Structural Engineering and Mechanics, *Vol. 58, No. 6 (2016) 1077-1085*
DOI: http://dx.doi.org/10.12989/sem.2016.58.6.1077

Usability of inclinometers as a complementary measurement tool in structural monitoring

Hüseyin Pehlivan*[1] and Halim Ferit Bayata[2]

[1]Department of Geodesy and Photogrametry Engineering, Gebze Technical University, P.K : 141 41400, Kocaeli, Turkey
[2]Department of Civil Engineering, Erzincan University, P.K : 24 100, Erzincan, Turkey

(Received April 18, 2015, Revised February 15, 2016, Accepted April 1, 2016)

Abstract. In the last few years, many structural monitoring studies have been performed using different techniques to measure structures of different scales such as buildings, dams or bridges. One of the mostly used tools are GPS instruments, which have been utilized in various combinations with accelerometers and some other conventional sensors. In the current study, observation series were recorded for 8 hours with GPS receivers (NovAtel) and Inclination Measurement Sensors mounted on a television tower in Istanbul, Turkey. Each series of observations collected from two different sensors were transformed into a single coordinate system (Local Topocentric Coordinates System). The positional changes of the tower were calculated from the GPS and the inclination data. These changes were plotted in two dimensions (2D) on the same graphic. Thus, the possibility of comparison and analysis were found using the data from both the GPS and the Inclinometer complement each other, in the real test area. The positional changes of the tower were modeled for further examination. As a result, the movement of the tower within an area of 1×1 cm^2 was observed. Based on the results, it can be concluded that inclinometers can be used for monitoring the structural behavior of the tower.

Keywords: structural health monitoring; GPS; inclinometers; time series; measurement

1. Introduction

All structures are affected by natural events which can create oscillation. Therefore, continuous and accurate monitoring of the amplitude of this oscillation has a significant importance in terms of structural health and human safety. GPS Global Positioning System) technology is commonly used in the continuous monitoring of dynamic and static displacements of large engineering structures for two main reasons. First, this technology can measure such displacements at mm level and with high sensitivity. Second, GPS allows the measurement of relative displacements of structures with a data sampling rate up to 100 kHz. Therefore, the GPS technology is appropriate for monitoring structures with high-frequency vibration (short-period) since it utilizes using a real-time or post-measurement kinematic positioning method (Yi *et al*. 2010, 2012, 2013).

Over the past decade, the number of studies using GPS-based structural monitoring has

*Corresponding author, Ph.D., E-mail: hupehlivan@gmail.com

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

considerably increased due to the accuracy and reliability of this technology in measuring structural displacement. Some GPS-integrated studies have also used auxiliary measurement instruments. For example, Kijewski *et al*. (2003) employed a combination of a GPS receiver and an accelerometer and applied a low-pass filter to eliminate noise in their analysis. Similarly, Yoshida *et al*. (2003) evaluated the combined use of a GPS receiver and accelerometer in a steel tower.

Cazzaniga *et al*. (2005) used GPS and accelerometer in an industrial chimney, collected data simultaneously and performed a frequency analysis using DFT (Discrete Fourier Transform). Using the same technology, Hristopulos *et al*. (2006) conducted a spectral analysis on displacements in a high building. Li *et al*. (2006) used FFT (Fast Fourier Transform) to analyze the data obtained using GPS and an accelerometer in as steel tower and compared it with the finite element modeling. Casciati and Fuggini (2009) examined the measurement accuracy and reliability of dual-frequency GPS receivers.

With the improvement in the recording speed of GPS receivers, they have become more widely applicable in different types of structures. Monitoring studies have been performed to determine the vibration values of suspension bridges (Xu *et al*. 2002, Lekidis *et al*. 2005, Figurski *et al*. 2009, Yi *et al*. 2010, 2013, 2013) or the displacement values of industrial chimneys and television towers (Breuer *et al*. 2002, Yoshida *et al*. 2003, Breuer *et al*. 2008, Pehlivan *et al*. 2013).

The main problem in GPS applications is the monitoring and the elimination of measurements that are outside the range in the GPS data. In continuous structural monitoring, the measurement accuracy of GPS is based on many factors such as satellite coverage, atmospheric effects, multipath and the data-processing method (Chan *et al*. 2006). Therefore, many studies have suggested the employment of auxiliary measurement instruments in structural monitoring requiring high sensitivity. To increase the level of accuracy and eliminate some of the shortcomings of GPS, additional measurement instruments such as inclinometers, accelerometers and laser scanners are used without computer assistance (Erol 2010).

