THE USE OF L1 GPS SIGNAL AS A TOOL FOR MONITORING STRUCTURAL OSCILLATIONS OF BRIDGES – A COMPENDIUM ABOUT THE PHASE RESIDUAL METHOD APPLICATIONS

A.P. C. Larocca[a]*, R. E. Schaal[b], M. C. Santos[c]

[a] Dept. of Transportation Engineering, Polytechnic School, University of São Paulo, São Paulo/SP, Brazil - larocca.ana@usp.br

[b] Dept. of Transports, Sao Carlos Engineering School, USP, São Carlos/SP, Brazil- rschaal@usp.br

[c] Dept. of Geodesy and Geomatics Engineering, University of New Brunswick, New Brunswick/Canada – msantos@unb.ca

KEY WORDS: Monitoring, Bridges, Frequency vibrations, Filtering Techniques.

ABSTRACT

This work presents the development of a methodology for using the Global Positioning System (GPS) as a tool for Civil Engineering to monitor the vibrations of large road structures, notably the bridges. To be characterized as a structural tool a method was developed and tested which is based upon the interferometry principle. The method uses the L1 carrier phase that needs to be collected from only two satellites and this particular characteristic makes it different to the methods used in other studies. The structure´s vibrations also defined by oscillations or areas of dynamic displacement characterized by the measuring of the extent of the displacement during the specific time in which it occurs and its frequency. The method included the use of an electro-mechanical oscillator specially projected to receive the GPS antenna which allows the calibration of the extent and frequency of the oscillation present in the structures tested. The method was assessed by means of field tests carried out on two structures: a cable-stayed wooden footbridge and a cable-stayed bridge as described below. The efforts to develop a method for using the GPS for the dynamic monitoring of bridges is based upon the value of the dynamic analysis of structures that allow an analysis of the real state of preservation of structure (independent of out appearance), an estimate of the extent of its useful life and the establishment of economic solutions for its recuperation in a way which can extend its durability.

1. INTRODUCTION

Since the late 1980´s, the Global Positioning System technology, which, until then, had been used to conduct geographical surveys, deploy geodetic networks, manage resources, track fleets of vehicles and ships, control the displacement of structures under static load, etc., began to be used to characterize the dynamic displacement of large structures and earthquakes, meaning it was being considered as a tool to pinpoint the values of frequency and extent of displacements with great accuracy (Roberts et al. 2006; Larocca, 2004; Larocca and Schaal, 2005; Patrick, 2005; Nassif et al., 2005; Schaal and Larocca, 2009; Larocca et al., 2010; Ragheb et al., 2010; TingHua et al., 2010). The range of the extent of the displacements detectable with GPS allows it to be used as a tool for monitoring displacement in several kinds of structures and, with the development of sensors which collect data at a rate of 100Hz, it will be possible to identify not only the natural frequencies of a structure, but also the frequencies of its various modes of vibration.

The dynamic analysis of a structure aimed to determine the maximum displacements allowed by the project (design constraints), speed and accelerations (comfort for users), internal efforts, stress and deformations (fatigue of the material of which the structure is composed) (Laier, 2000). Thus, the analysis can diagnose the actual state of the conservation of the structure (regardless of external appearance), predict its life span and determine economic solutions for its recovery in order to prolong the durability of the structure.

Field tests conducted on bridges - submitted to dynamic tests – mobile load - to test the GPS as a tool for monitoring structures are presented below.

2. THEORETICAL BASIS OF METHODS DEVELOPED

The method developed, based on the interferometer phase, only requires data collection from two satellites, with a phase angle of around 90 degrees and no greater constellation of any more than four satellites. Therefore, to measure vertical displacement, for example, it is necessary for one satellite to be close to 90 degrees and another with an elevation next to the horizon (Figure 1). In the processing of the double difference phase, the lowest satellite is considered as the reference satellite, allowing collection of the vector of the residues from the highest satellite, called here the 'measuring satellite' (Schaal and Larocca, 2002).

With this configuration, there will be a greater contribution in the final data processing results of double phase difference - residuals (Leick,1995) - due to changes in the phase, the signal of the satellite close to the zenith in relation to the satellite close to the horizon, which detects hardly any movement of the antenna.

