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DEVELOPING A REAL-TIME APPROACH FOR DETECTING AND REPAIRING CYCLE-SLIPS IN DIFFERENCE MODE

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ABSTRACT

The detecting and repairing of cycle slips in carrier phase measurements is considered one of the major quality control problems that needs to be addressed, especially when GPS is used for real-time applications, or for applications that require continuous and reliable positioning results. Generally, cycle slips occur when the ground receiver loses the phase lock of the satellite-transmitted signal. In other words, the cycle slip is a sudden break in the radio link between the satellite and the receiver. The loss of lock between the receiver and the satellite may happen for both the two carrier waves (L_1 and L_2), or for one carrier wave only (L_1 or L_2), according to the reasons that cause the cycle slip.

The process of the detecting and repairing cycle slips should be done for any GPS collected data, before the processing stage, to avoid any mistakes in the coordinates of the surveyed points. A new algorithm is developed to give the ability of detecting cycle slips in real-time applications with a little bit computation load burden. The developed algorithm is based upon finding an observation equation by modify the Extra Wide-laning technique to be a function of the two unknowns cycle-slips over L1 and L2 carriers. It does not require any pre-knowledge for any data like the coordinates of the satellites or the coordinates of the receiver stations. This observation equation will act together with the ionospheric residual observation equation to find deterministic values for the occurred cycle-slips as close as possible to their real values, of course, with minimum time. The new algorithm was tested by different data sets, in static and kinematic modes as well as in different ionosphere environments with low and high latitudes. The results show a high accuracy for both static and kinematic data.

1. INTRODUCTION

When a receiver is setup over the ground station and turned on, the fractional beat phase (the difference between the phase of the satellite transmitted carrier wave and the phase of the receiver generated replica signal) is observed, and an integer counter is initialized. During the tracking of the satellite, the counter is incremented by one whenever the accumulated phase changes from 2π to zero (Hofmann et al., 1994). Thus, at a given epoch, the observed phase is the sum of the fractional phase and the previously mentioned integer counter (Remondi, 1984). The initial integer number of complete cycles N (integer ambiguity) between the satellite and the receiver is unknown. This integer phase ambiguity N remains constant as long as no loss of the signal lock occurs, that is no cycle slips occur. If a cycle slip takes place during the tracking of the satellite, the integer counter is re-initialized, and that causes a sudden jump in the instantaneous accumulated phase by an integer number of cycles. This jump is called cycle-slip, which, of course, is restricted to phase measurements

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only. In other words, the pseudorange observations are immune to cycle slips (Rabah et. al, 1996).

With increasing demands for high precise real-time applications, like precise navigation, real-time crustal movements and real-time kinematic positioning, the occurrence of cycle-slip becomes one of the main problems that prevent from achieving this goal. Thus, to achieve the required high GPS-positional accuracy, it is necessary to free the GPS phase measurements from cycle-slips. Ideally, the method that can be used in detecting and estimating cycle-slips, should not depend on restrictive circumstances such as static or kinematic observations, the previous knowledge of the station position, the length of the baseline between the different stations and the amount of cycle-slips, but can give real-time cycle-slips detection and repair with enough flexibility for different GPS applications. In the following sections, the different techniques for detecting and estimating cycle-slips modes with their limitations are reviewed with emphasis on the accuracy of the involved quantities. In addition a developed algorithm is introduced, in which the precise predicted values are computed by using a developed dynamic multi-degree fitting polynomial for the data. The main idea behind the developed algorithm is trying to find a predicted value for the cycle slip, as close as possible to the real value. Results are given for simulated and real cycle-slips on different types of data (static and kinematic), under different conditions of ionospheric disturbances.

2. CYCLE SLIPS DETECTION AND REPAIR METHODS

Detection of cycle slips can be done during post-processing, by a variety of techniques, which are largely applicable to static measurements (Hofmann et al., 1994). On the other hand, it is much more difficult to detect the existence of cycle slips in kinematic mode of observations. Modern receivers are now capable of detecting the existence of cycle slips, using built-in algorithms that identify all or most of the cycle slips (Strang et al. 1997). Possibly, forthcoming receiver generations will have the capability to remove also the cycle slips from the data. However, for the time being, cycle slips repair belongs to the process of data editing, either automatic or interactive.

Nowadays, there are several methods for cycle slips detection and repair. Each of them is based on a certain criteria or a certain “test quantity”. The factors that govern the choice of a certain method are (Seeber, 1993):

- The kind of the used receivers (single or dual frequency).
- The kind of the performed survey (static or kinematic).
- The availability of a priori coordinates for ground stations and satellites.

Identification of the discontinuities in the test quantities can be performed using many different methods. However, three main approaches are usually used, which are:

- A low degree polynomial is fitted to the time series.
- A dynamic model is setup to predict subsequent observations by Kalman filtering.
- A scheme of first, second, third and fourth differences can be set up. Discontinuities show rather strong signals in the higher order differences.

In the following sub-sections, the main cycle slips detection and repair techniques are outlined. Each method is discussed according to its basic idea, data requirements, advantages and disadvantages.

