphere residual method (L) and the phrase reduction pseudo range method (R) on 17/10/2016

Under the circumstances that both methods could detect the cycle slips (Fig.6), it indicates that C7 have a bigger cycle slip at the beginning, but the cycle slip could be noticed on both frequencies which may influence the multi-valued Ionosphere residual Method for the better detection. In Fig.7, a cycle slip around the 200 epochs has been clearly detected by the Ionosphere residual Method. But, it was announced by the Phrase Reduction Pseudo Range Method that the cycle slip occurred on the carrier wave of B1. This proves that when the cycle slips showed on the both frequency carrier waves, the detecting effect by the Ionosphere residual Method would not be so ideal, and the Phrase Reduction Pseudo Range Method is more sensitive for the big cycle slips.

4. Comparative analysis of two methods using GPS and Beidou data

Both methods have a good effect on the detection of different levels of GPS cycle slip, but the application is slightly different when applied to the Beidou data. Therefore, the two methods are compared with the GPS and Beidou data. The applicability of the two methods to the Beidou data is analyzed. The following figure shows the cycle slip detection data of each satellite in the ephemeris file. The difference between the two is observed (the red line represents the Beidou satellite data and the blue line represents the GPS satellite data).

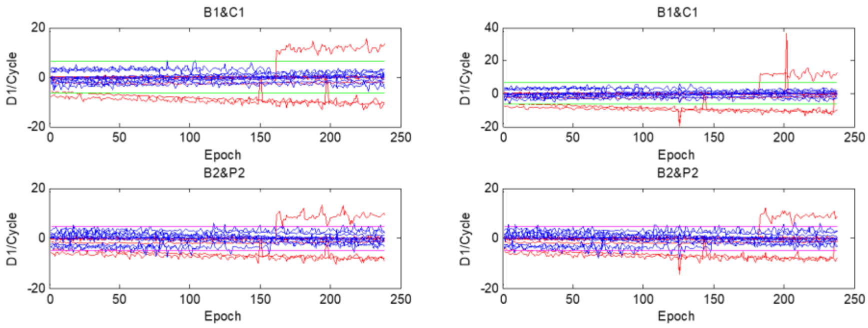

Figure 8. Phrase reduction pseudo range method 16th(L)&17th(R) full satellite data GPS satellite blue line, Beidou satellite red line

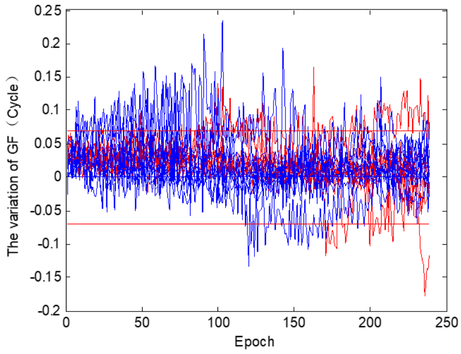

Figure 9. Ionospheric residual method 16th full satellite data GPS satellite blue line, Beidou satellite red line

It can be clearly seen from the above Fig.8 that the red line representing the satellite cycle slip detection amount of the Beidou data part deviates from the threshold line as a whole, and the blue line representing the GPS data detection amount is generally in the threshold range. Observation Fig. 9 the ionospheric residual method has a good detection effect on the Beidou data cycle slip detection. There is no phenomenon that the detection amount completely deviates from the threshold.

The phase-subtraction pseudo-distance method mentioned in this paper is more suitable for the cycle slip detection of GPS data. From the observation data processing results of two days, it can be seen that the measurement amount of beidou data obtained by this method is relatively large. However, the ionospheric residual method has a good effect on the detection of both data cycle slip. From the results, the ionospheric residual meyhod is more suitable for beidou data observation than the phrase reduction pseudo range method.

Part of the Beidou satellite data appeared in the phase-subtraction pseudo-distance method in the two-day period, and the threshold value was partially offset from the beginning part. It is speculated that the Beidou satellite signal and the GPS signal may be different due to the lack of more data. This article has not been verified.

