Monitoring the Deflection of the Pierre-Laporte Suspension Bridge with the Phase Residual Method

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BIOGRAPHY

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ABSTRACT

The civil engineering profession is continuously searching for reliable methods and tools to improve the quality and life span of large structures. It is well known that most studies in this field were based on static loading analyses. Nowadays, dynamic loads have been one particular concern within the civil engineering community and GPS can offer direct measures of dynamic displacements of suspension bridges induced by traffic, wind and earthquake forces.

This paper presents the results of the GPS data processing using the Phase Residual Method (PRM), to monitor the dynamic behavior of the Pierre-Laporte Suspension Bridge in Quebec City, Canada. Three, 48-hour GPS sessions were conducted during the months of July and October 1996 and February 1997 by researchers from the Centre for Research in Geomatics at Université Laval in Quebec City. The researchers from Université Laval initially processed GPS data in 1997, using a modified algorithm for on-the-fly ambiguity resolution and processed again by us using PRM. The main objective of this research is to measure small dynamic displacements and their precision by single frequency receivers. In order to verify if GPS, analyzed under PRM, can be used as a trustable and friendly tool for characterizing the dynamic behavior of large structures, comparisons between processing results obtained using the Modified GPS-OTF Algorithm and PRM are presented in this paper.

INTRODUCTION

The origins of the suspension bridge go back a long way in history. Primitive suspension bridges, or simple crossing devices, were the forebears to today's modern suspension bridge structures. Suspension bridges were constructed with iron chain cables over 2000 years ago in

China and a similar record has been left in India. The iron suspension bridge, assumed to have originated in the Orient, appeared in Europe in the 16th century and was further developed in the 18th century. Although wrought iron chain was used for the main cables in the middle of the 18th century, a rapid expansion of the center span length took place in the latter half of the 19th century, triggered by the invention of steel. Today, the suspension bridge is the most suitable type for very long-span bridges and is currently represented by 20 or more of all of the longest span bridges in the world [Okukawa et al., 1997].

Dynamic testing of bridges has become more prevalent in recent years as evidenced 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 the design of 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 experienced by a structure under its normal operating conditions. Obviously, this method is less costly than forced vibration testing since no extra equipment is needed to excite the structure. 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; Ren et al., 2004].

PRM [Schaal and Larocca, 2001; 2002], which has already been tested on man-made structures [Larocca, 2004a, b; Larocca and Schaal, 2005; Larocca et al., 2005] is based on the analysis of the L1 baseline double-difference phase residuals collected from a regular static observation session. The residuals incorporate all phase deviations from the adjusted double difference position during the observation. These phase deviations are due to electronic receiver noise, multipath, small dynamic antenna movements and other error sources. Cycle slips can be avoided by choosing an appropriate observation window. By converting the residuals to the frequency domain using the Fast Fourier Transform (FFT), it is possible to separate the phase deviations according to their different frequency components. The fundamental oscillation mode of the bridge, during the data collecting session, is represented by a peak in the spectrum while the receiver noise presents a white noise spectrum and the multipath presents a broad spectrum close to zero frequency. A sudden bridge deflection, due to heavy traffic, causes a peak in the phase residuals but this can be filtered out in the frequency spectrum. PRM needs a proper satellite configuration; i.e., one satellite closely aligned to the direction of the antenna displacement movement and another satellite orthogonal to it. In order to detect a vertical movement, for example, it is necessary to have a satellite close to the zenith and the other close to the horizon. The technique doesn't need very accurate a priori coordinates of the receivers to determine the amplitude and the frequency values of suspension bridge movements. Also, it is possible to choose arbitrarily the best place to install the base receiver(s).

The on-the-fly algorithm was modified by Santerre and Lamoureux [1997] to resolve GPS phase ambiguity, even if the receiver is in motion, as the objective was the study of suspension bridge movements. The algorithm had been designed to work with single frequency receivers. To calculate good a priori coordinates, these authors determined three criteria to identify the correct ambiguity set: the correction to the a priori coordinates must be smaller than 10 cm (approximately half the L1 wavelength); the residuals must be smaller than 10 cm and the ratio of the second smallest and the smallest a posteriori variance factors must be larger than 2. The Hatch approach [Hatch, 1990] was used to avoid mathematical correlation in double difference observations. More details about the Modified GPS-OTF Algorithm can be seen in Santerre and Lamoureux [1997].

