Experimental testing of high-rate GNSS precise point positioning (PPP) method for detecting dynamic vertical displacement response of engineering structures

Cemal Ozer Yigit and Eralp Gurlek

Department of Geomatics Engineering Faculty of Engineering, Gebze Technical University, Gebze-Kocaeli, Turkey; Division of Geodetic and Geographical Information Technologies, Graduate School of Natural and Applied Sciences, Gebze Technical University, Gebze-Kocaeli, Turkey

ABSTRACT

The fundamental dynamic property of the structures is the oscillation frequency, which can be derived from the response measurements. The structures with a short/medium/long span (e.g. suspended or cable bridges) vibrate vertically rather than horizontally. The potential of GNSS precise point positioning (PPP) for detecting the dynamic response of vibrating structures has been the focus of recent studies. In this study, the usability of GNSS PPP in detecting the dynamic displacement response of a vertically vibrating structure was experimentally investigated. A number of experiments on cantilever beam structures were conducted and four cases with different vibration frequencies, ranging from 0.94 to 2.90 Hz, were selected to compare the PPP and precise relative methods in the time, position and frequency domain. In addition, the effects of the ultra-rapid and final precise orbit product on the kinematic PPP solution were examined in terms of detecting vertical oscillation. The results clearly show that a high-rate kinematic PPP method can detect the fundamental frequency of vertical vibration to evaluate the dynamic movement of long/medium/short-span suspended bridges and highway viaducts.

1. Introduction

High-rate GNSS positioning is commonly used to measure dynamic displacements of engineering structures triggered by wind, earthquake and vehicle traffic loads. Recently, high-rate and ultra-high-rate GNSS receivers have been utilized to measure relative displacements at rates of 1–10 and 10–100 Hz, respectively. The dynamic displacement measurement using the relative GNSS positioning method requires two GNSS receivers, one placed on the deformable object and the other being a nearby reference station, and the accuracy of this method is at the sub-centimetre level.

The lateral movement of a bridge deck is usually activated by wind loads and vertical dynamic displacements, which are mostly caused by the change of vehicle traffic loads. These loads result in relative small movements in the longitudinal direction (Kalopoulou 2010). Up to now, numerous studies have been conducted concerning the technical feasibility of the precise relative GNSS positioning method to measure dynamic displacements of long-span suspension and cable-stayed bridges (Nakamura 2000; Xu et al. 2002; Roberts et al. 2004; Erdog/ et al. 2007; Meng et al. 2007; Yi et al. 2013), medium-span suspension (Meo et al. 2006; Yu et al. 2014) and short-span bridges (Moschas & Stiros 2011, 2014; Psimoulis & Stiros 2013).
Precise point positioning (PPP) (Zumberge et al. 1997; Kouba & Heroux 2001) is a powerful method for processing measurements from a single GPS/GNSS receiver to compute a position with high accuracy. When compared to precise relative (hereafter referred to simply as relative) positioning, PPP is more advantageous in terms of avoiding the cost of operating a reference station. However, PPP requires accurate satellite orbits and clocks corrections obtained from permanent global tracking network, absolute antenna phase-centre offset, variation and phase wind-up for receivers and satellites, solid earth tides, polar tides, and ocean tide loading, among others. In addition, contrary to relative positioning, using the conventional PPP method, it takes a long time to create an ambiguity float solution (or converged solution) at the centimetre-level positioning accuracy. Therefore, some researchers have developed PPP ambiguity fixing methods (Ge et al. 2008; Laurichesse et al. 2009; Collins et al. 2010; Geng et al. 2010) to shorten the convergence time and improve positioning accuracy. A further technical comparison of PPP with relative positioning can be found in Rizos et al. (2012).

High-rate PPP has been demonstrated to be a powerful and efficient method for GPS seismology (Kouba 2003; Collins et al. 2009; Avallone et al. 2011), earthquake early warning system (Li et al. 2013), the precise positioning of kinematic objects in land, air and marine environments (Gao et al. 2005; Zhang & Andersen 2006; Geng et al. 2010; Alkan & Öcalan 2013; El-Diasty 2016) and structural health monitoring (Yigit 2016).

