PRACTICAL CONSIDERATIONS FOR GLOBAL POSITIONING SYSTEMS IN URBAN ZONES

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Abstract

Global Positioning Systems (GPS) offer the ability to track in real-time the global displacements of large Civil Engineering Systems at a sub-centimeter level. As such, it has become a popular structural monitoring tool; however, its deployment on actual structures, particularly in urban zones, requires careful consideration of a number of practical issues. This paper overviews these considerations, building on experiences gained during five years of GPS deployments through the Chicago Full-Scale Monitoring Program and extensive field studies at the University of Notre Dame. Topics that are addressed in this paper include: comparison of GPS to traditional sensing technologies, influence of reference nonstationarity, improvements offered by redundant reference networks, implications of real-time kinematic (RTK) processing and mitigation of multipath effects.

Introduction

As most traditional structural health monitoring (SHM) sensors provide only dynamic or localized displacement estimates, there is a definitive need to explore alternate sensing technologies to capture the global, total displacements of structures. These displacement quantities are valuable for quantifying static and quasi-static phenomenon such as thermal expansion, settlement, permanent offsets due to damage, and mean and background components of wind-induced response. This latter need, in particular, prompted the first author and her collaborators to explore the use of Global Positioning Systems (GPS) for monitoring tall buildings in the Chicago Full-Scale Monitoring Program (Kijewski-Correa and Kareem, 2003; Kijewski-Correa, *et al.* 2006a). Through this effort, GPS units have been prototyped, extensively calibrated and deployed in full-scale since 2001. Their ability to capture the background and resonant responses of tall buildings in full-scale has been documented by Kochly and Kijewski-Correa (2005) and Kijewski-Correa, et al. (2006 a; b). To this day, the units remain in operation in the City of Chicago monitoring the motions of tall buildings under wind.

Despite the successes of these efforts, a number of practical considerations have also been underscored by these efforts, particularly as they relate to deployments in dense urban environments. These include: the influence of reference nonstationarity, improvements offered by redundant reference networks, accuracy degradations in real-time kinematic (RTK) processing and mitigation of multipath effects. To investigate these matters further, the authors launched a follow-up calibration program at the University of Notre Dame, featuring a highly reliable local GPS network of one stationary reference, one dynamic reference and one rover, i.e., structure whose motions are ultimately tracked by GPS. Through the dynamic calibration phases of this program, GPS performance was benchmarked against accelerometers and terrestrial positioning systems (TPS) to evaluate the performance of each over a suite of signals, including simulated structural responses to wind and earthquake excitations. Another key feature of the program was the experimental simulation, diagnosis and removal of multipath effects to recover the physically meaningful displacements of the rover. This study will summarize a number of the key findings of this research, as they relate to the practical considerations for GPS deployments in urban zones.

This study will first introduce the GPS network established at Notre Dame, which has provided much of the data for the subsequent discussions. A comparison of GPS to traditional sensing technologies is then presented, followed by a discussion of the aforementioned practical concerns associated with GPS deployments. Note that this study is not intended to chronicle the various applications of GPS to full-scale structures around the world, but rather to share the authors' experiences over the last five years.

Overview of Experimental GPS Array

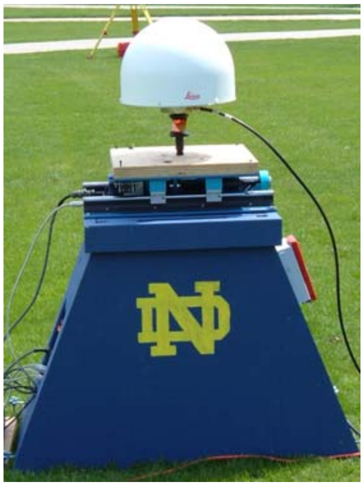

Figure 1. Rover in ND Array.

