SCIREA Journal of Geosciences
http://www.scirea.org/journal/Geosciences
May 15, 2023
Volume 7, Issue 1, February 2023
https://doi.org/10.54647/geosciences170261

Cycle Slip Detection in Multi Frequency GPS Monitoring under High Sampling Rate Based on P-code Constraint

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Abstract

GNSS cycle slip is one of the important factors affecting the reliability of monitoring results, and it is particularly crucial to accurately detect and repair the size of each frequency cycle slip. In response to the coefficient uncertainty problem of existing triple frequency combination cycle slip detection methods, this paper proposes global search method for triple frequency joint calculation of cycle slip based on the geometry-free observation equation, using single P-code observation values instead of triple frequency pseudorange to form a triple frequency cycle slip sequence and constrain its value range. The results of 1 Hz sampling data processing show that the method proposed in this paper can effectively solve the problem of cycle slip position and multi-value, with a detection success rate of over 98% and a false detection rate of less than 3%.

Keywords: cycle slip, detection, geometry-free, global search method

1. Introduction

When the satellite is obscured or interfered strongly, it will lose lock for a short time, which will lead to phase observation jump , i.e. cycle slip (Miao et al., 2010). Cycle slip is one of the factors affecting the quality of GNSS observation. High-precision monitoring results must ensure that there is no cycle slip in carrier phase observations (Fend et al.,2009). For single or dual frequency, cycle slip detection methods mainly include phase multiple difference method (Yan et al., 2007), wavelet analysis method (Huang et al., 1997), ionospheric residual method (Zhang et al., 2014 ;Cheng et.al.,2010 ;Feng et.al.,2020 ; Blewitt G,1990), non-differential dual frequency code phase combination method (Zou et al., 2014), fitting method (Li et al., 2008 ; Liu et al., 2011), TurboEdit method (Cai et al., 2016 ; Zhang et al., 2017) . The methods mentioned above have some limitations in practical application, such as: multiple difference and wavelet analysis are advantageous to large cycle slip detection; Dual frequency code phase combination method and ionospheric residual method are easy to cause cycle slip multi-value problem and special combination cycle slip fails. Although fitting method has no requirement for sampling rate, it requires high data quantity and fitting order, and is easy to bring fitting error and rounding error. The combined MW observations in TurboEdit method result in some cycle slips being submerged by noise, etc. At present, for triple-frequency GPS cycle slip detection (Huang et al., 2012 ; DAIZ et al., 2009), different combination methods of observation values are mostly used to restrict the coefficient of frequency combination, ensuring that: (1) the combination wavelength is as long as possible; (2) Combination observation values retain as much ambiguity as possible; (3). Eliminate ionospheric effects and generate as little noise as possible. Although this method is practical, the effect of different detection methods such as frequency is different due to the presence of frequency combination coefficients. For example, $f_i(i=1,2)$ of (9, 7) and (77, 60), $f_i(i=2,3)$ of (24,23) type cycle slips is not significant. In order to solve the above problems, this paper uses phase equation $\Delta\varphi_{ij} = \Delta N_i - (\lambda_j/\lambda_i)\Delta N_j$ and $\Delta N_i = \Delta\varphi_i - \frac{\Delta R_i}{\lambda_i}$ to consider the characteristics of cycle slip on sequence, constructs statistical test to detect the position of outliers, and uses global search to detect different combinations of cycle slip through the constrained range. The model is simple and practical, which can effectively improve the cycle slip detection effect.

2. Positioning basic equation and cycle slip detection model

The pseudorange and phase observation equations can be expressed as:

$R_i = \rho + I_{R_i} + T_i + m_{R_i} + \varepsilon_{R_i}$ （1）

$\lambda_i \varphi_i = \rho + I_{\varphi_i} + T_i + m_{\varphi_i} + \varepsilon_{\varphi_i} + \lambda_i N_i$ （2）

Where R_i denotes pseudorange observation, λ_i denotes the carrier wavelength, φ_i denotes the carrier phase observation, $I_{R_i}, I_{\varphi_i}, m_{R_i}, m_{\varphi_i}, \varepsilon_{R_i}, \varepsilon_{\varphi_i}$ respectively denotes pseudorange and phase measurement ionospheric error, multipath error and observation noise, ρ denotes the geometric distance between the receiver and satellite, T_i denotes the tropospheric error, N_i is the full cycle ambiguity of the carrier phase, $f_i (i = 1,2,3)$ denotes the triple frequency.

