Wavelet Analysis: Multipath Mitigation from GPS Carrier Phase Observation

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Abstract--**Multipath mitigation techniques using wavelet decomposition is proposed for extracting or modeling multipath from Global Positioning System (GPS) carrier phase observations. Multipath 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. Wavelet transform (WT) is a new tool for signal analysis that can provide simultaneously, time and frequency information of a signal sequence. Double Differencing (DD) technique was used to detect the multipath effect and the quality of GPS data was checked by using TEQC software.The wavelet technique Symlets(sym4) was used to perform the wavelet transform and de-noising the signal by using thresholding. GPS data which in RINEX format that supplied by JUPEM (Department Of Survey and Mapping Malaysia) and taken from receiver station located at Wisma Tanah Kuala Lumpur (3° 10' N, 101° 43' E) KTPK station and Universiti Putra Malaysia(2° 59' N, 101° 43' E) UPMS station on 8 November 2005. The DD multipath and wavelet decomposition is visualized using MatLab software. The results indicate that the proposed method is effective to reduce carrier-phase multipath effect.**

Keywords--**Global Positioning System (GPS), Wavelet Transform (WT), Multipath, Double Differencing (DD), De-noised Signal**

1.0 INTRODUCTION

Global Positioning System (GPS) carrier phase observations are widely used for all high precision static and kinematic positioning applications. 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 [1,2,3,4]. These methods have addressed some potential applications such as signal de-noising, outlier detection, bias separation and data compression. A new technique using wavelet decomposition is proposed for extracting or modeling 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.

2.0 MULTIPATH MITIGATION IN GPS

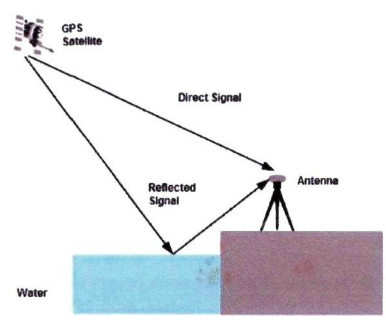

Fig.1: Multipath Effect in GPS Signal

Multipath is a significant source of error, especially for differential positioning in high accuracy applications. Multipath is the phenomenon whereby a signal is reflected or diffracted from various objects in the environment and arrives at the receiver via multiple paths. A GPS receiver cannot distinguish between a direct and reflected signal, and as a result, the receiver tracking loops align the locally generated code and carrier to the composite signal instead of the direct signal causing the multipath error.

If the reflecting surface is smooth, then the reflected signal is deterministic in nature and is called specular multipath. On the other hand, if the GPS signal incidents on sharp edges or rough surfaces, then the reflected signal is scattered in all directions and is called diffuse multipath. Specular multipath is a more serious problem in static applications whereby the periodicity of range error induced by it can reach values in the order of one hour. Multipath induced errors are prevalent in both code range and carrier phase measurements in a receiver.

3.0 BASELINE SOLUTION BY LINEAR COMBINATION

The accuracy achievable by pseudoranging and carrier phase measurement in both absolute and relative positioning surveys can be improved through processing that incorporates differencing of the mathematical models of the observables. Processing by differencing takes advantage of correlation of error between receivers, satellites, and epochs, or combinations thereof, in order to improve GPS processing. Through differencing, the effects of the errors that are common to the observations being processed are eliminated or at least greatly reduced. Basically, there are three broad processing techniques that incorporate differencing: single differencing, double differencing and triple differencing. Differenced solutions generally proceed in the following order: differencing between receivers takes place first, between satellites second, and between epochs third shown at Fig. 2.

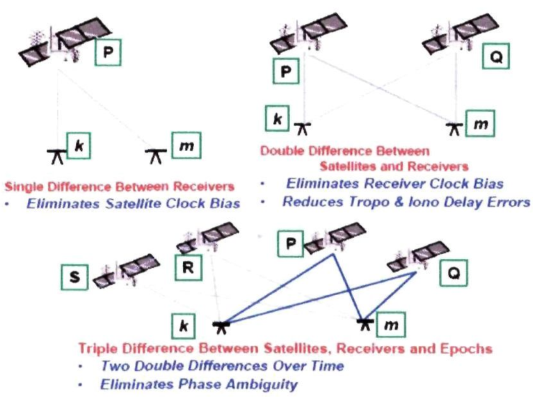

Fig.2: Carrier phase differencing techniques.

