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Dual-frequency GPS Cycle Slip Detection and Repair Based on Dynamic Test

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ABSTRACT

How to solve the multi-values and accurately detect the cycle slip of each frequency was particularly critical of dual-frequency GPS. This paper used the geometry-free phase combinations, proposed a dynamic test method to detect cycle slip outliers, which determined the cycle slip by constraining the value range of the cycle slip sequences of the dual-frequency GPS through the constantly updated its standard deviation. The dynamic test of cycle slip detection and repair method has been tested by using GPS data with sampling interval of 1s, 5s, 10 s and 15s. The method can not only solve the problem of multi-values, but also accurately detect the cycle slip values at various frequencies, whether the fixed cycle slip is added to the random position or the random cycle slip is added to the random position. Experiments with four different sampling intervals, the results showed that the proposed method of cycle slip detection and repair calculation success rate reaches 98.75%.

1. Introduction

When the satellite is blocked or strongly interfered, it will lose its lock for a short time, resulting in the jump of the phase observation value, which is called cycle slip. Cycle slip is one of the factors that affect the reliability of GPS quality. High precision measurement results must ensure that there is no cycle slip in the carrier phase observations (Fend et al., 2009; Miao et al., 2010). There are many cycle slip detection methods, mainly including phase multiple difference method (Yan et al., 2007), wavelet analysis method (Huang and Zhuo, 1997), ionospheric residual error method (Blewitt, 1990; Chen et al., 2010; Zhang and Yue, 2014; Feng et al., 2020), undifference dual frequency code phase combination method (Li et al., 2011; Cai et al., 2013; Zou et al., 2014; Li et al., 2016; Li et al., 2019), fitting method (de Lacy et al., 2008; Li et al., 2008; Liu et al., 2011), TurboEdit method (Wu et al., 2011; Wang et al., 2014; Cai et al., 2016; ZHang et al., 2017) and direct rounding method (Guo et al., 2017). The above methods have some limitations in practical application, such as: multiple difference method and wavelet analysis method have obvious effect on large cycle slip detection and are insensitive to small cycle slip (Feng et al., 2010). The dual-frequency code phase combination method and the ionospheric residual error method can not determine the frequency location and multi-value problem of cycle slips, and the cycle slips of special combinations are invalid; the fitting method of wavelet analysis has no requirements on the sampling rate, but it has higher requirements on the number of data involved in fitting and the order of fitting, which will also bring about fitting errors and rounding errors; MW combined observations in TurboEdit method are easily affected by pseudo range observation noise, and part of the cycle slips are easily submerged by noise.

In view of the above problems, this paper uses the phase geometry-free equation $\Delta\phi = \Delta N_1 - (\lambda_2/\lambda_1)\Delta N_2$ to take into account that the cycle slip occurrence will inevitably show the characteristics of outliers in the sequence $\Delta\phi$, ΔN_1 and ΔN_2, uses the "3σ" criterion and constructs statistical tests to detect ΔN_1 and ΔN_2 outliers, dynamically updates the standard deviation and detects different combinations of cycle slips through the restricted range of ΔN_1 and ΔN_2. Compared to other methods, it can solve the problem of the location and size of dual frequency cycle slips at once, and is also effective for special combination cycle slips, avoiding missed detections and multi value problems, which can effectively improve the efficiency and reliability of cycle slip detection and repair.

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2. Materials and Method

2.1 Dual Frequency Positioning and Cycle Slip Detection Model

$$\begin{cases} L_1 = \lambda_1\phi_1 = \rho + c\cdot(\delta t - \delta T) - \dfrac{If_2^2}{f_1^2 - f_2^2} + T + \lambda_1 N_1 \\ L_2 = \lambda_2\phi_2 = \rho + c\cdot(\delta t - \delta T) - \dfrac{If_1^2}{f_1^2 - f_2^2} + T + \lambda_2 N_2 \\ P_1 = \rho + c\cdot(\delta t - \delta T) - \dfrac{If_2^2}{f_1^2 - f_2^2} + T \\ P_2 = \rho + c\cdot(\delta t - \delta T) - \dfrac{If_2^2}{f_1^2 - f_2^2} + T \end{cases}, \quad (1)$$

Where the λ_i, f_i, ϕ_i, P_i and N_i denote the wavelength, frequency, phase observations, pseudo range observations and integer ambiguity of L_i carrier (i = 1, 2), respectively; ρ denotess the geometric distance between the receiver and the satellite, I and T denote the ionospheric and tropospheric delay error.

To detect cycle slip, the first and second, the first and third, and the second and fourth formulas in Eq. (1) are combined to eliminate the influence of range term ρ, clock difference between satellite and receiver, tropospheric delay, etc., and divide both sides of the formula by λ_i. Calculate the difference between adjacent epochs, and consider that the ionosphere changes slowly or is basically unchanged, which can be ignored.

$$\begin{cases} \Delta\phi = \Delta N_1 + \dfrac{\lambda_2}{\lambda_1}\Delta N_2 + \Delta_{ion} \\ \Delta N_1 = \Delta\phi_1 - \dfrac{\Delta P_1}{\lambda_1} + \Delta\varepsilon_1 \\ \Delta N_2 = \Delta\left(\phi_2 - \dfrac{\Delta P_2}{\lambda_2} + \Delta\varepsilon_2\right) \end{cases}, \quad (2)$$

where $\Delta\phi$ is the change value of phase observation between epochs, Δ_{ion} is the ionospheric residual at a certain time, and $\Delta\varepsilon$ is the total error term, which is mainly the difference between the ionosphere and multipath in the epoch.

