GPS Performance Assessment and Analysis, El Carrizo and Juarez Bridge in Sinaloa Mexico

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ABSTRACT: It has been already proved in literature that several approaches using Global Positioning System (GPS) can be intelligently used for the performance evaluation of bridges. This paper focused on GPS, since it naturally produces position estimates as compared to seismic or other instruments that record either velocity or acceleration; and thus, an integration is required. Hence, a research was conducted in order to evaluate the GPS capabilities in extracting the performance of two important bridges located at Sinaloa Mexico: (1) the Juarez Bridge in Culiacan, and (2) El Carrizo Bridge one of the most important bridges constructed in the Mazatlan-Durango federal highway. For the GPS data processing scheme at Juarez Bridge the authors used the traditional DGPS approach, while for El Carrizo Bridge the CSRS-PPP GPS was employed. Based on the data processing, GPS time series were generated for the proper calculation of semi-static and dynamic displacement (≤10cm) for the Juarez Bridge and (≤10mm) for El Carrizo Bridge. In addition, appropriate post-processing filtering was applied to the final displacements.

1 INTRODUCTION

The structural bridge evaluation is a very significant topic investigated for the last twenty years. Such structural conditions demand the proper assessment and analysis of bridges using alternative methodologies that provide adequate efficiency, cost, and reliability. For example, Ashkenazi and Roberts (1997) reported that to distinguish the response of bridges to stressing under use, the structural monitoring of bridges must be performed under real-time in-service conditions. Therefore, we evaluated the in-service performance conditions by means of high-rate GPS measurements of two important bridges located at Sinaloa Mexico. At first instance, the Juarez Bridge in Culiacan, which is a reinforced concrete structure that connects two significant zones of the city, Vazquez et al. (2017) and on the other hand, El Carrizo Bridge (reinforced concrete and cable-fixed) one of the most important bridges constructed in the Mazatlan-Durango federal highway, Trotin et al. (2015). For the GPS data processing scheme at Juarez Bridge the traditional DGPS approach was used. While for El Carrizo Bridge, the Canadian Reference System Station – Precise Point Position (CSRS-PPP) GPS was employed. The PPP-GPS approach is considered a very powerful technique when using a single GPS receiver to compute position with high accuracy Zumberge et al. (1997). The reason of using the PPP-GPS technique or the DGPS approach for practical bridge monitoring, relies in having favorable atmospheric conditions as good geometry of the satellites. The PPP-GNSS requires precise ephemerides, satellite and receiver clocks corrections, antenna phase-center, as well as adequate measurement time. However, the use of DGPS is costly since it requires at least two GPS receivers: one deployed on the structure as a rover, and the other must be static as a reference station. Based on GPS displacements generated by both approaches, the semi-static and dynamic displacement at both bridges, considering proper calculation, were generated. Semi-static displacement can be used to analyze the movement of the bridge, Kaloop (2012), while the dynamic vibration signal of a bridge can be monitored by GPS, Wang et al. (2015). However, GPS displacements obtained in terms of coordinates may not accurately reveal the behavior of the bridge without considering prior filtering of the data, Psimoulis et al. (2016). The main objective of this paper is to validate two different approaches proposed in literature for bridge monitoring, considering a performance assessement and analisis to evaluate the GPS capabilities of two important bridges located at Sinaloa Mexico. It is expected that the results will provide enough information to characterize the dynamic behavior and provide information in order to calibrate mathematical models to detect damage to address diagnosis of both bridges.

2 DESCRIPTION AND DEFORMATION EVALUATION

2.1 The Juarez Bridge

In the city of Culiacan, Mexico, some of the civil infrastructure is presenting non-adequate performance. It represents a problem that clearly exposes the safety of persons because of the possible collapse of such structures, Vazquez et al. (2017). The authors focused their scientific interest particularly on the Juarez Bridge that they evaluate using the traditional DGPS approach to compute dynamic and semi-static displacement. The Juarez Bridge represents an ideal case of study, since it was built approximately more than four decades ago to streamline the congested traffic between northern and southern parts of the city and thousands of vehicles, bicycles and pedestrians cross the bridge every day. It is a reinforced concrete structure with an approximate length of 200 meters. Figure 1 (a) illustrates in a general sense the dimension and currently condition of this bridge. In addition, the deformation evaluation of the Juarez Bridge was developed computing displacements using six geodetic-grade GPS receivers: two Topcon Hyper-V, denoted as Hyper1 and Hyper2; two Zenith Geomax-25, denoted as Zenith1 and Zenith2; and two Leica-SR530, denoted as Leica1 and Leica2. They were properly mount-leveled and fully fixed to the bridge; located in two parallel rows of three GPS on every side of the metal safety fence as shown in Figure 2 (b).

