Determination of Dynamic Displacements of the Roof of Sports Hall Arena Zagreb

Marendić, A.[1], Paar, R.[1], Duvnjak, I.[2] and Buterin, A.[1]

[1]University of Zagreb, Faculty of Geodesy, Kačićeva 26, HR-10000 Zagreb, Croatia, www.geof.unizg.hr, E-mail: amarendic@geof.hr, rpaar@geof.hr, anbuterin@geof.hr
[2]University of Zagreb, Faculty of Civil Engineering, Kačićeva 26, HR-10000 Zagreb, Croatia Web site:, www.grad.unizg.hr, E-mail:, iduvnjak@grad.hr

Abstract

Determination of construction displacements and deformations are an important parameter in assessing the condition and safety of the construction in its exploitation. Also, we get confirmation whether a structure is consistent with project solutions. Constant development of surveying instruments enables to deal with more complex and demanding tasks that are facing engineering geodesy. Surveying instruments can measure, not only static and very slow displacements of the constructions, but also and faster (dynamic) displacements.

In this paper, the possibilities of geodetic measuring instruments to determine the dynamic response of structures in exploitation, is presented. The instruments (GPS and Robotic total station) were used to measure dynamic response of main cable at the roof of the sports hall "Arena Zagreb" during an artificially induced excitation. Frequencies of main cable determined by GPS and robotic total station were compared to the frequencies determined by the accelerometer. The analysis and the results of comparison are presented in this paper.

Key words: Robotic total station, GPS, dynamic displacements of the structures

1 INTRODUCTION

By measuring the displacement of the structures during its exploitation we get confirmation whether a structure is consistent with project solutions. The results of measurements represent an important parameter in assessing the condition and safety of the structure.

Today's GNSS instruments can determine 3D coordinates of the moving point with 10 to 100 measurements per second and robotic total stations can perform up to 20 measurements per second. Thereby, the application of GNSS instruments and robotic total station (RTS) is no longer limited for monitoring static and very slow displacements of the structures, but also for faster (dynamic) displacements.

GNSS instruments with recording frequency 10-20 Hz are mainly used for monitoring the dynamic displacements of the constructions (Roberts et al 2004, Li 2004, Ogaja et al 2007). RTS has not been very often used in these projects due to their insufficient recording frequency. The newer models of RTS can precisely measure the position of the moving point (reflector) with recording frequency up to 20 Hz (Stempfhuber 2009). That should provide its wider use in these projects. Nevertheless, till now, only a few testing of RTS (with recording frequency 5-7 Hz) for measure simulated dynamic displacements of structures has been done (Gikas et al. 2006, Psimoulis and Stiros 2007, Gikas and Daskalakis 2008, Psimoulis et al. 2008). More researches were focused on determining the static displacement of structures (Kovačič and Kapović, 2005) and kinematic possibilities of RTS in which the reflectors were moving toward a predetermined trajectories at different velocities (Radovanovic et al. 2001, Kopačik et al. 2005, Kirschner and Stempfhuber 2008, Stempfhuber 2009).

All mentioned indicates the need for more detailed analysis of existing instruments and more detailed analysis of their achievable accuracy for measuring the dynamic displacement of structures. The possibilities of GNSS instrument (with recording frequency up to 20 Hz) and RTS instrument (with recording frequency up to 12 Hz) for determine the dynamic response of structures characterized by higher frequencies and smaller oscillation amplitudes, has been analyzed in this paper. The analysis and the results of measuring simulated dynamic displacements in the established test field and the results of measuring the dynamic response of a main cable at the roof of the sports hall "Arena Zagreb" are presented too.

2 INSTRUMENTATION AND EXPERIMENT PROCEDURE

In this study, surveying instruments were measuring position of the point that performs harmonic motion with a predetermined amplitudes and frequencies of oscillation in vertical plane.

Two instruments were tested:

- Robotic total station (Leica TCRP 1201) with recording frequency up to 10 Hz,
- GNSS device (Topcon Hiper Pro) with recording frequency up to 20 Hz.

By RTS it wasn't possible to record 10 measurements per second. Number of recorded data was 5-7 per second, with irregular time intervals between individual records. In order to increase the number of recorded measurements, Visual Basic (VB) application that relies on GEOCOM protocol, has been developed. The VB application controls the RTS measuring process via laptop and enables to record 12 to 13 measurements per second. By that, it is possible to determine the higher oscillation frequencies with the same instrument. Before any practical use of the VB application, it was necessary to examine whether the collection of a larger number of measurements will affect the accuracy of measurements.