If the sampling interval is small and the ionosphere is relatively stable, then Eq. (2) can be simplified as:

$$\begin{cases} \Delta\phi = \Delta N_1 - \dfrac{77}{60}\Delta N_2 \\ \Delta N_1 = \Delta\phi_1 - \dfrac{\Delta P_1}{\lambda_1} \\ \Delta N_2 = \Delta\phi_2 - \dfrac{\Delta P_2}{\lambda_2} \end{cases}, \quad (3)$$

The Eq. (3) can be regarded as three data sequences, ΔN_1 and ΔN_2 can be regarded as the integer solution of $\Delta\phi$. Once cycle slip occurs, the sequence value at the place where cycle slip occurs is abnormal. Therefore, if the abnormal values of the three sequences can be determined, the cycle slip can be found.

2.2 Double Frequency Cycle Slip Characteristics

If $\Delta\phi$ is assumed to obey the normal distribution $N(0, \sigma_{\Delta\phi}^2)$, the mean square error is $m_\varphi = \pm 0.01$ cycles, according to the error propagation law, $\sigma_{\Delta\phi} = \pm 0.023$ cycles. According to "3σ" theory, the tolerance of $\Delta\phi$ is 0.07 cycles, so:

1. For the $\Delta\phi = \Delta N_1 - (\lambda_2/\lambda_1)\Delta N_2$, once the value range [-0.07,0.07] is exceeded, it can be considered that there is cycle slip;
2. Considering the cycle slip integer property, when $\Delta N_1 - \dfrac{\lambda_2}{\lambda_1}\Delta N_2 \approx 0$ means $\Delta N_1 = 9\,k$ and $\Delta N_2 = 7\,k$ or $\Delta N_1 =$ 77 k and ΔN_2 = 60 k, $k \in z$, when the $\Delta\phi$ sequence is constrained by [-0.07,0.07], the outlier can't be detected; but ΔN_1 or ΔN_2 have abnormal values in pairs, which can be restricted by ΔN_1 or ΔN_2 to detecte cycle slips;
3. The abnormal value of $\Delta\phi$, ΔN_1 and ΔN_2 sequence can be regarded as cycle slip value.

2.3 Dynamic Test

In order to calculate the cycle slips ΔN_1 and ΔN_2 that can meet the requirements of $\Delta\phi = \Delta N_1 - \dfrac{77}{60}\Delta N_2$, it is necessary to determine the range of values for ΔN_1 and ΔN_2. If the range is too large or too small, it will lead to multi valued cycle slips or missed detections. Dynamic test is the process of removing all existing cycle slip values in ΔN_1 and ΔN_2 and calculating their mean square error m_1 and m_2. By constraining the range with the "3σ" criterion, cycle slip is calculated and the impact of cycle slip is repaired. After repairing a certain cycle slip, recalculate the mean square error m_1 and m_2 of the remaining ΔN_1 and ΔN_2, and continue to update the mean square error m_1 and m_2 of the cycle slip sequence to constrain the calculation range, and calculate the remaining cycle slips for repair, until all cycle slip detection and repairs are completed.

3. Statistical Test Construction

Set observation sequence, $S = (S_1, S_2, \ldots\ldots S_n)$, and construct test statistics:

$$\begin{cases} G = \dfrac{\max\limits_{i=1,2,\ldots,n} |S_i - \bar{S}|}{\sigma} \\ \bar{S} = \dfrac{\sum_{i=1}^{n} S_i}{n} \\ \sigma = \sqrt{\dfrac{\sum_{i=1}^{n}(S_i - \bar{S})^2}{n}} \end{cases}. \quad (4)$$

At the significance level α, if:

$$G > \frac{n-1}{\sqrt{n}}\sqrt{\frac{t^2_{\alpha/(2n),n-2}}{n-2+t^2_{\alpha/(2n),n-2}}}. \quad (5)$$

In Eq. (5): $t_{\alpha/(2n),n-2}$ denotes the critical value of T distribution with (n-2) degrees of freedom and significance level $\alpha/(2n)$. If Eq. (5) is true, it indicates that there are abnormal values and the position is recorded, and the sequence continues until all $S = (S_1, S_2, \ldots S_n)$ sequences are tested.

4. Cycle Slip Detection Process

For Eq. (3), cycle slip integer property of ΔN_1 and ΔN_2, if the range of ΔN_1 and ΔN_2 can be limited, use $\Delta\phi = \Delta N_1 - \frac{77}{60}\Delta N_2$ can calculate the value of ΔN_1 and ΔN_2 ,which is the cycle slip value.

No matter what kind of cycle slip, it is necessary to detect the abnormal value of the $\Delta\phi$, ΔN_1 and ΔN_2 sequence. In the calculation process, the key step is the rang of ΔN_1 and ΔN_2 directly affects the accuracy of the solution. If the range is too large, the solution will not be unique (multi-value problem), and if the range is too small, the correct solution will be missed. So once ΔN_1 and ΔN_2 are determined, the value range of ΔN_1 and ΔN_2 satisfies $\Delta\phi = \Delta N_1 - \frac{77}{60}\Delta N_2$, the integer solution is the cycle slip value. The cycle slip detection flowchart is shown in Fig. 1, the detailed steps are as follows:

Step 1: Assembling observation sequences $\Delta\phi$, ΔN_1 and ΔN_2;