Subtracting equations (1) and (2) yields:

$N_i = \frac{\lambda_i \varphi_i - R_i - (I_{\varphi_i} - I_{R_i}) - (m_{\varphi_i} - m_{R_i}) - (\varepsilon_{\varphi_i} - \varepsilon_{R_i})}{\lambda_i}$ （3）

Considering the high sampling rate and ignoring the influence of the ionosphere, equation (3) is subtracted between epochs t_1 and t_2 to obtain the estimated cycle slip at epoch t_2, which is:

$\Delta N_i = \Delta \varphi_i - \frac{\Delta R_i}{\lambda_i}$ （4）

Where $\Delta N_i = N_i(t_2) - N_i(t_1)$，$\Delta \varphi_i = \varphi_i(t_2) - \varphi_i(t_1)$，$\Delta R_i = R_i(t_2) - R_i(t_1)$.

According to the above, the estimated cycle slip of the triple frequencies is:

$$\begin{cases} \Delta N_1 = \Delta \varphi_1 - \frac{\Delta R_1}{\lambda_1} \\ \Delta N_2 = \Delta \varphi_2 - \frac{\Delta R_2}{\lambda_2} \\ \Delta N_3 = \Delta \varphi_3 - \frac{\Delta R_3}{\lambda_3} \end{cases} \quad (5)$$

Considering the receiver cannot receive all triple frequency P-codes, the received frequency P-code can be used to replace other unreceived P-codes. If any $f_i (i = 1,2,3)$ P-code is received, equation (5) can be written as:

$$\begin{cases} \Delta N_1 = \Delta \varphi_1 - \frac{\Delta R_i}{\lambda_1} \\ \Delta N_2 = \Delta \varphi_2 - \frac{\Delta R_i}{\lambda_2} \\ \Delta N_3 = \Delta \varphi_3 - \frac{\Delta R_i}{\lambda_3} \end{cases} \quad (6)$$

If calculates the difference between the frequencies of equation (2) , it is obtained that:

$\lambda_i \varphi_i - \lambda_j \varphi_j = \Delta I_{ij} + \Delta T_{ij} + \Delta \varepsilon_{ij} + \lambda_i N_i - \lambda_j N_j$ (7)

Considering the small changes in ionosphere, troposphere and noise at high sampling rates, calculate the difference between epochs t_1 and t_2 using equation (7), and divide both sides by λ_i, as follows:

$$\begin{cases} \Delta\emptyset_{12} = \Delta N_1 - \frac{77}{60}\Delta N_2 \\ \Delta\emptyset_{13} = \Delta N_1 - \frac{154}{115}\Delta N_3 \\ \Delta\emptyset_{23} = \Delta N_2 - \frac{24}{23}\Delta N_3 \end{cases} \quad (8)$$

From equations (6) and (8), it can be seen that considering the entire cycle characteristics of cycle slip, (6) should be an integer solution that satisfies (8). A constraint equation that can reach (8) within the integer range of constraint (6) is called ttiple frequency cycle slip detection.

3. Cycle slip characteristics

If $\Delta\emptyset$ obeys $N(0, \sigma_{\Delta\emptyset}^2)$ and $m_\emptyset = \pm 0.01$ cycles, then $\sigma_{\Delta\emptyset_{12}} = \pm 0.023$ cycles,$\sigma_{\Delta\emptyset_{13}} = \pm 0.024$ cycles and $\sigma_{\Delta\emptyset_{23}} = \pm 0.020$ cycles. Calculated based on three times the mean square error, the tolerances of them are 0.069 cycles, 0.071 cycles and 0.060 cycles respectively, so:

(1) For $\Delta\emptyset_{ij} = \Delta N_i - (\lambda_j/\lambda_i)\Delta N_j$, if its value is not within the range [-3$\sigma_{\Delta\emptyset_{ij}}$,3$\sigma_{\Delta\emptyset_{ij}}$], it can be suspected that there may be a cycle slip at this position;

(2) Considering the integer characteristic of cycle slip, when $\Delta N_i - (\lambda_j/\lambda_i)\Delta N_j \approx 0$, although the value of $\Delta\emptyset$ is within [-3$\sigma_{\Delta\emptyset_{ij}}$,3$\sigma_{\Delta\emptyset_{ij}}$] and cannot be determined through step (1) above, but there are $\Delta N_1 = 9k$ and $\Delta N_2 = 7k$ or $\Delta N_1 = 77k$ and $\Delta N_2 = 60k, N_1 = 154k$ and $\Delta N_3 = 115k$ or $\Delta N_2 = 24k, \Delta N_3 = 23k,$ k ∈ Z , there is a paired occurrence characteristic, there may be cycle slip at this position;

(3) The outlier position of $\Delta\emptyset_{ij}$ and ΔN_ican be regarded as the suspected cycle slip position, the integer solution calculated by constraint can be regarded as the estimation of cycle slip value.

4. Design of inspection quantity for cycle slip detection

Building statistical tests based on $\Delta N_{ij} (i = 1,2,3\ ;\ j = 1,2,3 \ldots n)$:

$$\begin{cases} G = \frac{\max_{j=1,2\ldots,n}|\Delta N_{ij}-\bar{S}|}{\sigma} \\ \bar{S} = \frac{\sum_{j=1}^{n}\Delta N_{ij}}{n} \\ \sigma = \sqrt{\frac{\sum_{j=1}^{n}(\Delta N_{ij}-\bar{S})^2}{n}} \end{cases} \quad (9)$$

At significance level α , if:

$$G > \frac{n-1}{\sqrt{n}}\sqrt{\frac{t_{\alpha/(2n),n-2}^2}{n-2+t_{\alpha/(2n),n-2}^2}} \quad (10)$$

Where $t_{\alpha/(2n),n-2}$ represents having (n-2) degrees of freedom and critical value of T-distribution at significance level $\alpha/(2n)$. If equation (10) is true, it indicates that there is outlier and record the position, and the sequence will continue until all ΔN_{ij} sequences have been tested.

5. Cycle slip detection process

Based on the following two situations:

a. if $\Delta\emptyset_{ij} = \Delta N_i - (\lambda_j/\lambda_i)\Delta N_j$ exceed [-$3\sigma_{\Delta\emptyset_{ij}}$,$3\sigma_{\Delta\emptyset_{ij}}$], the outlier is the place where the cycle slip occurs, which can be solved directly based on equation (6) and (8);

b. If $\Delta\emptyset_{ij} = \Delta N_i - (\lambda_j/\lambda_i)\Delta N_j$ has no outlier, but ΔN_{ij} has, the location of outlier can be found by equation (10).

In either case, it is necessary to detect the outlier position of $\Delta\emptyset_{ij}$ and ΔN_i, and then calculate according to equation (6) and (8). In calculation process, the key step is the range of ΔN_i, which directly affects the accuracy of the solution. The range is too large or small, it leads to a multivalued or missing the correct cycle slip problem of the solution. The detection process is as follows:

Step1: Constructing observation sequences $\Delta\emptyset_{12}, \Delta\emptyset_{13}, \Delta\emptyset_{23}, \Delta N_1, \Delta N_2$ and ΔN_3;

Step2: Determine if $\Delta\emptyset_{ij}$ is out of range $[-3\sigma_{\Delta\emptyset_{ij}}, 3\sigma_{\Delta\emptyset_{ij}}]$. If yes, record the corresponding position sequence as $T0$, execute Step3; If not, no calculation is required, execute Step3;

Step3: After removing $T0$, the remaining sequence record as $\Delta YN_1, \Delta YN_2$ and ΔYN_3 ; Utilizing statistical test quantities equation (8), detect whether $\Delta YN_1, \Delta YN_2$ and ΔYN_3 have outlier respectively. If yes, record the corresponding position sequence as $T1, T2\ and\ T3$, execute Step4; If not, without cycle slip, over;