3.1 Double Difference

Double differencing is actually a differencing of two single differences (as in Fig.2). There are two general double differencing processing techniques: receiver-time and receiver-satellite. Double difference processing techniques eliminate clock errors.

i) Receiver-time double differencing. This technique uses a change from one epoch to the next, in the between-receiver single differences for the same satellite. Using this technique eliminates satellite dependent integer cycle ambiguities and simplifies editing of cycle slips.

ii)Receiver-satellite doubles differencing. There are two different techniques that can be used to compute a receiver-satellite double difference. One technique involves using two between-receiver single differences, as shown in the upper right of Fig.2. This technique also uses a pair of receivers, recording different satellite observations during a survey session and then differencing the observations between two satellites. The second technique involves using two between-satellite single differences. This technique also uses a pair of satellites, but different receivers, and then differences the satellite observations between the two receivers.

The expressions for single differences between receivers and satellites can be formed from the general carrier phase observable given back in [5] which are repeated below. Refer also to Fig. 2. For a first receiver "k" equation can be written for propagation between satellite "P" and the first receiver "k":

$$\boldsymbol{\phi}_k^P(\boldsymbol{t}) = \phi_k^P(t) - \phi^P(t) + N_k^P + S_k + f\,\tau_P + f\,\tau_k - \beta_{iono} + \delta_{tropo} \qquad (1)$$

$\boldsymbol{\phi}_k^P(\boldsymbol{t})$ = length of propagation path between satellite "P" and receiver "k" ... in cycles
$\phi_k^P(t)$ = received phase of satellite "P" at receiver "k" at time "t"
$\phi^P(t)$ = transmitted phase of satellite "P"
N_k^P = integer ambiguity
S_k = measurement noise (multipath, GPS receiver, etc.)
f = carrier frequency (Hz)
τ_P = satellite clock bias
τ_k = receiver clock bias
β_{iono} = ionospheric advance (cycles)
δ_{tropo} = tropospheric delay (cycles)

For a second receiver "m" another equation can be written for the propagation path between satellite "P" and the second receiver "m":

$$\boldsymbol{\phi}_m^P(\boldsymbol{t}) = \phi_m^P(t) - \phi^P(t) + N_m^P + S_m + f\,\tau_P + f\,\tau_m - \beta_{iono} + \delta_{tropo} \qquad (2)$$

Differencing the propagation path lengths between the two receivers "k" and "m" to the satellite "P" (Equations 1 and 2) results in a "single difference between receivers".

$$SD_{km}^{P} = \phi_{km}^{P} + N_{km}^{P} + S_{km}^{P} + f\,\tau_{km} \quad (3)$$

When a second satellite "Q" is added, a "single difference between receivers" can be formed for the second satellite "Q":

$$SD_{km}^{Q} = \phi_{km}^{Q} + N_{km}^{Q} + S_{km}^{Q} + f\,\tau_{km} \quad (4)$$

The "single difference" equations 3 and 4 can be differenced between themselves, thus creating a "double difference" involving two separate receivers (*k* and *m*) and two separate satellites (*P* and *Q*).

$$DD_{km}^{PQ} = \phi_{km}^{PQ} + N_{km}^{PQ} + S_{km}^{PQ} \quad (5)$$

It is seen in the above "double difference" equation that most of the original unknown terms have been eliminated by these differencing techniques, with only the integer ambiguity (*N*) and noise (*S*) remaining to be determined. Additional "double difference" equations can be written for the two receivers between other combinations of epochs of satellites in view, and these multiple double difference equations can be again differenced (i.e. Triple Differenced) to remove the integer ambiguity term *Nkm PQ*.

$$TD_{km}^{PQ} = DD_{km}^{PQ}(t+1) - DD_{km}^{PQ}(t) \quad (6)$$

where t and $t + 1$ are successive epochs

The results of the Triple Difference baseline solution can then be input back into the Double Difference equations in order to resolve, or "fix," the integers in the Double Difference solution. Fixing the integers in a Double Difference solution constrains the integer ambiguity *N* to a whole number of cycles, and is the preferred baseline solution [6].

4.0 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 [7, 8]. 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 characterizing 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 [9]. The main advantage of WT is that it has a varying window size in which the wide one is good for slow frequency component and the narrow one for fast frequency; hence it provides good resolution in both time and frequency [10].

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. Fig.3 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.

