Comparing L1 GPS with displacement transducers and accelerometers in monitoring applications of bridges

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Resumo

O Departamento de Transportes da Escola de Engenharia de São Carlos, Brasil, tem desenvolvido pesquisas sobre monitoramento das deflexões de grandes estruturas, principalmente pontes, com o Sistema de Posicionamento Global (GPS), desde o ano de 2000. Este trabalho teve a colaboração de pesquisadores do Departamento de Madeiras da Escola de Engenharia de São Carlos e pesquisadores do *Department of Geodesy and Geomatics Engineering* da *University of New Brunswick*, Canadá. Os ensaios tiveram como objetivo comparar as medidas de dois instrumentos geotécnicos convencionais, transdutor de deslocamento e acelerômetro, com as medidas obtidas por meio de receptores GPS de uma freqüência, L1. A comparação com o transdutor de deslocamento foi realizada em uma passarela de madeira, medindo-se a amplitude e freqüência dos seus deslocamentos dinâmicos, induzidos pelo caminhar de pedestres. A comparação com o acelerômetro consistiu em aplicar um deslocamento periódico vertical nos instrumentos por meio de um oscilador eletromecânico. Os dados do GPS foram obtidos pelo Método dos Resíduos de Fase (MRF). Como este método não necessita do uso de coordenadas conhecidas é muito prático para medidas de oscilações de amplitude milimétrica. As análises dos resultados obtidos pelos diferentes instrumentos permitem indicar precisão e acurácia das medidas realizadas com o GPS.

Palavras-chave: *GPS. Oscilação dinâmica. Pontes. Deslocamentos milimétricos.*

Abstract

The Department of Transportation of São Carlos Engineering School, Brazil, has been researching about deflections monitoring of large structures, mainly bridges, with Global Positioning System (GPS), since year 2000. This work had technical support from researches of the Timber Wood Laboratory of Sao Carlos Engineering School and researches of the Department of Geodesy and Geomatics Engineering from the University of New Brunswick, Canada. The experiments had the objective to compare the measurements of two geotechnical conventional instruments, displacement transducer and accelerometer, with L1 GPS receiver measurements. The evaluation with the displacement transducer was performed at a cable stayed timber bridge, measuring the amplitude and frequency of its dynamic displacements induced by the stepping of pedestrians. The comparison with the accelerometer consisted in applying a periodic vertical movement by means of an electro-mechanical device. GPS results were obtained by Phase Residual Method (PRM). As this method is not based on coordinate determination, it is very useful for measuring short-lived oscillations at millimeter level. The PRM is not susceptible to multipath-induced position errors (which can be up to several centimeters) and there are minimal satellite visibility constraints. By analyzing results with the different techniques, repeated tests results were obtained which indicate the precision and accuracy of GPS.

Keywords: *GPS. Dynamic oscillation. Bridges. Millimetric displacements.*

1 Introduction

Two sets of tests were carried out to assess the precision and accuracy of GPS for monitoring the dynamic displacement of structures. The first set of tests, which was conducted with GPS and one displacement transducer, was carried out on a cable-stayed timber footbridge built at the São Carlos Engineering School, University of São Paulo, São Carlos, Brazil. The dynamics of footbridges are significantly affected by the use of it by pedestrians. A GPS receiver located in the middle of the bridge section that presented the highest vertical displacement was considered as the rover station and a receiver located over a reference point off the footbridge was considered as the static station [Larocca and Schaal, 2005]. The second group of tests was conducted with GPS and an accelerometer. They were carried out on the roof of Head Hall at the University of New Brunswick, Fredericton, Canada. The static antenna was fixed over one of the four reference pillars on the roof and the rover antenna and accelerometer were attached to an electro-mechanical oscillator (EMO) over another pillar providing a known sinusoidal vertical oscillation.

