HOW FAR COULD GPS GO IN MONITORING STRUCTURAL RESPONSE TO WIND EVENTS?

Chris RIZOS[1], Xiaojing LI[1, 2], Linlin GE[1], YukioTAMURA[2] and Akihito YOSHIDA[2]

[1] *School of Surveying & Spatial Information Systems, University of New South Wales, Australia*

[2] *Wind Engineering Research Centre, Tokyo Polytechnic University, Japan*

Abstract: Two techniques have been applied increasingly in recent years for monitoring the response of tall buildings to wind: the traditional accelerometer and GPS. The focus of this paper is to study how the two sensors perform relative to each other, and in particular the value of GPS measurements in improving wind effect modelling. The test site is a 192m high office tower in downtown Sydney (with a height of 222m to the tip of the spire). It is 45 levels above ground and has 20m of underground levels, and was completed at the end of 2004.

Accelerometers and anemometers have been installed on the tower since 2005, and in the middle of 2006 GPS was added to the monitoring system. Data from three reference stations in the SydNET GPS CORS network have been analysed together with data from the GPS rover on the tower, forming baselines of 1.1km, 5km and 21.1km in length. Large wind events were captured by the system on 7 September and 15 November 2006. The analysis will focus on the dynamic response to wind events derived from displacement measured using three GPS reference stations, how to validate GPS-derived resonant response with accelerometer measurements, and how to separate the static and quasi-static components from the GPS measurements. The full picture of structural response to wind will be established by combining the static and quasi-static components with the validated resonant component.

It has been demonstrated that the resonant response obtained from both GPS and accelerometers agree well with each other. The full-scale structural fundamental mode of natural frequencies is 0.25Hz for the NS direction and 0.29Hz for the EW direction, with a first torsional frequency of 0.41Hz. It is encouraging that results using the GPS reference station 21km away from the rover also captured the 0.25Hz resonant signal very clearly. Such information offers structural engineers the opportunity to refine their FEM analysis and develop models more representative of the real structure.

1. INTRODUCTION

The monitoring of a structure subjected to deforming loads such as wind events requires the measurement of three principal signals: 1) a static component due to mean wind force for its observational period; 2) a quasi-static component caused by low-frequency force fluctuations; and 3) a resonant component (natural vibration) due to force fluctuations near the structure's first mode natural frequency (Tamura et al, 2002). Two techniques have been applied together increasingly in recent years for monitoring the response of tall buildings to wind: the traditional accelerometer and more recently GPS. Traditional structural monitoring systems using accelerometers can only measure the third component effectively (Kilpatrick et al, 2003; Ashkenazi & Roberts, 1997; Brownjohn et al, 1998; Tamura et al, 2002). Advanced GPS and other surveying technologies have enabled the measurement of the first and second components. But how much do GPS measurements improve wind effect modelling?

A test bed has been set up by researchers from the University of New South Wales (UNSW) at the Latitude Tower (Office Building) in the Sydney CBD (George Street) in collaboration with University of Sydney researchers. The tower's height is 192m, and it is 222m to the tip of the spire (Figure 1). It is 45 levels above ground and was completed at the end of 2004. The tower is a composite structure, consisting of reinforced concrete and structural steel components. Core construction is reinforced concrete, with steel beams and a composite slab spanning to the perimeter columns, which consist of concrete-filled steel hollow sections. Block work in-fill is used at the core, but is not prevalent in the tower's design. The tower includes 20m of underground levels, and the base is surrounded by a six storey podium. The floor plan is approximately rectangular, with small rectangular sections of the floor plan removed in the north-east and south-west corners of the tower. The major axes of the building correspond to the cardinal points, and are displayed in Figure 2 (Moore & Wood, 2004).

Accelerometers have been mounted in orthogonal pairs (x and y components) at two opposite corners - East and West extremities of the tower's highest accessible level to capture both the sway and torsional responses to wind. An anemometer has been installed to measure wind speed and direction, together with the pair of accelerometers at the same level. A Leica AT504 choke-ring antenna has been installed together with a Leica MC500 GPS receiver at northwest corner of the rooftop of the tower collecting data at 10Hz. Three reference stations have been used, namely QUEN, UNSW and VILL, with distances of 1.16640km, 5.09074km and 21.18454km from the Latitude Tower respectively. Both QUEN and VILL are SydNET stations collecting data at 1Hz, but the UNSW station collected data at 10Hz. The post-processed kinematic time series are the subject of analysis in this paper.