In previous work, a biaxial comparison of an inclinometer and GPS measurements were made and their performance was tested. In these studies, the measurements were performed instantaneously and simultaneously on the same object using two GPS receivers and two inclinometer sensors (Pehlivan *et al*. 2009, Pehlivan 2013, Pehlivan *et al*. 2013, Pehlivan *et al*. 2014). In the current study, the data obtained from the combined use of a GPS receiver and a Inclinometer were evaluated to determine the capacity and usability of these instruments in structural monitoring.

2. Test area and measurements

Test data were obtained from the Endem television tower in Istanbul, Turkey. The tower was built in 2008. It was built on a 190 m hill is made of concrete and steel and has a total height of 234 m from the foundation level of -14 m to 220 m peak. The cylindrical mass of the concrete thickness of the tower varies between 35 and 40 cm. This thickness decreases with the height of the tower. The steel framework extends to a height of 163 m, at which the diameter is 9.35 m.

In the current study, GPS receivers and Inclinometers were used to determine the displacement movement of the tower. The relative displacement was measured using three 24-channel, dual-frequency GPS receivers with the Real Time Kinematic GPS (RTK-GPS) method. Of these receivers, one was a fixed station and two were mobile antennas. The fixed GPS station was

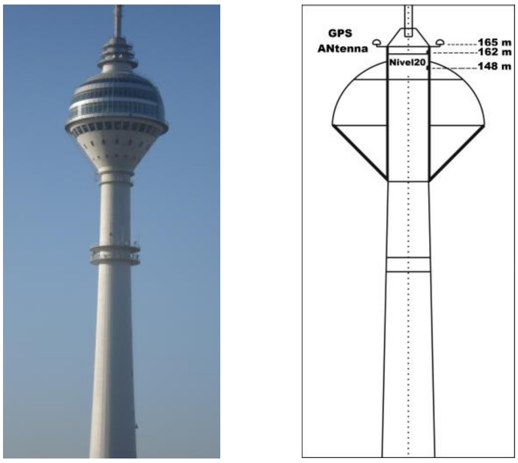

Fig. 1 The locations of GPS antennas and the Inclinometer sensors on the Endem television tower

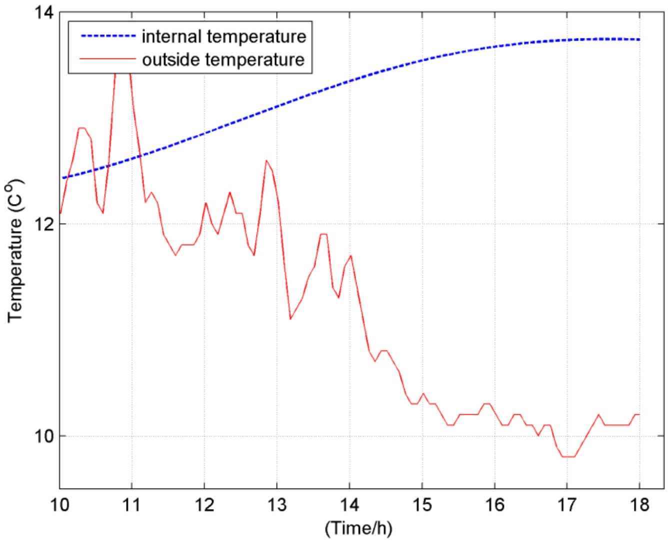

Fig. 2 The locations of GPS antennas and the Inclinometer sensors on the Endem television tower

erected near the tower about 100 m from the ground. The mobile (Rover) GPS antennas (R1 and R2) were positioned at the height of 165 m of the tower to obtain a clear view of the sky. The two Inclinometer sensors were vertically positioned at the heights of 162 m and 148 m. Fig. 1 schematically presents the installation locations of all GPS receivers and the Inclinometer sensor in relation to the tower.

2.1 GPS observations

GPS measurements was were carried out under normal weather conditions at an air temperature between 10 and 14℃ to monitor the displacements of the tower due to the changing temperature. Fig. 2 shows temperature changes during measurement for the internal and external environment.

