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Recent research and applications of GPS-based monitoring technology for high-rise structures

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SUMMARY

Monitoring the response of structures, especially tall buildings, under severe loading conditions is an important requirement for the validation of their design and construction, as well as being a maintenance concern. This paper presents a review of current research and development activities (since 1995) in the field of high-rise structure health monitoring using the Global Positioning System (GPS). The GPS monitoring technology and its accurate assessment method are firstly briefly described. Then, the progresses on monitoring the displacement of the high-rise structure caused by the ambient effects including wind, thermal variation, and earthquake-induced responses are discussed in details. Following that, the states of the art of augmenting the GPS monitoring technology are reviewed. Finally, existing problems and promising research efforts in the GPS-based health monitoring are given.

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1. INTRODUCTION

Today there are many more large and/or tall engineering structures than in the past. These structures are being designed to be more flexible and to resist extensive damage from changes in temperature, severe wind gusts, and earthquake tremors. The finite element model (FEM) analysis, shaking table, and wind tunnel tests of scaled models are often carried out to assist structural design (e.g., Li and Huo [1]). However, loading conditions in the real environment are always much more complicated than what engineers consider. On the other hand, during the service time, it is inevitable that these slender structures suffer from environmental corrosion, material aging, fatigue, and coupling effects with long-term load and extreme load. The induced damage accumulation and performance degeneration due to the aforementioned factors would reduce the resisting capacity of the structures against disaster, even resulting in collapse due to structural failure under extreme loads [2,3].

Therefore, there is significant interest in securing the investment with two fronts: first, the safe operation and maintenance of the project to ensure a long service life and, second, insuring safety and efficiency of modern design practice. Both of these intentions may benefit from instrumentation and monitoring of the structures. Structural monitoring serves several purposes. For example, it can provide structural response data allowed for the built performance to be checked against design criteria, which will be an increasingly useful exercise given for the movement towards 'performance based design' of structures. Over a long period, the monitoring can also provide the opportunity to identify 'anomalies' that may signal unusual loading conditions or modified structural behavior, which can, in the extreme case, include damage of failure. The final use is to provide data for calibrating design codes [4,5].

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Generally, the serviceability of high-rise buildings against external loads such as wind loads is evaluated in terms of two types of structural responses: lateral displacement and horizontal acceleration level [6,7]. The excessive lateral displacement can cause structural problems as well as other diverse problems on non-structural elements such as damage to finishing materials, whereas the excessive horizontal acceleration level can bring feelings of unpleasantness to building occupants. For these reasons, various studies have been conducted on methods of measuring and controlling relative lateral displacements and horizontal acceleration of high-rise buildings [8]. For many years, monitoring the dynamic behavior of high-rise structures has relied on measurements made by accelerometers installed on the structure of interest. To some extent, recordings of the acceleration response of structures have served the scientific and engineering community well and have been useful in assessing design/analysis procedures, improving code provisions, and correlating the system response with damage [9]. However, monitoring the global response via accelerometers can only provide an indication of resonant response and fails to capture static and quasi-static behaviors. Although the displacement can be obtained by a double integration process of acceleration response, the process is not readily automated because of the nature of signal processing, which requires (1) the selection of filters and baseline correction (the constants of integration) and (2) the use of judgment when anomalies exist in the records. Consequently, this process can lead to errors in the calculation of velocities and displacements. This problem is more acute for permanent displacements. It is doubtful that the accelerometer measurements can be used to recover the permanent displacements at the centimeter level, and even if they could, it is questionable if it can be carried out in real time [10]. Other methods of displacement sensing were also developed for these needs. Techniques including land-surveying techniques (theodolite, level, total station, etc.), measurement robot, laser displacement sensors, and photo/video imaging techniques have all received recent attention but have limited utility under inclement atmospheric conditions and are often not feasible for continuous, unattended, and long-term monitoring because they rely on the presence of surveyors to gather data thus demand manpower, which is often infeasible [11].