Xu et al. (2013) assessed high-rate kinematic PPP for measuring seismic wave motions generated by a shake table. The authors compared the PPP results with inertial measurement unit and demonstrated that high-rate kinematic PPP can produce absolute horizontal displacement waveforms at the accuracy of 2–4 mm and absolute vertical displacement waveforms at the sub-centimetre level of accuracy within a short period of time (a few minutes). In addition, Moschas et al. (2014) assessed the performance of 10 Hz PPP in two oscillation events by monitoring horizontal semi-static and harmonic oscillations at a frequency of approximately 3.3 Hz. The authors also compared the PPP results with those obtained from an accelerometer, robotic total station and differential GPS. Their findings showed that PPP can adequately constrain the time history of dynamic and semi-static displacements of the order of 1 or 2 cm in the horizontal component.

Most recently, Yigit (2016) evaluated the performance of high-rate PPP for measuring fundamental (natural) vibrations or frequencies generated by the model bar capable of oscillation with first and second natural frequencies. He compared the PPP results with those from relative positioning and reported that the high-rate PPP technique can capture both horizontal and vertical displacement waveforms at the sub-centimetre level of accuracy within a short period of time. However, in that study, vertical oscillation was generated by bending the bar while oscillating horizontally.

The current study extends the work of Yigit (2016) in terms of evaluating the performance of high-rate PPP in detecting the vertical dynamic oscillation frequency of engineering structures such as a long/medium(or short)-span cable-stayed bridge, pedestrian bridge and highway viaduct. The purpose of this research was to investigate how precisely high-rate PPP can measure the vertical dynamic oscillation of engineering structures and reveal its potential as an alternative to relative positioning techniques in cases where no base station is available on site. The assessment of vertical performance of high-rate PPP was performed on four different cases selected from a number of experiments with respect to their frequency characteristics. The PPP results obtained from each case were compared to the corresponding post-processed results from the kinematic relative method in the time, position and frequency domain. The PPP solutions based on both Natural Resources Canada (NrCAN) Ultra-Rapid products (commonly referred to as EMU) and IGS-Final products were compared in terms of their performance in detecting vertical dynamic oscillation.

The structure of the paper is as follows. Section 2 presents the experimental set-up, GNSS data collection and GNSS processing strategies for the PPP and relative positioning methods. Section 3 discusses the experimental results of four cases generated by simulation bars. The last section summarizes the main findings of the research and presents recommendations for future work.
2. Methodology

2.1. Experimental set-up

To assess the vertical performance of the high-rate kinematic PPP method, a number of oscillation tests were performed using three model structures with two dual-frequency GNSS antenna/receivers. Figure 1 illustrates the overall experiment set-up. Three steel flat bars with different dynamic characteristics were selected to represent a long/medium/short-span cantilever beam. The first natural frequencies of the bars are different because oscillation frequency depends on the geometry of the member (length, width, thickness and Young modulus) (Chopra 1995). Table 1 presents the geometrical properties of the bars and their numerical natural vibration frequencies calculated by taking into consideration the mass of the GNSS receiver. Each bar is a single degree of freedom (SDOF) system with vertical transition freedom, where the GNSS receiver is installed while the other tip is assumed to be fixed in all degree of freedoms throughout the test procedure. The placement of the fixed end of the bar under the weighing member (heavy concrete block on the top in Figure 1) causes uncertainty in restraining. To minimize this uncertainty, a few portions of the bar were kept under the weighing member to ensure the fixed end condition while compromising on the span length for oscillation. For this reason, the span length of the bar during all the experiments was shorter than the length provided in Table 1. This resulted in higher oscillation frequencies than initially calculated.

![Figure 1. Schematic view of experimental set-up.](image-url)
2.2. GNSS data collection

The bars were fixed onto a heavy concrete block to prevent them from slipping during the experiment and the GNSS antenna/receiver was attached to the free end of the bars. The reference GNSS antenna/receiver was installed 15 m away from the rover GNSS antenna/receiver since the accuracy of a coordinate estimate based on the kinematic relative positioning depends on inter-station baseline lengths. Hence, most of the GNSS errors, except for multipath error, were eliminated and the precise coordinates of the rover were determined. Figure 2 shows the three model structures and photographs taken during the experiment.

