International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-7 Issue-3, February 2018

New Scenario for GPS Cycle Slips Detection and Fixation Using Single Frequency Data

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Abstract— GPS high accuracy applications are based on the phase measurements. Such phase measurements are frequently subjected to cycle slips. So, special attention should be paid to the detection and fixation of cycle slips. Previous works concerned with this issue dealt with single frequency data was faced with the low sensitivity of these models as most of them are based on differencing the change in both code and phase differences between consecutive epochs. Although the resulted test quantity is free of most GPS biases, it is contaminated by twice the ionospheric error due to its opposite sign in both code and phase equations.

In this paper, a new test quantity is proposed. This test quantity, which was denoted as CPR, is defined as the ratio between the code and phase differences between consecutive epochs. CPR values exhibited very smooth manner between consecutive epochs. Different simulated cycle slips are introduced to different data sets. CPR graphs yielded detection sensitivity of one cycle for sampling rates up to 15 seconds and two cycles for higher sampling rates (up to 30 seconds).

Concerning the fixation process, two scenarios are introduced in this paper which are backward and forward scenarios. In backward scenario, the 1st corrupted CPR value is estimated. This estimated CPR is used backwardly to get the number of the slipped cycles by estimating the phase difference between the epoch of cycle slip and its preceding epoch. The same scenario was followed forwardly by estimating the 2nd corrupted CPR and going by it in a forward model. Both scenarios yielded slightly different float solutiosn and the same fixed solutions. Finally, estimating the corrupted CPR values was tried using weighted mean of uncorrupted CPR values. Weighting of CPR is taken inversely proportional to the time gap between the estimated and the used values. Results proved that weighting of the most recent seven CPR values yielded the best float solution in both backward and forward scenarios.

Index Terms—Cycle slips, Single frequency data, Code/Phase Ratio (CPR), Detection sensitivity, Fixation reliability.

I. Introduction

GPS phase observations can be subjected to the well-known phenomena of cycle slips. In this case, the GPS receiver losses, instantaneously, the tracking of the GPS satellite signals. Accordingly, the initial number of complete cycles (which is known as phase ambiguity) will be no longer constant [1]. This will certainly affect the correctness of the derived positions. So, any GPS phase data should be clear of any cycle slips before entered into any further processing. Otherwise, any undetected cycle slip will significantly degrade the accuracy of the GPS position solution [2].

Many previous works were concerned with the issue of the identification and fixation of cycle slips. The main differences among such works are based on the type of the used data, mathematical formulation, and existence of any previous data like some old control points…etc. [e.g. 3, 4 and 5]. In general, the main challenge in the treatment of cycle slips is the ability of performing such task with minimum requirements and also with maximum reliability. In this context, a minimum requirement means that the thought technique should have the ability of treating cycle slips with minimal data as the case of using single frequency receivers.

Treatment of cycle slips becomes more and more important, especially with the fast widespread of GPS RTK applications. This is due to the continuous motion of the rover receiver which makes it more subjected to loss the signal tracking. The situation becomes more complicated with high dynamics of rover receiver [6].

Previous works achieved very high reliability of fixing cycle slips up to an accuracy of only one cycle. Some of these works are based on applying both carriers (L_1 and L_2) in the determination of the number of the slipped cycles [e.g. 7 and 8], whereas some other works are based on some prediction algorithms that can not be applied in real time [9]. Overcoming these two drawbacks is considered here the main goal of this work. In this paper, another new scenario for treatment of cycle slips is introduced. Such new scenario is based on using single frequency data and it is proposed to have the ability to be applied in real time. Also, the correctness of the introduced scenario will be checked, to judge its degree of confidence, using simulated cycle slips of known values. This is to have the ability of comparing the computed number of the slipped cycles (by applying the introduced scenario) with its corresponding known values (simulated). Finally, the proposed scenario will be checked in different observational environments.

