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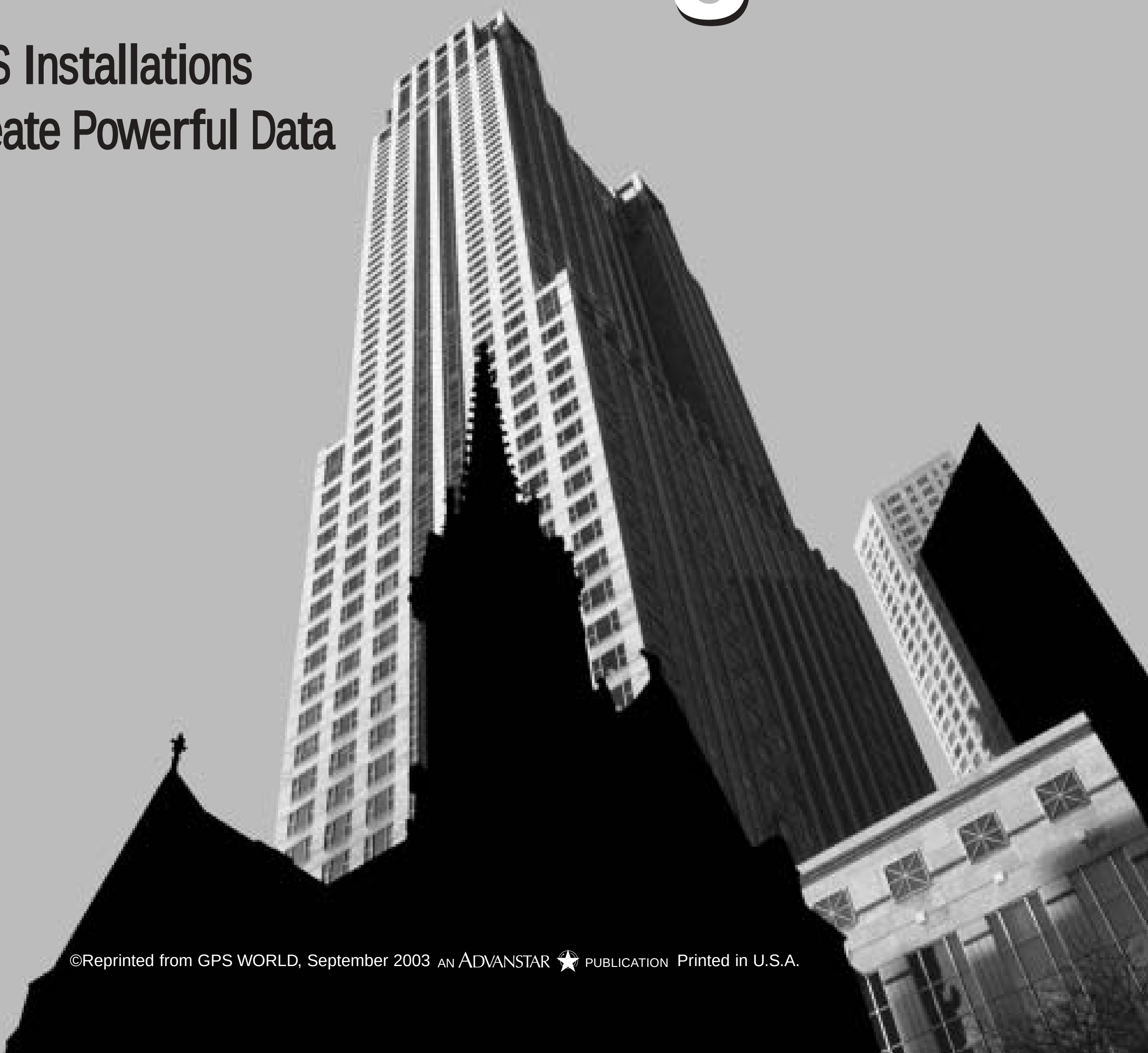

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The Height of Precision

Tall buildings are among the few constructed facilities whose design relies solely upon analytical and scaled models. Home to many important strides in the evolution of these structures — some say Chicago invented the skyscraper — the "Windy City" provides a fitting venue for full-scale investigations to improve understanding of these structures and and their behavior under wind conditions.

by Tracy Kijewski-Correa and Ahsan Kareem
University of Notre Dame

Acutely sensitive to the effects of wind, tall buildings must be designed under a unique set of criteria due to their increased flexibility and the nature of wind loading. Building geometry and surrounding topography and structures influence aerodynamic loads on highrises. Therefore scaled models of tall buildings are generally tested in commercial wind tunnels during design stage to determine the likely loads under both service-level and extreme wind events.