DESCRIPTION OF SUSPENSION BRIDGE

A trial of the phase-residual method was carried out on data collected on the Pierre-Laporte Suspension Bridge (Figure 1) which spans the St. Lawrence River at Quebec City, Quebec, Canada. Opened in 1970, it has 6 lanes, with total length of 1040 m and a width of 27 m. The bridge deck is composed of two end spans of 187 m and one center span with a length of 667 m. Two steel towers, 123 m high support the deck (total weight of 18,000 tons) by vertically hanging suspenders with two main cables of 62 cm diameter (Figure 2) [Labbé, 1997].

Figure 1. Pierre-Laporte Bridge, near Quebec City, Canada
(http://www.trekearth.com/gallery/North_America/Canada/photo30284.htm)

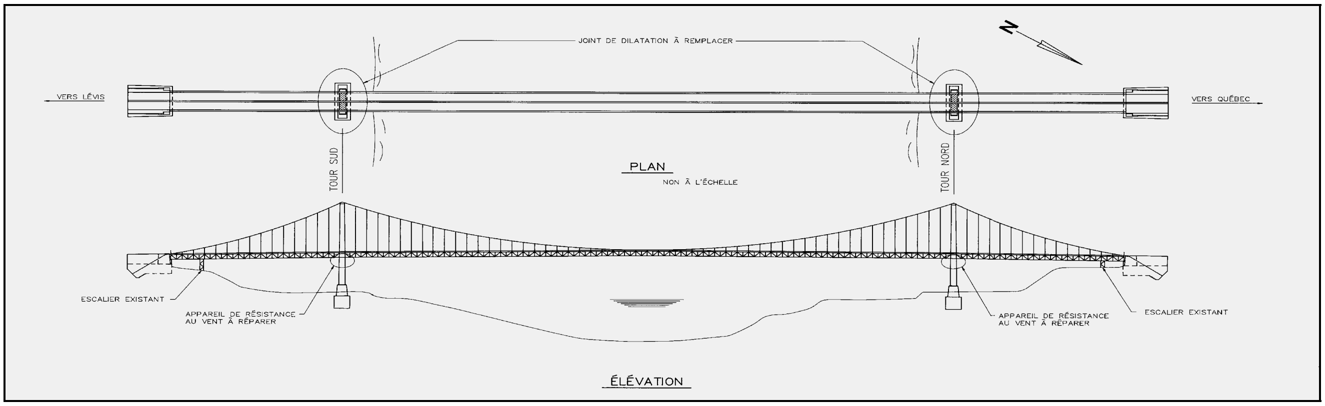

Figure 2. Plan layout and side elevation of Pierre-Laporte Suspension Bridge
(Ministère des Transportes du Québec)

BRIDGE TRIAL

Three, 48-hour GPS sessions were conducted during the months of July and October 1996 and February 1997 by researchers from Université Laval's Centre for Research in Geomatics. For each session, 5 geodetic-quality GPS receivers were used, observing with a data sampling interval of 2 seconds. The layout of the stations composing the deformation monitoring network can be seen in Figure 3. It shows the stations of the deformation monitoring network. The baseline length (D) and the height difference (h) between the stations are given in Table 1. Two reference stations (RIN1 and RIN2) were set up on bedrock on the north river bank close to the bridge. Stations TON and TOS were located on the top of the north and south towers, respectively. Station TACE was located on the deck of the bridge. No other sensors were used for measuring the deflections [Santerre and Lamoureux, 1997].

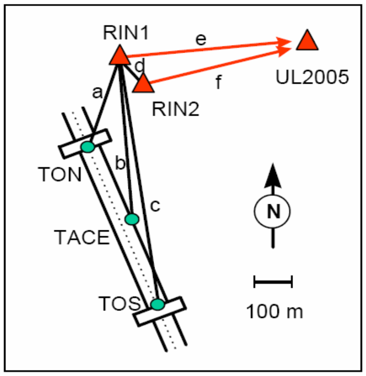

Figure 3. Instruments configuration of Pierre-Laporte Bridge [Santerre and Lamoureux, 1997]

Table 1. Approximate baseline lengths and station height differences. (See Fig. 3)

Baseline	a	b	c	d	e	f
D (km)	0.3	0.7	1.0	0.1	3.5	3.5
Δh	59	-4	59	-2	17	19

[Santerre and Lamoureux, 1997]

RESULTS FROM PRM DATA PROCESSING

Although the receivers were L1/L2 capable, only L1 data were used in the PRM analyses. From the three 48-hour GPS sessions in July 1996, data were chosen for processing from peak traffic hours (early evening hours). Data were processed from ten different observation sub-sessions. These sub-sessions were chosen also according to the particular satellite geometry required for the PRM technique. The RIN1-TACE 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 (DDPR).