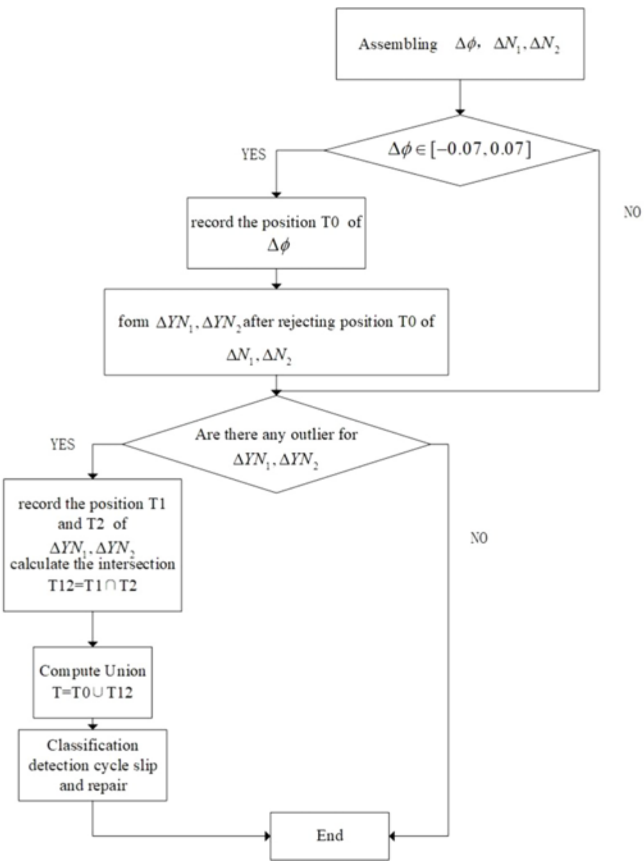

Fig. 1. Cycle Slip Detection Flowchart

Step 2: Determine whether the sequence $\Delta\phi$ is out of range, If yes, record the position sequence corresponding to $\Delta\phi$ as $T0$, execute Step 3;

Step 3: Reject after $T0$ position of sequence ΔN_1 and ΔN_2, the remaining sequences form a new sequence ΔYN_1 and ΔYN_2; use statistical test quantity to detect new sequence whether there is abnormal value in ΔYN_1 and ΔYN_2; If yes, record the position of the sequence of ΔYN_1 and ΔYN_2 outliers as T_1 and T_2, calculate the intersection of T_1 and T_2 as $T12 = T1 \cap T2$, then execute Step 4. If not, there is no cycle slip;

Step 4: Calculate the union of T_0 and T_{12} as $T = T0 \cup T12$; calculate the standard deviation m_1 and m_2 of sequence ΔN_1 and ΔN_2 after removing T;

Step 5: (1) First define the function Q[a, b] as follows:

```
If a ≥ 0
  Q [a, b] = [a round to +∞ b round to 0]
Elseif a < 0
  If b ≤ 0
    Q [a, b] = [a round to 0 b round to -∞]
  Elseif
    Q [a, b] = [a round to 0 b round to 0 ]
  end
end
```

(2) Starting from each element t_i in $T(t1, t3, t3, \ldots, tm)$, cycle slip detection and repair are carried out in the following two cases:

a. If $ti \in T$, calculate and solve according to the following Eq. (6).

$$\begin{cases} \left|C_1 - \frac{77}{60}\Delta C_2 - \Delta\phi(ti)\right| < 0.07 \\ C_1 \in [\Delta N_1(ti) - 3m_1 \quad \Delta N_1(ti) + 3m_1] \\ C_2 \in [\Delta N_2(ti) - 3m_2 \quad \Delta N_2(ti) + 3m_2] \end{cases} \tag{6}$$

Get cycle slip value C_1 and C_2, repair the original ΔN_1 and ΔN_2, where $\Delta N_1\ (ti) = \Delta N_1(ti) - C_1$ and $\Delta N_2(ti) = \Delta N_2(ti) - C_2$, calculate the standard deviation m_1 and m_2 after removing $T\ (ti + 1 \ldots tm)$; If not, there is no cycle slip;

b. If $ti \in T12$, calculate and solve (9, 7) type according to Eq. (7) and (77, 60) type according to Eq. (8).

$$\begin{cases} \left|9C_1 - \frac{77}{60} * 7C_2\right| < 0.07 \\ C_1 \in Q\left[\frac{\Delta N_1(ti) - 3m_1}{9} \quad \frac{\Delta N_1(ti) + 3m_1}{9}\right] \\ C_2 \in Q\left[\frac{\Delta N_2(ti) - 3m_2}{7} \quad \frac{\Delta N_2(ti) + 3m_2}{7}\right] \end{cases} \tag{7}$$

If $C_1 \cap C_2$, indicating the existence of (9, 7) type cycle slip; repair the original ΔN_1 and ΔN_2, where $\Delta N_1(ti) = \Delta N_1(ti) - 9C_1$ and $\Delta N_2(ti) = \Delta N_2(ti) - 7C_2$, and calculate the standard deviation m_1 and m_2 after removing $T(ti + 1 \ldots tm)$; otherwise, there is no (9, 7) cycle slip.

$$\begin{cases} \left|77C_1-\frac{77}{60}*60C_2\right| = 0 \\ C_1 \in Q\left[\frac{\Delta N_1(ti)-3m_1}{77}\ \ \frac{\Delta N_1(ti)+3m_1}{77}\right] \\ C_2 \in Q\left[\frac{\Delta N_2(ti)-3m_2}{60}\ \ \frac{\Delta N_2(ti)+3m_2}{60}\right] \end{cases} \tag{8}$$

If $C_1 \cap C_2 \neq \phi$, indicating the existence of (77, 60) type cycle slip; repair the original ΔN_1 and ΔN_2, where $\Delta N_1(ti) = \Delta N_1(ti) - 77C_1$ and $\Delta N_2(ti) = \Delta N_2(ti) - 60C_2$, and calculate the standard deviation m_1 and m_2 after removing $T(ti+1 \ldots tm)$; otherwise, there is no (70, 66) cycle slip.

