Accuracy of Simple GPS Kinematic Techniques: Evidence from Experiments, and Implications for the Study of Large Flexible Engineering Structures

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Key words:

SUMMARY

The possibility to monitor oscillations and quasi-static deformations of large flexible engineering structures using simple GPS kinematic techniques was investigated on the basis of a large number of experiments. Harmonic movements were simulated by a 1Hz, dual frequency rover receiver rotating on an electro-motorized device on a fixed horizontal plane with a constant angular velocity and radius, while a base receiver was operating at a distance of few tens of meters. A large number of experiments based on different combinations of the period (T= 3-19sec) and the radius of rotation (20-50cm) were made; in all these experiments the parameters of the movement of the rover were independently determined, and this permitted unambiguous estimations of the accuracy of the GPS recordings. Analysis of data revealed that short period outliers were <1.5%, and that the accuracy of horizontal and vertical coordinates was of the order of 2-12mm and 8-34mm, respectively. This study revealed that in areas with favorable satellite constellation simple kinematic GPS techniques can successfully describe the motion/short wavelength deformation of most flexible period engineering structures.

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1. INTRODUCTION

Can simple GPS kinematic techniques permit a low-cost monitoring of rapid deformations and oscillations of flexible engineering structures, such as wide-span bridges, cooling towers, high-rise telecommunication antennas and high-rise pillars? Which is the range of the motions, ranging from nearly harmonic oscillations (for instance in the case of seismic vibrations) to quasi-static displacements (for instance in the case of bending of structures due to a nearly constant wind) that can recorded, and at which level of accuracy?

In an effort to answer these questions, rarely addressed in the literature (Ashkenazi et al., 1997; Nakamura, 2000; Breuer et al., 2002) and occasionally representing a matter of debate among specialists (Greulich, 1997) we focused on the most unfavorable case of nearly harmonic movements, and made a large number of experiments. The aim of these experiments was the assessment of the accuracy and of the potential of kinematic GPS techniques to describe relative displacements of a moving body using two dual frequency receivers and commercial software.

The basic idea of the experiments was to force the rover receiver to rotate at horizontal orbits and at a wide range of known rotation parameters, somewhat similar to those characterizing the movements of most common engineering structures, and then to compare its changing coordinates with the real ones. This approach permits the assessment of the *accuracy* of the GPS coordinates, which is usually much different from the *precision* computed by conventional adjustments (see for instance, Cocard et al., 1999).

2. DESCRIPTION OF THE EXPERIMENT

Harmonic movements of structures to be monitored by GPS were simulated by a rover receiver mounted on an electro-motorized device rotating on a horizontal plane with a constant angular velocity. At the same time a base receiver was operating at a distance of few tens of meters at a fixed point in order to minimize systematic and other errors. During all sessions the center of rotation of the rover receiver were kept fixed at the same point (Fig. 1). Angular velocities and radius of rotation were, however, changing in the various sessions. Hence, the parameters of the movement of the rover during every session were independently known and reliable estimates of the quality of GPS recordings were possible (Hartinger et al., 1998).

