World Applied Sciences Journal 8 (3): 315-325, 2010
ISSN 1818-4952

A New Approach for Cycle Slips Repairing Using GPS Single Frequency Data

Tamer F. Fath-Allah

Department of Public Works, Faculty of Engineering, Ain Shams University Cairo, Egypt

Abstract: The existing reliable algorithms of treating cycle slips are based on the implementation of GPS dual frequency data. In this paper, a new approach is introduced that can be used for single frequency data. The main idea of the proposed approach is based on the construction of the *D*ifference between *C*hange in *P*hase and *C*ode (DCPC). This DCPC value is computed by differencing the change in the satellite-receiver range, between two consecutive epochs, resulted by code and phase measurements. In the absence of cycle slips, the values of the DCPC will change smoothly from epoch to epoch. Otherwise, a cycle slip is detected. In such a case, the number of the slipped cycles can be determined using the difference between the corrupted DCPC value and the original one (which should be predicted). Eight different polynomial orders were tested to fit the values of the DCPC's. One day of observation was processed every one hour. Results showed that the 6^{th} order is the optimum one. The performance of the developed technique is analyzed through four different tests by changing different observational conditions like hour, location, year of observation and the sampling rate. Results proved that the first three conditions have no effect on the model efficiency. In the final test, results showed that decreasing the epoch interval increases the efficiency of the proposed approach. Sampling rates of 1 second and 5 seconds resulted in an ideal fixation process.

Key words: Cycle slips · Single frequency data · DCPC

INTRODUCTION

The Global Positioning System (GPS) is rapidly replacing most of the traditional surveying techniques. This is due to the great flexible conditions of operation for the system like its ability to work 24 hours per day, un-necessity of intervisibility and un-limitation for the separation between surveyed points…etc. The main concept of positioning a new point using GPS is based on the determination of four distances from this point (which should be occupied by a GPS receiver) to four GPS satellites of known locations. Then, the location of the point (or receiver) can be determined by simply applying the well-known concept of resection [1]. This idea can be applied through two main types of observations. Such two types are the pseudo-ranges (code) observations and carrier phase observations.

The accuracy of phase observations is much more than that of the code observations [2]. So, all the high-accuracy GPS geodetic applications are based on this type of observations. In these applications, to determine the distance between the ground receiver and any considered satellite, the number of complete cycles between the receiver and this satellite must be resolved. This number of complete cycles is known as initial phase ambiguity and usually denoted by N (Figure 1). This phase ambiguity remains constant unless no loss of lock takes place between the satellite and the ground receiver. This loss of lock is usually called “Cycle Slip”. This cycle slip, if not discovered and treated, will lead to wrong derived positions for the considered points. So, for any collected GPS phase data, the data

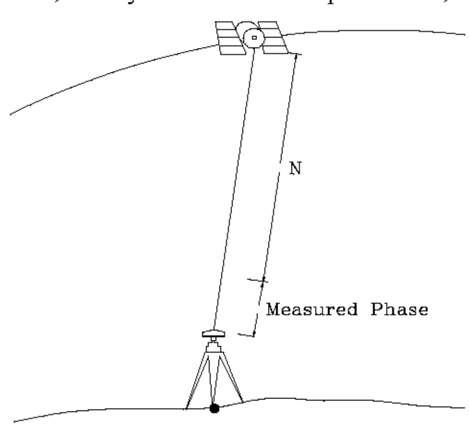

Fig. 1: Concept of Phase Observations

Corresponding Author: Dr. Tamer F. Fath-Allah, Assistant Professor of Surveying and Geodesy, Department of Public Works, Faculty of Engineering, Ain Shams University, Cairo, Egypt

must be checked against the existence of cycle slips before using such data in any further processing. Otherwise, the high accuracy of the phase derived positions may be destroyed.

The handling of cycle slips is conventionally composed of four sequential stages, which are [3]:

- Cycle slip detection, which checks the occurrence of cycle slips.
- Cycle slip determination, which quantifies the sizes of cycle slips.
- Cycle slip validation, which tests whether the cycle slips are correctly resolved.
- Cycle slip removal, which removes the cycle slips from the phase measurement.

Many researches were concerned with the handling of cycle slips, leading to many different techniques. Such developed techniques are different in their mathematical basis, required pre-requisite data, type of used GPS receiver and possibility of application in real-time. However, most of these techniques are based on using dual frequency receivers. This is to construct what so called “ionospheric residual”, which is capable of detecting cycle slips whatever its value. A cycle slip with a value of only one cycle can be detected using the ionospheric residual method [4]. So, dual and triple frequency receivers are superior in dealing with the problem of cycle slips. However, the single frequency receivers are much cheaper than these receivers. Consequently, it is of great importance to study the possibility of detecting and fixing cycle slips using single frequency GPS data. This is the main objective of the current paper.

