EMD-BASED DETECTION, IDENTIFICATION AND ADAPTATION OF CYCLE-SLIP FOR GNSS RELATIVE POSITIONING

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Abstract: Cycle-slip causes discontinuous integer cycle jumps in phase measurements, detecting and correcting cycle-slip is an important issue for GNSS relative positioning. In this paper, a novel method is proposed to deal with the problem based on empirical mode decomposition (EMD) method. The proposed method consists of three steps. Firstly, a time differentiated GNSS phase signal is decomposed into a trend signal and a finite number of intrinsic mode functions (IMFs) by EMD. Secondly, a "cycle-slip signal" is obtained by removing the trend signal and low frequency IMFs from the original signal. Finally, an edge detection operator is applied on the "cycle-slip signal" to detect and repair the cycle-slip. Experiments verified the success rate of the algorithm up to 100 % (15° mask angle) in various simulated scenarios. Several tests were performed based on real data over multiple days, and the results confirm that the proposed algorithm is applicable for relative positioning.

INTRODUCTION

Cycle slips are sudden jump in the carrier phase measurements by an integer number of cycles during GNSS signal tracking. The fractional portion of the phase is not affected by this discontinuity in the observation sequence. They occur during any non-particular epoch; it can happen to any satellite, or only occurs at a certain frequency. Biases are produced in phase observables during cycle slips. The consequential errors can influence the parameter estimation, according to the least square method for error distribution.

The processing of cycle slips mainly focuses on the detection and repairing of the discontinuity in the data time series. The algorithms include polynomial fitting, high order phase differential between epochs, Kalman filtering, phase combinations, and phase/code combination, and quality control (Zhen, et.al.2008). The combination of dual-frequency data which include geometry-free phase combination (Gao and Li, 1999), wide-lane combination, ionosphere combination (Blewitt, 1990) and wide-lane phase minus narrow-lane pseudorange combination (Bisnath, 2000). If phase combination and phase/code combination are used, detection would then be restricted by the precision of the phase/code measurements. And some specific cycle-slip pairs which cannot be readily detected by using the dual-frequency phase combination. Alternatively, Kalman filtering detects the cycle slips by the different between the predicted in the time series and the real status of the measurements. It is also essential to configure the dynamic model to prevent false estimation. The cycle slips correction was performed with baseline length constraint and double/triple difference observables (Liu and Huang, 2009). But the method is necessary that no cycle slips occur in the observables of four satellites in two adjacent epochs at least.

The most widely applied cycle slip detection method is detecting signal discontinuity. This method is not affected by the number of satellites, although large observable noises or signal trend changes can be misinterpreted as tiny cycle slips, causing positioning error. Recently, the EMD method has been applied to the GNSS data processing. It was used for reducing carrier phase noises for precise static GPS positioning (Wang, et.al. 2009). This study proposes a cycle slip detection method based on EMD. The EMD is similar to the signal filter, where components of various IMFs are sequentially decomposed from highest frequency to lowest frequency. These components are categorized by their characteristics as noise, trend, and additional composite signals. The noise and trend signals are disregarded and the remaining components are aggregated again as "cycle slip signals". Because most of the noise and trend signals are removed, this cycle slip detection method provides excellent accuracy.

METHODS AND EQUATION

Huang et al. (1998) presented a method for the analysis of random data, called Hilbert－Huang transform (HHT). The method can decompose a non-linear and non-stationary data into IMFs using the EMD method. It has the property of orthogonal, complete and adaptive, which directly analyze the original signal according to the interior time scale of data. The local energy and the instantaneous frequency derived from the IMFs through the Hilbert transform can provide a full energy–frequency–time distribution of the original data in the Hilbert spectrum.

Empirical Mode Decomposition (EMD) method

The EMD is the fundamental part of the HHT. It was developed from an assumption that any data consist of different IMF. The signal for EMD method must follow the assumption:

(1)The signal has at least two extrema: one maximum and one minimum.
(2)The characteristic time scale is determined by the time lapse between the extrema.
(3)If the signal were totally devoid of extrema but contained only inflection points, then it can be differentiated once or more times to reveal the extrema.

The procedure of EMD method is a sifting process iteratively. The process is comprised the following steps:

(1) Assume that *x(t)* is the original signal. Find out the entire extreme of the signal.
(2) Connect all the local maxima and minimum by a cubic spline as the upper and lower envelope respectively (*u(t)* and *l(t)*).
(3) Calculate the mean value of the upper and low envelope value ($m(t)=(u(t)+l(t))/2$). And calculate the difference between the original signal x(t) and m(t)($h(t)=x(t)-m(t)$)
(4) Check whether *h(t)* satisfy the IMF criteria or not.
(5) If not, the above procedure (1)-(3) repeat.