Step 6: The cycle slip detection is completed.

5. Experimental Verification Analysis

5.1 Data Description

In order to verify the cycle slip detection and repair method in this paper, the experiment used the abpo observation data of IGS station with a sampling rate of 1s, and the data download address (ftp://gssc.esa.int/gnss/data/daily, the 100th day data in 2012), the GPS satellite track is shown in Fig. 2. G15 satellite is selected for the experiment, and the track is shown in Fig. 3. On the basis of the original 1 s sampling rate data, the dual frequency observation data with 5 s, 10 s and 15 s sampling rates are extracted by TEQC for analysis. The observation time is 2.5 h with 1s, 5s, 10s and 15s sampling rate data, dynamic test confidence level $\alpha = 0.05$, two groups of eight experimental studies were conducted.

5.2 Group I Experiment

The first group of experiments adopted the random epoch method, artificially adding 20 groups of different sizes of combined cycle slips ΔN_1 and ΔN_2 at four sampling intervals. Add the cycle slip before and after of $\Delta\phi$, ΔN_1 and ΔN_2 are shown in Figs. 4 to 7, the cycle slip detection results are shown in Tables 1 to 4, and the comparison detection success rate statistics are shown in Table 5.

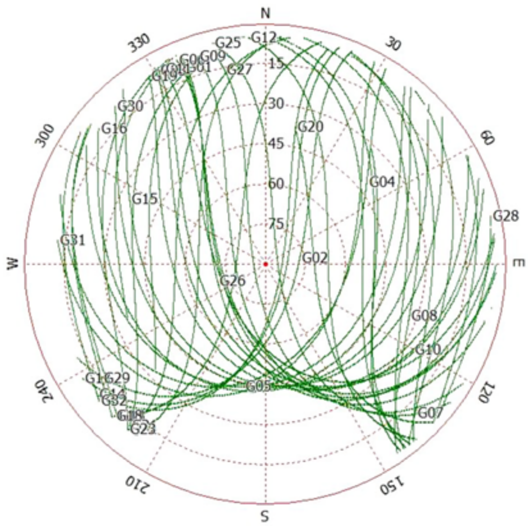

Fig. 2. GPS Satellite Track Map of Abpo Station

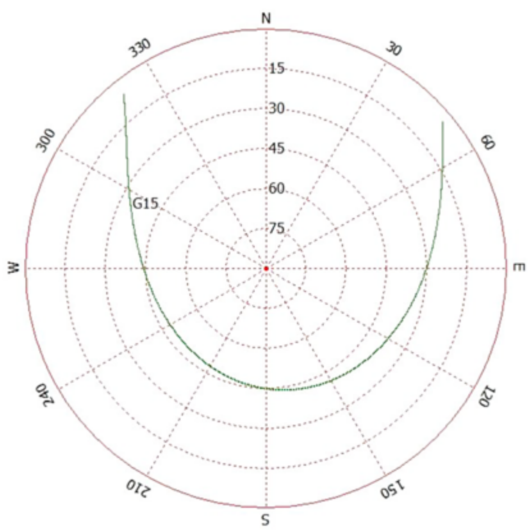

Fig. 3. G15 Satellite Track Map

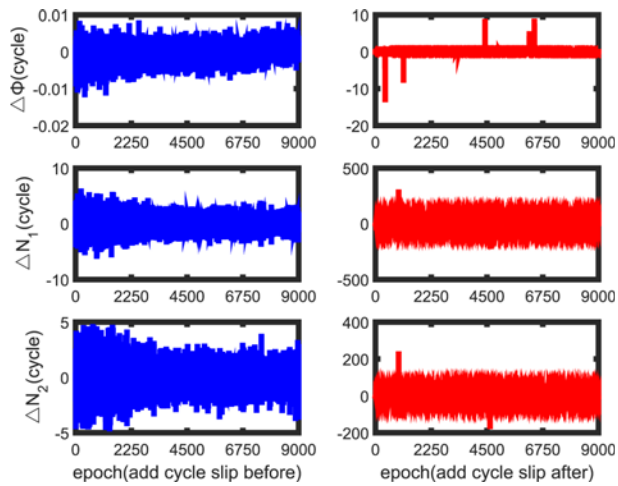

Fig. 4. Add Fixed Cycle Slip on Random Epoch before and after of 1s Sampling

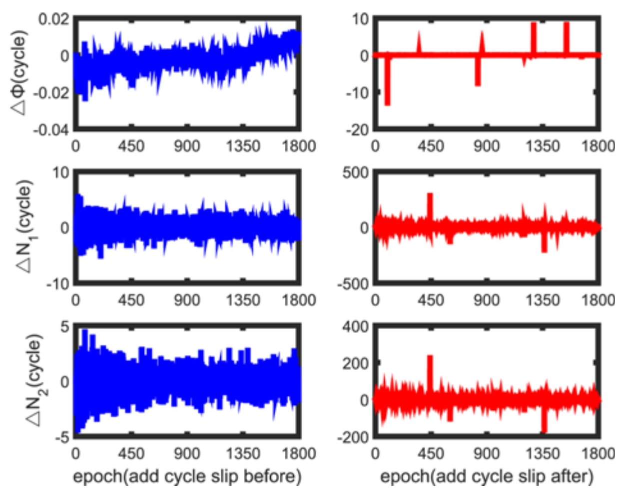

Fig. 5. Add Fixed Cycle Slip on Random Epoch before and after of 5s Sampling

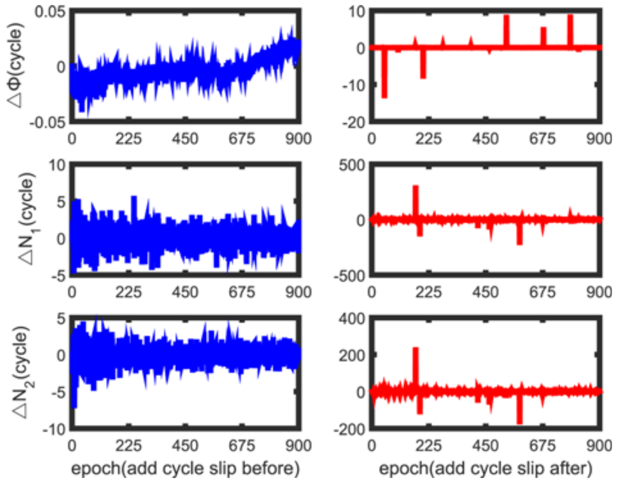

Fig. 6. Add Fixed Cycle Slip on Random Epoch before and after of 10s Sampling

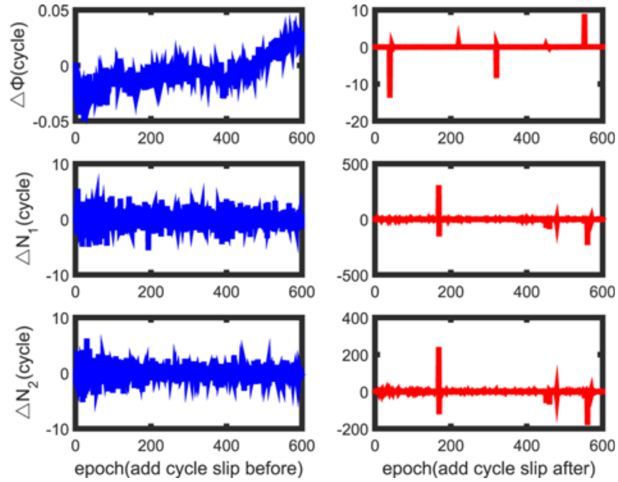