5. Conclusion

In this paper, Ionosphere residual and Phrase Reduction Pseudo Range methods have been applied to detect the cycle slips from the BDS observation data. From the through comparison analysis on the processing results, we could conclude that when the dual frequency carrier signals got the cycle slips, the Ionosphere residual method could not detect some of the special combinations sharply for its own limitations, yet for the smaller cycle slips detection, this method is more sensitive advantage than the Phrase Reduction Pseudo Range method. And the Phrase Reduction Pseudo Range method is more suitable for the bigger cycle slips detection and would not be affected by the multi-valued.

But the phase-subtraction pseudo-distance method for pseudorange data portion exists Beidou circumferential hop phenomenon detecting an offset amount of the entire threshold range, the phase subtraction method pseudorange still needs some improvement in cycle slip detection Beidou, Compass make it more consistent the characteristics of the satellite data carrier signal to avoid this situation

References

Acko B., Brezovnik S., Crepinsek Lipus L., Klobucar R. (2015). Verification of statistical calculations in interlaboratory comparisons by simulating input datasets. *Int. Journal of Simulation Modelling,* Vol. 14, No. 2, pp. 227-237. http://doi.org/10.2507/ijsimm14(2)4.288

Cai S. X., Zhang X. H., Li X. X. (2009). A modified method for cycle slips detection based on polynomial fitting. *Journal of Geomatics,* Vol. 34, No. 5, pp. 1-3.

Chen P. X., Zhang C. Y., Huang K. X. (2010). Cycle slips detecting and repairing by use of phase reduce pseudorange law and ionized layer remnant method of difference. *Journal of Geodesy and Geodynamics*, Vol. 30, No. 2, pp. 120-124. http://doi.org/10.1017/S0004972710001772

Cui L. L., Wen X. J., Yu H., Yang L., Su D. (2017). Research on detection and restoration of beidou cycle slip based on ionosphere residual method. *Journal of ChengDu University (Natural Science Edition)*, Vol. 36, No. 1, pp. 62-65.

Ham W. K., Kwon Y., Park S. C. (2014). Combat simulation framework including continuous detection system. *Int. Journal of Simulation Modelling*, Vol. 13, No. 4, pp. 395-408. http://doi.org/10.2507/ijsimm13(4)1.262

Kadri O., Mouss L. H. (2017). Identification and detection of the process fault in a cement rotary kiln by extreme learning machine and ant colony optimization. *Academic Journal of Manufacturing Engineering*, Vol. 15, No. 2, pp. 43-50.

Li B. (2016). Methods and strategies of cycle-slip detection and correction for beidou navigation satellite system. *Geomatics & Spatial Information Technology*, Vol. 39, No. 8, pp. 160-165. http://doi.org/10.3969/j.issn.1672-5867.2016.08.048

Ma X. D., Song B., Zhang S. B., Liu X. (2016). Real time cycle slip detection of Beidou single frequency carrier phase based on Kalman filtering. *Industry and Mine Automation*, Vol. 42, No. 4, pp. 58-61.

Wang J. J., Xu D. F. (2017). On the method of detecting cycle slips based on combination of triple frequency carrier. *Engineering of Surveying and Mapping*, Vol. 26, No. 11, pp. 69-70, 76. http://doi.org/10.19349/j.cnki.issn1006-7949.2017.11.015

Wei D. F., Li F. Y. (2017). Research and implementation of Node.JS-based defense against XSS and CSRF. *Review of Computer Engineering Studies*, Vol. 4, No. 1, pp. 9-16. http://doi.org/10.18280/rces.040103

Wu F. B., Zhang S. B., Zhang Q. Z., Hou X. Z. (2013). An algorithm for cycle slips detection and correction based on COMPASS dual-frequency data. *Journal of Geodesy and Geodynamics*, Vol. 33, No. 5, pp. 140-144.

Zhang L., Yue D. J. (2014). Research on detection and reparation for cycle slips using phase reduce false distance law and ionized layer remnant method of difference. *Engineering of Surveying and Mapping*, Vol. 23, No. 2, pp. 36-38.