II. Evaluation of the Traditional Approaches of Cycle Slips Detection and Fixation Using Single Frequency Data

Many different techniques are available for detection and fixation of GPS cycle slips using single frequency data [e.g. 3, 9 and 10]. Such techniques are based on comparing both code and carrier measurements in absolute or relative modes. Then, any observed abrupt change in the computed code-carrier differences are diagnosed as cycle slips in the phase data [10]. This is due to the fact that the code observations are immune against cycle slips.

Manuscript published on 28 February 2018.
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It is well known that the efficiency of any approach of cycle slips detection and treatment can be expressed in two complementary ways. First, the ability of the approach to diagnose the occurrence of cycle slips. Second, the reliability of the number of the slipped cycles determined by such approach. In this context, it was of great importance to evaluate the current situation concerning the efficiency of the existing approaches that are based on single frequency data. This can be considered the starting point of introducing the proposed scenario which should, of course, be based on the identified shortcomings in the current approaches. To achieve this goal, 30 minutes of GPS single frequency data are used. Such data were collected using sampling rate of 30 seconds.

Of course, evaluation of the efficiency of any technique of treating cycle slips should be started by its ability of detection. This is due to the fact that any cycle slips treatment algorithm will never start the treatment process unless it detected the existence of any cycle slips [11]. Accordingly, in this stage, the classical application of GPS single frequency data will be tested in the detection process. Here, three different trials were performed to check the ability of the classical implementation of both code and phase data in the detection process. In each trial, the adopted test quantity is plotted against time. Such test quantity is based on raw phase and/or code or any of their derivatives. Also, for each used trial, four simulated cycle slips are introduced on the used data. Characteristics of the used trials, as well as the introduced cycle slips, are given in table (1).

Table (1)
Characteristics of the used traditional tests

Trial No.	Used test quantity	No. of simulated slipped cycles	Time of cycle slip (hr min sec)
1	Raw phases	10	8 30 00
		1000	8 36 00
		100000	8 42 00
		1000000	8 48 00
2	Phase differences	50	8 30 00
		100	8 36 00
		250	8 42 00
		500	8 48 00
3	Difference between change in code and scaled phase	2	8 30 00
		3	8 36 00
		5	8 42 00
		10	8 48 00

The performed three trials will be discussed in the following three sub-sections.

A. Trial (1): Applying raw phase data:

In this trial, the behavior of the raw phase observations is studied against time. Cycle slips can be diagnosed by an observed sudden change in the drafted time-phase relation [1]. Referring to table (1), four simulated cycle slips are performed on the phase data, with values range from 10 to 10^6 cycles. Behavior of both original and slipped phases is drafted in figure (1).

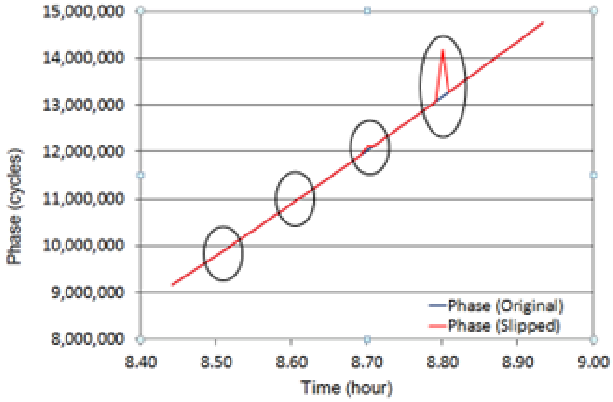

Fig. 1. Results of the 1st trial

Fig. (1) indicates that the first two cycle slips, whose values were 10 and 1000 cycles, were not observed. The 3rd cycle slip (with value 100,000 cycles) can be observed hardly. Finally, the 4th cycle slip (1 million cycles) is the only one that can be observed easily. This expected very low sensitivity can be interpreted by the large variations in the measured phases between consecutive epochs. This large variation makes the observation of cycle slips very hard unless it happened with very huge number of cycles.

