ANALYSIS ON GPS-RTK TECHNIQUES FOR CONTINUOUS STUCTURAL MONITORING

Muhammad Asyran, Halim Setan & Zulkarnaini Mat Amin

Department of Geomatic Engineering
Faculty of Geoinformation Science and Engineering
University Technology Malaysia
81310 Skudai
Johor
asyran_utm@yahoo.com, halim@fksg.utm.my, zulkarnaini@fksg.utm.my

ABSTRACT

GPS Real Time Kinematics (RTK) can be categorized as one of the new positioning techniques in Malaysia. Unlike the conventional geodetic measurements, RTK has made the task of continuous structural monitoring becomes quicker and effective, without sacrificing much in terms of accuracy and reliability. Continuous structural monitoring is important for safety assessment. This paper discusses the potential of using GPS RTK for continuous structural monitoring in Malaysia. For that purposes, GPS data was observed (at Penang Bridge) using Leica 500 GPS receiver at the rate of 1 Hz. The post processing strategy employs Fourier and Wavelet analysis, together with MATLAB® software, to analyze the bridge vibration and the movement trends. The results indicate the practicality of using GPS RTK for continuous structural monitoring.

1.0 INTRODUCTION

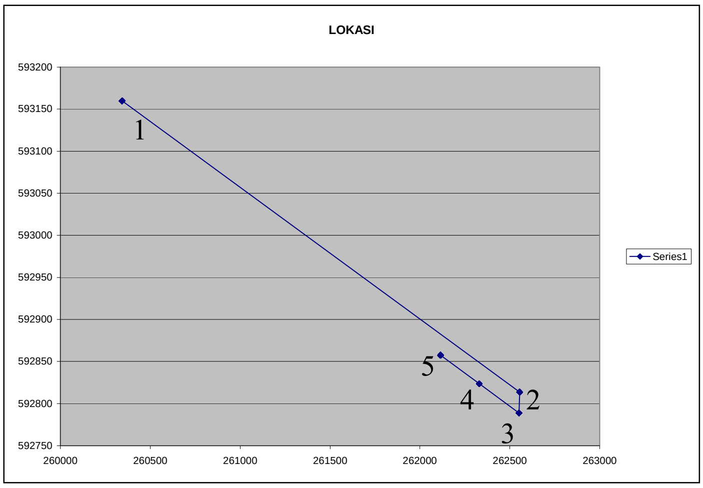
Penang Bridge is well known as the longest cable stayed bridge in Asia and the third longest in the world. The bridge consists of 6.5 km of dual carriageway and 2.2 km three lanes at the main span of Seberang Perai on the mainland to Penang Island across the Penang Channel. The typical dimensions of the bridge are shown in Table 1.

Table 1: Typical Dimensions Of The Bridge

No of spans	533
No of spans above water	192
Main span	225 m
Total length	13.5 km

The bridge is made of prestressed and concrete cable stayed at the main span. There are four towers located at the main span at a height of 101.5 m above the water. Although the bridge was built to withstand earthquake up to 7.5 Ritcher scale, it is also affected by strong constraints caused by winds, traffic loading and temperature variations. Due to those factors, structural monitoring is required for safety assessment and it can be executed in two ways, either by periodical or continuous technique. Currently, Penang Bridge Sdn Bhd (PBSB) is responsible for managing, operating, upgrading and collecting toll from the bridge (Zulkarnaini, 2002).

In this paper, GPS measurements have been executed at five points on the bridge. The location of each point, numbers of GPS RTK observations and their coordinates are shown in Figure 1.



Stations	No Observations	Coordinate	
		E	N
1	917	260343.903	593159.882
2	947	262554.818	592813.827
3	922	262550.379	592788.846
4	928	262329.222	592823.664
5	926	262113.902	592857.486

Figure 1: Location, numbers of observation and coordinates of each points on Penang Bridge

2.0 METHODOLOGY

The methodology of this research is divided into four main steps: pre-processing, processing, analysis and interpretation of result and conclusion (Figure 2).