Fig. 7. Add Fixed Cycle Slip on Random Epoch before and after of 15s Sampling

Table 1. Cycles Detection of 1s Sampling

Epoch	$\Delta\phi$	ΔN_1	ΔN_2	Add cycle slip		Region		Detection		m_1	m_2
				ΔN_1	ΔN_2	ΔN_1	ΔN_2	ΔN_1	ΔN_2		
392	-13.703	-3.579	5.112	-6	6	[-8 1]	[2 9]	-6	6	1.422	1.202
721	-1.279	-0.778	2.458	0	1	[-5 3]	[-1 6]	0	1	1.423	1.202
897	0.279	3.436	-0.751	-1	-1	[-1 8]	[-4 3]	-1	-1	1.422	1.202
934	0.006	307.571	241.426	308	240	[303 312]	[238 245]	308	240	1.423	1.202
1030	0.000	-154.175	-120.259	-154	-120	[-158 -150]	[-124 -117]	-154	-120	1.423	1.202
1099	0.717	0.565	1.859	2	1	[-4 5]	[-2 5]	2	1	1.423	1.202
1131	-8.423	-3.729	5.112	-2	5	[-8 1]	[2 9]	-2	5	1.423	1.201
1495	0.286	-0.795	-0.347	-1	-1	[-5 3]	[-4 3]	-1	-1	1.423	1.201
1971	0.283	-3.537	-0.323	-1	-1	[-8 1]	[-4 3]	-1	-1	1.423	1.201
2735	0.001	-75.643	-59.430	-77	-60	[-80 -71]	[-63 -56]	-77	-60	1.423	1.201
2857	-0.168	-89.796	-69.680	-90	-70	[-94 -86]	[-73 -66]	-90	-70	1.423	1.201
3244	-0.028	-20.709	-12.708	-18	-14	[-25 -16]	[-16 -9]	-18	-14	1.423	1.201
3367	-0.053	-26.409	-22.204	-27	-21	[-31 -22]	[-26 -19]	-27	-21	1.423	1.201
4421	8.913	-36.886	-35.848	-36	-35	[-41 -33]	[-39 -32]	-36	-35	1.423	1.201
4623	-0.001	-229.734	-180.524	-231	-180	[-234 -225]	[-184 -177]	-231	-180	1.423	1.201
4995	0.017	10.678	6.952	9	7	[6 15]	[3 11]	9	7	1.423	1.201
5867	-0.019	-8.475	-7.277	-9	-7	[-13 -4]	[-11 -4]	-9	-7	1.423	1.201
6211	5.570	0.369	-0.851	3	-2	[-4 5]	[-4 3]	3	-2	1.423	1.201
6411	9.002	7.925	2.211	9	0	[4 12]	[-1 6]	9	0	1.423	1.201
7562	-1.130	3.062	3.327	4	4	[-1 7]	[0 7]	4	4	1.423	1.201

5.3 Group II Experiment

The second group of experiments adopted the random epoch, different random sizes cycle slip are added in ΔN_1 and ΔN_2at four sampling rate. Add the cycle slip before and after of $\Delta\phi$, ΔN_1 and ΔN_2 are shown in Figs. 8 to 11, the comparison detection success rate statistics are shown in Table 6.