B. Trial (2): Applying phase differences between consecutive epochs:

In this trial, the difference between measured phases is applied instead of the very high fluctuating raw observed phases. This is to attain a smoother test quantity that is proposed to have higher sensitivity in monitoring cycle slips. Referring again to table (1) four cycle slips are performed here with values range from 50 to 500 cycles. Differences in phases are computed between each two consecutive epochs and drafted against time. The resulted two graphs, for both original and slipped phases, are drafted in figure (2).

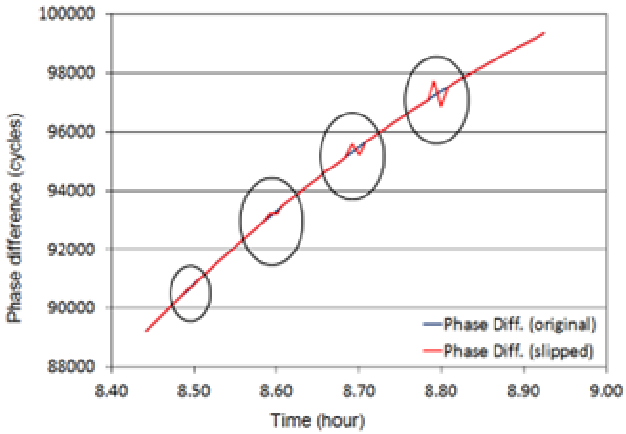

Fig. 2. Results of the 2nd trial

By observing figure (2) it can be seen that applying the phase differences as a test quantity increases the sensitivity of the cycle slip detection to a certain extent. Slips of 250 and 500 cycles are diagnosed on the figure by the shown spark (sudden raise followed by sudden drop). On the other hand, the first two simulated slips (whose values were 50 and 100 cycles) were not observed.

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It can be said that the sensitivity here is higher than trial (1) as the phase differences are smoother than raw phases. On the other hand, the achieved sensitivity, which is in the order of 250 cycles, is still very low. This is due to the fact that the differential biases, between consecutive epochs, are relatively high.

C. *Trial (3): Applying the difference between change in codes and scaled phases*

Here, the test quantity is formed by subtracting the change in measured codes from the change in the measured phases (after scaling it by the L_1 wavelength). This can formed mathematically as [9]:

$$(T.Q.)_3 = \lambda \times \Delta\varphi_{t_{i+1}}^{t_i} - \Delta C_{t_{i+1}}^{t_i} \qquad (1)$$

Where:

$(T.Q.)_3$	Adopted test quantity in trial (3)
λ	Wavelength of carrier L_1
$\Delta\varphi_{t_{i+1}}^{t_i}$	Difference in phases between two consecutive epochs i and i+1 (expressed in cycles)
$\Delta C_{t_{i+1}}^{t_i}$	Difference in codes between two consecutive epochs i and i+1

Equation (1) was applied twice for both the original phases and the simulated slipped cycles. Results are depicted in figure (3).

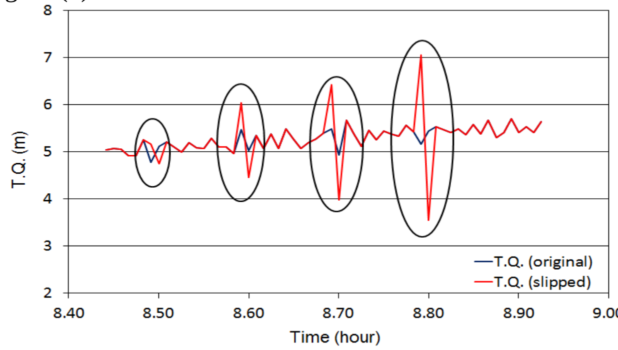

Fig. 3. Results of the 3rd trial

Based on figure (3) it is evident that the application of the 3rd test quantity increases the sensitivity of the detection process. Slips of 5 and 10 cycles are diagnosed very clearly. However, the first two slips (2 and 3 cycles) were not recognized. This can be easily referred to the residual biases between both code and phase differences, especially the ionospheric effect which has opposite sign in code and phase equations [6]. This means that the used test quantity (equation 1) is contaminated by twice the ionospheric effect. This doubled ionospheric effect degrades the sensitivity to the order of 5 cycles. As a closing remark, and based on the obtained results of the three performed trials, the traditional application of the GPS single frequency data can achieve a detection sensitivity in the order of 5 cycles. Such accuracy is not accepted by many GPS high accuracy applications. So, a better sensitivity is required to be achieved, which is the main goal of this paper.