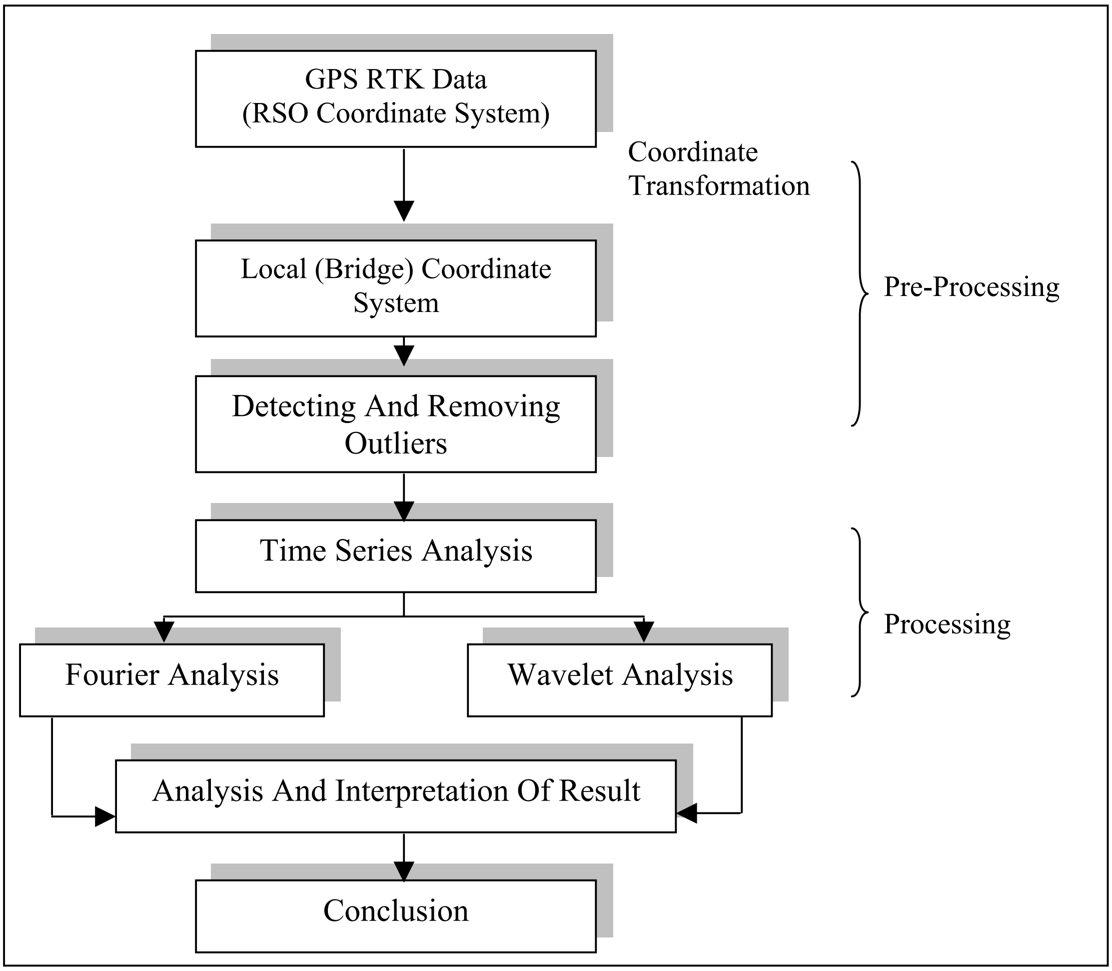


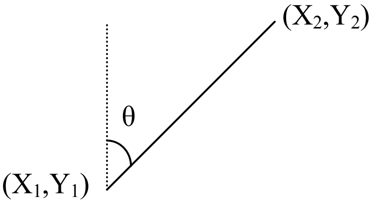
Figure 2: Research Methodology

3.0 PRE-PROCESSING

Pre-processing is a primary process to ensure the data for processing stage is free from outliers, represented in local (bridge) coordinate system and etc.

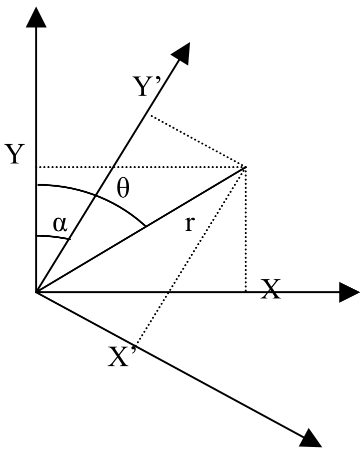
3.1 Coordinate Transformation

The data gained from GPS RTK observation is referred to Rectified Skew Orthomorphic (RSO) coordinate system while the height is based on ellipsoid or popularly known as ellipsoidal height. It is oriented to the True North. In order to make the analysis of movement more clearly, the coordinates are transformed into local coordinate system (longitudal, lateral and height components). The orientation of each point can be calculated from the coordinate itself by applying this simple mathematical model (Zulkarnaini, 2002).



