Full Scale Validation of Tracking Total Stations Using a Long Stroke Electrodynamic Shaker

Vassilis GIKAS and Stamatis DASKALAKIS, Greece

Key words: total stations, EDM, monitoring, deformation, dynamic

SUMMARY

In recent years, dynamic deformation monitoring equipment such as GPS, accelerometers and inclinometers was extensively used for the purpose of determining angular movements, displacements and vibrations of engineering structures. In contrast, the use of total stations in similar applications was limited for a number of reasons, including the low sampling rate, problems associated with operation in adverse weather conditions and the demand that a clear line of sight is necessary between the total station and the prism. However, the high accuracy measurements and the precise target pointing of such systems, along with their ability to operate indoors, render total stations excellent candidates for certain operations.

This article presents the results and the analyses derived from a large number of experiments aiming to identify the performance and the limitations of tracking total stations in terms of sampling rate and time stamping accuracy. An electrodynamic oscillator was used to generate periodic / sinunsoid vibrations for a preset range of accurately known frequency and amplitude values. Useful conclusions are drawn for the frequency, the amplitude and the data rate recorded as well as for the behavior of servo mechanism. In addition, useful statements are made for the significance possesses in the results that the direction of line of sight between the instrument and the prism in relation to the direction of motion.

Full Scale Validation of Tracking Total Stations Using a Long Stroke Electrodynamic Shaker

Vassilis GIKAS, Stamatis DASKALAKIS, Greece

1. INTRODUCTION

In the last ten years, new methods and techniques were developed for monitoring and analysis of quasi-static and dynamic deformations of man-made structures as well as natural processes. Depending on the application, different types of deformation measurements are utilized which make use of geodetic and/or geotechnical/structural instrumentation. In dynamic deformation studies of large engineering structures, Global Positioning System (GPS) was extensively used (for instance see, Lovse et al (1995), Li (2004), Roberts et all (2006)), as opposed to tracking total stations, for a number of reasons that relate to the intrinsic characteristics of GPS system. The greatest single asset of GPS is the wide range of recording rates (1Hz - 10Hz or faster). Also, the deformation parameters (movements and velocities on specific locations on the structure) are computed in absolute terms, and the operation of the equipment is insusceptible in adverse weather conditions. However, GPS can only be used outdoors, in locations where a clear line of sight to the satellites can be guaranteed.

Tracking total stations can be good candidates for certain applications of dynamic monitoring – in particular, those in which recording at a low sampling rate ($f < 0.3$ Hz) is deemed to be adequate, for instance recording of the displacements of tall buildings, bridges and large slender structures [Nickitopoulou et al, 2006]. Provided that a clear line of sight between the total station and the prism is sewn up, the high accuracy measurements and the precise target pointing of tracking total stations, along with their ability to operate indoors render them appropriate for a certain category of deformation studies. However, in order to exploit fully the potential of total stations, a multitude of aspects that influences their performance in dynamic environments need to be taken into account and to be studied thoroughly. As data acquisition takes place while the target is moving, these aspects relate to the time dimension. Stempfhuber et all (2000), Radovanovic and Teskey (2001) and Kopacik (2005) discuss the issue of time delaying between angle and distance measurements which contributes a systematic portion of error in the computation of the target position. Other known sources of error relate to the mechanism used for the automatic target recognition, the ability of the servomotors to follow the target, the behavior of the compensator during and after accelerations and the sophistication of the tracking algorithms to cope with situations of signal interrupts [Hennes, 1999, Gikas et al 2005]. Therefore, given the complexity of the various aspects that contribute to the total error budget of tracking total stations, it is imperative that their potential is fully investigated and exploited. Cosser et al (2003) studied the performance of tracking total stations for measuring the dynamic deformation of bridges. This work contributed some useful conclusions about the potentiality and the limitations of such systems. However, the main problem reported in this study is the slow data rate and the fact that time tagging was accurate to the nearest second.

This paper presents the results of a series of tests that were designed in order to fully exploit the potential of servo driven total stations in terms of sampling rate and time stamping accuracy. For this purpose, a controller tracking software was developed in order to operate the Leica TPS 1100 series instruments via a laptop. The moving target was mounted on an electrodynamic oscillator which was used to generate controlled vibration signals for a preset range of accurately known frequency and amplitude values. Useful conclusions are drawn for the frequency, the amplitude and the data rate recorded by the instrument as well as for the behavior of the servo mechanism. In addition, useful statements are made for the significance that possesses in the results, the direction of line of sight between the total station and the target in relation to the direction of motion.