2. MONITORING WIND LOADING EFFECTS: GPS VERSUS ACCELEROMETER

2.1. The wind event

A southerly wind shook the Sydney CBD on the morning of 7 September 2006, and the large wind event was recorded by the anemometer. A sample clip of wind data is shown in Figure 3. The mean wind speed was 20m/s but the peak speed reached more than 25m/s. As a result of this strong wind the combined GPS and accelerometer system on the Latitude Tower was activated and collected data for more than 5.5 hours. The authors analysed the GPS measurements first and then compared the extracted resonant component with the result derived from the accelerometer data.

2.2. Wind loading effects monitored by GPS

Due to system maintenance, the 10Hz reference station at UNSW was not working at the time of the wind event. The GPS-measured displacement was obtained by processing observations collected at the 1Hz QUEN reference station and the Latitude Tower rover station. The rover observations were down-sampled to 1Hz so that the time series of displacement from GPS has a sampling rate of 1Hz (red in Figure 4). This measurement period started from 4:00:00a, total duration was $2*10^4$ seconds (around five and a half hours). According to the weather report and anemometer data, wind speed was averaged 10m/sec from 4:00am to 5:00am, with its direction from 270 degree (W) to 160 degree (SSE). The wind speed was the lowest at 7m/sec with consistent southerly 160 at 6am. But it climbed in 10minutes to 24m/sec and then dropped back to 10m/sec. At 9:30am wind speed reached a peak speed of 25m/sec, as labelled in Figure 5. From 6:00am to 9:30am, the wind direction was mostly southerly at 160 degree cross to the tower's EW side. With this consistent wind, it is a good opportunity to research the cross wind effect to the tall tower with GPS measurements.

Power spectrum analysis on the GPS time series is conducted. The log-log FFT in Figure 4 shows a dynamic resonant peak at 0.25Hz ($10^{-0.6}$). FEM analysis by civil engineers has confirmed that it is the first mode frequency of the tower along the NS direction (Moore & Wood, 2004). The smooth low frequency end of the spectrum is much stronger than others, showing substantial amount of static motion. And in the range of quasi-static, a few spikes indicate energy concentration along the specific frequencies.

Figure 1 - Latitude Tower in the Sydney CBD.

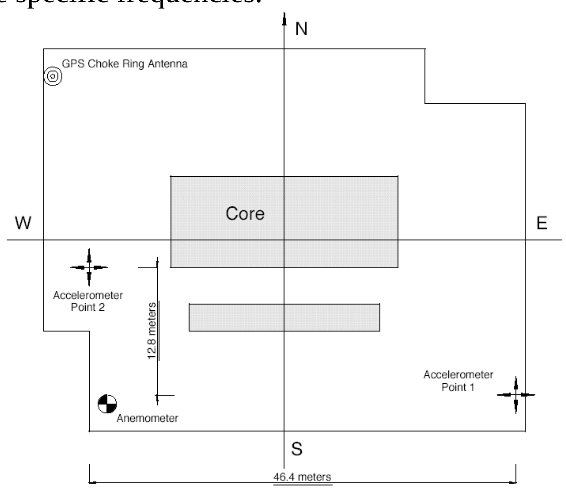

Figure 2- Plan view of Latitude Tower with major axes and orientation.

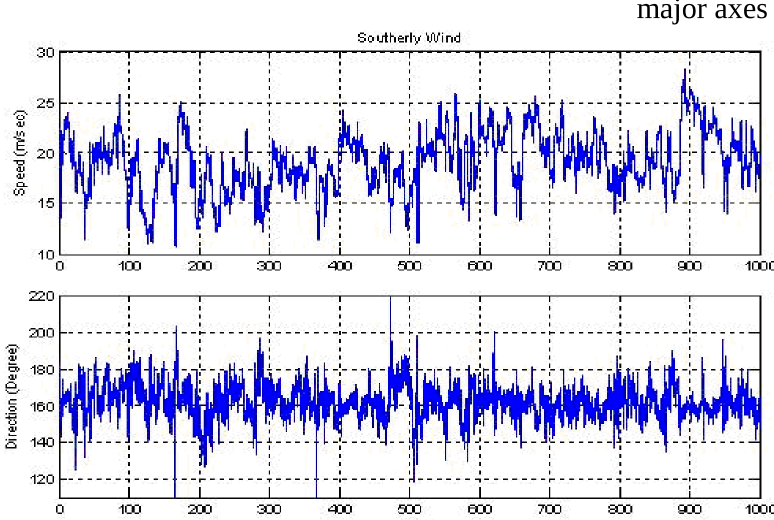

Figure 3 - Southerly wind event on 7 September 2006 from 8:30am.

