

Cover page

Title: *GPS: A New Tool for Structural Health Monitoring – Practical Considerations*

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ABSTRACT

Prior to the advent of Global Positioning Systems (GPS), the ability to monitor global displacements of structures in an unattended and continuous manner was significantly limited if not all together impractical. As a result, most continuous monitoring of structural response employed the use of accelerometers, losing any ability to completely characterize structural displacements, e.g. static drifts and settlements. However, recent advances in high-precision GPS sensors have enhanced the viability of this technology, as today's GPS receivers are capable of real-time displacement tracking at sub-second intervals with accuracy on a sub-centimeter level. This discussion now focuses on the lessons learned from a long term deployment in the City of Chicago, as part of a larger full-scale monitoring program, and reviews directions for future research in GPS for structural health monitoring.

INTRODUCTION

With the mounting burden of aging infrastructure throughout the United States, efficient and accurate means of health assessment are becoming vital components of the Civil Engineering discipline and have spawned a continual search for new sensing technologies that can provide reliable structural information in real-time. Most global response information is obtained through accelerometers; however, the overall structural response includes both a static/pseudo-static contribution arising from sources such as the background component of wind-induced response, racking, settlement, thermal expansion and even permanent offsets in damaged states, as well as a dynamic component due to the resonant contributions of wind-induced motion, seismic excitations and other ambient loadings (traffic, rail, pedestrian). As accelerometers can only capture the latter dynamic motions, a considerable amount of important structural information is lost due to limitations in sensing technologies. The advent of high-precision GPS provides the opportunity to capture total structural displacements continuously and in real-time. With GPS sampling rates exceeding 10 Hz and with sub-centimeter accuracy, now is an opportune time to explore the

feasibility of this technology for structural health monitoring. Despite the considerable merits and potentials of this technology, as with all new sensing tools, there is a definitive need to benchmark the performance of these systems prior to their deployment and to investigate the limitations of the technology. This objective has been undertaken by researchers at the University of Notre Dame for a number of years through both controlled field testing and full-scale verification as part of the Chicago Full-Scale Monitoring Program [1]. GPS units have been deployed on a tall a building and a nearby reference building in the City of Chicago since the Fall of 2002 and have resulted in the documentation of tens of significant wind events. This paper will present some of the lessons learned from these investigations, while providing a preview of continued research in GPS sensing at the University of Notre Dame.

OVERVIEW OF GPS CONFIGURATION

The transmission of GPS signals over great distances leaves them vulnerable to a variety of interferences that can slow the rate of transmission and introduce errors into pseudorange estimates. These are primarily the result of atmospheric effects. Ionospheric delays are corrected through the use of GPS receivers that track both L-band frequencies transmitted by orbiting satellites. Additional distortions due to changes in local temperature, pressure and humidity can be corrected through the use of a nearby reference GPS firmly mounted on a stationary object. This reference station serves as a stable checkpoint with known position and can therefore provide corrections to the GPS on the structure being monitored, termed the rover. The overall accuracy of such differential GPS (DGPS) configurations is proportional to the baseline separation between the reference and rover stations. Leica MC500 GPS dual-frequency receivers in a DGPS configuration were selected for this study, as they offered sub-centimeter resolution with the ability to capture displacements at 10 positions per second. Leica’s accuracy specifications for this system are listed in Table I.

TABLE I. RMS ACCURACY LEVELS FOR LEICA MC 500 GPS

Leica Specifications (Static)	3 mm + 0.5 ppm*
Leica Specifications (Dynamic)	5 mm + 2.0 ppm*
*ppm = parts per million, determined by dividing baseline separation in mm by 1,000,000.	

PERFORMANCE ASSESSMENT

Given the infancy of the technology, the GPS sensors used in this study were subjected to extensive field calibrations before their deployment in the City of Chicago. The tests explored the ability of the GPS to track controlled displacements of a portable shaking table for a variety of static and dynamic signals of varying frequency, amplitude and complexity. While a complete evaluation of the experiments is discussed in [2], relevant findings are summarized herein. Through all the static observations, the RMS background noise level was 1.5-3 mm, with an average value of 2.2 mm, surpassing the static performance indicated by the manufacturers (Table I). The maximum background noise in the system, determined from static testing,