The Phase Residual Method (PRM) [Schaal et al., 2002] is based on the analysis of the L1 baseline double-difference (BDD) phase residuals (PR) resulting from the processing of data from a "static" session. It is applicable over short baselines, a common scenario in structure displacement monitoring. Short baselines also allow the use of single-frequency receivers. By converting the residuals to the frequency domain, it is possible to see the different signatures of the receiver phase noise, multipath, and antenna periodic movements allowing the research to distinguish among them. A periodic displacement due to the fundamental oscillation mode of the structure is revealed by a spectral peak while the receiver noise presents a white noise spectrum and the multipath presents a broad spectrum close to zero frequency. PRM does not need accurate epoch-by-epoch coordinates to determine the amplitude and frequency values of the oscillations.

2 GPs versus Displacement Transducers – TESTS AND RESULTS

A cable-stayed bridge is a statically indeterminate structure. This fact has made the monitoring of their strength a particular concern within the engineering community [Sumitro, 2001; Ogaja et al., 2000]. Effective monitoring, reliable data analysis, rational data interpretation and correct decision making are challenging problems for engineers who specialize in bridge monitoring. The scope of monitoring includes two major types of parameters: load effects and responses. Load effects refer to those due to wind, temperature and live loads (pedestrians in the case of a footbridge). Responses refer to displacements, accelerations, strains and forces of the components of footbridge structures, and displacements and stresses of the main cables [Sumitro, 2001]. The responses allow the as-built performance to be checked against design criteria, an increasingly useful exercise given the move towards "performance based design of structures. Measurements of the responses can also provide the opportunity to identify "anomalies" that may signal unusual loading conditions or modified structural behavior, which can, in the extreme case, include damage or failure [Ogaja et al., 2001].

Tests were carried out on February 20 and 21, 2003. Equipment used in these tests consisted of a pair of Topcon [Either Topcon or JPS but not both.] , GPS receivers with JPS REGANT_SD_E choke-ring antennas, collecting data at a rate of 20 Hz, and a Kyowa DT 100 displacement transducer with a Vishay data acquisition unit with 20 channels and 10 Hz data rate. The mobile antenna was installed on an EMO that moved the antenna up and down in a sinusoidal movement exactly 6 millimeters with 1.1 Hz rate controlled by the voltage applied to the motor [Larocca and Schaal, 2005].

Figure 1 shows the equipment layout during the tests. The GPS receiver installed on the bridge (station Luci) and the transducer were placed on bridge module 02, which in a previous load static trial was found to have the highest vertical deflection. This module is supported by the longest stay cables and for that reason presents the greatest dynamic displacements. The GPS receiver reference (station Hora) was off the footbridge. The baseline length (Hora-Luci) is approximately 53 meters. For the baseline double-difference processing, the coordinates of the reference station were obtained from the navigation solution. To obtain the adjusted phase residuals, all GPS data were processed using the JPS Pinnacle 1.0 software which provides ASCII data solution files. Figure 2 shows the pedestrians walking on the bridge at the time of the tests.