In order to split the static and dynamic motions and suppress the multipath effect, a low-pass filter has been designed based on the FFT analysis to extract the very low frequency component from the GPS time series. The quasi-static motion is extracted by a band-pass filter with cut-off frequencies of 0.01Hz and 0.2Hz, which is just below the statistically defined multipath frequency range of 0.0008Hz – 0.01Hz. Then a high-pass filter is used to focus on the tower's natural frequencies range in order to obtain accurate resonant motion. The static extraction low-pass filter worked like a half hour mean for GPS time series. The static change caused by wind loads in the long hourly observation was non-stationary, as can be seen in Figure 4. If the light-blue line fluctuates with amplitude less than ±3.6mm it can be considered as the static baseline error of GPS. Post-processing with the precise ephemeris was used to produce the GPS displacement time series for Latitude Tower monitoring in this research. According to Leica's specifications for its GPS products, an error of 3mm + 0.5ppm would be introduced to the horizontal static and quasi-static measurement. Therefore the GPS result during the southerly wind event for the Latitude Tower would be contaminated with an error of about 3.6mm (baseline length of approximately 1.1km between the rover and the QUEN reference station). More static error analysis in relation to baseline lengths is presented in Section 3. As shown in Figure 3, the wind direction was SSE. The strong wind did push the building to the North (according to Figure 4). It is impossible to obtain these static and quasi-static displacements from accelerometer measurements. This is the unique value of GPS for monitoring and modelling wind loading effects.

Although a choke-ring antenna was incorporated at the rover station to minimise the effects of multipath errors induced by the delayed reception of reflected satellite transmissions, it was impossible to completely eliminate multipath errors due to the proximity of neighbouring structures and the presence of structural and architectural steelwork near the antenna (Li et al, 2006). A zoom-in randomly on the 14560 to 148560 second segment of processed GPS time series shows that the multipath noise at that time period was effectively removed (Figure 6). It can be seen clearly that this multipath noise produced an approximate 30mm displacement fluctuation. Therefore it is important to apply appropriate digital signal processing techniques on GPS time series before they are used for wind loading analysis. By using these accurate three components of displacement reconstruct the total displacement, we would find the ratio relation in between the maximum total displacement and static displacement, and the dynamic. Then it able to evaluate this monitored structural modelling upon cross wind loads.

2.3. Wind loading effects: GPS versus accelerometer

FFT spectrum analysis of the accelerometer measurements matched up with the wind data (Figure 3) at the time 8:30am, for duration 1000 seconds, revealed the first mode natural frequency in the NS direction is 0.25Hz, in EW direction it is 0.29Hz, and its first mode torsional frequency is 0.405Hz. All these frequencies agree well with predictions from the FEM based on full scale structural dimension and its constructional materials as computed by Prof Tamura in the Tokyo Polytechnic University. For this short segment the southerly maximum acceleration measured by the accelerometer attached to the top of building was more than 2Gal. The peak-to-peak velocity computed was 2cm/sec. By applying a Butterworth band-pass filter to suppress noise and then remove drift by using a combined velocity (Li et al, 2006), displacement was obtained from the double integration of acceleration. The derived displacement result for the first 200 seconds is shown in the upper plot of Figure 7. Obviously this transformed displacement can represent resonant motion only.

Figure 7 (lower plot) is the extracted resonant displacement from GPS measurements. It shows clearly how the building vibrated at its first mode natural frequency of 0.25Hz captured by both sensors. The acceleration-transformed displacements are bounded in the range ±5mm, and the displacements from GPS are bounded in the range ±5mm mostly, although there are a few deviations. The clear resonant wave envelope would make it possible to evaluate the building's damping ability using these displacement measurements.