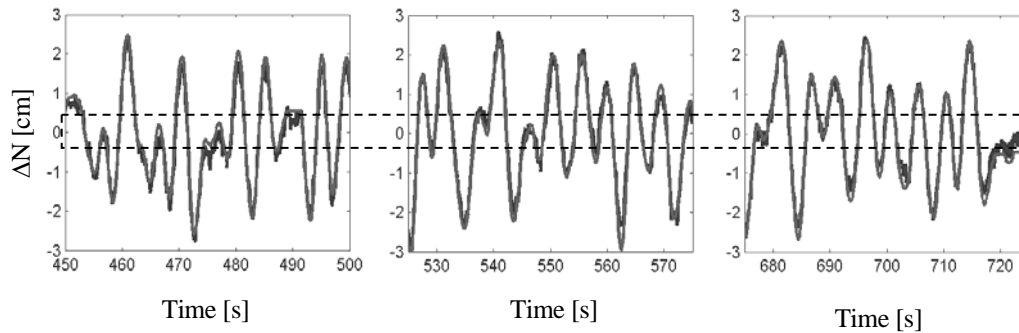


Figure 1. GPS displacement estimates overlaid by simulated motion of tall building, position quality thresholds are shown by the dotted lines.

remained under 1 cm in all experiments, with an average value of 7.1 mm. It should be noted that static tests with $GDOP > 4$ consistently produced higher levels of background noise. 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 sinusoidal motions above ± 1 cm. However, instantaneous statistics like peak values are more difficult to capture, though they tend to be consistently identified for signals with amplitudes above ± 2 cm. Tracking was improved for signals of lower frequency (< 2 Hz). As a result, the technology appears to be best suited for Civil Engineering structures that are dynamically flexible or undergoing significant static settlements. Of particular interest to this study was the ability of GPS to track the simulated motion of tall buildings under wind. An example of this capability is demonstrated by a lumped-mass tall building model, with fundamental frequency of 0.12 Hz and 1% critical damping excited by white noise to produce responses with an amplitude of $\sigma = 1.19$ cm. This simulated motion is shown in Figure 1 where the actual motions of the antenna are superimposed upon the GPS estimates of displacement and show good agreement.

As GPS displacements result from an over-determined set of equations, most algorithms provide an estimate of the standard deviation of the calculated positions. As shown by [3], these can be used to construct position-quality thresholds in full-scale to provide an “effective signal-to-noise ratio.” These position quantity thresholds are shown as dotted lines and are indicative of the “noise floor” in the GPS measurements. Note that the GPS is capable of accurately tracking a range of amplitudes in this signal, with the RMS error being 6% and error in the peak value being less than 10%. Finally, it should be noted that all calibration studies were conducted over short durations (< 5 min). 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.

BENEFITS OF GPS TECHNOLOGIES

One of the obvious benefits of GPS is the ability to detect global displacements of structures in virtually real-time, providing a means for rapidly evaluating performance

indices for the safe operation of structures, e.g., deck deflections of long-span bridges under high wind conditions. As these evaluations are in terms of displacements, the static, quasi-static and dynamic behavior of Civil Engineering structures can be readily assessed. Interestingly, there are other less obvious benefits. Unlike many traditional sensing technologies, GPS inherently provides a reliability measure on its displacement estimates, in the form of position quality thresholds discussed in the previous section.

LIMITATIONS OF GPS TECHNOLOGIES

Even though the aforementioned GPS hardware is capable of achieving tracking down to the sub-centimeter level, to do so requires the identification of a suitable nearby reference, and even with that differential approach, there are still residual sources of GPS errors that cannot be fully corrected. When the satellites involved in the position calculation are well-spaced, the position of the receiver can be determined with greater accuracy. When satellites are too close together, the resected area, and thereby the error in position, is increased. The Geometric Dilution of Precision (GDOP) error is a measure of the optimality of the satellite orientation and is output continuously from the GPS receiver. While GDOP cannot be controlled, users have some influence over the presence of another major error source in urban environments. Multipath errors are caused by a reflection of satellite transmissions that arrive at the antenna some time after the original signal resulting in long period trends in GPS phase data. As cities with large buildings present more reflective objects, these errors can be concerning in urban areas. To minimize this effect, multipath contamination must be rejected as the signal is acquired. In this study, an International GPS Service (IGS) gold anodized choke ring antenna (Fig. 2) is deployed. Although choke ring antennas offer a primary defense against multipath contamination, some residual effects may still infiltrate the signal. As a result, manufacturers of GPS receivers are now developing analysis frameworks that can identify, isolate and remove the traces of multipath errors in the satellite data and are incorporating hardware features to prevent the false lock points associated with the multipath problem.

