MULTIPATH MITIGATION BY WAVELET ANALYSIS FOR GPS BASE STATION APPLICATIONS

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ABSTRACT

It is well known that multipath disturbance is one of the major error sources impacting on high precision GPS positioning. The multipath disturbance is largely dependent on the receiver's environment since satellite signals can arrive at the receiver via multiple paths, due to reflections from nearby objects such as trees, buildings, vehicles, etc. Although the multipath effect can be reduced by choosing sites without multipath reflectors or by using choke-ring antennas to mitigate the reflected signal, it is difficult to eliminate all multipath effects from GPS observations. Since the geometry between the GPS satellites and a specific receiver-reflector location repeats every sidereal day, multipath tends to exhibit the same pattern between consecutive days. This repetition can then be useful for verifying the presence of multipath through the analysis of observations made at a static receiver on different days. In this study, the authors apply a wavelet decomposition technique to extract multipath from GPS observations. The extracted multipath signature is then applied directly to the GPS observations to correct for the multipath effects. The results show that the proposed method can be used to significantly mitigate the multipath effects at a permanent GPS station.

INTRODUCTION

GPS carrier phase observations are widely used for all high precision static and kinematic positioning applications. The least-squares estimation method is usually employed for the processing of such GPS observations. The least-squares method is based on the formulation of a mathematical model consisting of the functional model and the stochastic model. If the function model is adequate, the residuals obtained from the least-squares solution should be randomly distributed. However, the GPS observations are contaminated by several types of biases such as the orbital bias, the atmospheric biases, multipath disturbance, and receiver noise. A double-differencing technique is commonly used for constructing the functional model as it can eliminate or reduce many of the troublesome GPS biases (i.e. the atmospheric biases, the receiver and satellite clock biases, and the orbital bias). However, some unmodelled biases still remain in the GPS observations, even after such data differencing. Multipath is a major residual error source in the double-differenced GPS observables, and it can have a significant impact on the positioning results.

To obtain accurate positioning results from GPS it is necessary to minimise the magnitude of multipath disturbance of the GPS observations. Recently, some wavelet-based techniques have been introduced in the field of GPS data processing (e.g., [4], [5], [11], [13]). These methods have addressed some potential applications such as signal denoising, outlier detection, bias separation and data compression. A new technique using wavelet decomposition is proposed for extracting or modelling multipath from GPS carrier-phase observations. The technique is first applied in order to decompose GPS double-differenced residuals into low-frequency bias and high-frequency noise terms. The extracted bias component is then applied directly to the GPS observations to correct for the trend introduced by this error component. The remaining terms, largely characterised by the GPS range observations and high-frequency measurement noise, are expected to give the best linear unbiased solutions from a least-squares process.

This paper is organised as follows. An introduction to existing multipath mitigation techniques is presented. The theory of wavelet decomposition and its application to GPS data processing is then described. A discussion of experimental results and analyses are presented in a subsequent section. Finally, some concluding remarks are made.

MULTIPATH MITIGATION TECHNIQUES

Mulipath is a phenomenon whereby satellite signals can arrive at the receiver via multiple paths, due to reflections from nearby objects such as trees, buildings, the ground, water surfaces, vehicles, etc. It can be reduced by choosing sites without multipath reflectors or by using choke-ring antennas to mitigate the reflected signal. However, it is difficult to eliminate all multipath effects from GPS observations only through careful site selection and the use of special antenna types. For example, in structural monitoring applications it may not be possible to find suitable antenna sites that are *not* susceptible to multipath.

