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On the Emerging Role of GPS in Structural Health Monitoring

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Abstract

The following study discusses the application of Global Positioning Systems (GPS) in an existing full-scale monitoring program focused on several tall buildings in the City of Chicago. In the context of this program, the efficacy of GPS as a viable technology for structural health monitoring has been demonstrated in both controlled field validations and full-scale deployments. This paper discusses the performance of this full-scale installation with a sampling of full-scale displacement data. As an extension of this program, a second phase of GPS development is then introduced and the prototyping of an integrated GPS and terrestrial positioning system (TPS) for structural health monitoring using scalable networks of instrumentation and next-generation event notification/sensor management software is discussed. The study concludes with an evaluation of this Phase II system's potential for structural health monitoring in urban zones.

Keywords: Global Positioning Systems, Structural Health Monitoring, Full-Scale Measurements

Introduction

With the development of urban zones as the preferred venues for work and residence around the world, an increasing emphasis must be placed on tall building design in terms of economy, efficiency and safety. With respect to the last consideration, the fact that a large number of major urban zones are located in regions of high seismicity and/or frequented by hurricane/typhoon force winds, places an increased emphasis on understanding dynamic load effects due to natural hazards. To date, the design of tall buildings is rooted heavily in basic mechanics and years of research and practice that have rarely referenced the behavior of these structures in full-scale, largely due to the inability to accurately measure various response quantities of interest. However, with the need to refine the design state-of-the-art in response to growing high rise construction world wide, it is now necessary and important to conduct full-scale validations of design practice. A concerted effort toward this end was recently undertaken in the City of Chicago by researchers at the University of Notre Dame, in conjunction with the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario and Skidmore Owings and Merrill LLP in Chicago (Kilpatrick et al, 2003). The program included the instrumentation of several tall buildings in downtown Chicago so that response of the structures under various wind events could be documented in full-scale and compared to predictions from wind tunnel tests and finite element models used in their design, to verify the efficacy of the current design state-of-the-art and to recommend improvements where necessary. This work has also enabled designers and researchers to document in-situ periods and damping ratios and their dependence on the amplitude of motion.

The benefits of such full-scale monitoring, however, are not solely for the design community. With increased emphasis on structural health monitoring to diagnose changes in structural properties indicative of aging and even damage, particularly following natural and manmade disasters, advanced instrumentation is finding a useful and necessary role in infrastructure and property management (Celebi et al, 2004). Recent developments in cities like San Francisco, through the Building Occupancy Resumption Program (BORP, 2003), have advanced the notion of structural monitoring as one tool available to engineers and owners to aid in rapid reoccupation of structures following an event or as a diagnostic for preventative maintenance and even operation of day to day mechanical systems such as elevators. The most significant advantage of these frameworks is their ability to provide real-time information on

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structural response levels and notifications by email or pager in the event that safe operation thresholds have been surpassed due to unforeseen events.

While responses have been traditionally quantified in full-scale through accelerations, these measures are incapable of characterizing the total structural response, which is comprised by static/quasi-static and resonant components, the former of which cannot be recovered through a double integration of accelerations and is significant in a number of situations: identification of permanent offsets following a seismic event, determination of structural settlement, quantification of thermal expansions, and determination of background components of wind-induced response. In these and other instances, the measurement of total displacements or structural drifts is required, though the community has lacked a reliable means of measurement.

Recent advances in Global Positioning Systems (GPS) have now increased the viability of this technology for these applications. Today's systems feature high sampling rates (up to 20 Hz) and sub-centimeter accuracy, making them well-suited for monitoring the biaxial response of tall buildings under dynamic loads – a case in point being the alongwind and acrosswind responses of tall buildings under wind (Fig. 1). As such, GPS was added to the Chicago Full-Scale Monitoring Program to allow rare glimpses of the background component of wind-induced response in full-scale (Kijewski-Correa and Kareem, 2003). This paper will summarize the efforts associated with the Chicago Full-Scale Monitoring Program (Phase I) and discuss the next generation system now being prototyped for health monitoring (Phase II).

