# EXPERIMENTAL MONITORING OF OSCILLATIONS OF MAJOR FLEXIBLE STRUCTURES USING GPS AND RTS

*Panos A. Psimoulis, Stella Pytharouli, Panayiotis Triantafyllidis and Stathis Stiros*
*Geodesy Laboratory, Dept. of Civil Engineering*
*Patras University*
*Email:ppsimo@upatras.gr; spytha@upatras.gr; ptriant@upatras.gr; stiros@upatras.gr*

**Abstract:** In order to assess the performance of Robotic theodolite (RTS) and of GPS for monitoring semi-static and dynamic displacements of major flexible structures, experiments were made using an oscillation system producing computer-controlled oscillations. A GPS antenna and a reflector were mounted on the oscillating device, the movement of which was recorded by RTS and GPS recording at a rate of 10 Hz. Experiments were limited to linear, sinusoidal oscillations at the range of 0.05-4Hz and 1-6cm. Spectral and statistical techniques were used for the estimation of the GPS and RTS accuracy, which was based on the comparison of the pre-determined (real) and the GPS/RTS defined oscillation amplitude and dominant frequencies. Our analysis revealed that: a) for common flexible structures (natural frequencies <1Hz) GPS can accurate record oscillation amplitudes in the range ±1.0-1.5cm, while b) for more rigid structures (natural frequencies >1Hz) accurate results can be obtained only for oscillation amplitude over far ≥|2|cm, c) ignoring amplitudes, GPS can define accurately the dominant oscillation frequency up to 4 Hz and d) RTS was found that can accurately record oscillation amplitude of ±0.5cm and define accurately oscillation frequencies up to 1Hz. At higher frequencies a number of observations are lost causing a reduction in the accuracy of results.

## 1. Introduction

Until recently monitoring of oscillation of flexible structures was mainly based on accelerometers, and their displacements were calculated through double-integration of the accelerations records. Due to the law of error propagation small errors in the time or the acceleration can produce great errors in the calculated displacements. In particular for acceleration records >30sec the calculated distance may differ even several decimeters or meter from the real value (Wang et al., 2002; fig.1). Another disadvantage is that the accelerometers cannot detect semi-static displacement or oscillations of very low frequencies which are observed mainly in flexible structures (i.e. skyscrapers) as a result of wind forces or temperature (Tamura et al, 2002; Nickitopoulou et al., 2006).

In the last ten years there has been a growing interest to accurately monitor the oscillation of various flexible structures (suspension bridges, TV towers, musts, etc.) and to specify their oscillations characteristics (amplitudes and frequencies), using GPS (Roberts et al., 2004). Though GPS has been main tool for the monitoring of such structures, for instance the Tsing Ma Bridge in Hong-Kong (Wong et al., 2002), there are only very few studies which assess

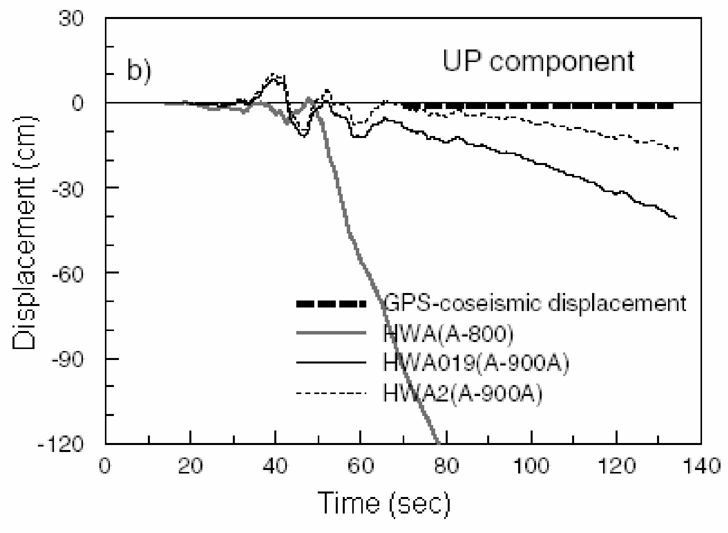

Figure 1: Ambiguities in estimation of displacements after a double integration of three different acceleration records. Comparing the acceleration displacements with the GPS displacements record (black solid line) is obvious that the accelerometer deduced displacements are noisy (Wang et al., 2002).

the precision and limitation of GPS in structure monitoring (Tamura et al., 2002; Nickitopoulou, 2006).