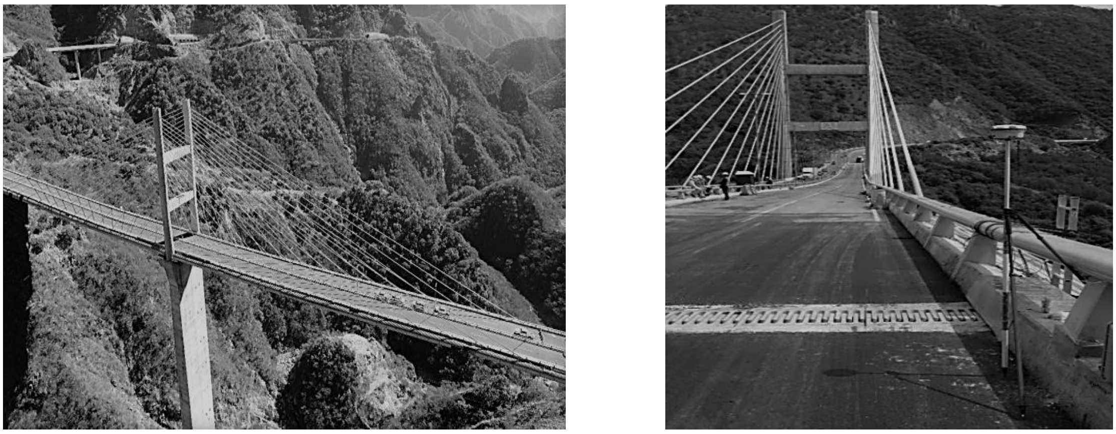
(a)

(b)

Figure 1. The Juarez Bridge: (a) Dimension and currently condition; (b) Location and fixing conditions of the GPS receivers.

2.2 El Carrizo Bridge

El Carrizo Bridge represents another ideal case of study, since is consider the second most important bridge constructed in the Mazatlan-Durango federal highway, which help to connect the Pacific Ocean with the Gulf of Mexico, Trotin et al. (2015). El Carrizo Bridge structural system consists on high strength cables fixed to a 226 m concrete tower providing stability to double-cantilevered metallic plate girders of 217.30 m; each one supporting the decking system. In addition, where the cable-stayed part is ending, there are two double cantilevered post-tensioned concrete box girders with a length of 35 m each, and then, Nebraska beams of 38 m are used to connect the bridge with the abutment system. It was built approximately six years ago and thousands of vehicles and eighteen-wheeler truck transporting, cross the bridge every day. Figure 2 (a) shows these structural sections of the bridge. In addition, the deformation evaluation of El Carrizo Bridge was developed computing displacements using a Hi-Target V60 geodetic-grade GPS receiver, denoted as HTV60. It was properly mount-leveled and fully fixed to the bridge; on the side of the metal safety fence as shown in Figure 2 (b). HTV60 receiver was placed one meter from the joint that connects the cable-stayed part of the bridge and the cantilevered one, specifically on the transversal beam of the body on the Durango state side. This point represents the larger distance from the concrete pylon that supports the cantilevered transversal beam. Therefore, the maximum deflection of the cantilever bridge was expected to be recorded there.



(a) **(b)**

Figure 2. El Carrizo Bridge: (a) Dimension and structural sections; (b) Geodetic-grade GNSS Hi-Target V60 receiver located on the cantilevered transversal beam.

