Using High-rate GPS Data to Monitor the Dynamic Behavior of a Cable-stayed Bridge

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BIOGRAPHY

Ana Paula Camargo Larocca received her Ph.D. degree in June 2004 from the Department of Transports of the Sao Carlos Engineering School of the University of Sao Paulo (EESC-USP) and she has been working with Dr. Ricardo E. Schaal since 2000. Ms. Ana Paula took her Master Degree and her under graduation course in Civil Engineering in the same University. She spent 5 months, in 2003, as a visitor student at Department of Geodesy and Geomatics Engineering of the University of New Brunswick, where she had the opportunity to work under the supervision of Dr. Marcelo C. Santos and to integrate with Geodetic Research Laboratory coordinated by Dr. Richard B. Langley.

ABSTRACT

This paper presents the results of the first real application, over one cable-stayed bridge, of a research under improvement since 2000 and presents the results of the monitoring of dynamic behavior under traffic load of Hawkshaw Cable-stayed Bridge, in New Brunswick, Canada. This bridge has 2 lanes, with total length of 301.20 m and its main span of 217.32 m is supported by two towers of 36 m of height. Two sessions of 1-hour GPS data have been conducted on the 30th October 2003. For each session, 5 GPS receivers (NOVATEL OEM4-DL4 and TRIMBLE 5700) were used, observing at a data rate of 0.2 seconds; one triaxial accelerometer and one total station. These GPS data were processed and analyzed by using a different method (SCHAAL et al., 2001; 2002; LAROCCA, 2004) that is described below. This method is part of a research in which the main objective is to confirm that GPS can be used as a trustworthy tool for characterizing the dynamic behavior of large structures, such as bridges, footbridges, tall buildings and towers, undergoing dynamic loads. Data analyses of Hawkshaw Bridge trial provide results that confirmed the potentiality of the method. Results presented on this paper agree with international trends in the engineering community. These trends include dynamic testing, monitoring of long span bridges and the dissemination and practice of monitoring systems that provide reliable data analysis and interpretation (SUMITRO, 2001; FARRAR, et al, 1999). This permits that assumptions used in the bridge design are correctly verified by conventional instrumentation and GPS. It is important to mention that there is not previous information about the Hawkshaw Bridge dynamic behavior, according to New Brunswick Department of Transportation.

INTRODUCTION

The concept and practical application of the cable-stayed bridge dates back to the 1600s, when a Venetian engineer named Verantiuns built a bridge with several diagonal chain stays. In 1817, two British engineers, Redpath and Brown, built a Meadows Bridge, a footbridge in England which had a span of 33.6 m, using sloping wire stay cable suspension attached to cast iron towers The concept was attractive to engineers and builders for many centuries. Since the completion of the Stromsund Bridge in Sweden in 1955, the cable-stayed bridge has been developed into the most popular bridge type. The concept of cable-stayed bridge is simple. A bridge carries mainly vertical loads acting on girder. The stay cables provide intermediate supports for the girder so that it can span a long distance being aesthetically appealing, technically innovative and very economic (TROITSKY, 1977; PODOLNY, JR. et al., 1976; TANG, 1999). As a cable-stayed bridge is a highly redundant or statically indeterminate structure, health monitoring has been one of particular concerns of the engineering community nowadays (SUMITRO, 2001).

Dynamic testing of bridges has become more prevalent in recent years as it is evident by the increasing number of tests on bridges reported. These tests are performed for a variety of reasons including studies of the aerodynamic response of bridges, correlation of numerical models with measured data, bridge condition monitoring and studies related to the development of dynamic impact factors for design of the bridges. In the course of these studies many different types of excitation methods have been applied to bridge structures. The methods of exciting a bridge for dynamic testing fall into two general categories, measured-input tests and ambient tests. For cable-stayed and suspension bridges, ambient tests become the only practical means of exciting the structure. Ambient excitation is defined as the excitation experience by a structure under its normal operating conditions. All bridges are subjected to ambient excitation from sources such as traffic, wind, wave motion and seismic excitation. The use of ambient vibration often provides a means of evaluating the response of the structure to the actual vibration environment of interest. The responses refer to displacements, accelerations, frequencies of interest, strains and forces of the members of bridge structures, and displacements and stresses of main cables Also, these responses allow the as-built performance to be checked against design criteria, which will be an increasingly useful exercise given the movement towards ‘performance based design’ of structures and can also provide the opportunity to identify ‘anomalies’ that may signal unusual loading conditions or modified structural behavior, which can, in an extreme case, include damage or failure (FARRAR et al., 1999; OGAJA et al., 2001).