Testing of the instruments has been done on the test field on calibration baseline of the Faculty of Geodesy, University of Zagreb. Electrodynamics oscillator was used to simulate the displacements of structures incurred due to the effects of dynamic excitation (Fig. 1).

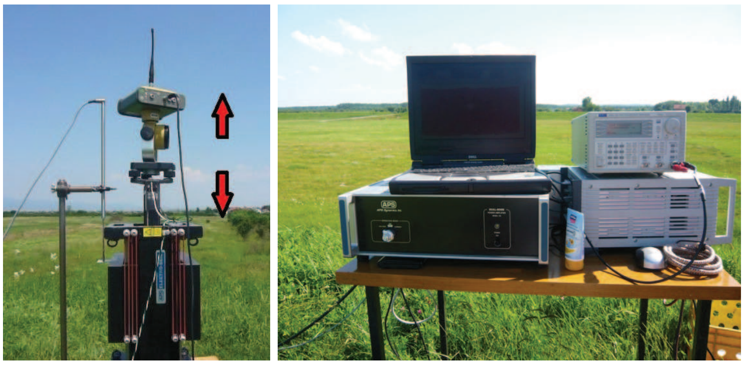

Figure 1 Electrodynamic oscilator with mounted circular prism and GNSS (a), frequency generator with amplifier (b)

GNSS base receiver and RTS were set up at a distance nearly 100 m away from the electrodynamic oscillator. GNSS rover and circular prism were mounted on the moving arm of the electrodynamic oscillator (fig. 1a). The electrodynamic oscillator was set to produce sinusoidal harmonic signals at different frequencies (0.1 Hz, 0.5 Hz, 1 Hz, 2 Hz, 3 Hz, 4 Hz, 5 Hz and 7.5 Hz) and amplitudes (0.3 cm, 0.5 cm, 1cm, 2.5 cm i 5 cm). The values of simulated (predefined) oscillation amplitudes were controlled by the LVDT sensor (fig.1a). LVDT sensor was used due to its high achievable accuracy (10^{-2} mm).

For tested instruments, the following tags are used in the paper; RTS-5Hz - robotic total station Leica TCRP 1201, RTS-12Hz - the same instrument when the measuring process is controlled by notebook using VB application, and GNSS-20Hz - Topcon HiPer Pro GNSS device (dynamic displacements determined by postprocessing kinematic method).

3 ANALYSIS OF RESULTS

The first step of data processing was to calculate the coordinates in the local coordinate system with origin defined in the initial (middle) position of the electrodynamic oscillator's moving arm. All recorded positions are then expressed in the form of a time-series (displacement vs. time).

Figure 2 shows a part of measuring results and results of spectrum analysis from experiments with predefined oscillation frequencies from 0.1 Hz to 2 Hz and amplitudes from 5 mm to 50 mm. In these experiments, all the tested instruments have accurately determined predefined oscillation frequencies.

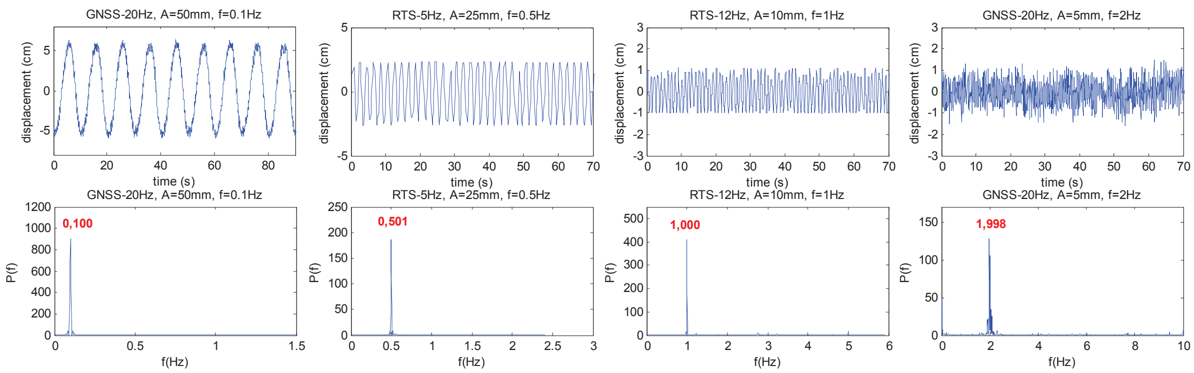

Figure 2 Results of measurements and spectral analysis (amplitudes 5mm -50 mm; frequencies 0,1Hz - 2 Hz)

Minimum oscillation amplitude in experiments was 3 mm. In those experiments, GNSS results weren't precise enough, and therefore, it was not possible to determine predefined oscillation frequencies.