3 GPS DATA PROCESSING TECHNIQUE

3.1 The Juarez Bridge – DGPS approach

Two very stable stations with previously precise determined coordinates that are part of the National GPS Network administrated by the Mexican National Institute of Statistics and Geography (INEGI) were used as control sites for the GPS data processing. The GPS displacement were obtained considering three directions: North-South (N-S), East-West (E-W), and Vertical (V). Every session was conducted collecting displacement data from Monday to Sunday during three rush hour periods (local time) per day: 8:00-9:00 (Session1), 12:00-13:00 (Session2), and 17:00-18:00 (Session3) hrs. The authors considered these conditions as real-time serviceability performance conditions of the bridge, representing a critical state of the structure. In addition, for the GPS data processing scheme at Juarez Bridge, the authors used the traditional DGPS approach by means of the ionosphere-free double-differenced (DD) carrier phase method given by Hofmann-Wellenhof et al. (2012) as shown in Equation (1). Finally, the we used the GAMIT/TRACK software (Herring et al. 2010; King & Bock 2005), considering 1-Hz sampling rate, 15-degree cutoff angle. The carrier phase ambiguity parameters were fixed at the rate of 99-100%, precise final orbits disseminated by IGS (International GNSS Service) and antenna calibration parameters provided by NGS (National Geodetic Survey) were used, Mader (1999).

$$\Phi_{AB,12}^{KL} = \rho_{AB}^{KL} + T_{AB}^{KL} + \alpha_1\lambda_1 N_1 + \alpha_2\lambda_2 N_2 + \alpha_1\varepsilon_{AB,1}^{KL} + \alpha_2\varepsilon_{AB,2}^{KL} \quad (1)$$

with

$$\alpha_1 = \frac{f_1^2}{f_1^2 - f_2^2} \quad \text{and} \quad \alpha_2 = \frac{f_2^2}{f_1^2 - f_2^2}$$

Where A and B are subscripts that denote receivers, K and L are superscripts that denote satellites, ρ_{AB}^{KL} is the DD-geometric distance between the respective satellites and receivers, 1 and 2 indicate that the carriers L_1 and L_2 are involved in the combination, T_{AB}^{KL} is the DD tropospheric refraction term, $\lambda_1 \approx 19cm$, and $\lambda_2 \approx 24cm$ are the wavelengths of the signals on the L_1 and L_2 carriers, respectively, N_1 and N_2 are the integer ambiguities associated with the phase measurements (in cycles) on L_1 and L_2, respectively, $\varepsilon_{AB,1}^{KL}$ and $\varepsilon_{AB,2}^{KL}$ are the random DD measurement noise terms (in meters) for the observed phases on L_1 and L_2, respectively.

3.2 El Carrizo Bridge – PPP-GPS approach

Similarly, the GPS displacement were obtained considering the three directions, as previously mentioned. However, here we used the PPP-GPS approach, since is considered a very powerful technique when using a single GPS receiver to compute position with high accuracy, Zumberge et al. (1997). In order to speed up the process of reaching an integer ambiguity-fixed solution, the GPS receiver started the data recording (10-Hz sampling rate) one hour before each loading test on the bridge. For El Carrizo Bridge, two loading tests were carried out, one of 28 minutes and another of 35 minutes, respectively. The post processing PPP approach was constructed based on the un-differenced observations given by Kouba and Héroux (2001) and Abou-Galala et al. (2017) as shown in Equations (2) and (3). Finally, the Canadian Spatial Reference System (CSRS) Precise Point Positioning (PPP) service software was used to process the GPS data in kinematic mode. For details about the post-processed position solutions of GPS, observation files uploaded by the user, type of GPS orbit and clock products used in the CSRS, please refer to Farah (2015).

$$\Phi_{1,2} = \rho_r^s + d_{orb} + c(dt^s - dt_r) - I_{1,2} + T_{1,2} - \lambda_{1,2}N_{1,2} + hd_{1,2}^r - hd_{1,2}^s + M_{1,2} + \varepsilon_{1,2} \quad (2)$$

$$P_{1,2} = \rho_r^s + d_{orb} + c(dt^s - dt_r) + I_{1,2} + T_{1,2} + dhd_{1,2}^r - dhd_{1,2}^s + m_{1,2} + e_{1,2} \quad (3)$$

