

Rigid Bridges Health Dynamic Monitoring Using 100 Hz GPS Single-Frequency and Accelerometers

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Abstract

This article presents the modal frequency recordings of a rigid bridge, monitored by the GPS receivers (Global Positioning System) with a data recording rate of 100 Hz and accelerometers. The GPS data processing was performed through the double-difference phase, using the adjusted interferometry technique (*i.e.* phase residue method—PRM[®]). In the method, the double-difference phase of the carrier L1 is realized by using two satellites only, one was positioned at the zenith of the structure and the other satellite was positioned near the horizon. The results of the parametric adjustment of the PRM observations were finalized through software Interferometry, mathematical algorithm were applied and compared with the accelerometer. The comparison served to validate the use of GPS as a fast and reliable instrument for the preliminary monitoring of the dynamic behavior of the bridge, road artworks which are common in several countries, especially in the Brazilian road network. The data time series from the GPS and accelerometers were processed using the Wavelet. The detection of frequencies means that the combination of 100 Hz GPS receivers and the PRM allows detecting vibrations up to 5 mm. It presented significant results which were never obtained by the Fourier Transform.

Keywords

GPS, Rigid Bridge, Modal Frequency, Wavelet, Accelerometer, Health Monitoring

1. Introduction

The ability to periodically monitor the structural condition of a bridge for the

detection of early stage damage or changes in design conditions is essential for maintaining the health of a structure. Sometimes, monitoring is performed by visual inspection, whereas, other times it requires the installation of sensors, for the detection of oscillation frequencies and displacement amplitudes of structure elements. The installation of conventional geotechnical and structural sensors is not always simple. Among many other things, the installation requires a source of energy near the monitored bridge, calibration, installation of supports and scaffolding to fix the sensor in the structure of the bridge and connection with data acquisition systems and microcomputers. This research presents procedures that allow the use of GPS receivers as primary and auxiliary equipment in identifying changes in structure. These methods use the values of the vibration frequencies (acceleration) and the behavior of the displacement amplitude. The obtained results can help in deciding whether to proceed with conventional instrumentation or not.

Thus, this work presents the results of the dynamic monitoring of oscillations of the concrete bridge deck, using the Global Positioning System (GPS) which is quite a simple and practical equipment. Two vertical axial accelerometer sensors were used to validate the methodology. They were installed next to the GPS antenna in the center of the bridge deck. The tests presented below are part of the continuity of the development of a method, initiated in 2000 by Schaal and Larocca [1], which is called Phase Residues Method, processed with the simple phase difference. In this research, we present the results of an innovative Phase Residue Method, using the double-difference phase of the monitoring performed by high frequency receivers at 100 Hz [1] [2] [3] [4]. The method seeks to improve the GPS detection threshold so that it can be used in the high frequency recordings, consonant with the Nyquist Theorem and in the dynamic monitoring of small rigid bridges through the analysis of the Morlet CWT (Continuous Wavelet Transform).

Furthermore, due to the number of rigid bridges e.g. small and medium-sized reinforced concrete bridges, on which the Brazilian road network is notably constituted [5], it was necessary to continue the development of the previous method. Other reasons were to empower the modified methodology to meet monitoring requirements of rigid structures and to allow the engineer to have another tool and technique in hand, for the ease of installation, improvement in measurement speed and reliability in the results.

2. Methodology

The methodology of this work is divided into three different stages: 1) data collection using the PRM technique, 2) observable processing and 3) spectral analysis of GPS data.

Stage 1: Phase Residue Method—PRM.

The methodology presented in this paper is based on interferometer principle. It uses the L1 carrier phase that needs to be collected from two GPS satellites via

receiver base and receiver rover with orthogonal configuration (a phase angle of 90 degrees) between each other and constellation of no more than four satellites. This characteristic makes PRM different from other state of the art studies, resulting in the robust results obtained for a concrete bridge [6]-[14].

To register the modal frequency of the structure, for example, it is necessary that one satellite should be close to zenith and another to be close to the horizon (reference satellite) (**Figure 1**). In the processing of the double-difference (DD) phase, the lowest satellite is the reference satellite, allowing collection of residuals from the highest satellite, which is also called the zenith satellite. Adopting this configuration, there will be a greater contribution of double difference phase in the final data processing results. It will be due to the changes in the phase, *i.e.* the signal of the zenith's satellite in relation to the reference satellite, which hardly detects any movement of the antenna.

The DDPR is generated by atmosphere scintillation, satellite and receiver electronics noise, multipath, antennas phase center pattern, satellites orbital dynamics and any antenna movement ranging from millimeters to some centimeters. Fortunately, in this case, the double differenced time variations of each one of these effects are quite distinguishable, presenting a different frequency spectrum. The electronics and atmosphere presents a rapid random behavior as a function of the equivalent phase detector noise bandwidth; multipath in most scenarios is a slow time varying function; antennas phase center pattern and satellites dynamics can be neglected for a short time observations and, finally, the antennas movement contribution will depend on inner product between the movement vector and unit vector to the satellites direction. The movement behavior mostly is a periodic time function [1].