In contrast, the Global Positioning System (GPS) technology can measure directly both static and dynamic responses, and nowadays, relative displacements can be measured at rates of 20 Hz and even higher up to 100 Hz. The accuracy of dynamic displacement measurement using the GPS is at a sub-centimeter to millimeter level and at a maximum distance from the reference GPS receivers to the building receivers of up to 30 km. These provides a great opportunity to monitor, in real time, the displacement or deflection behavior of high-rise structures under different loading conditions, through automated change detection and alarm notification procedures. The past 20 years have witnessed intense research and applications in the field of the GPS. In the following sections, the paper will describe this enabling technology and review its applications to tall building health monitoring.

2. GPS-BASED MONITORING TECHNOLOGY

2.1. Principles of GPS positioning

The GPS is made up of three parts: satellites orbiting the Earth, control and monitoring stations on Earth, and the GPS receivers owned by users. The GPS positions are calculated by the concept of triangulation, using the known position of satellites overhead to determine the position of a GPS receiver pair on Earth (Figure 1). Each satellite continuously transmits the current time, as well as information about its current position (x_i, y_i, z_i) in its orbital path. The distance, or slant range (S_i), of the ith satellite to the unknown position on Earth (x_i, y_i, z_i) is determined from the travel time of the transmitted GPS signals. This position (x_i, y_i, z_i) is defined in terms of the World Geodetic System 1984 (WGS-84) coordinate system, which provides, in Cartesian coordinates, the position on the surface of an ellipsoid representative of the earth, as described in [12]. This can then be projected onto a local coordinate system predefined for every region by the classic seven-parameter coordinate transformation model. For a constellation of N_{sat} satellites, a series of slant ranges can be defined as

$$S_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \quad i = 1, 2, \ldots, N_{\text{sat}} \tag{1}$$

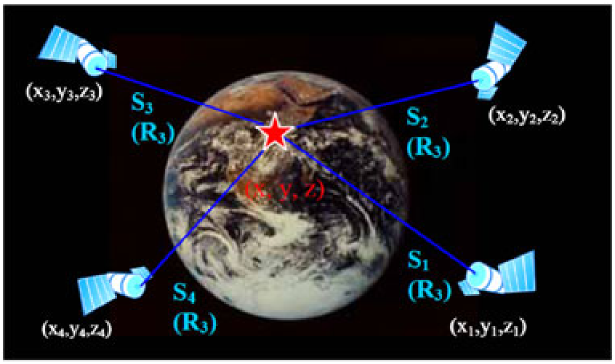

Figure 1. GPS strategy for determining position [38].

To account for the clock inaccuracies between satellites and civilian GPS receivers, a time bias b is then introduced into Equation (1), where slant range is replaced more appropriately by *pseudorange*, R_i, resulting in

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b \quad i = 1, 2, \ldots, N_{\mathrm{sat}} \tag{2}$$

It is necessary to expand the number of required satellites to a minimum of four to solve for all the system unknowns. Typically, as more than four satellites are available, an overdetermined set of equations can be generated using Equation (2) to obtain an even more accurate position for the receiver. The GPS satellite signals are freely available to all civilian users. For anyone with a GPS receiver, the system will provide location and time information in all weather, anytime, anywhere in the world.

2.2. GPS-based monitoring technology for high-rise structures

The GPS surveying techniques consist of static, fast-static, and real-time kinematic (RTK). Table I lists the accuracy potential of different GPS positioning modes. The early work in the GPS monitoring of civil engineering structures can be traced back to the static monitoring of settlements, thermal expansion and other long-period displacement trends in the high hank and dams [13]. Since the solution of the GPS Ambiguity Resolution on the Fly, the RTK technology has been developing fast in structural health monitoring (SHM). Under the mode of the RTK, the reference station serves as a stationary checkpoint whose 3D coordinates have been previously determined by the conventional static GPS method and constantly records the difference between its known position and the position calculated from the satellite data. The detected differences are indicative of the errors from the satellite hardware and more important, lower atmospheric delays. An ultrahigh-frequency radio set (or other data transmission method such as fiber-optic communication or high-speed internet link) is then used to send the errors to the rover. The rover, which is the GPS receiver whose position is being tracked, uses this error information to improve its accuracy. The clock offsets in the receivers and satellites and the atmospheric propagation delays can be ignored because the two receivers are in close proximity, which means that the errors are strongly correlated. By this approach, the position of the rover station can be accurately determined. Figure 2 shows the general schematic of the GPS deployment on a high-rise structure [14].