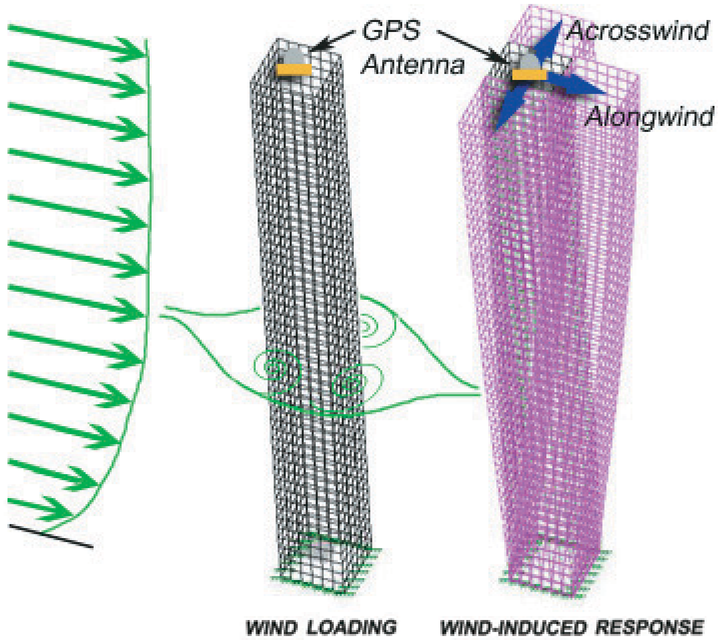
The extreme wind loadings are associated with *survivability limit states*, the first level of tall building design, in this case checking that the wind tunnel's predicted loads for 50 or 100-year wind storms can be safely carried. However, this may not always be the governing design scenario for tall buildings.

Structural drifts or displacements constitute a *serviceability design parameter* that must also be satisfied for more frequent 10-year events. This usually requires a building to be stiffened to limit wind displacements so non-structural elements (partitions, cladding systems) are not damaged and to ensure that mechanical services (elevators) can operate.

A third and final limit state is the *habitability limit state*, quantified in terms of structural accelerations predicted by the wind tunnel for service-level winds. Limiting structural accelerations can mitigate occupant discomfort and anxiety, ensuring the structure is functional from a human as well as a mechanical perspective. This limit state is often critical for tall building projects.

Full-Scale Validation

Engineers must know how accurately they are predicting building displacements and accelerations in the design phase, particularly when using wind tunnel studies, and how these responses affect daily performance and operation of tall buildings from the



▲ **FIGURE 1** Schematic of approaching wind velocity profile impinging on tall building's windward face and separating into vortices impacting the building's other faces (left). This results in the displacement of the building in the direction of the wind (alongwind), as well as side-to-side motions (acrosswind), which can be simultaneously captured by GPS.

perspectives of habitability and serviceability. A lack of systematic validation of these approaches brought about the Chicago Full-Scale Monitoring Program, led by the NatHaz Modeling Laboratory at the University of Notre Dame.

Monitoring three of the city's tall buildings will enable calibration and possible modification of wind tunnel models and subsequent analyses to better match full-scale behavior. This represents the first systematic validation of tall building design, permitting an appropriate calibration of the design process. Furthermore, the study will provide valuable information on *in-situ* dynamic properties of tall buildings (frequencies and damping) over a range of amplitudes. In so doing, international databases used as design guidelines for the highly uncertain damping parameter will be enhanced with tall building data, which is currently lacking. Further, the identified frequencies can be compared to those predicted by finite element models to verify how accurately structural properties of various systems are being modeled. As a result, the next generation of tall buildings can truly benefit from the experiences of their predecessors.

GPS Sensing. Typically, accelerometers monitor flexible structures to track their response to wind. These accelerations and their double integration back to displacements only capture the dynamic components of response. However, tall buildings are displaced by the quasi-static or background component of wind loads, in addition to the dynamic response induced by the resonant component. This background component of response is rarely captured in full-scale. By supplementing accelerometers with a high-precision GPS sensor pair, both the background and resonant components of alongwind and acrosswind displacements can be obtained, offering a rare glimpse at the background component of structural response in full-scale for comparison with wind tunnel-based predictions (see **Figure 1**).

Though GPS has been integrated into bridge monitoring programs worldwide, deployment in dense urban environments like Chicago introduces many other concerns. Therefore we conducted an extensive validation of the sensor before its full-scale deployment, and added further reliability measures before system implementation.

Instrumentation

This program integrates high-precision GPS with a suite of traditional sensors in a comprehensive and robust sensor array. Each building is equipped with four force-balance accelerometers, mounted in orthogonal pairs at opposite corners of the highest possible floor, to capture both sway and torsional responses. These sensor outputs are sampled every 0.12 seconds, archived by a 15-bit data logger, and automatically saved to memory under significant wind events. Considering accelerometer sensitivity, overall system resolution is estimated as 0.001 milli-g. This instrumentation was installed on two tall buildings in June 2002 and on a third in April 2003. The latter was supplemented by two ultrasonic anemometers atop masts at opposite corners of the rooftop, 41 meters above roof level, to map wind field characteristics above downtown Chicago.