A field test site was established at the University of Notre Dame to conduct controlled testing of GPS against other sensing technologies. Approximately 50 tests were run using this array in 2005. Full details of the experimental program are provided in Kochly (2006); however, some of the key features of the network, referred to herein as the ND Array, are now provided. The ND Array features two Quansar STII portable shaking tables capable of imparting any desired motion to the antenna. One shaking table hosted the rover site and the other hosted a dynamic reference site, as part of the traditional Differential GPS configuration. Though the ND Array's dynamic reference was held stationary for most of the tests conducted, motions were introduced at this site to emulate the possible deflections of a reference building under a wind or seismic event. A second completely stationary reference was also introduced for a valuable check point. Leica SR530 receivers were used for both the rover and the stationary reference, with Leica AT504 choke ring antennas. This technology is one generation removed from the SR500s deployed earlier in Chicago (Kijewski-Correa and Kareem, 2003). The dynamic reference employed the Leica GRX1200 PRO receiver with an AX1202 antenna. All receivers were set to log at 10 Hz either to internal memory or streamed in real-time. Real-time connectivity is achieved in the array through the use of UDS-200 2-port Lantronix terminal servers interfacing the GPS receivers to Notre Dame's local area network. Stated RMS accuracies of the receivers in this configuration is 10 mm + 1 ppm, where ppm is the separation distance in mm divided by 10^6, though calibration studies in Kijewski et al. (2006b) documented accuracies on the order of 5 mm RMS.

As shown in Figure 1, the rover shaking table was also equipped with a GRZ4360 reflector that could be tracked by a Total Station unit (Leica TPS1200) to form a Terrestrial Positioning System. A PCB 333B52 piezoelectric accelerometer (Sensitivity of 1.015 V/g) was also installed. The TPS can sample displacements at approximately 7.7 Hz with a stated RMS accuracy of 5 mm + 0.2 ppm. These more traditional technologies would be compared to the GPS throughout the course of the testing program.

Performance Assessment Against Traditional Sensing Technologies

In the development of any monitoring system, decisions must be made regarding the sensing elements to be used, given the needs of the client, cost constraints and parameters of interest. One objective of the research at Notre Dame was to compare the performance of GPS against other more-traditional sensing technologies to define the regimes over which each technology was best-suited. To do so, a suite of over thirty calibration studies were conducted using the ND array, comparing the performance of GPS, TPS and accelerometers for signals of varying frequency and amplitude (Kochly 2006). The major findings of this work are summarized by Table 1. It should be noted that a comparison of GPS and accelerometers has also been made in full-scale through the Chicago Full-Scale Monitoring Program as reported in Kochly and Kijewski-Correa (2005) and Kijewski-Correa *et al.* (2006 a,b). In full-scale, RMS deviations between the dynamic displacements of GPS and accelerometers were on the order of a few percent.

In general, GPS can provide a measure of total structural displacement, performing best at low frequencies ($f < 1$ Hz) and large amplitudes ($\sigma \geq 1$ cm). In fact, the sensor was even able to effectively track motions below its stated resolution limit. With respect to tracking simulated building motions, the

GPS was especially proficient for mid- to high-rise structures, including quasi-static displacements due to the background component of wind (Kochly and Kijewski-Correa, 2006). The technology has real-time capability and can be operated unattended and continuously. A significant drawback of the technology, though, is its reliance on satellite orientation, resulting in degraded accuracy in high position dilution of precision conditions (PDOP). However, since these experiments were conducted, satellite availability has increased due to the launch of the Russian GPS network GLONASS and the European Galileo System, which should help to eventually diminish inherent PDOP errors. The latest receiver models are now capable of tracking these new signals (*GPS World*, 2006).

This performance assessment, cost, and a number of other factors discussed by Kijewski-Correa (2005) and Kochly (2006) must enter into the decision-making process when GPS is being considered for any monitoring application. However, it should be noted that accuracy levels of GPS units are improving rapidly with each generation, which is refining not only the quality but also reducing the cost.