Using the state-of-the-art GPS technology for monitoring dynamic behavior of large structures, several groups of researches (ROBERTS et al., 2001, 2002; TSAKIRI et al., 2003; BARNES, et al., 2003; RADONOVIC, et al., 2001; SHUN-ICHI NAKAMURA, 2000l LAROCCA et al., 2004) have conducted feasible trials, developed a monitoring system configuration, designed data fusing and processing techniques and analysis and mitigation methodology.

The method employed on this work, to detect the dynamic behavior of the bridge is based on the analysis of the L1 double difference phase residuals of regular static data processes. Most scenarios of displacement control include a reference point in the neighborhood of the structure, allowing the use of single frequency receivers. The method needs data collected from two satellites, one close to zenith and other in direction of horizon and this specific satellite geometry permits that residuals incorporate all phase changes during the observation. These phase changes can be assumed as a vectorial sum of the rover antenna movement and phase deviation sources. Most of these deviations are receiver phase noise and multipath. In the frequency domain, the movement, receiver noise and multipath present different behaviors, allowing displacement detection. The periodic displacement presents a peak for the fundamental oscillation mode, while the receiver noise presents a white noise spectrum and the multipath presents an intense spectrum close to zero frequency. The last one is very dependent on how the antennas “see” the vicinity (SCHAAL et al., 2001; 2002).

DESCRIPTION OF CABLE-STAYED BRIDGE

The trial previously mentioned on this paper was carried out on a cable-stayed steel plate girder Bridge (FIGURE 1), built in 1967 and being located on Hawkshaw Bridge Road, 0.20 km north of the intersection with Route 2, in Nackwic, New Brunswick, Canada. The orthotropic deck is composed by one north span of 54.44 m; one south span of 29.44 m and the center span with 217.32 m of length. Two steel box section towers with 36 m of height support the deck by a harp-type arrangement with six steel cables (FIGURE 2). Figure 3 and 4 illustrates schematics representation of elevation and plan section of Hawkshaw Cable-stayed Bridge.