Receivers and Antenna. Due to the low amplitude response under wind, we selected GPS receiver pairs providing sub-centimeter resolution (3 millimeters +0.5 parts per million (ppm) static RMS accuracy, 5 millimeters +2.0 ppm dynamic) with a 10-Hz reporting capability. This is paired with an antenna with four concentric choke rings for operation in a dense urban zone populated by reflective surfaces that induce multipath errors.

ANTENNA with four concentric choke rings to allow operations in a dense urban zone populated by reflective surfaces

The accuracy of the differential GPS (DGPS) configuration we used is a function of the baseline separation between the rover station and its reference counterpart. As a result, identifying a suitable, stationary reference with easy access was one of the most challenging undertakings of the program. The reference station must be rigid, have a clear view of the sky, and be in close proximity to the rover: this dictated a low-rise building in downtown Chicago with minimal obstructions. In most cases, such rigid structures are overshadowed by taller neighboring buildings, limiting their ability to track satellites. Fortunately, the owners of a nearby 20-story building, relatively shielded from wind effects with negligible displacements, volunteered their building as the reference site. This location has an unobstructed view of 70 percent of the sky's quadrants, and based on its separation from the rover, the manufacturer's projected dynamic tracking accuracy is 7.6 millimeters (RMS).

Communications Challenges

The system utilized in this study has real-time data-streaming capability for continuous displacement monitoring and decision making, however this requires a reliable communications link between the

TABLE 1 Summary of calibration tests

Test	Description	Purpose
1a–c	Static	Background noise, influence of GDOP
2a–w	Sine wave: ±0.5 cm to ±3.0 cm at 0.1 Hz to 1 Hz	Tracking ability over varying amplitudes, frequencies
3a	Sinusoidal Chirp	Ability to track complex signals
3b	Random Noise	Ability to track complex signals
3c–3f	Simulated structural responses	Ability to track realistic building motions
4a–c	Static with gas capsule	Determine influence of in-line gas capsule
5	Sine wave: ±2.0 cm at 0.2 Hz	Validate on-site coordinate transformations
6a–b	Static	Determine influence of antenna mount

TABLE 2 Averaged statistics from static component of calibration tests

Range	± 0.71 cm
Mean Value	~ 0.00 cm
Standard Deviation	0.22 cm

FIELD EXPERIMENTAL VALIDATION of GPS sensor pair; inset closeup of shake table apparatus

reference and rover. With no clear line-of-sight between the two and the noisy RF environment around the rover, traditional radio telemetry links would be difficult to establish and maintain. This GPS application, intended for collection of displacement data in varying wind events for the evaluation of predictive design tools rather than for building operation, does not require real-time capability. So to avoid data loss, we chose a more conservative post-processing option for the prototyping phase.

We equipped both the reference and rover with a laptop running control-station software, remotely operated. Using this software, the system status can be continually checked, data acquisition direct to the receiver's PC card can be initiated, and any recorded data can then be downloaded from each site to an off-site post-processing station at the University of Notre Dame. Here, software determines the displacements of the rover relative to true North (ΔN) and East (ΔE) on a local coordinate grid, coincidentally aligning with the building's two primary sway axes. The data is then processed, low-pass filtered to remove high frequency noise, and then uploaded for analysis by authorized users at the project web site.

In addition to bypassing communications complications, the uncertainty information output by the post-processor also becomes a valuable tool in assessing the reliability of the GPS displacement solution.

Experimental Validation

With any new sensing technology, calibrations are essential to assess system performance before full-scale deployment. To determine sensor-pair accuracy and identify the level of background noise, we conducted nearly 40 static and dynamic calibration tests during spring 2002, in an open field sufficiently free from potential sources of multipath error and with limited obstructions to preserve a 15° mask angle.

Each choke ring antenna was mounted atop a rigid wood mount, approximately 2.5 meters apart along the North-South (N-S) direction, to avoid shielding and still provide negligible baseline separation errors. The rover unit's mount was firmly affixed to a portable, displacement-controlled shake table permitting introduction of a prescribed displacement time history. N-S motions would be compared to known table displacement to assess dynamic tracking ability. In this configuration, each dynamic test also provided a running measure of inherent background noise, as the East-West (E-W) displacements were always static.