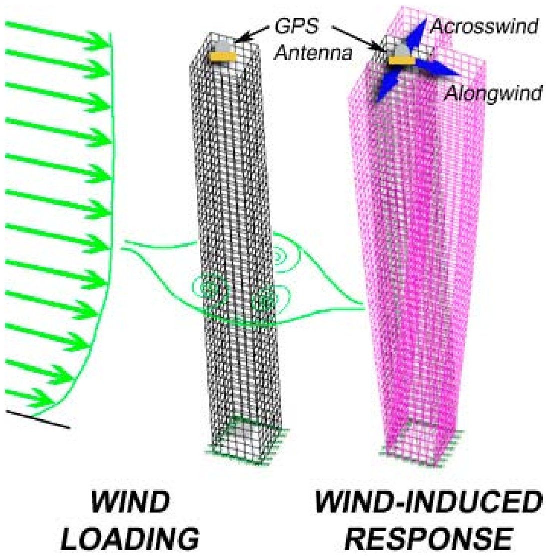


Fig. 1. Schematic of Wind-Induced Response Detected by GPS (Kijewski-Correa and Kareem, 2003).

Methods: Phase I Program

Though GPS has been integrated into bridge monitoring programs around the world, e.g., Akashi Kaikyo Bridge (Kashima et al, 2000), the deployment of GPS in dense urban environments like downtown Chicago introduces a host of other concerns. For this reason, an extensive validation of the sensor was conducted and additional reliability measures were proposed before the system was deployed in Chicago in September, 2002. More details on the validation program may be found in Kijewski-Correa and Kareem (2003). The Phase I Program utilized a pair of Leica MC500 GPS receivers -- 12 channel, dual frequency receivers that offer sub-centimeter resolution with the ability to capture displacements at 10 positions per second. As the system would ultimately be operated in a dense urban zone populated by reflective surfaces, an International GPS Service (IGS) gold anodized choke ring antenna (AT 504) was recommended for the full-scale application. Its use of a ground plane with an antenna encircled by four concentric choke rings helps to minimize the effects of multipath errors induced by the delayed reception of reflected satellite transmissions. The final deployment required two GPS stations in close proximity: one a top the tall building being monitored (termed the rover) and a second on a nearby stationary building (termed the reference). The use of two stations allows a differential GPS (DGPS) configuration that helps to cancel a number of error sources associated with local atmospheric conditions and receiver clock errors to insure sub-centimeter accuracy. Table 1 lists the accuracy specifications of the 500 series systems, while Figure 2 shows the GPS antenna with its protective Radome mounted on the reference's roof and the GPS supporting electronics housed on site. It should be noted that these electronics include a computer running Leica ControlStation (v. 4.2) software, remotely accessed via PC Anywhere (v. 9.2) to initiate data acquisition and download files. As such, full real time capabilities were not realized in Phase I and data was manually downloaded and post processed using Leica SKI Pro software. The Phase II program discussed later utilizes new software and communications capabilities for a fully real time monitoring solution.

Table 1. RMS Accuracy Specifications for Leica 500 Series.

Static	3 mm + 0.5 ppm*
Rapid Static	5 mm + 0.5 ppm*
Kinematic	10 mm + 1.0 ppm*

*ppm = parts per million, divide baseline separation between reference and rover [mm] by 1,000,000.

As with any new sensing technology, calibrations are essential to assess the performance of the system before the full-scale deployment. In order to determine the accuracy of the sensor pair and

Fig.2. GPS Antenna and Supporting Electronics at Reference.

identify the level of background noise, a series of nearly 40 static and dynamic calibration tests were conducted during the spring of 2002 in an open field in Indiana. During these tests, motion was simulated by placing the GPS rover antenna a top a small, portable shaking table that could be used to provide any number of desired excitations. The first test series was conducted to document the background noise of the system by holding the shaker fixed and determining the level of motion falsely detected by the GPS (static testing). An example of such a test is shown in Figure 3, where a random scatter of positions along a North and East grid are detected, all below 1 cm. Through repeated testing of this type, it was determined that the Leica system was surpassing the performance levels indicated in Table 1. The average statistics from the static tests are listed in Table 2.