The bar experiment was conducted at the Campus of Gebze Technical University in November 2015 and lasted approximately 60 minutes. Since relative positioning was adopted as a reference solution in this study, the bar was kept motionless for approximately 20 minutes before starting the oscillations in order to accelerate the process of achieving an integer ambiguity-fixed solution. The GNSS data (GPS and GLONASS) were collected using two dual-frequency TopconTM HiPer Pro GNSS receivers in the kinematic survey mode and recorded at a 10 Hz (0.1 s) sampling rate. In this mode, the advertised positional accuracy is 15 mm + 1 ppm(× baseline length) vertically. The experiment was conducted under open-sky conditions. The only multipath source depending on the environment may be heavy concrete block as it was close to the rover antenna. The satellite elevation cut-off angle was 10°. The weather was calm when carrying out the experiment. Eight GPS and seven GLONASS satellites were visible during the experiment.

2.3. GNSS processing strategies

Several researchers have demonstrated the feasibility of applying the real-time kinematic or post-processing kinematic (relative positioning) method to monitor displacement and detect the natural oscillation frequency of engineering structures (Çelebi 2000; Chan et al. 2006; Nickitopoulou et al. 2006; Psimoulis et al. 2008; Psimoulis & Stiros 2008). In these studies, the displacement history and natural frequency of engineering structures were determined using a relative kinematic method based on dual-frequency GNSS receiver data. Therefore, in this study, a relative positioning solution

| Bar name | Length (mm) | Width (mm) | Thickness (mm) | Calculated first natural frequency (Hz) |
|----------|-------------|------------|----------------|----------------------------------------|
| Long     | 1356        | 38         | 4.5            | 0.838                                   |
| Medium   | 891         | 45         | 3.8            | 1.420                                   |
| Short    | 427         | 94         | 2.2            | 2.894                                   |

Table 1. Length, width and thickness of the bars.

Figure 2. Steel bar models used in the study (left) and experimental set-up in the field.
was chosen to establish a reference trajectory for an accuracy assessment. The GNSS integer ambiguity-fixed solution was computed using the Leica Geo Office (LGO) 3.0 software. In processing, a standard L1 + L2 solution was adopted to eliminate the influence of the ionosphere. Furthermore, a Hopfield tropospheric model was utilized to correct the tropospheric delay error. Precise ephemeris data was used for the post-processed kinematic solution.

The GNSS data from the rover receiver on the bar were also processed in the kinematic PPP mode using the CSRS-PPP software developed by the Geodetic Survey Division of the NRCan (NRCan-GSD). Currently, contrary to other online post-processing services (e.g. APPS, MagicGNSS), CSRS-PPP is able to process GNSS data with high sampling rate (>1 Hz). For this reason, CSRS-PPP software was used since the sampling rate of the GNSS data used in this study was 10 Hz. CSRS-PPP is a free online post-processing service that allows GPS and GLONASS users all over the world to compute positions from their stand-alone single and dual-frequency GPS + GLONASS receiver data. CSRS-PPP uses different GNSS orbit and clock products (EMU, rapid and IGS-Final) depending on the time of a user’s data submission and the epoch of the last observation in users’ dataset (Mireault et al. 2008). Carrier-phase ambiguities are resolved within 30 minutes in the static mode and one hour in the kinematic mode. Once the phase ambiguities are resolved, all the parameters can be re-evaluated by substituting their final estimates back into the solution to effectively recover the optimal estimates for all parameters over the entire observation session. This is particularly important for the kinematic mode to recover optimal trajectory (Heroux et al. 2006). CSRS-PPP generates various forms of output, such as short and detailed summary reports and graphical time series plots. The ‘sum’ file is a session processing summary containing all processing parameters. The processing options used in this study are given in Table 2. The reader is referred to Tetreault et al. (2005) for further detail about the CSRS-PPP software.