Table 1 summarizes the tests. Static tests assessed the level of background noise in the system and the influence of geometric dilution of precision (GDOP). Tests 2–3 affirmed validation of dynamic tracking ability for a variety of signals with different amplitudes (±0.5–3 centimeters), frequencies (0.1–2 Hz), and waveform complexity. Tests 4–6 enabled us to assess potential signal deterioration due to in-line surge protection, the accuracy of field coordinate transformations, and mount elevation on the system performance.

The static calibration studies captured the background noise levels and resolution limits of the system, quantified by the statistics of motion detected by the GPS when both the reference and rover were held stationary over a range of GDOP conditions.

Table 2 summarizes the statistics of the displacements detected along this static direction in all the tests. From the studies, root mean square (RMS) static accuracy was found to be better than manufacturer specifications (see **Figure 2**), and any peak inaccuracies were at the sub-centimeter level.

In the dynamic calibration testing, satisfactory tracking, when quantified in terms of averaged measures like the standard deviation of the tracked displacements, was achieved consistently for motions above ±1 centimeter. However, instantaneous statistics like peak values are more difficult to capture, though they tend to be consistently identified for signals with amplitudes above ±2 centimeters.

Figure 3 presents one example of the experimental verification for a 0.1-Hz sine wave with varying amplitude levels. The RMS displacements were tracked in all four tests within 10 percent, though the peak values were best captured at the higher amplitudes, as expected.

In Test Series 3, a suite of tests determined the GPS tracking ability for simulated motions of tall buildings under wind (sample shown in **Figure 4**). In this test, the tracking is quite good, even at lower amplitudes of motion, with the RMS error at 8 percent and error in peak values at 9 percent.

All the calibration studies were conducted over short durations. Since GPS constructs its own models to correct for atmospheric delays, the accuracy improves as longer data sets are collected (45 minutes or more), therefore offering some additional improvement in tracking ability for the longer records customarily collected in full-scale.

Reliability Measures

Post-processing adds the advantage of tracking quality assessment, since the post-processing software outputs the standard deviations of the GPS horizontal position estimates (σ_N and σ_E) and their vertical counterpart at each epoch based on the uncertainties in the solutions from the available satellites. One project goal was to utilize this type of information to develop a reliability measure for GPS displacement estimates. Based on the static tests conducted in the field verifications, using the conservative assumption of a Gaussian distribution, over 99 percent of the background noise is captured within three standard deviations of the static test displacements.

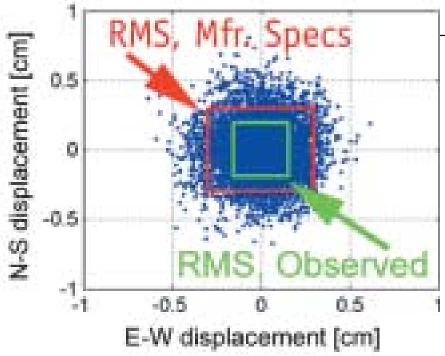
However, in full-scale implementation, there is no source of static data collected continuously that would allow assessment of background error sources. Therefore, we proposed using σ_N and σ_E from the post-processing solution in place of statistical information from static calibration tests. As the standard deviation of position estimates varies at each epoch, this yields a time-varying noise threshold Δ_{noise} that will quantify the reliability of GPS estimates, as

$$\Delta_{noise} = [-3\sigma(t), 3\sigma(t)]$$

where $\sigma = \sigma_N$ or σ_E depending on the direction being analyzed.

The standard deviation of the position estimate is time-varying, offering a direct measure of the inaccuracies anticipated in the calculated GPS displacements and independent of the characteristics of the motion undertaken by the GPS antenna. For comparative purposes, the standard deviations of the static tests are provided in **Table 3** with the average of the instantaneous standard deviations of the GPS post-processor position estimates in each direction. Note that the standard deviation of the background noise in the static tests is always greater than the averaged instantaneous standard deviation of the GPS solution, as the assumption of a Gaussian distribution was shown to be quite conservative. As a result, the use of the standard deviation of the GPS solution in the construction of Δ_{noise}, in lieu of static information in full-scale, is deemed acceptable.

To demonstrate the efficacy of this approach, **Figure 5** shows noise thresholds Δ_{noise} for one of the static tests. The constructed error thresholds, with the exception of a few spikes, conservatively define the upper and lower limits of the background noise in these GPS static tests. These error thresholds can indeed capture the random noise in the GPS sensor, but do not detect the level of systematic errors, for example multipath, in the solution.



▲**FIGURE 2** Example of static calibration test with manufacturer-predicted RMS bounds and observed bounds from experimental testing

This time-varying noise threshold Δ_{noise}, referred to as a Position Quality Threshold (PQT), can then assess the accuracy of a dynamic GPS displacement estimate through either the superposition of the noise thresholds on a tracked signature to show potential peak uncertainties, or by plotting them directly to determine an effective "signal-to-noise" ratio for the system (**Figure 6**). The more the tracked displacements surpass the noise thresholds, the better the tracking ability, with signal amplitudes at least twice the thresholds being ideal. This information is especially useful when moving to full-scale.