Recently robotic theodolite (RTS) have also been used for monitoring of static or semi-static displacements of flexible engineering structures. This is because RTS is characterized by a high frequency recording (up to 10 Hz) and a capability of following moving targets and recording its continuously changing coordinates. Till now, however, we are aware of only one study reporting comparison of dynamic characteristics of a bridge based on GPS, RTS and accelerometers (Lekidis et al., 2005) and none experimental attempt in order to assess the performance of RTS for monitoring of dynamic displacements.

In this study, based on experiments of computer-controlled oscillations, we tried to assess the performance and the limitations of GPS and RTS in monitoring oscillations of flexible structures

## 2. Description of the experiments

Our experiments were based on (fig.2):

- an experimental device which produced computed-controlled oscillations
- a pair of GPS station consisting of an antenna (JPS Legent-H) and dual frequency receivers (JPS Legent-E) with recording frequency up to 20 Hz
- a RTS (Leica TCA 1201) with recording frequency up to 10 Hz and a reflector (AGA).

The main parts of the experimental device were: an oscillator, a PC used to define the oscillations characteristics (frequency, amplitude etc.), a controller converting digital signal into analogic and transferring it to the oscillator. The last consisted of a servo-motor which generated linear oscillations of a wagon sliding on a linear rail. So, for each experiment the PC-adjusted oscillation characteristics, were transferred to the servo-motor which finally excited the wagon.