The IGS-Final products are available 13 days after the last observation while EMU products are generated hourly and are available 90 minutes after the last observation. The accuracy of final products generated by a research centre or IGS is better than that of ultra-rapid or rapid products. The accuracy of the position obtained from PPP highly depends on the accuracy of the products used. In this study, in order to assess the effect of ultra-rapid and final precise orbit product on the estimates of high frequency vertical displacement obtained by PPP, the GNSS data was processed 13 days and two hours after completing the experiment.

CSRS-PPP provides geocentric Cartesian coordinates in the International Terrestrial Reference Frame (ITRF). The geocentric Cartesian coordinates cannot be directly used in structural health monitoring (SHM) applications (Yigit 2016), and therefore need to be transformed to a local topocentric Cartesian coordinate system, which is physically feasible in terms of the separation of position and height. Therefore, the point coordinates estimated from both the CSRS-PPP and LGO 3.0 software were converted from geocentric Cartesian to the local topocentric Cartesian system.

### Table 2. Processing options used by CSRS-PPP.

| Mode                        | Kinematic                |
|-----------------------------|--------------------------|
| GNSS type                   | GPS + GLONASS            |
| Observation processed       | Code&Phase               |
| Frequency observed          | L1, L2                   |
| Satellite orbits            | Precise (EMU and IGS-Final) |
| Satellite product input     | CLK-RINEX                |
| Ionospheric model           | L1&L2                    |
| Tropospheric models         | Davis (GPT) for hydrostatic delay |
|                            | Hopf (GPT) for wet delay |
|                            | GMF for mapping functions|
| Troposphere zenith delay (TZD) | Estimated                |
| Clock interpolation         | Yes                      |
| Parameter smoothing         | Yes                      |
| Reference frame             | ITRF                     |

The IGS-Final products are available 13 days after the last observation while EMU products are generated hourly and are available 90 minutes after the last observation. The accuracy of final products generated by a research centre or IGS is better than that of ultra-rapid or rapid products. The accuracy of the position obtained from PPP highly depends on the accuracy of the products used. In this study, in order to assess the effect of ultra-rapid and final precise orbit product on the estimates of high frequency vertical displacement obtained by PPP, the GNSS data was processed 13 days and two hours after completing the experiment.

CSRS-PPP provides geocentric Cartesian coordinates in the International Terrestrial Reference Frame (ITRF). The geocentric Cartesian coordinates cannot be directly used in structural health monitoring (SHM) applications (Yigit 2016), and therefore need to be transformed to a local topocentric Cartesian coordinate system, which is physically feasible in terms of the separation of position and height. Therefore, the point coordinates estimated from both the CSRS-PPP and LGO 3.0 software were converted from geocentric Cartesian to the local topocentric Cartesian system.
3. Experimental results and discussions

This section presents the results obtained from four cases generated by a free oscillation experiment based on three model structures. A number of experiments were carried out to obtain various oscillations with different frequencies, from approximately 0.94 to 2.90 Hz. The dynamic performance of the PPP method using IGS-Final and EMU products was compared with that of the relative GNSS method.

The oscillations were produced in the following way. The free end of the bar was pushed by hand from the equilibrium position by about 20–100 mm and then left to oscillate freely. This induces oscillation to the bar with a fundamental natural frequency. In order to obtain various oscillation characters with different frequencies, three bar model lengths, long, medium and short, were used. The rover GNSS receiver was attached first to the long bar, then to the medium bar and finally to the short bar. The transfer of the GNSS receiver from one bar to another was performed carefully not to cause any integer-cycle discontinuities in the carrier-phase data.

Figure 3 presents vertical coordinate changes in 13 free-decayed oscillation cases with respect to their mean values obtained from relative positioning and PPP. It can be clearly seen that relative positioning-derived displacement is very consistent whereas the PPP-derived displacement fluctuates over a long period. These fluctuations in the PPP-derived displacement are due to the positioning convergence process since longer time is needed to achieve a converged solution (Cai 2009). As mentioned earlier, in this study, GNSS observation was conducted over 60 minutes, of which the first 20 was motionless. Extending the observation time at which the bar is motionless can reduce the convergence period of PPP. However, since the main focus of the present study was on the dynamic vertical movement over a short time, i.e. 4–40 s, long-term fluctuation and position offset caused by convergence process was not considered important. Therefore, offsets and trends for each case were independently removed from relative and PPP-derived displacement time series in order to extract data on the dynamic movements of the bars.

