Dynamic Monitoring of Structures at the Millimeter Level: GPS versus Displacement Transducers and Accelerometers – A Summary

Ana Paula C. Larocca and Ricardo E. Schaal, *Department of Transportation of the São Carlos Engineering School, University of São Paulo, Brazil*
Marcelo C. Santos, Richard B. Langley and Don Kim, Department *of Geodesy and Geomatics Engineering University of New Brunswick, Canada*

BIOGRAPHY

Ana Paula C. Larocca received her doctorate from the Department of Transportation of the São Carlos Engineering School of the University of São Paulo (USP), Brazil, in 2004. She spent six months, in 2003, as a visiting student at the Department of Geodesy and Geomatics Engineering, University of New Brunswick (UNB), Canada. One of her papers was a contest winner selected by the ION GNSS 2004 for presentation and student travel sponsorship. Lately she has been working on dynamic measurements with GPS and other sensors as a post-doctoral fellow at the Department of Transportation at USP.

Ricardo E. Schaal is a doctor lecturer in the Department of Transportation of the São Carlos Engineering School of the University of São Paulo (USP). Dr. Schaal received a B.S.E.E. from the Polytechnic School of the University of São Paulo and a doctorate in Transportation Engineering from the same school. He is working on applications of GPS in Civil Engineering.

Marcelo Santos is an associate professor in the Department of Geodesy and Geomatics Engineering at UNB. He holds a M. Sc. in geophysics from the National Observatory in Rio de Janeiro, and a Ph.D. in geodesy from UNB. He has been involved in research in the fields of space and physical geodesy, GNSS and navigation.

Richard B. Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching and conducting research since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Professor Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine. He is a fellow of the ION.

Don Kim is a research associate in the Department of Geodesy and Geomatics Engineering at UNB. He has a Bachelor in urban engineering, and an M.Sc.E. and a Ph.D. in geomatics from Seoul National University. He has been involved in GPS research since 1991 and active in the development of an ultrahigh-performance RTK system. He received the Dr. Samuel M. Burka Award for 2003 from the Institute of Navigation.

ABSTRACT

The Global Positioning System is becoming a leading technology for monitoring dynamic displacements of structures, notably large bridges and tall buildings. These structures have been monitored in the past by geotechnical instruments such as accelerometers and displacement transducers. In this paper we compare the precision and accuracy of displacements from GPS data with values from a displacement transducer and an accelerometer.

In order to compare GPS with a displacement transducer, an experiment was conducted on a footbridge to measure the amplitude and frequency of displacements induced by pedestrians. For comparing the performance of GPS with values from an accelerometer, an electro-mechanical oscillator (EMO) was used to apply the same periodic vertical displacements to both instruments. In this paper, we present a brief summary of the methodology used and the test results. The Phase Residual Method (PRM) was used to determine the displacements as sensed by the GPS antenna. An indication of the precision and accuracy of this method is shown from the analysis of results obtained from the different techniques. The uncertainty of amplitude determinations was estimated as being around 1 mm. GPS can be considered more precise than many accelerometers for detecting the frequency of periodic oscillations in part due to the higher precision of the raw

GPS measurements and to the higher-precision clocking of the data.

FIELD TESTS

The Phase Residual Method (PRM) [Schaal and Larocca, 2001; 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 where one end of the baseline is on the structure being monitored. The method is based on the combination of high-low elevation angle satellite pairs. The method does not depend on coordinate determination, adding greater flexibility for the determination of short-lived oscillations at the millimetre 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. It is applicable over short baselines, a common scenario in structure displacement monitoring. Short baselines also allow the use of single-frequency receivers [Larocca, 2004a, b; Larocca. and Schaal, 2005].

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 us 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. Furthermore, their determination is not affected by satellite geometry in the northern sky quadrant, which ordinarily leads to precision degradation particularly in the north-south position component.

First Test

We have carried out two sets of tests 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 way pedestrians use them [Pretlove et al., 1991; Hirsh and Bachmann, 1991]. A GPS receiver located in the middle of the bridge section, where the highest vertical displacement was present, was considered as the rover station and another receiver located over a reference point off the footbridge was considered as the static station [Larocca, 2004a; Larocca and Schaal, 2005]. The baseline length is approximately 53 meters. Tests were carried out on February 20 and 21, 2003. The equipment used in these tests consisted of a pair of Topcon-Javad Positioning Systems (JPS) Legacy 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 GPS receiver installed on the bridge, as well as the transducer, were placed on bridge module 02, which in a previous load static trial was found to have the highest vertical deflections. This module is supported by the longest stay cables and for that reason presents the greatest dynamic displacements. The rover 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]. 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.

Second Test

The second group of tests was 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 accelerometer 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. The static antenna was fixed over one of the four reference pillars on the roof and the rover antenna and accelerometer were attached to the oscillating post of an EMO placed over another pillar providing a known sinusoidal vertical oscillation. The Static-Rover baseline length was approximately 10 meters. The experiment design was to apply sinusoidal vertical movement to the rover antenna with an approximate frequency of 1 Hz and displacement of 6 mm. The baseline was processed using the OMNI software from the U.S. National Geodetic Survey, which provides ASCII data files of the double-difference phase residuals.

RESULTS: GPS versus displacement transducer

The phase residual (PR) values from two satellites, one close to 80 degrees elevation angle (G28) and the other at 14 degrees (G29), respectively, allowed us to observe graphically the vertical deflection amplitude of the footbridge module 02, under pedestrian load. The phase data from G28 is highly affected by the vertical displacement, whereas G29 is almost unaffected. In the frequency spectrum of the GPS results, it is possible to observe frequency peaks within the standard deviations of the theoretical values for this footbridge, presented by Pretlove et al. [1991] and Pletz [2003].