FIGURA 1 – Hawkshaw Cable-stayed Bridge in New Brunswick, Canada

FIGURA 2 – Longitudinal view of Hawkshaw Cable-stayed Bridge

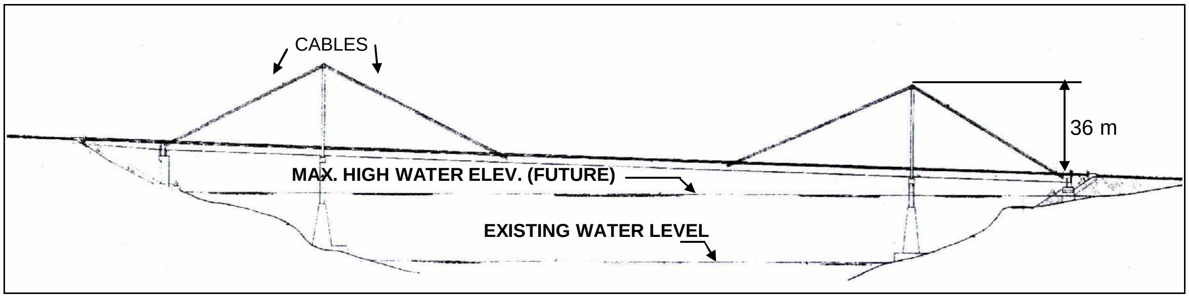

FIGURE 3 –Side elevation of Hawkshaw Cable-stayed Bridge

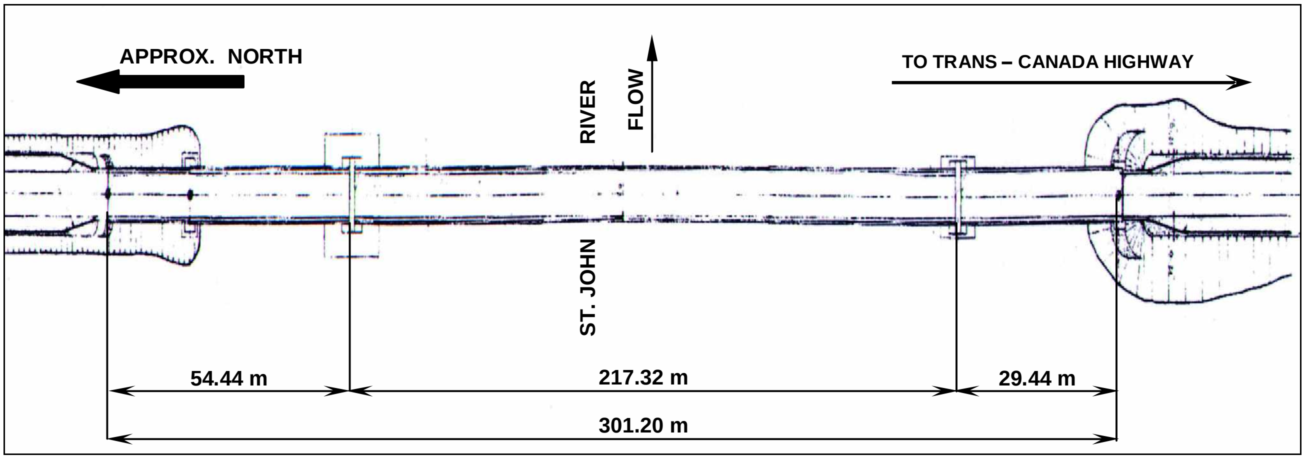

FIGURE 4 – Plan layout of Hawkshaw Cable-stayed Bridge

BRIDGE TRIAL

Some initial tests were conducted on the bridge to provide an idea about its dynamic behavior for establishing the necessary rate of GPS receiver and the accelerometer kind. Initially the behavior over the deck, under its normal operating conditions was observed with the total station and it was possible to closely determine the number of oscillations of a fixed target on the deck. This operation could also be done using a theodolite. The intensity of local traffic on Hawkshaw Bridge Road is low, presenting one truck crossing the deck each 5 minutes on average. Hence, GPS receivers, triaxial accelerometer and total station were installed and a trial was conducted on the cable-stayed bridge. It was used a pair of NOVATEL OEM4-DL4 receivers (one as reference station and the other as rover station) with two PIN WHEEL antennas, three TRIMBLE 5700 receivers with two Trimble Zephyr™ Geodetic antennas (on reference stations), one Trimble Stealth™ Ground Plane (as a rover antenna on the middle of the deck) and one ENTRAN EGA3 triaxial accelerometer. It was also used a TRIMBLE 5600 total station (distances to an accuracy of +/- 0.8 mm +1 ppm) for measuring the vertical displacement of the middle span caused by chosen design trucks namely, one truck full of wood (60 ton); the same truck empty (18 ton) and a truck loaded with paper (40 ton). It was possible to choose these types of trucks because there are paper and wood factories near the bridge.

The trial on Hawkshaw Bridge was authorized by New Brunswick Department of Transportation and was assisted by the bridge superintendent and the senior technical advisor who provided all existing structure information about bridge and traffic agents to control the local traffic during the trial. This support was particularly important because one lane was closed and trucks of local traffic were used as design trucks.

Trials were conducted on the 30th of October, 2003 during 3 hours and twelve tests were performed on the bridge. The objective of trial was to detect the dynamic behavior of the deck in the vertical and horizontal directions and the maximum vertical displacement of the deck when one or more trucks began to cross the deck. When one desired design truck was approaching the deck it was requested driver to stop and cross the deck. Sometimes, the local traffic was stopped to wait to gather more than one truck.

The layout of all instruments used can be seen in Figure 5. Figure 6 illustrates GPS rover stations installed on middle of span, over the guardrail. For that objective, was made a wood board to support the electro-mechanical device and two GPS antennas over it. The accelerometer was fixed on the wood board and the reflector target was fixed on the support for rover antennas.