The main objective of the current study is the establishment of the mathematical basis of the proposed technique, which is based on the range-residual method. Then, it will be tested to evaluate its ability in the two processes of detection and fixation. In other words, two main issues should be studied. First, what is the sensitivity of the proposed technique in the detection process? Second, what is the correctness of the proposed technique in the fixation process? These two questions could be answered through the current paper.

After introducing the mathematical basis of the proposed approach, its performance should be studied when varying some observation conditions. Four different tests are considered to study the effect of four different parameters on the efficiency of the proposed approach. Such parameters are the observation time, observation location, year of observation and the sampling rate.

Main Idea of Cycle Slips and Different Used Recovery Techniques: In the phase measurements, the GPS receiver, when turned on, measures the difference between the phase of the satellite transmitted carrier wave and the phase of the receiver generated replica signal in the first epoch [5]. For this first epoch, the receiver initializes an integer counter. During the tracking of the satellite, the counter is incremented by one whenever the accumulated phase changes from 2π to zero. So, for any epoch, the observed phase is the sum of the fractional phase and the above-mentioned integer counter [6]. The integer phase ambiguity (N), between the receiver and the considered satellite, is unknown. This integer ambiguity remains constant as long as no cycle slip occurs. If a cycle slip takes place during the tracking of the satellite, the integer counter is re-initialized. This will, of course, result in a sudden jump in the instantaneous accumulated phase by an integer number of cycles. This jump is the cycle slip value (Figure 2). Cycle slips are restricted only to phase measurements. In other words, code observations are immune to cycle slips [7]. This fact will be used as the key of the proposed approach.

Several causes of cycle slips may be identified. Such causes may be multi-path, receiver dynamics, low signal-to noise ratio, signal blockage and ionospheric scintillation. Any one of these reasons may be source of this type of rupture in carrier phase measurements [8]. Whatever the reason behind the cycle slip, it must be detected and treated before using such phase data in any further processing.

Several methods are now existing that can deal, reliably, with the problem of cycle slips. Most of these methods require a priori knowledge of some data, whereas some other methods are based on using dual frequency data. Generally, each method is based on some quantity, which is called

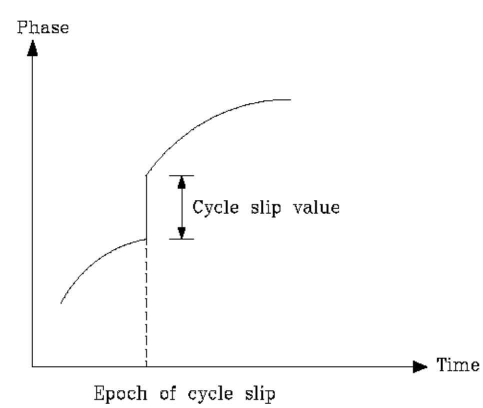

Fig. 2: Main Idea of Cycle Slip

the test quantity, to detect the existence of cycle slip. In all methods, the fixation process is always based on performing an estimation (prediction) process for a certain quantity (which is usually the test quantity or one of its derivatives). Generally, the factors that govern the choice of a certain method are: [9].

- The kind of the used receiver.
- The kind of the performed survey.
- The availability of a priori coordinates for the ground stations and/or the orbiting satellites.

The most famous methods of cycle slips detection and fixation are the ionospheric residuals method, range residual method, phase double difference and computed ranges method and a limited number of integrated combinations among these different methods.

The Main Challenges among All Different Techniques Can Be Summarized in Four Items, Which Are:

- Independency on any pre-information concerning receivers and/or satellites.
- Independency on the type of the used receiver.
- Sensitivity for small cycle slips (in the detection process).
- Reliability of the estimation (in the fixation process).

These Four Items Will Be Considered in the Proposed Approach.

Main Idea of the Proposed Technique and Mathematical Formulation: As mentioned before, the proposed technique here is based on the well-known method which called the range residual. However, some modifications are performed to reach the final form of the thought technique. The main idea here is based on the calculation of the change in the receiver-satellite distance, between each two consecutive epochs, twice. The first time using code measurements, whereas the second time using carrier phase measurements. Then, the difference between the two changes is calculated. This can be expressed mathematically by starting from the two main principle GPS observation equations as follows:

In the simplest form, the code observation equation reads:

$$P(t) = \rho(t) + \text{code error budget} + \varepsilon_p \qquad (1)$$

Where:

$P(t)$: Is the measured code (pseudo-range) between the receiver and the satellite.
$\rho(t)$: Is the geometric range between the receiver and the satellite.
ε_p: is the code measurement noise

Code Error Budget: Is the sum of all related errors (tropospheric delay, ionospheric delay, orbital error and both satellite and receiver clock biases)

Also, the simplified phase observation equation reads:

$$\phi(t) = \rho(t) + \lambda N + \text{phase error budget} + \varepsilon_\phi \qquad (2)$$

Where:

$\phi(t)$: Is the measured phase between the receiver and the satellite
N: Is the integer phase ambiguity.
λ: Is the wavelength of the carrier signal.
ε_ϕ: is the phase measurement noise.