The residuals, from the parametric-adjusted double-difference, incorporate all phase position deviations calculated during the observation. These phase deviations are due to electronic receiver noise, multipath, small dynamic antenna movements and other error sources. By converting the residuals in the frequency domain, via Morlet Continuous Wavelet Transform, it is possible to see the different

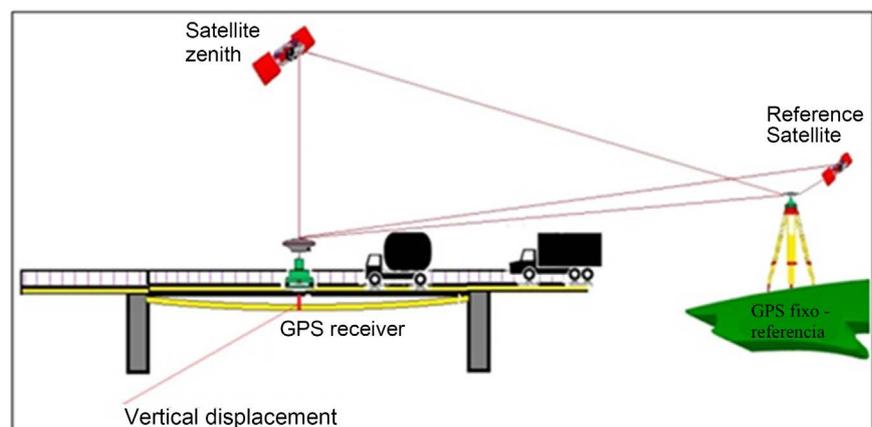


Figure 1. Satellite configuration in relation to the GPS rover and measuring vertical displacements based on the Bridge.

behaviors of the receiver phase noise, multipath, and periodic oscillations of bridge's span allowing the distinction between them, because these interferences are located at low frequency ranges.

An important activity for obtaining the phase residuals from the raw data is to verify the data quality, by looking for cycle slips and missing epochs. This can be achieved by observing the data continuity of the chosen satellites. The presence of some sporadic epoch and any cycle slips that stays within the noise level will not compromise the results.

The L1 double difference phase observable is given by Leick (2004):

$$\varphi_{km,1}^{pq} = \frac{f}{c} \rho_{km}^{pq}(t^p) + N_{km,1}^{pq}(1) + I_{km,1,\varphi}^{pq}(t) + \frac{f}{c} T_{km}^{pq}(t) + d_{km,1,\varphi}^{pq}(t) + \varepsilon_{km,1,\varphi}^{pq} \quad (1)$$

Multiplying both side of Expression (1) by L1 wavelength λ_1 :

$$\lambda_1 \varphi_{km,1}^{pq} = \rho_{km}^{pq}(t^p) + \lambda_1 N_{km,1}^{pq}(1) + \lambda_1 I_{km,1,\varphi}^{pq}(t) + T_{km}^{pq}(t) + \lambda_1 d_{km,1,\varphi}^{pq}(t) + \lambda_1 \varepsilon_{km,1,\varphi}^{pq} \quad (2)$$

The first term of the right side of Expression (2) is the double difference of topocentric distances between p, q satellites and k, m receivers. The second term is the first epoch ambiguity and it has no time dependence. The time dependence of third and fourth terms is related to the Ionosphere and Troposphere respectively, which can be separated into two behaviors. For a short baseline, one is almost a steady state and the second will depend on the non-correlation among the Ionosphere and Troposphere scintillation, with a random time behavior. The fifth term is any time-dependent phase disturbance. Finally, the last term is related to receiver phase noise with a random behavior.

Rearranging the Expression (2) joining terms with similar time behavior:

$$\lambda_1 \varphi_{km,1}^{pq}(t) = \rho_{km}^{pq}(t^p) + S + \lambda_1 d_{km,1,\varphi}^{pq}(t) + N \quad (3)$$

The term S comprises of the stationary components and N is the random phase noise. The topocentric distance, between satellite p and receiver k as a function of time is given by the expression:

$$\rho_k^p(t^p) = \sqrt{(x^p(t^p) - x_k)^2 + (y^p(t^p) - y_k)^2 + (z^p(t^p) - z_k)^2} \quad (4)$$

Same expressions are for the other three distances. The double difference among topocentric distances, in a short baseline as a function of time can be represented by a polynomial function:

$$\rho_k m^p q(t^p) = a_n (t^p)^n + a_{n-1} (t^p)^{n-1} + \dots + a_0 \quad (5)$$

Substituting (5) in (3):

$$\lambda_1 \varphi_{km,1}^{pq}(t) = a_n (t^p)^n + a_{n-1} (t^p)^{n-1} + \dots + a_0 + S + \lambda_1 d_{km,1,\varphi}^{pq}(t) + N(t) \quad (6)$$

In the Expression (6) the coefficient a_0 can be added to the steady satiate components S . The time behavior of observed double-difference can be fitted to the polynomial function. The residuals contain the time-dependent phase disturbances and random phase noise. Expression (7) gives the phase residuals, $R(t)$, in meters:

$$R(t) = \lambda_1 d_{km,1,\varphi}^{pq}(t) + N(t) = \lambda_1 \varphi_{km,1}^{pq}(t) - a_n (t^p)^n - a_{n-1} (t^p)^{n-1} - \dots - a_0 - S \quad (7)$$

The polynomial fit can be done by parametric minimum least square method. With this approximation, it is possible to obtain the phase residual directly from the raw data, independent of a regular data processing program, to be analyzed in the frequency domain by the CWT, as mentioned previously.