3. ASSESSMENT OF MEASUREMENT ACCURACY OF GPS

The GPS technology is an emerging tool for measuring and monitoring both static and dynamic displacement responses of slender engineering structures to ambient loads. As a relatively new

Table I. Accuracy levels for different GPS positioning modes.

Item	Static	Fast-static	RTK
Time required to calculate a position	Several hours	8–25 min	Approximately 15 s
Positions measured within	0.5–2 cm	1–5 cm	1–5 cm

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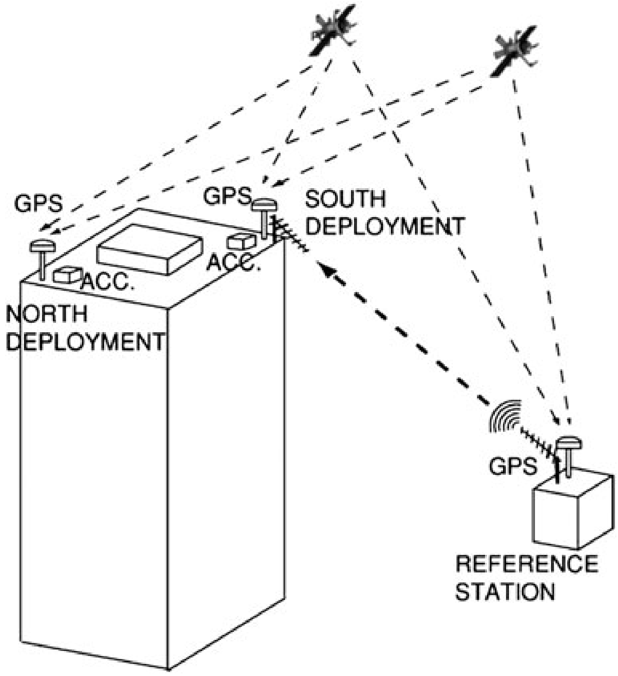

Figure 2. General schematic of the GPS deployment on a high-rise structure [14].

approach, the GPS performance must be thoroughly validated before its application in full scale. Many researchers have conducted feasibility trials to investigate the following problems [15]: (1) What is the range and level of accuracy of modal frequencies determined with the GPS? (2) Does this accuracy depend on the frequency of recorded oscillations? (3) Can variations in modal frequencies and multiple modal frequencies in a single displacement record be identified?

3.1. Evaluation of GPS receivers' performance in static status

There are generally two evaluation approaches of GPS receivers' performance: the zero-baseline test (ZBL) and short-baseline test (SBL) [11]. The guidelines are not too prescriptive with regards to the frequency of such tests, simply requiring that the test should be performed at regular intervals or before any GPS monitoring activity is carried out.

A ZBL is performed to determine the correct operation of a pair of GPS receivers, associated antennas and cabling, and data processing software. The test is carried out by connecting the two GPS receivers to a single antenna using an antenna splitter appropriate for the brand of receiver/antenna. This is a comparatively simple test that can verify the precision of the receiver measurements as well as validate the data processing software.

An SBL is a truer representation of survey conditions, and so, the performance of the receivers in practice can be assessed. Two antennas are positioned on two established points, the coordinates of which are known from previous static surveys. The two points are roughly no longer than 50 m apart. At each end of the baseline, each receiver is connected to the same kind of antenna, meaning that the baselines measured by each receiver combination are the same. Similar to the ZBL, atmospheric errors and clocks are still mitigated, but multi-path effect will be presented in the solution.