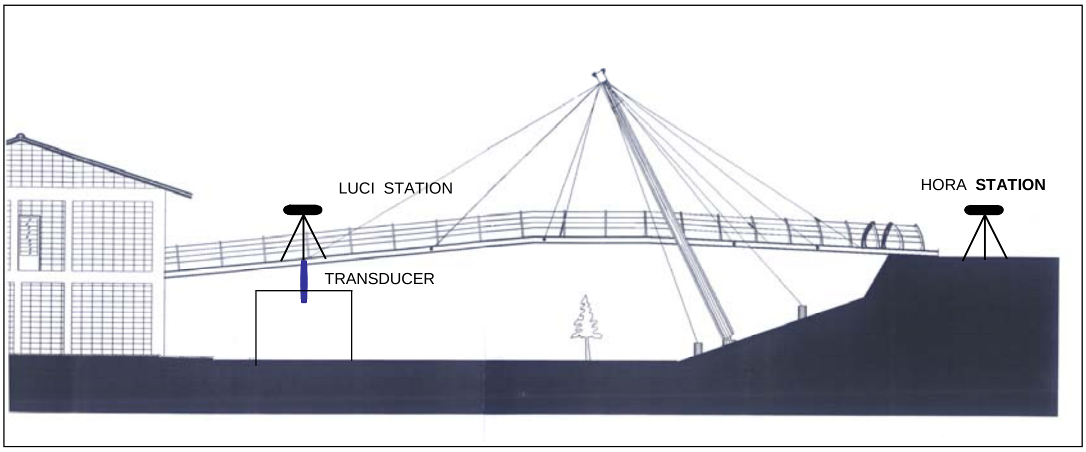

Figure 1: The layout of the GPS receivers and displacement transducer during trials on the cable-stayed footbridge

Figure 2: Loading test with "organized" pedestrians

Figure 3 illustrates the Phase Residual (PR) over a period of 25 seconds from two satellites, one close to 80 degrees elevation angle (G28) and the other at 14 degrees (G29), respectively. The phase data from G28 is highly affected by the vertical displacement, whereas G29 is almost unaffected. It is possible to graphically observe the vertical deflection amplitude of the footbridge module 02 under pedestrian load and the approximated vertical frequency oscillation due to peaks with about 10 epoch (0.5 seconds) period due to deflections caused by the people-walking period, 2 Hz .

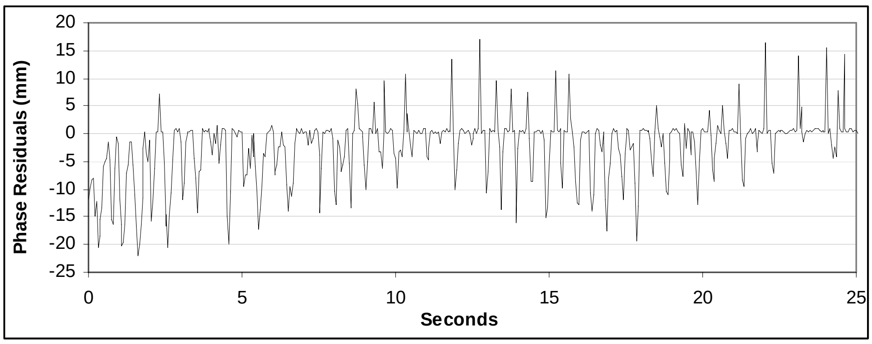

Figure 3: Phase residuals from the static Hora-Luci baseline DD

Figure 4 presents the corresponding spectrum using 1024 phase residual values (51.2 second sample). The first peak at 1.09 Hz is due to oscillations applied by the EMO. The second peak at 2.02 Hz is due to vibrations induced by pedestrians' motion. It agrees with the average walking rate presented by Pretlove et al. [1991] in Chapter 1 of Bulletin D' Information no 209, of Committee Euro-International Du Beton [CEB]. The third peak at 3.11 Hz corresponds to the natural vertical frequency of the footbridge and fourth peak at 4.05 Hz is the first modal frequency. Both of these latter values are in the range due to standard deviation of the theoretical values obtained by Pletz [2003] using Finite Element Analysis. Multipath and some other low frequency structural movements generate frequencies below about 0.1 Hz.

From the frequency spectrum it is possible to determine the deflection amplitude of module 02 of the footbridge. It is possible to obtain this from a comparison between the amplitudes of the peak due to pedestrian movement and the peak due to the known oscillations applied to the mobile antenna by the EMO. In this case, the EMO works as a calibrator for the unknown amplitude oscillations.