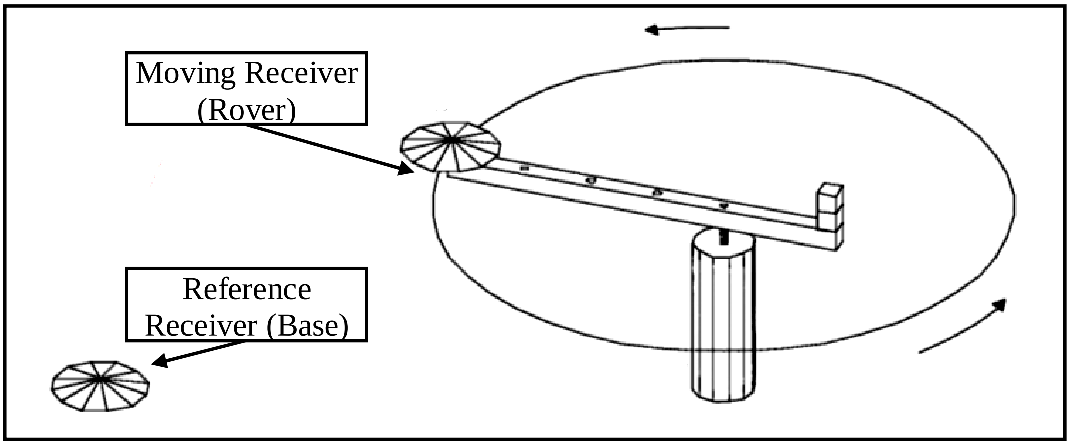


Figure 1: Sketch of the receivers' positions. The moving receiver was fixed on a rotating rod and the reference receiver was installed in a nearby (approximately 20m) position. Both the receivers and the rotating device were located in fixed points during all experiments (sessions). Fixed was also kept the angular velocity of the rover during each experiment.

All experiments reported here were made in the Patras University Campus (approximate coordinates φ=38°15'N λ=21°45'E), in different periods of the day and days of the week, under different satellite constellations and atmospheric/ionospheric conditions; periods of medium to strong winds were, however, avoided because of a possible impact on the rotation parameters. All experiments were made by the same team and with the same instruments: two 1Hz JAVAD/TOPCON receivers recordings at a rate of 1Hz, and a single electro-motorized device. Extreme care was taken to avoid exchanges of the antennas and receivers, as well as centering, eccentricity and elevation errors when assembling the experiment device.

During a period of 12 months a large number of experiments (sessions) corresponding to all 44 possible combinations of four selected lengths of radius (20, 30, 40, 50cm) and of 11 periods of rotation (T=3,4,6,7,9,10,11,12,17,18,19 sec) of the rover receiver were made. Among them, 44 sessions, each for one different combination was randomly chosen, and this set represents the set of sessions analyzed below.

4. DATA ANALYSIS

All computations reported in this article were made using the PINNACLE software and refer to the Greek Datum (HGRD87) and to the coordinates of the base station defined from an analysis of a GPS database much wider than that examined in this article.

At a first step the time series of x, y and z coordinates were calculated for each session and were plotted in diagrams. It is evident that x and y coordinates are confined to a circular band, while that of z-coordinates to a linear band (Fig. 2). This most probably indicates that, due to the favorable constellation of satellites in the region, the precision of calculated coordinates in both the x and the y axis were nearly equal.

The coordinates of the center of rotation C_k for each session k were subsequently computed as the mean values of all coordinates of points in this session. These coordinates provided a first test on the quality of our computations: Since the centre of rotation of the rover was fixed in all sessions, the coordinates of the 44 centers of rotation corresponding to each of our sessions points should be statistically equal. Adopting the 3-sigma criterion two sessions were discarded as outliers (Fig. 3). The x and y coordinates of the center of rotation C_k of each of the remaining 42 sessions (k=1, 2, ..42) were found to deviate from their mean values by 1-89 and 14-78mm, respectively. These coordinates were subsequently analyzed for smaller scale systematic errors and blunders. Since the radial velocity was constant during each experiment and both the base receiver and the center of rotation were fixed in nearby positions, coordinates are expected to define a nearly sinusoidal curve, with limited deviations due to random, mainly errors.

Our analysis revealed that our data followed this pattern, and among the 14,000 points in total recorded during our 44 experiments, only 220 points could be regarded as outliers on the basis of the 3-sigma criterion (Fig. 4); this proved that there was no need for further cleaning of our time series.

In order to simplify calculations, using a linear transformation, the coordinates of the rotation center C_k were identified as the origin for each session i. Hence, since the radius of rotation R_k was constant in a session k, it is evident that the distance between the instantaneous horizontal coordinates X_{ik}, Y_{ik} of the rover when at point i and those of the rotation center C_k of the rover are defined by the relationship

$$Ri_{\kappa} = \sqrt{(Xi_{\kappa}{}^{2} - Yi_{\kappa}{}^{2})}$$

and the difference ΔRi_{κ} computed from the formula $\Delta Ri_{\kappa} = Ri_{\kappa} - R$ defines the deviation of the real from the computed value, presumably a random error (Fig. 5). Hence, for a session κ with n recorded points, n formulas of this type were formed, and from their statistical analysis an estimate $\sigma_{\Delta R_{\kappa}}$ of the precision in determination of the radius of rotation for one single observation was obtained.