III. PROPOSED SCENARIO FOR CYCLE SLIPS TREATMENT USING GPS SINGLE FREQUENCY DATA

As mentioned before, the main goal of this paper is to achieve the highest possible sensitivity and accuracy in the two processes of cycle slips detection and fixation. To achieve this goal, a newer test quantity should be formed. Such test quantity will be the key for both the detection process (by observing an odd value in it) and in the fixation process (by estimating a reliable value for it in the case of cycle slips). So, the thought test quantity should satisfy the following properties:

- Has a fairly smooth behavior with time.
- Small cycle slip values are reflected in it with fairly large values.
- It can be interpolated easily (for the fixation process).

Here, a new test quantity is established to be matched with the above mentioned properties. This test quantity can be obtained by some slight modifications for the used third test quantity $(T.Q.)_3$, defined by equation (1). Recalling that the main drawback of the used test quantity in trial (3) is the relatively high ionospheric residual, which equals the sum of ionospheric effects of both phase and code measurements. To avoid this high ionospheric residual in equation (1), a new test quantity is performed by finding the ratio between the code difference and the phase difference (in cycles). This test quantity will be named Code/Phase Ratio, and denoted as CPR. Mathematically, the new test quantity CPR can be expressed as:

$$CPR = \frac{\Delta C_{t_{i+1}}^{t_i}}{\Delta\varphi_{t_{i+1}}^{t_i}} \qquad (2)$$

Where:

CPR	New established test quantity (expressed in meters)
$\Delta C_{t_{i+1}}^{t_i}$, $\Delta\varphi_{t_{i+1}}^{t_i}$	As defined in equation (1)

By noticing equation (2) it can be seen, from the theoretical point of view, that the introduced new test quantity in nothing else the wave length of the carrier signal. Consequently, in the absence of cycle slips, the CPR values should have very slight variations between consecutive epochs. Even in the case of very bad ionospheric conditions (like ionospheric scintillations), CPR changes will follow a smooth pattern. Another very important advantage of the established CPR is that the opposite sign of the ionospheric effect for both code and phase measurements is no longer critical as the case in equations (1). Whatever the value of the ionospheric effect for both code and phase, they will be reduced in equation (2) through the division process.

IV. TESTING THE SENSITIVITY OF CPR IN THE DETECTION PROCESS

After introducing the new test quantity (CPR), it is very important to check its sensitivity in the monitoring of cycle slips before going through the fixation process. Recalling that the difference between scaled phase and code differences (test quantity 3) failed in the detection of cycle slips with values less than 5 cycles, the sensitivity of the CPR will be checked for slips less than 5 cycles.

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In this test, 4 different simulated cycle slips are introduced with values 1, 2, 3 and 4 cycles. CPR values are computed using both original and slipped phases. Results are drafted in figure (4).

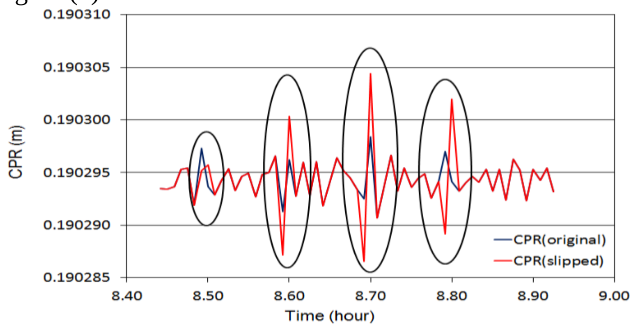

Fig. 4. CPR values for original and slipped phases (Sampling rate 30 seconds)

Based on figure (4) it is evident that the new established test quantity (CPR) can detect cycle slips of small values. Slips of 2, 3 and 4 cycles can be observed very clearly in figure (4). However, the smallest possible cycle slip (with value of only one cycle) was not monitored in figure (4). This can be referenced to the fact that variations in the CPR, in the used data, are higher than that caused by only one cycle. Such relatively high variations can be a direct reflection of the relatively high used sampling rate (30 seconds). So, the sensitivity of the CPR in detecting cycle slips should be tested using smaller sampling rates.