2.1 Double Differences and Computed Ranges

The main idea of this method is based on observing double difference phase measurements, and comparing them with the double difference geometric ranges for two receivers and two satellites. Here, the test quantity is taken as the residual between the two double differences. The mathematical formulation for the test quantity of this method can be formed as:

$$r_{a,b}^{j,k}(t)=\phi_{a,b}^{j,k}(t)-\frac{1}{\lambda}\{(\rho_{a}^{j}(t)-\rho_{b}^{j}(t)-\rho_{a}^{k}(t)+\rho_{b}^{k}(t))+\Delta_{a,b}^{j,k}Trop\,(t)\} \quad (1)$$

Where:

$r_{a,b}^{j,k}(t)$	The test quantity, computed at each epoch,
$\phi_{a,b}^{j,k}(t)$	The measured double difference phase
λ	The carrier phase wavelength,
$\rho_{a}^{j}(t)$	The range between the receiver at station *a* and satellite J,
$\Delta_{a,b}^{j,k}Trop\,(t)$	The double difference tropospheric delay in meter.

To apply this method, it is required to have a priori knowledge for the coordinates of the considered satellites (*j*, *k*), as well as the considered two receiver stations (*a*, *b*), in order to compute the four geometric ranges. After substituting the values of the geometric ranges in equation (1), and getting the test quantity $r_{a,b}^{j,k}(t)$ for all the considered epochs, the relation between the test quantity and time is analyzed by fitting a curve to the obtained series. Any discontinuity in the curve fit identifies the existence of cycle slip (Seeber, 1993).

The main advantage of this method is that it can be applied in real-time either for single or dual frequency receivers. Another advantage is that, the double difference observations eliminate many observational biases as the clock offsets (for both receivers and satellites), inter-channel biases and the correlated part of both the tropospheric and ionospheric delays. The main disadvantage of this method is that the ionospheric variation between the two stations may causes a large noise, which can result in wrong results, specially in the case of large inter-station distances, where the relative ionospheric delay is significant between the two stations. In such a case, a discontinuity in the fitted curve may be observed and attributed falsely to a cycle slip, where it is due to the large relative ionospheric delay. Another disadvantage of this method is that it requires the pre-knowledge of the approximate coordinates for the considered two satellites and two receiver stations.

2.2 Ionospheric Residuals Method

The main idea of this method is based on the differencing between the two carrier phases L_1 and L_2 for the current epoch. This differencing will remove completely all the frequency independent biases, like the orbital biases, tropospheric delay and clock offsets. The test quantity in this method can be formed as:

$$d\varphi(t) = \varphi_1(t) - f_1 / f_2 . \varphi_2(t) \tag{2}$$

Where:

$d\varphi(t)$ ionospheric residual for epoch (t) (L1 cycles),

φ_1, φ_2 the carrier phase for L1 and L2,

f_1, f_2 the carrier wave frequency for L1 and L2.

It is evident that the ionospheric residual *($d\phi$ (t))* depends only on the ionospheric delay, which is frequency dependent parameters are only present in equation (2). The test variable is, of course, changing smoothly with time, as the change in the ionospheric delay will be, in general, changing in smooth manner from epoch to epoch, in the case of normal ionospheric conditions (Rabah, 1998). So, by computing the ionospheric residual *$d\phi$ (t)* for the considered epochs, and plotting them against time, cycle slips can then be discovered very easily by observing a sudden change in the ionospheric residual at the epoch of cycle slip occurrence.

By differencing the ionospheric residual between two consecutive epochs, say $(t_{i-1}), (t_i)$ one obtains:

$$D\varphi(t) = (\varphi_1(t_i) + n_1(t_i) - \varphi_1(t_{i-1})) - f_1 / f_2 . (\varphi_2(t_i) + n_2(t_i) - \varphi_2(t_{i-1})) \tag{3}$$

Where:

$D\varphi(t)$ the change of the ionospheric residual (L1-cycles).

n_1, n_2 the cycle-slips values on L1 and L2 (L1-cycles) at time (t_i).

The behavior of the change in the ionospheric residual *($D\phi$ (t))*, computed between every two consecutive epochs, is very smooth with time. Even a cycle slip of only one cycle on both carrier waves L_1 and L_2 (i.e., $n_1 = n_2 = 1$) can be detected very easily, as these critical cycle slips will give a change in the ionospheric residual by a value of about 0.284 L_1 cycle (Goad, 1986). It is evident that, by observing equation (3), this method cannot be used separately for the purpose of cycle slip repair, as it gives one equation in two unknowns *(n_1* and *n_2)*. So, the solution can be found by various combinations of n_1 and n_2, and by looking for the solution that can verify the contaminated value of the ionospheric residual. Therefore, to use this method, another condition is needed which can give approximated values of n_1 and n_2. This condition is required for the searching process with an accuracy of about (6 - 8) cycles (Bastos and Landau, 1988).

The ionospheric residual method has the advantage that it does not require any pre-knowledge for any data like the coordinates of the satellites or the coordinates of the receiver stations. Also, this method has the advantage of working for single station, and hence, it can be applied in un-differenced and differenced modes of observations. On the other hand, the ionospheric residual method has two main disadvantages. First, it cannot be used alone for the repairing process as it gives one equation in two unknowns. Second, it cannot be applied for single frequency receivers.

2.3 Code-Carrier Combinations

This method is also called the range-residual method. The basic idea of this method is based on the determination of the satellite-station range twice, firstly by using pseudorange code observations, and the secondly by using carrier phase observations. Then, the two ranges are differenced at each epoch to give the test quantity, which is called the range residual (Mader, 1986). Here, the range residual is dependent only on the number of integer ambiguity N.

$$d\rho(t) = (\varphi_i(t) - \varphi_i(t_o)) - 1/\lambda_i(\rho(t) - \rho(t_o)) \quad (4)$$

Where:

φ_i = carrier phase of the current epoch, subscript *i* denotes to L1 or L2.