From the law of propagation of errors and assuming for simplicity that the standard deviations of both coordinates are practically equal (a result supported by Figure 2-top) and weakly only correlated, the following estimates of the precision of the coordinates of the rover can be obtained

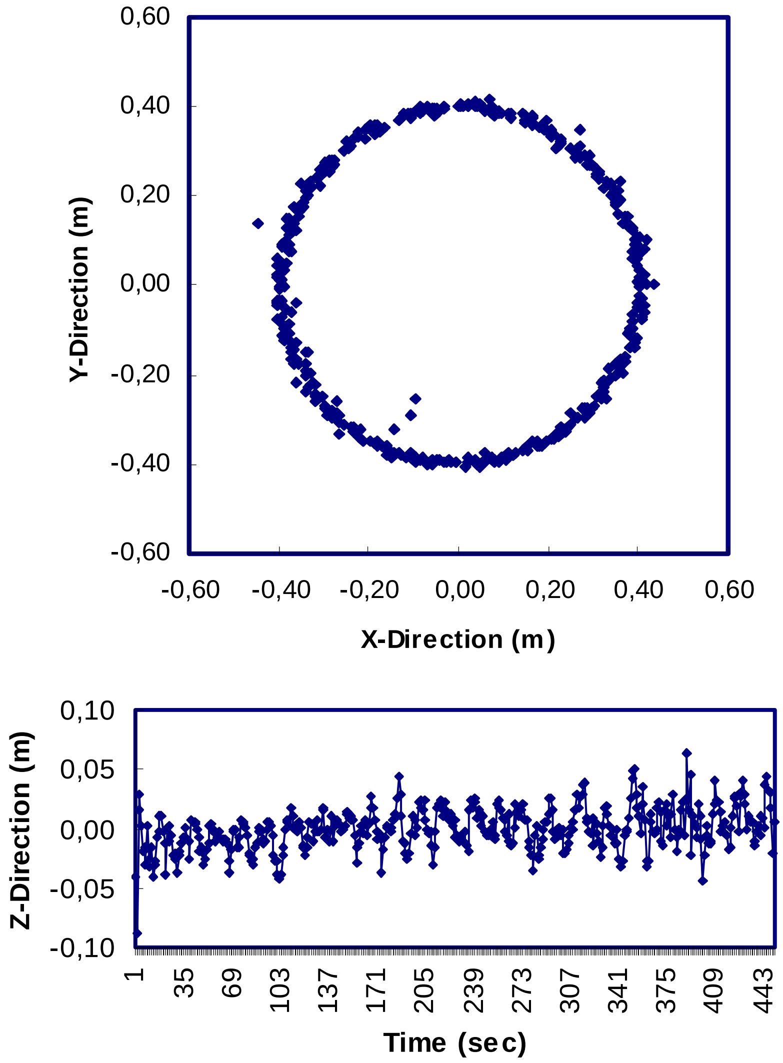


Figure 2: Plot of horizontal (top) and vertical (bottom) coordinates of the rotating rover receiver recorded during a representative session (T=17sec, R=40cm, n=450dots). Recorded coordinates are confined to a circular and a horizontal band, respectively.

$$\sigma_{X_K} \cong \sigma_{Y_K} \cong \frac{\sigma_{\Delta R_K}}{\sqrt{2}}$$

As far as vertical coordinates are concerned, the average value of the z-coordinates of points of each session k can define a mean height Z_k of the plane of rotation, which can be easily transformed to origin of the z-coordinates. Consequently, for a point i of session k with computed Zi_{κ} coordinate, the difference