Advantages of GNSS in relation to RTS were showed in experiments characterized by higher amplitudes and oscillation frequencies. The highest predefined oscillation frequency in the experiments was 7.5 Hz. Number of recorded data with RTS-5Hz was 5-7 per second and therefore, from recorded data, it wasn't possible to determine the frequencies higher than 3 Hz. Figure 3 shows results obtained by GNSS-20Hz in experiments with oscillation amplitudes of 5 and 10 mm, and with frequencies of 5 Hz and 7.5 Hz. In those experiments, GNSS-20Hz has accurately determined oscillation frequencies.

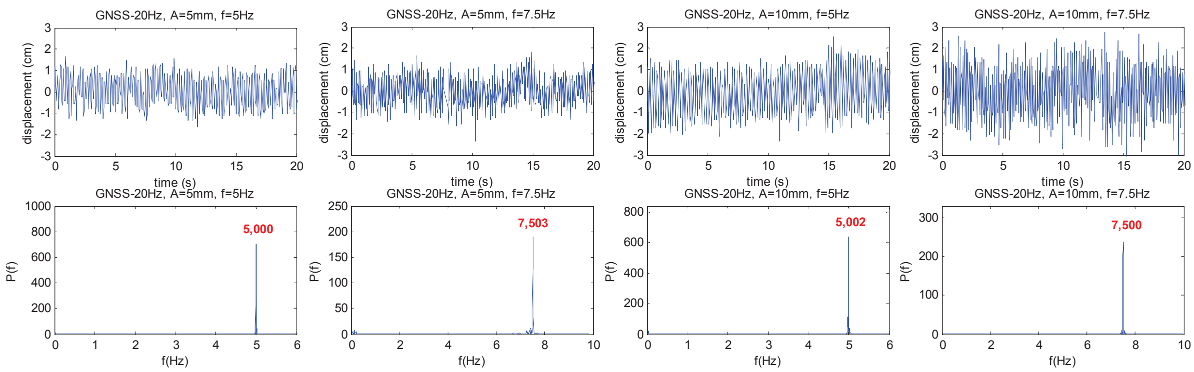

Figure 3 GNSS results of measurements and spectral analysis (amplitudes 5mm and 10 mm; frequencies 5Hz and 7.5 Hz)

Unlike GNSS, by using RTS in both measuring modes (RTS-5Hz and RTS-12Hz), the oscillation frequencies were accurately determined in experiments with frequencies from 0.1 Hz to 3 Hz (Fig. 4) and with oscillation amplitude 3 mm.

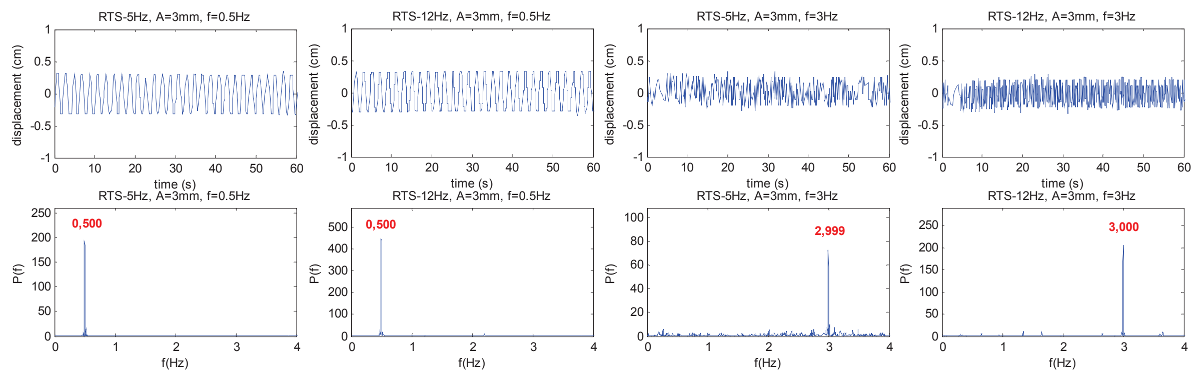

Figure 4 RTS-5Hz and RTS-12Hz results of measurements and spectral analysis (amplitude 3mm; frequencies 0.5Hz and 3 Hz)

