

THE TIME SERIES ANALYSIS IN GPS STRUCTURAL MONITORING SCHEMES

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ABSTRACT

Nowadays, the Global Positioning System (GPS) has evolved as an important tool for estimating structural deformation in large engineering structures for examples bridges, dams and high rise buildings. Continuous GPS measurement can be employed in order to ensure that the engineering structures is exhibiting safe deformation behaviour for the purpose of safety assessment as well as preventing any disaster in the future. Today, GPS receivers for positioning and timing are capable to output range observations at high rates, typically once per second or even higher, for instance at 5 or 10 Hz. One is easily provided with dense and extensive time series of code and phase observations to all GPS satellites in view, on both the L1 and L2 frequency. Here, continuous solution enables time series of increased temporal resolution, from which deformation motion can be estimated from a shorter data time span and with more confidence of the episodic sampling of deformation signals. Furthermore, it offers the ability to mitigate systematic biases that results from multipath, atmospheric delays and other temporal considerations. In this study, we examined the GPS results collected from the instrument installed on top of the tower, in order to evaluate the existence of low and high frequency noises embedded in the observed data. The low pass filter, also known as least squares smoothing has been used to extract the high frequency noise and finally, the time series analysis was used to detect structural movement.

1.0 INTRODUCTION

As engineered structures such as tall buildings are designed and built, an increase in the efficiency of detecting deflections or drift of each building under loading for example wind loading becomes necessary. The most common instrument used by the structural engineer was the accelerometer, which measures the acceleration of the structure's response to loading. However, the data obtained from the accelerometer is not a straightforward measure of displacement because they need to go through integration process in order to obtain distance or displacement. As a result, equipment such as GPS, which can directly, derives displacement that recently has focussed on engineered structures monitoring. The GPS also provides opportunity for a rapid assessment of the state of structures after extreme events for example typhoon or related wind effects. The use of GPS for monitoring tall buildings has evolved rapidly since the onset of processing and instrumentation improvement of the technology. To this end, tests have been done prior to investigation on the dynamic response of tall buildings to wind using GPS. These are described in Section 4.

The challenge of monitoring dynamic structures such as large dams, bridges and high rise buildings using GPS technology has received growing attention during the last few years, see for examples *Ashkenazi and Roberts*,

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(1997), *Duff and Hyzak*, (1997), *Guo and Ge*, (1997), *Ogaja et al.*, (2001] and *Mat Amin Z et al.* (2001) In contrast to accelerometer mentioned earlier, the GPS technology can measure directly the position coordinates, and nowadays relative displacements can be measured at rates of 10Hz or higher. Thus, one is easily provided with dense and extensive time series of code and phase observations to all GPS satellites in view, on both the L1 and L2 frequency. This provides a great opportunity to monitor, in real-time, the displacement behaviour of engineering structures under different loading conditions.

In the Real Time Kinematic GPS (RTK), a continuous solution enables time series of increased temporal resolution, from which deformation motion can be estimated from a shorter data time span and with more confidence from the sampling of deformation signals. In this study, we examined the Real Time Kinematic GPS (RTK) results collected from the instrument installed on top of the tower, in order to evaluate the existence of low and high frequency noises embedded in the observed data. Subsequently the capability of RTK GPS in structural monitoring is validated.

2.0 REVIEW OF RTK GPS

At present, instead of episodic deformation monitoring approach, continuous monitoring methods have been increasingly used to monitor the stability of manmade structures. Here, RTK GPS technology is an important development to aid continuous deformation monitoring where timely detection of any deformation is critical. The kinematic parameters of deformation are computed in order to predict failure events. The RTK is currently carrier phase observations processed (corrected) in real-time resulting in position coordinates to a 1-2 centimetre accuracy level being available to the surveyor in the field. In other words, what the surveyor sees is what he gets. In principle, the RTK hardware configuration consists of two or more GPS receivers, three or more radio-modems and a handheld survey data collector/computer. In RTK, one receiver occupies a known reference station and broadcasts a correction message to one or more roving receivers. The roving receivers process the information to solve the WGS-84 vectors by solving the integers in real-time within the receiver to produce an accurate position relative to the reference station. Precision of RTK is $\pm 2 \text{ cm} + 2 \text{ ppm}$.