$\Delta Zi_{\kappa} = Zi_{\kappa} - Zk$

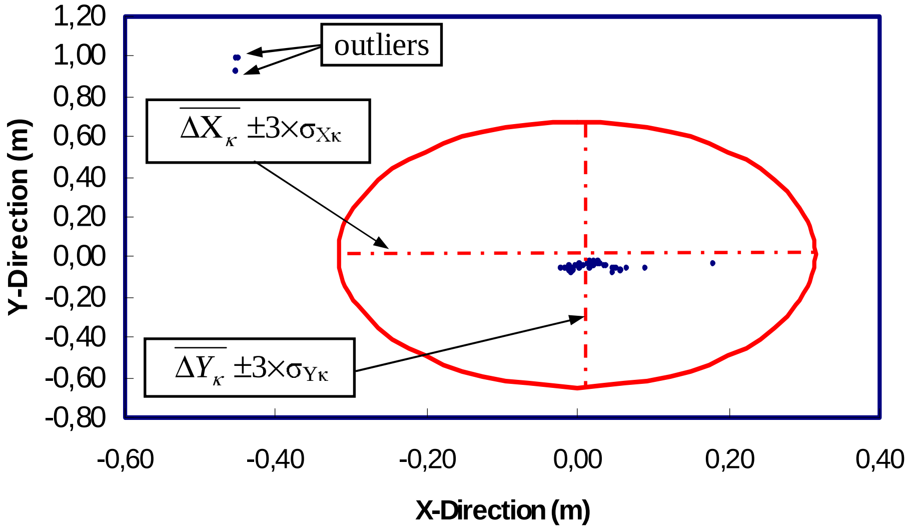


Figure 3: Plot of the centers of rotation C_K of the 44 sessions (experiments) examined in this paper. These coordinates were obtained as mean values of all recorded coordinates during each session. Centers of rotation of two sessions were discarded as outliers on the basis of the 3sigma criterion, with the value of 1-sigma deduced from the coordinates of all 44 sessions.

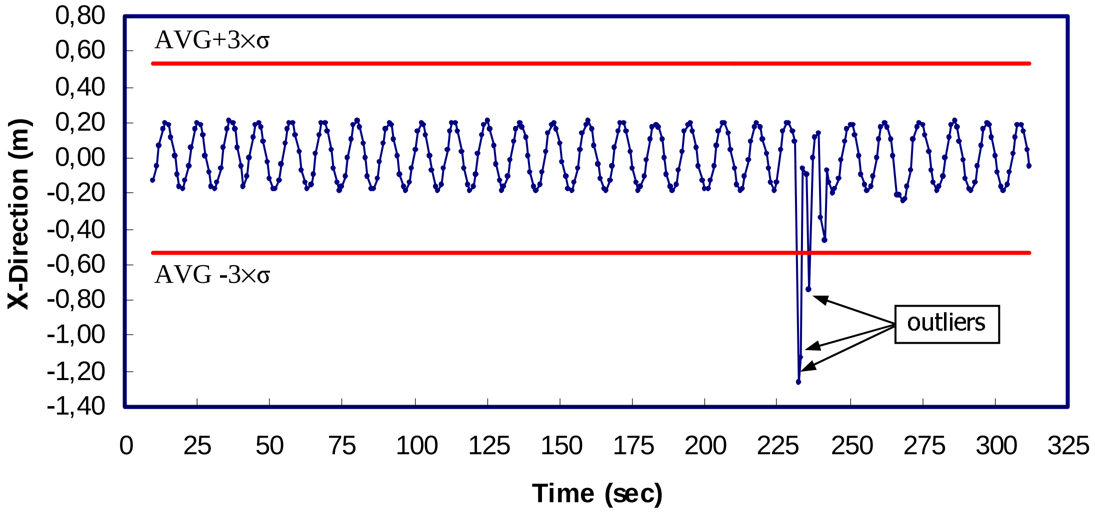


Figure 4: An example of recorded coordinates including small-scale deviations from a sinusoidal curve; the latter reflects the rotation of the rover with a constant angular velocity (T=12sec, R=20cm).