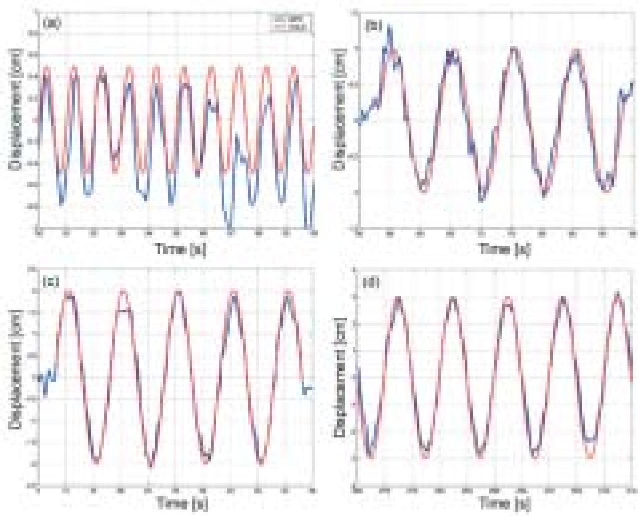
Full-Scale Implementation

Reference and rover equipment was installed in Chicago in September, 2002. The choke ring antennas, topped by protective radomes, were mounted on 2.5-inch diameter galvanized pipes 3 feet taller than any surrounding objects and firmly affixed to the buildings' rooftop to prevent deceptive levels of tracked motion and higher GDOP due to obstructions of lower elevation satellites and an occasional inability to resolve ambiguities. The antenna on the rover structure was mounted on the tall building's penthouse rooftop frame at the building centerline, to capture the sway response, neglecting torsion.

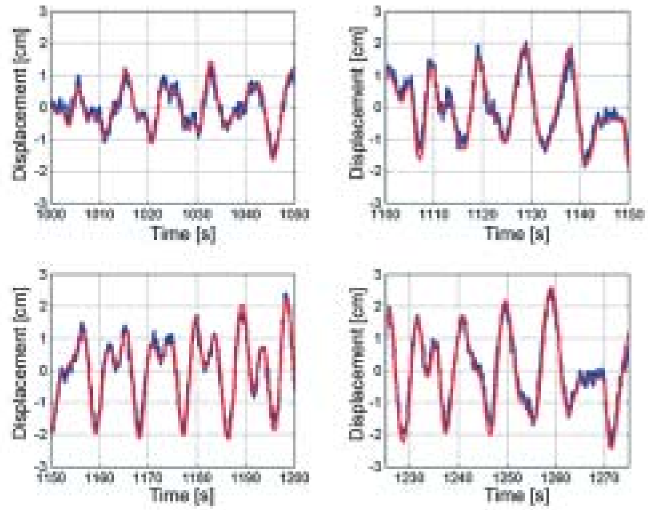
All receivers had grounded in-line protection from electrical surges and other electromagnetic fields intercepted by the antenna. These gas-filled surge protection devices behave as fuses and are easily serviced following a lightning strike. At each site, ventilated enclosures installed at the highest mechanical floors in each building house the GPS receiver, laptop, and back-up power supply (see **Figure 7**).

Communication. Since high-speed internet connections were not available onsite, the laptops controlling the GPS at each building were interrogated by modem, posing an additional challenge. The large amount of satellite data that must be downloaded from the reference and rover for post-processing over state lines (up to 8 satellites, at two locations, at 10 positions per second) could make long distance charges prohibitive.

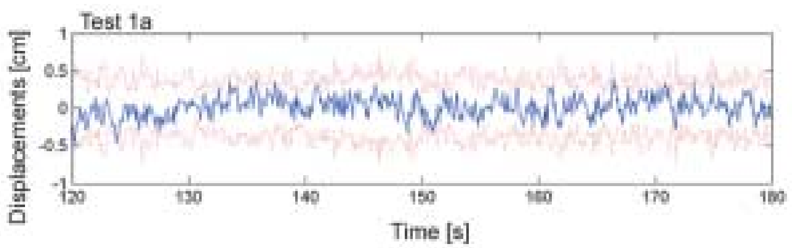
Instead, we established a local communications hub in the Chicago offices of Skidmore Owings and Merrill (SOM), a partner in the study. From the post-processing portal at Notre Dame, the computer housed at SOM could be remotely operated using a high-speed Ethernet connection and commercial software. Once logged on to the hub, a second portal is established by dial-up to the reference or rover laptops to allow their remote operation. In this



▲**FIGURE 3** Verification of GPS dynamic tracking ability for sine wave at 0.1 Hz with amplitudes of motion from **(a)** ±0.5 cm, **(b)**±1.0 cm, **(c)** ±2.0 cm and **(d)** ±3.0 cm. GPS displacements blue, shaking table motion red.