[17] described two techniques, namely Multipath Elimination Technology and Multipath Elimination Delay Lock Loop, used to mitigate multipath at the receiver signal processing level. Most modern GPS receivers now employ similar algorithms. However, multipath cannot be completely removed and the residuals may still be too large to ignore when high accuracy positioning results are required. It is therefore essential to investigate post-reception data processing techniques for mitigating the effect of multipath. Fortunately the multipath disturbance has a periodic characteristic and is repeated every sidereal day for a static receiver if the antenna environment remains the same. Several post-reception methods to mitigate multipath have been proposed. [8] suggested a technique that requires a preparation of 'maps' of the multipath environment surrounding the GPS antenna. The limitation of this technique is that it will only work well if the antenna environment remains unchanged. [1] proposed a technique that relies on the analysis of the signal-to-noise-ratio (SNR) values of GPS signals. However, this technique cannot be used in real-time. [2] proposed the use of a 'multipath template' for mitigating multipath. [9] also proposed the use of finite impulse response (FIR) filters to extract or eliminate multipath. However, the limitation of such techniques is that signals (for example, crustal deformation) falling in the same frequency band as the FIR filters will be filtered out [6]. An effective technique based on the use of an adaptive filter to extract and eliminate multipath was suggested by [7]. This is due to the fact that GPS observation noise tends to change with time, it is therefore more appropriate to use an adaptive filter rather than a fixed filter for the purpose of multipath mitigation. The implementation of such a technique is dependent on the selection of appropriate value for the step-size parameter and the filter length. Further investigations are still needed on post-reception techniques.

WAVELET TRANSFORM

Wavelet Transform (WT) is a new tool for signal analysis that can provide, simultaneously, time and frequency information of a signal sequence. WT has many potential applications in filtering, sub-band coding, data compression and multi-resolution signal processing (see, for example, [3], [18]). In particular, the WT is of interest for the analysis of non-stationary signals such as GPS observations because it provides an alternative to the classical Fourier Transform (FT), which assumes stationarity in signals. It can be viewed as an extension to Fourier analysis that is well-suited for characterising signals whose spectral character changes with time. Such signals are not well represented in time and frequency by the Fourier Transform methods. The method of wavelet analysis is closely related to the time-frequency analysis based on the Wigner-Ville distribution [12]. Mathematical details on wavelet analysis can be found in [3], [12] and [18].

Multi-resolution analysis provides a formal approach to constructing the wavelet basis. The basic concept of multi-resolution analysis is to analyse the signal at different scales by using filters of different cut-off frequencies. The signal is passed through a series of high-pass filters to analyse the high frequencies, and it is passed through a series of low-pass filters to analyse the low frequencies. Therefore, the Wavelet Transform can be used to achieve enough frequency resolution to discriminate these terms in the original GPS observation. Figure 1 illustrates the multi-resolution analysis process using the wavelet transform. Applying a narrow daughter wavelet to the original signal is equivalent to applying a high-pass filter, which completes path 1. Extracting the leading low-frequency requires applying a number of daughter wavelets that are wider than the signal you need to match, then applying a final daughter wavelet that becomes a high-pass filter, completing path 2.

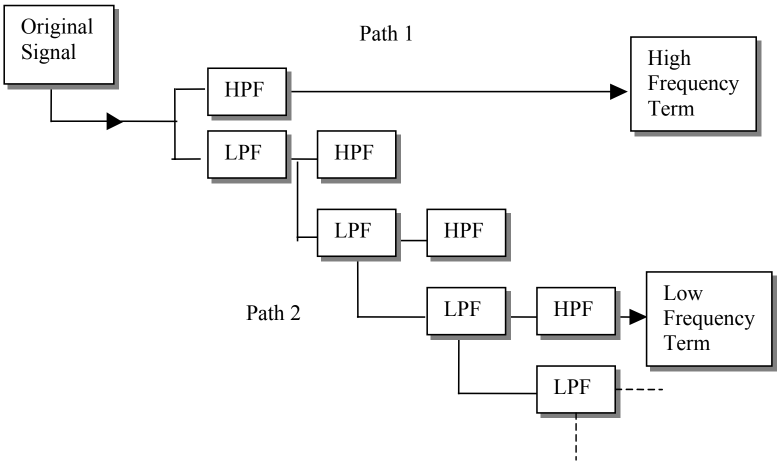

Fig. 1 Multi-resolution analysis using the wavelet transform [15].