Orientation to the True North, $\theta = \tan^{-1} \dfrac{(X_2 - X_1)}{(Y_2 - Y_1)}$

In this observation, orientation to the true north is defined as 98.95° (refer Figure 1). The equations for the transformation process are:



$X = r.\sin\alpha$
$Y = r.\cos\alpha$

$X' = r.\sin(\alpha - \theta)$
$= r.\sin\alpha.\cos\theta - r.\cos\alpha.\sin\theta$
$= X.\cos\theta - Y.\sin\theta$ ………………………………………………..………..(1)

$Y' = r.\cos(\alpha - \theta)$
$= r.\cos\alpha.\cos\theta + r.\sin\alpha.\sin\theta$
$= Y.\cos\theta + X.\sin\theta$ ……………………………………………………………(2)

$$\begin{pmatrix} X' \\ Y' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

Where:

- X' : East in new (local / bridge) coordinate system and also represents longitudal components
- Y' : North in new (local / bridge) coordinate system and also represents lateral components
- X : East in old (RSO) coordinate system
- Y : North in old (RSO) coordinate system
- θ : Orientation angle

* Height components remain unchanged because its move toward gravity center for both system.

3.2 Detecting And Removing Outliers

One of the major things to consider when applying GPS RTK technique are outliers. It is normal when the data contain a numbers of outliers causing by blocking of the correction signal from the reference station by vehicles such as buses, lorry and others. In this observation, the reference station was set at the condominium not far away from the bridge. Outliers will influence the result of the analysis and therefore, it must first be removed before continuing further process. Detection of outliers can be done by plotting the variation of position for each data. Data with outliers will come out with a spike shape. However in this observation, there are no outliers detected (Voon, 2004).

4.0 ANALYSIS FOR CONTINUOES MONITORING

One of the well-known signal analyses techniques is Fourier analysis, which breaks down a signal into sinusoids of different frequencies. It is a mathematical technique where the signal from time-based is transformed to frequency-based. However, it has a serious drawback because when transforming to frequency domain, time information is lost (Ogaja, et.al, 2001).

In an effort to correct this deficiency, Gabor (1946) adapted the Fourier transform to analyze only a small section of the signal at a time. It is a technique call windowing the signal where it maps a signal into a two-dimensional function of time and frequency. However, it can only obtain this information with limited precision and that precision is determined by the size of the window. The drawback is that once a particular size of time window is being choose, that window is the same for all frequencies. Many signal require a more flexible approach, one where we can vary the window size to determine more accurately either time or frequency.

Wavelet analysis represent the next logical step call a 'windowing technique' with variable-sized regions. It allows the use of long time intervals where we want more precise low-frequency information and shorter regions where we want high-frequency information. One major advantage afforded by wavelets is the ability to perform local analysis i.e. to analyze a localized area of a larger signal. Wavelet analysis is capable of revealing aspect of data that other signal analysis techniques miss like trends, breakdown points, discontinuities in higher derivatives and self-similarity. Figure 3 shows comparison among those techniques (Ogaja, et. al, 2000).

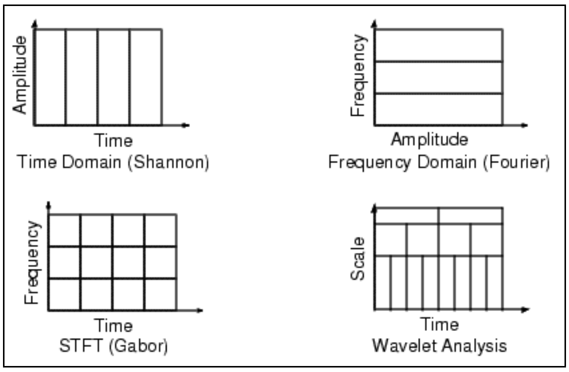


Figure 3: Technique Comparison

4.1 Time Series Analysis

Time series analysis transforms the data from variation of position to displacement of data based on centoid value. In general, there are two common methods to define the centroid value. The first method is by plotting the signal and chooses the stable part of it (Hamdan, 2002). The second technique uses the results of rapid static observation. This technique is more practical and was applied in this paper. For numerical example, Figure 4 represents the result of time series analysis in height component at a station.