V.EFFECT OF SAMPLING RATE ON THE SENSITIVITY OF CPR IN THE DETECTION PROCESS

As mentioned before, and referring to equation (2), the new established test quantity (CPR) can be interpreted physically as the wavelength of the carrier signal L_1. From the theoretical point of view, this wave length has constant value. Actually, this value is changing according to many observational conditions, especially the degree of both tropospheric and ionospheric activities [1]. This is the main reason behind the obtained fluctuations in CPR values. In the initial evaluation of the CPR, these fluctuations prevent the detection of cycle slips less than 2 cycles. Considering smaller sampling rate, lower fluctuations in CPR values can be achieved. This will certainly lead to higher detection sensitivity. To test the effect of shrinking the sampling rate on the sensitivity of the cycle slips detection process, another GPS data set is used. Such data set was collected using a sampling rate of 1 second. A simulated cycle slip of only 1 cycle is applied on this data (at time 12hr 26min 49sec) and the CPR values are computed for both the original and slipped phases. Resulted CPR values are drafted in figure (5).

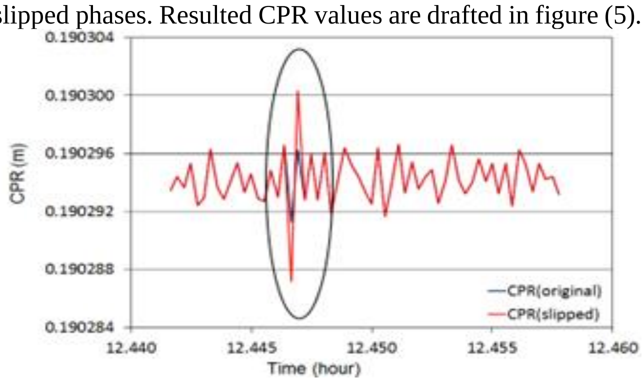

Fig. 5. CPR values for original and one cycle slipped phases (Sampling rate 1 second)

From figure (5) it is very evident that the most critical cycle slip (whose value is only one cycle) can be monitored very easily, on the CPR graph, when using a sampling rate of 1 second. This is due to the larger similarity in error budget between consecutive epochs which is reflected by smaller range of fluctuation in CPR values.

To finalize the issue of the detection process using CPR, it is very necessary to check the sensitivity for different sampling rates between the previously tested values (which were 1 and 30 seconds) for the case of critical cycle slip (one cycle). Also, it is important to check the ability of CPR to detect critical cycle slips during different times of the day. To achieve this goal, a simulated slip of only one cycle was applied to different data sets with sampling rates between 1 and 30 seconds, collected at different times along the day. Each time, CPR values are computed and drafted against time to check its ability to monitor the cycle slip occurrence. Results are summarized in table (2).

Table (2) CPR detection sensitivity for different sampling rates and times

Used sampling rate (seconds)	Data start time (hr min sec)	Detection of Critical cycle slip (one cycle)	
		Detected	Not detected
1	12 26 30	√	
2	15 26 30	√	
3	18 26 30	√	
5	21 26 30	√	
10	00 26 30	√	
15	03 26 30	√	
20	06 26 30		√
30	08 26 30		√

Based on the obtained results in table (2) it can be stated that, the application of the established CPR values can monitor the occurrence of the most critical cycle slip (whose value is one cycle) for sampling rates up to 15 seconds. Beyond this sampling rate (and up to 30 seconds), sensitivity of CPR graph degraded to the level of two cycles. No higher sampling rates were tested in this paper as the higher most commonly used sampling rate is 30 seconds.