Table 2. Averaged Statistics from Static Component of Calibration Tests.

Range	+/- 0.71 cm
Mean Value	~ 0.00 cm
Standard Deviation (RMS)	0.22 cm

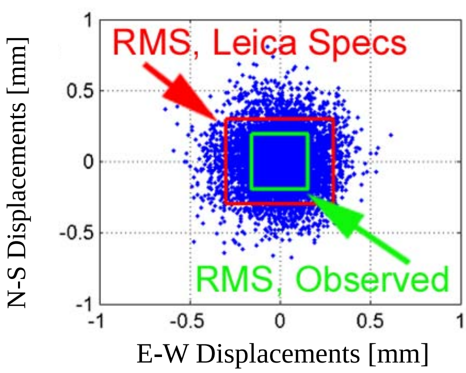


Fig. 3. Static Test Result.

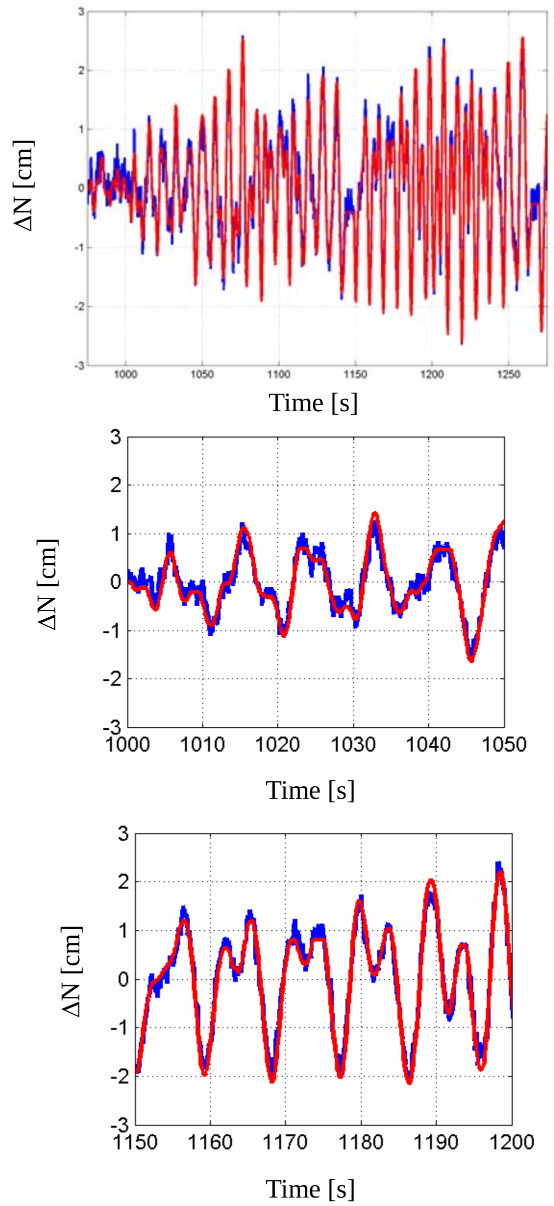


Fig.4. Comparison of GPS Displacements Plotted on Top of the Simulated Shake Table Motions of Tall Building Under Wind, Full Record (top) with Zoom (below).

The next stage of testing involved the simulation of a number of motions using the portable shaking table. The most relevant tests for this discussion were the simulations of a tall building under the action of wind. A demonstration of GPS tracking ability for this test is shown in Figure 4, where a tall building with fundamental period of 8.33 seconds and first mode damping of 1% is simulated. In this case, the RMS response is 1.01 cm, yet the GPS is capable of tracking the motion with significant accuracy, having errors of less than 10%.