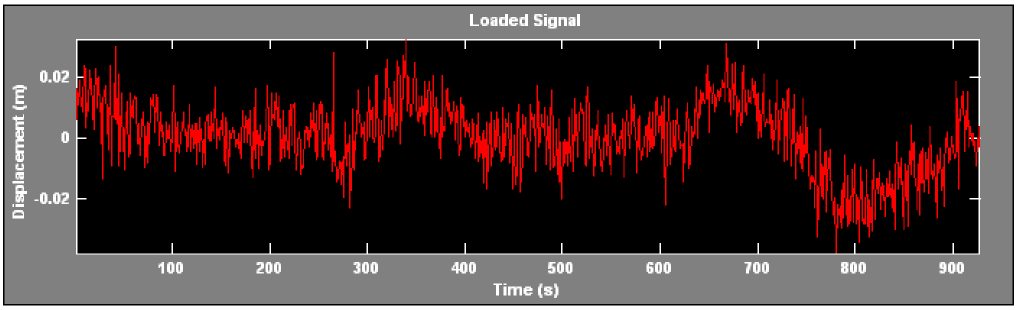


Figure 4: Plot Of The Displacement From Centroid Value

From the plot (Figure 4), we could see that the highest displacement is 0.033 m at the top and -0.038 m at the bottom, at time 340 and 781 respectively. Table 2 represents the height displacement with respect to time.

Table 2: The Most Highest Displacement And Its Time

No	Time	Displacement (m)	No	Time	Displacement (m)
1	41	0.030	8	804	-0.035
2	339	0.031	9	805	-0.031
3	340	0.033	10	814	-0.033
4	668	0.031	11	817	-0.031
5	762	-0.033	12	841	-0.030
6	780	-0.037	13	850	-0.030
7	781	-0.038			

4.2 Fourier Analysis

Fourier analysis is the sum over all time of the signal, f(t) multiplied by a complex exponential where the complex exponential can be broken down into real and imaginary sinusoidal components. Results of that transformation are the Fourier coefficients, F (ω) which when multiplied by a sinusoid of frequency, yield the constituent sinusoidal components of the original signal. Mathematically, the process of Fourier analysis is represent by the Fourier transform (Ikram, 2003):

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-j\omega t}\, dt$$

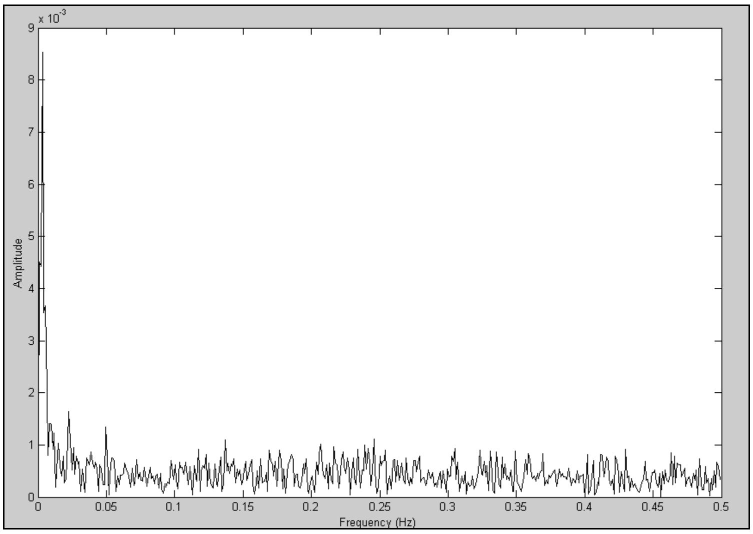


Figure 5: Plot Of Amplitude Again Frequency

The plot in Figure 5 shows that the signals have stable behaviors. Most of the amplitude of every frequency is stable. At the frequency 0.0226 Hz, the amplitude is a little bit higher than other where its magnitude is 0.0016321 and when the frequency is 0.0496 Hz, the magnitude of amplitude is 0.0013477.

4.3 Wavelet Analysis

Wavelet analysis is one of the newest techniques being study today. It is more practical because it has the capability to represent the result in 3D view (coefficient, frequency and time).