Millimeter or unstable periodic oscillations caused by movements of a large structure are difficult to separate from the random noise, which results in degrading the precision of the measurement. One-way to improve the signal to noise ratio is the use of auto-correlation technique. Autocorrelation enhances periodic functions and lessens random values. The autocorrelation of data of n samples is converted to a half time sample because the delay can only be shifted by half the original sample. Expression (8) presents the applied autocorrelation function with the delay (t) ranging from 0 to $n/2$.

$$R(\tau) = \sum_{t=0}^{\frac{n}{2}} R(t) * R(t + \tau) \quad (8)$$

Stage 2: processing of data by Interferometry[®] software.

For the data processing, the authors had difficulties to find scientific or commercial software that allowed applying the proposed methodology exclusively. Several softwares were tested. However, none was applicable for two main reasons, 1) the selection of reference satellite in the post-processing of GPS observations was not allowed by any software because it is not a commercial purpose and 2) the software does not process observations collected at 100 Hz. Since, GPS receivers were from the manufacturer called JAVAD, the authors chose to propose a scientific partnership with the manufacturer. The company accepted the invitation to develop software that would perform post-processing with the permission of selecting the reference satellite. After two years of combined efforts, sharing ideas, suggestions and testing, the authors of this work and the manufacturer's developer team were able to finalize the "Interferometry software"—used only by authors. It was developed for the sole purpose of meeting the demands of this research. The "Interferometry package", despite being available for free, can be found within the Justin[®] trading software platform of Javad manufacturer in versions 2016 onwards (Justin v.2.123.161.2). Additionally, it is possible to use open source software such as RTKLIB that can be modified to replace the post-processing reference satellite. In addition, 100 Hz data can also be processed (<http://www.rtklib.com/>).

In order to use the software, it is necessary that the user proceed in the same manner as the conventional software. It is essential to create project, assign coordinate system, import data, select antenna, set and assign coordinates of the reference station, view quality of GPS observables, assign cutting angle, and observation rate, among others. Nevertheless, the software simply processes and adjusts data by parametric mode only with the proposed methodology. The user has to use the commercial version of the software, if he attempts to use conventional post-processing to get adjusted coordinates or a geodetic traverse.

Figure 2 shows the pattern of Interferometry® software structure on the verge of a processing. After importing the GPS observables, which can be made in RINEX format or the manufacturer's, it is possible to observe, the graph of the raw data in the center. It is used to verify if there was a loss of cycle at the moment of the observation or not, and consequently the quality of observables. In the upper right corner (highlighted), it is possible to choose the methodology presented. Below that, the reference satellite is defined. In this case, it is important to observe the quality of the GPS data and the positioning of the reference satellite, since the traffic flow on the bridge should never be between the reference satellite and the GPS receiver located on the monitored structure. This would compromise the measurement result due to multipath and/or loss of cycle. After processing, the results export icon allows you to save a spreadsheet file with the residuals in millimeters to be used in the next step, as shown in the left column (**Figure 2**).

Stage 3: Spectral Analyses of GPS Data.

The tool Wavelet analysis was chosen to perform the analysis of the double-difference phase residuals, from Interferometry® Javad software. It uses interferometry technique in the frequency domain, to identify the corresponding frequencies due to periodic displacements. This tool also uses the results from Wavelet transform algorithm provided by MATLAB routine (v.R2015a). The spectrum also presents frequencies due to multipath, noise and other sources (e.g., the effects of variation of the antenna's phase center), which is accentuated in highly reflective environments and in non-static observations.

The Wavelet analysis involves an operation called "linear" that can be used in the analysis of non-stationary signals for extracting information of variations in frequency. It allows the detection of periodic phenomena located in time or space. This technique has been used widely in various areas of research and studies, for example, geophysics, hydrology, climate data analysis, medicine, study of sound, GPS data analysis, and others [2] [15].

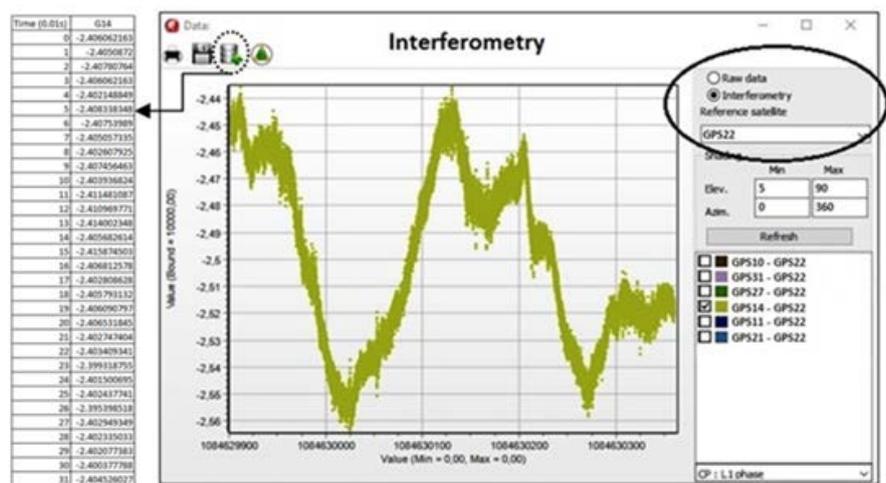


Figure 2. Layout software Interferometry®.