3.2. Evaluation of GPS receivers' performance in dynamic status

Although the versatility of GPS receiver technology has been dramatically improved, the GPS kinematic monitoring results still suffers from many factors, such as the data sampling rate, satellite coverage, atmospheric biases, multi-path effects, receiver noise, and GPS data processing methods [16]. Many calibration tests have been conducted to investigate the feasibility of applying the GPS technology to monitor structural dynamic responses by various kinds of equipments.

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3.2.1. Shaking table test. Ogaja *et al*. [17] investigated the feasibility of the GPS for detecting and discriminating the tall building displacement from a GPS seismometer experiment; the results indicated that the GPS is capable of resolving the high-frequency vibration signature, provided the Nyquist sampling theorem is obeyed. In the same year, Ge *et al*. [18] used two Trimble MS750 (Trimble Navigation Ltd., Sunnyvale, CA, USA) GPS receivers in the RTK mode with a fast sampling rate of up to 20 Hz to test the feasibility of a 'GPS seismometer' in measuring displacements directly. The GPS antenna, an accelerometer, and a velometer were installed on the roof of an earthquake shake-simulator truck, as shown in Figure 3. The simulated seismic waveforms resolved from the RTK time series were in very good agreement with the results from the accelerometer and the velometer, after integrating twice and once, respectively.

Tamura *et al*. [19] compared the temporal variations of the displacements measured by RTK-GPS and the wire displacement transducer. As shown in Figures 4 and 5, when the vibration frequency of shaking table was lower than 2 Hz and the vibration amplitude was larger than 2 cm, the RTK-GPS results seemed to closely follow the actual displacement.

(a) Earthquake shake-simulator truck

(b) Setup of the equipment

Figure 3. GPS seismometer experiment [18].

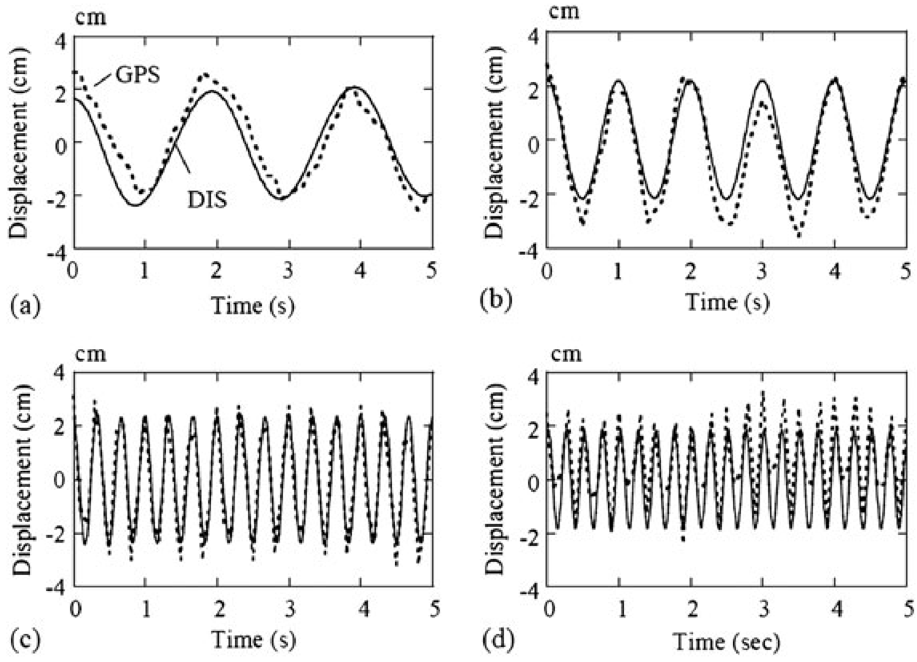

Figure 4. Comparison of RTK-GPS output and actual displacement by wire displacement transducer ($Y = 2$ cm): (a) $f = 0.5$ Hz; (b) $f = 1$ Hz; (c) $f = 3$ Hz and (d) $f = 4$ Hz [19].