An Intrinsic Mode Function (IMF) is any function defined as follows:

(1)The number of extreme and the number of zero-crossings equal or differing at most by one in the whole data set.
(2)Having symmetric envelopes defined by the local minima and maxima, respectively.

When the *h(t)* components were checked, then it is designated as $c(t) = m(t)$. And we can calculate the residual designated as $r(t)=x(t)-c(t)$. To repeat the process above n times, then n -IMFs of signal $x(t)$ could be obtained. When *r(t)* becomes a monotonic function, the decomposition process can be stopped and there is no more IMFs can be extracted from the signal. Following the process above, the equation below is gained:

$$x(t) = \sum_{n=1}^{n} h_k(t) + m(t) \tag{1}$$

Hilbert-Huang Transform (HHT)

For an arbitrary time series X*(t)*, the Hilbert transform Y*(t)* can be written as:(Huang et al., 1998)

$$\mathrm{Y(t)} = \frac{1}{\pi} \mathrm{PV} \int_{-\infty}^{\infty} \frac{\mathrm{X}(\tau)}{t-\tau} d\tau \tag{2}$$

where PV represents the Cauchy principal value. X*(t)* and Y*(t)* form a complex conjugate pair, so an analytic signal Z*(t)* can be obtained as:

$$Z(t) = a(t)e^{i\theta(t)} = X(t) + Y(t) \tag{3}$$

According to the definition of Hilbert transform, the instantaneous frequency and amplitude are defined as:

$$\omega = \frac{d\theta(t)}{dt} \tag{4}$$

$$a(t) = \sqrt{X(t)^2 + Y(t)^2} \tag{5}$$

With the IMF expansion, the amplitude and the frequency modulations are also clearly separated. Then a variable amplitude and frequency representation of the original data is obtained.

Cycle Slip Detection, Identification, and Adaptation (DIA) Method Based on the HHT

In recent years, the development of global navigation satellite systems (GNSS) has diversified. GNSS include GPS, GLONASS, Compass, Galileo, and other augmentations (satellite-based augmentation systems; SBAS). Systems that are being planned include the Galileo and GPS/GLONASS renewal programs. Therefore, considering method versatility and generality, we used original observables to perform the cycle-slip detection, identification, and adaptation (DIA) processes in this study.

Receiver clock biases can cause signal jump in original observables. These jumps are similar to cycle slip behavior and should be disregarded and eliminated in advance. The effect of receiver clock biases is universal throughout all satellites and can be eliminated by the between-satellite single differences. In this method, a reference satellite with the strongest signal and highest elevation is typically selected from all of the receiving satellites, and the difference between this reference satellite and the remaining satellites is calculated to form a single difference observable. Considering the single difference observable formed by the reference satellite and satellite *i*, when cycle slips occur, they can exist in the reference satellite or satellite *i*, affecting the relevant single difference observable. In addition, if cycle slips occur in the reference satellite, all of the single difference observables are affected. This assists in determining the cycle slips (i.e., in the reference satellite or remaining satellites). To consider the simultaneous occurrence of cycle slips in multiple satellites, a more complex logical judgment method is required. In practical application, the double differencing model is used for relative positioning typically. Consequently, cycle slip compensation for single difference observables satisfies the double differencing model requirements.

The input signals for the EMD method require a maximum and a minimum value. Subsequently, GNSS observables have linear trends during satellites' ascending and descending stages. This shows that GNSS observables do not comply with EMD input signal requirements. The EMD method typically uses one or multiple differential to produce the extreme value, and uses one or several integrations to produce results. However, one or multiple derivatives can alter the physical significance of the input signals. Therefore, we substituted the input signals that were produced by derivative methods with residuals following low-degree polynomial fitting. The polynomial order sequentially follows one order, two orders, three orders, and so on until the residuals comply with the EMD input signal requirements. In addition, the polynomial signals must be included during signal recomposition or recovery.

After the data is decomposed by EMD, the generated IMF signals undergo a Hilbert Transform to determine the signal amplitude and instantaneous frequency. The higher the level of IMF component signals, the higher the frequency. Therefore, following signal decomposition through EMD, the high frequency IMF components are disregarded and the signals are recomposed. This process is a type of low-pass filter.