The analyses for detecting the frequency due to the small dynamic vibration were done by applying the Continuous Wavelet Transform algorithm—CWT—with the Morlet Wavelet [16]. The selection of the best mother wavelet is not a simple task. Usually, there are more than a couple of alternatives [17]. This research aims to study the frequency in the time domain from GPS data that have the contribution of electronic noise and multipath. It is observed that Morlet Wavelet is most efficient at identifying the signs of the frequencies expected due to a signal with the amplitude variation in peak to peak up to 5 mm in the low frequency region. The first study developed by the authors, using CWT was published in 2009 [2]. Similar to that, a particular wavelet, Morlet is used, and is defined by Equation (9) as:

$$\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-1/2\eta^2} \quad (9)$$

where Ψ_0 is dimension less frequency and η is dimension less time. When using wavelets for feature extraction purposes, the Morlet wavelet is a good choice, since it provides a good balance between time and frequency localization.

The idea behind the CWT is to apply the wavelet as a band pass filter to the time series. The CWT of a time series $(f(t), t = 1, \dots, N)$ with uniform time steps dt is defined as the convolution of $f(t)$ with the complex combination of the scaled and normalized mother wavelet, see Equation (10):

$$W_{j,k}(t) = \sqrt{\frac{1}{j}} \int_{t=1}^N f(t) \Psi_0\left(\frac{t-k}{j}\right) dt \quad (10)$$

where $W_{j,k}(t)$ represents the similarity between Wavelet function and the analyzed time series $f(t)$, *i.e.*, the higher the value of $W_{j,k}(t)$, the greater the similarity between the analyzed function and mother wavelet function which modulates the signal analyzed.

The idea behind the CWT is to apply the wavelet as a band pass filter to the time series. It is important to note that the authors did several tests with the Fourier Transform (FT) and their variations, in order to analyze the random data originated by the bridge even though FT is not an appropriate method for analyzing random vibrations [2]. The reason that prompted the authors to use Wavelet was that FT represents spectral responses through peaks only, *i.e.*, detected frequency (The peak is recorded), or undetected, the peak with amplitude close to the multipath spectral response threshold [3]. However, it is not indicative in what time or period of time, one or other frequency were recorded. This means that only one Wavelet has scaling (expansion/compression) and translation. Unlike FT, it allows translation only, *i.e.*, Wavelet only captures low and high frequency signals at the same instant and in more detail, as shown in **Figure 3**.

3. Data Collection and Analysis

3.1. Bridge Characteristics

The bridge is located on the Jaguari River, on a portion of the Federal Highway

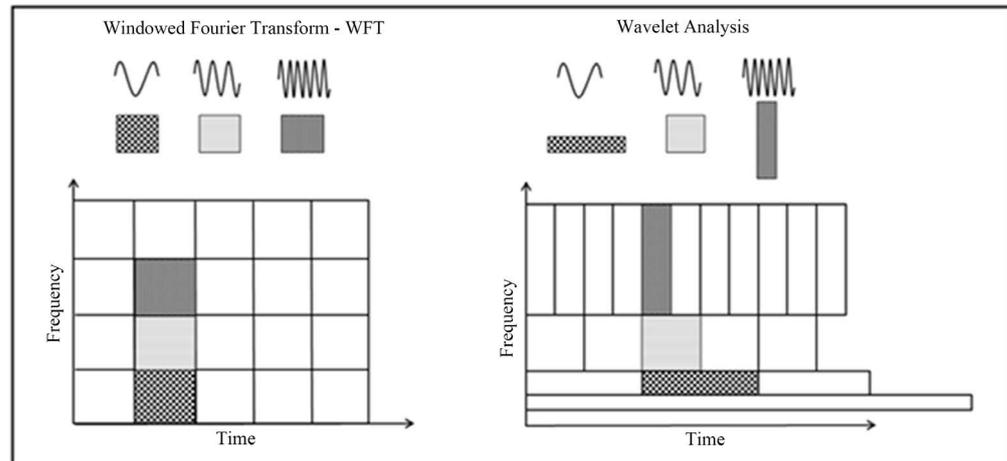


Figure 3. Relationship to time-frequency WFT (left) and Wavelet (right)—Source: adapted from Faria [18].

Fernão Dias—BR 381, southbound, 947 km, in the city of Extrema, Minas Gerais, Brazil.

The south reinforced concrete bridge is curved and gradient, these characteristics emphasize the need of dynamic monitoring. The sliding of the deck may occur in the direction of the roadway or sideways. It is divided into five symmetrical spans of 20 m, 26 m, 30 m, 26 m and 20 m, with the superstructure supported on 6 pairs of vertical abutments (**Figure 4(A)**). Its longitudinal axis shows 5.9% slope (southwards), and continuous superelevation of 8% for the deck. The radius of curvature in projection is of 305.50 m. Due to the superelevation, there is a maximum gap of approximately 50 cm between the abutment pairs. The total width of the deck is 11.70 m, of which 10.90 m are divided into the two traffic lanes and shoulder belts and 0.40 m space is for New Jersey type road barrier, all consisting of reinforced concrete. The cross section shows a π -shaped formation having space of 6.40 m between the piers (center to center). They have a width of 40 cm and a total height of 2.80 m.