Where $\Phi_{1,2}$ and $P_{1,2}$ are the carrier-phase and pseudo-range measurements, respectively (in meters); 1 and 2 indicate the carriers on L_1 and L_2; ρ_r^s is the geometric distance between the satellite (s) and the receiver (r), respectively (in meters); d_{orb} is the satellite orbit error (in meters); c is the speed of light in vacuum, (in meters per seconds); dt_r and dt^s are the clock error of the receiver and satellite, respectively (in seconds); $I_{1,2}$ is the first-order ionosphere effect (in meters); $T_{1,2}$ is the troposphere delay (in meters); $\lambda_{1,2}$ is the wavelength of the frequency (in meters); $N_{1,2}$ is the ambiguity term on the frequency (in cycles); $hd_{1,2}^r$ and $hd_{1,2}^s$ are the receiver and satellite hardware delays for the carrier-phase, respectively (in meters); $dhd_{1,2}^r$ and $dhd_{1,2}^s$ are the receiver and satellite hardware delays for the pseudo-range, respectively (in meters); $M_{1,2}$ and $m_{1,2}$ are the multipath errors of the carrier-phase and pseudo-range, respectively (in meters); $\varepsilon_{1,2}$ and $e_{1,2}$ are the noise errors of the carrier-phase and the pseudo-range, respectively (in meters).

4. RESULTS AND DISCUSSION

4.1 GPS semi-static and dynamic displacement: The Juarez Bridge

The DGPS receivers' coordinates were transformed into time-series of apparent displacement around a relative zero representing the equilibrium level of the monitoring point, Moschas, and Stiros (2011). However, the particular behavior of the bridge cannot be obtained based on the apparent displacement because of the dominating noise. Furthermore, long period is equal to long wavelength, low frequency and slow movement (semi-static displacements). Short period is short wavelength, high frequency and fast movement (dynamic displacements). Hence, GPS time-series (apparent displacement) were separated in semi-static and dynamic displacement by applying adequate post-processing filters. Semi-static displacement is calculated using moving average filter, while dynamic displacement is obtained using Chebyshev filter type 1. In order to illustrate the above characteristics corresponding to the Juarez Bridge, the semi-static and dynamic displacement in the three components: North-South (N-S); East-West (E-W) and Vertical (V) for the Zenith Geomax-25 (Zenith1) GPS receiver for the first session (Session1: 8:00-9:00 hrs.) corresponding to the first day (Monday) of measurements are illustrated in Figures 3 and 4. Results from Figure 3 allowed that the semi-static displacements could be used to analyze the movement of the Juarez Bridge considering that the Zenith1 GPS receiver experienced the greatest values. On the other hand, the dynamic displacement illustrated in Figure 4 describes the quality of the filter used during the analysis and it may be considered as a guide to understand the behavior of Juarez Bridge.

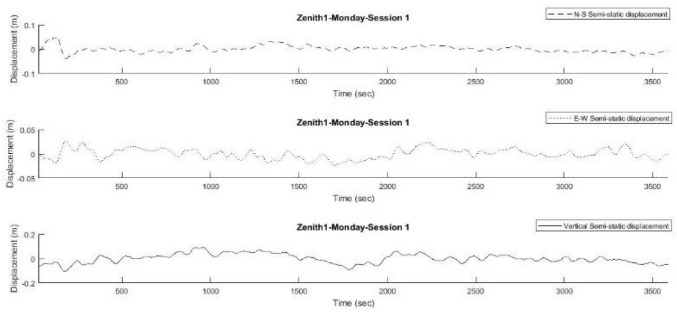


Figure 3. Semi-static displacement for Zenith Geomax-25 GPS receiver corresponding to Monday 8:00-9:00 hrs (Session1).

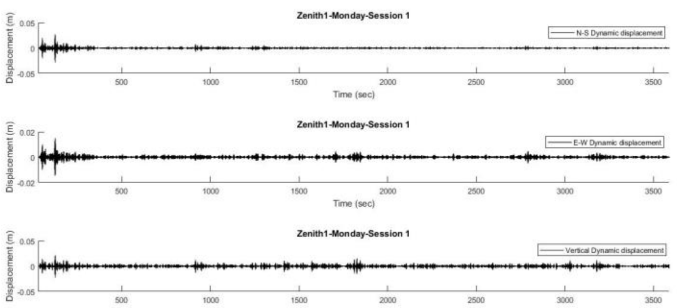


Figure 4. Dynamic displacement for Zenith Geomax-25 GPS receiver corresponding to Monday 8:00-9:00 hrs (Session1).