GPS SIGNAL PROCESSING USING WAVELETS

[4] first introduced the wavelet transform for the purpose of GPS cycle slip correction. [5] has outlined some of the applications of wavelets to GPS data processing. According to their study, GPS bias terms such as multipath and ionospheric delay behave like low-frequency noise and the observation noise as high-frequency noise. [11] introduced the wavelet transform to analyse the GPS-RTK results in a structural monitoring application. [13] and [14] applied wavelets to

separate the systematic error component from the noise component in the GPS double-differenced (DD) residuals. Figure 2 shows an example of signal extraction using wavelets.

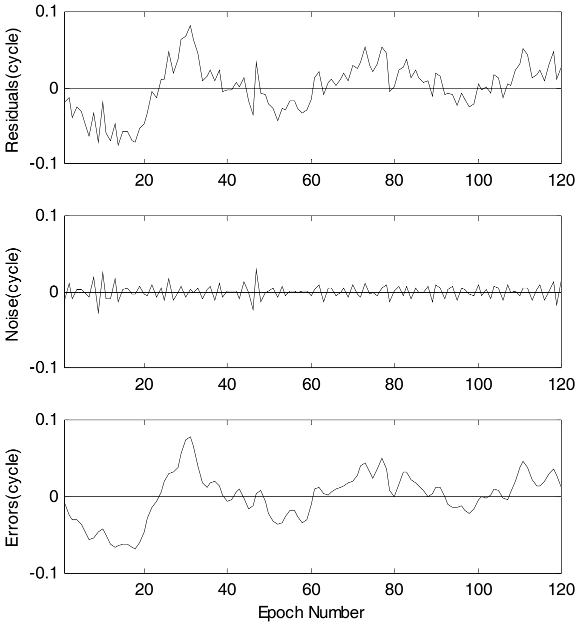

Fig. 2 Signal extraction using wavelets.
Top: Original DD residuals. Middle: Extracted noise component. Bottom: Extracted systematic component.

An important step is to find the most suitable mother wavelet to use in the transformation process. The properties of Symlets wavelet are well-suited for processing GPS signals [10]. However, an optimal level for the decomposition of multipath disturbance must be decided upon.

EXPERIMENTAL RESULTS AND ANALYSES

Data Acquisition

The experiment was carried out on top of the Vidhayanives building at the Chulalongkorn University, Bangkok, Thailand, using data collected by three dual-frequency GPS receivers (Leica system 500). The data were collected in static mode from 25 October 2002 to 28 October 2002 at a 15-second data rate. In order to investigate the noise characteristics for this receiver type, data were collected by connecting a pair of receivers (the first and second receivers) to the same antenna at Station ‘A’. Station ‘A’ can be considered as a multipath-free site since it has a very good observing environment (see figure 3). The third receiver was used to collect data at Station ‘B’, which is very close to a concrete wall (see figure 4). The baseline length between A and B is about 8 metres. Figure 5 illustrates the configuration of the experiment.

Fig. 3 Station 'A' on top of the Vidhayanives building, Chulalongkorn University.

Fig. 4 Station 'B' on the Vidhayanives building, Chulalongkorn University.

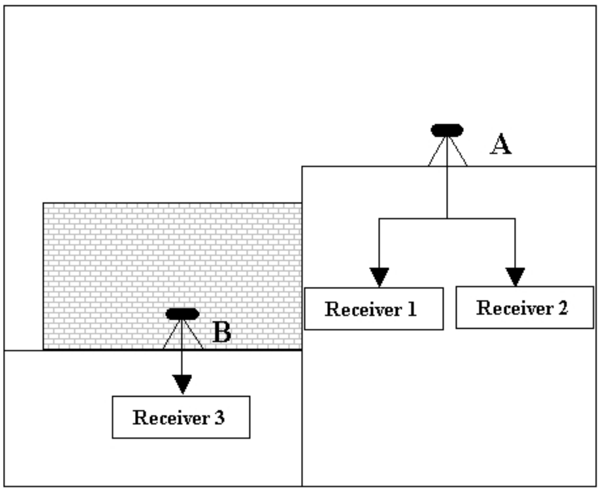

Fig. 5 Configuration of the experiment

In relation to the configuration shown in figure 5, the following can be noted:

- The double-differenced carrier-phase residuals obtained from the first receiver and the second receiver represents only observation noise because the other error sources are eliminated due to the use of the same antenna for both receivers. This configuration is known as the 'zero baseline' test.

- Since the baseline length is only about 8 metres, errors such as ionospheric, tropospheric and orbit biases are assumed to be essentially zero. The double-differenced carrier-phase residuals obtained from the first (or second) receiver and the third receiver, therefore, exhibit only multipath and observation noise.

Data Processing

In this investigation the TEQC software was used to check the multipath effect on all the satellites tracked. As expected, significant multipath effects were found on many satellite signals at Station 'B'. The data obtained from stations 'A' and 'B' were then processed using the SNAP baseline software to produce DD residuals for all satellite pairs. The DD residuals show multipath disturbance for many satellite pairs such as PRN8-7, PRN15-14, PRN26-18, and PRN31-2. Figure 6 shows an example of multipath series on DD carrier-phase observations from four consecutive days for satellite pair PRN8-7.

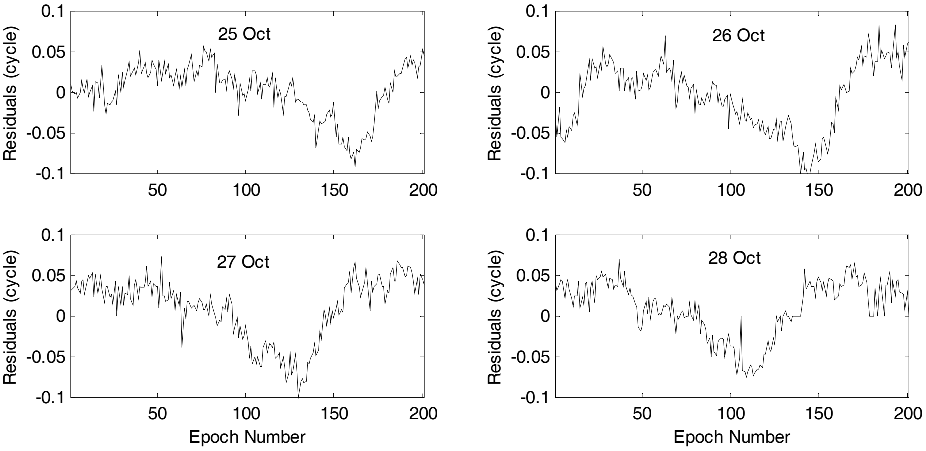

Fig. 6 Multipath series on DD carrier-phase observations (PRN8-7) for four consecutive days.

The zero baseline data collected at Station 'A' was also processed using the SNAP baseline software. The DD residuals obtained from the zero baseline should represent the true GPS observation noise. Figure 7 shows the DD residuals obtained from the zero baseline for satellite pair PRN8-7.