λ_i wavelength (m).

ρ = pseudorange (m).

$d\rho$= the range-residual (cycles).

(t) = GPS-week time for the current epoch (s).

(t_o)= GPS-week time for an initial epoch (s).

The change in the range residual between two consecutive epochs (say t_0 and t) can be formed as:

$$d\rho(t) = (\varphi_i(t) + n_i - \varphi_i(t_o)) - 1/\lambda_i(\rho(t) - \rho(t_o)) \quad (5)$$

Where:

n_i is the value of the cycle slip.

By comparing the computed value of the range-residual before and after the cycle-slip occurrence, an approximate estimate for the cycle-slip on L1 and L2 can be computed. To improve these values, to a few cycles, Mader (1986) made a best fitting linear regression for all the available data before and after the cycle-slip to reduce the level of the noise. The key for a successful application of this method is the precise determination of pseudo ranges. So, if a P-code receiver is used, whose observation noise is in the order of ± 0.6m, it will allow the determination of cycle slips with an accuracy of about ± 3 cycles (Seeber, 1993). This accuracy is sufficient enough to be used as an input value (approximate solution for the cycle slip) for the ionospheric residual method.

The range residual method has many important advantages. First, in this method, the differencing process between pseudo range and carrier phase observations cancels out many observational systematic errors, as the values of these errors are the same for both two kinds of observations. Such errors like satellite and receiver clock offsets, orbital errors, tropospheric delay and relativistic errors. Another advantage of this method is that it can be applied for any kind of receivers (dual or single frequency receivers), as it does not need simultaneous observations for the two carriers L_1 and L_2. Also, this method can be applied in un-differenced and differenced modes of observations. The main disadvantage of the range residual method is the low accuracy of the pseudo range observations, due to the measurement noise associated with the pseudo range multi-path (Bastos and Landau, 1988). So, this method can be used only to get an approximate value for the cycle slip, to be used as an input (initial) value for other more accurate method, like the ionospheric residual method.

2.4 Kalman Filter Method

While Mader (1986) used a linear regression method to fit the data to derive an average value for the range-residual before and after the cycle-slip, (Bastos and Landau, 1988) have used comparable filtered quantities to reduce the influence of the measurement noise and multipath. Based on the periodical behavior of the range residual data due to multipath (e. g. with a period of 10 minutes), in the first step, they applied a filter following this periodic behavior to reduce the data noise. They obtained an accuracy of ± 3 cycles for the approximate values of n_1 and n_2 .In the second step, they applied the Kalman filtering technique to the ionospheric residual data to determine the effective slips on L1 and L2 on the value of the ionospheric residual. In case of a higher noise, some problems will be faced with this method.

2.5 The Multi-Degree Polynomial Method

As it is known, the critical factor for estimating the correct cycle-slips, especially in un-differenced mode, is the value of the computed range-residual, and how its value is near to the real one. To improve these values, Rabah et al. (1996) computed the range-residuals between the consecutive epochs instead of computing them with respect to an initial value as done by Mader (1986). Then, they applied an algorithm of multi-degree dynamic polynomial for predicting the values of range residuals and the ionospheric residual at the epoch that had a cycle-slip. Those predicted values would be used as a threshold value for the cycle-slip search process to facilitate the estimation of the correct cycle-slips. The accuracy of the predicted range residuals was ±3 cycles for static data and ±5 cycles for high-noise data. The only disadvantage of the developed algorithm is the burden load of the computation that consumes a time, especially in differenced mode, which is considered the most critical factor in real-time processing.

3. THE COMBINATION OF IONOSPHERIC RESIDUALS AND EXTRA WIDE-LANING TECHNIQUE

As it was mentioned before, the ionospheric residual method has the advantage that it does not require any pre-knowledge for any data like the coordinates of the satellites or the coordinates of the receiver stations. Also, it has the advantage of working for single station, and hence, it can be applied in un-differenced and differenced modes of observations. On the other hand, as it is indicated in equation (3), the ionospheric residual method cannot be used separately for the purpose of cycle slip repair, as it gives one equation in two unknowns *(n_1* and *n_2)*. So, a deterministic solution can be found by solving the last equation with another equation of n_1 and/or n_2, and by looking for the solution that can verify the contaminated value of the ionospheric residual.

The mathematical approach of the developed algorithm is based upon finding an observation equation that is a function of the two unknowns (n_1 and n_2) and does not require any pre-knowledge for any data like the coordinates of the satellites or the coordinates of the receiver stations, namely the Extra Wide-laning technique as described by Wuebbena, (1989), Blewitt (1989), Euler and Goad (1991), and Goad (1992). The Extra Wide-laning technique utilize the code pseudoranges and carrier phase, in a way such that they remove the effect of the geometric errors effect, namely the orbital errors, the tropospheric errors, the receiver clock offset, the position errors in the baseline two ends and all other frequency independent errors. The mathematical details are given in the following and are based on single difference observations:

Equation (3) can be reformulated as:

$$n_1(t_i) - f_1 / f.n_2(t_i) = D[\Delta\varphi(t_{i,i-1}) - \{(\Delta\varphi_1(t_i) - \Delta\varphi_1(t_{i-1})) - f_1 / f_2.(\Delta\varphi_2(t_i) - \Delta\varphi_2(t_{i-1}))\} \quad (6)$$

The observation equations for the wide-lane linear combination of the single difference carrier phase ranges can be represented as:

$$\Delta\varphi^{j}_{AB,WL} = \Delta R^{j}_{AB}(t) + \lambda_{WL}\Delta N^{j}_{AB,WL} + \Delta T^{j}_{AB} + \Delta I^{i}_{AB;WL} + \Delta c.dt^{j}_{AB} + \varepsilon^{jk}_{1,AB} - \varepsilon^{jk}_{2,AB} \quad (7)$$

And

$$\Delta\varphi^{J}_{AB} = \lambda_{WL}(\Delta\varphi^{jk}_{1,AB} - \Delta\varphi^{jk}_{2,AB})$$

$$\Delta I^{j}_{AB,WL} = -(77/60).\Delta I^{j}_{AB,L1}$$

The observation equations for the narrow-lane linear combination of the code pseudoranges single difference can be written as:

$$\Delta\rho^{j}_{AB,NL} = \Delta R^{j}_{AB}(t) + \Delta T^{j}_{AB} + \Delta I^{i}_{AB,NL} + \Delta c.dt^{j}_{AB} + \varepsilon^{j}_{1,AB} + \varepsilon^{j}_{2,AB} \quad (8)$$

And

$$\Delta\rho^{j}_{AB,NL} = \frac{f_1\Delta\rho^{jk}_{AB,1} + f_2\Delta\rho^{jk}_{AB,2}}{f_1 + f_2}$$

$$\Delta I^{j}_{AB,NL} = +(77/60).\Delta I^{j}_{AB,L1}$$

Where:

φ_i	carrier phase of the current epoch, subscript *i* denotes to L1 or L2 (cycles)
λ_i	Wavelength (m)
ρ	pseudorange (m)
R	geometric range between the station and the receiver (m)
c	speed of light (m/s)
I	Ionospheric effect (m)
T	tropospheric effect (m)
ε_{φ}	carrier phase noise
ε_R	pseudorange noise
(t)	GPS-week time for the current epoch (s)
dt	combined satellite and receiver clock offset (s).

Subtracting equation (8) from equation (7), one can get the value of the single difference wide-lane ambiguity at time (t_{i-1}) as:

$$\Delta N^{j}_{AB,WL} = \Delta\varphi^{j}_{AB,WL}(t_{i-1}) - \frac{\Delta\rho^{j}_{AB,NL}(t_{i-1})}{\lambda_{WL}} \quad (9)$$

Assume that a cycle-slip of n_1, n_2 is occurred at time (t_i), thus equation (9) can be rewritten as:

$$\Delta N^{j}_{AB,WL} = \Delta\varphi^{j}_{AB,WL}(t_i) + (n_1 - n_2) - \frac{\Delta\rho^{j}_{AB,NL}(t_i)}{\lambda_{WL}} \quad (10)$$

Keep in mind that the wide-lane ambiguity is fixed, so by subtracting equation (9) from equation (10), the value of ($n_1 - n_2$) equals:

$$(n_1 - n_2) = \frac{\Delta\rho^j_{AB,NL}(t_i) - \Delta\rho^j_{AB,NL}(t_{i-1})}{\lambda_{WL}} - (\Delta\varphi^j_{AB,WL}(t_i) - \Delta\varphi^j_{AB,WL}(t)_{i-1})$$

scaled by the wide-lane wavelength (11)

By simple manipulations of equations (6) and (11), one can obtain the value of n_2 as:

$$n_2 = \frac{\Delta\rho^j_{AB,NL}(t_i) - \Delta\rho^j_{AB,NL}(t_{i-1})}{\lambda_2} - \{(\Delta\varphi^j_{AB,2}(t_i) - \Delta\varphi^j_{AB,2}(t)_{i-1})\} - \{\frac{D\Delta\varphi(t_{i,i-1})}{f-1}\}$$

scaled by the L2 carrier wavelength and $f = \frac{f_1}{f_2} = \frac{77}{60}$ (12)

In case of clean observations, equations (10) and (11) can give a very good impression about the coherent noise of observations as well as for what accuracy the approximate value of the cycle-slip values.

4. VERIFICATION OF THE DEVELOPED ALGORITHM

As it was mentioned above, the main key of a successful algorithm, utilizing for detecting and estimating cycle-slips, that is how close the estimated values to the actual occurred cycles-slips. Thus, to verify the developed algorithm (equations (11) and (12)) should be tested against the other algorithms, namely the range-residuals as computed by equations (4) and (5). Different data sets were used. The first data set was very noisy data collected in May 16, 2002 between station Raas-Ghareb and Gabal-Alziet on Red Sea Coast, Egypt with baseline length about 32.0 km on static mode. The second data set was collected in USA on March 10, 1996 between stations Carrhil and cat1 with length about 324.5 km, also in static mode. The last data set was collected on July 26, 2001 in Sudan and Egypt territories, in kinematic mode where the reference receiver was set up on the roof of the seismic center in Aswan, and the rover receiver was stand on the roof of a vessel sail from Dakka fall towards the north, the baseline length was ranged between 369.0 and 340 km.