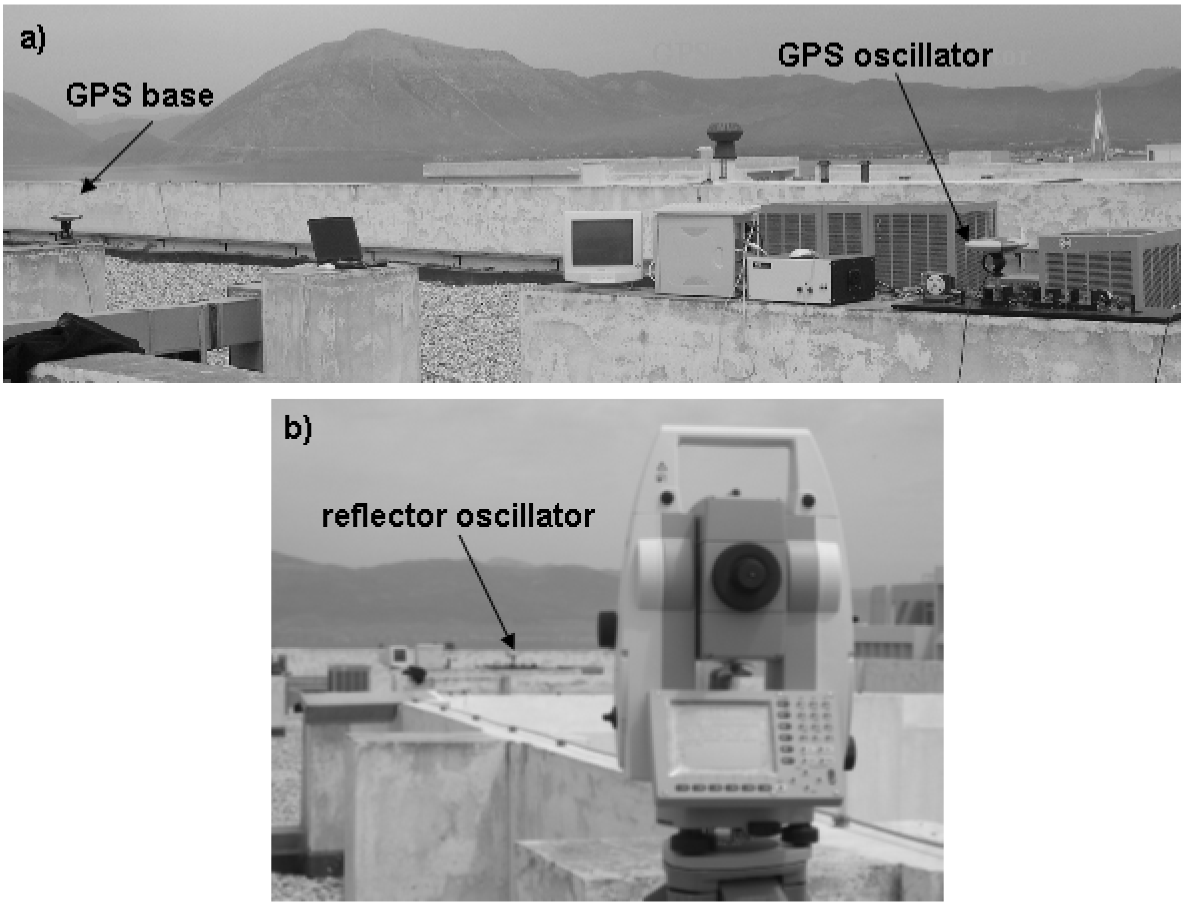

Figure 2: a) The experiment architecture of the oscillation device and the two GPS systems. One GPS is set on stable base and the other GPS is placed on the oscillator, on top of the reflector. b) RTS is set on a tripod monitoring the reflector movement.

On top of the oscillating wagon were mounted the RTS reflector and the GPS antenna connected with the rover receiver (fig. 2a). The RTS, recording the movement of the wagon, and a second GPS base receiver were fixed on stable ground (fig. 2b). A large number of experiments for various conditions of frequency and linear oscillation amplitude were made, and the measurements of GPS and RTS records were converted in a new common coordinate system, where the x-axis coincided with the oscillation axis and the y-axis was perpendicular to it. These experiments therefore could determine the accuracy of the recordings, since movements along the x-axis were known, and apparent movement along the y and the z axis reflected measurement noise.

## 3. Problems during the experiments

During the processing of the GPS and RTS records, two main problems were faced. First, gaps in GPS records lasting up to 10 sec which were present even when the oscillator was not moving. The duration and the frequency of the data gaps in the GPS timeseries correlated with the length of the cable connecting the antenna with the receiver and the recording frequency; for 10 Hz recording frequency fewer gaps were present than for 20 Hz. Hence, when using the shortest available cable and 10 Hz recording frequency, data gaps were minimized and in many cases eliminated (fig. 3). On the other hand, for RTS timeseries, the preset recording frequency did not match the real recording frequency. For instance while nominal recording frequency was 10 Hz, the real frequency was approximately 7 Hz.