3.2. Instrumentation Layout of the Structure

The instrumentation used: 1) a pair of GPS JAVAD Sigma receivers, with 100 Hz data rate, 2) choke ring antennas, model RegAnt_DD_E and 3) two K-Beam[®] accelerometers, AC10g and AC2g. **Figure 4(A)** illustrates the positioning of the lower part of the Jaguari bridge, giving highlights of the pillars and platform. **Figure 4(B)** illustrates the instruments used and **Figure 4(c)** shows the rover GPS antenna and accelerometers at the middle of the large span at around 30 meters distance.

A broad view of Jaguari bridge and geodetic pillar (built for this study) is shown in **Figure 5(A)**. It can be observed that the geodetic pillar was built with in a circular roadway near the structure. The geodetic mark was homologated by the IBGE (Brazilian Institute of Geography and Statistics). **Figure 5(B)** illustrates the static antenna over the geodetic pillar, 300 m away from the Jaguari



Figure 4. Details of the bridge monitored with GPS antenna and Accelerometers.



Figure 5. Static antenna over a pillar 300 m away from the Jaguari Bridge.

Bridge (baseline) with an azimuth of 185° . As baseline is very short, most of the GPS errors are cancelled when using a double differencing data processing technique. The remaining background noise errors are mainly due to a multipath effect [7] [19].

If there is no control point available nearby and the post-processing with data from dual-frequency GPS receiver is required, a possible option would be to use the Absolute Plus Loop-based-solution Accumulated Time-relative method—A-PLAT [20]. Although it is possible, this method hasn't been tested with the proposed method.

3.3. Selection of Jaguari Bridge

The Jaguari bridge has been monitored since 2011 by the team from the infrastructure department of USP. The fact of having previous studies of the structural behavior of the bridge by conventional instrumentation of civil engineering and the authors having partnership with the technical administration favored in selection of the Jaguari bridge.

Before starting GPS measurements, the USP team had already worked on the Jaguari bridge to measure deformation levels, as well as to record their accelerations and displacements caused by vehicle traffic. It resulted in fiducial information that served as reference for this study, such as Dynamic analysis, Nonlinear numerical modeling, Fatigue limit state analysis, Adequacy of infrastructure, Traffic control, Long-term monitoring and others.

In June 2013, the observation with GPS receiver was started on the bridge and the span's natural frequency and its harmonics due to the traffic were confirmed, with the proposed methodology. It was observed in initial results that the information obtained by conventional techniques was equalized with that, obtained with the proposed methodology [3] [4]. Although the first results were satisfactory, the authors observed that there was a need to carry out new measurements on the structure simultaneously with conventional civil engineering apparatus, preferably precision accelerometers, to validate the proposed methodology. Finally, graphical information of the time series is presented for better perception and understanding, like spectral analyzes of the signals obtained in the field by the accelerometer, in the same way as presented with GPS data *i.e.*, by applying a Morlet continuous Transform Wavelet on both data sets. The chronological progress of this study can be observed in Araújo Neto *et al.* [21], Larocca *et al.* [3], Oliveira *et al.* [4].

3.4. Data Collected at Jaguari Bridge

The field study was focused on the central span of the Jaguari concrete bridge. It started at 9:10 am in July 2016 and a pair of GPS receivers with a 100 Hz recording rate was used. One of the receivers was installed on the bridge whereas the base receiver remained in the geodetic frame. In the same period, two axial accelerometers of high sensitivity were installed. Although the measurements were made by both accelerometers, data from the AC2g accelerometer will be presented in this work, considering that the AC10g accelerometer served as a safety measure, in case of failure of AC2g accelerometer.

Accelerometers AC2g, AC10g and radio data were installed on the parapet of the Jaguari bridge near the GPS antenna in a way that they did not interfere with the operation of the GPS antenna (**Figure 4(B)**). The data of the accelerometers was measured in the bands of ± 2 g, ± 10 g respectively, and the recording was performed on a Laptop with radio signal reception, at recording rate of 100 Hz.

The monitoring lasted for 12 minutes and the satellite positions were as follows: 1) the highest satellite—PRN14—remained near the zenith, around 82° , with 115° of azimuth and 2) the satellite—PRN22—around 19° , with 260° of azimuth (**Figure 6**). It is important to clarify that the choice of lower satellite is influenced not only by the near-horizon arrangement, but also, by the position regarding the traffic movement at the time of the study. Hence, the vehicles in transit do not affect the signal quality of the L1 carrier wave. Moreover, a cut-off angle of 10° was used, the resolutions of ambiguity and choice of antenna model

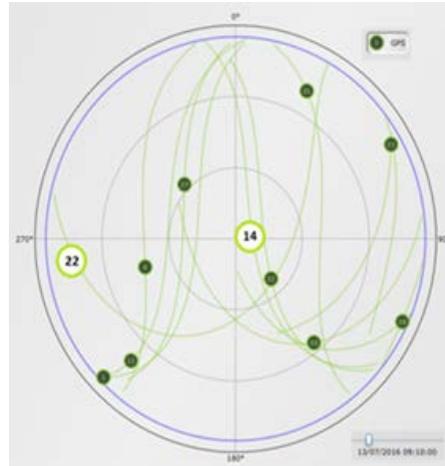


Figure 6. Distribution of satellites at the time of measurement.

in software were observed as well. Precise ephemeris was not necessary due to the short length of the base vector [19].