VI. FIXATION OF CYCLE SLIPS USING CPR

After assessing the sensitivity of the CPR in the cycle slips detection process, its application in the fixation process should be studied and evaluated. The fixation process here is meant by the determination of the number of the slipped cycles (for the case when a cycle slip is already diagnosed). In addition, the evaluation stage is meant by judging the reliability (correctness) of the estimated number of the slipped cycles. Starting the fixation process should start by considering any GPS single frequency data set infected with a cycle slip at a certain epoch (say epoch no. 4). This cycle slip will corrupt two phase differences (between epochs 3, 4 and epochs 4, 5). The resulted two corruptions will have same values and opposite signs. Consequently, and referring to equation (2), the corresponding two CPR values will be corrupted in the same manner. This is illustrated in the following thematic table (table 3). In this table, red cells indicate corrupted data.

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Table (3)*
Corrupted data in the case of cycle slip occurrence

Epoch No.	Code	Phase	Δ code	Δ phase	CPR
1	C_1	ϕ_1			
			ΔC_{12}	$\Delta \phi_{12}$	CPR_{12}
2	C_2	ϕ_2			
			ΔC_{23}	$\Delta \phi_{23}$	CPR_{23}
3	C_3	ϕ_3			
			ΔC_{34}	$\Delta \phi_{34}$	CPR_{34}
4	C_4	ϕ_4			
			ΔC_{45}	$\Delta \phi_{45}$	CPR_{45}
5	C_5	ϕ_5			
			ΔC_{56}	$\Delta \phi_{56}$	CPR_{56}
6	C_6	ϕ_6			
			ΔC_{67}	$\Delta \phi_{67}$	CPR_{67}
7	C_7	ϕ_7			

**N.B. Thematic table*

As mentioned before, the detection process here is based on the monitoring of any abrupt changes in the CPR graph as it was found the most smooth test quantity. Consequently, in the case of cycle slip occurrence, the fixation process should start by the estimation of the most reliable values for the two corrupted CPRs (as it seen by table 3). Actually, the estimation of only one value of the two corrupted CPRs can lead to the determination of the number of the slipped cycles. If a reliable value for the 1st corrupted CPR is estimated, a backward computational scenario can be followed to get the phase difference and then the actual phase. The same can be done using forward scenario if the 2nd corrupted CPR is estimated. However, in this paper, both backward and forward scenarios will be followed. So, two different independent solutions will be available for the number of the slipped cycles. Averaging of the two solutions will certainly enhance the final solution.

As a first solution, the CPR is estimated as the average of the last two correct CPR values before the slip occurrence, whereas the 2nd estimation for the CPR is the average of the first two correct CPR values after the slip occurrence. This can be expressed as:

$$CPR^{t_{i-1}}_{t_i} = \frac{CPR^{t_{i-3}}_{t_{i-2}} + CPR^{t_{i-2}}_{t_{i-1}}}{2} \quad (3)$$

$$CPR^{t_i}_{t_{i+1}} = \frac{CPR^{t_{i+1}}_{t_{i+2}} + CPR^{t_{i+2}}_{t_{i+3}}}{2} \quad (4)$$

Where:

$CPR^{t_{i-1}}_{t_i}$ Estimated CPR between the epoch of cycle slip and its preceding epoch.

$CPR^{t_i}_{t_{i+1}}$ Estimated CPR between the epoch of cycle slip and its next epoch.

t_i Epoch of cycle slip

The first estimated CPR (equation 3) is used backwardly to get an estimated value for the measured phase at the epoch of cycle slip. Comparing this estimated value with the measured (slipped) one yields a float value for the number of the slipped cycles. This float value is approximated to the nearest integer. The same scenario is followed forwardly using the second estimated CPR (equation 4) to get the number of the slipped cycles. Finally, the two solutions are averaged to get the most reliable value for the number of the slipped cycles.