3. THEORETICAL BASIS OF METHODS DEVELOPED

The method, based on the interferometer phase, only requires data collection from two satellites, with a phase angle of around 90 degrees and no greater constellation of any more than four

* Corresponding author. This is useful to know for communication with the appropriate person in cases with more than one author.

satellites. Therefore, to measure vertical displacement, for example, it is necessary for one satellite to be close to 90 degrees and another with an elevation next to the horizon (Figure 1). In the processing of the double difference phase, the lowest satellite is considered as the reference satellite, allowing collection of the vector of the residues from the highest satellite, called here the 'measuring satellite'. With this configuration, there will be a greater contribution in the final data processing results of double phase difference - residuals (Leick,1995) - due to changes in the phase, the signal of the satellite close to the zenith in relation to the satellite close to the horizon, which detects hardly any movement of the antenna.

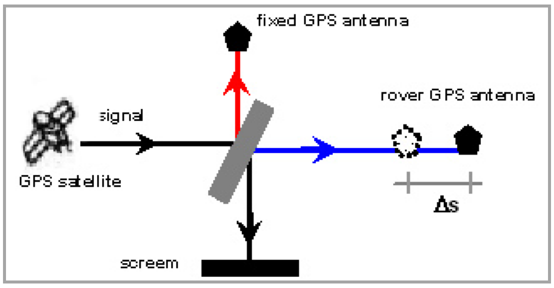

Figure 1. Interferometer of the phase related to GPS signal and antennas

Similarly, when the characterization of horizontal displacements is required, the highest satellite is considered as a reference, allowing the vector of residuals from the lowest satellite to be obtained, where the largest contribution of 'errors' due to changes in the phase of the signal from the satellite close to the horizon will be found.

1.1 Electro-mechanical oscillator for calibrating vibrations

To calibrate the measurement of previously unknown dynamic displacements an electro-mechanical oscillator was developed which applies controlled movements - related to displacement and the speed of such - to the GPS antenna that will suffer the movements of the footbridge span and the bridge. The oscillator is powered by a battery. Figures 2 and 3 present a GPS antenna mounted on the oscillator and a detail of the system that controls the extent of the displacement.

Figure 02. GPS antenna over the electro-mechanical oscillator

Figure 03. Detail of the electro-mechanical oscillator

4. SPECTRAL ANALYSIS OF GPS DATA

The Fast Fourier Transform was the tool chosen to perform the analysis of the double difference phase residuals, here called raw residuals, in the frequencies domain and, consequently, to identify the corresponding frequencies due to periodic displacements in a spectrum that also presents the very low frequencies due to multi-pathing of the environments and other noises and others – the effects of variation of the antenna’s phase center - which is accentuated in highly reflective environments and in non-static observations (Wells et al., 1986). The essence of the Fourier Transform (FT) of a wave is to decompose or separate it into a sum of different frequencies senoides. If the sum of these senoides results in the form of an original wave form, then it was given its Fourier Transform. One wavelength function in the time domain is transformed to the frequencies domain, where it is possible to determine the magnitude and frequency of the wave and filter the undesired frequencies (noise), Brighan (1974).

5. STRUCTURES TESTED FOR THE METHOD OF ANALYSIS

The first structure tested was a cable-stayed wooden footbridge built at the Sao Carlos Engineering School, University of São Paulo, São Paulo State, Brazil, in 2002 (Figure 04), Pletz (2003). The footbridge, which is the first wooden footbridge to be built in Brazil with the deck in a curved shape, has a deck that is 35 meters long made of Pinus taeda wood, whilst the wood used for the tower was Eucalyptus citriodora. The tower consists of a pole that is thirteen meters long, 55cm in diameter at the base and 45 cm at the top. The footbridge was divided into seven modules with nominal dimensions of 5m long, 2m wide and 20cm high; each consisting of 37 slides measuring 5 cm in width and 20 cm in height and 5m in length (Pletz, 2003).