6. Results

Through two groups of four different sampling rate data experiments, it can be seen that:

1. It can be seen from Figs. 4 to 7, Figs. 8 to 11 that, the amplitude of $\Delta\phi$, ΔN_1 and ΔN_2 sequence increases, especially with the increase of sampling interval, $\Delta\phi$ changes obviously, which may be caused by ionospheric fluctuation;
2. After adding cycle slips to the two groups of experiments, the sequence was abnormal, indicating that cycle slips had an effect on the sequence;
3. From Tables 1 to 4 of data statistics that the cycle slips

Table 2. Cycles Detection of 5s Sampling

Epoch	$\Delta\phi$	ΔN_1	ΔN_2	Add cycle slip		Region		Detection		m_1	m_2
				ΔN_1	ΔN_2	ΔN_1	ΔN_2	ΔN_1	ΔN_2		
97	-13.709	-8.185	4.059	-6	6	[-12 -4]	[1 7]	-6	6	1.340	1.137
112	-1.291	-2.627	1.727	0	1	[-7 1]	[-2 5]	0	1	1.341	1.137
352	0.275	-2.088	-1.649	-1	-1	[-6 2]	[-5 2]	-1	-1	1.342	1.137
441	-0.006	307.554	240.145	308	240	[304 312]	[237 244]	308	240	1.342	1.137
603	-0.009	-154.559	-119.139	-154	-120	[-159 -151]	[-123 -116]	-154	-120	1.342	1.137
702	0.709	2.335	-0.093	2	1	[-2 6]	[-4 3]	2	1	1.341	1.137
827	-8.421	-2.640	4.390	-2	5	[-7 1]s	[1 8]	-2	5	1.341	1.137
857	0.283	-0.894	-1.499	-1	-1	[-5 3]	[-5 2]	-1	-1	1.341	1.136
865	0.280	0.874	-2.482	-1	-1	[-3 5]	[-6 1]	-1	-1	1.340	1.136
952	0.000	-77.080	-60.107	-77	-60	[-81 -73]	[-64 -57]	-77	-60	1.341	1.136
1203	-0.172	-91.042	-69.866	-90	-70	[-95 -87]	[-73 -66]	-90	-70	1.340	1.136
1240	-0.038	-17.989	-14.438	-18	-14	[-22 -14]	[-18 -11]	-18	-14	1.340	1.136
1255	-0.056	-27.209	-21.895	-27	-21	[-31 -23]	[-25 -18]	-27	-21	1.340	1.135
1278	8.913	-36.556	-35.992	-36	-35	[-41 -33]	[-39 -33]	-36	-35	1.339	1.135
1364	0.000	-231.303	-179.217	-231	-180	[-235 -227]	[-183 -176]	-231	-180	1.339	1.135
1372	0.014	8.816	7.559	9	7	[5 13]	[4 11]	9	7	1.339	1.135
1468	-0.015	-9.358	-5.453	-9	-7	[-13 -5]	[-9 -2]	-9	-7	1.338	1.135
1542	5.566	1.863	-1.744	3	-2	[-2 6]	[-5 2]	3	-2	1.338	1.135
1543	9.001	9.130	1.354	9	0	[5 13]	[-2 5]	9	0	1.338	1.135
1665	-1.126	4.493	3.899	4	4	[0 9]	[0 7]	4	4	1.337	1.135

Table 3. Cycles Detection of 10s Sampling

Epoch	$\Delta\phi$	ΔN_1	ΔN_2	Add cycle slip		Region		Detection		m_1	m_2
				ΔN_1	ΔN_2	ΔN_1	ΔN_2	ΔN_1	ΔN_2		
50	-13.708	-2.860	7.381	-6	6	[-7 2]	[4 11]	-6	6	1.457	1.249
104	-1.302	0.292	1.529	0	1	[-4 5]	[-2 5]	0	1	1.460	1.249
172	0.278	-1.001	0.240	-1	-1	[-5 3]	[-4 4]	-1	-1	1.459	1.249
173	0.003	308.860	240.156	308	240	[304 313]	[236 244]	308	240	1.458	1.249
190	-0.010	-151.869	-123.147	-154	-120	[-156 -147]	[-127 -119]	-154	-120	1.458	1.248
201	0.703	0.069	3.282	2	1	[-4 4]	[0 7]	2	1	1.459	1.252
203	-8.424	-1.520	5.314	-2	5	[-6 3]	[2 9]	-2	5	1.459	1.253
281	0.268	-1.884	-0.735	-1	-1	[-6 2]	[-4 3]	-1	-1	1.458	1.253
391	0.278	-0.541	0.124	-1	-1	[-5 4]	[-4 4]	-1	-1	1.458	1.252
419	0.000	-78.090	-60.633	-77	-60	[-82 -74]	[-64 -57]	-77	-60	1.457	1.252
464	-0.169	-89.613	-70.467	-90	-70	[-94 -85]	[-74 -67]	-90	-70	1.457	1.251
472	-0.031	-17.958	-11.868	-18	-14	[-22 -14]	[-16 -8]	-18	-14	1.456	1.251
511	-0.052	-25.536	-21.917	-27	-21	[-30 -21]	[-26 -18]	-27	-21	1.455	1.252
532	8.906	-34.948	-34.843	-36	-35	[-39 -31]	[-39 -31]	-36	-35	1.455	1.252
584	-0.017	-230.238	-178.378	-231	-180	[-235 -226]	[-182 -175]	-231	-180	1.455	1.251
593	-0.002	8.161	6.086	9	7	[4 13]	[2 10]	9	7	1.454	1.252
675	-0.019	-11.216	-7.378	-9	-7	[-16 -7]	[-11 -4]	-9	-7	1.454	1.251
678	5.568	3.639	-3.518	3	-2	[-1 8]	[-7 0]	3	-2	1.455	1.251
784	9.008	9.245	-0.012	9	0	[5 14]	[-4 4]	9	0	1.454	1.251
817	-1.125	5.032	4.122	4	4	[1 9]	[0 8]	4	4	1.453	1.250