A GPS observation carries information on the geometric range between satellite and receiver (position) and on the clocks in use (time). In order to extract the desired position information by processing the collected data using a least-squares algorithm, one has to formulate a mathematical model. Most elementarily the GPS range observable can be split into a signal part and a noise part

3.0 THE TIME SERIES ANALYSIS

The continuous GPS observations were generally considered as a random process or time series as the sequences of data represent a process taken with respect to time. The properties of random process can be determined by computing the mean and variance of the ensemble [Chatfield, 1996]. For a random process $x(t)$ with discrete sample values, the mean $\mu(t)$ and the variance $\sigma^2(t)$ are given by

$$\mu(t) = E(x(t)) = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n x_i(t) \quad (1)$$

$$\sigma^2(t) = E[(x(t) - \mu(t))^2] = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n (x_i(t) - \mu(t))^2 \quad (2)$$

where n is the total number of sample values. This is a strict definition of stationary, which is rarely to demonstrate. In practice, it is sufficiently to have weakly stationary in which the mean value of any random variable is independent of the time origin and the covariance of two random variables depend only upon the time difference or lag. This condition can be expressed as

$$E[x(t_1)] = E[x(t_2)] \quad (3)$$

$$C[x(t_1), x(t_2)] = C[x(t_1), x(t_1 + \tau)] \quad (4)$$

where C and τ are the auto covariance function and lag between the values of the process $x(t)$. The normalised auto covariance function is called autocorrelation function (ACF). ACF represent the statistical dependence or simply correlation between successive observations in random process at different lags. This function can provide insights into the properties and behaviour of a random process. These two functions have their own applications in random data analysis.

For stationary and discrete random processes, the auto covariance function from Equation 3.4 can be defined by the following expression since

$$\mu = \frac{1}{n} \sum_{i=1}^n x(t_i) \quad (5)$$

$$C(\tau_k) = \frac{1}{n} \sum_{i=1}^{n-k} (x(t_i) - \mu)(x(t_i + \tau_k) - \mu) \quad 0 \leq k \leq n-1 \quad (6)$$

where n and k are the total number of sample values and lags, respectively. Now, the ACF at lag k is defined as

$$R(\tau) = \frac{C(\tau)}{C(0)} \quad (6)$$

Conventionally, the ACF is calculated for lags from 0 to $n/4$ or 25% of the data [Chatfield, 1996] and it has a magnitude not greater than one and thus

$$-1 \leq R(\tau) \leq 1 \quad (7)$$

The plot of ACF is called correlogram. It provides a useful check for patterns of time series. One of the properties of ACF, which is of concerned in this study, is the periodicity. In this study, we explore in this contribution of the time series analysis to the GPS structural monitoring applications.

4.0 EXPERIMENTAL PROCEDURE

To serve the purpose of this study, two experiments were carried out under two different wind speed conditions at the Tower Block, Loughborough, UK. The Tower blocks consist of 2 separate towers linked by a stairwell and lift shaft. The west and east blocks are a 21 and 17-story buildings, respectively, which are for student accommodation. A view of the blocks (looking Southeast) is shown in Figure 1. The stairwell is the tallest among the blocks, which is about 62.5 high followed by the west and east blocks of 55 and 50 m, respectively.



Figure 1: The Tower Block.

The two experiments took place in February 2000. In both experiments, the reference antenna was located at the ground station. The other antenna was mounted on an existing bracket of the tower. For each experiment, data was collected from all receivers at a 1 s or 1 Hz sampling rate over 2-hour period. On average, the GDOP value for the first and second experiments was less than 4.0 and 4.5, respectively.

5.0 DATA ANALYSIS

The raw time series of two-dimensional positions (Easting and Northing) of the antenna mounted on the tower are plotted in Figure 2 for the first experiment and Figure 3 for the second experiment. Figures were plotted with respect to zero value, taken from static initialisation. The time series presented in these figures are dominated with high-frequency noise, which requires low pass filtering. From these figures, one hardly can see the difference between two sets of experiments.