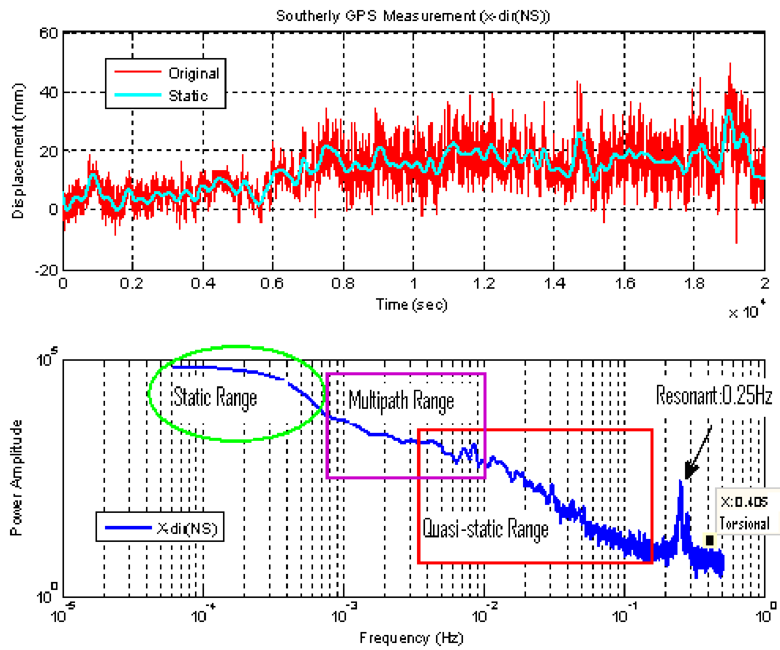

Figure 4 - GPS displacement time series in 2×10^4 seconds and its spectrum.

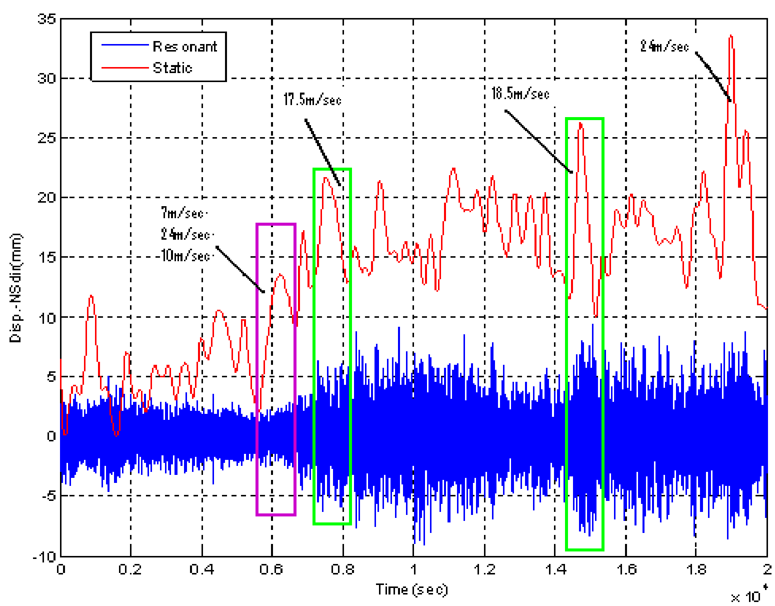

Figure 5 - GPS static & resonant displacements time series vs wind speed information.