2. SYSTEM COMPONENTS AND EXPERIMENTAL SETUP

2.1 ElectroDynamic Oscillator

In this study, an electrodynamic shaker (model 400 ELECTRO-SEIS shaker supplied by APS Dynamics, Inc) was used to generate controlled vibration signals. This system is a long stroke, electrodynamic oscillator, designed to be used alone or in arrays for exciting and studying the dynamic response characteristics of structures in the frequency range 0-200 Hz [APS Dynamics Inc, 2003]. The model 400 provides modal test excitation of complex structures such as piping systems, electrical substation structures and apparatus, floors, missiles, etc. According to the manufacturer, the unit employs permanent magnets and is configured such that the armature coil remains in a uniform magnetic field over the entire stroke range. Drive power for the shaker is obtained from a power amplifier. Its basic operating principle is that of force generation in a current carrying conductor, located in a direct current magnetic field which is perpendicular to the direction of the current. Corresponding to the force generated on the current carrying conductor and associated armature structure, there is an equal and oppositely directed reaction force, developed on the magnetic field structure. The shaker is thus capable of generating any timed waveform of force acting between its armature and body, in accordance with an identical time waveform of current supplied to it [APS Dynamics Inc, 2003].

Figure 1: The electrodynamic shaker with the circular prism mounted on the oscillating arm.

With reference to the specific needs of this study, a circular prism was firmly mounted on the oscillating arm of the shaker's body as shown in Figure 1. Then, the shaker was programmed to reproduce a preset group of vibration signals as detailed in Section 2.3.

2.2 Tracking Total Station Unit

The tracking total station examined in this study is the Leica TCA 1800. Also, some preliminary experiments were conducted with the Leica TDA 5005. The technical specifications for Leica TCA 1800 are 3^{cc} for angle measurements and for tracking (TRK) and rapid tracking (RTRK) distance measurements 5mm + 2ppm and 10mm + 2ppm respectively. However, as stated already in Section 1.0, the instrument performance can vary depending on the kinematic characteristics of the moving target (velocity / acceleration vectors), the relative geometry between the instrument and the prism as well as the operating conditions.

The Leica Tracking Controller software is an on-purpose built piece of software which was developed for the on-line operation in tracking mode of the total station directly from a laptop via serial connection – interface RS-232. The software developed in Visual Basic and relies on the GeoCOM protocol supplied by Leica Geosystems [Leica Geosystems, 2000]. By design, the software was developed so that the instrument can operate both in tracking and rapid tracking modes. When operating the instrument with the Leica Tracking Controller software the recording rate of the instrument can reach nearly 5.8 Hz and the time stamping of the observations equals the resolution of the internal clock of the instrument, namely 0.001 seconds. These features of the software are considered to be very important as the system is capable to recover deformations of harmonic frequencies up to 2.9 Hz. This is due to the Nyquist sampling theorem, which states that information with a bandwidth of q Hz must be sampled at a rate of 2q Hz [Schwartz, 1975].

2.3 Design of the Experiments

It was stated already that the overall goal of this study is to examine the performance of tracking total stations when the reflector performs harmonic motion with known amplitude and frequency values. The observation scenario assumed the tracking total station to be connected serially to a laptop. Then, the instrument was set up at a distance nearly 100 m away from the shaker, on the moving arm of which a circular prism was suitably mounted to face the instrument as shown in Figure 2. As indicated in this figure, four sets of experiments were conducted in total. Each one of these sets of tests corresponds to a different twist angle which is defined by the direction of the line of sight between the instrument and the shaker and the direction of the motion of the oscillating arm. Thereby, when the reflector oscillates at 0 grad the servomechanism of the total station is not in use as the angle measurements practically remain unchanged. On the very opposite, when the reflector oscillates at 100 grad the servomechanism is in constant use as the angle measurements change. Obviously, by collecting measurements under these observation scenarios it would be possible to rate the amount and to identify the nature of the errors that the angle and distance measurements contribute independently to the total error budget of the prism location.