detected by this method are completely consistent with those artificially added. According to the statistics in Table 6, the success rate of experimental detection is 100%;

4. From Table 5 that the detection success rate is above 98.75% for random cycle slip combination of random epoch;
5. The update of standard deviation of ΔN_1 and ΔN_2 series can

Table 4. Cycles Detection of 15s Sampling

Epoch	$\Delta\phi$	ΔN_1	ΔN_2	Add cycle slip		Region		Detection		m_1	m_2
				ΔN_1	ΔN_2	ΔN_1	ΔN_2	ΔN_1	ΔN_2		
74	-13.728	-5.433	8.196	-6	6	[-10 -1]	[4 12]	-6	6	1.554	1.355
111	-1.286	-0.753	-0.711	0	1	[-5 4]	[-5 3]	0	1	1.553	1.357
131	0.259	-3.594	-1.372	-1	-1	[-8 1]	[-5 3]	-1	-1	1.552	1.357
135	-0.020	308.049	242.723	308	240	[303 313]	[239 247]	308	240	1.554	1.356
142	-0.016	-149.899	-120.821	-154	-120	[-155 -145]	[-125 -117]	-154	-120	1.553	1.360
158	0.701	2.005	2.834	2	1	[-3 7]	[-1 7]	2	1	1.561	1.359
225	-8.423	-3.185	6.719	-2	5	[-8 1]	[3 11]	-2	5	1.559	1.360
232	0.277	-2.252	-0.702	-1	-1	[-7 2]	[-5 3]	-1	-1	1.559	1.361
257	0.279	-1.902	0.438	-1	-1	[-7 3]	[-4 5]	-1	-1	1.558	1.360
268	-0.005	-75.053	-58.905	-77	-60	[-80 -70]	[-63 -55]	-77	-60	1.558	1.360
291	-0.173	-91.625	-71.233	-90	-70	[-96 -87]	[-75 -67]	-90	-70	1.558	1.359
293	-0.031	-20.308	-13.249	-18	-14	[-25 -16]	[-17 -9]	-18	-14	1.558	1.359
322	-0.051	-26.069	-20.929	-27	-21	[-31 -21]	[-25 -17]	-27	-21	1.560	1.358
333	8.917	-36.700	-36.565	-36	-35	[-41 -32]	[-41 -32]	-36	-35	1.559	1.357
358	-0.009	-230.466	-180.346	-231	-180	[-235 -226]	[-184 -176]	-231	-180	1.558	1.358
437	0.011	11.920	7.048	9	7	[7 17]	[3 11]	9	7	1.557	1.356
455	-0.026	-10.894	-7.998	-9	-7	[-16 -6]	[-12 -4]	-9	-7	1.560	1.355
462	5.555	2.651	-4.134	3	-2	[-2 7]	[-8 0]	3	-2	1.561	1.355
539	9.004	9.149	1.424	9	0	[4 14]	[-3 5]	9	0	1.560	1.357
573	-1.104	4.323	4.008	4	4	[0 9]	[0 8]	4	4	1.558	1.357

Table 5. Comparison Statistics of Detection Success Rate with Fixed Cycle Slip on Random Epoch

Sampling interval	Epoch number	Cycle slip number	Success	Failed	Success rate (%)
1 s	9000	20	20(18)	0(2)	100(90)
5 s	1800	20	20(19)	0(1)	100(95)
10 s	900	20	20(16)	0(4)	100(80)
15 s	600	20	20(15)	0(5)	100(75)