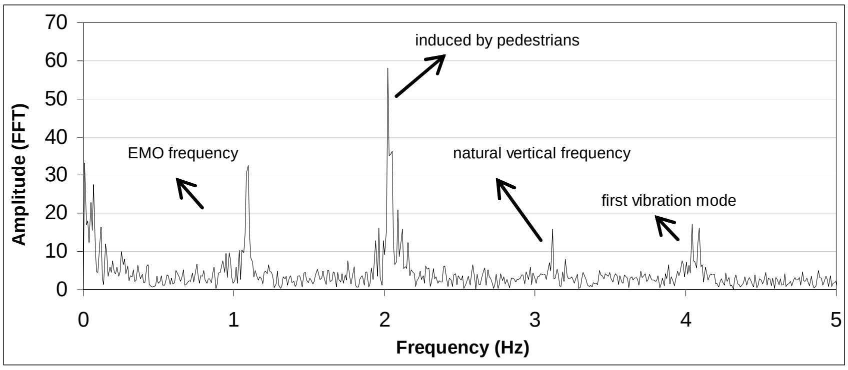

Figure 4: Spectrum of the static solution residuals

Peaks are due to EMO displacement, displacement induced by pedestrians, and the displacements due to the natural vertical frequency and the first vibration mode of footbridge. The induced frequency response under people walking is close to 2 Hz with a standard deviation of ± 0.175 Hz. The footbridge natural vertical frequency is 3.20 Hz and the first vertical vibration model 4.10 Hz also according Finite Element Method [Pletz, 2003].

From a simple rule of thumb, it is possible to estimate the amplitude of the unknown oscillations. The EMO applied a vertical sinusoidal of 6.0 mm total displacement, resulting in a 31-unit-peak in the spectrum, so the oscillation induced by pedestrians with a 59-unit-peak has an approximately 11.4 mm displacement. In the same way, the natural vertical frequency peak resulted in a 2.7 mm displacement and the first vibration mode, 3.3 mm. The uncertainty in the peak estimates is about 5 spectrum units, which represents a 1 mm displacement. The uncertain is estimated by noise amplitude around the sidebands of peak.

Figure 5 presents the transducer values. The values are quite variable due to different cadence of the pedestrians with a span in the order of 12.2 mm. This result is quite in agreement with the GPS results. An FFT was applied on these data resulting in the spectrum presented in Figure 6.

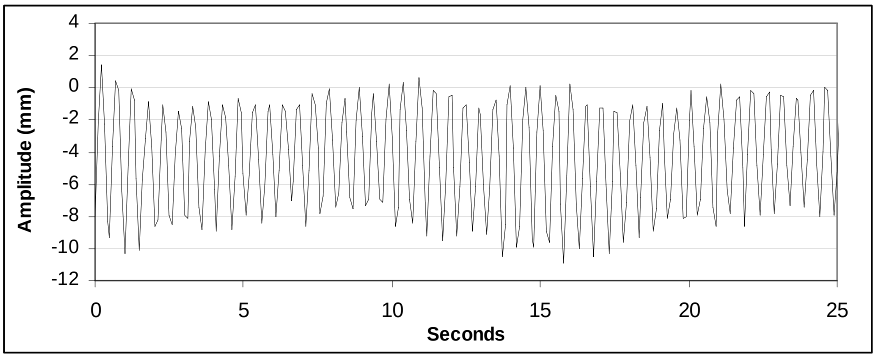

Figure 5: Values of displacement registered by the displacement transducer

The first peak close to 0.05 Hz is due to electronic noise of the displacement transducer. The second peak at 1.97 Hz is due to the oscillation induced by pedestrian motion. The third peak, at 3.06 Hz, corresponds to the natural vertical frequency and the fourth, at 4.04 Hz, is the first vibration mode frequency.