▲**FIGURE 4** Verification of GPS dynamic tracking ability for simulated building response at various times. GPS displacements blue, shaking-table motion red



▲**FIGURE 5** Position Quality Threshold validation: constructed noise thresholds (red), compared to background noise in system from three static tests (blue)

"nested host" configuration, data and commands were transferred using local telephone connections and then uploaded by Ethernet over state lines to provide an economical solution to the data transmission dilemma.

Data Analysis. Efficient transfer, analysis, and dissemination of post-processed GPS displacements and other sensor outputs can generate large amounts of data over the course of this full-scale monitoring program. In this project, many redundant and time-consuming tasks are conducted "on-the-fly" through software interfaced with a Java applet for analysis and display of large stores of full-scale data from any location worldwide.

In the case of GPS data, the applet takes the two position coordinates of the rover and subtracts rover's baseline position (established earlier in the program), plots the resulting displacements of the building along its N-S and E-W axes, constructs and superimposes the PQTs for that record, and calculates a statistical summary of the displacements. Users can then download the processed data to their desktop for further analysis, if desired. A secured prototype site is available at project website www.windycity.ce.nd.edu and is being expanded using structured query language (SQL) to allow authorized users to search the archives of accelerometer, anemometer, and GPS data to identify noteworthy files by specifying a desired response or wind speed/direction level.

A data sample taken on January 7, 2003, demonstrates the ability of GPS to monitor the static and dynamic displacements of this tall building in full-scale (**Figure 8**). During the monitoring interval (15:00 and 15:30 CST), mean hourly wind speed at a nearby meteorological station was 13 meters/second, from the west-northwest with a mean wind angle of 290°. The data was filtered to separate the quasi-static or background components of the wind-induced response from their resonant counterpart, for displacements along the Northerly (ΔN) and Easterly (ΔE) axes of the rover building, respectively. Background displacements are on the order of a few centimeters, more pronounced along the N-S axis. Despite the resonant displacements along the E-W axis being beneath the sensor pair's resolution limits, the system's fundamental frequency is still accurately identified, in agreement with accelerometer data and finite element model predictions.

Urban Environments

Applications in dense urban environments raise a number of concerns, including potential RF interference. Since September 2002, there has been no loss of tracking ability due to RF interference, though at times the ambiguity solution for GPS displacements cannot be achieved satisfactorily, leading to lesser reliability of displacement predictions. This results from satellite blockage at the 20-story reference station building, leading to higher GDOPs here and at

TABLE 3 Standard deviation of GPS static displacements compared to average of instantaneous standard deviation in GPS displacement solution

Test	std (ΔE)	avg (σ_E)	std (ΔN)	avg (σ_N)
1a	0.156	0.129	0.193	0.165
1b	0.186	0.134	0.208	0.179
1c	0.207	0.195	0.229	0.198
4a	0.171	0.143	0.301	0.225
4b	0.166	0.157	0.215	0.212
4c	0.197	0.135	0.227	0.169
6a	0.199	0.202	0.284	0.243
6b	0.224	0.224	0.269	0.252

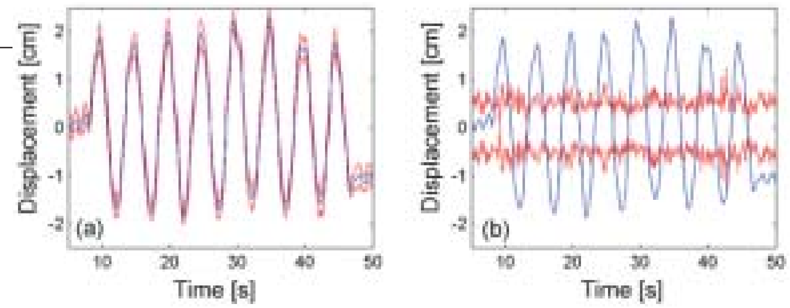
times tracking of only 4–5 satellites, in comparison with the taller rover structure, tracking 8 or more satellites. System performance may be enhanced by moving the reference site to a less shielded location, though it is difficult to find such a site close to downtown Chicago. Despite this, data satisfying ambiguity checks and possessing satisfactory amplitudes of motion relative to the PQTs are being evaluated.

These PQTs become quite important in distinguishing meaningful displacements from inherent errors in the GPS tracking. Consider the data sample from November 30, 2002, filtered to isolate the resonant response of the rover structure along the Northerly and Easterly axes (**Figure 9**). Both filtered displacements (light blue) manifest an upward ascent at the end of their records. To see if this is meaningful, the PQTs are superimposed in green. The PQTs are elevated relative to levels observed in the experimental validations: during calibrations the thresholds were on the order of 5–7 millimeters, whereas they are at times doubled in full-scale.