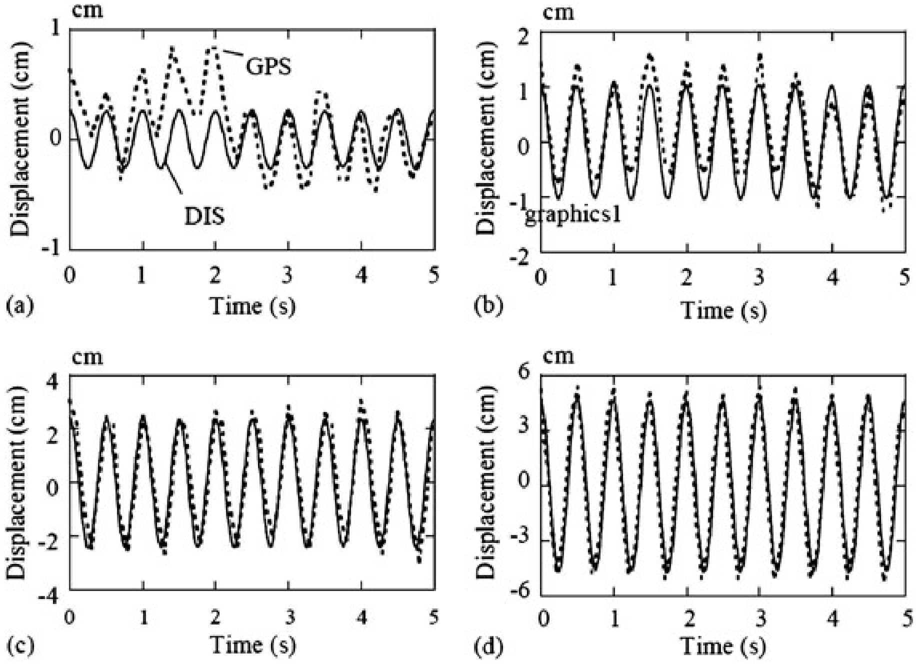

Figure 5. Comparison of RTK-GPS output and actual displacement by wire displacement transducer ($f=2$ Hz): (a) $Y=0.25$ cm, (b) $Y=1$ cm, (c) $Y=2$ cm, and (d) $Y=5$ cm [19].

Kijewski-Correa and Kochly [20] conducted approximately 40 tests by a pair of Leica MC500 (Leica Geosystems, Heerbrugg, Switzerland) dual frequency and 12 channel receivers to investigate the recever's dynamic tracking ability, background noise, influence of in-line surge protection, influence of mount dynamics, and corrections for orientations not aligned with true North. The GPS antennas were mounted on wooden platforms to avoid blockages during testing, were separated by a 2.5-m baseline, and were oriented so that motions of the simulator would be along the N–S direction, as shown in Figures 6 and 7. The calibration program demonstrated that at sufficiently large amplitudes, the GPS performance was independent of the frequency of motion; however, for low amplitude

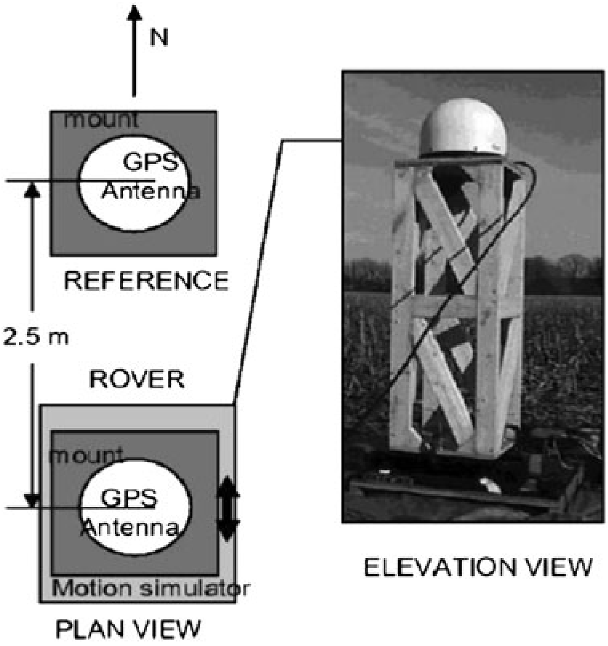

Figure 6. Schematic of reference and rover antenna [38].