Phase I Data Set

To demonstrate the efficacy of GPS for structural monitoring, full-scale response data for the tall

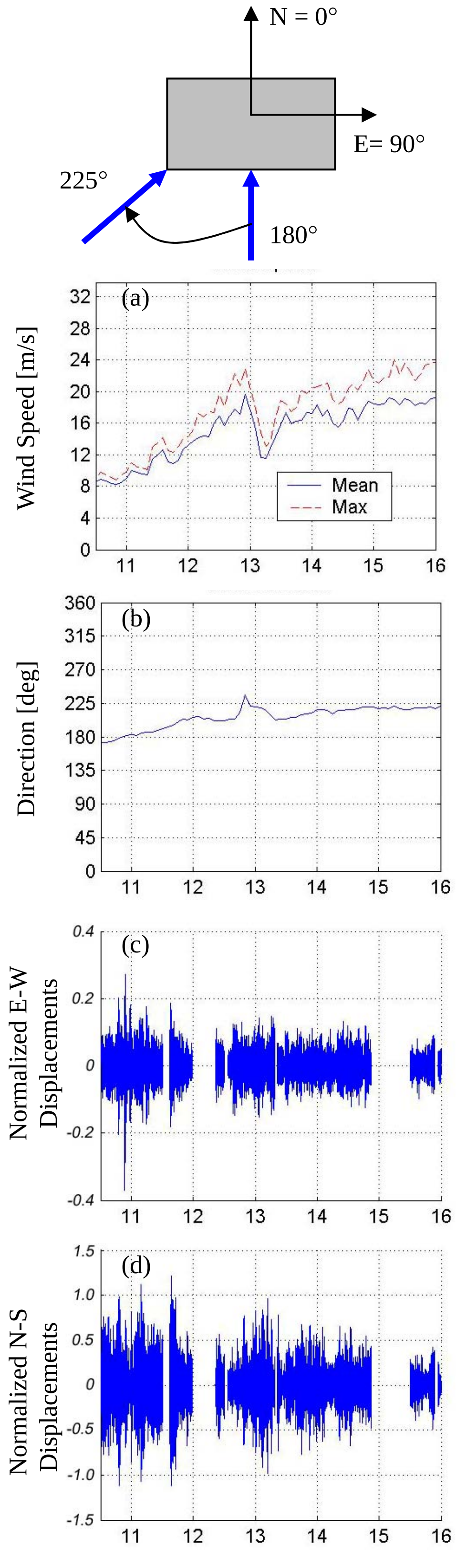


Fig. 5. NOAA 5-Minute Averaged (a) Wind Speed and (b) Direction with Full-Scale GPS Resonant (c) Easterly and (d) Northerly Displacements.

building in Chicago is shown for the March 5, 2004 wind event. During this event, gusts of up to 60 mph were recorded at Chicago's midway airport, causing damage to several buildings in the Loop due to falling debris and broken windows (Janega and Munson, 2004). A sample of the 5-minute averaged surface wind speed and direction measured at a NOAA meteorological station, just east of downtown Chicago, is shown in Figure 5. This is accompanied by the resonant displacements along the Northerly and Easterly axes of the building measured by GPS during that time period. Note that all response values presented here are normalized by a response factor to preserve data privacy, as per owner request. The gaps in GPS measured displacements are the result of shielding of satellites at the reference site, leading to an inability to track at those times. A remedy to this problem is discussed further in a subsequent section. Note that the wind data shown here merely illustrate general trends at Lake Michigan's surface. The wind effects at the location of the GPS-instrumented building may have marked differences due to the aerodynamic complexity of the built environment and variations of wind speed with height. As the wind is approaching in this event from the South to Southwest, the NOAA wind sensor is actually downwind of the instrumented building. These plots are accompanied by a schematic representation of the wind direction relative to the building axes.