4.3.1 Discrete Wavelet Analysis

Sometimes, the trend of the original signal cannot be estimated. The trend is important when we concern on how the movement looks like. Wavelet has a tool called approximation of the original signal to make it smoother so that we can analyze the trend of the movement whether it is getting higher or not. The common goal of decomposition process is for signal clearance and simplification, which are a part of de-noising or compression. Basically it filters the original signal into two components, which are low frequency component and high frequency component (Gilbert, et. al, 1998). The plot of the approximation signal (low frequency component) is shown in Figure 6.

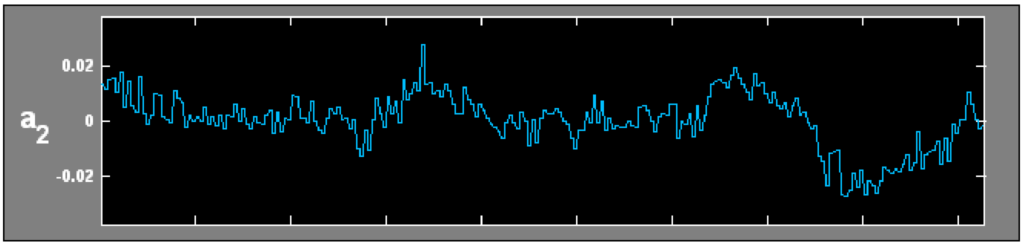


Figure 6: Signal After Second Decomposition

Signal may also contain noise information that won't be needed in analysis. Wavelet toolbox also offers a tool to de-noise the original signal. The plot of the signal after de-noising is shown in Figure 7. The red color represent original signals while the yellow one represent the signal after de-nosing. Figure 8 shows the different of original and de-noise signal.

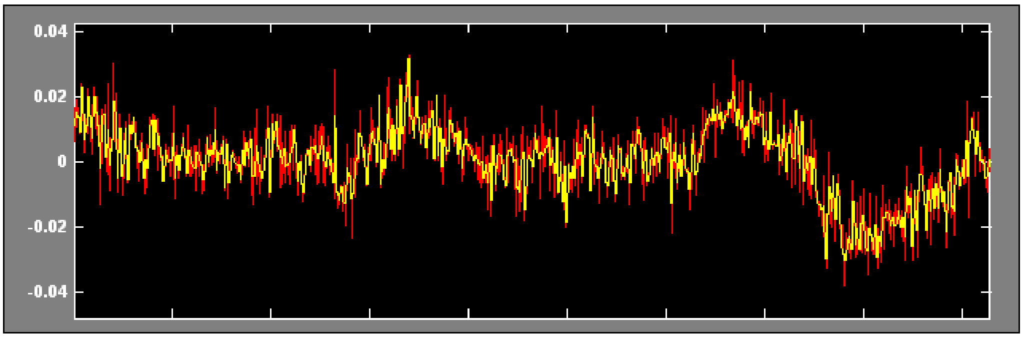


Figure 7: Signal After De-noising

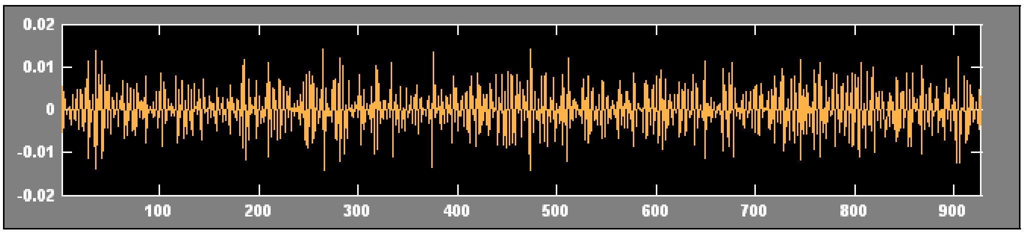


Figure 8: Different Of Original And De-noise Signal

4.3.2 Continuous Wavelet Analysis

Continuous wavelet analysis is the sum over all time of the signal, f(t) multiplied by scaled, shifted versions of the wavelet. This process produces wavelet coefficients that are a function of scale and position. Multiplying each coefficient by the appropriately scaled and shifted wavelet yields the constituent wavelets of the original signal.

$$C\,(\text{scale, position}) = \int_{-\infty}^{\infty} f\,(t)\ \psi\ (\text{scale, position, } t)\ dt$$

Here are the five steps for continuous wavelet transform:

i. Compare a wavelet to a section at the start of the original signal.

ii. Calculate a number, C that represents how closely correlated the wavelet is with this section of the signal. The higher C is, the more the similarity.
iii. Shift the wavelet to the right and repeat steps 1 and 2 until the whole signal have been covered.
iv. Scale (stretch) the wavelet and repeat steps 1 through 3.
v. Repeat steps 1 through 4 for all scales.