Table 1 RTK GPS measurement parameters

Parameters	Value
Active number of satellites	Minimum: 6
Satellite height	Minimum: 10 degrees
Recording range	20 Hz
Recording date/time	November 25, 2007 8 hours 10:00 to 18.00
Vertical Dilution of Precision	0.9
Cut-off angle	20
Ionospheric models	0.5-2 ppm free model

GPS measurements of the parameters listed in Table 1 are from November 25, 2007.

Data recording was carried out on the GPSolution software (v 4.3.2.3) under relatively low influence of ionosphere and clear and windless weather conditions. Possible GPS errors related to atmosphere and satellite coverage were prevented using a double-differencing data-processing technique. However, other problems specific to the use of the RTK-GPS technique were experienced. Due to the fixed and mobile GPS antennas being close to the main body of the tower, reflected signals (multipath) caused errors in the results of the analysis. Furthermore, the number of satellites captured by the receivers was not sufficient. Therefore, prior to the evaluation process, there was a need to filter the results of analysis and records from observations (raw GPS data).

The data were filtered using Matlab (2013). Firstly, a series of observations were eliminated based on their overall errors being over the ±5 cm threshold. GPS sets were obtained by recording 20 data per second (sec). These datasets were then re-sampled at 1 sec intervals and their –10 and +10 point averages were calculated (Pehlivan *et al*. 2013).

The data obtained from both GPS receivers were obtained in the Earth-Centered, Earth-Fixed (ECEF) coordinate system and then manually converted to the local topocentric coordinates system for a more convenient evaluation.

2.2 Inclinometer observations

Inclination changes were recorded at 1 sec intervals using a Leica Nivel 20 electronic Inclinometer. The sensors were positioned at an elevation of 148 m and 162 m. The resolution of this inclinometer is 0.001 mrad (0.001 mm/m) and the accuracy of measurement is ±0.005μ mrad. Since Inclinometer sensors are extremely sensitive to changes in temperature, the measurements were performed by placing the sensors in a storage box.

Inclinometer changes were obtained in the mrad unit. As shown in previous research, after the fixed level at 108 m, the tower makes rotary movements (Pehlivan *et al*. 2013). Taking into account this nodal point, the arc unit (mrad) was converted into the length unit (mm). Since both Inclinometer sensors performed the measurement in mrad along two circles with the same center and radii of 40 m and 54 m, the conversion into length unit (mm) was carried out using the following equation

$$\text{Horizontal Distance (mm)} = \frac{\text{Arc(mrad)}}{1000}.\text{Radius(mm)} \tag{1}$$