The discussion will first focus on the East-West (E-W) axis response. For this axis, the critical wind angle is 180°, producing acrosswind motion. The sample data begins with this critical acrosswind response, producing the largest displacements observed along this axis during the course of the event, despite the fact that wind speed intensifies later in the record, but fortunately at a less critical wind angle. Shortly thereafter, the wind begins switching toward the Southwest, and the response diminishes despite the increasing wind speed, consistent with wind tunnel predictions, which also fall off sharply as the azimuth rotates away from the critical wind angle. Wind tunnel tests similarly predict minimal variations of response when azimuths are between 200° and 250°. These studies also reflect that at these azimuths, increases in wind speed for sub-annual to annual events such as this one do not lead to any significant increases in response. The GPS displacements are again consistent with this wind tunnel prediction.

The North-South axis (N-S) has critical wind azimuths of 90° and 270°, again associated with acrosswind motion. As such, the initial azimuth of this event is not critical for this direction, though being approximately 30% softer along this axis, the building does experience noteworthy alongwind motion in the first half hour of Figure 5. Consistent with wind tunnel predictions, responses in the N-S

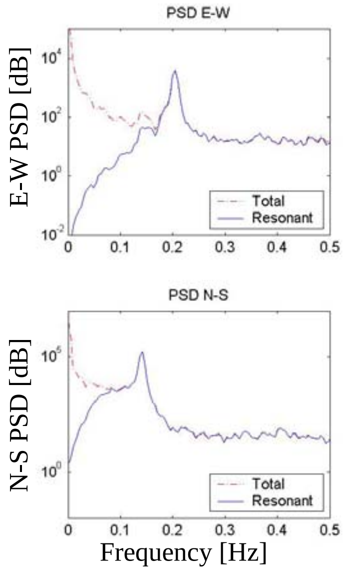


Fig. 6. Building Power Spectral Density from GPS Displacements.

direction diminish as the wind switches from 180° to 200°, remaining relatively constant in magnitude from 200° to 225°. As with the E-W direction, wind angle sensitivity, as opposed to wind speed, largely governs the response here for such annual events.

While the primary advantage of GPS for structural health monitoring lies in its ability to capture static and quasi-static components, this region of the response is also one frequented by multipath effects. The magnitude of these components can be gauged from the power spectral densities in Figure 6. The fundamental periods of the building, identified as 0.14 Hz in the N-S axis and 0.20 Hz in the E-W axis, consistent with the predictions from finite element models, are clearly evident and from the zoomed time histories in Figure 7, the dynamic behavior of the building is well captured. However, these motions pale in comparison to the large energy in the low frequency regions in Figure 6, encompassing both mean, background and GPS multipath contributions, which remain the primary error source for GPS in urban zones (Chen et al, 2001). The multipath distortions arise from satellite signals bounced off of neighboring reflective surfaces. As a result, the GPS intercepts not only the original but also the reflected version at a slight delay. This results in long period trends in the displacement data, whose period depends on the proximity of the reflected surface from the object as well as the elevation and orientation of the transmitting satellite. An example of these periodicities in full-scale are shown in Figure 8, where resonant components of response have been filtered out. Here, along both building axes, patterns with the same periodicity (90 and 180 seconds) are apparent, though of differing amplitude. Their appearance in both components of the building response confirms that the phenomena

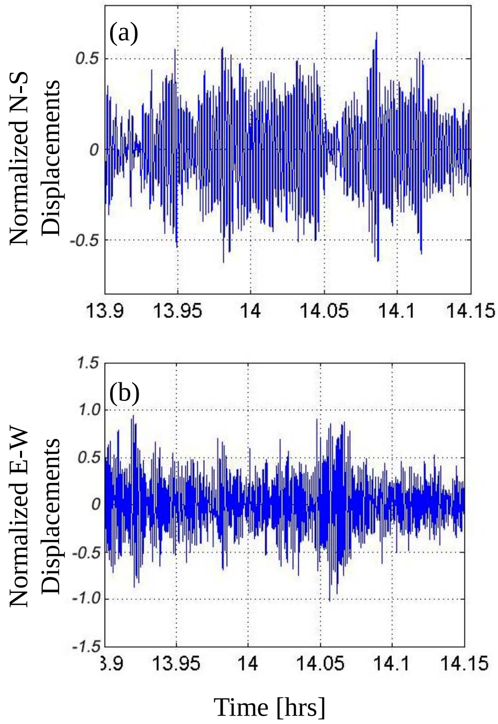


Fig. 7. Zoom of GPS resonant (c) alongwind and (d) acrosswind displacements.

are not wind-induced but rather a consequence of multipath effects, motivating more extensive work in Phase II for accurate diagnosis, isolation and removal of these errors.