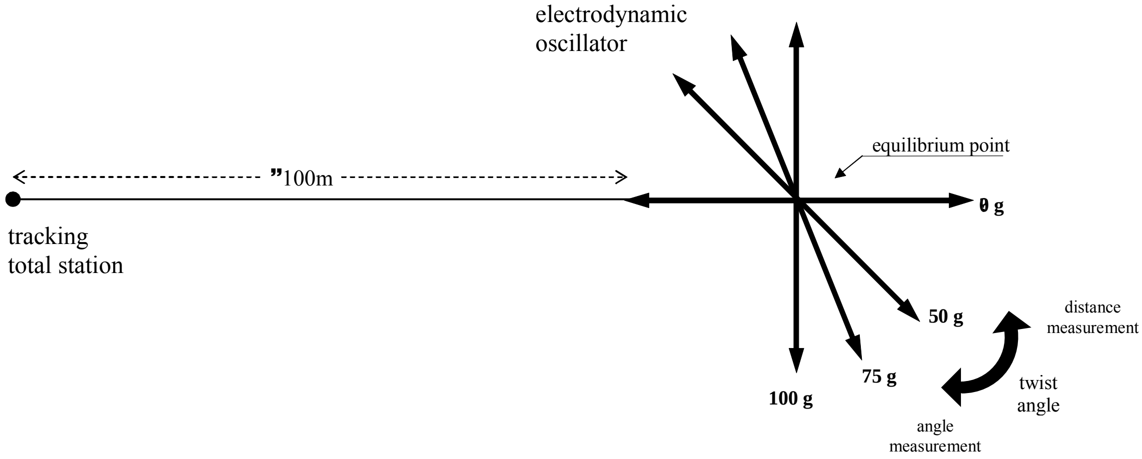

Figure 2: Observational geometry.

The instrument was set to operate in the rapid tracking mode. For every set of tests (i.e., tests performed at twist angles 0, 50, 75 and 100 grad) twenty experiments were conducted. More specifically, the electrodynamic shaker was set to produce sinusoidal harmonic signals at five frequencies ranging from 0.1 Hz to 2 Hz and at four amplitude values ranging from ±0.005 m (Δl= 0.01 m) to ± 0.05 m (Δl= 0.1 m). Each experiment lasted for nearly 90 seconds, resulting approximately in more than 500 observations. In total, 80 experiments were conducted.

3. PROCESSING METHODOLOGY

The tests were conducted according to the observation scheme shown in Figure 3. This experimental setup resulted in two independent sources of information for the displacements of the oscillating prism. At first, an electromagnetic sinusoidal signal was generated with nominal frequency and amplitude attributes f_{nom} and A_{nom} respectively. This signal was then amplified and consequently, the circular prism was forced to oscillate according to the equation:

$$f(t) = A_{nom} \sin(2\pi f_{nom} t + \varphi) \tag{1}$$

At the same time, the tracking total station was set to record the polar coordinates $\{\rho(t_i), \theta(t_i), \upsilon(t_i)\}$ of the moving prism in the local topocentric coordinate system, which was then translated to the Cartesian coordinates $\{x(t_i), y(t_i)\}$ (Figure 2). It is evident that the computed time series $\{t_i, f(t_i)=[x(t_i), y(t_i)]\}$ are confined to the harmonic motion of the electromagnetic shaker. More specifically, the time series obtained for the experiments at twist angles 0 grad and 100 grad are directly comparable with the nominal signal, as the displacements of the moving target are clustered along the x-axis and y-axis respectively (Figure 2). In contrast, the time series obtained in twist angles other than 0 grad and 100 grad were rotated suitably about the equilibrium point of the oscillation so that, the complete motion is fully described in one dimension. Given the rational character of the periodic motion of the tests, the coordinates $\{x_m, y_m\}$ of this point were computed as the average value of all recorded coordinates in that experiment. At this stage, the resulting time series of the prism location are directly comparable with the signal generated in the oscillator, except for the drift value φ, which describes the phase difference in amplitude. An estimate of φ is computed, so that the recorded time series of the prism location fit the nominal signal in the least squares sense.