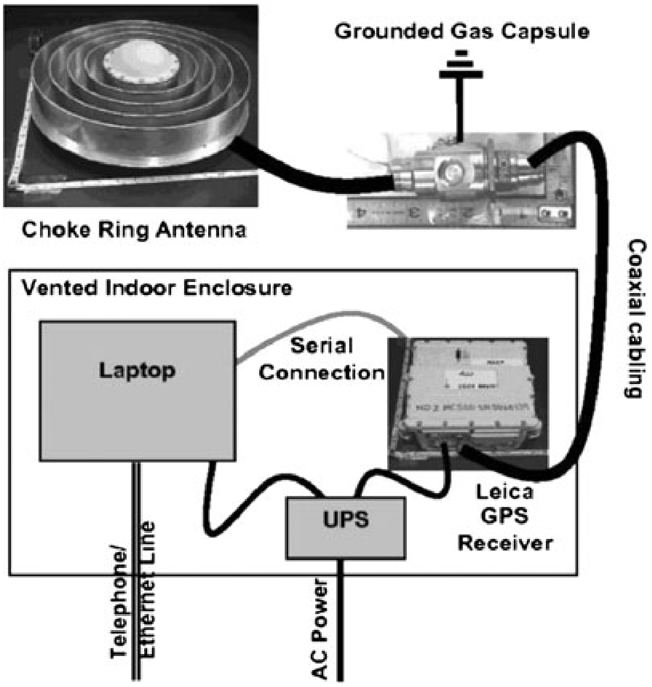

Figure 7. Schematic configuration of GPS components [38].

motions, tracking is superior at lower frequencies, further motivating its application to the monitoring of flexible tall buildings. Similarly, Chan *et al*. [21] carried out a series of field tests in an open area also using a motion simulation table and a GPS consisting mainly of two sets of a Leica GX1230 receiver and AT504 chock ring antenna (Leica Geosystems). The test results indicated that the background noise measured by the moving receiver was very close to that measured by the stationary receiver between sidereal days. Those also showed that for the 2D sinusoidal and circular motions in the horizontal plane and for the 1D sinusoidal motion in the vertical direction, the GPS could measure dynamic displacements accurately if the motion amplitude was not less than 5 mm in the horizontal plane or 10 mm in the vertical direction, provided that the motion frequency was less than or equal to 1 Hz.

Casciati and Fuggini (2009) [22] designed a specific set of system to assess the achievable accuracy of the GPS units for long-term precise monitoring applications that is often ignored in both practice and literature in civil engineering. The amplitudes of the oscillations imposed on the moving GPS antenna vary in a range from ±0.5 cm up to ±5 cm with frequencies of 0.1, 0.2, 0.5, 1.0, and 2.0 Hz. The time history of any possible combination of these parameters has the duration of 300 s, assumed to be long enough to assess the stability of the measurements. The major outcome of the study showed that the GPS allows displacements on the order of sub-centimeters to be monitored with frequencies of motion up to 2.0 Hz and that the precision of the GPS depends on the combination of amplitude and rate of the imposed movements. This experimental finding is very interesting and useful in enhancing the GPS-based SHM of engineering structures.