Note: The brackets indicate the results of Method TurboEdit

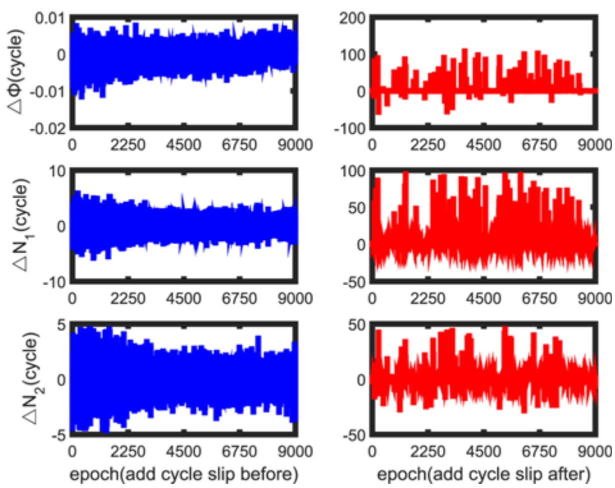

Fig. 8. Add Random Cycle Slip on Random Epoch before and after of 1s Sampling

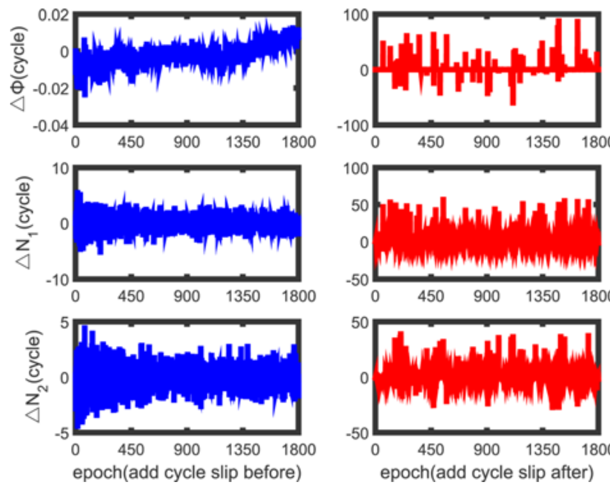

Fig. 9. Add Random Cycle Slip on Random Epoch before and after of 5s Sampling

adjust the size of calculation space in time. From the added small cycle slips such as (0, 1), (-1, -1) or (2, 1), when its value is equal to or less than the standard deviation of the series, the method in this paper can still accurately detect cycle slips. Compared with the TurboEdit method, this method has a better success rate within sampling intervals of 1s, 5s, 10s, and 15s.

6. The method in this paper can also accurately detect the special type of cycle slips, such as (9, 7) or (77, 60).

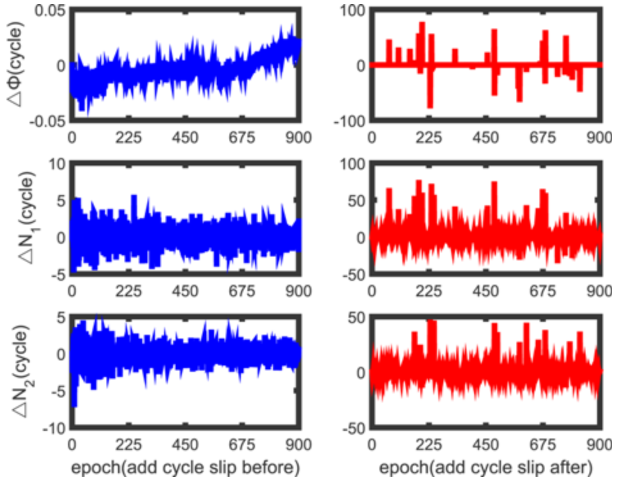

Fig. 10. Add Random Cycle Slip on Random Epoch before and after of 10s Sampling

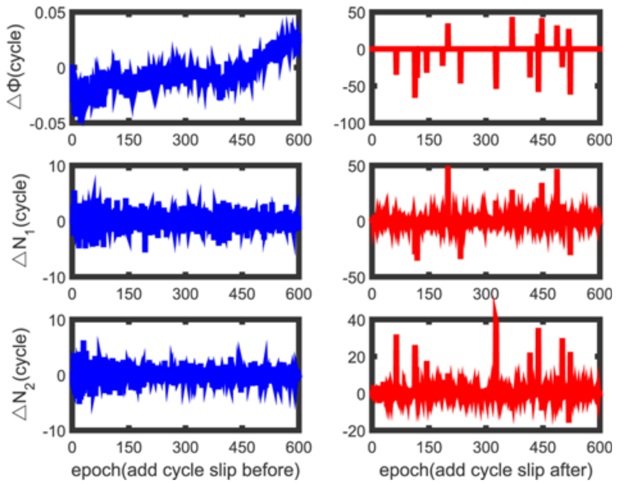

Fig. 11. Add Random Cycle Slip on Random Epoch before and after of 15s Sampling

Table 6. Comparison Statistics of Detection Success Rate with Random Cycle Slip on Random Epoch

Sampling interval	Epoch number	Cycle slip number	Success	Failed	Success rate (%)
1 s	9,000	100	100(98)	0(2)	100.00(98)
5 s	1,800	80	79(76)	1(4)	98.75(95)
10 s	900	30	30(27)	0(3)	100.00(90)
15 s	600	20	20(18)	0(2)	100.00(90)

Note: The brackets indicate the results of Method TurboEdit

7. Conclusions

In this paper, the dynamic test method is proposed for dual-frequency GPS cycle slip detection and repair. Based on the analysis and results of test data at four different sampling intervals, some conclusions are drawn as follows:

1. Adopt $\Delta\phi = \Delta N_1 - (\lambda_2/\lambda_1)\Delta N_2$, the cycle slip value can be uniquely determined with constraints based on the integer property of cycle slip to avoid multi-value problems;
2. Update the standard deviation of sequence ΔN_1 and ΔN_2 weakens the influence of outliers by constantly repairing cycle slips, constrains the range of cycle slips of dual-frequency, and avoids the problem of noise submergence in observations;
3. The dynamic test method can not only detect the location of the cycle slip, but also calculate the size of the cycle slip;
4. The dynamic test method in this paper can accurately detect the cycle slips, whether they are ordinary cycle slips or (9,7) or (77,60) cycle slips, large cycle slips or small cycle slips;
5. The analysis of experiment shows that for the data with the sampling rate less than 15s, whether the fixed cycle slip is added at the random epoch or the random cycle slip is added at the random epoch, the detection accuracy is high, and the experiment detection success rate is above 98.75%.

In addition to GPS, multi constellation, such as BDS, GALILEO and GLONASS, multi frequency combination can be considered for subsequent research and different confidence levels. In the algorithm design, in addition to the sampling rate, the influence of satellite altitude angle and cycle slip detection of less than full cycle can be considered.

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