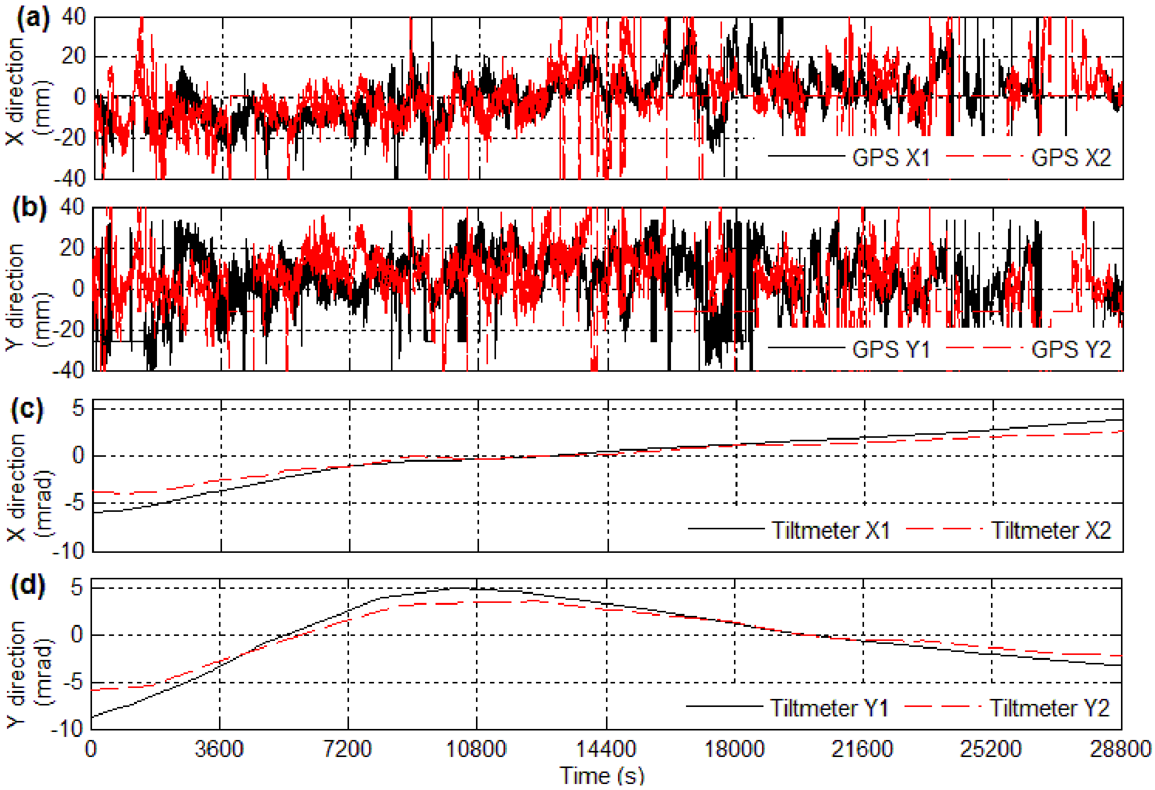

Fig. 3 The initial time series of GPS and Inclinometer sampled by 1 second, between 10:00 - 18:00; GPS series in the *X* direction (a), GPS series in the *Y* direction (b), Inclinometer series in the *X* direction (c) and Inclinometer series in the *Y* direction (d)

2.3 Analysis of the series

The series of observations were carried out simultaneously with GPS and Inclinometer receivers for 8 hours (between 10:00 - 18:00 on November 25, 2007) (Fig. 3).

A sequential processing technique was adopted to compare the original GPS and Inclinometer time series presented in Fig. 1. Firstly, GPS and Inclinometer time series were filtered and resampled at 1-second intervals. In addition, the time series of the Inclinometer were converted from the units of radians to into the units of length. The coordinates in all datasets were then transformed to the local topocentric system. The arranged time series from both receivers were analyzed in terms of the frequency, and the frequency spectrums were calculated.

Frequencies were computed using the Fast Fourier Transformation algorithm after applying low-pass filtering to the whole series of observations. All signals were remodelled in the time domain using the dominant frequency values with the Fourier equality. These new signals were considered to be model signals of our sensor observations. GPS and Inclinometer measurements and the calculated model functions are presented in Fig. 4. As shown in the figure, random oscillations of high frequency components were at ± 20 mm levels in the GPS time series and at ± 10 mm levels in the Inclinometer time series.