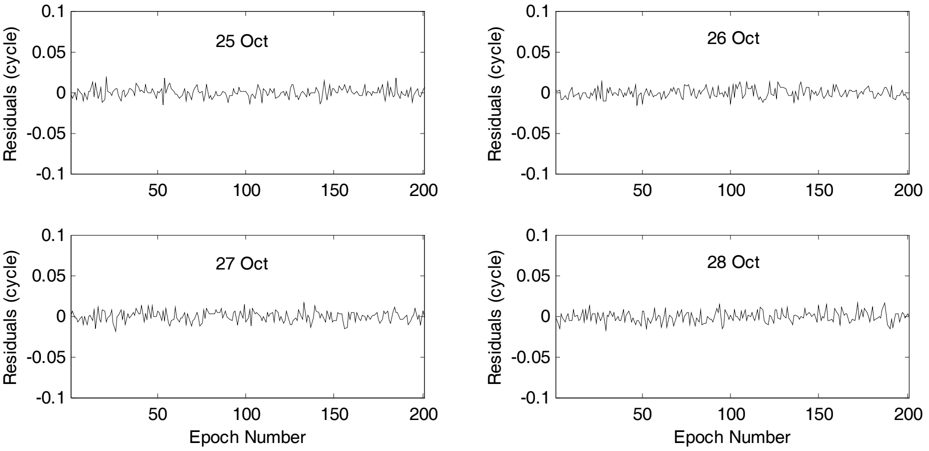

Fig. 7 DD residuals obtained from zero baseline for PRN8-7 between 25 and 28 Oct 2002.

The wavelet transform was used to decompose the DD residuals from the short baseline into low-frequency bias and high-frequency noise terms for each satellite pair. Three levels of decomposition were performed, resulting in the high-frequency noise term at each level. Since the results showed a similar trend for all satellite pairs, extracted high-frequency and low-frequency terms at different decomposition levels were plotted against the original DD observations for the satellite pair PRN8-7 only in figure 8. In figure 8(a), the black line denotes multipath series on DD carrier-phase observations, while the grey line shows the zero baseline DD residuals. Figures 8(b) to 8(d) show the extracted multipath component (in black) and noise component (in grey) at 1st, 2nd and 3rd decomposition levels respectively.

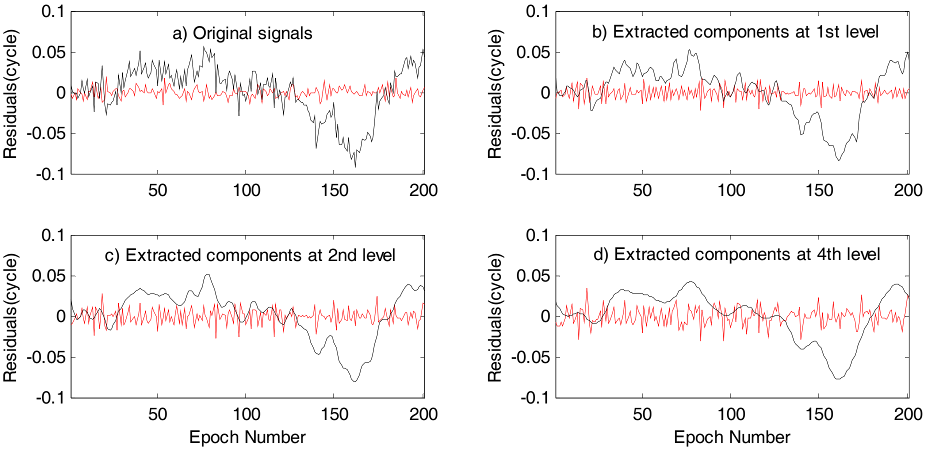

Fig. 8 Comparison of the extracted bias and noise components at different decomposition levels using wavelets and original observations for PRN8-7 on 25 Oct 2002.

Analysis of Results

The results obtained in the previous section have been tested for the equality of standard deviations of the two samples: the real GPS observation noise obtained from zero baseline and the extracted noise component at each level of decomposition. The commonly used two-tailed F-test was chosen to test if the standard deviations of the two samples are equal. Since GPS observation noise changes with time implies a nonstationarity property for the GPS signal, the standard deviation value calculated using an entire data span should not be used in the statistical test. We therefore restricted the time span to 5 minutes for the tests. A total of ten standard deviation values for each data set were calculated using the 5-min data span. The F hypothesis test is defined as [16]:

$$H_0 : \sigma_1 = \sigma_2 \text{ (Null hypothesis)}$$
$$H_a : \sigma_1 \neq \sigma_2 \text{ (Alternative hypothesis)}$$