Phase Error Budget: Is the sum of all previous related errors (with only opposite sign for the ionospheric delay)

Considering two consecutive epochs free of cycle slip (say t_1 and t_2), equations (1) and (2) can be differenced between such two epochs as:

$$\Delta P_{12} = \Delta\rho_{12} + \text{Res.code error budget} + \Delta\,\varepsilon_p \qquad (3)$$

$$\Delta\phi_{12} = \Delta\rho_{12} + \text{Res.phase error budget} + \Delta\,\varepsilon_\phi \qquad (4)$$

Where:

ΔP_{12}: Is the change in the measured codes between the two epochs t_1 and t_2.
$\Delta\phi_{12}$: Is the change in the measured phases between the two epochs t_1 and t_2.
$\Delta\rho_{12}$: Is the change in the receiver-satellite geometric range between the two epochs t_1 and t_2.

Res. Code Error Budget: Residual code biases between the two epochs t_1 and t_2 (relatively small).

Res. Phase Error Budget: Residual phase biases between the two epochs t_1 and t_2 (relatively small).

$\Delta \varepsilon_p$: Residual code measurement noise (relatively small).
$\Delta \varepsilon_\phi$: Residual phase measurement noise (relatively small).

Note here that the term (λN) was cancelled out in equation (4), when differencing equation (2) between the two considered epochs t_1 and t_2. This is only valid under the assumption that no cycle slip occurred between such two epochs.

The main idea here is based on the formulation of the test quantity, which is the difference between both the changes in the measured codes and phases. This quantity will be called Difference between Change in Phase and Code and it will be denoted as DCPC for simplicity. So, DCPC can be obtained simply by subtracting equations (3) and (4) as follows:

$$DCPC = \Delta P_{12} - \Delta \phi_{12} \qquad (5)$$

$$DCPC = \text{Res. code error budget} + \Delta\varepsilon_p - \text{Res. phase error budget} - \Delta\varepsilon_\phi \qquad (6)$$

Both equations (5) and (6) are of great importance. Equation (5) will be used to calculate the test quantity (DCPC), using the considered GPS data. On the other hand, the importance of equation (6) that it clarifies the behavior of the used test quantity. By observing the right hand side of equation (6) it can be stated that, regardless the values of the implied four terms, the resulted DCPC will change smoothly in the absence of cycle slip. This is due to the fact that all the implied terms, in the right hand side of equation (6), should vary smoothly among different consecutive epochs. In other words, all the involved quantities in the residual code error budget are nearly the same as the corresponding quantities in the phase measurements. Also, all these terms have the same sign except the ionospheric effect [10]. So, the value of the DCPC contains mainly the ionospheric effect (scaled by two) plus the other remaining very small errors and noises.

Detection of Cycle Slips Using DCPC: As mentioned before, for any set of phase data that is free of cycle slips, when plotting the variation of the DCPC against time, a fairly smooth curve should be resulted. On the other hand, if a cycle slip occurs at any epoch (say t_s), by a certain an integer number of cycles (say n), equation (4) will read:

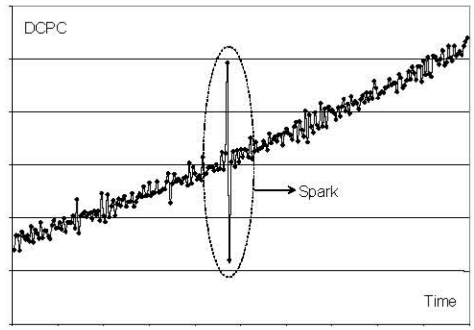

Fig. 3: DCPC Spark in case of Cycle Slip

$$\Delta\phi = \Delta\rho_{12} + \lambda n + \text{Res. phase error budget} + \Delta\varepsilon_\phi \qquad (7)$$

Consequently, Equation (6) Will Read:

$$DCPC = \text{Res. code error budget} + \Delta\varepsilon_p - \text{Res. phase error budget} - \Delta\varepsilon_\phi - \lambda n \qquad (8)$$

So, a sudden jump, followed by a sudden drop with the same value (spark) will be noticed when plotting the variation of the DCPC with time. The value of DCPC will be increased suddenly, with the value of the slipped cycles after scaled to meter units, when calculated between the two epochs t_{s-1} and t_s. Also, it will be decreased suddenly, with the same value, when calculated between the two epochs t_s and t_{s+1} (Figure 3). This spark will be used as an indicator for the occurrence of cycle slips.

Based on the above discussion it can be stated that, the detection of cycle slip in the proposed approach is based on the observation of a sudden change in the DCPC values (spark). The question arises now is *"Does any value for the cycle slip will result in an observable spark?"* In other words, to be able to detect a cycle slip using the proposed approach, its value should make a shift in the DCPC value large enough to be noticed. So, to establish the range of applicability of the proposed approach, the fluctuations of the DCPC values, in the absence of cycle slips, should be studied. This will be shown in details in section (4.2).