These concepts can separate the effects of satellite movement and atmospheric changes (low frequencies, large amplitudes) from input signals. Furthermore, remaining signals can be summed and considered "cycle slip signals." Specifically, all IMF components initially undergo frequency analysis. The IMF components with corresponding maximum frequency values of less than 1/1200 Hz (20 min) are disregarded. The remaining signals are retained, summed, and considered to be "cycle slip signals." In addition, to decrease noise influences, frequency evaluation and signal summing are only used on components with amplitudes greater than 0.2 cycle. Because cycle slip signals only comprise cycle slip values and partial observable noise values, the calculated value can be directly rounded to the nearest integer number to obtain the cycle slip value. Calculated data that are not 0 indicate the occurrence of cycle slips, and with further verification of the occurrence epoch and size, detected cycle slips can be compensated. The following flow chart explains relevant procedures:

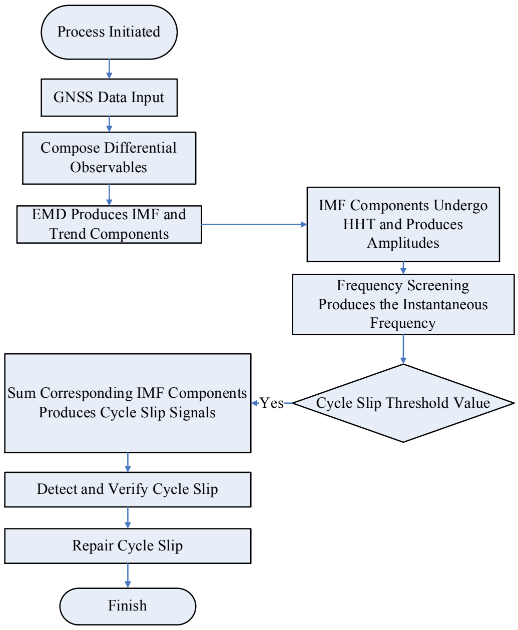

Figure 1: Application of EMD for Cycle Slip Correction Flow Chart

RESULTS

In this study, the method proposed was conduct experiments employing actual observational data with simulated cycle slips in New Taipei City, Taiwan. The Leica SR530 receivers were as the experimental instrument and obtained data on the August 18, 2011 from 02:00 to 03:00 at sample intervals of 1 second. In addition, we adopted L1 carrier phase measurements as the original signals in this test. The PRN 6 satellite (PRN 3 as reference satellite) was selected signal out of the total 3,600 epoch signal sequences as the test object. At the 1800 epoch, we included simulated cycle slips with values of 1 and analyzed the results.

Figure 2 shows the observable and IMF component chart. The first row represents the signal time sequence following the satellite differential measurements. The second row represents the EMD input signals (the residuals from polynomial fitting). IMF1 to IMF10 represents the IMF components after the signals were decomposed by EMD. The last row represents the obtained trend signals following decomposition.

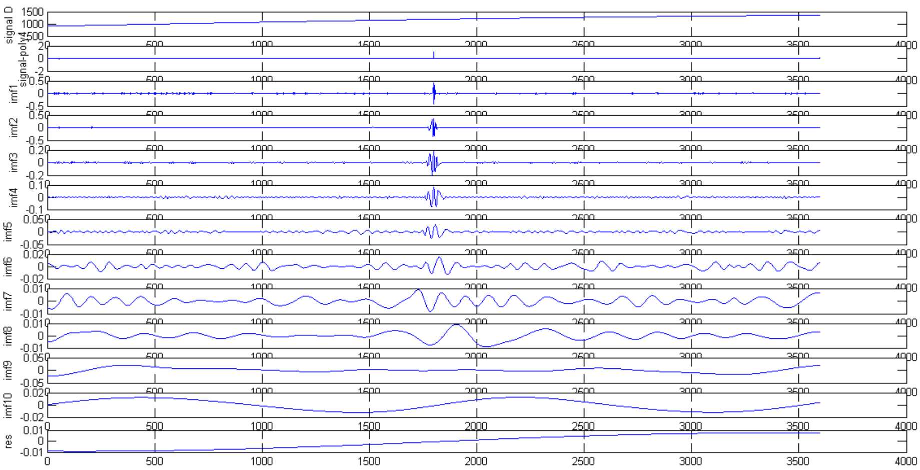

Figure 2: Component Chart with One Cycle Slip Signal Inclusion Following EMD

Figure 2 shows that the first several IMF components possessed abnormal jumps following cycle slip epoch inclusion. This indicates that the cycle slip effects were distributed among the first few high-frequency IMF components. Subsequently, the various component amplitudes and instantaneous frequency relation were determined by using HHT on the IMF components. Figure 3 shows the component amplitudes and Figure 4 shows the component instantaneous frequency.