3.2.2. Slender structure simulating equipment. Celebi and Sanli [14] selected two stock steel bar specimens according to length, thickness, and width to yield a fundamental period of approximately 4 s in the weak direction to simulate a 30-story to 40-story flexible building. By providing an initial displacement, each bar was set into free vibration, and its motion was recorded. The test showed that sampling at 10 Hz with the GPS units could provide a clear and accurate displacement response history (with high signal-to-noise ratio) from which the drift ratios and dynamic characteristics of the specimen could be derived. Roberts *et al*. [23] investigated the use of high-rate carrier phase GPS receivers for the deflection monitoring of structures. They purchased two JNS100 GPS OEM boards from the Javad Navigation Systems, Inc. (San Jose, CA, USA), which were able to output raw data and positions at 100 Hz without interpolation (Figure 8). A wooden frame was suspended

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Figure 8. The JNS100 OEM board GPS receiver [23].

from a tall tripod by means of a bungee cord, which allowed free oscillation of the platform, as shown in Figure 9. The reference receiver was located approximately 10 m away from the test rig, where an AT503 antenna was connected via a splitter to the Leica SR510 and JNS100 receivers. The AT502 navigation antenna was mounted on the test rig, which was then, via a splitter, connected to the JNS100 and Leica SR510 receivers. Using the test rig, they conducted two different trials. For the first test, the platform was in rotation either held still or disturbed from its resting position by someone forcing the platform to move up and down. For the second trial, the platform was just left to swing. The results revealed that the Leica receivers performed slightly better than the JNS100 in the static trials, but the difference was small. The JNS100 receivers did have a high-precision carrier phase observables. These studies significantly expanded the valid measurable frequency of the GPS receiver to higher than 100 Hz.

Although the straight rule, or the edges of a right-angled triangle, could be used as a convenient template for a test, along the edges of which the GPS rover antenna is moved in a straight line manually, the disadvantage of a manually guided antenna is the inaccuracy in following the edge and the loss of antenna verticality caused by the friction along the template and the roughness of the surface. In order to verify the reliability of the GPS measurement data more precisely, Park *et al.* [24] designed a physical model that had a wooden board of 2.44 m × 1.24 m supported by six vertical D10 deformed rebars, as shown in Figure 10. On the model, they installed braces on the vertical elements with a

Figure 9. Platform for the dynamic test [23].

Figure 10. Experimental model [24].

deformed rebar in order to prevent *Y*-axis vibration when the model vibrates in the *X*-axis direction. Furthermore, they installed rubber pads at all connection joints to reduce energy loss at such points during the free vibration of the model. A GPS receiver, servo-type accelerometers and a laser displacement meter were taken at 5 Hz to collect the data, which is more than twice the natural frequency of the structure. Comparisons with the acceleration as differentiated from measured displacements using the GPS and laser displacement meter against the actual measured acceleration using the servo-type accelerometer is as Figure 11. As shown in Figure 11, the acceleration obtained using a GPS receiver coincided well with the actual acceleration measured with an accelerometer.

Psimoulis *et al.* [25,26] set up an experimental apparatus consisting of an oscillator, PC used to define the oscillation characteristics (frequency, force amplitude, oscillation iterations, etc.), and a controller converting the PC digital signal into an analog one and transferring it to the oscillator. The later consisted of a servo-motor, which generated linear oscillations of a wagon sliding on a linear, horizontal rail. For each experiment, the PC-adjusted oscillation characteristics were transferred into the servo-motor, which finally excited the wagon, as shown in Figure 12. Three sliding wagons (W_1, W_2, W_3) were connected with springs (K_1, K_2, K_3) permitting up to 3° of oscillation. The rover GPS antenna was mounted on the wagon W_3 and the base GPS receiver on the stable ground. For the cases of experiments of single-degree of freedom, the GPS antenna was mounted on the wagon W_1. The outcome of the study demonstrated that GPS was suitable for the identification of dynamic characteristics of even relatively rigid civil structure. They also explored the possibility of using the GPS and robotic total stations (RTSs) for measurements of oscillations of relatively rigid structures (modal frequencies up to 3–4 Hz). The experimental results showed that the GPS could record oscillations with the frequencies up to 4 Hz with a minimum amplitude of 5–10 mm with an accuracy of a few millimeters and that RTS could record peaks of oscillations with sub-millimeters to a few millimeters accuracy, but at high frequencies, some cycles were lost. Based on recordings of both, the instrument frequencies of oscillations were