Phase I Performance Assessment

The GPS pair has been in operation since September 2002, over which period its performance in full-scale has been evaluated. Such applications in dense urban environments raise a number of concerns, including potential RF interference. To date, 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 is a result of the blockage of satellites at the reference site, leading to the tracking of only 4-5 satellites at times, in comparison with the rover, where deployment on the taller structure permits tracking of 8 or more satellites at a given time. The performance of the Phase I system may be enhanced with the recent acquisition of a new reference site on the west side of the city, so that the drop outs in Figure 5 can be remedied. Another issue that must be addressed in urban monitoring is multipath interference, which can still be present even when choke ring antennas are used (Fig. 8), due to satellite signals reflected off of surfaces above the antenna. A more comprehensive treatment of this error source is now presented in Phase II.

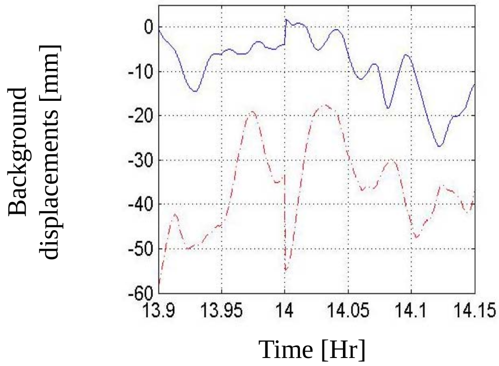


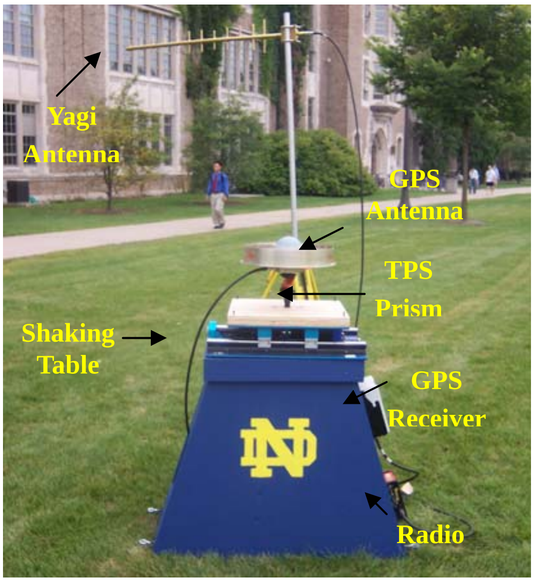
Fig. 8. Static/Quasi-Static Components Displaying Multipath Effects in E-W (solid) and N-S Directions.

Methods: Phase II Program

Given the success of initial deployments of GPS units in Chicago, as well as in other Civil applications (Tamrua et al, 2002, Brownjohn, 2003, Celebi and Sanli, 2004), a second generation GPS program was recently initiated at the University of Notre Dame. This second phase takes full advantage of the real time kinematic (RTK) potential of the GPS units, which enables the corrections necessary for DGPS to be executed in real time so that an accurate, fully corrected position can be output to end users continuously. Phase II will additionally take advantage of the latest software and firmware developments in the Leica line, making GPS even better suited for structural health monitoring. In addition, the tracking ability of a sister technology, terrestrial positioning systems (TPS), will be verified to provide a secondary means of displacement sensing without need for satellite constellations. This technology has already proven useful in construction programs at several long span bridges around the world.