For the first data set, the n_2 residuals were computed twice by using the extra widelaning technique equation (11) and the normal range-residual equation (5) for the Gareb-Ziet baseline. The results were depicted in figure (1). Table (1) gives the main statistical characteristics of both results. As it is indicated in figure (1) and table (1), in spite of the data was very noise, the developed algorithm improves the resulted accuracy as reflected by the variances and the mean of both results. Those improvements were clearly appeared for the computed n_1 - n_2 residuals as demonstrated in figure (2) and table (1), where the variances was largely reduced to 0.142 for the computed n_1 - n_2 residuals by the developed approach instead of 5.088 of the range residual.

The above processing was repeated for the baseline that extends between Cat1 and Carrhile in USA with a 324.5 km length for observations collected in a static mode. The corresponding results were given in figures (3) and (4) and table (2). Figure (3) shows how the developed algorithm enhances the estimation process of the cycle-slips. The resulted accuracy of the estimated n_2 was in the range of ±3.0 cycles for the developed algorithm, while the estimated n_2 of range–residuals were in the range of ±6.0 cycles. This improvement in accuracy was reflected into the values of the variances of both results, where the variance of the developed algorithm was equal 0.928, whereas for the range residual was 2.1. On the other hand, the n_1 - n_2 residuals computed by the extra widelaning technique, was drawn into the lower curve of figure (4), and the normal range-residual was outlined in the upper curve of figure (4). As it is indicated in figure (4) and table (2), the accuracy of n_1 - n_2 residuals, computed by the extra widelaning technique is less than ±1.0 wide-lane cycle, while for the values computed by the normal range-residuals is ranged between –5.0 and +6.5 wide-lane cycle. In addition, the variance was reduced from 3.082 to 0.074.

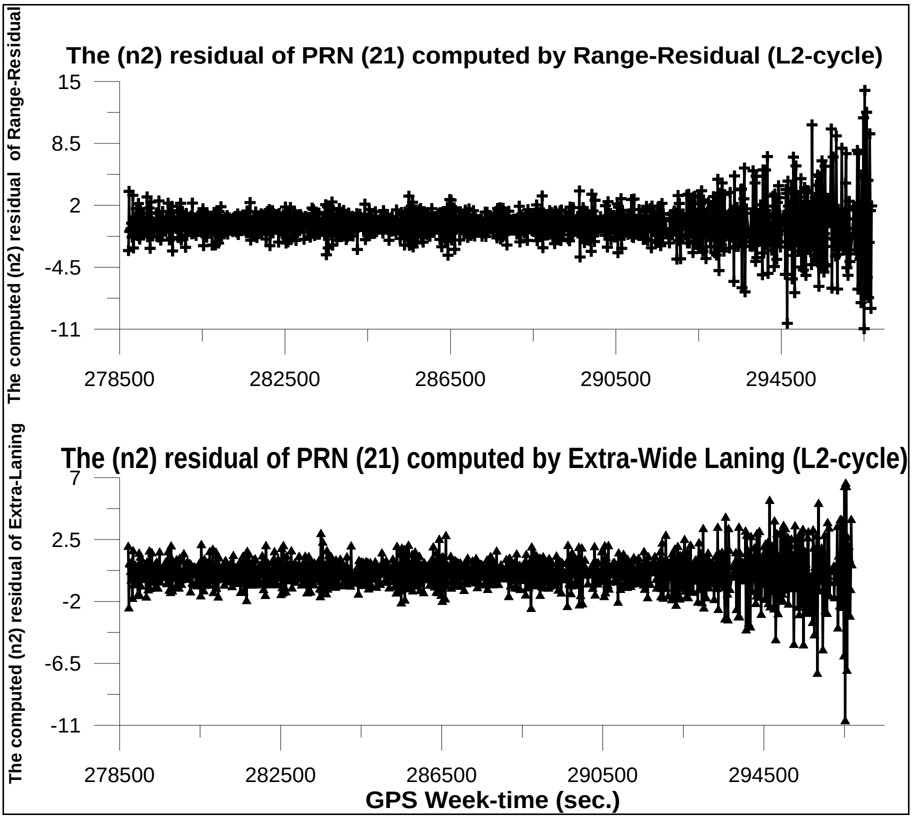

Figure (1): The n_2 residuals as computed from the extra widelaning technique, the lower curve, and the normal range-residual (L2-cycle) for Gareb-Ziet baseline.

Table (1): The main statistical characteristics of the developed algorithm results and the classical method for Gareb-Ziet baseline.

Statistical Features	The n_2 residuals		The n_1 - n_2 residuals	
	Extra-widelaning	Range-Residual	Extra-widelaning	Range-Residual
Minimum Value	-10.718	-10.955	-3.033	-16.463
Maximum Value	6.552	14.065	1.853	12.769
Mean	-0.0029	0.0032	-0.0025	-0.007
Variance	1.790	4.364	0.142	5.088