In the present study, four cases indicated by a rectangle in Figure 3 were selected based on their oscillation characteristics, such as natural frequency and initial amplitude. Table 3 summarizes the properties of these cases.

Figure 3. Vertical displacements obtained from the relative method and the PPP method. The experiment lasted approximately 60 minutes, a portion of which was allocated to the observation of the long-term behaviour of both methods.
3.1. Long bar experiment (Case 1)

In Case 1, oscillation was generated using long bar. Figure 4 shows the time series of the relative GNSS and PPP-derived displacements and their FFT spectrums. The initial amplitude of oscillation was approximately 50 mm. The total length of the time history was 40 s. For the purpose of comparison, any offsets or linear trends were removed. Figure 4 (top plot) shows that there is low frequency fluctuation in PPP solutions compared to the relative solution. To remove these fluctuations, a five-order Butterworth high-pass filter with a cut-off frequency of 0.20 Hz was designed and applied to the two PPP-derived time series. In this way, the focus was placed on the fundamental frequency of oscillation in order to evaluate the three (two PPP and one relative method) solutions in terms of their ability to capture dynamic movement. Although the time series from the relative method did not have any low frequency fluctuation as in the PPP-derived time series, the same filter was applied to the relative time series with the same cut-off frequency to compare the results under the same conditions. As shown in Figure 4 (middle plot), PPP-derived displacement was in good agreement with that of the relative GNSS-derived displacement. In addition, the corresponding FFT spectrum results from the three solutions were in good agreement with each other, giving a peak frequency of 0.941 Hz with around 20 mm of amplitude. The FFT results were similar in terms of the ability to capture dynamic movement. In this study, the FFT method was employed to assess the frequency of oscillation in order to examine the data in the frequency domain. The PPP solutions and the relative solution were compared in terms of the peak frequency, representing the dominant Fourier frequency in the signal, and its average amplitude, indicating the strength of each frequency in the signal.

In addition, we performed a comparison on the solutions in the position domain. Figure 5 shows the histograms of differences between the relative positioning and PPP solutions. These differences were calculated for each case after removing the offset and linear trend and implementing a high-pass

![Figure 4. Displacement time series and FFT spectrum of the relative and PPP methods for Case 1.](image-url)
filter. For all four cases, the differences were generally in the range of −10 to 10 mm and followed a normal distribution. When PPP solutions based on IGS-Final and EMU and relative positioning were compared, no significant difference was observed.

3.2. Long bar experiment (Case 2)

To examine the effect of the change of the free span length on oscillation, Case 1 was modified by shortening the length of the long bar to yield a higher frequency oscillation (Case 2). Figure 6 shows the time series of the relative GNSS- and PPP-derived displacements and their FFT spectrums. The initial amplitude of oscillation was about 20 mm. The total length of the time history was 31 s. After the offset and linear trends were removed (Figure 6 – see top plot), a five-order Butterworth high-pass
filter with cut-off frequency of 0.20 Hz was designed and applied to the three time series as in Case 1. As shown in Figure 6 (middle plot), the PPP-derived displacement was consistent with that of the relative GNSS-derived displacement. The results of the corresponding FFT spectrums obtained from the three solutions were in good agreement with each other with the peak frequency being 1.529 Hz at the amplitude of approximately 10 mm. The FFT results were also similar in terms of the ability to capture dynamic movements.

### 3.3. Medium bar experiment (Case 3)

In Case 3, oscillation was generated using medium bar. The GNSS receiver was attached near the free end of the bar. Figure 7 presents the time series of the relative GNSS and PPP-derived displacements and their FFT spectrums. The initial amplitude of oscillation was approximately 20 mm. The total length of time history was 35 s. For the comparisons, the offset and linear trends were removed (top plot in Figure 5) and a five-order Butterworth high-pass filter with a cut-off frequency of 0.20 Hz was designed and applied to the three time series as in the previous cases. Figure 7 (see middle plot) shows that similar displacement was observed in both methods. In addition, the FFT spectrum results from the three solutions were in agreement. The peak frequency was found to be 1.980 Hz at the amplitude of approximately 7 mm. The FFT results were similar in terms of the ability to capture dynamic movements.