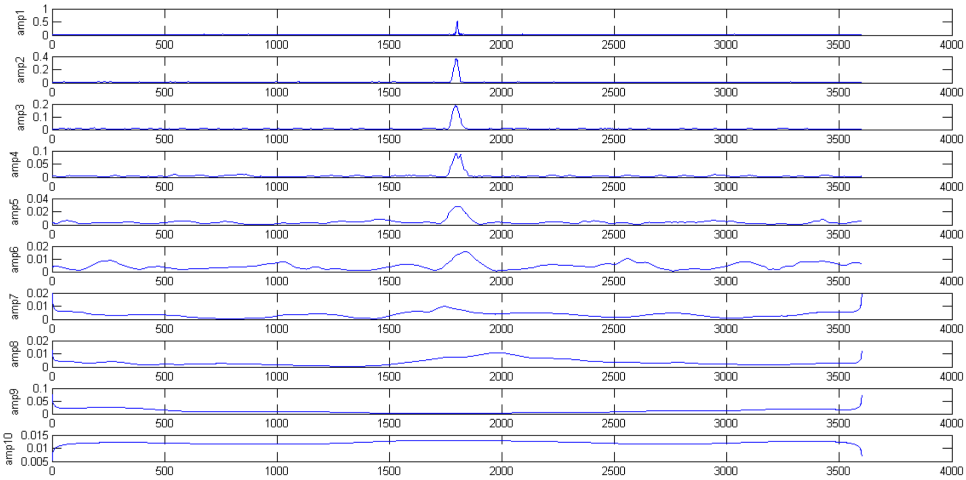

Figure 3: Amplitude Diagram with One Cycle Slip Signal Inclusion Following HHT

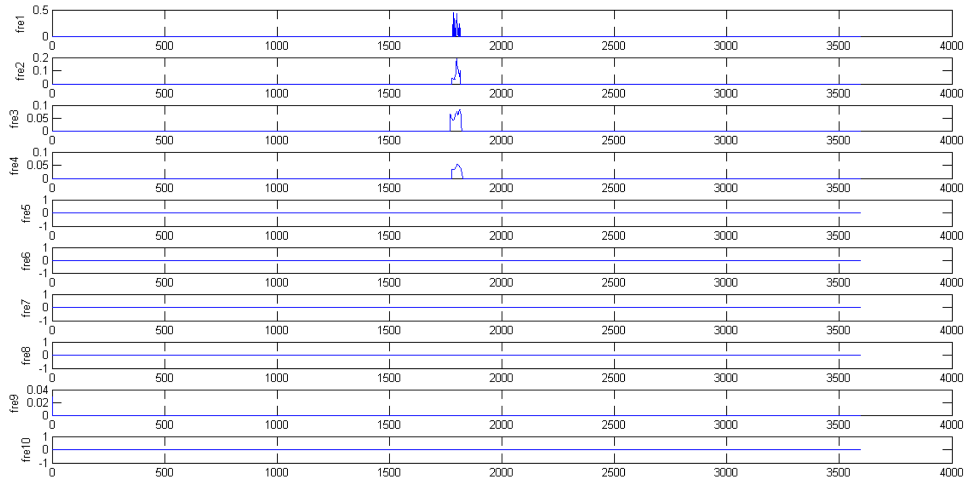

Figure 4: Instantaneous Frequency Diagram with Value 1 Cycle Slip Signal Inclusion Following HHT

Figure 3 shows that the amplitude in the abnormal signal section of the IMF component were greater than the other time or epoch sections. We compared these results with the instantaneous frequency diagram (Figure 4), and found that the instantaneous frequency for this epoch was greater than the threshold value (1/1200 Hz). By applying the methods previously mentioned and employing frequency and amplitude threshold values for screening, the corresponding IMF components for satisfying cycle slip signal threshold conditions were summed and cycle slip signals were obtained (Figure 5). Figure 5 shows that one cycle slip occurred and precisely matched the simulated epoch and size of the cycle slip that we included. The same simulation was conducted 11,947 times with varying cycle slip sizes of 1, 5, and 10. In addition, we simulated various times and satellites. All 11,947 simulations successfully compensated for the cycle slips.

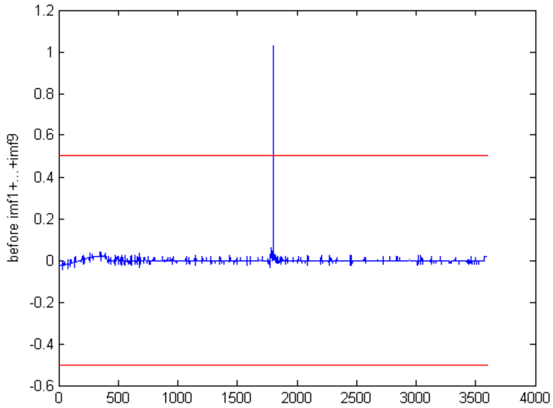

Figure 5: Cycle Slip Signal Diagram with One Cycle Slip Signal Inclusion

CONCLUSIONS & RECOMMENDATIONS

This study proposed a cycle slip DIA method based on HHT that successfully completed cycle slip detection and compensation. Because the method proposed in this study primarily analyzes sequential data, the number of observation satellites is not a limitation. During the testing, we included cycle slips of various sizes into the static data and verified that the method proposed in this study can successfully perform compensation. However, the compensation of kinematic data remains to be tested.

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