Sensor	f = 0 Hz	f ≥ 1 Hz	0 < f < 1 Hz	Continuous & unattended operation	Δ < 1 cm	Δ ≥ 1 cm	Cost
GPS	+	✓	+	+	✓	+	$$$
TPS	+	-	+	-	✓	+	$$
Accelerometer	-	+	-	+	+	+	$

Notes: (+) = sensor performs well, (✓) = sensor performs average, (-) = sensor unable to perform

Table 1. Summary of sensor performance.

Influence of Reference Nonstationarity

The identification of a suitable reference site in urban zones can prove to be one of the most problematic issues for building monitoring by GPS. Besides right-of-way issues, three key constraints are placed on candidate reference sites: (1) as GPS errors increase in proportion to the distance between the reference and rover, the reference should be nearby, (2) the reference site must have an unrestricted or minimally restricted view of the sky, and (3) the reference site must be stationary, i.e., it should experience minimal lateral motions. Generally one or more of these constraints must be compromised in the selection of a practical reference site for urban applications. For example, if a low-rise building is selected to satisfy the third requirement and is located in close proximity to the rover, it is likely surrounded by neighboring tall buildings that will obstruct its views of the sky. This trade-off process often yields a reference site that does undergo some motions itself. While low-rise structures are generally more rigid and thus less susceptible to wind-induced excitations, they can be significantly displaced during seismic events. Thus, the ND array was used to explore the implications of a nonstationary reference.

The results presented here focus on the simulated motions of a low- and a mid-rise RC building under the Loma Prieta Earthquake (Tests #1.1 and #1.2, respectively). Fundamental frequencies were 0.66 and 2.2 Hz, respectively, with 2% damping in the first mode. The reference antenna was displaced to represent the actions of a low-rise reinforced concrete building under the same ground motion. The rover time histories are shown in Figure 2, where the GPS estimates of these motions are processed against both the nonstationary reference and the array's stationary reference. The original shake table command for the rover structure is also provided as evidence of the actual displacement. Note that the rover's motions could not be tracked accurately by the GPS when processed against the nonstationary reference, as demonstrated by the RMS errors in Table 2. From these findings and others reported by Kochly (2006), it was concluded that tracking ability is sacrificed when the reference's displacements meet or surpass (i) the background noise levels of the GPS technology (~1 cm RMS), as in Test #1.2, or (ii) the displacements of the rover itself, as in Test #1.1.

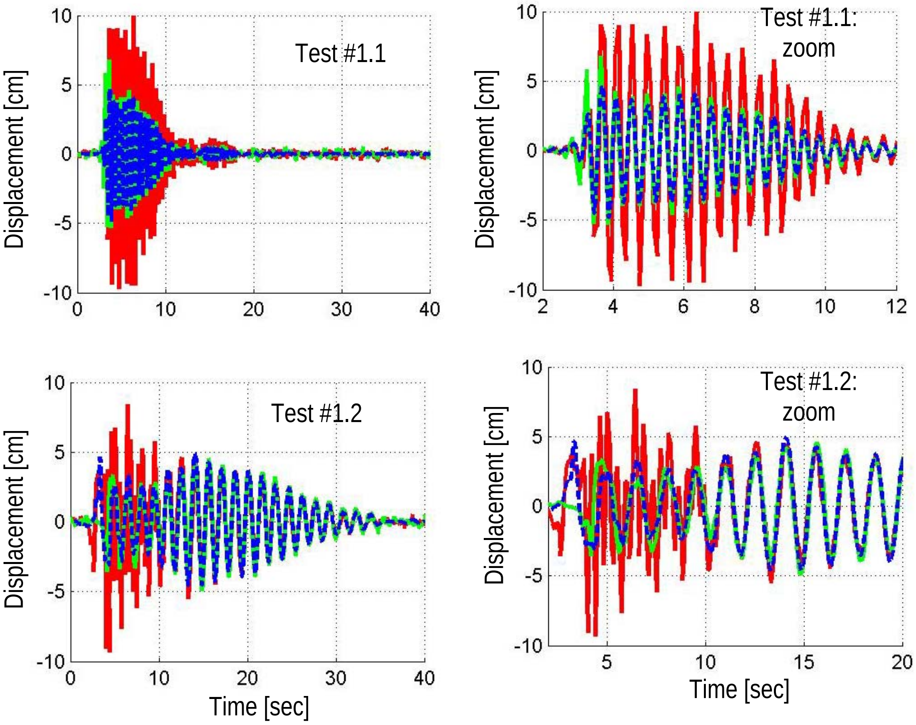

Figure 2. Rover time histories for Tests #1.1-1.2: simulated earthquake response with a nonstationary reference.