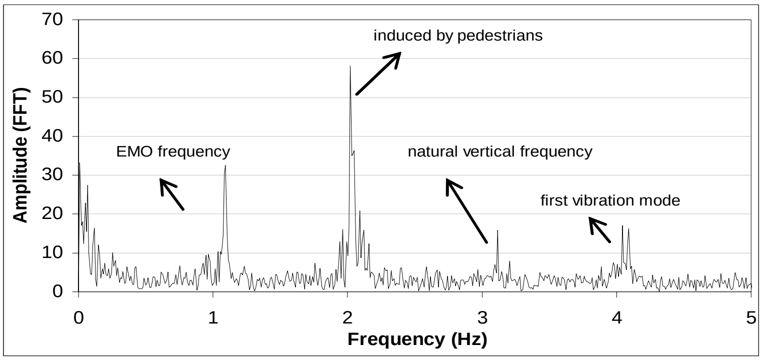

Figure 6: Spectrum of data registered by the displacement transducer

From the same rule of thumb that was applied earlier, it is possible to estimate the amplitude of the unknown oscillations. The oscillation induced by pedestrians with 41-unit peak has an approximately 12.6 mm displacement, while the natural vertical frequency resulted in 1.5 mm and the first harmonic 2.4 mm displacements. The uncertainty is about 1 unit, which represents 0.3 mm.

Table 1 summarizes the results obtained by both instruments. As the uncertainty is at the millimeter level, the results are in good agreement, showing that L1 GPS receivers can monitor the dynamic behavior of bridges.

Table 1: Values obtained by GPS and the displacement transducer for the footbridge under forced motion

Instrument	Frequency induced by pedestrians (Hz)	Natural vertical frequency of footbridge (Hz)	Frequency of first vibration mode	Pedestrian-induced displacement (mm)
GPS	2.02	3.11	4.05	11.4 ± 1.0
Displacement transducer	1.97	3.06	4.04	12.6 ± 0.3
Theoretical Values	2.0 ± 0.175	3.20	4.10	

3 GPs versus accelerometer – Tests and Results

Tests were carried out on the roof of the Head Hall engineering building, located on the University of New Brunswick (UNB) Fredericton Campus on October 24th, 2003. The equipment included NovAtel OEM4 GPS receivers and pinwheel antennas (graciously loaned by UNB's Canadian Center for Geodetic Engineering) and a Vernier Software & Technology LGA-BTA single-axis Low-g accelerometer which is based on the Analog Devices ADXL05 MEMS sensor. The accelerometer has a manufacturer's stated accuracy of ± 0.5 m/s^2, a range of -50 to +50 m/s^2 and a frequency response of 0 to 100 Hz. The data was collected with a Handspring Visor Prism Palm OS handheld and an Imagiworks interface module. Selectable data rates included 10, 100 and 1000 Hz. Figure 7 illustrates the environment where the tests were carried out, as well as the related equipment.

Figure 8 shows details of the EMO on one of the pillars. The mobile antenna (station Mobile) and the accelerometer are seen fixed on an aluminum rod attached to the EMO. The static receiver (station Static) was installed on another pillar. The baseline length was approximately 10 meters. The experiment design was to apply vertical movements to the mobile GPS antenna with a nominal frequency of 0.976 Hz and a peak-to-peak displacement of 6 mm.

Figure 7: The Head Hall roof-top environment at UnB

Figure 8: Illustration of the EMO with GPS rover antenna and accelerometer

Figure 9 presents the phase residuals of the Static-Mobile baseline for a pair of satellites: one close to 81 degrees elevation angle (G02) and the other at 9 degrees (G27). The GPS session ran from 11h22min and 11h30min local time (change) and data was collected with a 5 Hz rate. Due to its high elevation angle, the phase data from G02 is highly affected by the vertical displacement whereas G27 is almost unaffected.

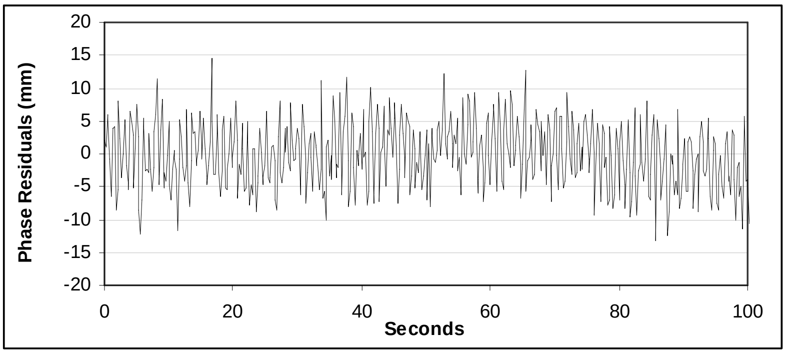

Figure 9: Phase residuals from the Static-Mobile baseline DD

Figure 10 presents the corresponding spectrum from 1024 samples from the above residuals. The isolated peak at 0.974 Hz is in agreement with the frequency of the periodic oscillation applied by the EMO. The peaks below 0.05 Hz are generated by multipath.