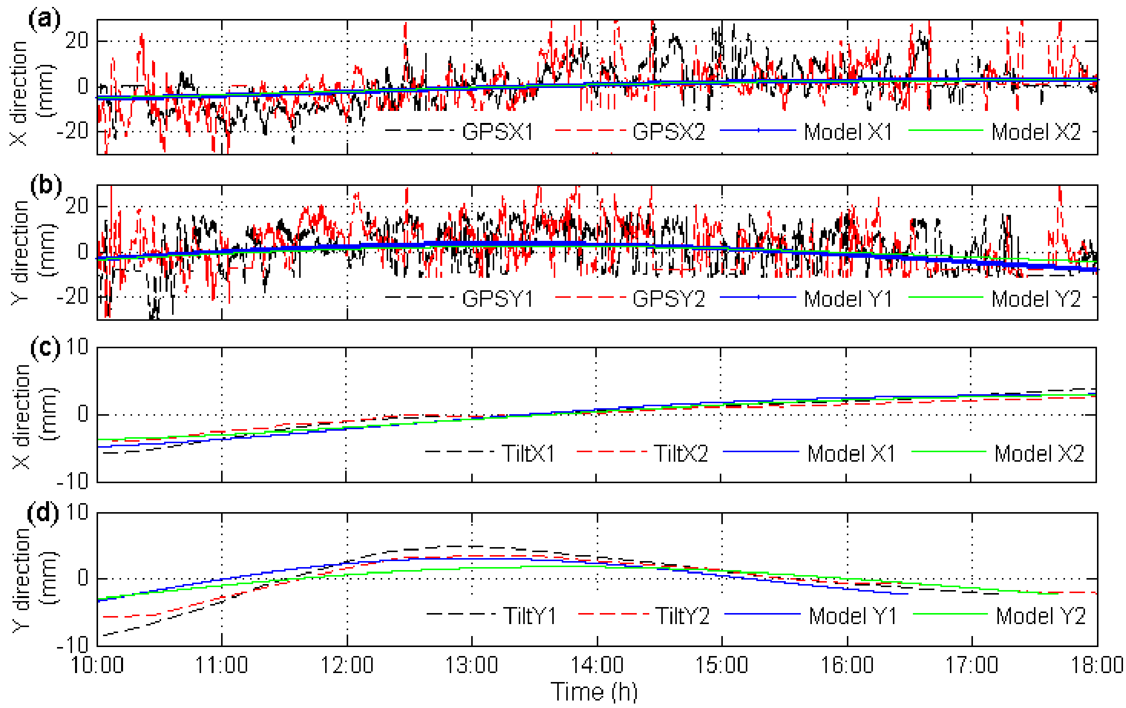

Fig. 4 Model functions of GPS and Inclinometer time series between 10:00 - 18:00; GPS *X* series and modal signals in the *X* direction (a), GPS *Y* series and modal signals in the *Y* direction (b), Inclinometer *X* series and modal signals in the *X* direction (c), Inclinometer *Y* series and modal signals in the *Y* direction (d)

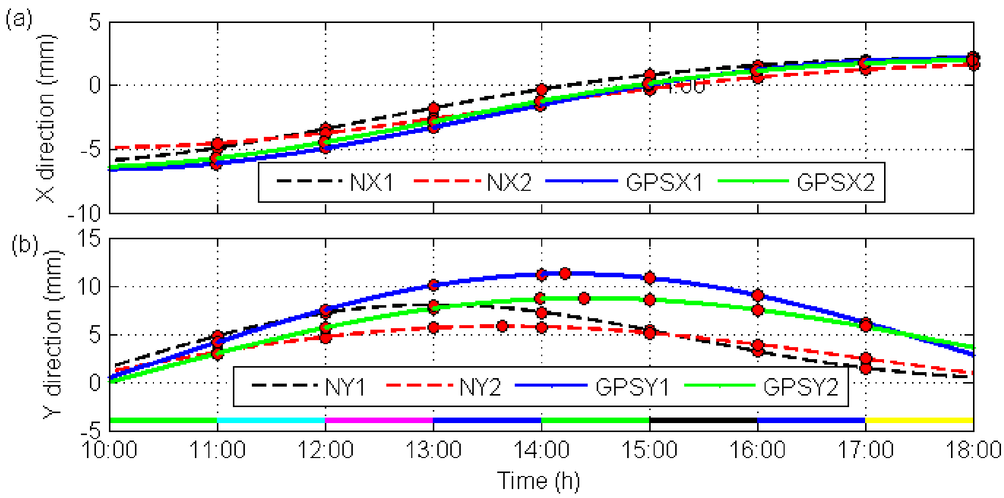

Fig. 5 Model series computed using GPS and Inclinometer data

3. Comparisons and evaluation

The calculated model series are based on the 8-hour movement of the tower. The *X*- and *Y*-