Step4: Calculate the union of T0, $T1, T2$ and $T3$, denoted as $T = T0 \cup T1 \cup T2 \cup T3$;

Step5: Calculate the standard deviation of $\Delta\emptyset_{12}, \Delta\emptyset_{13}, \Delta\emptyset_{23}, \Delta N_1, \Delta N_2$ and ΔN_3 after removing position T, and record it as $m_{12}, m_{13}, m_{23}, m_1, m_2$ and m_3.

Step6: Starting from each element ti in $T(t1, t2, t3 \ldots tm)$, perform cycle slip detection according to equation (11):

$$\begin{cases} C1 \in [\Delta N_1(ti) - 3m_1 \quad \Delta N_1(ti) + 3m_1] \\ C2 \in [\Delta N_2(ti) - 3m_2 \quad \Delta N_2(ti) + 3m_2] \\ C3 \in [\Delta N_3(ti) - 3m_3 \quad \Delta N_3(ti) + 3m_3] \\ |\Delta\emptyset_{12} - (\Delta N_1 - (\lambda_2/\lambda_1)\Delta N_2| < 3m_{12} \\ |\Delta\emptyset_{13} - (\Delta N_1 - (\lambda_3/\lambda_1)\Delta N_3| < 3m_{13} \\ |\Delta\emptyset_{23} - (\Delta N_2 - (\lambda_3/\lambda_2)\Delta N_3| < 3m_{23} \end{cases} \quad (11)$$

Step7: Cycle slip detection completed.

6. Experimental validation analysis

6.1 Data source and description

To verify the triple frequency cycle slip detection method in this article, high-frequency data from IGS stations were used for experimental verification, and the confidence level was $\alpha = 0.05$. The CUT0 observation data of IGS station with a sampling rate of 1 Hz was collected on the 15th day of 2021, covering the observed values of triple frequency phase and f_2 P-code (ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/data/highrate/).

6.2 experimental verification

The experimental observation duration is about 1 hour, using G25 and G26 satellites, and randomly adding 100 sets of different sizes of combined cycle slips in random epoch. The $\Delta\emptyset_{ij}$ histogram and QQ diagram are shown in Figures 1 and 2 of the combination of G25 and G26 satellites. The comparison of $\Delta\emptyset_{ij}$ and ΔN_i before and after adding cycle slips is shown in Figures 3 to 5, and the detection effects is shown in statistical table 1.

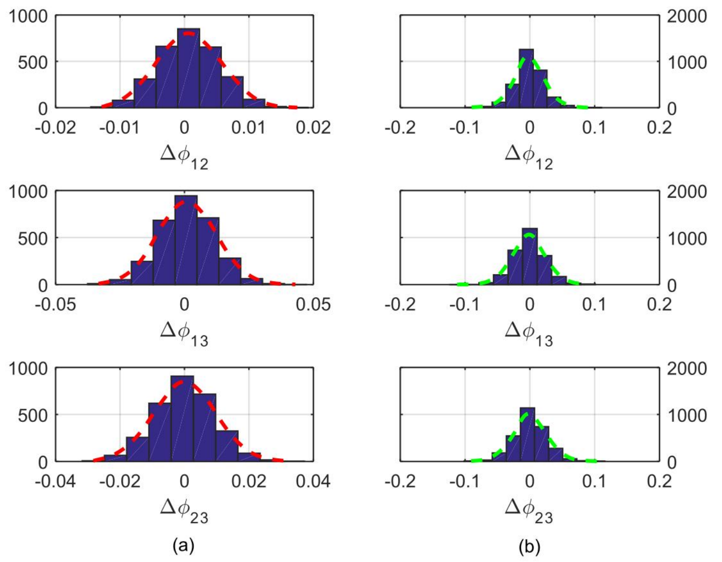

Figure 1: (a) $\Delta\emptyset_{ij}$ histogram of G25, (b) $\Delta\emptyset_{ij}$ histogram of G26