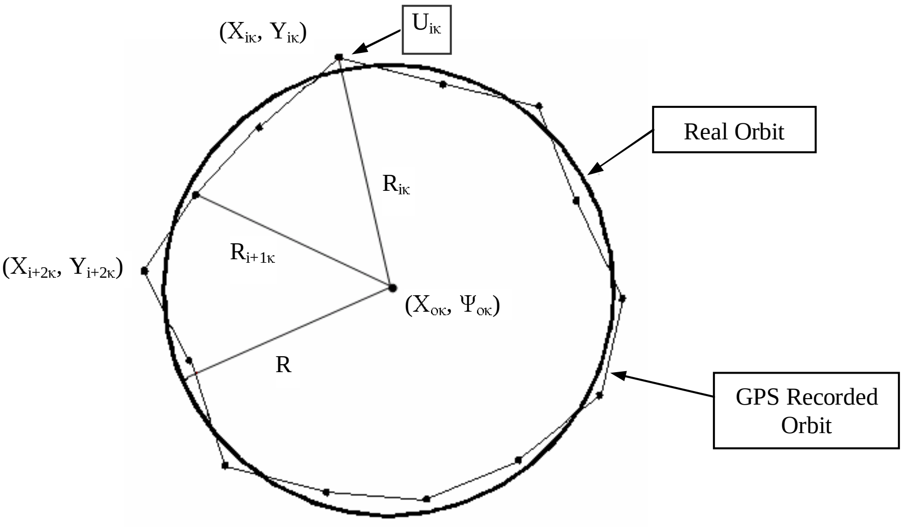


Figure 5: Conceptual model for estimation of the quality of measurements. The rover is moving on a circular path, but due to random, mainly, errors, recorded coordinates define a radius with length different from the real one.

presumably defines a random error, and its statistics the precision of the z-coordinate in session k can be deduced.

The results of our analysis for the 42 valid sessions are summarized in Figures 6 and 7 as plots of the obtained mean accuracy of each observation in each session versus the linear velocity and period of movement of the rover station.

4. DISCUSSION

The data and analyses presented above are only a part of experiments made to investigate the possibility to use simple GPS kinematic techniques to monitor the kinematics of various engineering structures.

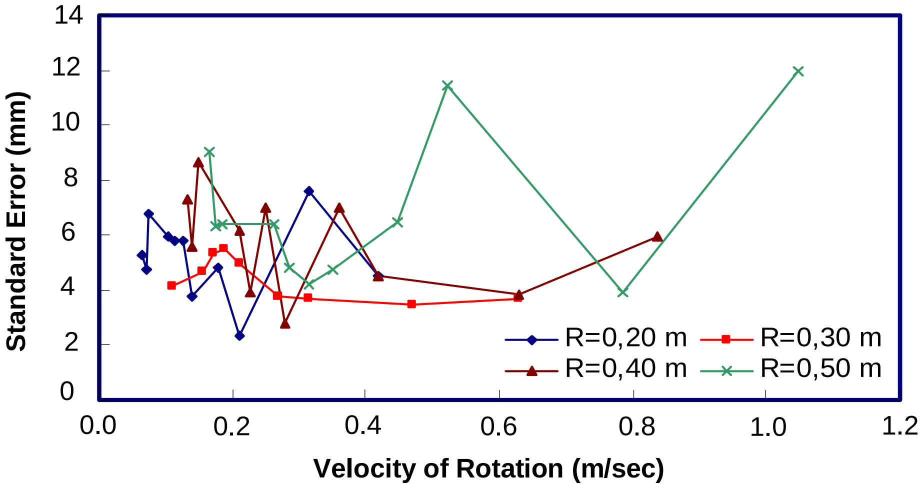
The results of this study reveal that a pair of dual frequency 1Hz receivers and commercial software can be used to monitor velocities up to at least 1 m/sec and oscillations with a frequency of at least 0.33Hz.

For movements in the horizontal plane, the standard deviation in the difference between recorded and real radius of rotation for each point in a session was ranging between 3.3-17mm, corresponding to an accuracy of coordinates between 2.3-12mm.