Figure 4. Cable-stayed wooden footbridge at the Sao Carlos Engineering School, USP

The second structure where the method was tested is the Hawkshaw Bridge (Figure 5), a cable-stayed bridge with cables anchored in a harp shape. The bridge is located in the province of New Brunswick, Canada, on the Hawkshaw Bridge Road, at 0.20 km North on the intersection with Highway 2, in the Nackwic district, spanning the Saint John River (Larocca, 2004).

Figure 5. Hawkshaw Cable-Stayed Bridge, New Brunswick, Canada

6. TESTS ON A CABLE-STAYED WOODEN FOOTBRIDGE

6.1 Instruments used

The instrumentation used consisted of a pair of GPS receivers with a 20Hz data rate with choke ring antennas and a Kiowa DT 100 displacement transducer, with Vishay data acquisition system of 20 channels and a 10Hz data rate, model 5100B Scanner. Figure 12 illustrates the layout of the instruments used on the footbridge and Figures 13 and 14 illustrate the layout of these instruments on the footbridge. The electro-mechanical oscillator was adjusted to apply a displacement with an extent of 12 mm and a frequency of 1.0 Hz.

Preliminary tests with pedestrians walking on the bridge were made to gain a rough idea of the dynamic behavior of the bridge and monitor the extent and frequency of vertical displacement, which was conducted by two observers. One observer, using a total station and a piece of tape measure set in the center of the 2nd leg, determined the average extent of the approximate vertical displacement caused by pedestrians. Another observer determined the approximate frequency of the footbridge at the same time using a stopwatch. The values obtained for the scale ranged between 8mm and 12 mm and the frequency varied from 100 to 120 cycles per second, this value of frequency of vibration being induced by pedestrians, as established by Pretlove et al. (in CEB, 1991).

During the tests, the antenna was set in the electro-mechanical oscillator to obtain a peak in the spectrum of known frequency and extent, and then serve as a calibrator for the peak due to the displacement of the bridge. The oscillator was therefore adjusted to apply an extent of movement of 3mm, with a frequency of 1 Hz at the antenna. The forced vibration tests were performed using people as mobile cargo, who walked over the deck in an orderly manner (Figures 6).

Figure 6. Front view of pedestrians walking on the footbridge and view of the GPS antenna over the oscillator

6.2 Footbridge tests results

The data processing collected with the GPS and transducer displacement are described below.

Figure 7 presents the data obtained with the displacement transducer during the field test carried out on the footbridge with moving pedestrians - figures above. By means of maximum and minimum recorded amounts the amplitude of displacement was determined, with a result of 13 mm.

Applying the Fast Fourier Transform (FFT) to these sums in the spectrum, the peak corresponding to the periodic movements recorded by the displacement transducer can be clearly seen, with a frequency of 2.0Hz (Figure 8).

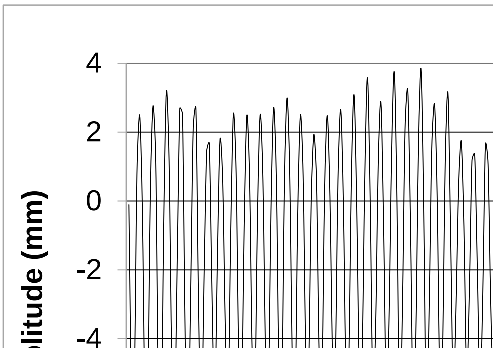

Figure 7. Data collected by displacement transducer

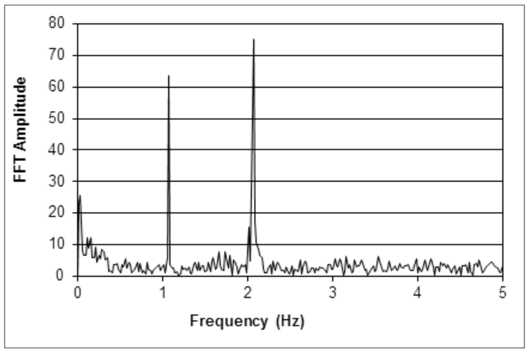

Figure 10. Power spectrum of the raw residuals with peaks due to vertical dynamic displacements applied to the GPS antenna