CHALLENGES OF URBAN DEPLOYMENT

The most challenging aspect of the GPS deployment in Chicago was the identification of a suitable reference site. As the reference station must be rigid, have a clear view of the sky above, and be in close proximity to the rover, it generally requires identification of a low-rise structure in the urban zone having neighboring obstructions limited to a height of 15° from the antenna plane on all sides. In downtown areas, this can be difficult as potential reference sites are often overshadowed by taller neighboring buildings, limiting their ability to track satellites. The Old Republic Building is serving as the primary reference in this study, as it provides a reasonable view of all quadrants in the sky (only one quadrant is obscured), while preserving the stationary reference assumption. The less than ideal visibility at the site has however led to the occasional loss of satellite transmissions at the rover,

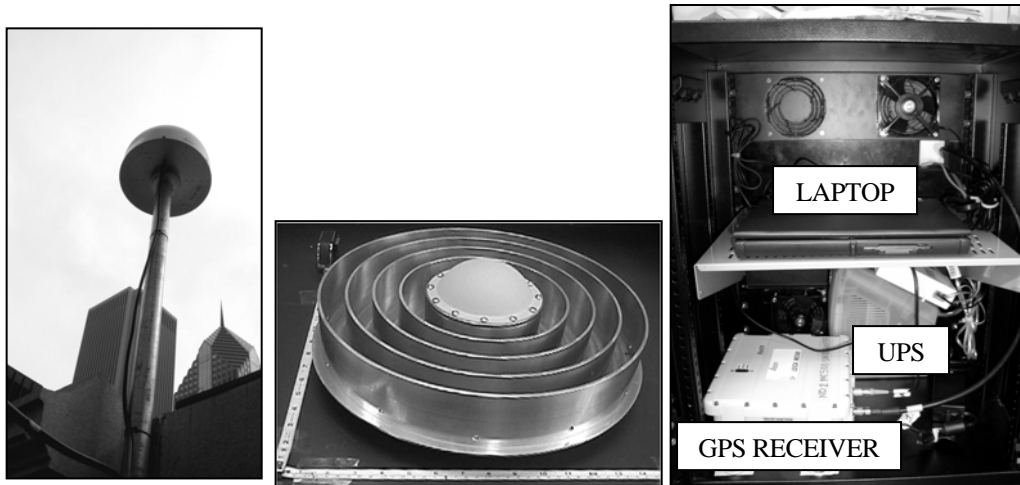


Figure 2. GPS antenna installed on rooftop, choke ring antenna, GPS receiver and supporting electronics (left to right).

thus impacting the quality of GPS displacement measurements at the rover. The system, as deployed in full-scale, is shown in Figure 2. Fortunately, in a number of urban areas, reference stations are being established by municipal agencies and port/harbor authorities. Access to these data transmissions will help to relieve the burden of reference selection from Civil Engineering users. Secondary issues, such as RF interference and jamming can also pose concerns, though these have yet to be encountered by the equipment in place in Chicago. The system did experience a temporary loss of tracking ability in the Fall of 2003 due to increased solar flare activity that caused interference with satellite transmissions both for GPS as well as a number of other communications services.

NEW RESEARCH DIRECTIONS

Based on the experiences acquired thus far in urban zone monitoring, a new GPS research program is now being undertaken at the University of Notre Dame to further evaluate the technology and prototype a new system in conjunction with Leica Geosystems. This program will focus on validation of new softwares developed by Leica, including the Spider system for real time monitoring and assessment, and will evaluate a new radio communications system that promises more robust capabilities within dense RF environments. As part of this program, a second series of controlled validation field studies is planned for the summer of 2004. These will incorporate documentation of performance with respect to amplitude and frequency tracking similar to the investigations in [2], but will explore additional issues, including:

(1) Impact of reference nonstationarity: A second portable shaking table will be incorporated to mimic the deflections of a low-rise building hosting the reference to determine the impact on tracking ability at the rover. Such investigations are important considering that most references installed in urban zones will undergo some displacement associated with their host structure.

(2) Influence of shielding: The selective omission of satellites in the GPS solution will be investigated to quantify the impacts of blockage in urban canyons.

(3) Controlled multipath testing: As multipath is a lingering issue in urban monitoring, an extensive suite of experiments will introduce controlled multipath effects using mobile reflective surfaces. Multipath patterns will then be characterized as a function of distance from reflective source and site-specific multipath prediction maps will be developed to allow users to distinguish multipath trends from meaningful background components. These investigations will not only examine the capabilities of new firmware and software for detecting multipath but also develop wavelet-based post-processing methodologies to remove multipath that has infiltrated the resulting solutions, particularly for short duration data sets.

(4) Post Processing vs. Real Time Processing: The suspected loss of accuracy encountered when using a fully real time kinematic (RTK) scheme will be identified through comparisons of post-processed GPS results with those obtained using a fully RTK scheme with broadcast corrections from the reference.

(5) Multi-reference processing: Following the field studies, the new system will be installed on a 183 m tall building in Chicago for full-scale validation. In this process, positions will be determined using the existing reference station from the Chicago Full-Scale monitoring program [1] and from a second reference station located at the west side of the loop to assess the robustness of rover displacement estimates.

(6) Using the information gathered in tasks 1-5, the existing database of GPS measured displacements for the rover in the Chicago Full-Scale Monitoring program [1] will be re-evaluated and any multipath effects will be identified and removed to improve the reliability of that data set and allow comparisons of design displacement predictions and measured full-scale observations.

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