For the z coordinate and for each session average offsets in the range of 67-112mm (with the exception of one single value of 338mm) with a standard deviation for each session ranging between 8-34 mm were obtained.

Because the error analysis is made relative to real values deduced from independent methods, our estimates do not simply reflect precision, but accuracy of measurements.

These results prove that, with the exception of areas with poor satellite configuration, simple kinematic GPS techniques can describe the motion of most long-period oscillating/temporarily deforming engineering structures relative to nearby base receivers with an accuracy of the order of a few and 10cm in the horizontal and vertical axes, respectively, with outliers limited to <1.5%. Short period movements can definitely also be recorded, but more sophisticated hardware and software is necessary (Ge et al., 2000).



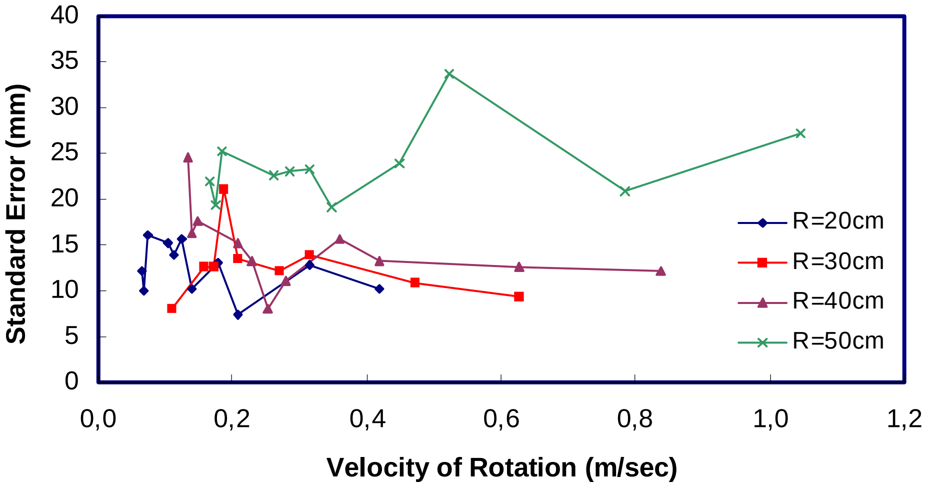


Figure 6: Plot of standard errors in horizontal (top) and vertical (bottom) coordinates of a single point versus the velocity of movement. It is obvious that the accuracy in coordinate estimation is of the order of a few centimetres.