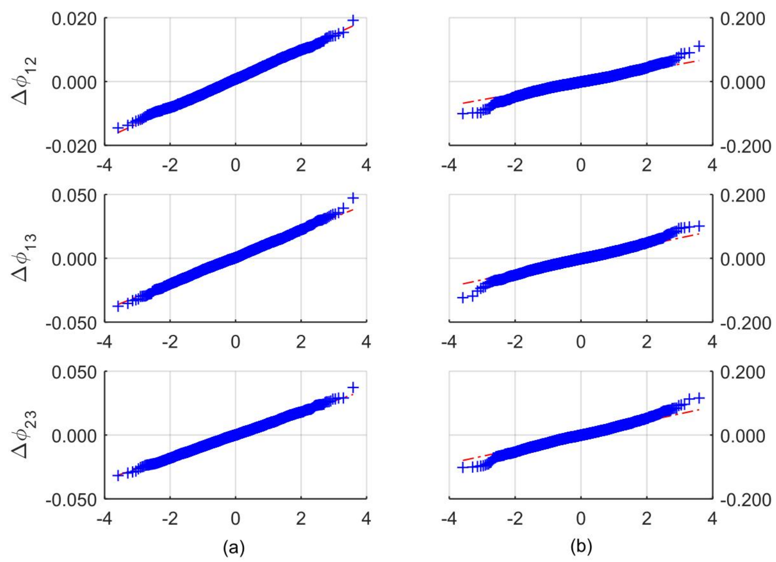

Figure 2: (a) $\Delta\emptyset_{ij}$ QQ diagram of G25, (b) $\Delta\emptyset_{ij}$ QQ diagram of G26