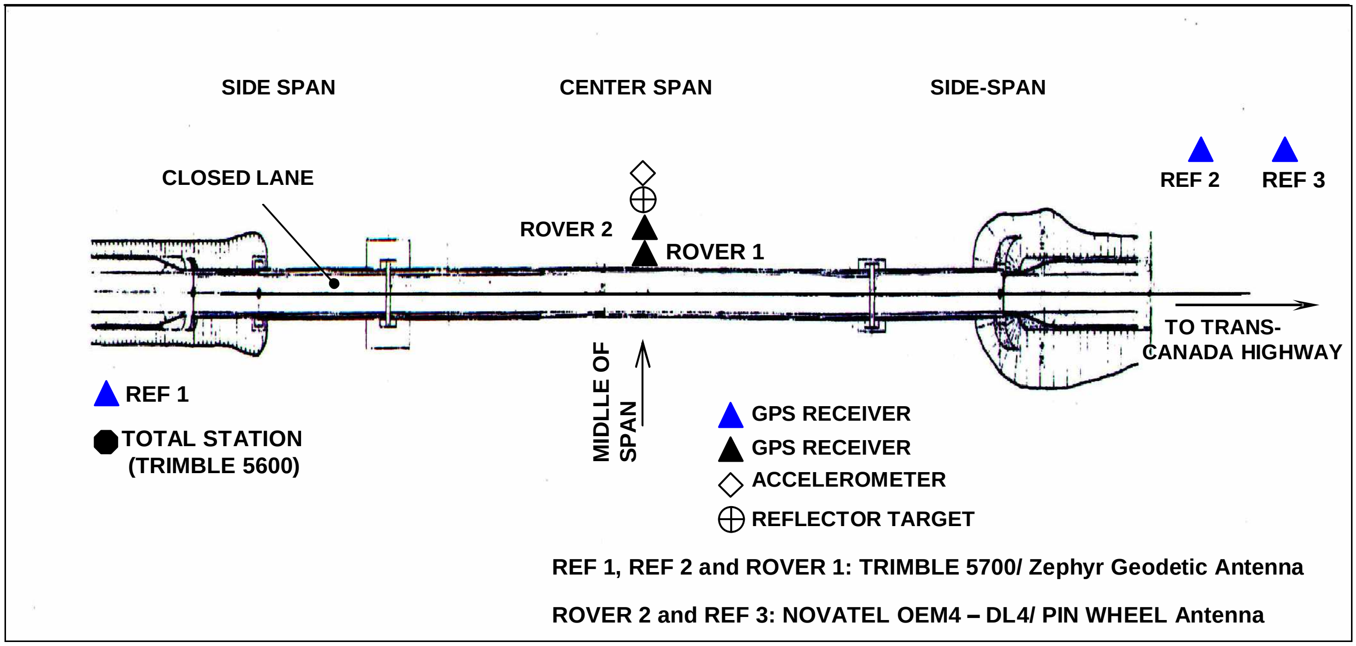

FIGURE 5 – Instruments configuration of Hawkshaw Cable-stayed Bridge

FIGURE 6 – - GPS antennas, reflector target and accelerometer housed together on the guardrail of middle center span of Hawkshaw Bridge

Figure 7 shows two reference GPS stations on the southeast side of Hawkshaw Bridge. One reference station was located on the northwest side of the bridge.

FIGURE 7 – GPS reference stations over gravel mountain

GPS receivers were maintained collecting data during 3 hours of trial and it was marked the exact time that trucks began to cross the deck of the bridge and the load type of each truck. This information is important to detect the frequency and amplitude of dynamic displacement in vertical and lateral directions after GPS data processing. Figures 8 and 9 show some trucks which were considered as design trucks.

FIGURE 8 – Design truck with 60 ton wood load (information got in wood manufactory)

FIGURE 9 – Design truck with 50 ton paper load (information got in Paper Manufactory - Pulp Mil)

MISSION PLANNING OF TRIALS

According to the method used and described in SCHAAL, et al. (2001, 2002) the movements of bridge contribute to the residual absolute value and they depend of on an oscillation amplitude and relative direction of satellites, reference and measuring. In a particular situation, when the oscillation occurs in the vertical direction and the measurement is done with one overhead satellite and the reference satellite is the one close to the horizon. In this case, the phase contribution from the movement will be the maximum. Figure 10 shows the satellites geometry to measure a vertical movement.

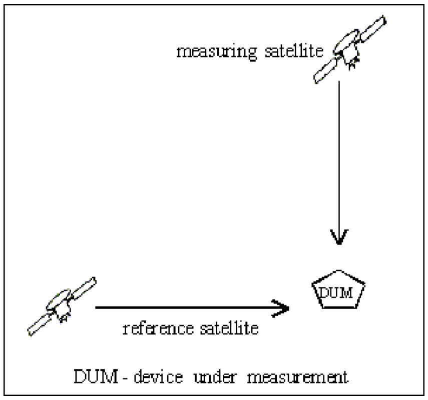

FIGURE 10 – Satellites geometry for vertical measurement

This limitation of satellite geometry configuration required attention to carry out the trial during a time when the constellation had one highest satellite and one lowest satellite. Figure 11 show the satellite sky view of the reference station site and Figure 12 shows the satellite elevation, both in GMT (00:00). For local time in October 2003, it is necessary to discount - 4 h.

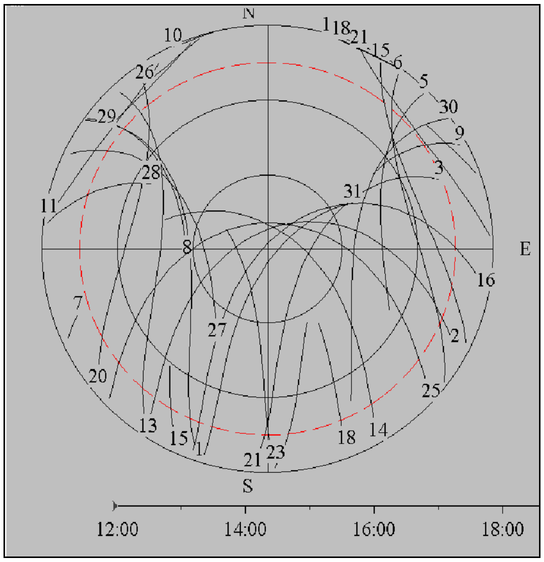

FIGURE 11 – Satellite visibility at reference station (30 October 2003)