Fixation of Cycle Slips Using DCPC: Of course, the cycle slip fixation process does not take place unless a cycle slip is detected. In such a case, the computed two values of the DCPC will be biased or shifted with the amount of the number of the slipped cycles, scaled to meter units. So, from the theoretical point of view, the number of the slipped cycles can be obtained as the difference between the biased value of the DCPC and its original value, divided by the wavelength of the considered carrier signal L_1. However, it is not possible practically to follow this manner as the original value of the DCPC is not known.

Based on the above discussion it can be stated that, the main challenge in the proposed approach is the estimation of a reliable value for the DCPC for the case when a cycle slip is detected. Just this is done, the number of the slipped cycles can be estimated as the difference between the biased (computed) value of the DCPC and the corresponding estimated value, divided by the wavelength of the considered carrier signal L_1. Of course, this will result in a float value for the number of the slipped cycles, due to the estimation error of the value of DCPC. So, the number of the slipped cycles should be the nearest integer of the resulted float value. This can be formulated mathematically as:

$$n = \text{NINT}\left(\frac{DCPC_{comp} - DCPC_{est}}{\lambda}\right) \quad (9)$$

Where:

NINT: Is the nearest integer operator
$DCPC_{comp}$: Is the biased DCPC.
$DCPC_{est}$: Is the estimated DCPC
λ: Is the wavelength of the carrier wave L_1.

In equation (9), the computed DCPC will be the biased (shifted) one. Based on the fact that two values of the DCPC will be shifted in the case of cycle slips, equation (9) can be applied for any of these two values of the DCPC (constructed just before or just after the cycle slip occurrence).

Based on the above discussion it is very clear that, the core of the fixation process is the estimation of the value of the test quantity DCPC. So, the reliability of the proposed technique in the fixation process is controlled only by the reliability of the estimation process of the value of DCPC. As it will be shown later, different orders of polynomial (linear, 2nd degree…etc) will be tested for the estimation of the DCPC.

Evaluation of the Proposed Approach in Detection and Fixation Processes: After the formulation of the mathematical basis of the proposed approach, an evaluation process should be performed to study the efficiency of this approach for both detection and fixation processes. The efficiency of the detection process of any technique can be defined as its sensitivity to detect the occurrence of cycle slips that having small values. On the other hand, the efficiency of the fixation process can be defined as the uncertainty in the estimated number of the slipped cycles. As an example, if the estimated number of the slipped cycles is 19, with an uncertainty of 4 cycles, this means that the actual number of the slipped cycles could be any value varies from 15 to 23. So, as long as the uncertainty of any technique decreases, the fixation efficiency of this technique will be higher. In the following, a practical application for the proposed approach will be performed to explain the main idea of finding out the sensitivity and uncertainty of the proposed approach.

Validation of the Used Data: In this research, many GPS data sets, collected at different locations, different times and using different receivers are used. Although the main task of this paper is the handling with GPS single frequency data, all the used data were gathered using GPS dual frequency receivers. This is to guarantee that the used data is free of cycle slips by applying the ionospheric residual detection method. After the data passed this test, it will be handled as it is single frequency data.

To validate the used data, the ionospheric residual cycle slip detection method was applied. The test quantity here (ionospheric residual) can be calculated as:

$$d\varphi = \varphi_1 - \frac{f_1}{f_2} * \varphi_2 \quad (10)$$

Where:

$d\varphi$: Is the ionospheric residual.
φ_1: Is the measured carrier phase for L_1.
φ_2: Is the measured carrier phase for L_2.
f_1: Is the frequency of the carrier signal L_1.
f_2: Is the frequency of the carrier signal L_2.

The behavior of the change in the ionospheric residual, computed between consecutive epochs, is very smooth with time. Even a cycle slip of only one cycle can be detected easily as a sudden change in the ionospheric residual - time curve, with a value of 0.284 L_1 cycle [11]. A simple C^{++} program was prepared to calculate the ionospheric residuals for all the used data. The output of this program is the change in the ionospheric residual between each two consecutive epochs. A threshold of 0.284 L_1 cycle is fixed in the program as an indicator for the occurrence of cycle slips. All the used data are passed through this program and no cycle slips were detected. At this stage, all the used data will be processed as single frequency GPS data.

Sensitivity of the Detection Process: As mentioned before, to detect a cycle slip using the proposed approach, its value should make a shift in the DCPC value large enough to be identified. In other words, the cycle slip should bias the DCPC with a value greater than its normal variation. So, the main concern in the detection process is the difference between the consecutive DCPC values, not the DCPC values themselves.