### 3.4. Short bar experiment (Case 4)

In Case 4, oscillation was generated using short bar. Figure 8 demonstrates the time series of the relative GNSS and PPP-derived displacements and their FFT spectrums. The initial amplitude of oscillation was approximately 80 mm. The total length of time history was 4 s. Only the offset and linear trends were removed (Figure 8 – see top plot) since the duration of Case 4 was very short. As shown in Figure 8 (middle plot), the PPP-derived displacement was in good agreement with that of the relative GNSS method. The FFT spectrum results obtained from all three solutions were similar in terms of the ability to capture dynamic movements, with the peak frequency being 2.903 Hz at the amplitude of approximately 36 mm.

![Figure 7. Displacement time series and FFT spectrum of the relative and PPP methods for Case 3.](image-url)
In contrast to other cases, the duration of Case 4 was very short because of the rapid decaying oscillation. Accordingly, the data evaluated in the FFT analysis were relatively limited, inevitably resulting in a reduced peak frequency resolution (Schaal and Larocca 2009). Although increasing the data-sampling rate would not affect the peak frequency resolution, this would significantly improve the data quality in the time domain. Thus, it is better to use a 50 or 100 Hz GNSS receiver for stiff structures with a high-frequency natural vibration.

4 Conclusions

The experiments based on model structures demonstrated an excellent agreement between the relative and PPP-derived spectrum after removing the offset and trends, and implementing a high-pass filter to remove the low frequency components of the PPP-derived time series. Similarly, the overall difference between PPP and relative positioning was generally below ±10 mm. These results indicate that the high-rate kinematic PPP method can capture the vertical natural frequency of engineering structures, such as the deck of long-span, medium-span and short-span bridges and highway viaducts, as well as the relative positioning method. Thus, stand-alone GNSS monitoring and the PPP method are potentially an ideal alternative to the relative positioning method in determining the natural frequencies of bridge structures and vibration-based health monitoring systems in cases where no reference GNSS data is available.

This study also showed that there is no significant difference between the IGS-Final and EMU-Ultra-Rapid products in terms of capturing dynamic oscillation. Therefore, the vertical natural frequency of flexible and stiff bridge structures induced by dynamic loads can currently be determined 90 minutes after the event occurred using a PPP method based on EMU-Ultra-Rapid product. The current study is based on post-processing of the data to allow a better understanding of the behaviour of the structure. Therefore, the performance of a real-time PPP method for real-time SHM needs to be tested in future work.

Acknowledgments

The authors would like to thanks Dr A. Anil Dindar for contribution.
Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Cemal Ozer Yigit http://orcid.org/0000-0002-1942-7667

References

Alkan RM, Öcalan T. 2013. Usability of the GPS precise point positioning technique in marine applications. J Navigation. 66:579–588. doi: 10.1017/S0373463313000210.

Avalone A, Marzario M, Cirella A, Pietanesi A, Rovelli A, Di Alessandro C, D’Anastasio E, D’Agostino N, Giuliani R, Mattone M. 2011. Very high rate (10 Hz) GPS seismology for moderate–magnitude earthquakes: the case of the Mw 6.3 L’Aquila (central Italy) event. J Geophys Res. 116:B02305. doi: 10.1029/2010JB007834.

Cai C. 2009. Precise point positioning using dual-frequency GPS and GLONASS measurement [master thesis]. Calgary: University of Calgary.

Chan WS, Xu YL, Ding XL, Xiong YL, Dai WJ. 2006. Assessment of dynamic measurement accuracy of GPS in three directions. J Surv Eng-ASCE. 132:108–117. doi: 10.1061/(ASCE)0733-9453(2006)132:3(108).

Chopra AK. 1995. Dynamics of structures: theory and applications to earthquake engineering. Englewood Cliffs (NJ): Prentice Hall.