To check the validity of the above discussed technique, a simulated cycle slip of one cycle is applied to six data samples with different sampling rates (1, 2, 3, 5, 10 and 15 seconds). For each data set, after the detection of cycle slip, equations (3) and (4) are applied and the above scenario was followed to get the number of the slipped cycles using both forward and backward models. The final solution is then computed as the average of the fixed two solutions. Results are summarized in table (4).

Table (4)
Results of the fixation process for different sampling rates (Using the nearest two uncorrupted CPR)

Sampling rate (sec)	Backward model (cycles)		Forward model (cycles)		Final solution
	Float	Fixed	Float	Fixed	
1	0.81	1	0.79	1	**1**
2	0.78	1	0.88	1	**1**
3	0.80	1	0.82	1	**1**
5	0.68	1	0.73	1	**1**
10	0.70	1	0.69	1	**1**
15	0.64	1	0.68	1	**1**

Referring to table (4) and by observing the final solution (last column) it can be seen that all cycle slips are fixed successfully. However, it can be seen also that the float solutions are not stable, especially for the high sampling rates. For example, the float solution of the backward model yielded a value of 0.64 cycles for the sampling rate 15 seconds. This result did not affect the final solution as it was approximated to its nearest integer (which is 1). However, this value is not accepted to a large extent as its difference from the one cycle is relatively high. In other words, if the resulted float solution dropped under 0.5 cycles, it will be approximated to its nearest integer (zero), which is wrong fixation. So, although the previous table indicates a complete success in the fixation process, final trial will be performed to enhance the quality of the float solution.

VII. INCREASING THE ACCURACY OF THE FLOAT SOLUTION THROUGH WEIGHTING CPR VALUES WITH TIME

Referring to figures (4 and 5) it is very evident that CPR values are fluctuating in a random pattern. So, in both forward and backward models, it is not suitable to consider only two CPR values (equations 3 and 4) in the estimation of the number of the slipped cycles. Instead, the CPR value will be estimated as the weighted mean of some previous CPR values (in the case of backward estimation) or some next CPR values (in the case of forward estimation). Of course, each used CPR value should be weighted inversely to the time gap between its time and the epoch of cycle slip occurrence.

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This implies higher weights for CPR values just before and after the corrupted two CPR values. For both backward and forward models, weighted CPR values can be expressed, respectively, as:

$$CPR_{t_i}^{t_{i-1}} = \frac{\sum_{j=(i-1)}^{j=n} W_j^{j-1} \times CPR_j^{j-1}}{\sum_{j=(i-1)}^{j=n} W_j^{j-1}} \quad (5)$$

$$CPR_{t_{i+1}}^{t_i} = \frac{\sum_{j=(i+1)}^{j=n} W_{j+1}^{j} \times CPR_{j+1}^{j}}{\sum_{j=(i+1)}^{j=n} W_{j+1}^{j}} \quad (6)$$

Where:

$CPR_{t_i}^{t_{i-1}}$	Estimated CPR (backward model)
$CPR_{t_{i+1}}^{t_i}$	Estimated CPR (forward model)
W_j^{j-1}	Weight of the CPR, computed between the two epochs (j-1) and (j)
n	Number of CPRs considered in the solution

In equations (5) and (6) the adopted weight (W_j^{j-1}) is expresses as:

$$W_j^{j-1} = \frac{1}{k \times SR} \quad (7)$$

Where:

k	Number of epochs between the used and estimated CPR values.
SR	Sampling rate

Equations (5) and (6) are used to estimate the CPR values for both backward and forward mathematical scenarios. The same used six data samples in the previous test are used (table 4). For all data sets, ten CPR values are considered. Five of these ten values are selected as the last five values before the first corrupted CPR (backward) and the remaining five values are selected as the first five values after the second corrupted CPR (forward). Results are summarized in table (5).