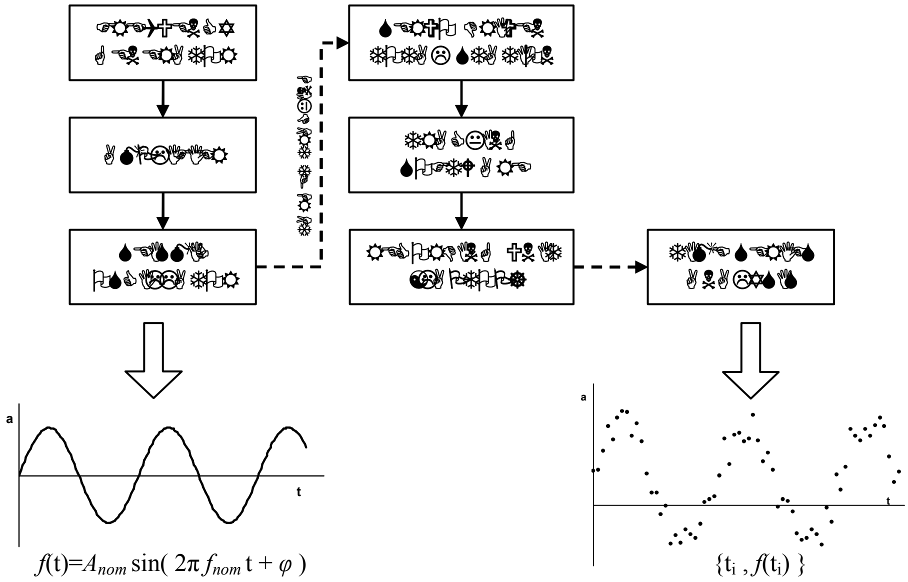

Figure 3: Experimental setup.

4. DATA ANALYSIS AND RESULTS

Figure 4 shows the time series $\{t_i, f(t_i)\}$ of the recorded location of the prism (circles) superimposed by the nominal signal generated in the oscillator (continuous line) for a twist angle 50 grad and nominal frequency and amplitude values 0.1 Hz and 0.5cm respectively. From this diagram it is evident that the total station follows the moving prism unexceptionably, reproducing the original signal with accuracy better than ±2 mm. This type of analysis was repeated for all available experiments and it was found that, if the oscillator was set to operate at a low frequency / small amplitude values the resultant residuals exhibit a similar pattern in terms of magnitude and trend. Nevertheless, the higher the frequency and amplitude values applied in the electromagnetic shaker, the more burdensome is for the total station to track successfully the prism.

In order to assist interpretation of the analysis and to facilitate valid inferences, the mean differences in amplitude Δa for all twist angles, between the nominal and the observed amplitude are summarized in Figure 5, as a function of the nominal frequency and the twist angle. In fact, every curved line in this diagram depicts the rate per cent Δa/a (%), which represents the mean value for all experiments conducted at a specific frequency for all twist angles. From this graph several conclusions can be drawn. The most distinct observation to note is that, as expected, the lower the operating frequency in the oscillator, the more accurate the recordings of the tracking total station. More specifically, for nominal frequencies $f \leq 2$ Hz, the ratio Δa/a (%) is of the order of 10%, and there is a clear evidence for this accuracy to decrease by a factor of three with increasing the nominal frequency. From the same plot, it also is evident that for frequencies $f > 0.5$ Hz, the tracking total station can be used satisfactorily for phenomena which exhibit amplitude values in the range 0-1.5 cm. Moreover, note that the ratio Δa/a (%) deteriorates in the low range of amplitude (a < 1 cm) compared to the transitional range of amplitude (1 cm < a < 2 cm). It is anticipated that this phenomenon probably relates to the accuracy limitations of the instrument.