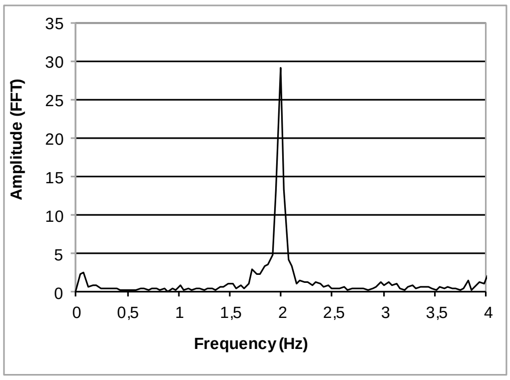

Figure 8. Power spectrum of data collected by displacement transducer

During the tests carried out, the measuring satellite and the reference were close to 74 degrees (PRN 28) and 5 degrees PRN (26), respectively. Figure 9 illustrates the residuals of the double phase difference between these satellites. The spectral analysis of these residues (Figure 20) allows for the extracting of the frequency value of the electro-mechanical device, 1.1Hz, and the sum of the footbridge, 2.1Hz, under forced vibration. In the same

Figure 10 it can also be observed that the peak corresponding to the displacement applied by the oscillator at the antenna is perfect because the movements are applied by a machine - the electro-mechanical device. Already, the peak corresponding to the displacement caused by the pedestrian’s action of walking, although ordered, is not perfect, because each person has a different step length and weight.

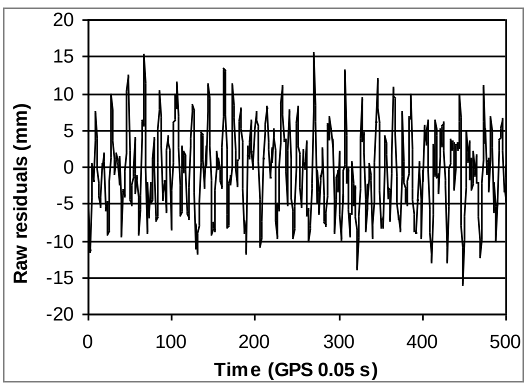

Figure 9 - Raw phase residuals of the dynamic vertical displacement response

The comparison of the values obtained with the GPS and the transducer can be summarized as can be seen in the table below.

Equipment	Frequency of footbridge response to pedestrians walked (Hz)	Vertical amplitude displacement (mm)
GPS – 20 Hz and antenna Choke ring	2.1	13.0
Displacement transducer – 100mm	2.0	13.0

Table 1. Values of natural frequency and the extent of displacement obtained with the GPS and the transducer

7. TESTS ON A HAWKSHAW CABLE-STAYED BRIDGE, CANADA

With the objective of monitoring the dynamic behavior of the Hawkshaw bridge, forced vibration tests were planned to be carried out, using design trucks, on the deck, during the author's doctoral internship at the University of New Brunswick, Canada, in October 2003. The trial was sponsored by the Department of Geodesy and Geomantics Engineering of University of New Brunswick, Geodetic Research Laboratory, and Canadian Center for Geodetic Engineering and the New Brunswick Department of Transportation (NBDT).

7.1 Instruments used

Two GPS receivers that were the reference stations were installed on top of a gravel mountain, 30m from the end of the bridge running along the south span, which is the highest place close to the bridge (Figures 25 and 26). For each fixed station, REF 2 and REF 3, a Novatel OEM4-DL4 receiver with a Pinwheel antenna and a Trimble 5700 receiver with a Geodetic antenna ZephyrTM were used. Two GPS receivers were installed on the electro-mechanical device in the bodyguard of the central span to register already known oscillations in addition to those of the deck of the bridge (Figures 11, 12 and 13). All the receivers were programmed to collect data with a rate of 5Hz. A total station was used to perform measurements with the design trucks on the deck and an accelerometer for measurement of the vibration frequencies of the bridge´s deck.