A visual examination of the raw time series (Figure 2 & 3) suggests that it is important to remove features that are not clearly due to the movement. This is one of the challenges on the application of GPS for structural deformation monitoring i.e. to separate positions resulting from deformational signal and noise [Rizos *et al.*, 1996]. This indicates that the high frequency noise observed in the measurements can easily be reduced in amplitude by low pass filter.

As a first step, the high frequency noise was eliminated from all three components using the low pass filter. The Savitsky-Golay filter has been used to extract high frequency. This filter also known as least squares smoothing or polynomial smoothing filters [Press *et al.*, 1986] is selected because it can remove as much noise as possible and still without degrading the underlying information. Filtering a noisy signal with the Savitsky-Golay filter is equivalent to replacing them by values that lie on smooth polynomial. The order of polynomials can either be linear, quadratic, quartic etc. In other words, we attempt to fit a polynomial $y(t)$;

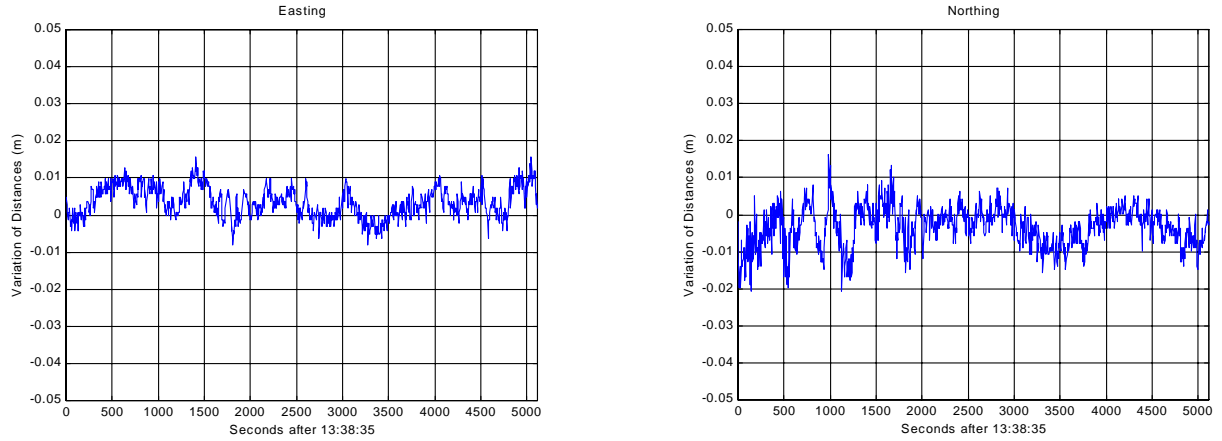


Figure 2: Variation of Co-ordinates on First Observation.