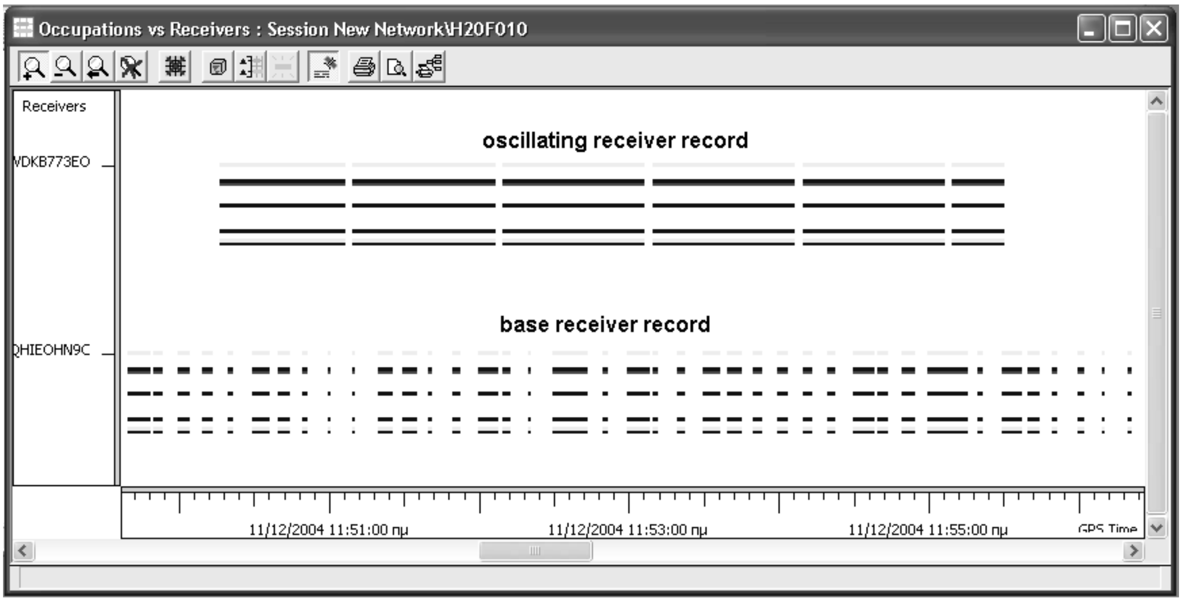

Figure 3: Data gaps of GPS records. It is obvious that the gaps in the record of the base receiver (a 30m cable length was used) are more and last longer than the gaps of the oscillator receiver (a 2 m cable length was used)

## 4. Timeseries analysis

The first step of the analysis was the recognition of gross errors. Gross errors indeed were found only in the GPS records. Most of these errors corresponded to the first measurements recorded just after data gaps, and probably reflected integer resolution ambiguities (fig. 4). All RTS records, on other hand, were found free of gross errors in all experiments.

The next step was to assess the accuracy of the GPS/RTS measurements examining:

- the oscillation amplitude and
- the oscillation frequency.

The amplitude of the oscillation during each experiment computed using GPS and RTS records was compared with the real amplitude (fig. 5, 6) deduced also by independent optical observations.

On the other hand, the dominant frequency in the GPS and RTS records deduced from spectrum analysis was compared with the real preset values. For the spectrum analysis the most known technique is the FFT, which was used for GPS timeseries free of gaps (fig.6). For the GPS timeseries with data gaps more sophisticated spectrum techniques were used, because FFT technique can analyse only equidistant data. More specifically, were used the "Norm-Period" code based on the Lomb periodogram (Pytharouli et al., 2005). As for the RTS record, we supposed that the data were equidistant, and spectrum analysis was based on the FFT technique (fig.7).

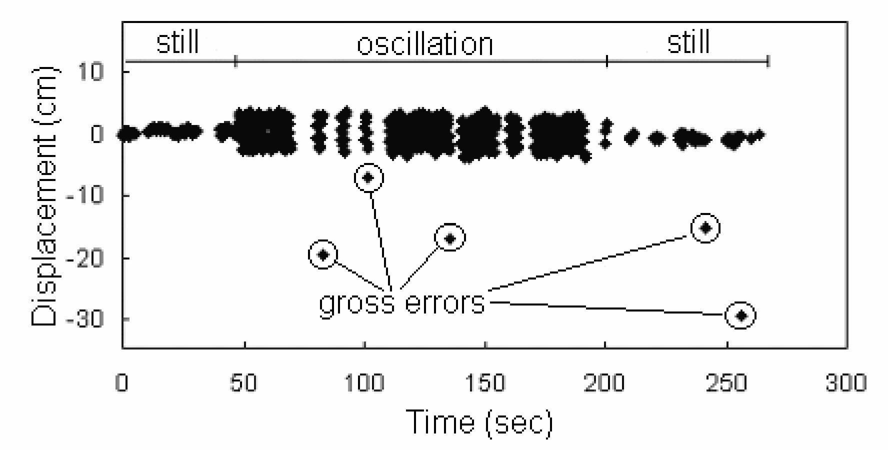

Figure 4: An example of gross errors in GPS records, usually occurring after gaps in records.

## 5. Discussion and conclusions

From the timeseries analysis it was revealed that RTS can estimate precisely the oscillation amplitude up to ±0.5cm. As for GPS, it can estimate precisely oscillation with amplitude up to ±2cm when the oscillation frequency is greater than 1Hz. For smaller oscillation frequencies (≤1 Hz), GPS can accurately estimate oscillation amplitude up to ±1cm.