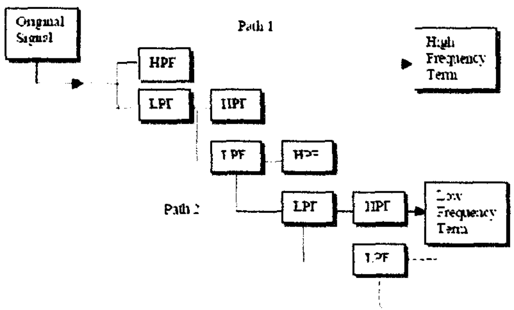

Fig.3: Multi-resolution analysis using the Wavelet Transforms [11]

4.1 GPS Signal Processing Using Wavelet

GPS signal processing using wavelet first introduced the wavelet transform for the purpose of GPS cycle slip correction [1]. Fu and Rizos (1997) have 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. Introduced the wavelet transform to analyse the GPS-RTK results in a structural monitoring application [3]. Applied wavelets to separate the systematic error component from the noise component in the GPS double differenced (DD) residuals [4, 12]. Figure 4 shows an example of signal extraction using wavelets.

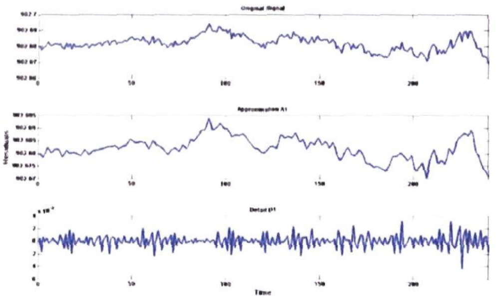

Fig.4: Signal extraction using wavelets.

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 [13]. However, an optimal level for the decomposition of multipath disturbance must be decided upon.

5.0 METHODOLOGY

5.1 Data Acquisition

GPS data which in RINEX format collected on 8 November 2005 measured from receiver station located at Wisma Tanah Kuala Lumpur (3° 10' N, 101° 43' E) KTPK station and Universiti Putra Malaysia(2° 59' N, 101° 43' E) UPMS was processed and analyzed. The data used in this research is supplied by JUPEM (Department Of Survey and Mapping Malaysia). The GPS data was recorded in GPS time system, whereby the sampling interval was 15s and the cut-off elevation mask was 10°. The symlets wavelet was used in this research because it properties well-suited for GPS data processing. The TEQC software used to check the quality of the RINEX data. The data used has been chosen from Local Time Clock (LTC) 10.00 am to 1.00pm (Universal Time Clock, UTC 03:00 am to 06:00 am) and it has been separated to 3 set of data that contain 1 hour period per data. It is from baseline between KTPK station and UPMS station of 27km.

5.2 Method

According to the flow chart at Fig. 5, there are several steps to process the data. First, the TEQC software was use to check the quality of the RINEX data. Then the data obtained from Station KTPK and UPMS were processed using MatLab software to produce DD residuals for satellite PRN 19- 23. The wavelet transform was used to decompose the DD residuals from the 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 PRN19-23 only. Then the signal was de-noised using wavelet analysis. The de-noising process was done by using threshold.

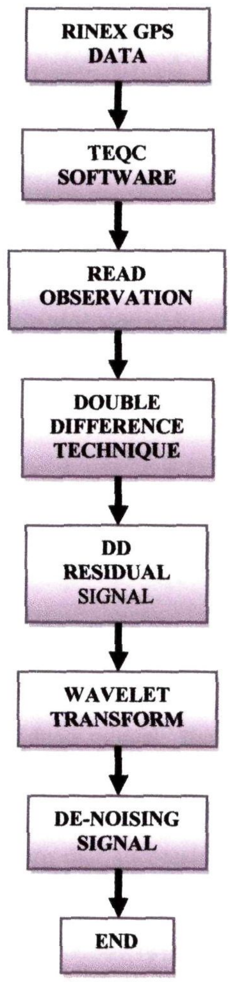

Fig.5: Methodology Flow Chart

6.0 RESULTS AND DISCUSSION

The results of the wavelet transform are presented in this section. The result data has been chosen from Local Time Clock (LTC) 10.00 am to 1.00pm (Universal Time Clock, UTC 03:00 am to 06:00 am) and it has been separated to 3 set of data that contain 1 hour period per data. Also the L1 phase for both KTPK and UPMS stations in 10 minutes period.

After checked the quality of RINEX data using TEQC software, the result shows that the significant multipath effects were found on many satellite signals at UPMS Station. Fig.(6 to 8) shows multipath on DD carrier-phase observations signal for raw data. This signal is for every one hour from 3-4, 4-5 and 5-6 for satellite pair PRN19-23.