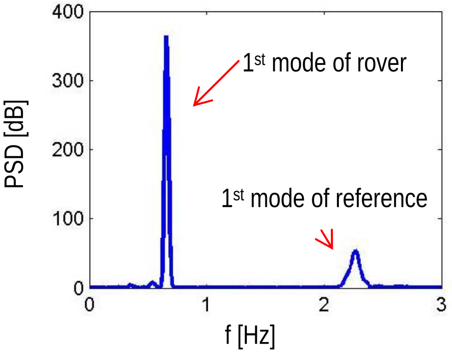

Figure 3. PSD for Test #1.2.

Legend for Figures 2 and 4

- - Shake table
— GPS- nonstationary
— GPS- stationary

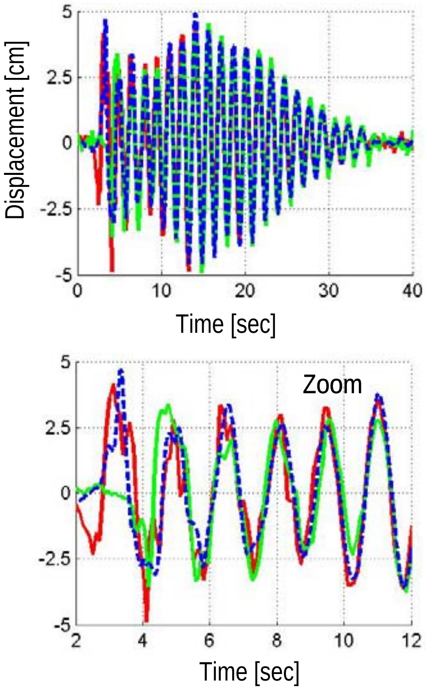

Figure 4. Time history for Test #1.2 after band-pass filtering.

It is interesting to note, though, that for the mid-rise RC structure (Test #1.2), after the initial 10 seconds of the record, the GPS tracking improves dramatically (Figure 2). This is due to the fact that the motion of the reference is greatest during these first 10 seconds, surpassing the inherent background noise in the GPS sensor. During this interval, the GPS response at the rover also manifests a high-frequency distortion, which does not match the natural frequency of the rover structure. In fact, this high-frequency component actually matches the natural frequency of the low-rise reference site. Figure 3 shows the power spectral density (PSD) of the rover response for this test, containing two distinct peaks, with the second peak corresponding to the reference building's fundamental frequency. Using a band-pass filter, this distortion can be removed from the GPS's estimate of the rover displacements, which results in a much cleaner tracking of the signal, as shown in Figure 4. The statistics for the filtered data, referred to as Test 1.2*, quantify the level of improvement introduced by the filtering operation (Table 2). Hence, in a seismic zone, this method may be employed in some cases to remove the reference building dynamics from the displacements recorded at the rover.

						Stationary REF	
Test	Rover Motion	Reference Motion	Table (cm)	GPS (cm)	% Diff	GPS (cm)	% Diff
1.1	low-rise RC, seismic	low-rise RC, seismic	0.97	2.39	146.7	1.20	23.7
1.2	mid-rise RC, seismic	low-rise RC, seismic	1.89	2.28	20.5	1.85	2.2
1.2*	mid-rise RC, seismic	low-rise RC, seismic	1.89	1.83	3.3	1.85	2.2

Notes: Table = shake table command; Stationary REF = tests where reference was held stationary.

Table 2. Performance of GPS under seismic motions with nonstationary reference.