In order to test the proposed method, the observations were conducted under a controlled condition. The weather conditions were favorable, with an average temperature of 22°C, wind speed of 18 km/h and 71% humidity. The traffic conditions were normal without having any restriction at traffic lanes. The software Interferometry v.1.0 was used for the post-processing, it allows to select the reference and measurer satellites, as suggested by the proposed methodology. The residues used to apply CWT were from “measure” satellite PRN14.

4. Data analysis and Results

4.1. Bridge's Frequency Due Vibration from GPS Receiver 100 Hz

In **Figure 7**, the graphical information of the time series, obtained through the residuals resulting from the adjustment of observations of the double phase difference L1, is shown. Although the observation time is around 12-minutes, wavelet graphs will be displayed in 5-minute intervals (30,000 observations). This proposed interval will present sufficient information to represent the modal frequency of the monitored bridge and can be clearly represented on a scalogram (**Figure 8**) [3]. Experience has shown that a graph with a data rate of 100 Hz masks the visualization of results without the zoom tool. In addition, the authors assert that the information contained in the remaining intervals maintains the pattern of the spectral response presented, without compromising the interpretation.

Figure 7 shows the data of the residuals without any type of bandpass filter, through which it is possible to visualize the response peaks of the structure. However, it is not possible to identify the estimated frequency.

For a better representation of the modal frequency, it was essential to apply a filter (mathematical model) that presented the real response characteristic of the structure, with easy visualization and comprehension. Hence, it was necessary to

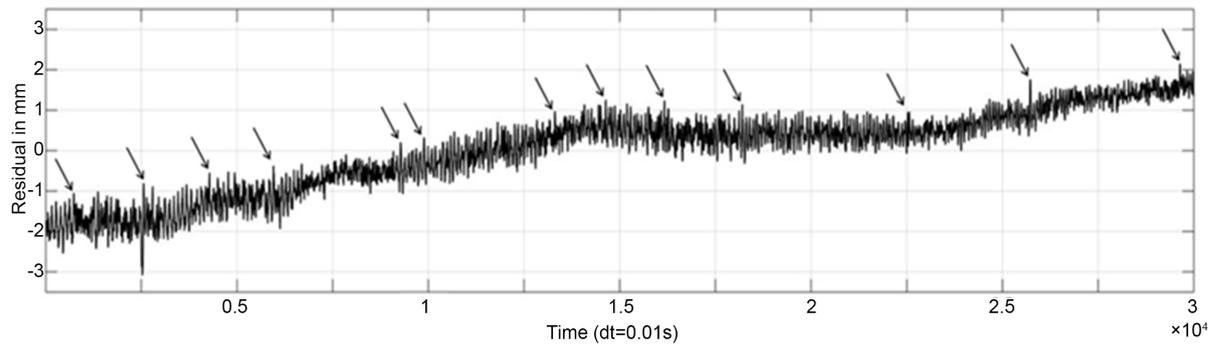


Figure 7. The residuals data without filtering.

apply the Morlet CWT transform in the time by series. These data were filtered by CWT-Morlet and are shown on a scalogram that allowed us to identify the concentration of energy by hot colors regions with a confidence level of 95%.

Figure 8 shows distinct regions with high level of energy due to vehicles of significant weight crossing the bridge and close to the expected frequency region. The interval of five minutes of GPS observations, was extracted from the entire measured observation period. It is important to show wavelet image with 5-minutes (30,000 observations) because in this interval Bridge excitations can be observed. These are clearly highlighted within the limit created in the image, close to 4 Hz and 8 Hz. However, for better visualization, a zoom in the main image is created in smaller intervals (around 1-minute, 6000 observations) to lighten the response frequency between 4 to 8 Hz. It is possible to verify the modulus frequency of the structure starting at 4 Hz in the enlarged interval image. The strong energy level presented in this range stands out in the spectrum image over much of the enlarged range. Furthermore, the frequencies in the 4 to 8 Hz range are identified, coinciding with the numerical model and with the load test values performed in 2011 (more details in Andrade *et al.*, 2013 [22]).

Therefore, these frequencies show clearly the possibility of energy transfer between scales, in other words, between the natural vibration of the bridge and the frequency generated by the passage of vehicles. The spectral responses recorded by the accelerometer and the mathematical model, served as a parameter in previous studies. However, the authors saw the need to carry out simultaneous measurements with other instruments to validate the research work. The collected information will be presented below and will serve as a new comparative parameter.

Moreover, the energies captured in the multipath region of the GPS observations did not influence the observation of the modal frequency of the Jaguari bridge because they are located in a low frequency region, with a magnitude of values lower than 0.25 Hz, where the multipath is presented normally as shown in **Figure 9**. Errors caused by multipath, interferes directly with the observables (pseudorange and carrier phase observables). Thus, it leads to errors in the computed position solution, consequently on the residual values. The bridge