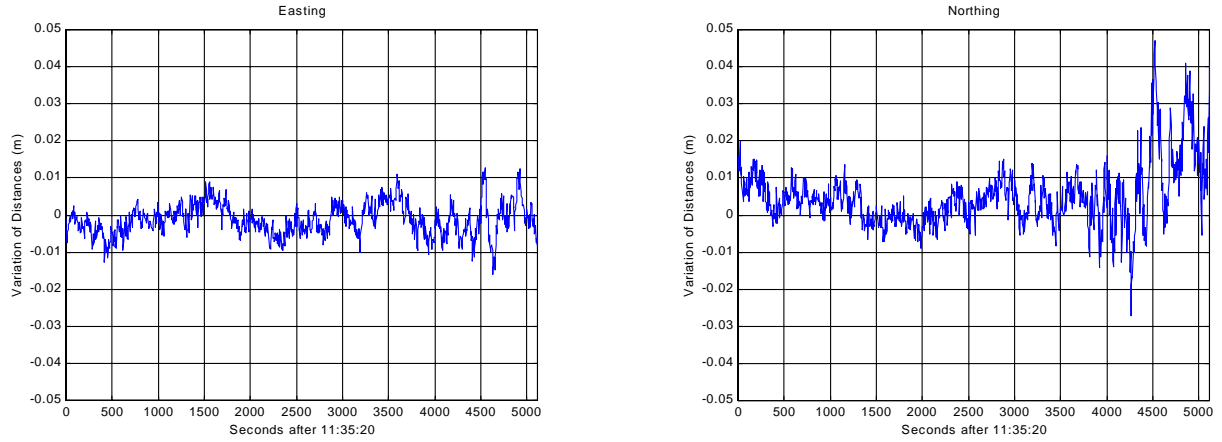


Figure 3: Variation of Co-ordinates on Second Observation.

$$y(t) = c_0 + c_1 t + c_2 t^2 + \dots + c_n t^n \quad (9)$$

For each choice of polynomial order, the coefficients can be determined using the least-squares fit. These coefficients were evaluated at some point in the interval (window). The whole process is repeated when moving to the next point in the signal.

Shown in Figure 4 and 5 are the plots of filtered time series of first and second experiments, respectively. These figures illustrate the residuals for each co-ordinate component. The characteristic of wind action is clearly shown in those figures. The average wind speeds during the experiments were 11.1 and 7.7 m/s on the first and second observations, respectively. From these plots, one can make a conclusion that the cyclic patterns of time series

due to wind loading are shown up. Since the dynamic response of building was largely due to wind load, the best way to examine overall building behaviour was to look data sets during wind speed extremes i.e. that of first observation. In addition, the data set was obtained during a period of strong easterly airflow.

An alternate approach for obtaining periodicity is to compute the degree of correlation between epochs of measurement discussed in Section 3. Autocorrelation coefficients for all components were computed using different time lags. The related curves are plotted in Figure 6 and 7. There is pronounced fluctuations at the East-West direction of the data set obtained on first observation (Figure 6). This is in agreement with the findings mentioned earlier. Indeed, there is strong evidence that the easterly airflow has produced a bluff body effect on the Tower blocks. The experimental research of the airflow surrounding the Tower blocks leading to vortex shedding was taken by [Boucher, 1980]. He studied the effects of Tower blocks on the wind environment by measuring two different data sets of wind speeds at the following period conditions:

- a. strong south-westerly airflow;
- b. light to moderate easterly airflow.

Using this information, he analysed the effects of airflow on the building and found that the maximum vortex flow occurred near the west block. This effect is due to easterly airflow and shows that it is more prevalent compared to southwesterly airflow, which results in induced fluctuation. In addition to the generation of vortex and wind loads, the fluctuations are also caused by the results of oscillation of the building.

6.0 CONCLUSION

The tower, which is subjected to wind loading, has been investigated in this study. In the experiment, data was collected during the period when there was extreme wind speed. The study has demonstrated the feasibility of GPS and time series analysis technique to detect dynamic deflection of the structures. The test done on this technique has proven that it can provide solutions to structural monitoring and contributes toward efforts in the application of GPS as non-destructive evaluation technique for civil structures. Nevertheless, more research is still required to fully understand all sources of errors and their influences on GPS results.

7.0 REFERENCES

- Ashkenazi, V., and G.W. Roberts, (1997). "Experimental Monitoring of the Humber Bridge Using GPS ", *Proc. Instn. Engrs. Civ. Engng* (120), 177-182
- Boucher, K., (1980). "The Wind Environment Around A Tall Building", , pp. 39, Department of Geography, Loughborough University, Loughborough
- Chatfield, C., (1996). *The Analysis of Time Series: An Introduction*, 283 pp., Chapman & Hall, London.
- Duff, K., and M. Hyzak, (1997). "Structural Monitoring with GPS ", *Public Roads* (Spring 1997)
- Guo, J., and S. Ge, (1997). "Research of Displacement and Frequency of Tall Building under Wind Load Using GPS", in *The 10th International Technical Meeting of the Satellite Division of the Institute of Navigation*, pp. 1385-1388, Kansas City.
- Mat Amin, Z. H. Setan and D.R. Twigg (2001). "Structural Monitoring Using High Precision Kinematic Global Positioning System and Rigorous Analysis, *Conference on Construction Technology, CONTEC 2002*, Sabah, Malaysia, pp. 361-373
- Ogaja, C., C. Rizos, J. Wang, and J. Brownjohn, (2001). "GPS and Building Monitoring Case Study: Republic Plaza Building, Singapore ", *Australian Surveyors*
- Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling, (1986). *Numerical Recipes, The Art of Scientific Computing*, 818 pp., Cambridge Univ. Press, New York.
- Rizos, C., R. Galas, and C. Reigber, (1996). "Design Challenges in the Development of a GPS-Based Volcano Monitoring System", in *The 8th International FIG Symposium on Deformation Measurements*, pp. 7-15, Hong Kong.