Collins P, Henton J, Mireault Y, Héraux P, Schmidt M, Dragert H, Binsath S. 2009. Precise point positioning for real-time determination of co-seismic crustal motion. Proceeding of the 22nd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2009); 2009 Sept 22–25; Savannah (GA); p. 2479–2488.

Collins P, Binsath S, Lahaye F, Héraux P. 2010. Undifferenced GPS ambiguity resolution using the decoupled clock model and ambiguity datum fixing. Navigation. 57:123–135. doi: 10.1002/j.2161-4296.2010.tb01772.x.

Celebi M. 2000. GPS in dynamic monitoring of long-period structures. Soil Dyn Earthquake Eng. 20:477–483. doi: 10.1016/S0267-7261(00)00094-4.

El-Diasty, M. 2016. Development of real-time PPP-based GPS/INS integration system using IGS real-time service for hydrographic surveys. J Surv Eng. 142:1–8. doi: 10.1061/(ASCE)SU.1943-5428.0000150.

Erdoğan H, Akpinar B, Gülal E, Ata E. 2007. Monitoring the dynamic behaviors of the Bosporus Bridge by GPS during Eurasia Marathon. Nonlinear Proc Geophys. 14:513–523. doi: 10.5194/npg-14-513-2007.

Gao Y, Wojciechowski A, Chen K. 2005. Airborne kinematic positioning using precise point positioning methodology. Geomatica. 59:275–282.

Ge M, Gendt G, Rothacher M, Shi C, Liu J. 2008. Resolution of GPS carrier-phase ambiguities in precise point positioning (PPP) with daily observations. J Geod 82:389–399. doi: 10.1007/s00190-007-0187-4.

Geng J, Teléfer FN, Meng X, Dodson AH. 2010. Kinematic precise point positioning at remote marine platforms. GPS Solut. 14:343–350. doi: 10.1007/s10291-009-0157-9.

Héraux P, Kouba J, Beck N, Lahaye F, Mireault Y, Tétreault P, Collins P, MacLeod K, Caissy M. 2006. Space geodetic techniques and the CSRS evolution, status and possibilities. Geomatica. 60:137–150.

Kaloop M.R. (2010). Structural health monitoring through dynamic and geometric characteristics of bridges extracted from GPS measurements [PhD thesis]. China: Harbin Institute of Technology.

Kouba J, Héraux P. 2001. Precise point positioning using IGS orbit and clock products. GPS Solut. 5:12–28. doi: 10.1007/PL00012883.

Kouba J. 2003. Measuring seismic waves induced by large earthquakes with GPS. Stud Geophys Geod. 47:741–755. doi: 10.1023/A:1026390618355.

Laurichesse D, Mercier F, Berthias JP, Broca P, Cerri L. 2009. Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP and satellite precise orbit determination. Navigation. 56:135–149. doi: 10.1002/j.2161-4296.2009.tb01750.x.

Li X, Ge M, Zhang X, Zhang Y, Guo B, Wang R, Klotz J, Wickert J. 2013. Real-time high-rate co-seismic displacement from ambiguity-fixed precise point positioning: application to earthquake early warning. Geophys Res Lett. 40:295–300. doi: 10.1002/grl.50138.

Meng X, Dodson AH, Roberts GW. 2007. Detecting bridge dynamics with GPS and triaxial accelerometers. Eng Struct. 29:3178–3184. doi: 10.1016/j.engstruct.2007.03.012.

Meo M, Zumpano G, Meng X, Cosser E, Roberts G, Dodson A. 2006. Measurements of dynamic properties of a medium span suspension bridge by using the wavelet transforms. Mech Syst Signal Process. 20:1112–1133. doi: 10.1016/j.ymssp.2004.09.008.

Mireault Y, Tétreault P, Lahaye F, Héraux P, Kouba J. 2008. Online precise point positioning: a new, timely service from natural resources Canada. GPS World. 19:53–64.
Moschas F, Stiros S. 2011. Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer. Eng Struct. 33:10–17. doi: 10.1016/j.engstruct.2010.09.013.