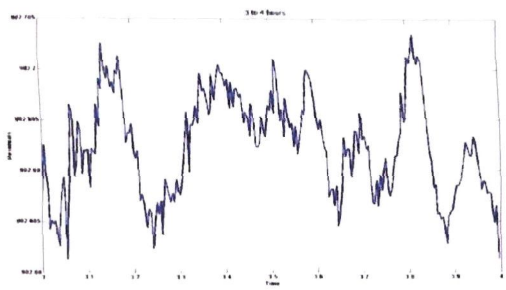

Fig.6: Multipath on DD carrier-phase observation (PRN19-23) for First Data Set: 03:00-04:00 hours.

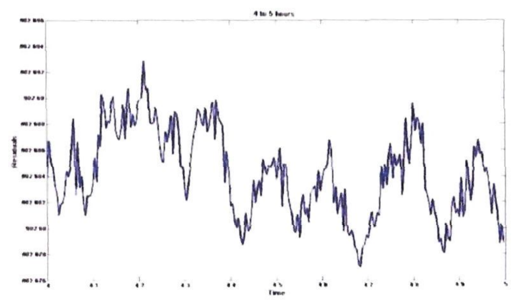

Fig.7: Multipath on DD carrier-phase observation (PRN19-23) for Second Data Set: 04:00-05:00 hours.

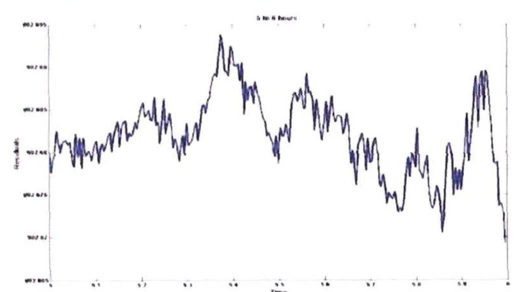

Fig.8: Multipath on DD carrier-phase observation (PRN19-23) for Third Data Set: 05:00-06:00 hours.

The data first decomposed using Symlets (sym4) wavelet at level 3. Then the approximation and detail coefficients were extracted from the wavelet decomposition structure. Reconstructed the original signal from wavelet decomposition structure and the waveform of original signal, approximation and detail were plotted.

Fig.9 and Fig.10 below shows the signal decomposition using Symlets (sym4) at level 3. The first row show the L1 phase signal, second row show the approximation part of signal at level 3 decomposition and 3rd ,4th and 5th row show the detail part of signal. The approximation show the low frequency term and detail show the high frequency term of signal.

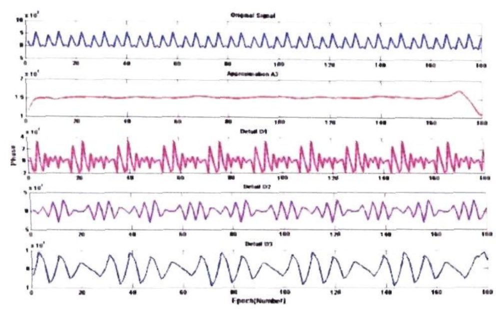

Fig 9: The extracted L1 phase component at level 3 using wavelets. (1st row: L1 phase. 2nd row: Approximation at level 3. 3rd, 4th and 5th row: Detail at level 1, 2 & 3.) for KTPK station.

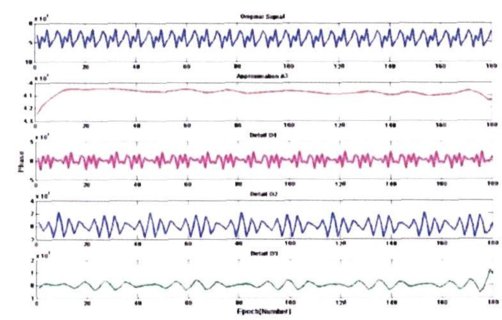

Fig.10: The extracted L1 phase component at level 3 using wavelets. (1st row: L1 phase. 2nd row: Approximation at level 3. 3rd, 4th and 5th row: Detail at level 1, 2 & 3.) for UPMS station.

For DD residuals signal, the result obtained shows below. Fig.11, Fig.14 and Fig.17 below showed the original, approximation and detail of signal decomposition using wavelet decomposition. In this project, note that successive approximations become less and less noisy as more and more high-frequency information is filtered out of the signal. As in figure 11, 14 and 17, the approximation at level 3 it shown that is quite clean compared to the original signal.