Considering that a cycle slip occurred, at a certain epoch, with a value of only one cycle. Then, two DCPC values will be shifted with one scaled cycle. One DCPC value will be shifted up, whereas the other will be shifted down. Consequently, the change in the DCPC values will be twice the occurred cycle slip. As a result, the sensitivity of the detection process can be expressed mathematically as:

$$SEN = 1 + \frac{INT\,(\Delta DCPC_{max})}{2\lambda} \tag{11}$$

Where:

SEN: Is the sensitivity of the detection model.

$\Delta DCPC_{max}$: Is the maximum difference between two consecutive DCPC values.

INT: Is the integer operator.

The first data set in this paper was collected along one day, at station namely ASHM. However, equation (11) was applied for only one hour of observations. Recalling that these data were checked against cycle slips and it was found free of it. A computer program was written, using C^{++} programming language, to find out the values of DCPC, as well as the changes in these values, through out the selected one hour (from 9:00 am to 10:00 am). Results of the DCPC values are depicted in Figure (4), whereas the DCPC changes are given in Figure (5).

From the obtained data in Figure (5), the maximum change in the DCPC values was found to be 0.64m, observed at the time 9.8625. So, applying by the value 0.64m in equation (11), the resulted sensitivity will found to be 2 cycles. This means that the introduced algorithm is capable for the detection of any cycle slips of values of two cycles or greater. To clarify this result, a simulated cycle slip was introduced to the phase data twice, by values of 1 and 2 cycles, respectively (at time 9.8625).

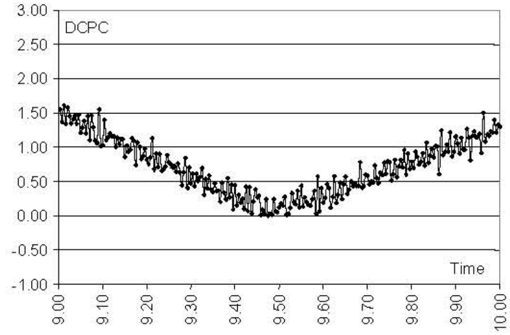

Fig. 4: DCPC Values (ASHM Data)

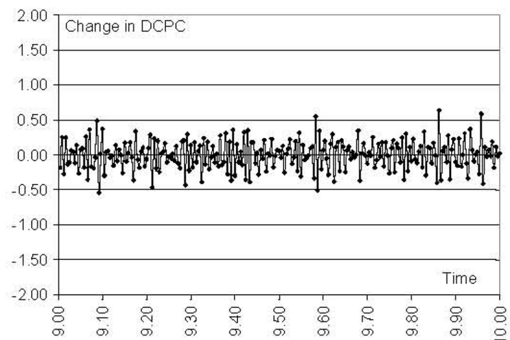

Fig. 5: Changes in DCPC Values (ASHM Data

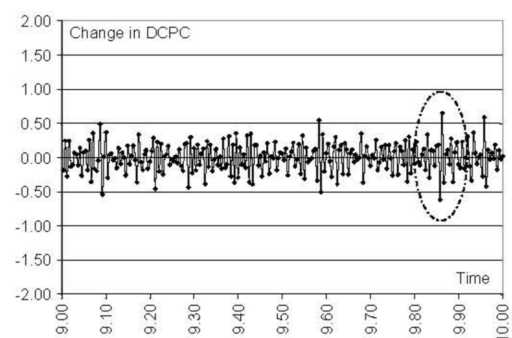

Fig. 6: Case of slipping one cycle (not detected)

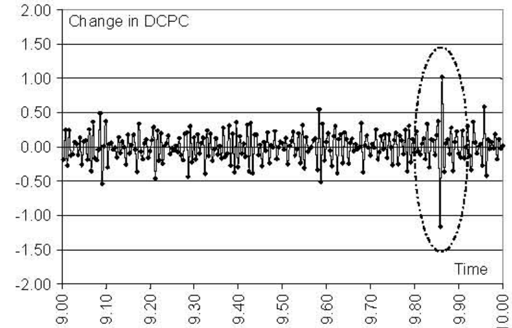

Fig. 7: Case of slipping two cycles (detected)

The prepared software was run for the two simulated cycle slips. The resulted DCPC changes are depicted in Figures 6 and 7.

By observing Figures (6) and (7) it is very evident that, the introduced algorithm failed to detect the cycle slip of the one cycle value (Figure 6), whereas it succeeded in the detection of the two cycles slip (Figure 7). This is matched with the result of equation (11).

Uncertainty of the Fixation Process: Of course, the accuracy of the estimation of the number of the slipped cycles (equation 9) depends only on the accuracy of the estimation of the DCPC value at the event of cycle slip. In other words, the uncertainty in the estimated number of the slipped cycles can be expressed as the maximum estimation error in the DCPC value, through the considered observation period, divided by the L_1 carrier signal wavelength. This relation can be formulated mathematically as:

$$\text{UN-CER} = \text{NINT}\left(\frac{\text{DCPC}_{\text{max-error}}}{\lambda}\right) \quad (12)$$

Where:

UN-CER: Is the uncertainty of the proposed approach in the fixation process.