The result of the process is the coefficients produced at different scales by different sections of the signal. The coefficients constitute the result of a regression of the original signal performed on the wavelets. The different between discrete and continuous wavelet transform is the set of scales and positions at which it operates. Unlike the discrete wavelet transform, continuous wavelet transform can operate at every scale from that of the original signal up to some maximum scale that has been determined (Ogaja, et. al, 2000).

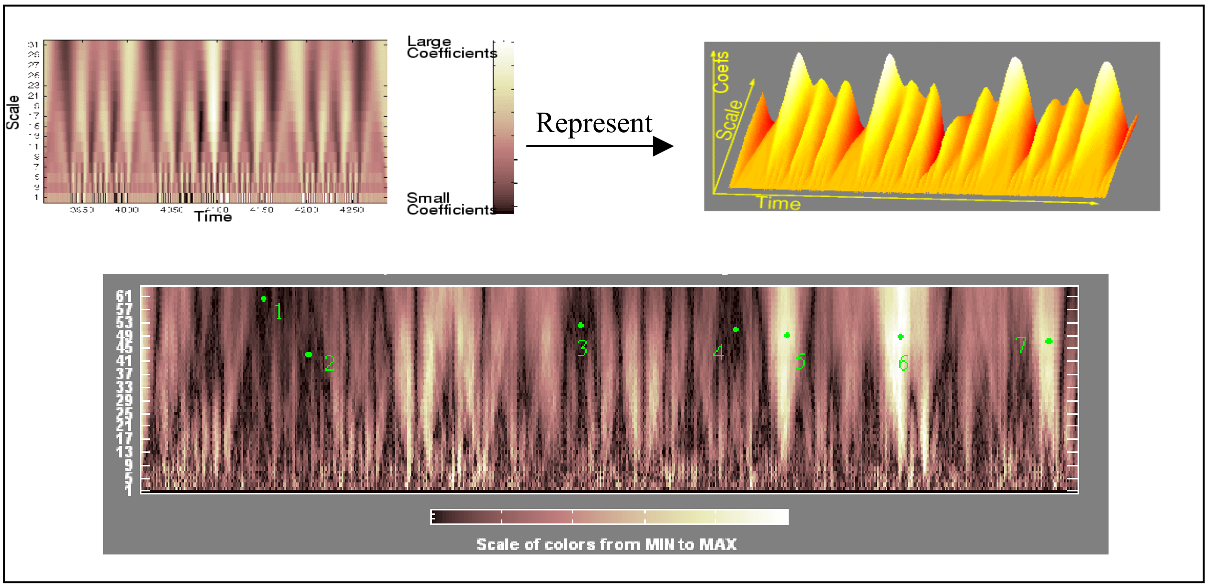


Figure 9: Plot Of Continuous Wavelet Analysis

- Low scale, a → Compressed wavelet → Rapidly changing details → High frequency ω
- High scale, a → Stretched wavelet → Slowly changing, coarse features → Low frequency ω

Table 3: Points And Frequency

Points	Frequency (Hz)	Time	Points	Frequency (Hz)	Time
1	0.016	122.10	5	0.020	639.62
2	0.022	169.15	6	0.020	754.62
3	0.018	437.49	7	0.020	897.51
4	0.019	589.09			

From Figure 9 and Table 3 above, points 1, 2, 3 and 4 are the points where its have less coefficients compare to others. Points 5, 6 and 7 show frequency of most high coefficients of the signal.

5.0 CONCLUSION

We can conclude that the signal is stable with no unusual movement was detected at station 6. Wavelet is capable of giving a better result for the analysis (3D view). However, other techniques such as Fourier is still necessary as a complementary to wavelet analysis. A lot more study should be done to improve knowledge in the analysis. From the complete analysis of the data, the height components show more reliable displacement compare to longitudal and lateral components.

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