Due to the baseline separation and noise level in the urban environment, the PQTs observed here should not be alarming, though this situation does require motions of the building to be on the order of a few centimeters to be reasonably tracked. Note the escalating displacements at the conclusion of this record are accompanied by increased PQTs, indicating that this feature is not a multipath effect, but instead a function of satellite availability and GDOP.

Incidentally, inspection of log files for this data revealed that a satellite at the reference station was obstructed over this period of time. The gradual loss of this satellite began to degrade the GDOP, elevating the PQTs as shown just beyond the 2000th second of Figure 9. This demonstrates the importance of these thresholds in analyzing full-scale GPS data and determining the quality of the tracked positions.

Multipath. Another issue that must be addressed in urban monitoring is multipath interference, which can still be present even when choke-ring antennas are used, due to satellite signals reflected off surfaces above the antenna. We have initiated generation of full-scale baseline multipath signatures and a series of controlled multipath tests to identify and remove these systematic errors that may surface in GPS displacement data collected in this program. As the project progresses, multipath errors will be more accurately identified and removed to allow a more reliable correlation of GPS displacements against



▲**FIGURE 6** Two applications of Position Quality Thresholds for evaluating GPS dynamic displacements: **(a)** superposition of noise thresholds (red) on tracked displacements (blue); **(b)** direct threshold plotting (red) for comparison with tracked displacements (blue)

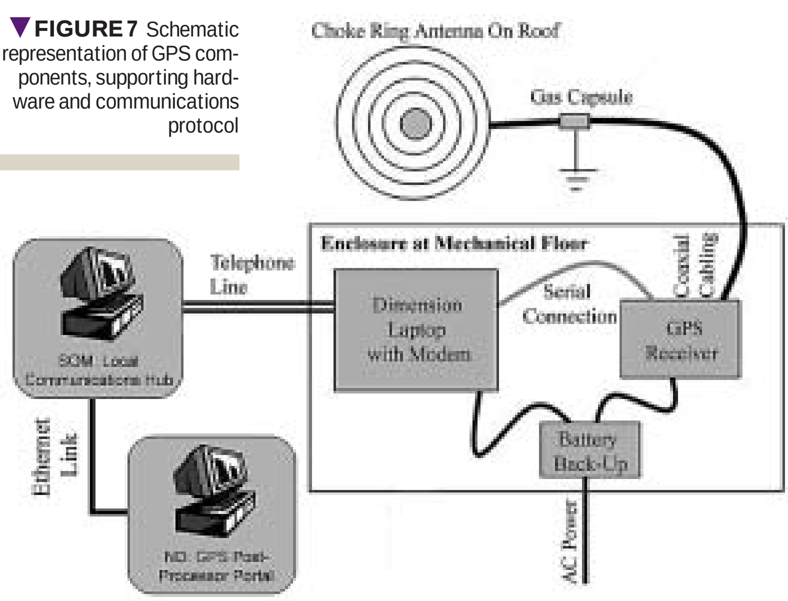
the predicted structure displacements under varying wind events.

Operations. The utility of the information collected in this monitoring program, particularly the GPS data, can be extended beyond the validation of modeling and analysis techniques used in design. If direct dialogs between the reference and rover enable near real-time capabilities, displacements can be streamed not only to the project team but also building owners to assist in operation of building systems such as elevators, skydecks, and coordination of rooftop and other exterior maintenance. However, this requires rectification of many of the communications issues.

Previous work in GPS monitoring had the added benefit of being in relatively open areas so that radio telemetry links could be readily utilized, for example transmitting over water between an instrumented long-span bridge and shoreline. Others have used direct fiber optic links to the reference, again only feasible over short, simple runs. Both these approaches would be very difficult in this application due to the poor line-of-sight and heavily-populated separation between the reference and rover. We also considered cellular links, but the poor reception quality at the rover site precluded that option.

Spread-spectrum wireless radios may present a viable solution that has already been applied in other GPS monitoring programs. Though the rover site hosts a number of two-way radio communications transmitters, interference issues can be minimized through the selection of wireless systems with occu-

▼**FIGURE 7** Schematic representation of GPS components, supporting hardware and communications protocol