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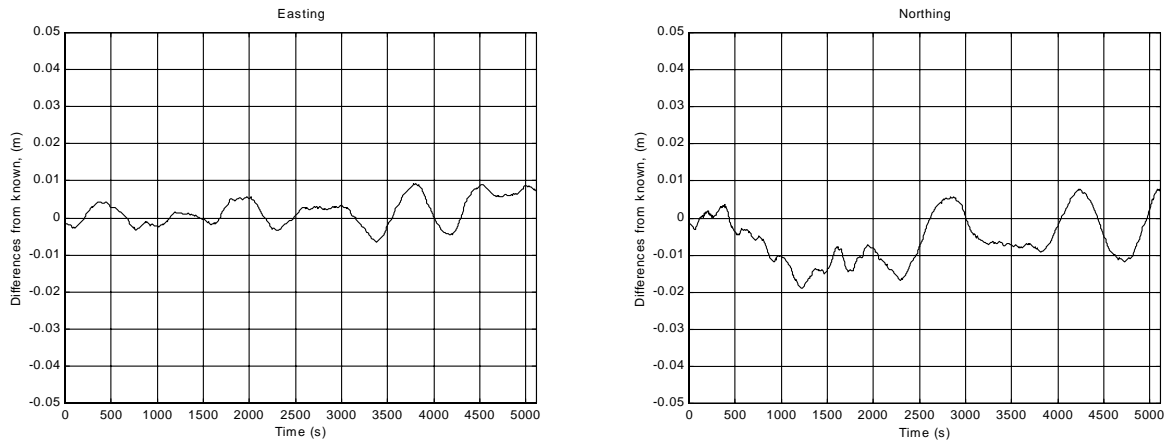


Figure 4: Filtered Time Series of First Epoch.

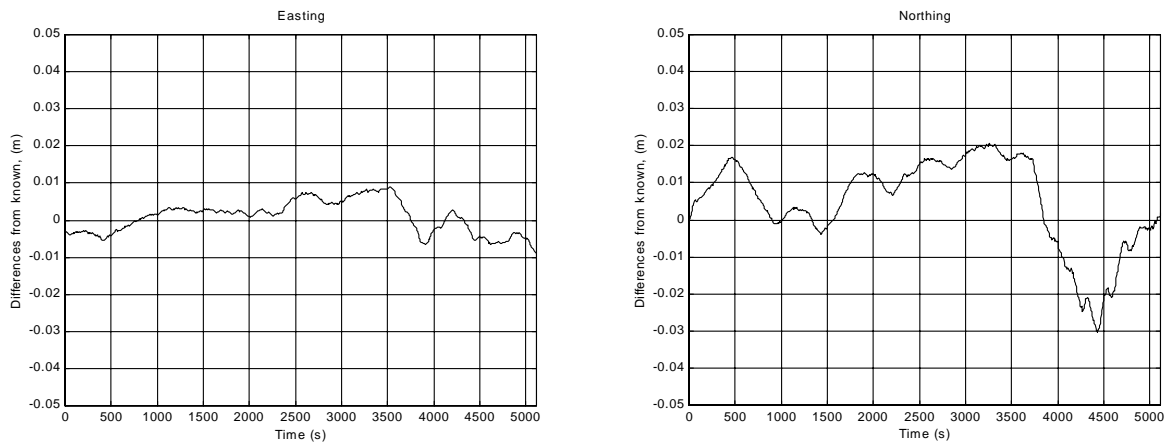


Figure 5: Filtered Time Series of Second Epoch.