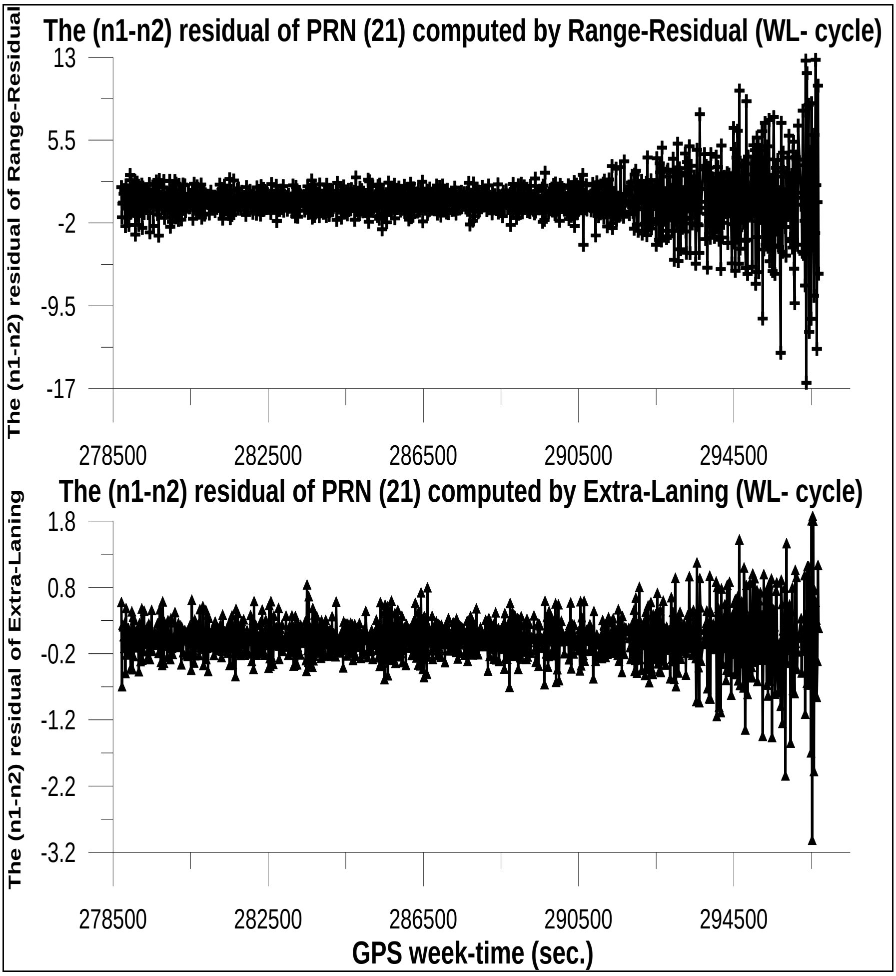

Figure (2): The n_1 - n_2 residuals as computed from the extra widelaning technique, the lower curve, and the normal range-residual WL-cycle) for Gareb-Ziet baseline.

Finally, the developed algorithm was tested by data collected in kinematic mode, where the dynamic noise of this data is so high compared with the static data, especially the data was gathered at low latitude (20.5 degrees) where the ionosphere activity is so high compared with the moderate and high latitude. The results of the developed algorithm were presented in figures (5) and (6) for n_2 and n_1 - n_2 residuals. The accuracy of the estimated n_2 was in the range of ±3.0 cycles for the developed algorithm, while the estimated n_2 of range–residuals was in the range of ±5.0 L2-cycles. In addition, the n_1 - n_2 residuals accuracy of the developed algorithm is less than ±1.0 wide-lane cycle, while for the values computed by the normal range-residuals is ranged between ±5.0 wide-lane cycles.

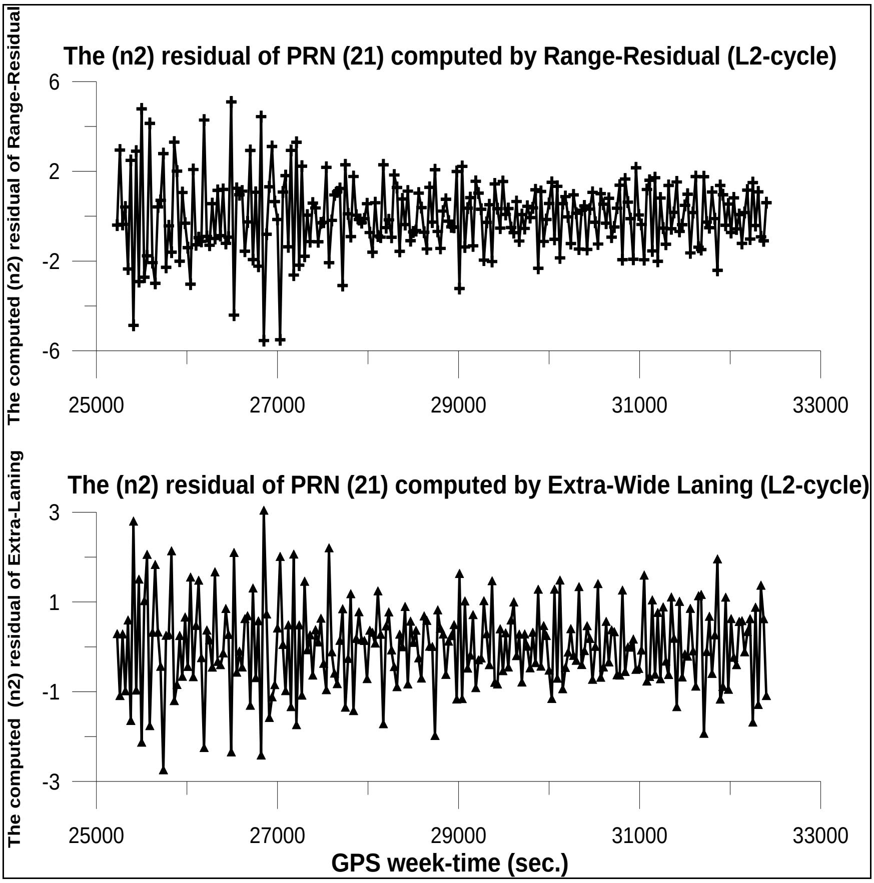

Figure (3): The n_2 residuals as computed from the extra widelaning technique, the lower curve, and the normal range-residual (L2-cycle) for Cat1-Carrhile baseline, USA.