σ_1 denotes the standard deviation value calculated from the real GPS observation noise, while σ_2 is the standard deviation value calculated from the extracted noise component at each decomposition level. 5% significance level was used for the hypothesis testing. Table 1 shows a summary of the results obtained from the hypothesis testing. It is clearly seen from table 1 that the largest number of acceptances of the null hypothesis is achieved from the extracted noise component at the 1st level of decomposition. Similar results can also be obtained from different days and for other satellite pairs. It can be concluded that the use of 1st level wavelet decomposition produces the best fit to the multipath disturbance signal.

Table 1. *Summary of results using F-test at 5% significance level*

Decomposition level	Null hypothesis (H_0)	
	No. of Accept	No. of Reject
1st level	8	2
2nd level	6	4
3rd level	3	7

In a further investigation, we attempted to evaluate the effectiveness of the wavelet decomposition technique. The multipath series of DD carrier-phase observations (PRN8-7) for four consecutive days, as displayed in figure 6, were removed using the 1st level wavelet decomposition technique. Figure 9 illustrates the results for carrier-phase multipath for the four consecutive days.

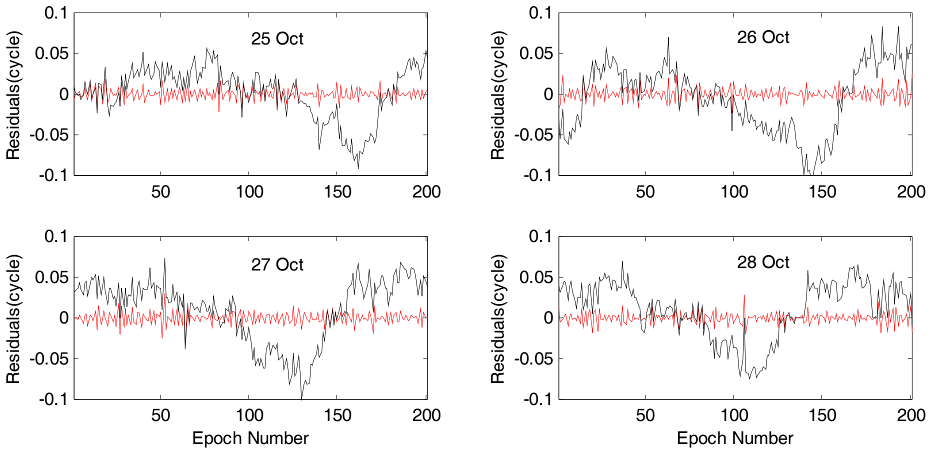

Fig. 9 Applying the 1st level of wavelet decomposition to multipath series on DD carrier-phase observations (PRN8-7) for four consecutive days.

The black line in each subplot represents the original multipath series, while the grey line is the time series after the multipath disturbance has been removed. The results are summarised in Table 2.

Table 2. *Standard deviation of carrier-phase time series before and after multipath reduction using wavelets (unit: cycle)*

Data set used	Multipath reduction	
	Before	After
Day 1 (25 Oct)	0.0318	0.0076
Day 2 (26 Oct)	0.0415	0.0085
Day 3 (27 Oct)	0.0388	0.0082
Day 4 (28 Oct)	0.0345	0.0074

The results from Table 2 clearly demonstrates the performance of the proposed method. Carrier-phase multipath has been significantly reduced.

CONCLUDING REMARKS

In this paper, multipath mitigation techniques and wavelet transform have been briefly reviewed, and a new multipath mitigation technique based on the use of wavelet decomposition has been proposed. The optimal level for wavelet decomposition of multipath disturbance has been identified. The results from the proposed method indicate that carrier-phase multipath can be removed, leaving only the GPS observation noise. The proposed method can therefore be used to correct for multipath at permanent GPS stations which support many differential positioning applications.

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