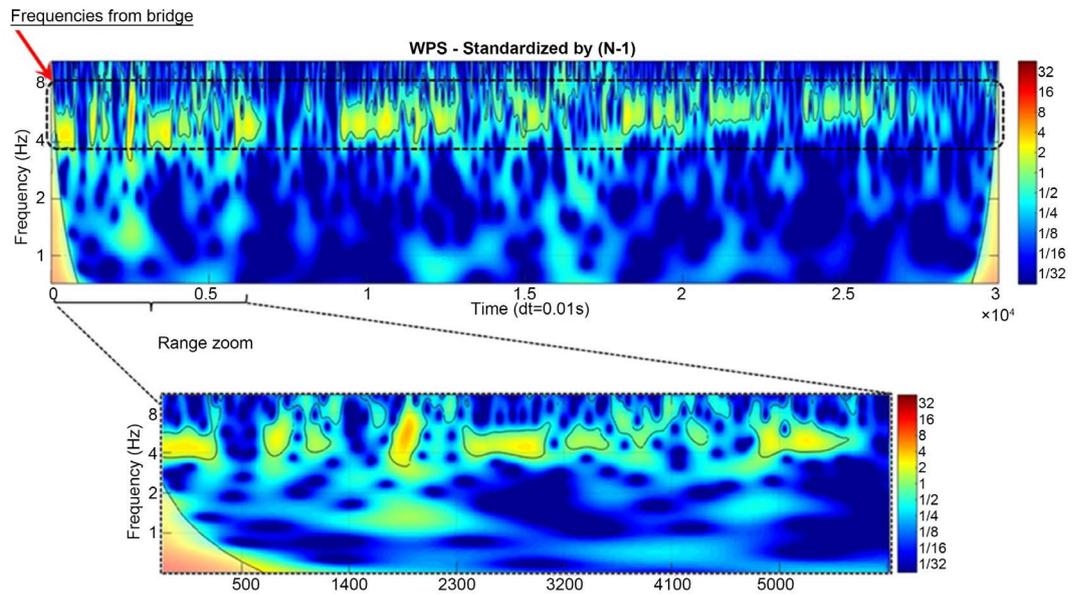


Figure 8. CWT of the residual GPS time series from 5-minute. The 5% statistical significance level of sine wave detection is shown as a yellow to red thick contour.

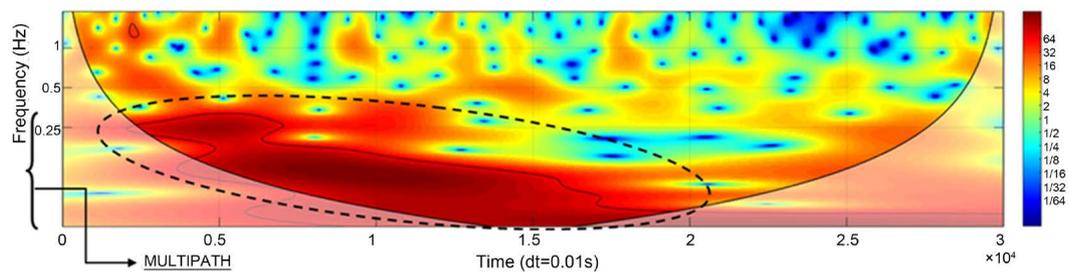


Figure 9. Multipath GPS regions affected in CWT. The 5% statistical significance level of sine wave detection is shown as a red thick contour.

structure as well as moving objects, such as vehicles and people, would be potential sources of multipath. It is assumed that the other errors and interferences inherent to the GPS system are: tropospheric and ionospheric delay errors, orbit errors and clock errors, which were eliminated or significantly reduced with DD.

4.2. Bridge's Frequency Due Vibration from Axial Accelerometer

To match with GPS recording rate, the accelerometer data rate was down sampled at the 100 Hz level to be compatible with GPS data, even though the AC2g axial accelerometer, used in this phase of the research allowed recording up to 1000 Hz. The accelerations obtained during simultaneous readings taken via GPS receivers were separated and analyzed at similar time intervals. It offered an expected delay but did not compromise on the comparison and diagnosis of both results. The simultaneously measured sections of GPS/accelerometer were fractionated in an interval of 5-minute (30,000 observations). To represent the GPS observations, sections were carefully divided into time slots in which the bridge had free vibration immediately after the traffic influence on the structure.

Accordingly, the results will be presented by CWT, the domain signal frequencies in the time domain, where it was possible to highlight the bridge vibration frequencies in the same way as represented by the GPS time series.

As shown in **Figure 10**, it is possible to identify the dominant frequency in the entire measured ranging from 4 Hz up to 8 Hz, which corresponds to the vertical vibration mode. It is worth mentioning that although the modal frequency of the structure presents a single value, by the spectral analysis of the signals obtained in the field, it is possible to verify a variable performance in the interval between 4 and 8 Hz. A magnification of the first minute of the image generated by the interval of 5-minute allows to clarify the spectral response of the structure due to the excitations caused by vehicular traffic on the Jaguari bridge and it means that it was possible to detected the vibrations close to 5 mm of rigid span that has 30 meters longer.

In **Figure 10**, the intensity of the spectral response of the vehicle or vehicle group is also observed, keeping in mind that the bridge has two lanes of traffic and two or more vehicles are constantly in transit. By the magnitude recorded in the range, bounded by the contour between 4 to 8 Hz, it is possible to verify the intensity of the spectral response in the intervals of each influence independently. This characteristic was also clearly observed in the presented methodology.