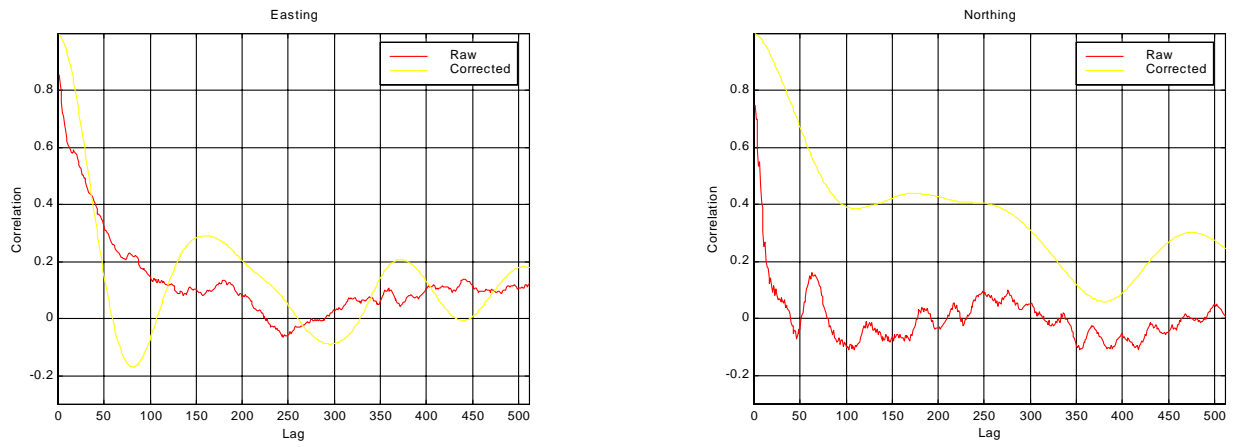


Figure 6: Autocorrelation Curves at Tower Blocks. First Observation

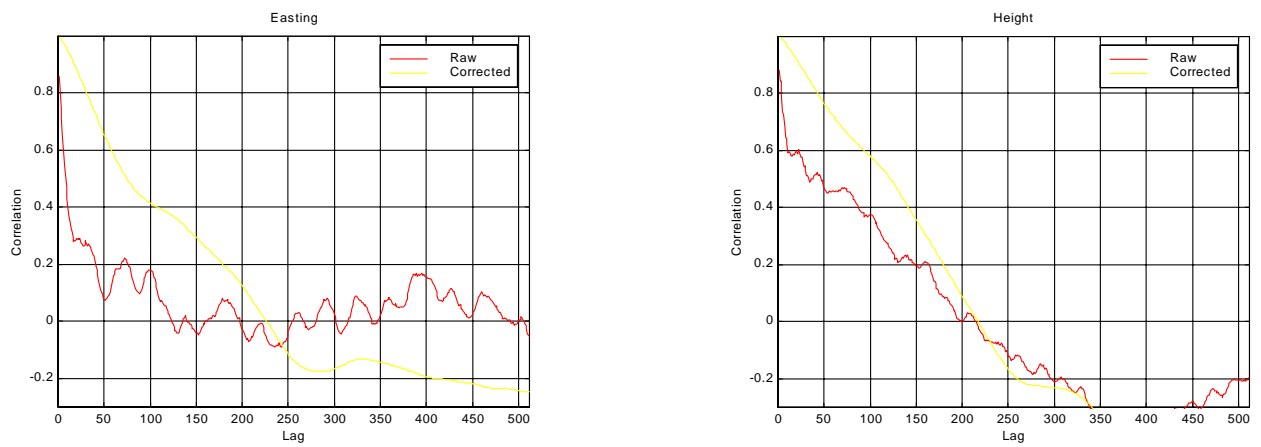


Figure 7: Autocorrelation Curves at Tower Blocks. Second Observation

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