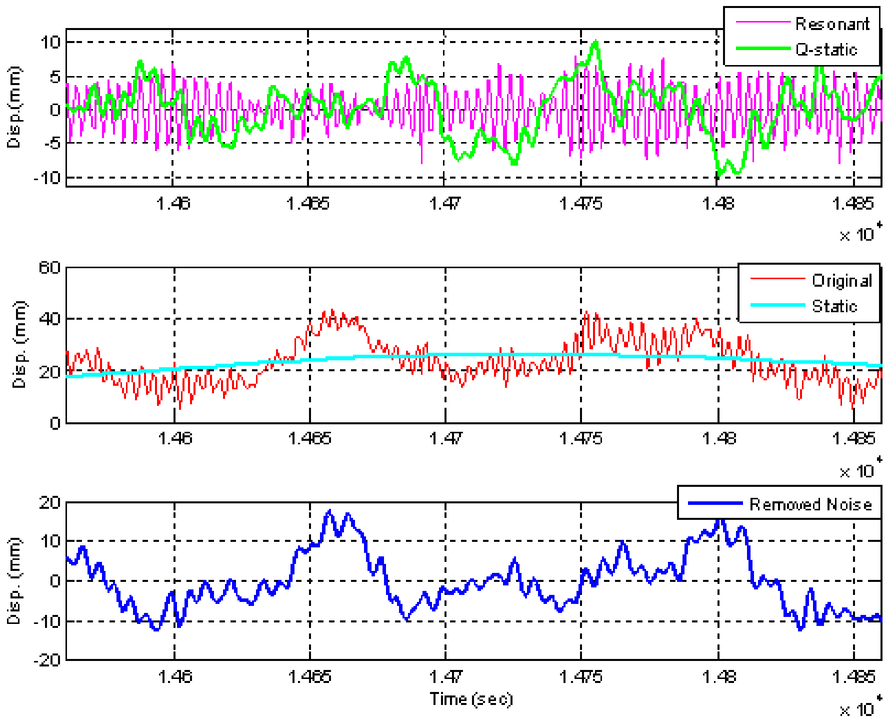

Figure 6 - The results of processing GPS measured components.

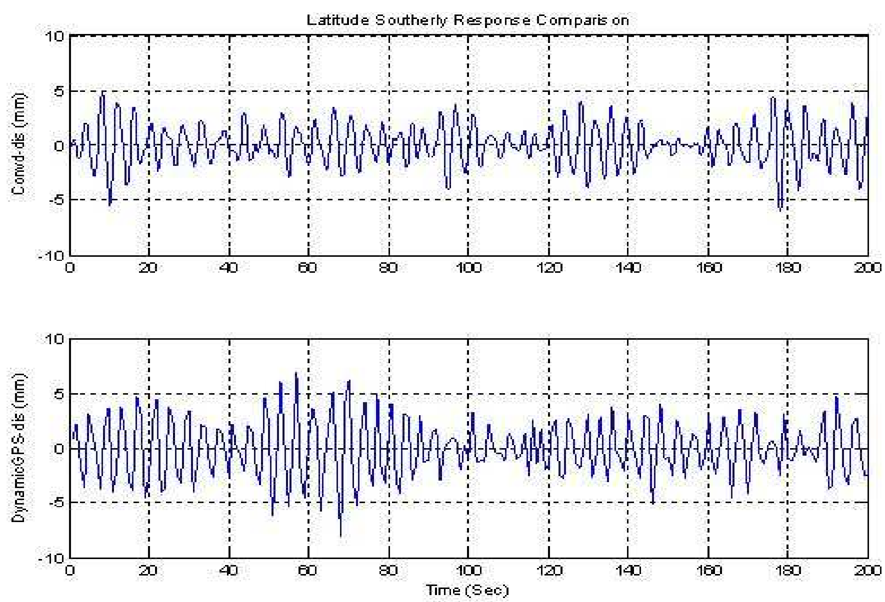

Figure 7 - Comparison between GPS-measured and accelerometer-derived resonant displacement.

3. IMPACT OF BASELINE LENGTH ON STRUCTURAL DEFORMATION MONITORING

It is anticipated that most large-scale civil engineering structures such as high-rise buildings will be located in the centre of large cities. Urban canyons will present a significant challenge to the single-baseline GPS relative positioning methodology because the reference station has to be placed on a stable point, ideally on the ground, and the distance between reference and rover stations limited to about 15km or less due to the presence of distance-dependent errors. For the purpose of structural monitoring, civil engineers require the detection of displacement to better than ±5mm accuracy for the dynamic component and ±1cm for the static component. This means that the reference GPS antenna will typically have to be placed in an urban canyon environment within, say, 15km from the city centre, and hence may have very limited sky view. Furthermore, signals from the GPS satellites will be reflected by multiple structures around the reference antenna producing multipath errors (Ge et al, 2000) which degrade the capacity to measure the true movement of structures. The SydNET CORS network provides a test bed to study the impact of baseline length on structural deformation monitoring.