$\text{DCPC}_{\text{max-error}}$: Is the maximum error in the estimated DCPC values.

As a first trial, the DCPC values are fitted using linear model. Of course, the one hour of observations, collected with sampling rate of 15 seconds, result in an over-determined mathematical model. This is due to the fact that the fitting line is defined using two parameters, where as the used data gives 240 DCPC values. So, 240 equations can be formed to solve for the two line parameters. This step was done using parametric least squares adjustment process. A MATLAB program was prepared for this task. The resulted line, superimposed on the original DCPC values, is given in Figure (8).

Differences are computed between the original DCPC values and the estimated ones. A maximum error of 0.87 m was found at time epoch t = 9.9625 (denoted by the dashed circle in Figure 8). So, by substituting by the value 0.87m in equation (12), the resulted uncertainty will be 5 cycles. So, using these data and using linear model, the accuracy of the fixation process will be ±5 cycles.

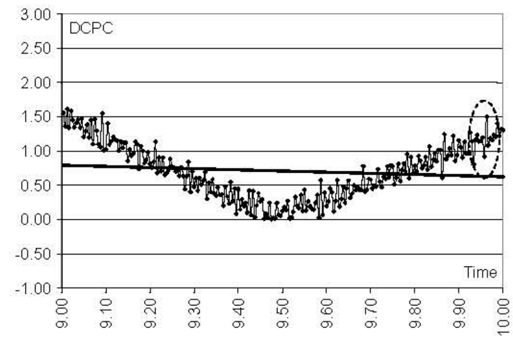

Fig. 8: Linear Fitting of DCPC values

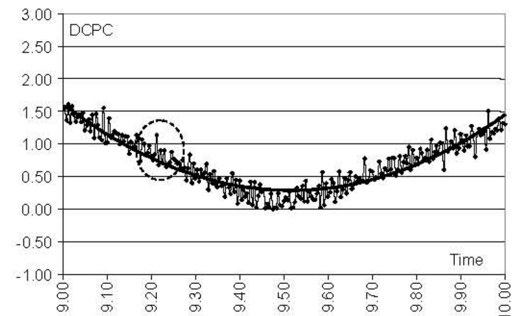

Fig. 9: Fitting of DCPC values Using 2nd Degree Polynomial

Effect of Changing the Polynomial Order on the Accuracy of the Fixation Process: By observing Figure (8), it is very clear that the used linear model does not fit the DCPC values well. The DCPC values exhibit the behavior of 2nd order polynomial or higher. So, other trials should be performed for the fitting process of the DCPC values, using different polynomial orders. The first trial was done by fitting the DCPC values using 2nd order polynomial. So, 240 equations are now formed in three unknowns (2nd order polynomial coefficients). Consequently, least squares scenario should be followed. A MATLAB program was prepared to perform this step. The resulted 2nd order polynomial, superimposed on the original DCPC values, is given in Figure (9).

As it was done in the linear fitting, the differences between the original DCPC values and the estimated ones are computed. A maximum error of 0.38m was found at time epoch t = 9.2125 (denoted by the dashed circle in Figure 9). So, by substituting by the value 0.38m in equation (12), the resulted uncertainty will be 2 cycles. So, using these data and using 2nd degree polynomial model, the accuracy of the fixation process will be ±2 cycles.

Table 1: Effect of fitting polynomial order on the fixation uncertainty

Used polynomial order	Max. DCPC error (m)	Uncertainty (cycles)
1st (linear)	0.87	5
2nd	0.38	2
3rd	0.41	2
4th	0.40	2
5th	0.36	2
6th	0.39	2
7th	0.42	2
8th	0.37	2

Table 2: Best fitting polynomial orders along one day (ASHM data)

Hour	PRN	Min. Order	Hour	PRN	Min. Order
1	6	1st	13	13	1st
2	17	1st	14	2	6th
3	22	2nd	15	2	1st
4	3	2nd	16	2	1st
5	3	2nd	17	7	1st
6	11	2nd	18	7	3rd
7	1	1st	19	9	6th
8	1	6th	20	9	2nd
9	1	1st	21	5	1st
10	13	2nd	22	5	1st
11	13	1st	23	6	1st
12	13	1st	24	6	1st

Based on the above results it is very clear that, the efficiency of the fixation process is enhanced when fitting the DCPC values as a 2nd degree polynomial instead of the linear fitting. As a result, it was of great importance to study the possibility of increasing the fixation efficiency by using higher order polynomials. To perform this study, different polynomials were used to fit the DCPC values. All the previous steps were performed and the uncertainties are calculated for each used polynomial. Results of all tested polynomials are summarized in Table (1).