6.1 First Data Set: 03:00 to 04:00 for PRN19-23

In Fig.11, the detail part shown that most of multipath effect occurs at the start of signal, where the details show their greatest activity. There are some noisy at the start of signal.

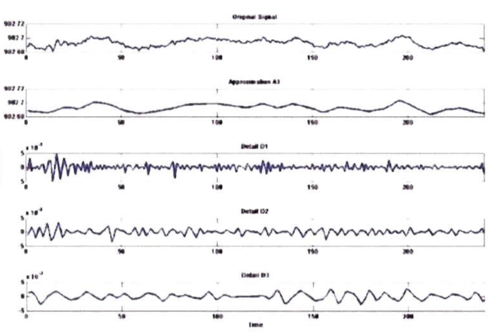

Fig.11: The extracted multipath component at level 3 using wavelets. (1st row: Original DD residual. 2nd row: Approximation at level 3. 3rd, 4th and 5th row: Detail at level 1, 2 & 3.)

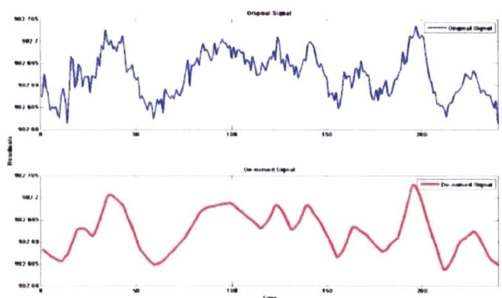

Fig.12: The original signal and de-noised signal for first data set.

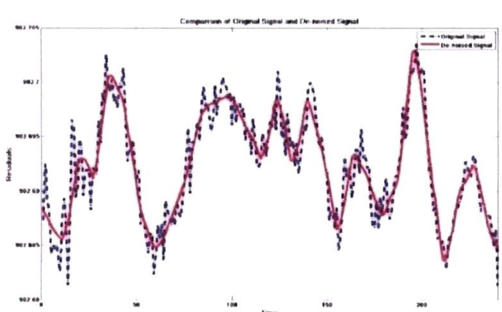

Fig.13: Comparison of original signal and de-noised signal for first data set.

6.2 Second Data Set: 04:00 to 05:00 for PRN19-23

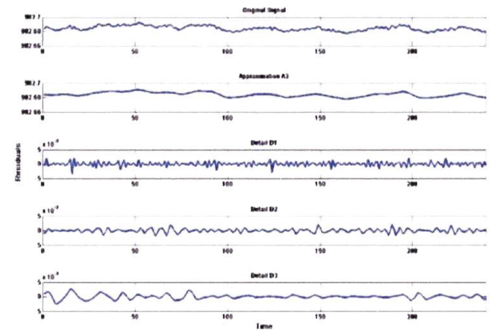

Fig.14: The extracted multipath component at level 3 using wavelets. (1st row: Original DD residual. 2nd row: Approximation at level 3. 3rd, 4th and 5th row: Detail at level 1, 2 & 3.)

As in Fig.14 above, the waveform shows that there are less multipath effect occurred. It can be seen at the detail part in figure above, the waveform of Detail level 1 shows that there are similar trend of multipath from the start to the end of signal.

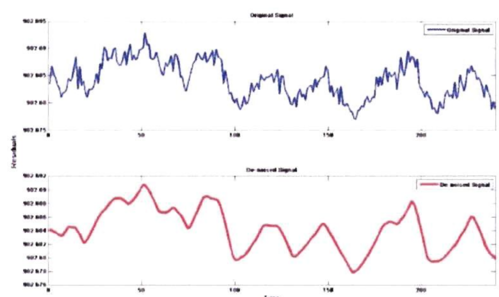

Fig.15: The original signal and de-noised signal for second data set.

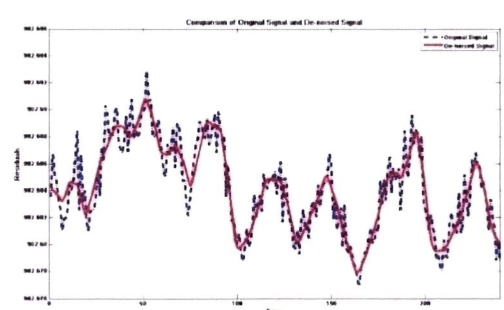

Fig.16: Comparison of original signal and de-noised signal for second data set.