Figure 11. Detail of reference stations used for monitoring the bridge

Figure 12. Wooden support for the electro-mechanical device

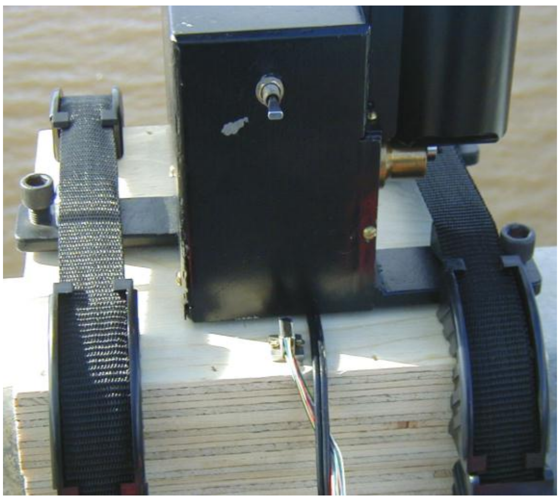

Figure 13. View of the accelerometer fixed to the wood support

Figure 14 illustrates an example of the trucks that were used as mobile loads during the dynamic tests on the bridge deck.

Figure 14. Haulage truck of the type used

7.2 Results of tests on the Hawkshaw Bridge

7.2.1 Monitoring of vertical displacement of the deck

During one of several tests performed on the bridge, the measuring and reference satellites were close to an elevation of 81 degrees (PRN 02) and 9 degrees (PRN 31), respectively. Figure 15 illustrates the residuals of the double difference phase of all satellites in relation to PRN 31, since at that time it was seeking to check the vertical dynamic behavior of the central span when it four trucks were allowed to cross the bridge. The crossing took nearly 75 seconds. In Figure 16 it is possible to clearly see the graphic description of vertical displacement of the instrumented middle span section that reached an extent of 8cm. Another four design trucks were therefore asked to stop in the middle of the central span to take the measurements using the Total Station, obtaining a mean value 8.3 cm.

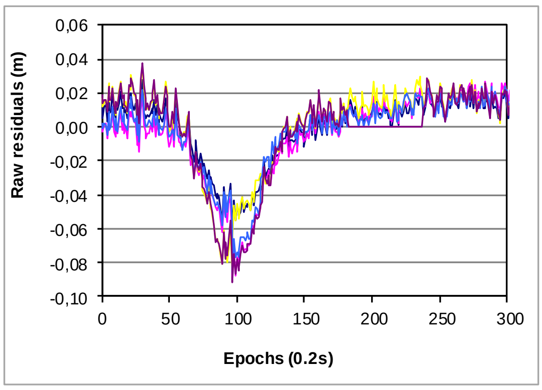

Figure 15. Raw residuals of the vertical displacement of the central span – 4 design-trucks

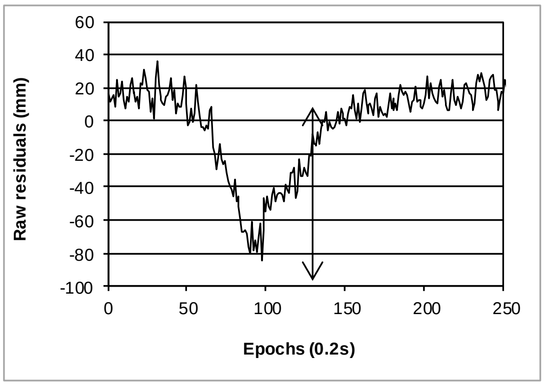

Figure 16. Raw residuals showing the vertical displacement of the central span

7.2.2 Monitoring of lateral displacement of the deck

During a second test, the reference and measuring satellites were close to 80 degrees of elevation (PRN 02) and 6 degrees of elevation (PRN 31), respectively. Figure 17 illustrates the residuals of the double difference phase for all the satellites in relation to the PRN 02, since it was seeking to verify the behavior of the lateral dynamic of the central span. In Figure 33 it is possible to clearly see the graphic description of the lateral displacement of the instrumented section in the central span, where a design truck of 60 tons crossed the bridge. The crossing took nearly 45 seconds.