The Phase II program also features an extensive verification program, during which dynamic tracking ability of both GPS and TPS will be quantified again using small portable shaking tables capable of imparting target motions of varying frequency and amplitude. The simulated motions include the wind and/or seismic response of low-, mid- and high-rise buildings of steel and concrete construction with properties based on measured full-scale databases (Lagomarsino and Pagnini, 1995, Arakawa et al, 1996). The properties of the simulated buildings are listed in Table 3, while a photo of one of the shaking table testing podiums used in Phase II is shown in Figure 9a. A prism is mounted beneath the GPS antenna (Fig. 9b), which is tracked through a rapid scan by a Leica Total Station (Fig. 9c) for non-contact displacement measurements with sub-millimeter accuracy. Such non-contact techniques can be integrated with GPS for a comprehensive health monitoring strategy for major Civil structures. In total, dynamic tracking

(a)



(b)

(c)

(d)

Fig. 9. (a) Testing Podium, (b) Zoom of GPS Antenna and TPS Prism on Shaking Table, (c) Total Station for TPS Measurements, (d) Network GPS Reference Antenna.

ability will be verified by comparing the GPS and TPS displacements against those of the shaking table, quantified using the shaking table's digital position command, and a traditional accelerometer.

The validation study will be conducted within a reliable GPS network recently established on the campus of the University of Notre Dame. The network consists of a reference unit (Leica 1200 receiver with AX 1202 antenna, shown in Figure 9d) and two rovers (Leica SR 530 receivers and AT 504 choke ring antennas). One rover will remain static to give a running static accuracy check, while the other will be mounted on a shaker table platform (Figure 9) that will mimic the motions of a building being monitored by GPS, in accordance with building properties in Table 3. In select tests, the reference will also be moved as a simulated low rise building under ambient motion (Table 3) to emulate potential motions of the reference site and investigate the impacts on tracking accuracy at the rover. In addition to tracking ability, susceptibility of the GPS to error sources commonly encountered in urban zones will be investigated, specifically the distortions caused by multipath reflections in dense urban areas and the effect of shielding by nearby tall buildings. The former error source will be simulated in short duration tests by introducing reflective surfaces in various positions to induce the reflections causing the phenomenon. Longer tests under identical conditions will then follow to determine the efficacy with which new firmware/software features detect, isolate and remove multipath distortions. As shown in the previous example, these error sources were of considerable concern in the Phase I program. The program will also document the accuracy lost when utilizing full RTK potential in comparison to the post-processing approach (reverse RTK) currently being applied in Phase I.

Table 3. Properties of Simulated Buildings in Phase II.

Building Type	Height [m]	f_{1-3} [Hz]	ξ_{1-3}
Low-rise Steel	32	0.990, 3.125, 5.000	1%
Mid-rise Steel	142	0.315, 0.990, 1.852	1%
High-rise Steel	337	0.214, 0.602, 1.111	1%
Low-rise RC	21	2.272, 7.143, 14.75	2%
Mid-rise RC	94	0.592, 1.695, 3.125	2%
High-rise RC	183	0.267, 1.053, 1.754	2%

Phase II Software and Hardware Enhancements

The major advantage of the Phase II effort resides in the real time capabilities. As shown in Figure 10, the system being validated at the University of Notre Dame is capable of streaming RTK position corrections from the stable reference site to the rover using radio communications so that corrected positions are available to the end user in pseudo-real-time (any delay being purely associated with communications travel time). This is accomplished using Intuicom Communicator II and Navigator II spread spectrum transceivers with frequency hopping capabilities, enabling the secure transmission of corrections over longer distances without the requirement of FCC licenses and with minimal susceptibility to noise. The systems are capable of transmitting 115.2 kBaud in a frequency range from 902 to 928 MHz. Each transceiver requires a dedicated Yagi antenna installed on the rooftop, as shown in Figure 10.