DATA ANALYSES

Figure 4 presents the DDPR of the RIN1–TACE baseline during the GPS sub-session between 16h50min and 17h25min [on 27 July 1996]. The reference satellite (G06) was at 15 degrees elevation angle and the measuring satellite (G25) was at 76 degrees. Even though the reference and measuring satellites were not orthogonal, the angle between them is large enough to detect the antenna oscillation.

It is possible to observe graphically the sudden vertical deflections of the TACE station under normal traffic conditions. Detailed data about the traffic during the sessions were not collected. Figure 5 illustrates a detail of the phase residuals for better visualization of the deflection amplitude caused by traffic load. The traffic caused deflections ranging from 4 to 8 cm.

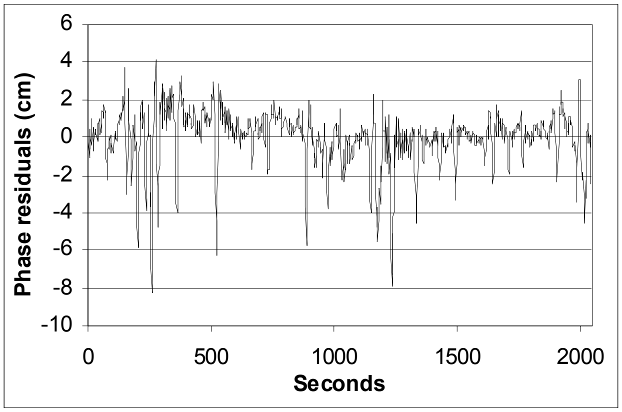

Figure 4. DDPR of the RIN1-TACE baseline

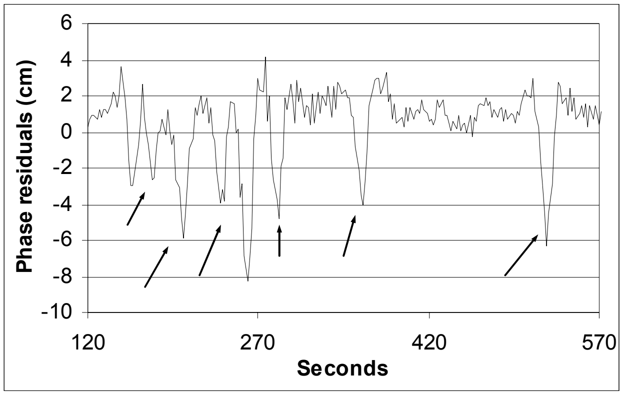

Figure 5. Detail of first session DDPR showing the sudden phase deviations caused by traffic [indicated by arrows]

Figure 6 presents the corresponding spectrum over 1024 data values with a sampling interval of 2 seconds from the above residual data. Larger data samples do not improve the results. The isolated peak at 0.21 Hz is in agreement with the theoretical value of the natural vertical frequency of the bridge center span as presented by Hirsch and Bachmann [1991]. The peaks below 0.1 Hz are generated by multipath, random traffic and some other low frequency structural movements.

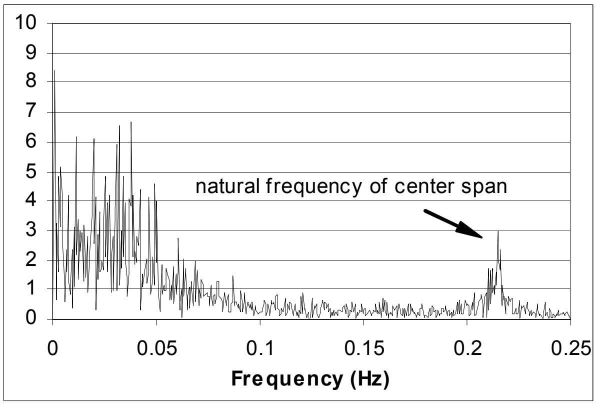

Figure 6. Frequency spectrum from the static solution residuals with a peak due to natural vertical frequency of the center span

To provide a comparison of the PRM results with that of another approach, the FFT was applied to the height coordinates of TACE station (Figure 7) as obtained by the Modified GPS-OTF Algorithm (kindly supplied by the Université Laval's Centre for Research in Geomatics).