Oscillation frequencies higher than 3 Hz could not be determined with the instrument RTS-5Hz. In the experiments with oscillation frequencies of 4 Hz and 5 Hz, instrument RTS-12Hz has accurately determined oscillation frequencies (Fig. 5).

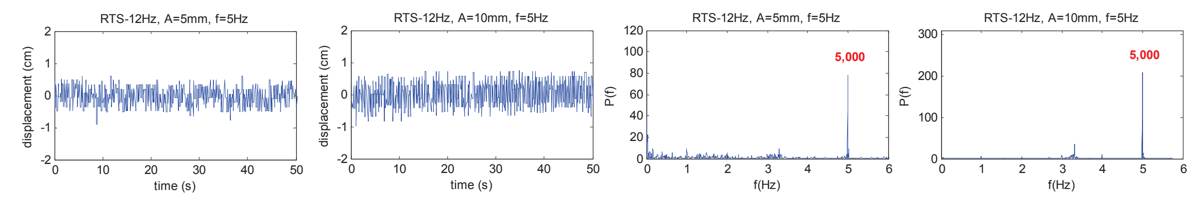

Figure 5 RTS-12Hz results of measurements and spectral analysis (amplitudes 5mm and 10 mm; frequency 5 Hz)

By analysing the measurement results obtained by RTS, dependence of measurements precision and the velocity of the moving prism can be noticed. The achieved precision is higher in experiments with lower oscillation frequencies, and based on the measurement, simulated response of the building is well defined. In experiments with higher oscillation frequencies, measurement precision decreases and certain cycles are poorly described or even lost.

4 MEASUREMENT AT THE ROOF OF SPORTS HALL ARENA ZAGREB

The possibilities of geodetic instruments to determine the dynamic response of structures was checked at the roof of the sports hall "Arena Zagreb". The sports hall "Arena Zagreb" (Fig. 6) is the largest sports hall in Croatia. Due to the complexity and size of the sports hall, monitoring system was set up for monitoring the mechanical behavior of the roof structure.

Figure 6 Sports hall "Arena Zagreb"

The roof structure of the sports hall consists of the main and secondary steel girders. The main girders are suspended with steel tie rods to the tops of the facade of concrete beams in the east-west direction and secondary steel beams in a north-south direction (Duvnjak et al 2010). In the direction of the secondary beams, approximately in thirds of the range main girders, two parallel spatial stabilization steel grids are designed. Their task is to equally transfer designed roof load to the main roof girders.

Modal frequencies of the main cables at the roof of sport hall were determined by accelerometer which was mounted in the middle of the cable length (Fig. 8c). Excitation of the cable has been carried out by swinging the cable in the transverse direction. The modal frequencies were determined from power spectra density function. Figure 7 shows first two modal frequencies of main cable determined by the accelerometer.

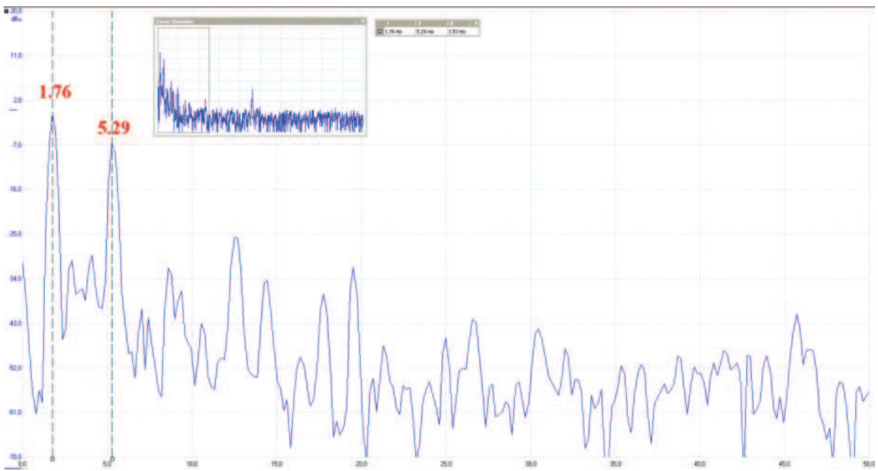

Figure 7 First (1,76 Hz) and second (5,29 Hz) modal frequencies of the main cable.