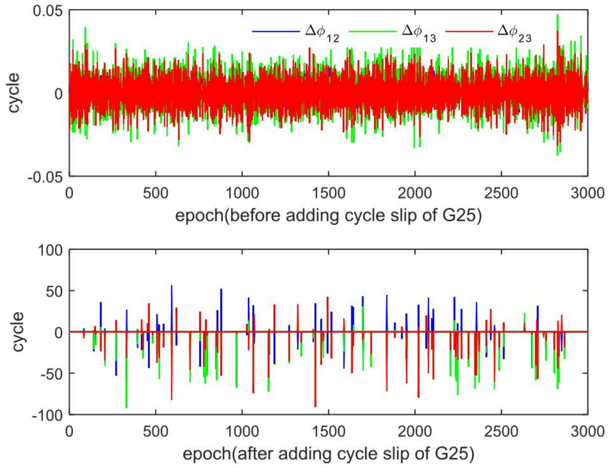

Figure 3: $\Delta\emptyset_{ij}$ add cycle slip before and after of G25

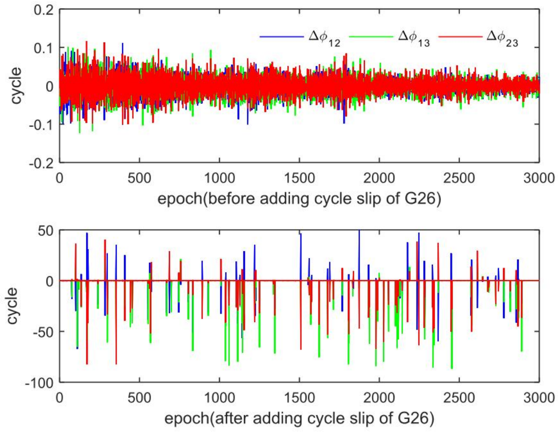

Figure 4: $\Delta\emptyset_{ij}$ add cycle slip before and after of G26

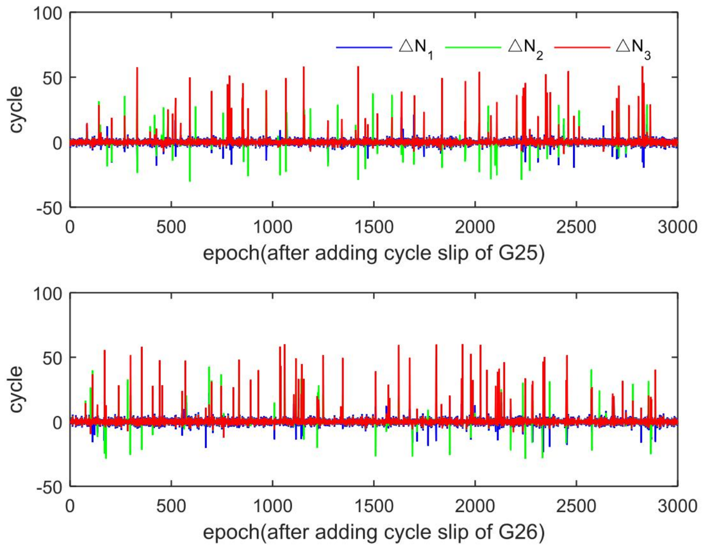

Figure 5: add cycle slip after of ΔN_i

Table. 1 Comparison Statistics table of cycle slip detection

satellite	number of cycle slip	detected	success	mistake	leakage dection	misdetection	success rate (%)	false rate (%)
G25	100	99	99	1	1	0	99.00	0.00
G26		97	97	0	3	3	97.00	3.00

Note: The number of detected epochs refers to the consistency between the detected and the artificially added epochs; Success refers to the consistency between the detected cycle slip and artificially added; error detection refers to an error in the calculation of cycle slip despite the correct detection position; Leakage detection refers to the failure to detect cycle slip at artificially added positions; misdetection refers to the incorrect detection outside the human position; Success rate=success/number of cycle slip, false rate=misdetection/number of cycle slip.

6.3 Validation analysis

From the above data validation, it can be seen that:

(1) From the histogram and QQ diagram of $\Delta\emptyset_{ij}$ in Figure 1 and Figure 2, it basically conforms to the normal distribution which is consistent with the assumption of $\Delta\emptyset_{ij}$ in the cycle slip detection model;

(2) From Figure 3 and Figure 4, it can be seen that before adding the cycle slip, the fluctuation of $\Delta\emptyset_{ij}$ is relatively small, indicating that at a sampling rate of 1 Hz, its value changes smoothly and the vibration amplitude is small; After adding cycle slip, the abnormality of $\Delta\emptyset_{ij}$ is significant, especially the amplitude fluctuation, indicating that the cycle slip has an impact on sequence $\Delta\emptyset_{ij}$;

(3) From Figure 5, it can be seen that the amplitude of ΔN_i changes significantly after adding cycle slip, indicating that the addition of cycle slip changes the stationarity of the original sequence. Constraining its range is the key to solving cycle slip detection.

(4) From the data statistics table 1, it can be seen that in terms of detection success rate, the P-code constraint in this article simultaneously calculates the triple frequency cycle slip success rate to reach 98%; However, there are also leakage detections and misdection. The reason for false detections is that the special cycle slip is smaller than the standard deviation of the sequence, resulting in the calculation of cycle slip being overwhelmed by errors, and it is not possible to correctly distinguish between cycle slip and error.

7. Conclusion

Through experimental analysis, it can be seen that the following conclusions can be drawn from the triple frequency GPS cycle slip detection in this article:

(1) By constructing $\Delta\emptyset_{ij} = \Delta N_i - (\lambda_j/\lambda_i)\Delta N_j$ equation and using a single P-code observation to constrain the range of cycle slips, utilizing the integer characteristics of cycle slips, more than 98% of cycle slips can be successfully detected and multi-value problems can be avoided;

(2) By calculating the standard deviation of the sequence after removing suspected cycle slip in $\Delta\emptyset_{ij}$ and ΔN_i, the "3σ" criterion is adopted to weaken the influence of cycle slip, constrain the range of triple frequency cycle slip, and avoid the problem of noise submergence in the observation values;

(3) The method in this article can solve the problem of the position and size of each cycle slip in the triple frequencies at once;

(4) The method presented in this article indicates that under triple frequency conditions, as long as any type of P-code can be observed, constraint ΔN_i can solve for each cycle slip. The model is simple and effective.