Table (5)
Results of the fixation process for different sampling rates (Using weighting of the nearest five uncorrupted CPR)

Sampling rate (sec)	Backward model (cycles)		Forward model (cycles)		Final solution
	Float	Fixed	Float	Fixed	
1	0.91	1	0.89	1	**1**
2	0.88	1	0.88	1	**1**
3	0.87	1	0.85	1	**1**
5	0.90	1	0.81	1	**1**
10	0.92	1	0.86	1	**1**
15	0.79	1	0.80	1	**1**

Although the final solution of the fixation process in table (5) is the same as that of table (4), there is a very significant enhancement in the reliability of the float solutions for both backward and forward approaches. It can be noted that all the resulted float solutions in table (5) are much closer to the true number of the slipped cycles (one simulated cycle slip). So, weighting the CPR values inversely with time can produce higher accuracy for the fixation process.

Finally, it is of great importance to investigate the effect of the number of CPR values entered in the weighting process of CPR estimation (which is denoted by n in equations 5 and 6). Here, different numbers of CPR values are involved in the weighting process for both backward and forward scenarios. The same data sets in table (5) are used. Results are given in table (6).

Table (6)
Results of the fixation process for different sampling rates (Using weighting of different number of uncorrupted CPR)

Sampling rate (sec)	Number of used CPR values	Backward model (cycles)		Forward model (cycles)		Final solution
		Float	Fixed	Float	Fixed	
1	3	0.84	1	0.82	1	**1**
	5	0.91	1	0.89	1	**1**
	7	0.93	1	0.94	1	**1**
	9	0.85	1	0.89	1	**1**
2	3	0.81	1	0.86	1	**1**
	5	0.88	1	0.88	1	**1**
	7	0.89	1	0.90	1	**1**
	9	0.89	1	0.89	1	**1**
3	3	0.84	1	0.84	1	**1**
	5	0.87	1	0.85	1	**1**
	7	0.89	1	0.91	1	**1**
	9	0.88	1	0.91	1	**1**
5	3	0.74	1	0.75	1	**1**
	5	0.90	1	0.81	1	**1**
	7	0.91	1	0.84	1	**1**
	9	0.92	1	0.82	1	**1**
10	3	0.78	1	0.73	1	**1**
	5	0.92	1	0.86	1	**1**
	7	0.91	1	0.88	1	**1**
	9	0.90	1	0.85	1	**1**
15	3	0.67	1	0.70	1	**1**
	5	0.79	1	0.80	1	**1**
	7	0.83	1	0.85	1	**1**
	9	0.82	1	0.79	1	**1**

Based on the obtained results in table (6) it can be stated that, for all the tested sampling rates, involving larger number of CPR values in equations (5) and (6) yields higher reliability of the resulted fixations process (as the float solution approaching the unity). This significant enhancement is very clear up to using seven CPR values in the weighting process.

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Beyond this value, results are fluctuating up and down nearer and farer from the unity (when using 9 values). So, application of seven uncorrupted CPR values is considered the optimum one in estimating the number of the slipped cycles in both backward and forward fixation scenarios.

VIII. CONCLUSIONS

Based on the performed work and obtained results many important conclusions concerning the detection and fixation of cycle slips in GPS single frequency data can be extracted. These conclusions are:

- Using the raw measured phase can not detect cycle slips except that in the order of million cycles, whereas phase differences can monitor cycle slips in the order of few hundreds of cycles.
- Comparing code and scaled phase differences between consecutive epochs yields detection sensitivity in the order of 5 cycles.
- Dividing the change in code by the change in phase between consecutive epochs yields the new test quantity CPR. Such CPR is capable for monitoring cycle slips up to two cycles for sampling rate of 30 seconds.
- CPR can detect cycle slips of only one cycle for sampling rates up to 15 seconds.
- Sensitivity of CPR is independent on the time of observation within the day.
- Fixation of cycle slips using CPR can be done using backward scenario by estimating CPR corresponds to the first corrupted value and going back. The same scenario can be followed in a forward scenario by estimating the 2nd corrupted CPR value.
- In both backward and forward scenarios, averaging the nearest two uncorrupted CPR yields relatively bad results in the float solution.
- Weighting the CPR values inversely with the time produces better float solutions than that produced by averaging the nearest two values.
- Seven CPR values are optimum in the weighting process for the estimation of the corrupted CPR values.

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