In addition to firmware upgrades in the Leica 500 Series receivers, two new software packages are also being introduced in the Phase II program. The first is Spider, whose server package controls, configures and monitors any number of deployed GPS receivers, downloading, converting and archiving measured data automatically. The flexibility to coordinate several sensors is particularly important for owners monitoring multiple properties or even in the case of monitoring a single property equipped with two rovers to monitor sway along the primary axes, in addition to torsion. Spider clients can then be distributed to a variety of end users, e.g. owners, designers and building management, who can remotely and securely access data on the Spider server for up to date information on structural response levels. This communications network is also shown schematically in Figure 10. In the event that RTK updating cannot be accomplished on the fly, SKI Pro (used in Phase I) or its replacement, Leica GeoOffice (LGO), can be scripted to run on the SPIDER server and automatically post-process and export the downloaded reference and rover data.

Benefits of Phase II System for End Users

The Phase II system has a number of benefits in the context of structural health monitoring, as the transmission of real time corrections now make accurate displacements available continuously. As such, the client-side remote data access via web will enable owners, designers and building management to have a more active role in structural monitoring, maintenance and operation. Such access to real-time information can assist in day to day operations of building systems such as elevators and skydecks, coordination of rooftop and other exterior maintenance, and in response to unforeseen events. As the Spider system automatically sends messages to end users when motions surpass particular thresholds of interest, owners and management can be immediately notified when action is required.

Conclusions

The Civil Engineering profession is constantly seeking new sensor technologies for health monitoring, particularly those with the ability to track total displacements, including static and quasi-steady components not recovered from accelerometer data, in an unattended and continuous manner. With the rapid development of Global Positioning Systems with higher sampling rates and

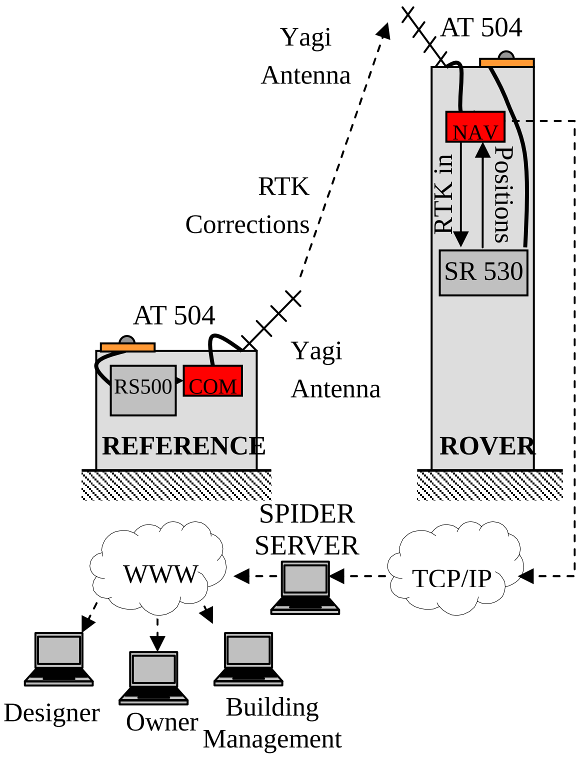


Fig. 10. Phase II Deployment in Full-Scale.

sub-centimeter accuracy, now is an opportune time to investigate the efficacy of this technology for monitoring motions of Civil Infrastructure, including tall buildings. However, like any new technology, it is relatively untested at the precision levels required for structural health monitoring, especially in urban zones where it is most needed. Based on the experiences in the Chicago Full-Scale Monitoring Program, which deployed a GPS unit on a tall building in Chicago in 2002, a more extensive, second phase of prototyping and verification was introduced in this study. While Phase I field validations established the ability of the technology to track centimeter level motions with less than 10% error in both statistical measures, the full scale deployments also affirmed the promise of the sensing technology, though with a need to further investigate multipath effects, the influence of nonstationarity of the reference station, and the limitations in tracking ability due to shielding by neighboring tall buildings. The Phase II validation study is exploring these areas using a next-generation GPS configuration with full real-time capabilities to demonstrate how this system can be used in the context of structural health monitoring for more pro-active management and maintenance of building systems. This study also introduces the use of TPS for more robust monitoring solutions, allowing displacements to be accurately tracked on components of the building not exposed to the sky.

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