Ignoring amplitude; GPS can accurately define all the oscillation frequencies examined (≤4 Hz). Even for timeseries characterized by data gaps; in this case the "Norm-Period" code was used. On the other hand, RTS can define accurately frequency for oscillation frequencies up to 1 Hz. For greater oscillation frequencies (for instance 2 Hz) there is error in frequency oscillation of about 10 %, due to the assumption that the RTS data are equidistant.

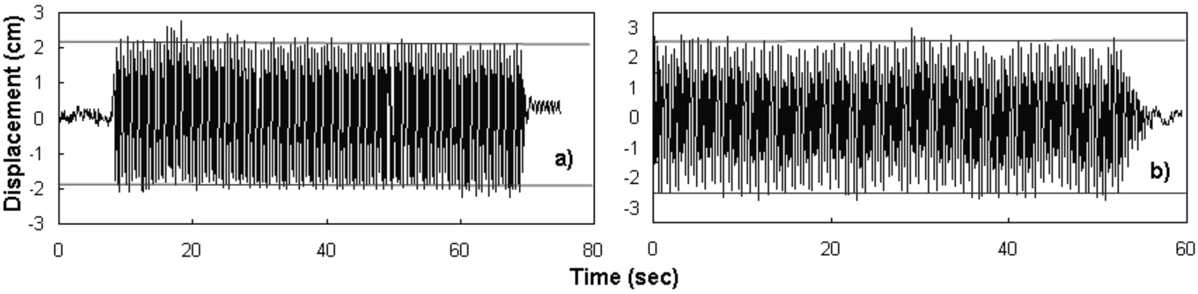

Figure 5: GPS timeseries for amplitude and frequency oscillation a) 4cm and 2Hz and b) 5cm and 3Hz. Solid lines indicate the real oscillation amplitude.

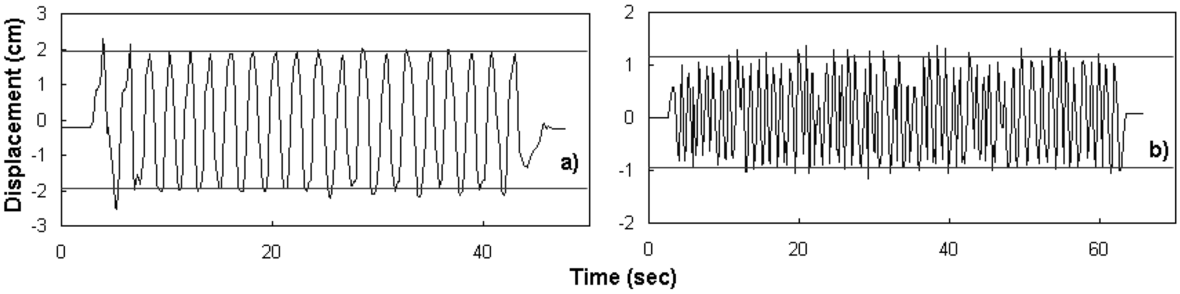

Figure 6: GPS timeseries for amplitude and frequency oscillation a) 4cm and 0.5Hz and b) 2cm and 1.5Hz. Solid lines indicate the real oscillation amplitude.

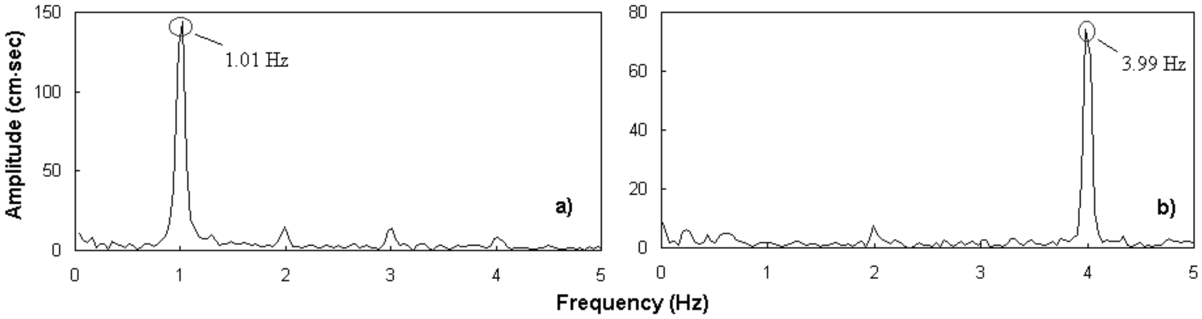

Figure 6: FFT analysis of GPS timeseries of oscillation frequency a) 1 Hz and b) 4Hz.