Table (2): The main statistical characteristics of the developed algorithm results and the classical method for Cat1-Carrhile baseline, USA.

Statistical Features	**The n_2 residuals**		**The n_1 - n_2 residuals**	
	Extra-widelaning	**Range-Residual**	**Extra-widelaning**	**Range-Residual**
Minimum Value	-2.771	-5.543	-0.786	-4.737
Maximum Value	3.013	5.094	0.852	6.494
Mean	-0.0032	2.695	-0.0015	0.0072
Variance	0.964	1.642	0.074	3.082

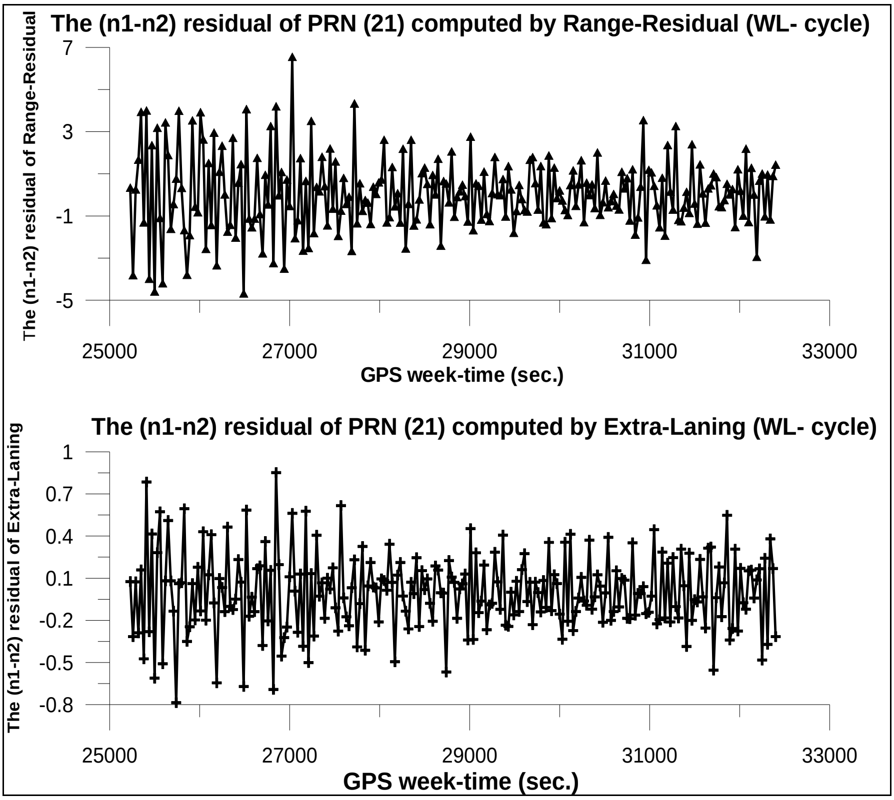

Figure (4): The n_1 - n_2 residuals as computed from the extra widelaning technique, the lower curve, and the normal range-residual (WL-cycle) for Cat1-Carrhile baseline, USA.

Table (3): The main statistical characteristics of the developed algorithm results and the classical method for Dakka-Aswan baseline, Sudan and Egypt

Statistical Features	**The n_2 residuals**		**The n_1 - n_2 residuals**	
	Extra-widelaning	**Range-Residual**	**Extra-widelaning**	**Range-Residual**
Minimum Value	-2.946	-4.06	-0.836	-4.612
Maximum Value	2.807	4.486	0.795	4.314
Mean	0.0038	0.0024	-0.0002	0.015
Variance	1.022	1.928	0.0792	1.638