Considering the fact that the Juarez Bridge main problem is that it presents considerable vibrations in its vertical component, Figure 5 illustrates the minimum to maximum dynamic displacement only for this component. This was achieve for the whole experiment (Monday to Sunday), including all the 21-sessions (three per day) for the six geodetic-grade GPS receivers

(Hyper1, Hyper2, Geomax1, Geomax2, Leica1 and Leica2) used. The results presented in Figure 5, clearly indicate that Zenith1, Zenith2, Leica1 and Leica experienced maximum values above 10 cm.; however, the most affected was the Zenith2 GPS receiver in 17 sessions out of 21. These bigger values at the center of the bridge may be attributed to possible torsion phenomenon; since, initially the Juarez Bridge was designed only to carry loads corresponding to two lanes of traffic and pedestrians. Inappropriately, two more lanes for traffic and one small lane for bicycles were incorporated to the bridge.

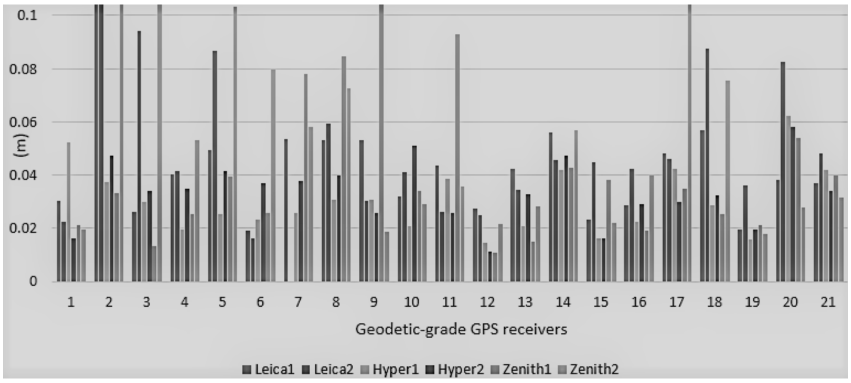


Figure 5. Maximum vertical dynamic displacement for each GPS session duration.

4.2 GPS semi-static and dynamic displacement: El Carrizo Bridge

The PPP-GPS post processed receiver coordinates were transformed into time-series of apparent displacement, that were also separated in semi-static and dynamic displacement by applying adequate post-processing filters as did for the Juarez Bridge. Hence, the corresponding characteristic behavior of El Carrizo Bridge for the Load test 1, using the Hi-Target V60 GPS in terms of the semi-static and dynamic displacement in the mentioned three components, are illustrated in Figures 6 and 7. It can be observed in these figures HITV60 receiver experienced less sensitivity in measuring the changes on the double cantilever section of the structure as compared with other sensors such as LVDT (Linear Variable Different Transform). This fact can be justified because the displacements that occurred on the bridge during Load Test 1 were in the order of the millimeter level, which was detected by the used PPP-GPS approach method.

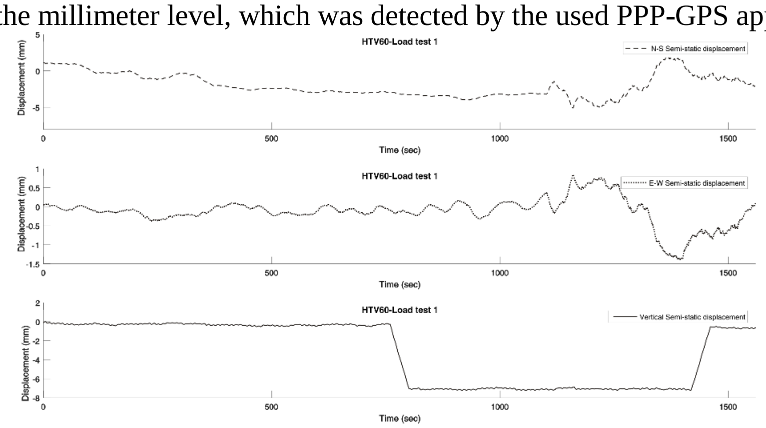


Figure 6. Semi-static displacement for Hi-Target V60 GPS receiver corresponding to Load test 1.