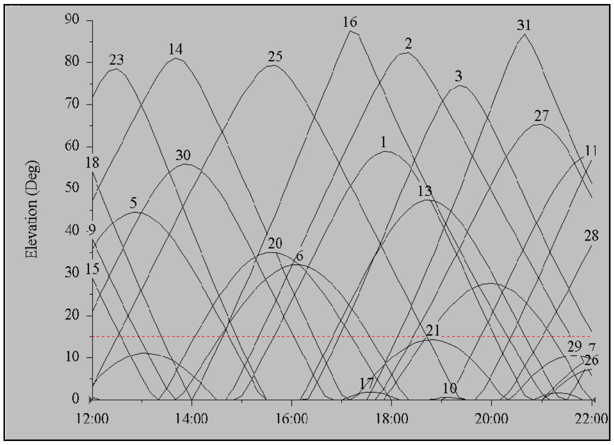

FIGURE 12 – Satellite elevation at reference station (30 October 2003)

BRIDGE TRIAL RESULTS

Data from the trials (L_1) were processed on OMNI (NGS) software, which permits to choose the reference satellite for data processing and the MathCAD 2001 Software, was used to treat and to apply FFT on the raw residuals.

During the first trial, the highest satellite (G16) had 82 degrees of elevation and the lowest satellite (G31) had 7 degrees of elevation. Figure 13 shows the raw residuals of all satellites where it is possible to clearly see the vertical displacement of the deck at the middle of the center span when one empty truck (18 ton) crossed the bridge. It took around 40”. It is also possible to see the behavior of multipath. Figure 14 presents the raw residuals of the highest satellite for better visualization of the vertical displacement caused by the empty truck. Figure 15 illustrates the power spectrum of residuals with the peak, which represents the periodic displacement that the GPS antenna was submitted by the vibration caused on the deck by the loading test with an empty truck crossing the deck. The vertical frequency value is 0.57 Hz. NOVATEL OME4 receivers collected these GPS data.

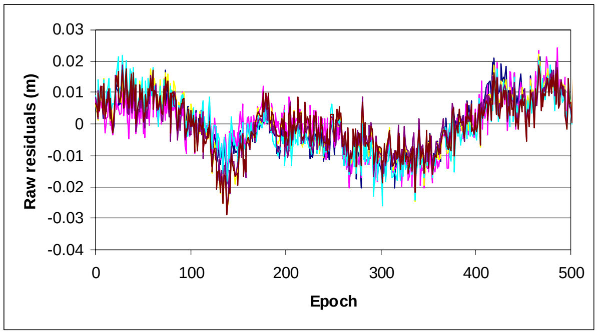

FIGURE 13 – Raw phase residuals of vertical displacement response caused on the deck by one empty truck crossing the bridge

The amplitude of vertical displacement caused by the empty truck and detected by GPS is around 3 cm and the same value was determined by measurements made by the total station. Another truck with the same characteristics was stopped in the middle of the span of the bridge and three measures were made with TRIMBLE 5600. Other measurements were also done when the truck was not over the deck.

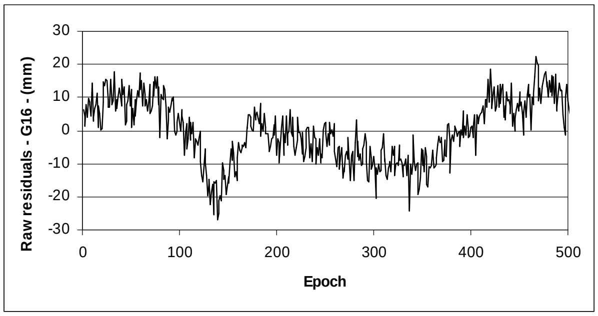

FIGURE 14 – Raw phase residuals of highest satellite

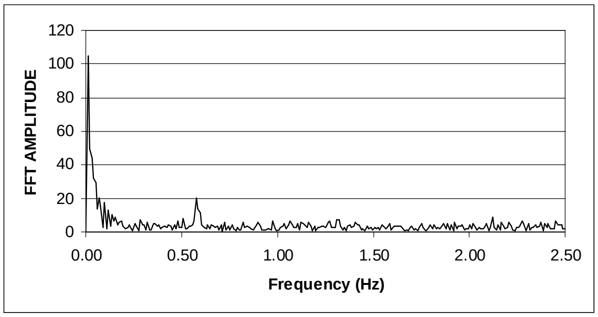

FIGURE 15 - Power spectrum of raw residuals with peak due to vertical dynamic response of the deck