From Table (1) it can be stated that, increasing the polynomial order from the 1st degree to the 2nd degree increases the fixation efficiency significantly. On the other hand, increasing the polynomial order beyond the 2nd order does not affect the efficiency of the fixation process, as the uncertainty remains constant. To validate and generalize this result, it was necessary to repeat the previous test on another GPS data. As mentioned before, the GPS data, collected at station ASHM, is available for 24 hours of observations. The RINEX file of such station was partitioned every one hour and the different polynomials (1st to 8th order) were applied for each hour. Of course, the considered satellite was changed, some times, between different hours. For each hour, different polynomials are tested to find out the minimum order of the best fitting polynomial. This minimum order should be the first one at which the uncertainty reaches its minimum value. Results for the 24 hours are given in Table (2).

Based on the results given in Table (2) it can be stated that, the optimum polynomial order that is capable for fitting the DCPC values is ranging between 1st and 6th orders. So, the 6th order will be selected as the used polynomial order, in spite of the uncertainty sometimes becomes constant at lower orders. This is to generalize the best used polynomial order in the further data processing stages.

Effect of Different Observation Conditions on the Reliability of the Proposed Technique: After determining both the detection sensitivity and fixation uncertainty of the proposed approach, it is of great importance to study the effect of the different observation conditions on the performance of this approach. Such studied observation conditions are the time of observation (through the same day), the location of observation, the year of observation and the sampling rate. These four parameters can certainly affect the DCPC values. The effect of these four parameters on the performance of the introduced approach will be studied through four different tests. In all these four tests, the changes of the DCPC values are used to compute the sensitivity (equation 11), whereas the estimation errors of the DCPC values are used to determine the uncertainty of the fixation process (equation 12). Based on the shown results in Table (2), the 6th degree polynomial will be used to detect the DCPC values in all the performed four tests.

Effect of Changing Time of Observation (Test 1): The main task of this test is to study the effect of the time of data acquisition on the performance of the proposed approach. The main parameter that may affect the DCPC value, along the time of the day, is the ionospheric effect. This is due to the fact that it reaches its maximum value at day hours and its minimum value during night hours. To achieve the goal of this test, the data collected at ASHM station was processed every one hour. For each hour, both the sensitivity (SEN) and the uncertainty (UN-CER) are computed. Results are summarized in Table (3).

Using Table (3) it can be stated that, the sensitivity of the proposed approach ranges between 2 and 3 cycles. The same results are produced for the uncertainty of the proposed approach. In spite of the fact that the ionospheric effect is higher at day hours, both the SEN

Table 3: Effect of changing observation time on the performance of the proposed approach (ASHM data)

Hour	SEN	UN-CER	Hour	SEN	UN-CER
1	±3	±3	13	±2	±2
2	±3	±3	14	±2	±2
3	±3	±3	15	±2	±2
4	±2	±2	16	±2	±2
5	±3	±2	17	±2	±2
6	±2	±2	18	±3	±3
7	±3	±3	19	±2	±2
8	±2	±2	20	±2	±2
9	±2	±2	21	±2	±2
10	±2	±2	22	±2	±2
11	±2	±2	23	±2	±2
12	±2	±2	24	±2	±2

Table 4: Effect of changing observation location on the performance of the proposed approach

Station	SEN	UN-CER
ASHM	±2	±2
SDT	±2	±2
BLS	±3	±2
KTM	±2	±2
SAF	±2	±2
MSL	±3	±3
BGR	±2	±2

and UN-CER did not exhibit a trend to increase at these hours. This result can be interpreted by recalling that both the detection and fixation processes do not depend on the values of the DCPC themselves. The sensitivity of the detection process is dependent on the variation of the DCPC values, whereas the uncertainty of the fixation process depends on the estimation errors of the DCPC values. So, even with higher values of DCPC (during high ionospheric activity), the efficiency of the proposed approach will not be degraded.

Effect of Changing the Location of the Observing Station (Test 2): The main purpose of this test is to study the validity of the obtained results for different locations of GPS stations. Of course, to investigate this issue, all other parameters should be unified. Such parameters are the time of observation, year of observation and the sampling rate. 7 GPS data sets were available on the same day, at the same hour and with the same sampling rate (15 seconds). The previous station (ASHM) was one of these seven stations, whereas the remaining six stations are namely SDT, BLS, KTM, SAF, MSL and BGR. These stations constitute a part from the Egyptian national geodetic network that established for the monitoring of the earth's crustal movement. The spacing between the considered seven stations ranges between 35 and 215 km.

The seven data sets were processed, using the same methodology and prepared software. At each station, the sensitivity (SEN) and the uncertainty (UN-CER) are computed for the same hour (from 09:00 am to 10:00 am). Results are depicted in Table (4).

From Table (4) it is obvious that the location of the observing station does not affect the efficiency of both the detection and fixation processes. Although the location of the observing station affects the value of the ionospheric effect and consequently the DCPC value, both the SEN and UN-CER values do not affected. This result can be interpreted in the same way as the previous test.