6.3 Third Data Set: 05:00 to 06:00 for PRN19-23

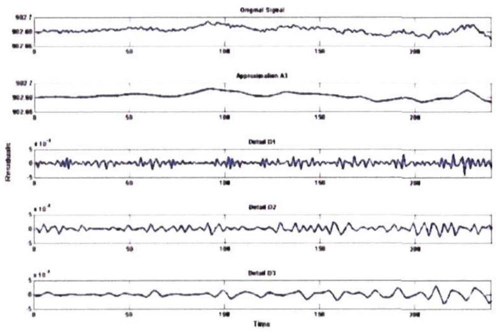

Fig.17: The extracted multipath component at level 3 using wavelets. (1st row: Original DD residual. 2nd row: Approximation at level 3. 3rd, 4th and 5th row: Detail at level 1, 2 & 3.)

For third data set, more multipath effect occurs at latter part of signal. It can be seen at Fig.17 above, original signal and detail signal waveform shows that there are some noisy at the end of it.

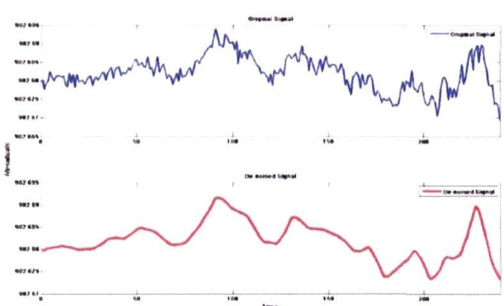

Fig.18: The original signal and de-noised signal for third data set.

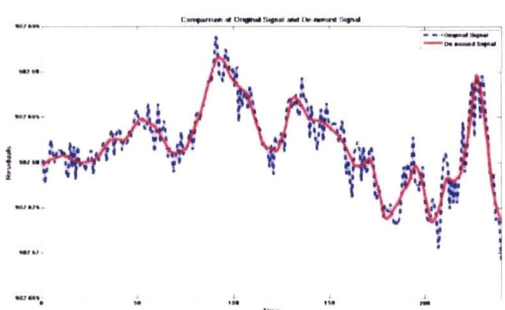

Fig.19: Comparison of original signal and de-noised signal for third data set.

Of course, in discarding all the high-frequency information, many of the original signal's sharpest features have been lost. Optimal de-noising requires a more subtle approach called thresholding. This involves discarding only the portion of the details that exceeds a certain limit.

After signal have been de-noised, it shown that the waveform of de-noised signal are smoother than the original DD multipath signal. Fig.(12, 15 and 18) shows the original and de-noised signal of DD carrier-phase observations signal. The comparison between the original signal and de-noised signal shows in Fig.(13, 16 and 19). The result of de-noised signal can be improved by using more level of decomposition to make it smoother, but the more level of decomposition use, the more of the original signal sharpest features will lost. So, the suitable level of decomposition must be decided first. For this research the level of decomposition use is 3.

The value of standard deviation of the two samples: the original DD residual and de-noised signal have been analyse from the results obtained. Table 1 below shows the value of standard deviation.

Table 1: Standard deviation of carrier-phase time series before and after multipath reduction using wavelets (unit: cycle)

Data Set Used	Multipath Reduction	
	Standard Deviation Before De-noised	Standard Deviation After De-noised
First Data Set	0.004966	0.004613
Second Data Set	0.003323	0.003066
Third Data Set	0.004445	0.004103

The results from Table 1 clearly demonstrate the performance of the proposed method. As shown in the table, carrier-phase multipath has been significantly reduced.

7.0 CONCLUSION

In this project, 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, by de-noised signal using threshold. The more level of decomposition performed, the de-noised signal waveform will be smoother but it will lost the original signal sharpest. The important step is to consider the suitable level of wavelet decomposition. The values of standard deviation shows in Table 1 clearly demonstrate the performance of the proposed method. The proposed method can therefore be used to correct for multipath at permanent GPS stations which support many differential positioning applications.

8.0 FUTURE RECOMMENDATION

The study about Wavelet Analysis by using GPS data has to carry on and need to investigate these features more deeply. This is because this research can contribute to the better way of GPS data processing. There are as follows:

1. Use more data set and analysis the data for more than one day. It can show more multipath pattern for signal in different day.
2. Research about effectiveness of wavelet decomposition technique.
3. Research about the noise in GPS and how to classify it by using wavelet analysis.
4. Research using other de-noising technique to find the best wavelet de-noising technique for GPS signal.
5. Comparison between wavelet and s-transform analysis for GPS signal processing.

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