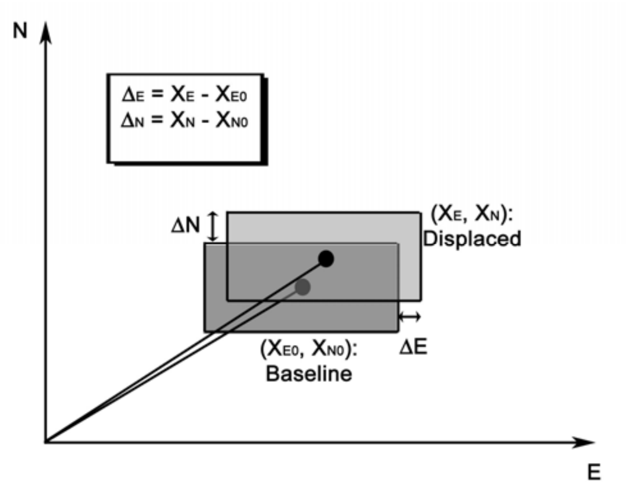

Figure 5. Schematic of rover building showing baseline and displaced position (Kijewski-Correa, 2005).

Establishing a Baseline Position: The Importance of Redundant References

One of the major benefits of GPS technology is the ability to quantify static and quasi-static displacements that cannot be recovered from acceleration data; however, to do so, one must have an accurate baseline position (X_{E0},X_{N0}) of the rover in the local coordinate system in its undisturbed state. Positions in pre-defined regional coordinate systems are cast in terms of its Northing and Easting from the origin of that local grid. Subsequent relative displacements are then determined by subtracting the displaced position (X_E,X_N) from this baseline position, as illustrated in Figure 5. In the absence of highly accurate survey data, this baseline position can be determined in full-scale by logging position data on the rover at night (to avoid thermal expansion/contraction) when wind speeds are very low (< 5 m/s) and satellite orientations are favorable (PDOP < 4). The resulting coordinates of the rover under repeated measurements in these conditions are averaged to determine the baseline position of the rover.

This process was conducted for the rover skyscraper in the Chicago Full-Scale Monitoring Program. Despite honoring all of the aforementioned conditions, the calculated baseline position displayed significant scatter, as demonstrated by a sampling of results in Table 3. This finding underscored the importance of also triangulating a precise initial position for the reference site. The initial position of the reference was established using a self-survey feature inherent to GPS without a reference network. To better identify the initial position of the reference building, its self-survey data was processed against an existing array of reference stations in the Chicago area managed by Kara Company. By processing the reference station against Kara Company's fixed references for several nights with low wind speeds, a more stable average position was determined, with standard deviations of approximately 1 cm for both the N-S and E-W directions. This triangulated reference site is now used to process all data collected at the GPS rover.

Date	Original Rover Baseline Position		Re-Processed Rover Baseline Position	
	Northing (m)	Easting (m)	Northing (m)	Easting (m)
03/07/03	581117.5140	358938.4513	581115.3799	358936.9207
07/13/03	581116.5301	358936.2693	581115.3924	358936.9203
08/05/03	581116.2607	358936.4807	581115.3817	358936.9195
10/06/03	581117.3523	358936.3848	581115.4065	358936.9236
10/23/03	581117.2100	358936.4901	581115.3931	358936.9251
06/15/04	581117.2589	358936.3944	581115.3830	358936.9244
07/15/04	581116.4718	358936.1895	581115.3931	358936.9332
Mean Position (m)	581116.8869	358936.5324	581115.3874	358936.9206
Std Position (cm)	47.95	58.56	2.14	1.43

Table 3. Full-scale rover baseline position data.

Next the rover's earlier baseline position data is re-processed using the newly triangulated reference station coordinates as well as the Kara Network of reference stations. The result shown in Table 3 is a highly accurate baseline position for the rover -- a 25-fold improvement in performance compared to the earlier result. Subtraction of this re-processed rover baseline position (X_{E0},X_{N0}) from all subsequent rover displacements allows static displacements due to wind and thermal effects to be clearly identified. This affirms the enhanced accuracy of processing positions against multiple stable references. Fortunately most cities now have distributed reference stations managed by local municipalities and GPS corporations that can be used to triangulate any new reference point before it is used to process rover station data.