The dynamic response of main cable during an artificially induced excitation was measured by GNSS and RTS instruments (Fig. 8).

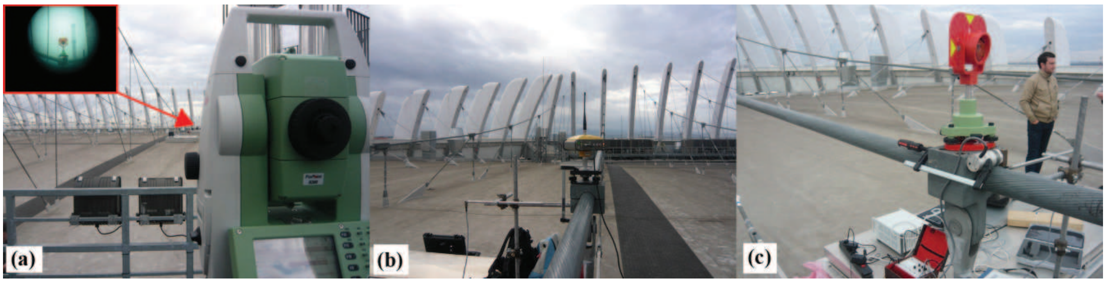

Figure 8 RTS (a), GNSS rover and LVDT sensor (b), prism and accelerometer mounted on the main cable (c)

Figure 9 shows measured response of the main cable in the horizontal plane caused by excitation during the testing.

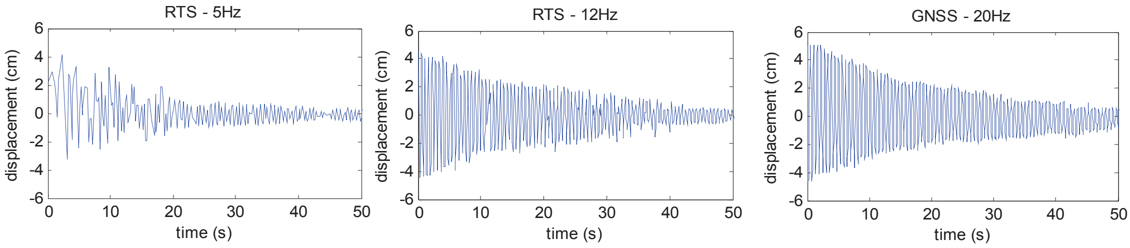

Figure 9 Measured response of the main cable in the horizontal plane caused by excitation

Figure 10 shows the modal frequencies of the main cable determined from recorded data of each instrument using spectral analysis methods.

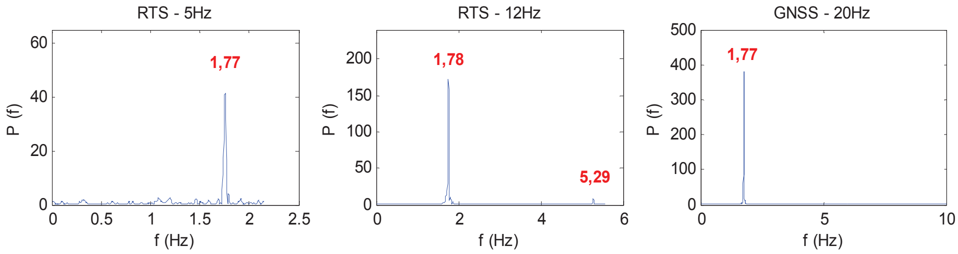

Figure 10 Determined frequencies of the main cable

The first modal frequency (1,76 Hz) of the main cable has been successfully determined by all instruments while the second modal frequency (5,29 Hz) has been determined only by RTS-12Hz instrument. Usage of RTS for determining the frequency of the main cable reveals the advantage and importance of collecting a large number of measurements per second. The second oscillation frequency of the main cable has been successfully determined from the RTS records collected with VB application. From the measured data obtained by functions built into the RTS instrument (RTS-5Hz), the second oscillation frequency could not be determined.