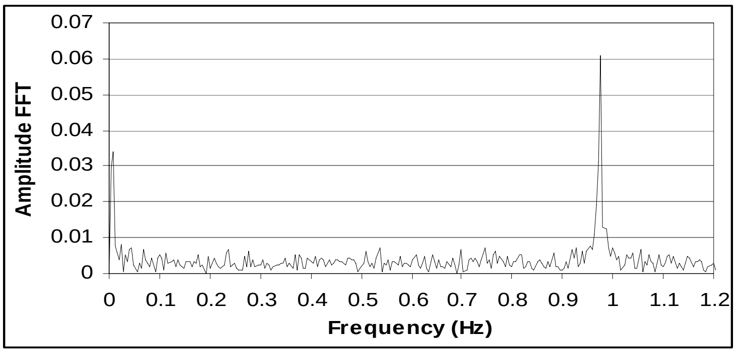

Figure 10: GPS frequency spectrum

The output of the accelerometer is in units of volts. The conversion to acceleration units is carried out according to a calibration equation (Equation 1):

acceleration (m/s^2) = 20.77·*measurement* (volts) -36.81 (1)

The displacement applied by the EMO to the mobile antenna is given by:

displacement(m) = 0.003·sin(2pft) (2)

Figure 11 shows the values registered by the accelerometer at a 100 Hz-data rate and the corresponding moving average (MA) values. It is possible to note that the output is quite noisy. In spite of that, the MA, which smoothes a data series and makes it easier to spot trends, shows that the values obtained have a absolute range variation of around 0.20 m/s^2. This value is closer to the theoretical value of 0.19 m/s^2. These values are in agreement with the theoretical acceleration values obtained from the second derivative of Equation 2 (Equation 3):

acceleration(m/s^2) = -0.003·2pf·2·sin(2pft) (3)

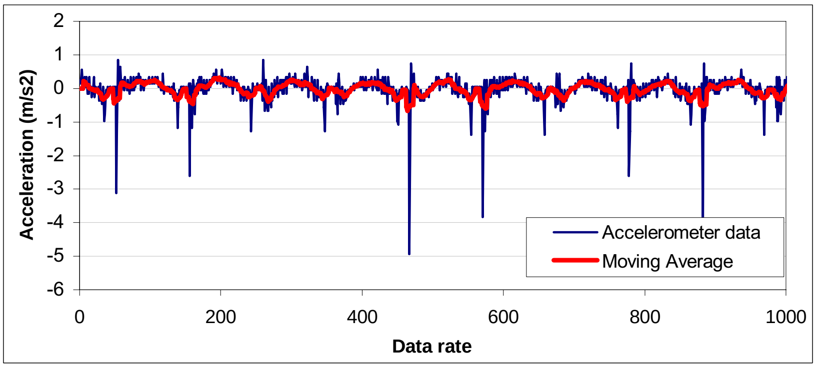

Figure 11: Values registered by the accelerometer and corresponding MA values

The FFT was applied to a 1024-sample of accelerometer data and Figure 12 shows the resulting frequency spectrum with a peak at 0.975 Hz