In this study, the spectral response of the concrete bridge was conferred, measured by the accelerometer, similarly, the results found by GPS are presented. In order to facilitate the comparison of the monitoring results obtained by the different forms presented in this work, all figures from CWT and the accelerometer data are generated from Morlet Continuous Wavelet Transform to identify modal-frequency from Jaguari Bridge. Moreover, in **Figure 10**, the level

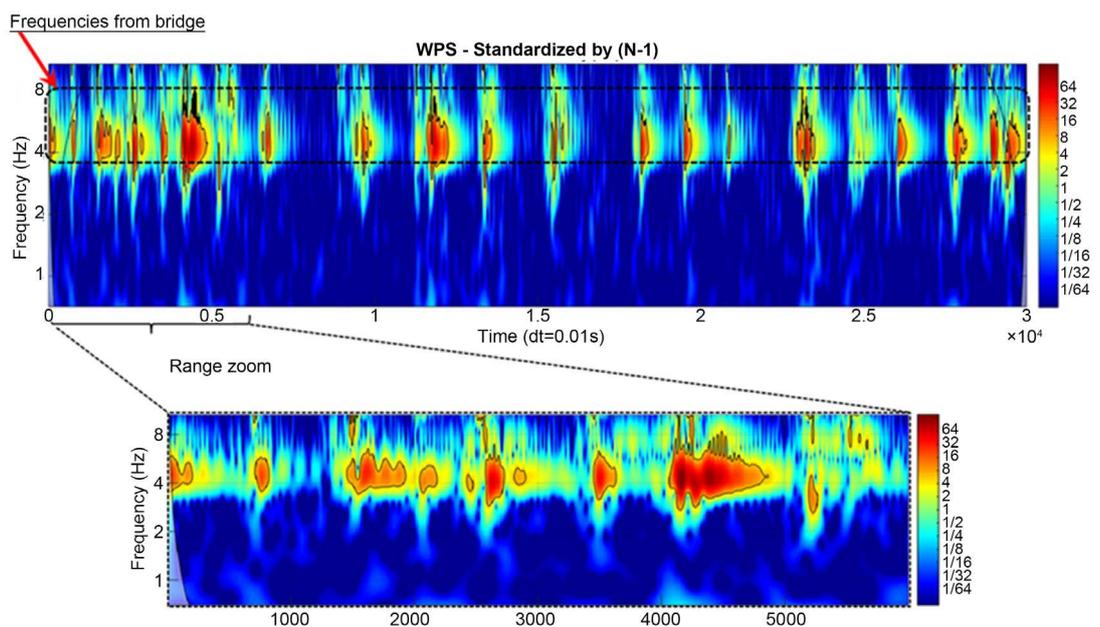


Figure 10. CWT of the Acceleration spectrum (frequency) from accelerometer with 5-min interval. The 5% statistical significance level of sine wave detection is shown as a red thick contour.

of significant signal information is limited by the thick contour with 5% of significance and 95% confidence. The abscissa axis represents the number of observations (for each 0.01 s) and the left vertical axis represents the value of the frequency in hertz and the right vertical axis represents the energy intensity scale in which the frequency is displayed in the area of confidence

5. Conclusions

In this work, the results of the tests carried out at Jaguari Concrete Bridge showed that it is possible to detect and monitor modal frequency and structure behavior using GPS receivers, combined with Continuous Wavelet Transform algorithm (CWT) under PRM. Regarding the representativeness of the data measured by the GPS receiver, it is observed that the CWT is more functional in relation to the application of the Fourier transform, particularity in representing the frequencies existing in the time series in the same interval of time. It is concluded that bridge characteristics found by CWT would hardly be seen by the frequency graphs generated by the Fourier transform.

The values from double-difference phase residuals exactly correlate with the theoretical results of the frequencies presented by the axial accelerometer (conventional instrument). Both measurements were performed simultaneously for the first time for this structure and settled for a value between 4 and 8 Hz, which are bridge's natural frequency and its harmonics due to the traffic. Furthermore, the results generated by the presented methodology are also harmonized with the theoretical values of the frequencies found in other research studies on the Jaguari bridge [3] [4] [21] [22].

This fact confirms the potential of the presented methodology as a technique which permits to determine the small vertical frequency of the concrete bridge deck, without using accelerometer in special situations. Additionally, it is necessary to have attention in selection of reference satellite for the methodology to present reliable results because results cannot be obtained by the deficiencies of satellite GPS geometry. The selected reference satellite cannot have the carrier signal obstructed by vehicle traffic during the monitoring of the bridge, it causes loss of carrier cycles and results in increased multipath. Consequently, it compromises the quality of the results. Like any other developing technology, GPS has its limits, when it is applied to meet engineering needs, multipath is still one of the major degradation sources for this system.

The use of modern GPS receivers with a high recording rate as 100 Hz, does not only limit the device's ability to record structure information, but also improves the quality of GPS observations with the help of the modern hardware and software used, as well as with sampling rate similar to the main accelerometers available in the market. GPS receivers also help in recording the acceleration of the structure, with greater quantity of samples per unit time of a signal, without error of "aliasing", according to Nyquist's Theorem.

In view of the results obtained, this research validates the capability of GPS

receivers combined with Continuous Wavelet Transform algorithm (CWT) for monitoring the dynamic behavior of a rigid bridge. It allows to obtain the repeatability of GPS results at the millimeter level, which is equivalent to the most accurate geotechnical instruments.

At no time, the research presented here is based on the replacement of conventional instrumentation used in engineering structures. Rather, it enhances pioneer the potential in aggregate with existing tools. That is, making the GPS 100 Hz as the first instrument to be used in the monitoring of rigid bridges, in any climate or unfavorable condition, without the need for any calibration, with the only difference of allowing global positioning in a milli-meter manner.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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