5 CONCLUSION

Purpose of the testing explained in this paper was to determine the possibilities of geodetic instruments to measure the dynamic response of structures. For this reason, instruments were measuring simulated dynamic displacements with oscillation frequencies up to 7.5 Hz, and amplitudes from 3 mm to 50 mm.

Minimum oscillation amplitude in experiments was 3 mm. Based on the measurement results achieved by RTS, it can be concluded that the mentioned instrument can determine, under favorable conditions, the dynamic responses of buildings characterized by the oscillation amplitude lower than 3 mm if the oscillation frequency is lower than 5 Hz.

In experiments with oscillation amplitudes lower than 5 mm, GNSS did not achieve quality results due to its achievable accuracy in kinematic measuring mode. Advantages of GNSS in relation to RTS were showed in experiment with higher oscillation frequencies where GNSS has accurately determined the highest predefined oscillation frequency of 7.5 Hz in experiments with oscillation amplitudes higher than 5 mm.

In order to increase the number of recorded measurements using RTS, VB application was developed. Using this application it is possible to increase the number of recorded measurements from 5-7 measurements to 12 measurements per second. The analysis of the measurement results showed that collection of a higher number of measurements did not affect the accuracy of measurements, but it has enabled the determination of higher oscillation frequencies. That has been confirmed by measurements at the roof of the sports hall, where the second modal frequency of the main cable (5,29 Hz) has been successfully determined only from the RTS records collected with developed VB application (RTS-12Hz). The first modal frequency of the main cable (1,76 Hz) has been successfully determined by all instruments. Based on all above mentioned it can be concluded that the instruments have proved the possibility of determining the dynamic response of structures in exploitation.

REFERENCES

DUVNJAK, I., RAK, M., DAMJANOVIĆ, D. (2010): Load testing for roof structures of big sports facilities, Građevinar, 10, 887-896.

GIKAS, V., DASKALAKIS, S. (2006): Full scale validation of tracking total stations using a long stroke electrodynamic shaker, XXIII FIG congress shaping the change, Munich

GIKAS, V., DASKALAKIS, S. (2008): Comparative testing and analysis of RTS vs. GPS for structural monitoring using calibration measurements upon sinusoidal excitation, XXIII FIG symposium on deformation measurement and analysis. Lisbon, Portugal.

KIRSCHNER, H., STEMPFHUBER, W. (2008): The Kinematic Potential of Modern Tracking Total Stations - A State of the Art Report on the Leica TPS1200+, 1st International Conference on Machine Control & Guidance.

KOPÁČIK, A., KYRINOVIĆ, P., KADLEČÍKOVÁ, V. (2005): Laboratory tests of robot stations, Proceedings of FIG working week, Cairo.

KOVAČIČ, B., KAPOVIĆ, Z. (2005): Precision and results reliability analysis of different instruments for investigating vertical micro-displacement of structures. Survey review - Dir. Overseas Surv., 38 (2005), 297, 190-203.

LI, X. (2004): Integration of GPS, accelerometers and optical fibre sensors for structural deformation monitoring, 17th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation, Long Beach, California, 211-224.

OGAJA, C., LI, X., RIZOS, C., (2007). Advances in structural monitoring with Global Positioning System technology: 1997-2006, Journal of Applied Geodesy, 1 (3), 171-179.

PSIMOULIS, P., PYTHAROULI, S., KARAMBALIS, D., STIROS, S. (2008): Potential of GPS to measure frequencies of oscillation of engineering structures, Journal of Sound and Vibration 2008.

PSIMOULIS, P., STIROS, S. (2007): Measurement of deflections and of oscillation frequencies of engineering structures using robotic theodolites (RTS), Engineering Structures, 29, 3312-3324.

RADOVANOVIC, R.S., TESKEY, W.F. (2001): Dynamic monitoring of deforming structures: GPS versus robotic tacheometry systems, Proceedings of 10th FIG symposium on deformation measurements, Orange, California, 61-70.

ROBERTS, G. W., COSSER, E., MENG, X., DODSON, A. H. (2004): High frequency deflection monitoring of bridges by GPS, Journal of Global Positioning Systems, 3(1-2), 226-231.

STEMPFHUBER, W. (2009): Verification of the Trimble universal total station (uts) performance for kinematic applications, Grün/Kahmen (Eds), Optical 3-D Measurement Techniques IX, 2009, Vienna, 211-221.