Moschas F, Stiros SC. 2014. Three-dimensional dynamic deflections and natural frequencies of a stiff footbridge based on measurements of collocated sensors. Struct Control Health Monit. 21:23–42. doi: 10.1002/stc.1547

Moschas F, Avarlone A, Saltogianni V, Stiros SC. 2014. Strong motion displacement waveforms using 10-Hz precise point positioning GPS: an assessment based on free oscillation experiments. Earthquake Eng Struct Dyn. 43:1853–1866 doi: 10.1002/eqe.2426.

Nakamura S. 2000. GPS measurement of wind-induced suspension bridge girder displacements. J Struct Eng-ASCE. 126:1413–1419. doi: 10.1061/(ASCE)0733-9445(2000)126:12(1413).

Nickitopoulou A, Protosalti K, Stiros S. 2006. Monitoring dynamic and quasi-static deformations of large flexible engineering structures with GPS: accuracy, limitations, and promises. Eng Struct. 28:1471–1482. doi: 10.1016/j.engstruct.2006.02.001.

Psimoulis PA, Pytherouli S, Karambalis D, Stiros SC. 2008. Potential of global positioning system (GPS) to measure frequencies of oscillations of engineering structures. J Sound Vib. 318:606–623. doi: 10.1016/j.jsv.2008.04.036.

Psimoulis PA, Stiros SC. 2008. Experimental assessment of the accuracy of GPS and RTS for the determination of the parameters of oscillation of major structures. Computer-Aided Civil Infrastruct Eng. 23:389–403. doi: 10.1111/j.1467-8667.2008.00547.x.

Psimoulis PA, Stiros SC. 2013. Measuring deflections of a Shorth-Span railway bridge using a robotic total station. J Bridge Eng. 18:182–185 doi: 10.1061/(ASCE)BE.1943-5592.0000334.

Rizos C, Janssen V, Roberts C, Grinter T. 2012. GNSS: precise point positioning PPP versus DGNSS. Geomat World. Sept/Nov:18–20.

Roberts GW, Meng X, Dodson A. 2004. Integrating a global positioning system and accelerometers to monitor deflection of bridges. J Surv Eng. 130:65–72. doi: 10.1061/(ASCE)0733-9453(2004)130:2(65).

Schaal R, Larocca A. 2009. Measuring dynamic oscillations of a small span cable-stayed footbridge: case study using L1 GPS receivers. J Surv Eng. 135:33–37. doi: 10.1061/(ASCE)0733-9453(2009)135:1(33).

Tétreault P, Koubi J, Héroux P, Legree P. 2005. CSRS-PPP: an internet service for GPS user access to the Canadian spatial reference frame. Geomatica. 59:17–28.

Xu L, Guo JJ, Jiang JJ. 2002. Time-frequency analysis of a suspension bridge based on GPS. J Sound Vib. 254:105–116. doi: 10.1006/jsvi.2001.4087.

Xu P, Shi C, Fang R, Liu J, Niu X, Zhang Q, Yanagidani T. 2013. High-rate precise point positioning (PPP) to measure seismic wave motions: an experimental comparison of GPS PPP with inertial measurement units. J Geod. 87:361–372. doi: 10.1007/s00190-012-0606-z.

Yi T, Li H, Gu M. 2013. Experimental assessment of high-rate GPS receivers for deformation monitoring of bridge. Measurement. 46:420–432. doi: 10.1016/j.measurement.2012.07.018.

Yigit CO. 2016. Experimental assessment of post processed kinematic precise point positioning method for structural health monitoring. Geomat Nat Hazards Risk. 7:363–380. doi: 10.1080/19475705.2014.917724.

Yu J, Meng X, Shao X, Yan B, Yang L. 2014. Identification of dynamic displacements and modal frequencies of a medium-span suspension bridge using multimode GNSS processing. Eng Struct. 81:432–443. doi: 10.1016/j.engstruct.2014.10.010.

Zhang X, Andersen OB. 2006. Surface ice flow velocity and tide retrieval of the Amery ice shelf using precise point positioning. J Geod. 80:171–176. doi: 10.1007/s00190-006-0062-8.

Zumberge JF, Hefflin MB, Jefferson DC, Watkins MM, Webb FH. 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. J Geophys Res. 102:5005–5017. doi: 10.1029/96JB03860.