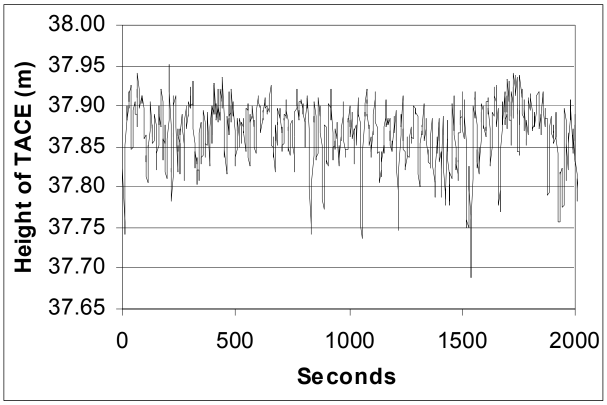

Figure 7 Height coordinate of TACE station

As with the DDPR, the natural vertical oscillation is embedded in all other height noise sources. Applying the FFT, the obtained spectrum agrees closely with the spectrum obtained by PRM, as shown respectively in Figures 8 and 9. Figure 9 is a repeat of Figure 6 and is included for ease of comparison.

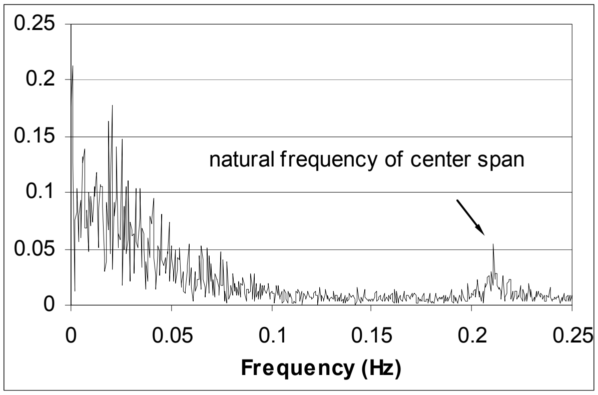

Figure 8. Frequency spectrum from the height coordinate of station TACE obtained by Santerre and Lamoureux [1997]

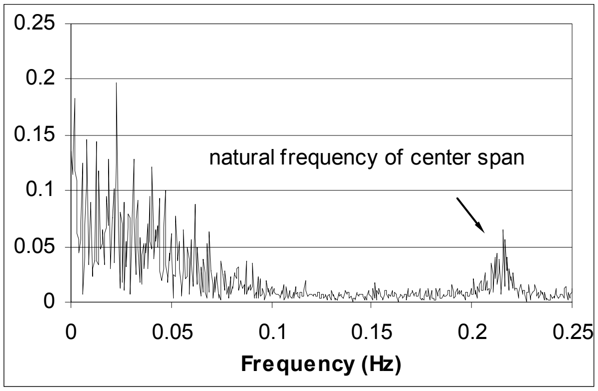

Figure 9. Frequency spectrum as determined using the PRM

Filtering out the low frequency spectrum and applying the inverse FFT, it is possible to extract the antenna amplitude oscillation corresponding to the natural vibration amplitude of the center span. The amplitude is approximately 1 cm, well below all other sources of phase deviation.

CONCLUDING REMARKS

According to the results obtained by the Phase Residual Method and by the Modified GPS-OTF Algorithm, it was verified that they agree very well in the determination of the natural vertical frequency of the bridge center span even though they use different algorithms and programs for data processing and satellite selection. This fact confirms the potential of the PRM as a technique which permits us to determine the vertical frequency of the main span of the Pierre-Laporte Bridge without the use of an accelerometer. Additionally, results obtained by PRM are not affected by the deficiencies of GPS satellite geometry in the northern sky quadrant. One of the specified aims of this research has been confirmed: single frequency GPS receivers can be used for measuring deflections of structures. Nevertheless, like any other developing technology, GPS positioning has its limits when it is applied to precise engineering needs and multipath is still one of the major degradation sources.

ACKNOWLEDGMENTS

The first author would like to thank CNPq, the Brazilian Agency for Scientific and Technological Development which supported her doctorate course 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, University of New Brunswick, Canada (2003). Thanks also to Université Laval's Centre for Research in Geomatics for kindly supplying the GPS data collected from sessions conducted at the Pierre-Laporte Bridge and coordinate values obtained by the Modified GPS-OTF Algorithm and to Dr. Boussaad Akrour for providing additional material and information about the bridge.

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