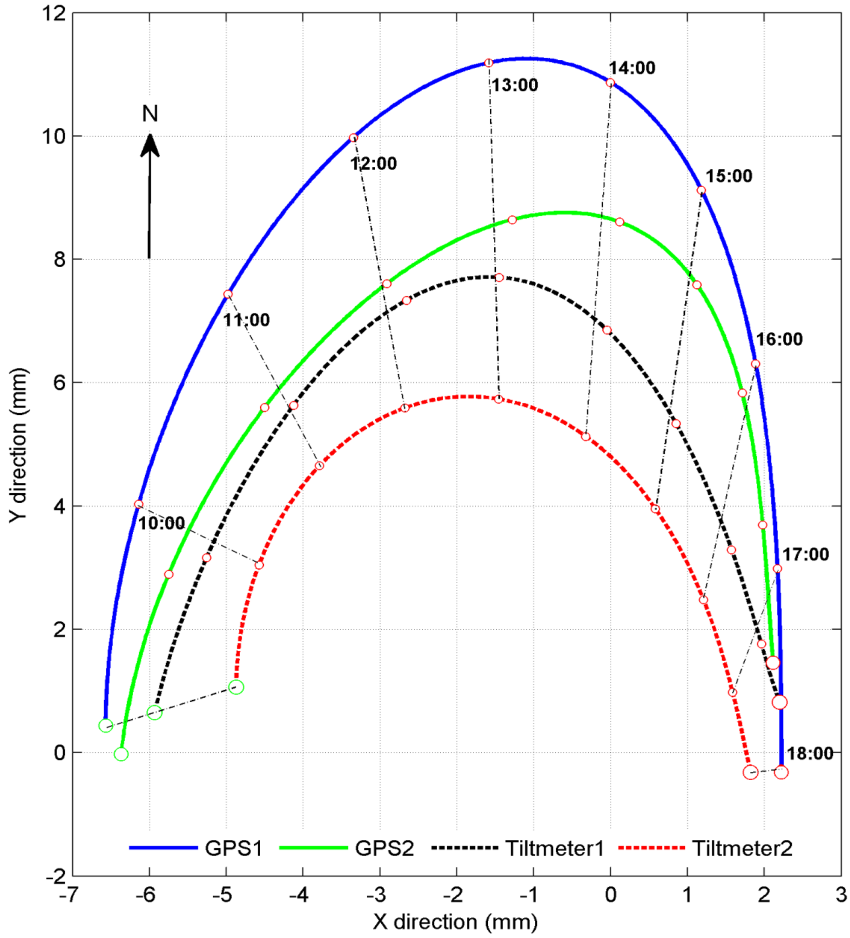

Fig. 6 The ground sketch of horizontal displacements between 10:00 - 18:00

direction series computed using the GPS and Inclinometer data are presented in Fig. 5. It can be seen that the results from the two GPS series and two Inclinometer model series match each other.

These computed model series provide precise information as to how the tower moved over the 8 hours. The model series in the *X*-*Y* plane in Fig. 5 provides a model for the positional changes of each receiver and Fig. 6 presents a model for the positional changes of the tower. Here, we observe that the movement of the tower (in cm) depends on the movement of the sun. The tower started to move to the east at 11:00 subsequent to an increase in temperature. The body of the tower started to cool after 12:00 and 13:00 when the heat of the sun was at the maximum level, and moved back to its previous position between 14:00 and 15:00.

4. Conclusions

In this study, the data obtained simultaneously from GPS and Inclinometer receivers were used in the structural monitoring of a television tower. GPS observations have previously been reported to result in errors due to multipath and satellite geometry. Therefore, Inclinometer sensors were chosen to perform a comparative evaluation of the data. Mounting GPS receivers on the opposite sides of the tower allowed for obtaining data from different satellite geometries and resulting in different multipath errors. Inclinometer receivers were positioned in the same direction but at different heights, which ensured that the data obtained from all receivers complemented each other. The analysis of the 8-hour data demonstrated that random oscillations of high-frequency components were at ±10 mm levels in the GPS time series and at 7 mm levels in the Inclinometer time series (Fig. 5). GPS and inclinometer series were processed and converted into the same coordinate system and presented in an *X*-*Y* axis. Fig. 6 presents the positional changes of the tower within an area of approximately 1 cm^2 as measured by the GPS and inclinometer receivers. The comparison of the results indicate that inclinometer which is commonly used as an auxiliary measurement tool complements the GPS and can be employed as a testing instrument. Furthermore, the accuracy and performance of the inclinometer are sufficient in terms of determining dynamic structural movements at mm level in continuous structural monitoring. However, with a inclinometer, it is not possible to determine the static and semi-static components of the movement nor the positional changes in the *Z*-axis. GPS can be used to determine such static, quasi-static and dynamic structural behaviors.

References

Breuer, P., Chmielewski, T., Gorski, P. and Konopka, E. (2002), "Application of GPS technology to measurements of displacements of high-rise structures due to weak winds", *J. Wind Eng. Ind. Aerodyn*., **90**, 223-230.

Breuer, P., Chmielewski, T., Gorski, P., Konopka, E. and Tarczynski, L. (2008), "The stuttgart TV tower displacement of the top caused by the effects of sum and wind", *Eng. Struct*., **30**(10), 2771-81.

Casciati, F. and Fuggini, C. (2009), "Engineering vibration monitoring by GPS: long duration records", *Earthq. Eng. Eng. Vib*., **8**(3), 459-67.

Cazzaniga, N.E., Pinto, L., Forlani, G. and Abruzzi, P. (2005), "Monitoring oscillations of slender structures with GPS and accelerometers", *New Measurement Technology and Its Application to Archaeological and Engineering Surveys*, FIG Working Week 2005 and GSDI-8, Cairo, Egypt, April.