In this study position quality thresholds were introduced to evaluate an effective measurement error threshold for monitoring the full-scale displacements in the light of fluctuating satellite availability. Consistent tracking of peak displacement values requires accuracy greater than the centimetre-level if civil engineers are to evaluate the designer's model. These thresholds were in the order of 5-7mm, whereas they are at times double this magnitude in full-scale, partially attributed to the separation between the reference and rover receivers, though this situation does require motions of the building to be of the order of a few centimetres to be reliably tracked (Kijewski-Correa & Kareem, 2004). Hence it is of interest to investigate the GPS data from baselines over 15km in length after removing the multipath noise.

Data collected on 15 November 2006 were used for this purpose, when the wind speed was 20m/sec, almost constant, and in the direction 275 degrees. Based on the 3mm+0.5ppm specification given earlier, the horizontal error for the static measurement will therefore be 3.6mm, 5.6mm and 13.6mm using the three reference stations QUEN, UNSW and VILL respectively. Figure 8 gives the displacement of the Latitude Tower when QUEN, UNSW and VILL were used as reference stations. In the QUEN result (Figure 8a) the baseline is the shortest. The green line shows the static sway of the tower with 400 – 500 second per cycle over the 1000 second period. The UNSW result (Figure 8b) was the only 10Hz time series. The static displacement (green line) result is reasonable. Note the three circled parts and compare with the QUEN result bearing in mind the 5.6mm error that could occur because of the baseline length. In the VILL result (Figure 8c) the static movement was also distorted by about 13.6mm, as circled in the figure.

In Figure 9 a 200 second segment has been selected to compare with the resonant displacement derived from the accelerometer data (top plot). It can be seen clearly that both the converted and QUEN results are mostly bounded in the range ±2mm and ±3mm respectively, the UNSW result is acceptable, being mostly bounded in the range ±5mm, but the VILL result was contaminated by distance-dependent errors because of the greater than 20km length baseline. But its result is still bounded in the range ±6mm. Therefore all three GPS results agree with the accelerometer-derived resonant displacement to better than 5mm.

In particular, GPS can be successfully used in structural monitoring even when the baseline length is as long as 21km.

When the baseline error is considered, the three processed displacement components will be linked to the structural modeling incorporating full scale measurements, which will be presented in a separate paper.