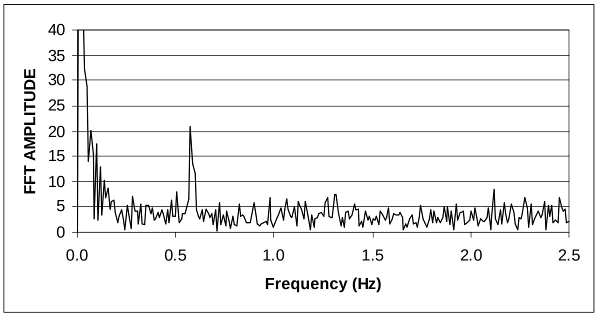

FIGURE 16 – Zoom in the power spectrum of raw residuals with peak due to vertical dynamic response of the deck

The results of the data processing obtained by TRIMBLE receivers and collected at the same time as the results mentioned above. The highest satellite (G16) had 82 degrees of elevation and the lowest satellite (G31) had 7 degrees of elevation. Figure 16 shows the raw residuals of all satellites. Figure 17 presents the raw residuals of the highest satellite for better visualization of the vertical displacement caused by the truck. Figure 18 illustrates the power spectrum of residuals with the peak, which represents the periodic displacement to which GPS antenna was submitted by the deck vibration caused by the loading test with an empty truck crossing the deck. The vertical frequency value is also 0.57 Hz.

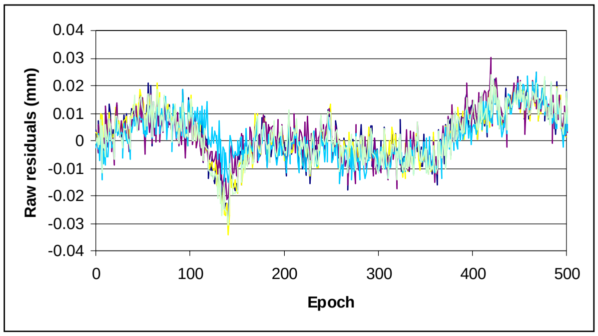

FIGURE 17 – Raw phase residuals of vertical displacement response caused on the deck by an empty truck crossing the bridge

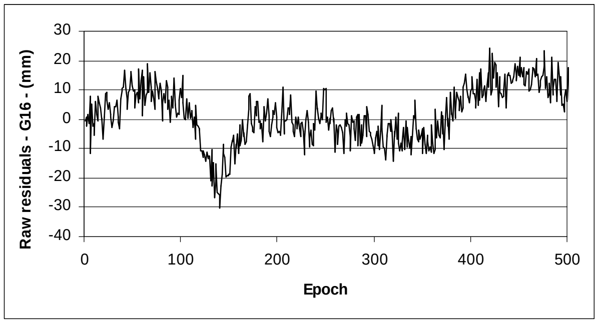

FIGURE 18 – Raw phase residuals of highest satellite

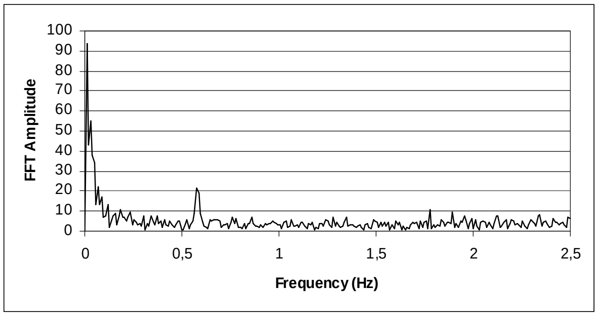

FIGURE 19 - Power spectrum of raw residuals with peak due to the vertical dynamic response of the deck

During the second trial, the highest satellite (G02) had 77 degrees of elevation and the lowest satellite (G31) had 8 degrees of elevation. Figure 19 shows the raw residuals of all satellites where it is possible to clearly see the amplitude of vertical dynamic displacement of the deck at the middle of center span when a full truck (60 ton) crossed the bridge. It took around 45”. It is also possible to see the vertical displacement of the deck when the truck began to cross it and when the truck finished crossing the bridge. Figure 20 presents the raw residual of the highest satellite for better visualization of the vertical displacement caused by the truck. The amplitude of the vertical dynamic displacement has a value around 2.5 cm. The vertical frequency value is 0.57 Hz. NOVATEL OME4 receivers collected these GPS data. The variation on dynamic loading causes change on the amplitude of displacement, not on the value of frequency.