Effect of Changing Year of Observation (Test 3): The solar activity varies according to the famous 11-year solar cycle, also called sunspot cycle [12]. The peak of this solar cycle was on 2001 [10]. So, it is of great importance to investigate the stability and efficiency of the proposed approach through different years of different solar activities. To achieve the goal of this test, 8 GPS data sets were collected, from different sources; each set was collected during different year. The only unified parameter among these eight data sets is the sampling rate (15 seconds). They are collected at different times and at different locations. However, as it was proved by tests 1 and 2, this will not affect the results of this test. For each data set, the SEN and UN-CER are computed using the same manner. Also, the time gap between the considered data set and the year having the peak of solar activity (2001) is computed. All results are summarized in Table (5).

As it was expected, Table (5) shows that also the year of observation does not affect the efficiency of the proposed approach. This is due to the same previous reason that the ionospheric effect (which is varying from year to another) affects the DCPC values, where the sensitivity of the model depends on the changes in the DCPC values, not the values themselves. Also, the uncertainty of the model depends on the estimation errors of the DCPC values. So, the values of the DCPC do not affect either the sensitivity or the uncertainty of the introduced model.

Effect of Changing Sampling Rate (Test 4): After it was proved that none of the time, location and year of observation is affecting the efficiency of the proposed

Table 5: Effect of changing year of observation on the performance of the proposed approach

Year	Years since the peak of solar activity (2001)	SEN	UN-CER
1993	8	±3	±3
1996	5	±2	±2
1998	3	±3	±3
2001	---	±2	±2
2002	1	±2	±2
2005	4	±3	±2
2006	5	±1	±1
2007	6	±2	±1
2009	8	±2	±2

Table 6: Effect of changing the sampling rate on the performance of the proposed approach

Sampling Rate (sec)	Processed Time (min)	SEN	UN-CER
1	4	±1	0
5	20	±1	0
10	40	±2	±1
15	60	±2	±2
20	80	±2	±2
30	120	±4	±3
60	240	±5	±5

approach for both the detection and fixation processes, this test was assigned to study the effect of changing the sampling rate on the efficiency of the proposed approach. Here, seven different GPS data sets are considered. These seven data sets are gathered using epoch intervals of 1, 5, 10, 15, 20, 30 and 60 seconds. Although these data sets were collected at different locations and at different times, this will not affect the results of this test as it was proved in the previous three tests.

In the previous three tests, a time period of one hour of observation was processed. However, in this test, it was more logic to unify the number of the considered epochs not the processed observation period. This is to get the same number of the DCPC values and the same degree of freedom when fitting the DCPC values into the adopted 6^{th} degree polynomial. As a result, only 241 consecutive epochs were considered in each data set. This results in 240 DCPC values. The assignment of 241 epochs was done to unify the processed number of the DCPC values in this test with all the previous tests (which considered one hour of observation with sampling rate of 15 seconds). For each data set, the DCPC values are computed and both the sensitivity and uncertainty are estimated using equations (11) and (12). Results are summarized in Table (6).

From Table (6) it is very evident that decreasing the epoch interval increases, very significantly, the efficiency of the proposed approach. This is due to the smaller time gaps between each two consecutive DCPC values. Consequently, the variation in the DCPC values will be certainly smaller. This will lead to better sensitivity. Also, the estimation of the DCPC values will be more reliable as these values should be smoother. This will result in better (smaller) uncertainty. The first two considered sampling rates (1 second and 5 seconds) resulted in the ideal efficiency for the proposed approach. This ideal efficiency is expressed by a sensitivity of one cycle (it can detect any cycle slip even with a value of only one cycle) and by an uncertainty of zero cycle (it can estimate the number of the slipped cycles without any error).

CONCLUSIONS

Based on the performed tests and based on the obtained results, many important conclusions can be extracted from this paper. Such conclusions can be summarized in the following items:

- The use of the Difference between Change in Phase and Code (DCPC) as a test quantity for the cycle slip recovery is very useful. The values of this parameter (DCPC) contain only the ionospheric effect scaled by two and other remaining very small biases and noises.
- The implementation of the DCPC can be used in the detection and fixation of cycle slips for single frequency GPS data.
- The introduced approach can be applied for the un-differenced mode of observation.
- The proposed approach does not require and apriori information for both the detection and fixation processes.
- The sensitivity of the detection process is expressed in terms of the maximum difference between each two consecutive DCPC values.
- The uncertainty of the fixation process is expressed in terms of the maximum estimation error of the DCPC values.
- The 6^{th} degree polynomial is sufficient for fitting the DCPC values in all the considered cases.
- Collection of GPS data at any time within the day does not affect the performance of the proposed approach.
- The position of the GPS observation station does not affect the efficiency of the proposed approach.

- The year of observation does not have any impact on the performance of the proposed approach.
- Decreasing the epoch interval increases the reliability of the proposed technique for both the detection and fixation processes.
- With the use of epoch intervals of 1 or 5 seconds, the proposed approach can detect any cycle slip without any errors.

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