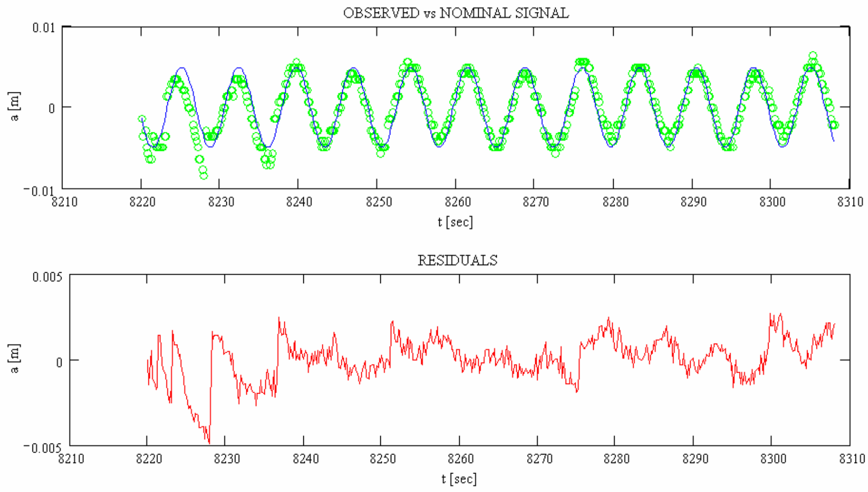

Figure 4: Recorded time series by the total station (circles) superimposed by the nominal signal (continuous line) [top]. Residual values [bottom]

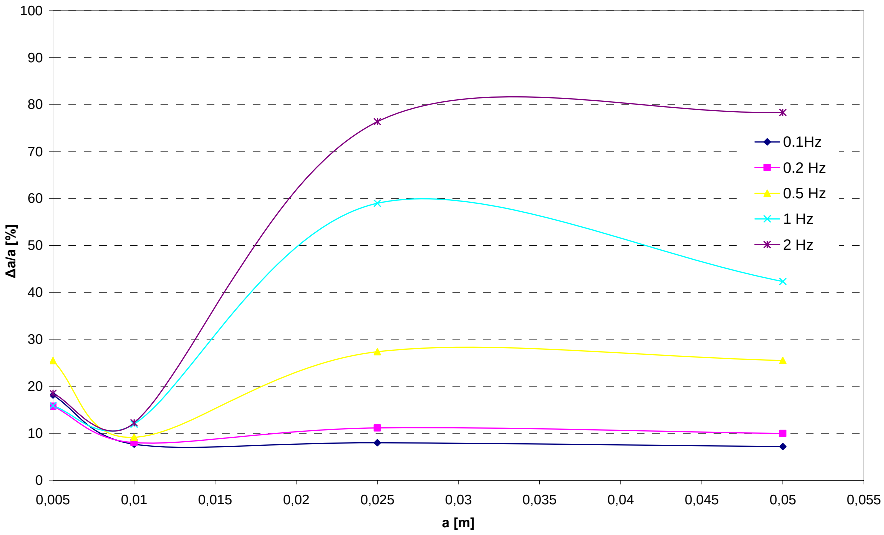

Figure 5: Percentage Δa/a (%) of the mean differences between the nominal and the observed amplitude as a function of the nominal frequency and the twist angle.