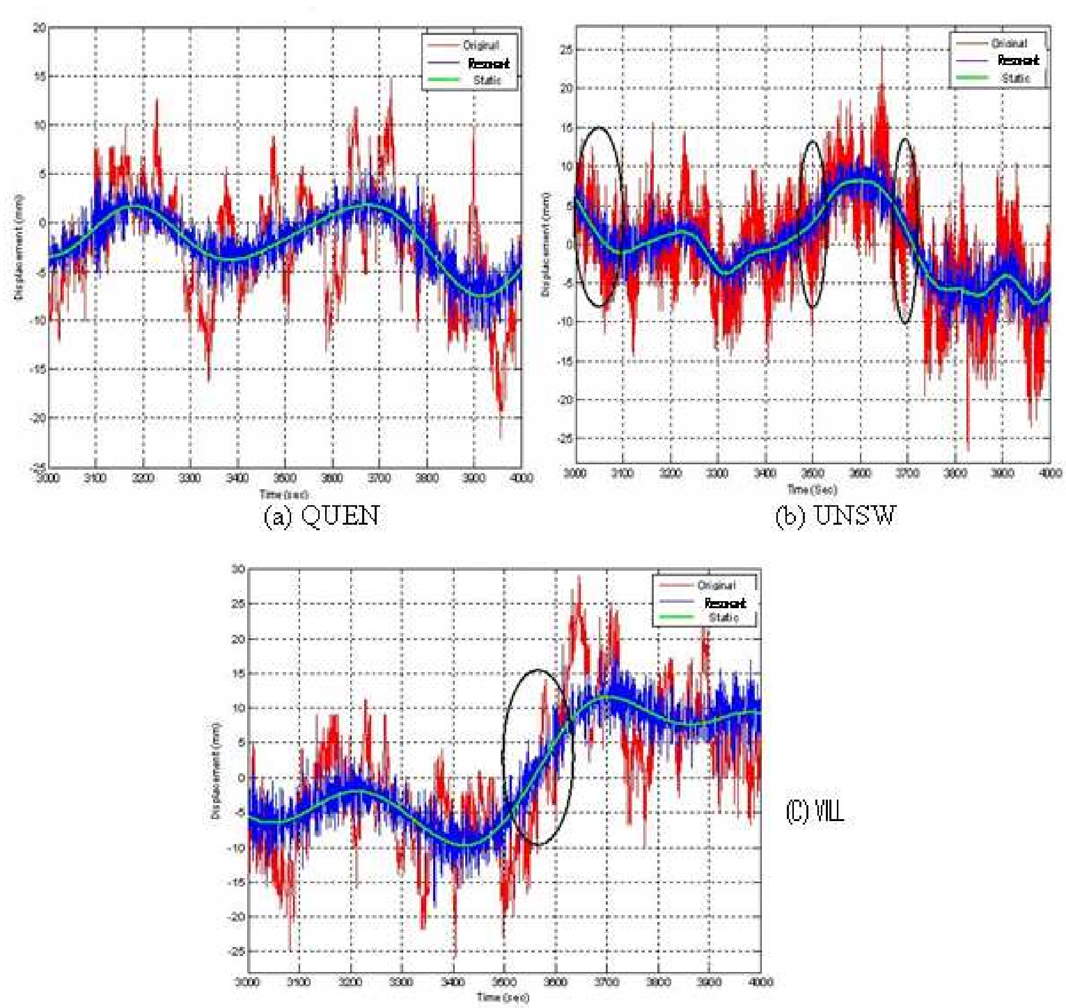

Figure 8 - Static displacement in x direction measured by GPS with different baseline lengths.