Accuracy of RTK GPS

It had been theorized that due to the near-instantaneous position estimate being made by a GPS sensor operating in RTK mode, a less accurate atmospheric model would be employed than that used when longer durations of data have been collected in a post-processing (PP) mode. Several tests were conducted on the ND Array using terminal servers to stream GPS corrections via Internet in near real-time to calculate positions on-the-fly in RTK mode. The uncorrected position data was also logged on the PC card of the receivers to be later post-processed for comparison. The simulated signals included the tracking of a simple sine wave of ±3 cm amplitude and 0.2 Hz frequency and the dynamic tracking of a simulated high-rise steel building under wind. The results summarized in Table 4 show no discernable effect of RTK processing. However, while the real-time capabilities of GPS are quite attractive, it should be cautioned that this is contingent upon a reliable communications link between the reference and rover. Security and packet loss over local area networks, cellular links or wireless radio communications are quite likely in dense urban environments, particularly since line of sight is difficult to maintain.

Signal Description	Table (cm)	PP (cm)	% Diff	RTK (cm)	% Diff
Sine wave: ±3 cm, 0.1 Hz	2.08	2.05	1.1	2.06	0.7
High-rise steel building, wind excitation	2.01	2.03	0.8	2.04	1.6

Table 4. Effect of RTK mode on GPS accuracy.

Mitigation of Multipath Effects

Despite the numerous advances that have been made in GPS technologies, there is still one factor that limits its utility in dense urban zones: multipath errors. Multipath is the result of satellite signals being reflected off of neighboring objects and arriving with some delay at the receiver. The effect is a long period distortion in the GPS displacement estimate, leading to position errors of up to several meters (Evans and Hermann, 1990). The authors have documented these multipath effects in the Chicago Full-Scale Monitoring Program, using wavelet-based tools to distinguish persistent multipath components from intermittent low frequency energy associated with the background component of wind-induced response (Kochly and Kijewski-Correa, 2005). Despite this, it can still be difficult to discern multipath effects from meaningful background response in full-scale, necessitating a series of controlled tests using the ND Array. Multipath errors were generated using a stationary aluminum sheet oriented to the North of the GPS antenna. Since satellite constellations repeat themselves every sidereal day (23 hours, 56 minutes), observations of these repeating long-period multipath trends over consecutive days provided a useful diagnostic tool that was exploited by the authors. As demonstrated in Kochly and Kijewski-Correa (2006), a GPS Distortion Signature (GDS) could be generated through a least squares fit of the following expression to the measured test data:

$$\bar{u} = \sum_{k=0}^{K} b_k \left(n\Delta t\right)^k \qquad n = 1, 2, ..., N \qquad (1)$$

With the 24-hour GDS in hand, any future tests conducted with the GPS antennas at that particular site can be filtered by subtracting out the signature for the appropriate time window under consideration. An example GDS is provided in Figure 6, demonstrating low-frequency multipath trends. Though these results were generated under controlled field studies, a similar procedure can be conducted in full-scale under the idealized baseline conditions discussed previously to establish an in-situ GDS for any location.

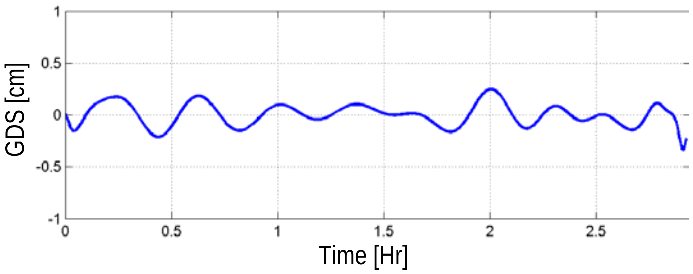

Figure 6. Example of GPS Distortion Signature from field tests in ND Array.