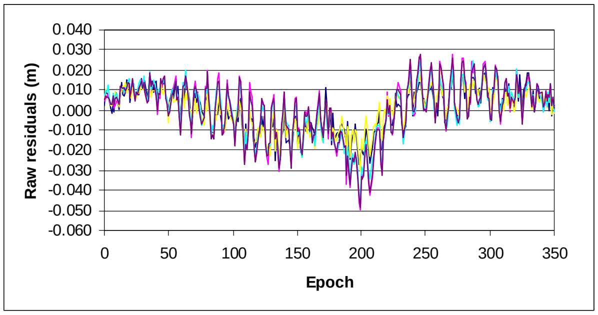

FIGURE 20 – Raw phase residuals of dynamic vertical response caused on the deck by a full truck crossing the bridge

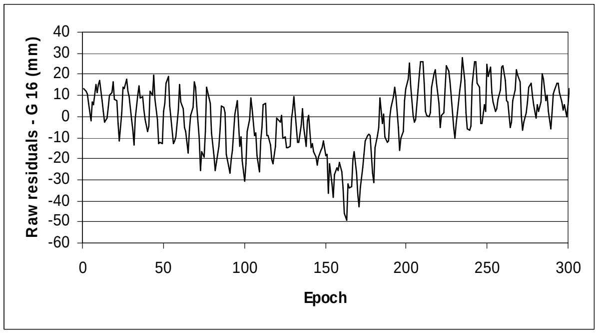

FIGURE 21 – Raw phase residuals of the highest satellite - amplitude of dynamic and vertical displacements caused by the truck entering and leaving the bridge

During the third trial, the highest satellite (G02) had 80 degrees of elevation and the lowest satellite (G31) had 6 degrees of elevation. Data processing was realized using the highest satellite as reference because it is on the residuals of the lowest satellite that it is possible see the horizontal dynamic responses of deck during loading trial. Figure 21 shows the raw residuals of all satellites where it is possible to clearly see the amplitude of horizontal dynamic displacement of deck at middle of center span when one full truck (60 ton) crossed the bridge. It took around 45”. It is also possible to see the horizontal vibration of the deck caused when the truck began to cross it and when the truck finished crossing the bridge. Figure 22 presents the raw residual of the lowest satellite for better visualization of the horizontal displacement caused by the truck. The amplitude of the horizontal dynamic displacement has the value around 2 cm and the horizontal displacement is around 3 cm. Figure 23 illustrates the power spectrum of residuals with the peak, which represents the periodic displacement that GPS antenna was submitted from the vibration caused on the deck by the loading test with a full truck crossing the deck. The horizontal frequency value is 0.60 Hz

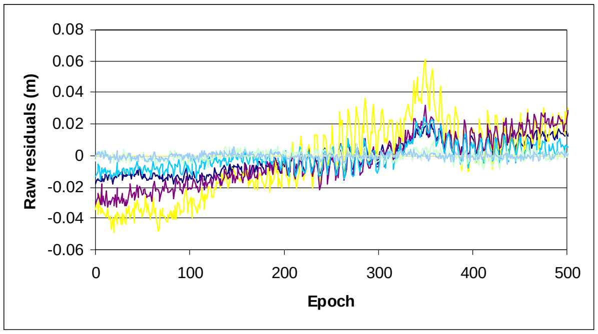

FIGURE 22 – Raw phase residuals of the dynamic horizontal response caused on the deck by a full truck crossing the bridge

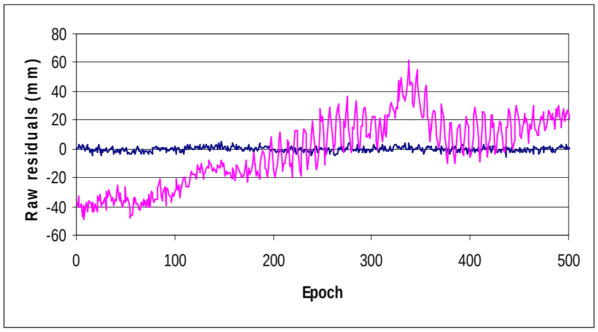

FIGURE 23 – Raw phase residuals of lowest satellite - amplitude of the dynamic and horizontal displacements caused by the entering and leaving of the truck over the bridge

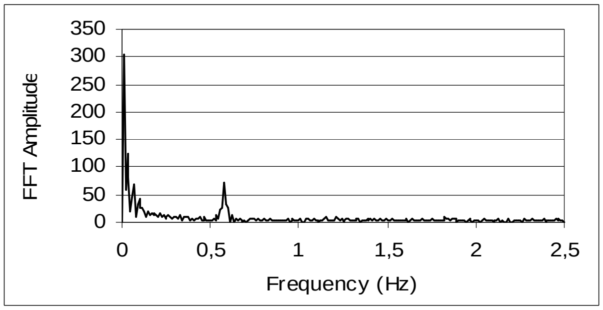

FIGURE 24 - Power spectrum of raw residuals with peak due to the horizontal dynamic response of the deck