Chan, W.S., Xu, Y.L., Ding, X.L. and Dai, W.J. (2006), "An integrated GPS-accelerometer data processing technique for structural deformation monitoring", *J. Geodesy*, **80**, 705-719.

Erol, B. (2010), "Evaluation of high-precision sensors in structural monitoring", *Sensors*, **10**, 10803-10827

Figurski, M., Galuszkiewicz, M. and Wrona, M. (2009), "An investigation of using high rate GNSS data in structural monitoring process", ANNO LXVIII - Bollettino Di Geodesia e Scienze Affini N. 1.

Hristopulos, D.T., Mertikas, S.P., Arhontakis, I. and Brownjohn, J.M.W. (2006), "Using GPS for monitoring tall-building response to wind loading: filtering of abrupt changes and low-frequency noise, variography and spectral analysis of displacements", GPS Solutions, Springer.

Kijewsji-Correa, T.L. and Kareem, A. (2003), "The Chicago monitoring project: a fusion of information technologies and advanced sensing for civil infrastructures", *Proceedings of 1th International Conference on Structural Health Monitoring and Intelligent Infrastructure*, Tokyo, November.

Lekidis, V., Tsakiria, M., Makrab, K., Karakostasb, C., Klimisb, N. and Sous, I. (2005), "Evaluation of dynamic response and local soil effects of the Evripos Cablestayed Bridge using multi-sensor monitoring systems", *Eng. Geology*, **79**, 43-59.

Li, X., Ge, L., Ambikairajah, E., Rizos, C., Tamura, Y. and Yoshida, A. (2006), "Full-scale structural monitoring using an integrated GPS and accelerometer system", *GPS Solutions*, **10**, 233-247.

Pehlivan, H. (2009), "The investigation of dynamic behaviors in structures with real-time Kinematic GPS", PhD Thesis, Yildiz Technical University, Istanbul, Turkiye.

Pehlivan, H. (2013), "Spectral analysis of real-time Kinematic GPS data, harita dergisi, 2013/149", Harita Genel Komutanlığı, Ankara, Turkiye.

Pehlivan, H. and Bayata, H.F. (2014), "Comparison of GPS and inclinometer data in structural monitoring", *Proceedings of the First International Conference on Engineering and Applied Sciences Optimization (OPT-i)*, the Island of Kos, Greece, June.

Pehlivan, H., Aydın, Ö., Gülal, E. and Bilgili, E. (2013), "Determining the behavior of high-rise structures with geodetic hybrid sensors", *Geomatic Nat. Hazard. Risk*., **6**(8), 702-717.

Xu, L., Guo, J. and Jiang, J.J. (2002), "Time frequency analysis of a suspension bridge based on GPS", *J. Sound Vib.*, **254**(1), 105-116.

Yi, T., Li, H. and Gu, M. (2010), "Recent research and applications of GPS based technology for bridge health monitoring", *Sci. China: Tech. Sci.*, **53**(10), 2597-2610.

Yi, T.H., Li, H. and Gu, M. (2013), "Wavelet based multi-step filtering method for bridge health monitoring using GPS and accelerometer", *Smart Struct. Syst.*, **11**(4), 331-348.

Yi, T.H., Li, H.N. and Gu, M. (2011), "Characterization and extraction of global positioning system multipath signals using improved particle filtering algorithm", *Measur. Sci. Tech*., **22**(7), 075101..

Yi, T.H., Li, H.N. and Gu, M. (2012), "Effect of different construction materials on propagation of GPS monitoring signals", *Measurement*, **45**(5), 1126-1139.

Yi, T.H., Li, H.N. and Gu, M. (2012), "Recent research and applications of GPS-based monitoring technology for high-rise structures", *Struct. Control Hlth. Monit*., **20**(5), 649-670.

Yi, T.H., Li, H.N. and Gu, M. (2013), "Experimental assessment of high-rate GPS receivers for deformation monitoring of bridge", *Measurement*, **46**(1), 420-432.

Yoshida, A., Tamura, Y., Matsui, M. and Ishibashi, S. (2003), "Integrity monitoring of buildings by hybrid use of RTK-GPS and FEM analysis", *Proceedings of the 1st International Conference on Structural Health Monitoring and Intelligent Infrastructure*, November, Tokyo

CC