Figure 18 illustrates only the residuals of the lowest satellite (PRN 31) for better visualization of the lateral dynamic displacement caused by a mobile load of 60 tons. The spectral analysis of these residuals (Figure 19) allows for the extracting of the level of the deck´s lateral frequency vibration when subjected to vibration caused by a mobile load. The lateral frequency level of the deck was 0.60 Hz. The extent of dynamic displacement showed an average of 3.5 cm.

Furthermore, the lateral displacement of the deck, when the truck starts to cross, reaches the middle of the deck and starts to exit the bridge, has an average extent of 3.5 cm.

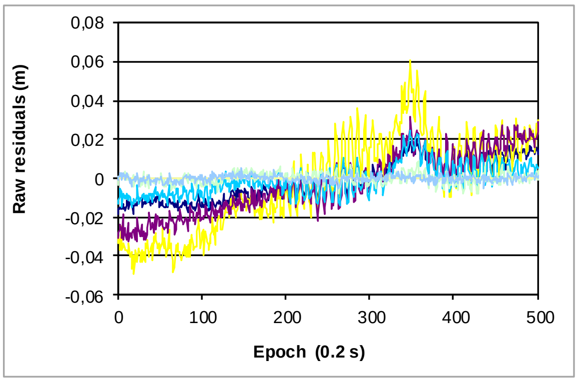

Figura 17. Raw residuals of lateral dynamic displacements of the deck

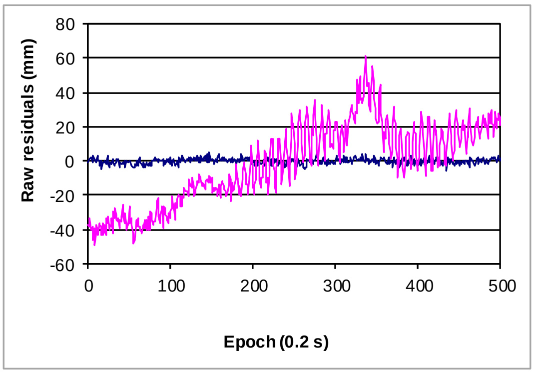

Figura 18. Raw residuals showing the lateral dynamic displacements of the deck

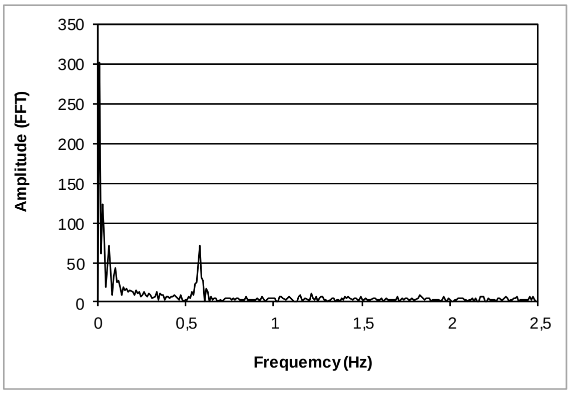

Figura 19. Spectrum of residuals with the peak due to the lateral frequency vibration of the central deck

8. CONCLUSIONS

Based on the studies, field experiments and analysis of the results presented in this research, it can be concluded that the GPS data collection research method has been established as valid due to its capability and efficiency. GPS may therefore be guaranteed a role as a monitoring instrument for the measurement of the dynamic behavior of structures.

A comparison of results obtained using the GPS and the displacement transducer, and resulting from vibration tests conducted on a wooden cable-stayed footbridge to confirm the reliability of the results obtained by GPS to characterize the dynamic behavior of structures, agreed satisfactorily with the results of the Finite Elements theory and theoretical values of the CEB (Comite Euro-International du Beton - Bulletin D´ Information no. 209). Therefore, the results proved the efficiency and capability of the collection method and GPS data analysis to obtain the frequency values and amplitude of dynamic displacement, showing that the limitation imposed by the necessity of a particular geometric configuration of satellites, in this case, did not prejudice the program and performance of the tests. As the method does not require a good geometric distribution of satellites - only two satellites – it allows for the obtaining of reliable results in the dynamic behavior of a structure anywhere around the globe. The use of an electro-mechanical oscillator as a calibrator proved to be reliable, further providing calibrated values of frequencies and extents of unknown displacements, since the electro-mechanical oscillator can be used to produce known oscillations.