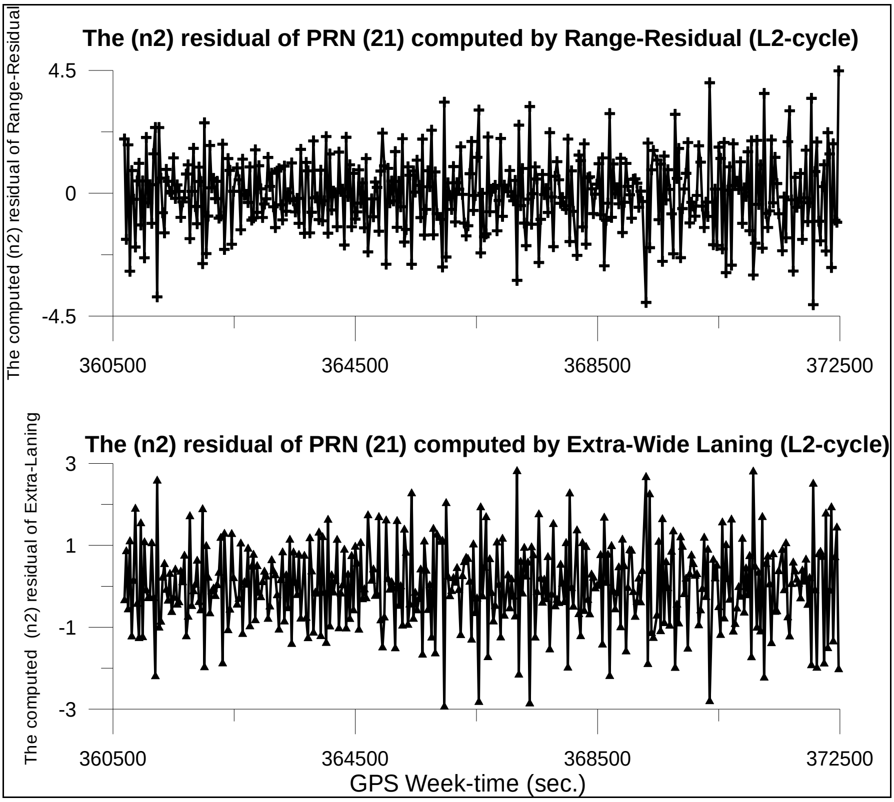

Figure (5): The n_2 residuals as computed from the extra widelaning technique, the lower curve and the normal range-residual (L2-cycle) for Dakka-Aswan baseline, Sudan and Egypt.

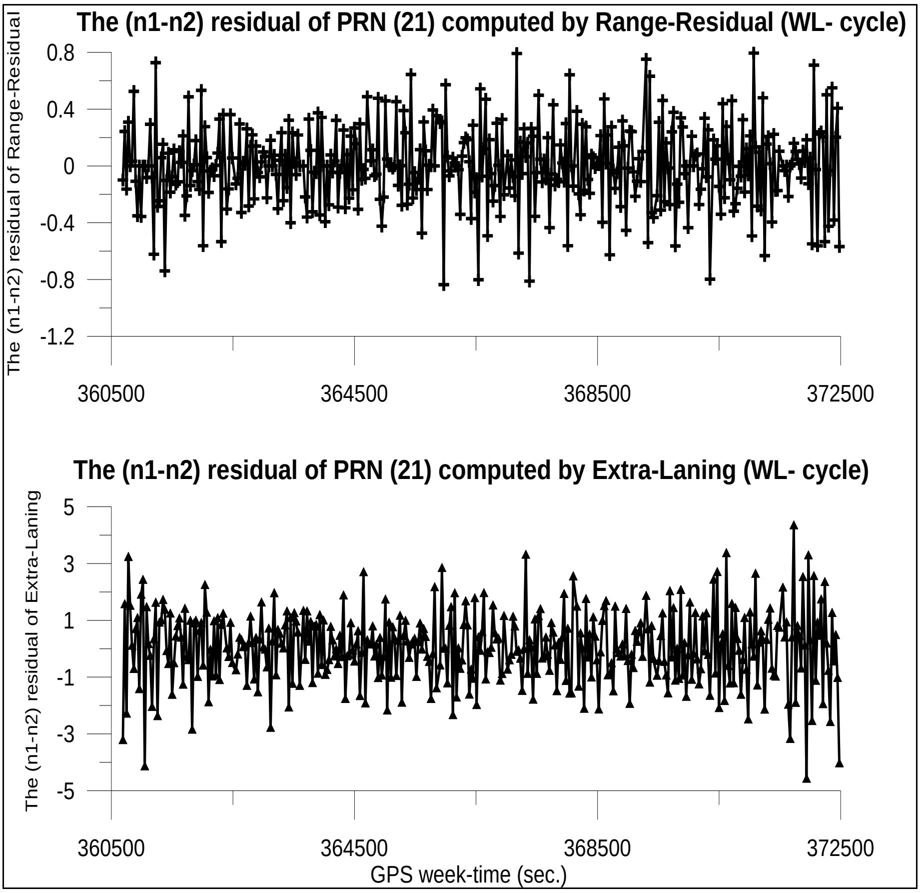

Figure (6): The n_1 - n_2 residuals as computed from the extra widelaning technique, the lower curve, and the normal range-residual (WL-cycle) for Dakka-Aswan baseline, Sudan and Egypt.

5. CONCLUSION

To guarantee a good continuity of the GPS observations that are required for sound processing, it is necessary to support the system with a tool that can detect and correctly repair the discontinuities of GPS data, namely cycle-slips. Of course, this should be in real-time. Thus, the common techniques that are currently in use for detecting and repair cycle-slips were discussed. In addition, a new algorithm is introduced, which is based upon finding an observation equation that is a function of the two unknowns (n_1 and n_2) and it does not require any pre-knowledge for any data like the coordinates of the satellites or the coordinates of the receiver stations, namely the Extra Wide-laning technique. This observation equation will act together with the ionospheric residual observation equation to find deterministic values for the occurred cycle-slips as near as possible to their real values, of course, with minimum time. This will reduce the load burden of the mathematical computation of the multi-degree dynamic polynomial that was developed before. The developed algorithm was tested by different sets of data, in static and kinematic modes as well as in different ionosphere environments, namely in low and high latitudes as in Sudan, and USA. The developed algorithm shows an accuracy of a range of ±3.0 L2-cycles for n_2 and less than ±1.0 wide-lane cycle for n_1 - n_2 residuals for static and kinematic data.

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