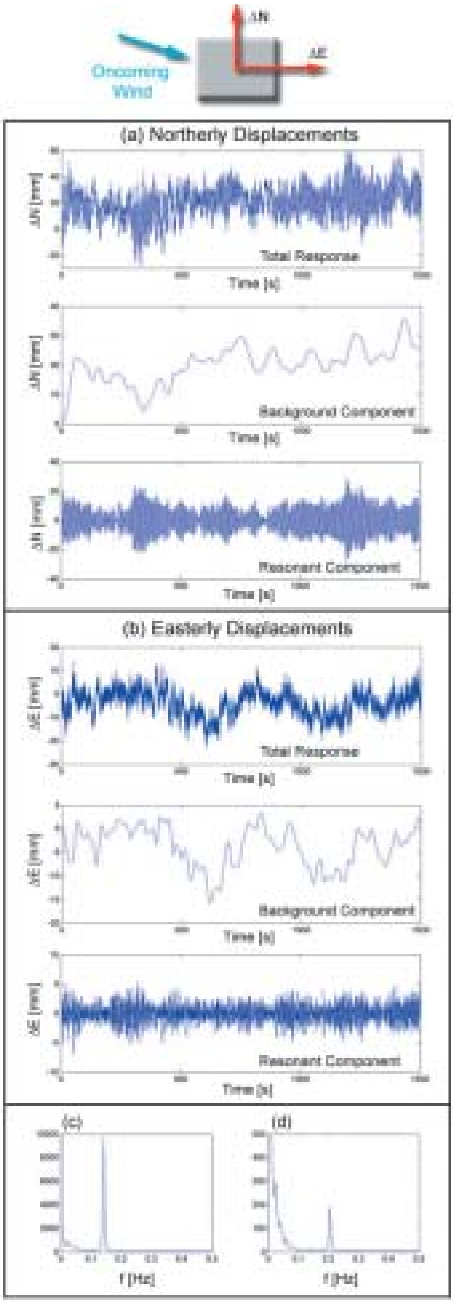


FIGURE 8 Sample of GPS sway displacements of tall building in Chicago under winds on January 7, 2003, decomposed into background and resonant components for **(a)** Northerly and **(b)** Easterly displacements with power spectra for GPS displacements along **(c)** Northerly and **(d)** Easterly axes of the building

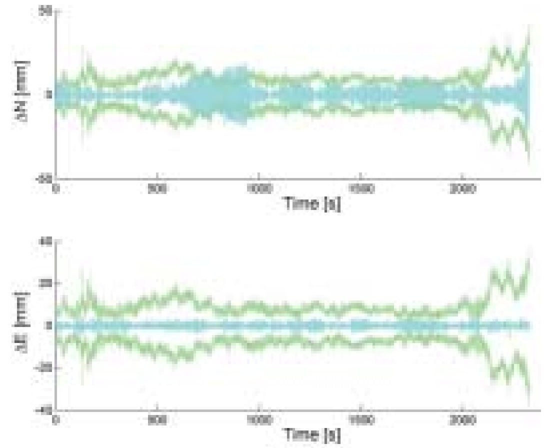


FIGURE 9 Example of Position Quality Thresholds (green) for evaluating reliability of GPS displacements (light blue) of tall building in Chicago on November 30, 2002

pied bandwidths distinct from other transmission sources onsite. In addition, recent advances in the technology have further improved noise immunity and transmission security. We will therefore launch a pilot study to assess the feasibility of radio spread-spectrum wireless radios to enable communications between the reference and rover stations and near real-time displacement tracking in this program.

Conclusion

Just as Chicago's skyline helped set the precedent for tall buildings, these structures continue that innovative tradition by ushering in a new era in GPS monitoring in the United States, advancing the current state-of-the-art in high-rise design. Through the Chicago full-scale monitoring program, the first-ever systematic comparison of tall building response against finite element and wind tunnel models used in their design is currently underway.

In this program, we emphasize the need to calibrate and experimentally validate any GPS sensor before installation in full-scale, so that displacement tracking limitations and resolutions can be accurately benchmarked. As the accuracy of GPS continuously fluctuates throughout the day due to the position and availability of satellites, it is especially important to provide some reliability measure, such as PQTs. Ultimately, the ongoing collection of GPS data and its assessment throughout this project will address the unique challenges facing applications in dense urban environments.

GPS reference antenna

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Manufacturers

The system used **Leica Geosystems** (Heerbrugg, Switzerland) *MC500* GPS receivers; Leica *AT504*/**International GPS Service** (Pasadena, California) choke ring antenna; Leica *ControlStation* software, remotely operated via *PC Anywhere* (**Symantec**, Cupertino, California); Leica *SKI-Pro* software; surge protection devices from **Huber+Suhner** (Herisau, Switzerland); *SA-107 LN* accelerometers from **Columbia Research Laboratories,** (Woodlyn, Pennsylvania); **Campbell Scientific Inc.** (Logan, Utah) *CR23X* data logger; *Matlab 6.1 (R 12)* from **Mathworks** (Natick, Massachusetts) and *Java SDK 1.41-01* and *Java Webstart 1.2* from **Sun Microsystems, Inc.** (Santa Clara, California).

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