One of the observed peaks is due to oscillations applied by the EMO. A second peak 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 n^{o} 209, of Comité Euro-International du Beton [CEB]. A third peak corresponds to the natural vertical frequency of the footbridge and a fourth peak is the first vibration modal frequency. Multipath and some other low frequency structural movements generate frequencies below about 0.1 Hz. A simple rule of thumb permits us to estimate the amplitude of the unknown oscillations. The EMO applied a vertical sinusoidal displacement of 6.0 mm resulting in a 31-unit-peak in the frequency spectrum. Accordingly, the oscillation induced by pedestrians with a 59-unit spectral peak should have 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 uncertainty in the amplitudes is estimated by considering the noise amplitude in the vicinity of the peaks. The same analysis was carried out for the transducer displacement results and the only different peak detected, at 0.05 Hz, is due to electronic noise.

Table 1 summarizes the results obtained by GPS and the displacement transducer. 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. Although the displacement transducer presents a smaller standard deviation for the displacement measure than GPS under PRM, during the four trials carried out it failed in two of them and, furthermore, also needs a period of time for calibration.

Table 2 lists the theoretical values for those frequencies detected.

	Frequency induced by pedestrians (Hz)	**Natural vertical frequency of footbridge (Hz)**	**Frequency of first vibration mode (Hz)**	**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

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

	Frequency induced by pedestrians (Hz)	**Natural vertical frequency of footbridge (Hz)**	**Frequency of first vibration mode (Hz)**	**Pedestrian-induced displacement (mm)**
Theoretical values	2.0 ± 0.175	3.20 ± 0.20	4.10 ± 0.20	--------

Table 2. Theoretical values for footbridge obtained by Pretlove et al. [1991] and Pletz [2003]

RESULTS: GPS versus ACCELEROMETER

GPS data were collected with a 5 Hz rate. The frequency spectrum of the PR of the Base-Rover baseline for a pair of satellites: one close to 81 degrees elevation angle (G02) and the other at 9 degrees (G27) presented one peak, at 0.974 Hz, due to the periodic oscillation applied by the EMO. The values registered by the accelerometer at a 100 Hz data rate presented a spectral peak at 0.976 Hz. A comparison of the GPS and accelerometer results is presented in Table 3.

Equipment	Oscillation Frequency (Hz)
GPS	0.974
Accelerometer	0.976

Table 3. Oscillation frequency values obtained with GPS and accelerometer

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

CONCLUDING REMARKS

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. A more complete description of our tests and analyses will be presented in a forthcoming paper.

ACKNOWLEDGMENTS

The first author would like to thank CNPq, the Brazilian National Council for Scientific and Technological Development, for supporting her doctorate studies at the Department of Transportation of the São Carlos Engineering School at the University of São Paulo (2000 to 2004) and the time spent at the Department of Geodesy and Geomatics Engineering, UNB (2003). Thanks are also directed to the Timber Laboratory of the São Carlos Engineering School of the University of São Paulo, to the Department of Geodesy and Geomatics Engineering, UNB and to UNB's Canadian Center for Geodetic Engineering.

REFERENCES

Hirsh, G. and H. Bachmann, (1991). "Vibration Problems in Structures and Suspension and Cable-Stayed Bridges." In: *Bulletin d' Information* no. 209. Chapter. 3.6, pp. 109-114. Published by Comité Euro-International du Béton (CEB), Lausanne.

Larocca, A. P. C. (2004a). *O Uso do GPS como* Instrumento *de Controle de Deslocamentos Dinâmicos de Obras Civis – Aplicação da Área de Transportes* (The Use of GPS as Control Instrument of Dynamic Displacements of Civil Structures). Ph.D. Thesis. São Carlos Engineering School, University of São Paulo.

Larocca, A. P. C. and R.E. Schaal (2002). "Degradation in the Detection of Millimetric Dynamic Movements due to Metallic Objects close to the GPS Antenna". In: COBRAC 2002, Nov. 21-27, Paper n. 20, Florianópolis, Santa Catarina, Brazil. CD-ROM.

Larocca, A.P.C. (2004b). "Using High-Rate GPS Data to Monitor the Dynamic Behavior of a Cable-Stayed Bridge". Proceedings of ION GNSS 2004, Sept. 21-24, 2004, Long Beach, CA.

Larocca, A.P.C. and R.E. Schaal (2005). "Millimeters in Motion – Dynamic Response Precisely Measured". *GPS World*. Vol. 16, No. 1, Jan. 2005, pp. 16-24.

Pletz, E. (2003). *Passarela Estaiada com Tabuleiro de Madeira Laminada Protendida em Módulos Curvos* (Cable-stayed Footbridge with Stress Laminated Timber Deck Composed of Curved Modules). Ph.D. Thesis. São Carlos Engineering School, University of São Paulo.

Pretlove, A., J. Rainer, H. Bachmann. (1991). "Vibrations Induced by People". In: Bulletin d' Information no. 209 – Vibration Problems in Structures. Chapter 1, pp. 1-10. Published by Comité Euro-International du Béton (CEB), Lausanne.

Schaal, R.E. and A.P.C. Larocca (2001). "A Methodology to Use the GPS for Monitoring Vertical Dynamic Subcentimeter Displacement." Digital Earth 2001, Fredericton, New Brunswick, Canada, Jun.24-28. <http://www.digitalearth.ca/abstract4.html#de-a-137>.

Schaal, R.E. and A.P.C. Larocca (2002). "A Methodology for Monitoring Vertical Dynamic Sub-Centimeter Displacements with GPS." *GPS Solutions,* Vol. 5, No.3, pp.15-18.