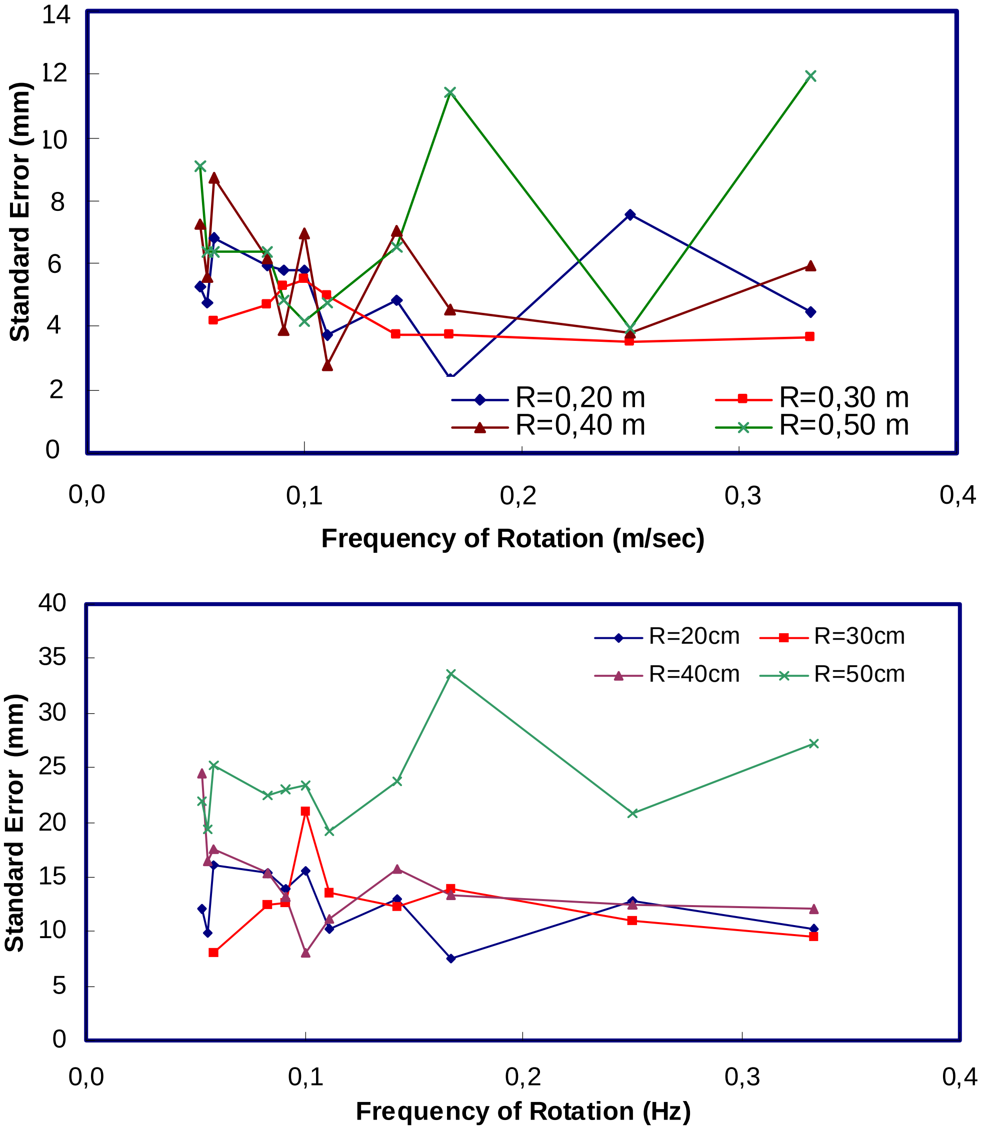


Figure 7: Plot of standard errors in horizontal (top) and vertical (bottom) coordinates of a single point versus the period/frequency of rotation. It is obvious that the accuracy in coordinate estimation is of the order of a few centimetres.

ACKNOWLEDGMENTS

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REFERENCES

Ashkenazi V., and Roberts G. W. (1997). “Experimental monitoring of the Humber Bridge using GPS.” *Proc., Instn of Civ. Engrs*, 177-182.

Breuer P., Chmielewski, T., Gorski, P. and Konopka, M. (2002). “Application of GPS technology to measurements of displacements of high-rise structures due to weak winds.” *J. Wind Engineering and Industrial Aerodynamics*, 90, 223-230.

Cocard M, H.-G. Kahle, Peter, Y., Veis, G., Felekis, S., Paradissis, D. and H. Billiris (1999). “New constraints on the rapid crustal motion of the Aegean region: recent results inferred from GPS measurements (1993-1998) across the Hellenic Arc, Greece.” *Earth planet. sci. Lett.*, 172, 39-47.

Ge L., Han S., Rizos C., Ishikawa Y., Hoshiba M., Yoshida Y., Izawa M., Hashimoto N. and Himori S. (2000). “ GPS seismometers with up to 20 Hz sampling rate.” Earth Planet Space, 52, 881-884.

Greulich F. (1997). “Dynamic deformations monitoring of tall structure using GPS technology.” *J. Surv. Eng.*, February, 49-50.

Hartinger H. and Brunner F.K. (1998). “Experimental Detection of deformations using GPS.” *Proc., Symposium on Geodesy for Geotechnical and Structural Engineering*, April, 145-152.

Nakamura S. (2000). “GPS Measurement of wind-induced suspension bridge girder displacements.” *Journal of Structural Engineering*, ASCE, 126 (12), 1413-1419.

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