This approach was found not only to successfully remove multipath effects but also other long period distortions resulting from sudden changes in the satellite constellation (Kochly and Kijewski-Correa, 2006). This is an important added benefit, since even in pristine environments free from reflective surfaces, satellite constellations are always changing. Low-frequency distortions due to satellite constellation changes can actually be distinguished from those induced by multipath through a comparison between the power spectra of the PDOP data and the GPS positional data for the same time period (Kochly, 2006). By doing so, the second author was able to quantify that 75% of all long period distortions observed were due to multipath.

Note that choke-ring antennas such as the one used in this research are capable of deflecting multipath signals from low elevations and from beneath the ground plane; however, they cannot disperse multipath signals arriving from higher elevations. For this reason, the diagnostic tools and removal techniques discussed in Kochly and Kijewski-Correa (2005; 2006) and hardware/firmware detection schemes being implemented by a number of manufacturers are a necessity for GPS installations in urban environments.

Conclusions

This study focused on a number of practical considerations for deployments of GPS in urban zones. The major findings of this research are now summarized:

1. GPS was shown to provide reliable, continuous, real-time global displacement data and is best suited for monitoring longer period structures (T > 1s) undergoing motions of 1 cm or more.
2. Nonstationarity of the reference site can become an issue if the motion of the reference site exceeds the background noise inherent in the GPS receiver (10 mm) and/or reaches amplitudes of motion comparable to that of the rover site. This is of greatest concern in seismic zones, though filtering of the rover displacements can mitigate this effect in some cases.
3. The use of a multi-reference network was shown to improve the baseline position estimate 25-fold and is a vital first step in establishing initial positions of the reference and rover in full-scale.
4. Aside from potential communications challenges, there were no observed losses in accuracy in RTK mode.
5. Multipath effects remain a significant error source accounting for nearly 75% of the RMS errors in field studies; however, their long period distortions and those resulting from changes in satellite orientation can be removed using the proposed site-specific GPS Distortion Signature.

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References

Evans, A. and B. Hermann (1990), “A Comparison of Several Techniques to Reduce Signal Multipath from the Global Positioning System,” *Global Positioning System: an Overview*, Bock, Leppard and Cedd, Eds., 74-81.

GPS World (2006), “Leica System 1200 Features GNSS Engine,” *GPS World*, **17(**6).

Kijewski-Correa, T. and A. Kareem (2003), The Height of Precision,” *GPS World*, **14**(9), 20-34.

Kijewski-Correa, T. (2005), “GPS: A New Tool for Structural Displacement Measurement,” *APT Bulletin*, **36**(1): 13-18.

Kijewski-Correa, T., J. Kilpatrick, A. Kareem, D.K. Kwon, R. Bashor, R., M. Kochly, B.S. Young, A. Abdelrazaq, J. Galsworthy, N. Isyumov, D. Morrish, R.C. Sinn and W.F. Baker (2006a), “Validating the Wind-Induced Response of Tall Buildings: A Synopsis of the Chicago Full-Scale Monitoring Program,” *Journal of Structural Engineering*, (in press).

Kijewski-Correa, T., A. Kareem and M. Kochly (2006b), “Experimental Verification and Full-Scale Deployment of Global Positioning Systems to Monitor the Dynamic Response of Tall Buildings,” *Journal of Structural Engineering*, **132**(8).

Kochly, M. and T. Kijewski-Correa (2005), “Monitoring Tall Buildings Under the Action of Wind: The Role of GPS in Urban Zones,” *Proc. of 4th European and African Conference on Wind Engineering*, Prague, July 11-15.

Kochly, M. and T. Kijewski-Correa (2006), “Experimental Verification of a GPS Network: Characterization and Removal of Multipath Effects,” *Proc. of SPIE Intl. Symposia on Smart Structures & Materials/NDE*, February 26-March 2, San Diego.

Kochly, M.C. (2006), *Validation of Global Positioning Systems for Monitoring Civil Infrastructure Systems: Performance Assessment and Removal of Multipath Effects,* Masters Thesis, University of Notre Dame, Notre Dame, IN.