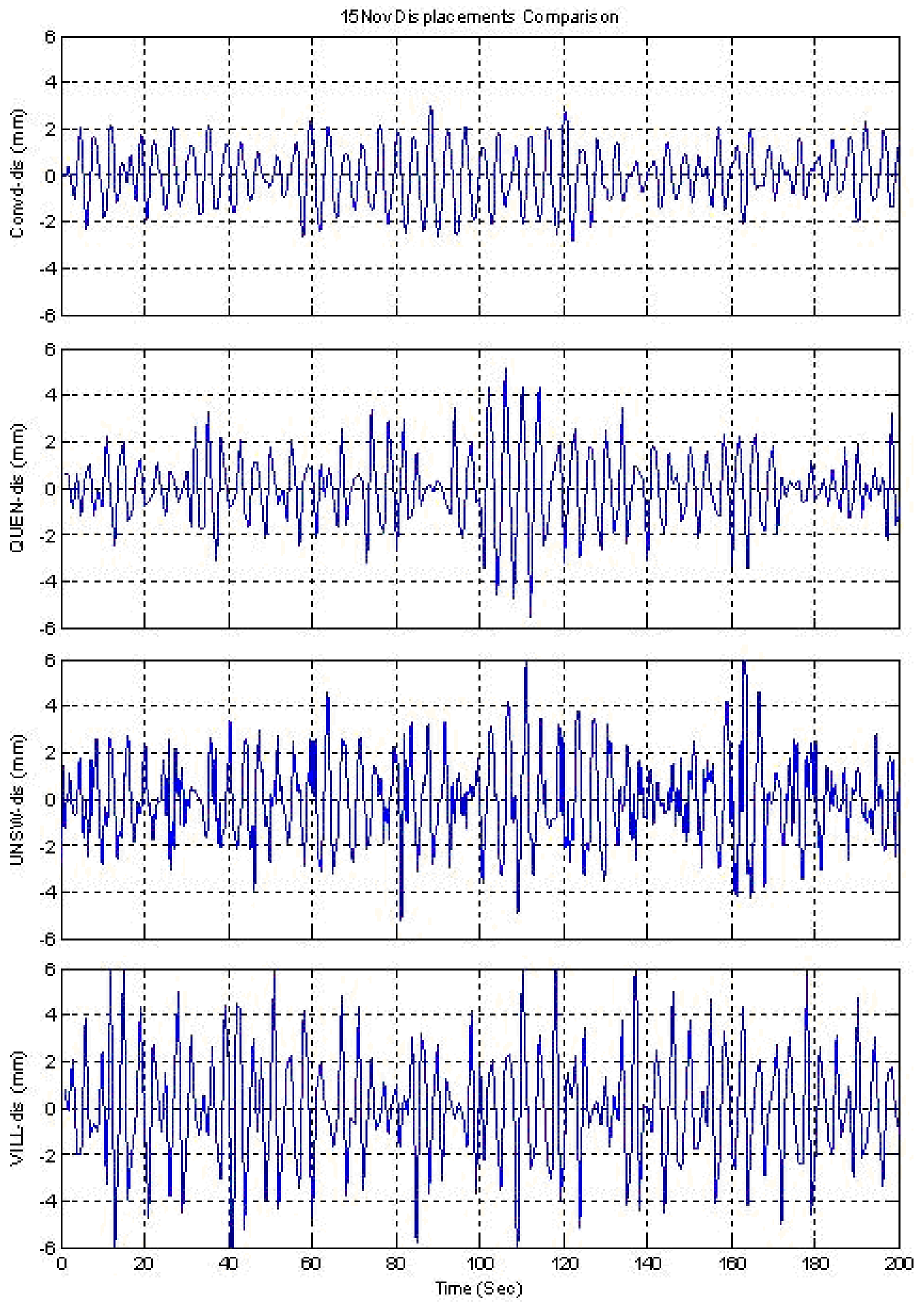

Figure 9 - Resonant displacement comparison - GPS with different baseline lengths vs accelerometer-derived values.

4. CONCLUDING REMARKS

Data captured from two wind events by an integrated monitoring system deployed on the Latitude Tower in the Sydney CBD have been used to study how GPS and accelerometer sensors perform relative to each other, and in particular the value of GPS measurements in improving wind effect modelling. Data from three reference stations in the SydNET GPS CORS network have been analysed together with data from the GPS rover on the tower, forming baselines of 1.1km, 5km and 21.1km in length. It has been demonstrated that the resonant response obtained from both GPS and accelerometers agree well with each other. It is encouraging that results using the GPS reference station 21km away from the rover also captured the 0.25Hz signal very clearly, although contaminated by distance-dependent errors.

References

Ashkenazi, V., & G.W. Roberts, 1997. Experimental monitoring of the Humber Bridge using GPS, *Civil Engineering, Proceedings*, Institution of Civil Engineers, 120, 177-182.

Brownjohn, J., T.C. Pan, A. Mita, & K.F. Chow, 1998. Dynamic and static response of Republic Plaza, *Journal of the Institution of Engineers Singapore*, 38(2) 35-41.

Ge, L., S. Han, & C. Rizos, 2000. Multipath mitigation of continuous GPS measurements using an adaptive filter. *GPS Solutions*, 4(2), 19-30.

Kijewski-Correa, T., & A. Kareem, 2004. The Wind Engineer: Newsletter of American Association for Wind Engingeering (www.aawe.org/docs/newsletters/aawenews_jan_04.pdf).

Kilpatrick, J., T. Kijewski, T. Williams, D.K. Kwon, B. Young, A. Abdelrazaq, J. Galsworthy, D. Morrish, N. Isyumov, & A. Kareem, 2003. Full scale validation of the predicted response of tall buildings: Preliminary results of the Chicago monitoring project, in *proc. 11th Intern. Conf. on Wind Engineering*, Lubbock, TX, USA, 2-5 June 2003. Lubbock, TX: Texas Tech University.

Li, X., C. Rizos, L. Ge, E. Ambikairajah, Y. Tamura, & A. Yoshida, 2006. Building monitors - The complementary characteristics of GPS and accelerometer in monitoring structural deformation, *Inside GNSS*, 1(2), 40-47.

Li, X., L. Ge, E. Ambikairajah, C. Rizos, Y. Tamura, & A. Yoshida, 2006. Full-scale structural monitoring using an integrated GPS and accelerometer system, *GPS Solutions*, Vol.10, 233-247 (DOI: 10.1007/s10291-006-0023-y).

Moore, A., & G. Wood, 2004. Measurement of dynamic characteristics of a tall building during construction, *11th Australasian Wind Engineering Society Workshop*, Darwin, Australia, June 2004.

Tamura, Y., M. Matsui, L.C. Pagnini, R. Ishibashi, & A. Yoshida, 2002. Measurement of wind-induced response of buildings using RTK-GPS, *Journal of Wind Engineering and Industrial Aerodynamics*, 90(12-15), 1783-1793.

Corresponding author contacts:

Chris RIZOS, Professor & Head
c.rizos@unsw.edu.au
School of Surveying & Spatial Information Systems
The University of New South Wales
Australia