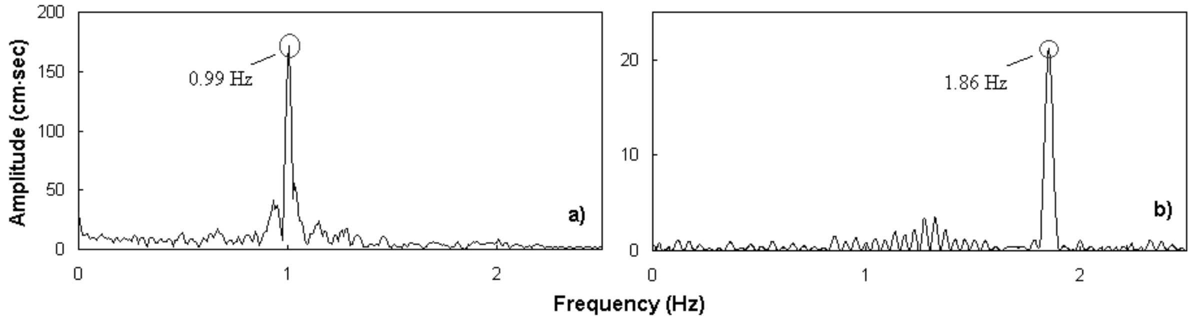

Figure 6: FFT analysis of RTS timeseries of oscillation frequencies a)1Hz and b)2Hz.

So, based on our experiments we can conclude that:

- GPS can estimate accurately oscillation amplitude of ±2cm for high frequencies( up to 4 Hz) and even ±1cm for low frequencies (≤1 Hz), which are mostly the oscillation frequencies of the flexible structures. For high oscillation frequency up to 4 Hz the oscillation frequency can be accurately defined.

- RTS can estimate accurately oscillation amplitude up to ±0.5cm, regardless of the oscillation frequency. For the oscillation frequency definition, due to the problem of the recording frequency and based on our assumption, RTS can define accurately up to 1 Hz oscillation frequency. By using more sophisticated software probably the recording frequency problem will not come up and the oscillation frequency definition will be accurate.

## 6. References

[1] Wang, G.Q., Boore, D., Igel, H., and Zhou, X.Y.: Some observations on collocated and closely spaced strong ground-motion records of the 1999 Chi-Chi, Taiwan, Earthquake, Bulletin of the Seismological Society of America, Vol. 93, N. 2, pp. 674-693, 2003.

[2] Tamura, Y., Matsui, M., Pagnini, L.C., Ishibashi,R and Yoshida A.: Measurement of wind-induced response of buildings using RTK-GPS, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 92, pp. 1783-1793, 2002.

[3] Nickitopoulou, A., Protopsalti, K. and S. Stiros: Monitoring dynamic and quasi-static deformations of large flexible engineering structures with GPS: accuracy, limitations and promises, Engineering Strucure, (in press), 2006.

[4] Roberts, G., Meng, X. and Dodson, A.: Integrating a Gobal Positionig System and accelerometers to monitor deflection of bridges, Journal of Surveying Engineering, May 2004, pp. 65-72, 2004.

[5] Wong, K.Y., Man, K.L., Chan, W.Y.: Monitoring Hong Kong's Brigdes Real-Time Kinematic Spans Gap, GPS World, July 2001, p.10-18, 2001

[6] Lekidis, V., Tsakiri, M., Makra, K., Karakostas, C., Klimis, N., Sous, I.: Evaluation of dynamic response and local soil effects of the Evripos cable-stayed bridge using multi-sensor monitoring systems, Engineering Geology, Special Volume in Applications of Geodetic Techniques in Engineering Geology (eds. S.Stiros-A.Chrzanowski), Vol. 79, pp. 43-59, 2005.

[7] Pytharouli S. and Stiros S.: Spectral analysis of unevenly spaced or discontinuous data using the “Normperiod” code, Computers and Structures, (submitted).