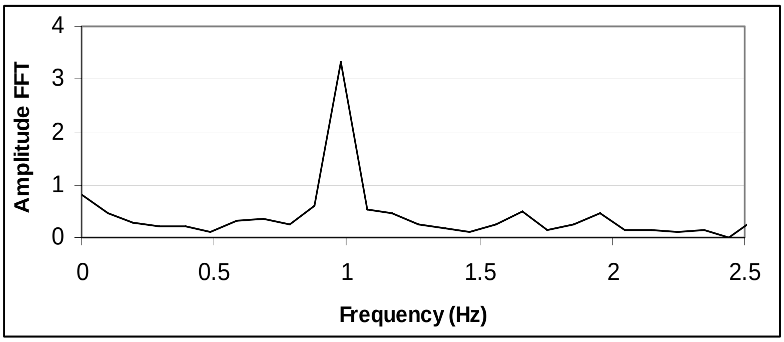

Figure 12: Accelerometer frequency spectrum

A comparison of the GPS and accelerometer results is presented in Table 2.

Table 2: Oscillation frequency values obtained with GPS and accelerometer

Equipament	Oscillation Frequency (Hz)
GPS	0.974
Accelerometer	0.975
Theoretical	0.976

Although the values agree very well, the frequency values obtained by GPS can be considered more precise than those obtained by the accelerometer. In part, this is due to the higher precision of the raw GPS measurements and the higher-precision clocking of the data. The agreement shows that L1 GPS receivers can be used for detecting and measuring oscillations with small amplitudes.

4 Conclusions

Both sets of tests showed that the GPS phase observable of a satellite closely aligned to the direction of a periodic displacement can be used to detect its frequency and, with a proper calibration, its amplitude with millimeter uncertainty. Both comparisons confirm the potential of PRM for monitoring the dynamic behavior of structures, showing that it allows us to obtain a repeatability of GPS results at the millimeter level, equivalent to the most accurate geotechnical instruments. GPS can be considered a more practical tool because it does not need time for calibration as does a displacement transducer. Furthermore, since accelerometers are sensitive to structure vibrations with high frequencies, it is difficult for them to sense accurately very slow vibrations with large deformation amplitudes.

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References

LAROCCA, A. P. C.; SCHAAL, R. E. Degradation in the detection of millimetric dynamic movements due to metallic objects close to the GPS antenna. In: CONGRESSO BRASILEIRO DE CADASTRO TÉCNICO MULTIFINALITÁRIO, 2002, Florianópolis. *Anais*... Florianópolis: COBRAC, 2002. Paper n. 20. 1 CD-ROM.

LAROCCA, A. P. C.; SCHAAL, R. E. Millimeters in motion: dynamic response precisely measured. *GPS World,* Santa Ana ,CA, v. 16, n. 1, p. 16-24, 2005.

OGAJA, C.; RIZOS, C.; WANG, J. A dynamic GPS system for on-line structural monitoring. In: INTERNATIONAL SYMPOSIUM ON KINEMATIC SYSTEM IN GEODESY, GEOMATICS & NAVIGATION, 2001, Banff. *Proceedings*… Banff: KIS, 2001.

PLETZ, E. *Cable-stayed footbridge with stress laminated timber deck composed of curved modules.* 211 f. Ph.D. Thesis. Tese (Doutorado em Engenharia de Estruturas)-Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2003.

PRETLOVE, A.; RAINER, J.; BACHMANN, H. Dynamic forces from rhythmical human body motions: vibration problems in structures In: *Bulletin d' Information.* Lausanne: Comité Euro-Internacional du Béton, 1991. n. 209, Chapt. 1, p. 1-10

SCHAAL, R. E.; LAROCCA, A. P. C. A methodology for monitoring vertical dynamic sub-centimeter displacements with GPS. *GPS Solutions*, Dallas, v. 5, n. 3, p.15-18, 2002.

SUMITRO, S. *Long span bridge health monitoring system in Japan*. Workshop Sponsored by the National Science Foundation on Health Monitoring of Long Span Bridges., Mar. 9-10, University of California, Irvine Campus, CA, 2001. Disponível em:

<http://www.krcnet.co.jp/papers/pdf/International/UCI2001_sumitoro.PDF>. Acesso em: 10 fev. 2004.

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