During the fourth trial, the highest satellite (G02) had 81 degrees of elevation and the lowest satellite (G31) had 9 degrees of elevation. On the time of this trial four trucks were permitted to cross the bridge. Figure 24 shows the raw residuals of all satellites where it is possible to clearly see the amplitude of the vertical displacement of the deck at the middle of the center span when trucks began to cross the bridge and when they finished cross. The amplitude of the vertical displacement was 8 cm. This value agrees very well with the measurements made by the total station. In this case, four trucks stopped on the middle of the center span and three measurements were made by the total station.

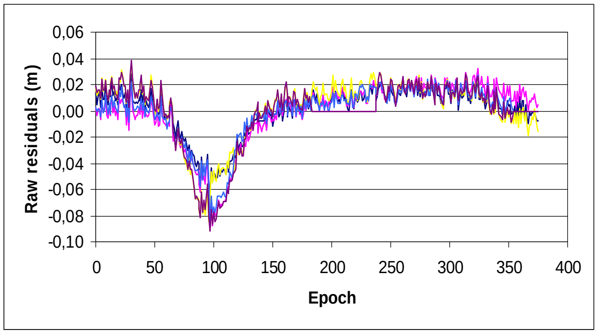

FIGURE 25 – Raw phase residuals of the dynamic vertical response and the vertical displacement caused on deck by four trucks crossing the bridge

The results obtained by accelerometer were not mentioned because the data acquisition system generated noisy data and it was impossible to detect any frequency from them.

CONCLUSION

The results of the trials carried out in Hawkshaw Cable-stayed Bridge show that it is possible to characterize dynamic displacements using L_1 GPS receivers. GPS data collected and treated by the method used on this research matches well with the results obtained from the measurements by the total station.

The center span of Hawkshaw cable-stayed Bridge, under trials carried out with truck loading presented vertical frequency of 0.57. Hz and lateral frequency of 0.60 Hz. These values agree exactly with the theoretical values of the frequencies for the cable-stayed bridge with an orthotropic deck presented by HIRSCH et al. (1991). A vertical dynamic displacement of the center span has values around 2.5 cm. The center span presents vertical displacements around 4 cm during the entrance and the exit of a truck. On the other hand, center span presented vertical displacement around 8 cm during entrance and exit of four trucks. The amplitude precision ranges between 0.5 mm and 0.8 mm and the frequency precision presents values that match exactly with values measured by conventional instruments because it is based on GPS time.

FUTURE WORK

The author intends to process data from sessions that have not been analyzed yet. Also, she intends to use Wavelets Transform and apply Finite Element Analysis to compare the results with the values presented on this paper and organizing a complete document about the dynamic behavior of Hawkshaw Bridge discussing its actual structural conditions. The final document will be sent to the New Brunswick Department of Transportation.

ACKNOWLEDGMENTS

I would like to express my gratitude to CNPq, Brazilian agency supporting my doctorate course; to my supervisor Dr. Ricardo Ernesto Schaal (Department of Transports – Sao Carlos Engineering School of the University of Sao Paulo); to Dr. Marcelo C. Santos (Associate Professor of Dept. of Geodesy and Geomatics Engineering - University of New Brunswick - UNB) for accepting me as a visitor student at the University of New Brunswick and providing me all the conditions to carry out the research and trials on Hawkshaw Cable-stayed Bridge; to Dr. Richard B. Langley (coordinator of Geodetic Research Laboratory Dept. of Geodesy and Geomatics Engineering - University of New Brunswick) for providing several inputs and ideas for the trials on the bridge; to the Canadian Center for Geodetic Engineering (CCGE) for loaning NOVATEL receivers; to New Brunswick Department of Transportation (NBDT) for helping and giving permission to carry out the trials on the bridge; to Ronald H. Joyce (Senior Technical Advisor from NBDT); Neil Hill (Bridge Superintendent of Hawkshaw Bridge from NBDT); Howard Biggar (Geomatics Technologist of UNB); E. Daniel Wheaton (Chief civil engineering technician of UNB) and to Jason Donald Bond (PhD Candidate at the Department of Geodesy and Geomatics Engineering of UNB).

FIGURE 25 – From left to right: Howard Biggar, E. E. Daniel Wheaton, Ana Paula C. Larocca, Neil Hill and traffic agents

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