Acknowledgments: This research was funded by The Second batch of New Engineering Research and Practice Projects (grant number: E-TMJZSLHY20202148), Subject Construction Fund of Yunnan College of Business Management (grant number :2022XKJS06).

References

[1] MIAOY, SUN Z W, WU S N. Error analysis and cycle-slip detection research on satellite-borne GPS observation [J].Journal of Aerospace Engineering, 2010, 24(1):95-101.

[2] FEND S, OCHIENG W.MOORS T, et al. Carrier phase-based integrity monitoring for high-accuracy positioning [J].GPS Solutions, 2009, 13(1):13-22.

[3] Yan Xinsheng, Wang Yiqiang, Bai Zhengdong, et al. Automatically detect and repair cycle slips using alliance of high difference and TurboEdit [J]. Bulletin of Surveying and Mapping, 2007(9):5-9,16.

[4] Huang Dingfa, Zhuo Jiancheng. Wavelet Analysis for Cycle Slip Detection and Reconstruction of GPS Carrier Phase Measurements [J]. Acta Geodaetica et Cartographica Sinica,1997(4):73-78.

[5] Zhang Liang, Yue Dongjie. Research on detection and reparation for cycle slips using phase reduce false distance law and ionized layer remnant method of difference [J].Engineering of Surveying and Mapping, 2014, 23(2):36-38.

[6] Chen Pinxin, Zhang Chuanyin, Huang Kunxue. Cycle slips detecting and repairing by use of phase reduce pseudorange law and ionized layer remnant method of difference [J]. Journal of Geodesy and Geodynamics, 2010, 30(2):120-124.

[7] Feng, W., Zhao, Y., Zhou, L. et al. Fast Cycle Slip Determination for High-Rate Multi-GNSS RTK Using Modified Geometry-Free Phase Combination [J]. GPS Solution, 24, 42 (2020).

[8] Blewitt G. An Automatic Editing Algorithm for GPS Data [J].Geophysical Research Letters, 1990, 17(3):199- 202.

[9] Zou Zhengbiao, He Xiufeng, Tang Xu. Cycle slip detection using TECR and MW combined method for un-differenced GPS data[J].Journal of Hohai University :Natural Sciences, 2014, 42(2):155-158.

[10] Li Ming, Gao Xingwei, Xu Aaigong. An improved method of the polynomial fitting of the cycle-slip [J].Science of Surveying and Mapping, 2008, 33(4):82-83, 99.

[11] Liu Ning, Xiong Yongliang, Xu Shaoguang. Detection and repair of cycle slip using improved TurboEdit algorithm and Chebyshev polynomial method [J]. Geomatics and Information Science of Wuhan University, 201l, 36(12):1500-1503.

[12] Wang Zhenjie, Nie Zhixi, Ou Jikun. An improved cycle slip detection based on TurboEdit method for dual frequency GPS receiver [J]. Geomatics and Information Science of Wuhan University, 2014, 39(9):1017-1021.

[13] Wu Jizhong, Shi Chuang, Fang Rongxin, Improvement of detection method TurboEdit of GPS data cycle slip in single station[J]. Geomatics and information Science of Wuhan University, 2011, 41 (1):29-33.

[14] HUANG Lingyong, SONG Lijie, WANG Yan, et al.Beidou triple frequency geometry-free phase combination for cycle-slip detection and correction [J]. ActaGeodaetica et Cartographica Sinica,2012, 41（5）:763-768.

[15] DAIZ, KNEDLIK S, LOFFELD O. Instantaneous triple-frequency GPS cycle slip detection and repair[J].International Journal of Navigation and Observation,2009,23（1）:28-43.

[16] RICHERT T, EL-SHEIMY N. Optimal linear combinationsof triple frequency carrier phase data from futureglobal navigation satellite systems[J]. GPS Solutions,2007,11（1）:11-19.

[17] HUANG Lingyong, ZHAI Guojun,OUYANG Yongzhong, et al. Triple-frequency turbo editcycle-slip processing method of weakening ionosphericactivity[J]. Acta Geodaetica et Cartographica Sinica,2015,44（8）:840-847.