The results of the second application test of the method used in this study on a large, man-made road structure, the Hawkshaw cable-stayed bridge showed the full possibility of using GPS for characterizing the dynamic behavior of this type of structure.
Given the above, it was concluded that GPS, or the method of data collection employed, allows for the graphical description of the dynamic displacement amplitude of the middle span deck and the identification of modal frequencies of bridges be it under controlled traffic action or not, and may be used by engineering as a tool for monitoring structures.

8.1 References

References from Journals:

Larocca, A. P. C., Schaal, R. E., and Barbosa, A.C.B. (2010). "A. Low-Frequency Vibrations Detection with High-Rate Data and Filtering". *GPS World*, 21 (4), 28-35.

Larocca, A.P.C., and Schaal, R.E (2005). "Millimeters in Motion Dynamic Response Precisely Measured". *GPS World,* 16 (1), 16-18, 20, 21-23.

Nassif, H. H., Gindy, M., and Davis, J. (2005). "Comparison of laser Doppler vibrometer with contact sensors for monitoring bridge deflection and vibration". *NDT & E International*, 38 (3), 213-218.

Ragheb, A.E., Edwards, S. J., and Clarke, P. J. (2010). "Using Filtered and Semicontinuous High Rate GPS for Monitoring Deformations". *J. Surv. Eng*, 136 (2), 72-79.

Roberts, G. W; Brown, C., and Meng, X. (2006). "Bridge Deflection Monitoring - Tracking Millimeters across the Firth of Forth". *GPS World,* 17 (2), 26-31.

Schaal, R.E., and Larocca, A.P.C. (2002). "A Methodology for Monitoring Vertical Dynamic Sub-Centimeter Displacments with GPS". *GPS Solutions*, 5 (3), 15-18.

Schaal, R.E., and Larocca, A.P.C. (2009). "Measuring Dynamic Oscillations of a Small Span Cable-Stayed Footbridge: Case Study Using L1GPS Receivers". *J. Surv. Eng.*, 135 (1), 33-37.

TingHua, Y.I.; HongNan, L. I.; Ming., G. (2010). Recent research and applications of GPS based technology for bridge health monitoring. *SCIENCE CHINA Technological Sciences*. Volume 53, Number 10, 2597-2610.

Xiaodong J., Fenves, G. L., Kajiwara, K., and Nakashima, M. (2011). "Seismic Damage Detection of a Full-Scale Shaking Table Test Structure". *J. Struct. Eng.*, 137 (1), 14-21.

References from Books:

Leick, A. (2004). *GPS Satellite Surveying*. 2nd Ed., Willey, New York.

Patrick, F. D. (2005). *Measurement and Data Analysis for Engineering and Science*. New York: McGraw–Hill.

Wells, D., Beck, N., Delikaraoglou, D., Kleusberg, A., Lachapelle, G., Langley, R. B., Nakiboglu, M., Schwarz , K., Tranquilla, J.M., and Vaníček, P. (1999). *Guide do GPS Positioning*. Canadian GPS Associates, New Brunswick, Canada.

References from Other Literature:

Larocca, A.P.C. (2004). "Using High-Rate GPS Data to Monitor the Dynamic Behavior of a Cable-Stayed Bridge". *ION GNSS 2004,* Institute of Navigation, Manassas, VA.

Pletz, E. (2003). Passarela estaiada com tabuleiro de Madeira laminada protendida em módulos curvos. Thesis (Doutorado). São Carlos Engineering School – University of São Paulo. 164p.

Pretlove, A. J.; Rainer, H.; Bachmann, H. (1991). Bulletin d' Information no. 209 – Vibration Problems in Structures. In CEB: Vibrations Induced By People. Lausanne. Cap. 1,p. 1-10.

8.2 Acknowledgements

The authors would like to thank the CNPq – the National Council for Scientific and Technological Development – that provided an author's productivity grants (CNPQ-PQ2) and FAPESP for providing sponsorship for attending ISDM 2011.