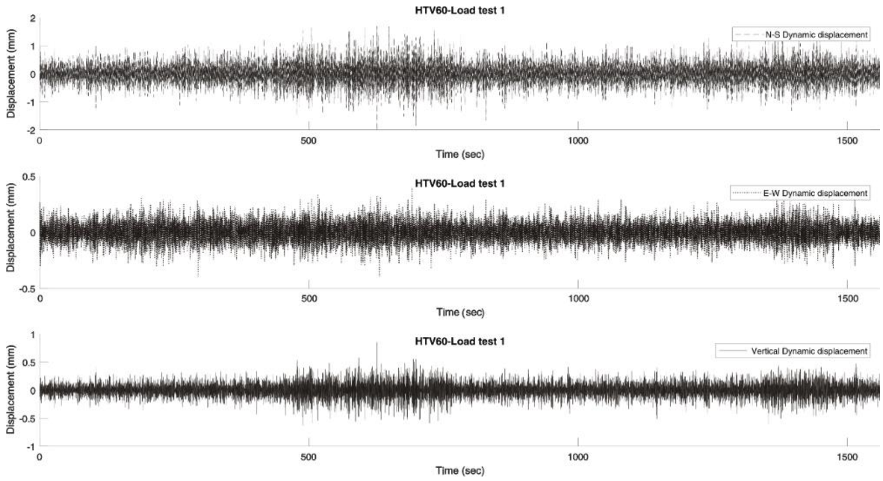


Figure 7. Dynamic displacement for Hi-Target V60 GPS receiver corresponding to Load test 1.

Based on the fact that, two loading tests were carried out at El Carrizo Bridge, Figure 8 illustrates the minimum to maximum dynamic displacement in the mentioned three components, when using the Hi-Target V60 GPS receiver. The results presented in Figure 8, clearly indicate that Load test 2 experienced bigger values in terms of the three analyzed components (3 to 5 mm). On the other hand, displacement are less than 2-mm for the three components at Load test 1.

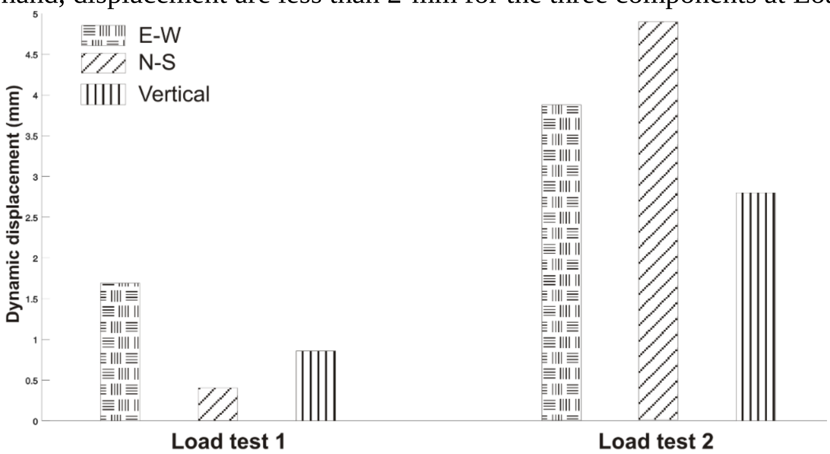


Figure 8. Maximum dynamic displacement (three components) for Hi-Target V60 25 GPS receiver corresponding each load test duration.

A summary of the results extracted via GPS and LVDT sensor are reported in Table 1. For both GPS and LVDT instruments, it can be noted that for the first and second tests differences of 3.49 and 0.36 mm, respectively. Such differences may be justified because the instruments were located in different bodies of the structure.

Table 1. Differences between GPS and LVDT

Test	**GPS (mm)**	**LVDT (mm)**	**Difference "│∆│" (mm)**
1	7.22	10.71	3.49
2	11.25	11.61	0.36

5. CONCLUSIONS

A GPS performance assessment and analysis was conducted based on two different approaches reported in literature for bridge monitoring to evaluate the GPS capabilities. It was demonstrated based on two cases of study that both analyzed GPS approaches are efficient, accurate, and reliable procedures for evaluation of under normal service conditions. Both semi-static and dynamic displacement obtained for the Juarez Bridge and El Carrizo Bridge allowed analyzing their structural behavior. Finally, based on the obtained results from this addressed research it is possible to contribute to a structural diagnosis of both bridges.

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