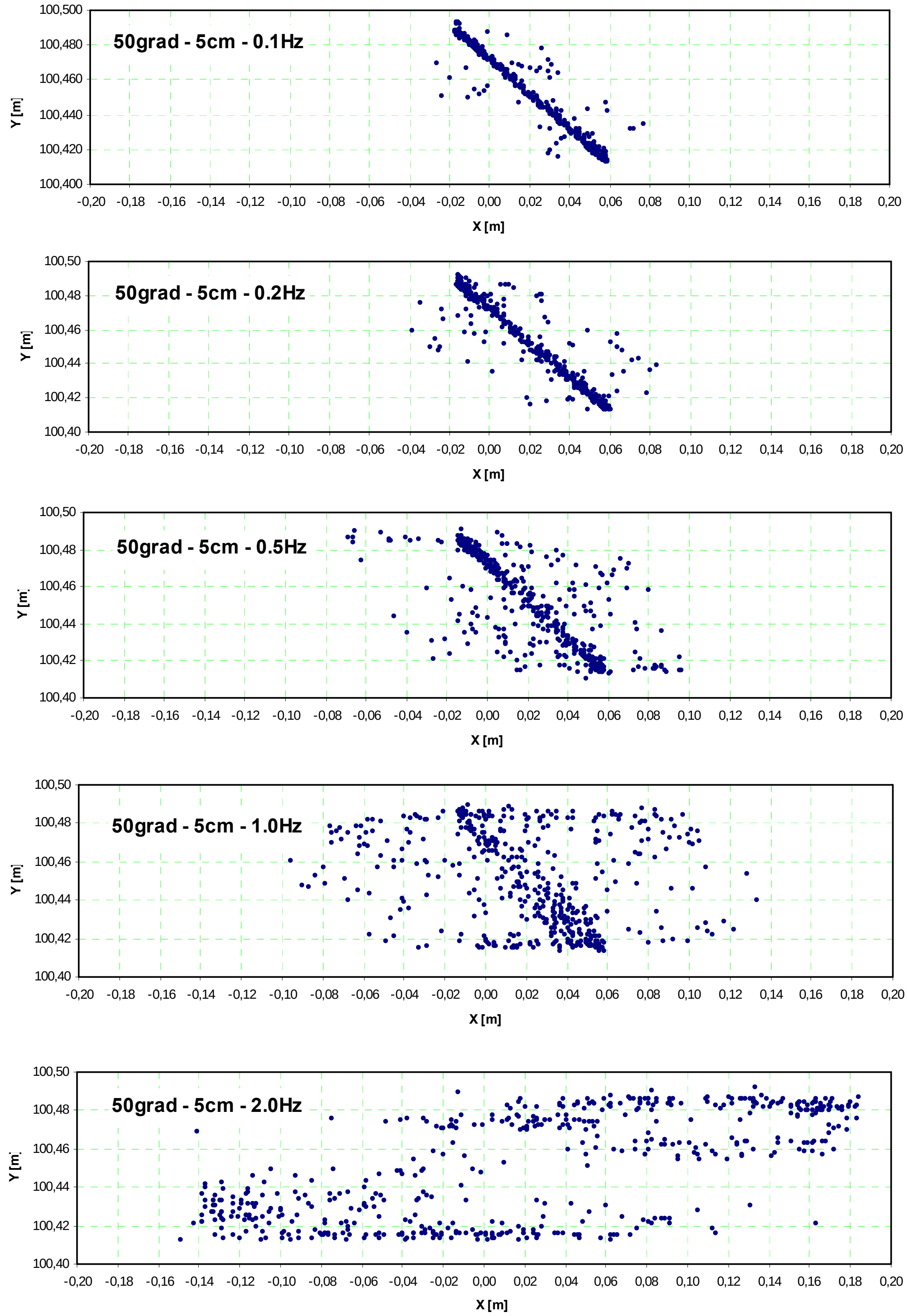

Figure 6: Recorded coordinates of the prism location for a 50 grad twist angle, 5 cm amplitude and for a frequency bandwidth ranging from 0.1 Hz to 2 Hz.

In addition to the analyses that rely on the comparisons between the nominal signal and the total station recordings further analysis was performed. In this paper, only some of the findings that relate to the known problem of time delaying between angle and distance measurements will be discussed. Figure 6 shows the recorded coordinates of the prism location for a 50 grad twist angle, 5 cm amplitude and for a frequency bandwidth ranging from 0.1 Hz to 2 Hz. This diagram exhibits an interesting phenomenon. For frequencies $f < 0.2$ Hz the observed positions of the prism exhibit a linear trend which represents the actual movement of the target. However, as the nominal frequency increases, the recorded coordinates of the prism seem to rotate about the equilibrium point of the oscillation and to pull apart, forming two clear-sighted areas of high density dots as shown in the bottom graph of Figure 7. This phenomenon reveals that the angle and distance measurements do not correspond to each other exactly. It appears, that in the time it takes for the total station to complete a distance measurement the angle measurement has been change – hence, it can be concluded that when the prism oscillates at 2 Hz frequency the recording mechanism of angles and distances is tuned up. This observation is important because it shows the operational limits of the instrument, and therefore, it helps to identify potential areas of application.

5. CONCLUDING REMARKS

In this paper the results of a large number of experiments aiming to identify the performance and the limitations of tracking total stations is presented. The testing procedure relies on the use of an electrodynamic shaker, as a means to produce motion of a periodic character, while the processing methodology is based on comparisons derived from the signal generated by the oscillator and the prism locations recorded by the total station. From the results presented it can be concluded that tracking total stations are capable for monitoring successfully deformations of harmonic frequencies $f < 0.5$ Hz. This is important as this range covers towers, suspension bridges and tall buildings, as well as large slender engineering structures such as antenna masts. The analysis also revealed the issue of time delaying between angle and distance measurements in tracking total stations. Although the results presented in this study contribute in the understanding of the problem, further analysis and experiments are planned for the future to fully describe this phenomenon and to identify the operational limitations of the instruments. Such experiments will include testing of tracking total stations and comparisons with other instruments such as accelerometers and fibre optics.

ACKNOWLEDGEMENTS

The experiments were conducted at the Laboratory of Structural Mechanics and Technical Works of the School of Rural and Surveying Engineering – NTUA. The authors would like to acknowledge Mr. J. Stratakos for his substantial help for setting up and for operating the electrodynamic shaker during the experiments.

REFERENCES

APS Dynamics (2003).Electro-Seis Model 400 Shaker, "*Instruction Manual*", Carlsbad, CA, USA.

Cosser E., Roberts G., Meng X. and Dodson A. (2003). "Measuring the Dynamic Deformation of Bridges Using a Total Station", *Proceedings of the 11th FIG Symposium on Deformation Measurements*, Santorini, May 25-28.

Gikas V., Daskalakis S., Stathas D. (2005). "Investigation of the Performance Characteristics of Tracking Tacheometers: Preliminary Tests and Results", *Proceedings of the International Symposium on Modern Technologies, Education and Professional Practice in Geodesy and Related Fields*, Sofia, November 3-4.

Hennes M. (1999). "On the Determination of the Performance of Tracking Tacheometers", *Proceedings of the 3rd Turkish German Joint Geodetic Days*, Istanbul, June 1-5.

Kopacik A., Kyrinovic P., Kadlecikova V., (2005). "Laboratory Tests of Robot Stations", *Proceedings of the FIG Working Week,* Cairo, April 16-21.

Leica Geosystems (2000). "TPS-System 100: Electronic Theodolites and Total Stations", *User Manual, Leica Geosystems*, Heerbrugg, Switzerland.

Li X. (2004). "Structural Deformation during a Typhoon as Monitored by an Integrated Multi-Sensor System", *Proceedings of the 2004 Int. Symposium on GNSS/GPS*, Sydney, December 6-8.

Lovse J., Teskey W., Lachapelle G., Member, ASCE, and Cannon M. (1995). "Dynamic Deformation Monitoring of Tall Structure Using GPS Technology", Journal of Surveying Engineering, Vol.121, No.1 February, p35-40.

Nickitopoulou A., Protopsalti K. and Stiros S. (2006). "Monitoring Dynamic and Quasi-Static Deformations of Large Flexible Engineering Structures with GPS: Accuracy, Limitations and Promises", *Engineering Structures*, [in press].

Radovanovic R., Teskey W. (2001). "Dynamic Monitoring of Deforming Structures: GPS versus Robotic Tacheometry Systems", *Proceedings of the 10th FIG Int. Symposium on Deformation Measurements*, Orange, California, March 19-22.

Roberts G., Brown C. and Meng X. (2006) "Bridge Deflection Monitoring", *GPS World*, February, p26-31.

Schwartz M., Shaw L. (1975). "Signal Processing: Discrete Spectral Analysis, Detection, and Estimation", McGRAW-HILL Kogakusha Ltd.

Stempfhuber W., (2000). "The Integration of Kinematic Measuring Sensors for Precision Farming", *Proceedings of the 3rd International Symposium on Mobile Mapping Technology*, Cairo, January 3-8.

BIOGRAPHICAL NOTES

Vassilis Gikas joined as a lecturer the National Technical University of Athens in 2004. His previous appointments include a research position in the Department of Geomatics at the University of Newcastle upon Tyne, UK. In the past he served the offshore industry in the UK and the USA as a navigation and positioning specialist and more recently, he served the private sector in a series of surveying and transportation engineering projects under the same capacity. His principal areas of research include navigation, high precise GPS and surveying engineering applications.

Stamatis Daskalakis holds a degree from the School of Rural and Surveying Engineering of NTUA. He is currently undertaking postgraduate studies at NTUA in the field of Geo-informatics.

CONTACTS

Dr. Vassilis Gikas
National Technical University of Athens
Department of Rural and Surveying Engineering
Laboratory of General Geodesy
9 Heroon Polytechniou Str., 15780, Zographou
Athens
GREECE
Tel. +30 210 772 3566
Fax. +30 210 772 2728
Email: vgikas@central.ntua.gr