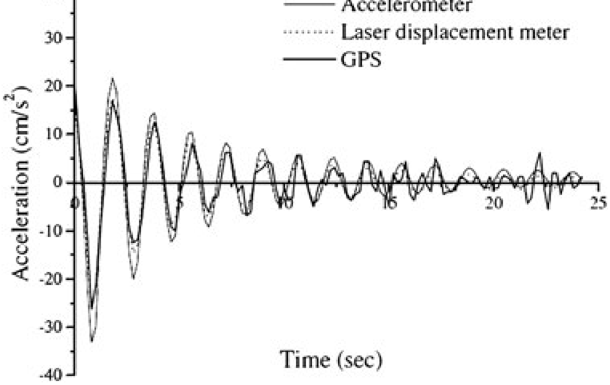

Figure 11. Acceleration measurement by GPS, laser displacement meter, and accelerometer [24].

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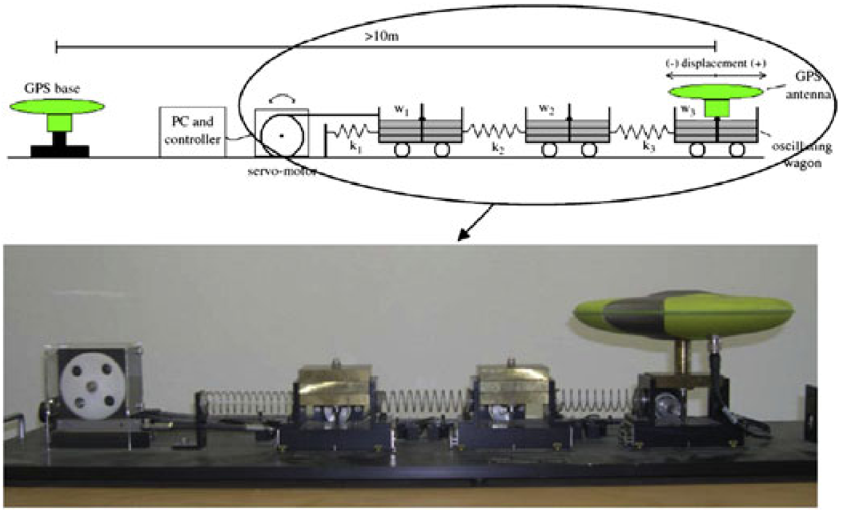

Figure 12. The experimental apparatus used in Psimoulis's investigation [26].

also accurately determined although the noise seems to increase with increasing of frequency. This indicates that these two geodetic instruments are compatible, even supplementing each other.

3.2.3. Rotating arm equipment. The circular course is a very appropriate way to check the precision of tracing in every direction. Breuer *et al*. [27] used a Leica 300 GPS unit attached at the edge of the horizontal bar, which moved rotationally with a constant angular velocity to find out the dependence of the distance baseline length between the GPS rover unit and the GPS reference unit in the accuracy of measurements. For the distance between the rover unit and reference unit changed from 10, 100, 250, 1000, 5000, to 10 000 m, the experimental results indicated that the standard deviations, calculated from sample data in the direction of the radius of the rotation, varied from 2 to 6 mm. This variation is dependent on the number of available satellites. In 2006, Nickitopoulou *et al*. [28] made a large number of experiments, in which the harmonic movements were simulated by a rotating GPS receiver antenna, and the recorded coordinates were compared with the real ones. The major outcome of this study was that the GPS could monitor displacements with an amplitude better than 15 mm, at a level of outliers <1.5%, as shown in Figure 13. Careful GPS studies, both the post-processing kinematic and the RTK, could therefore permit modeling of quasi-static and low-frequency harmonic movements of most of major slender engineering structures.

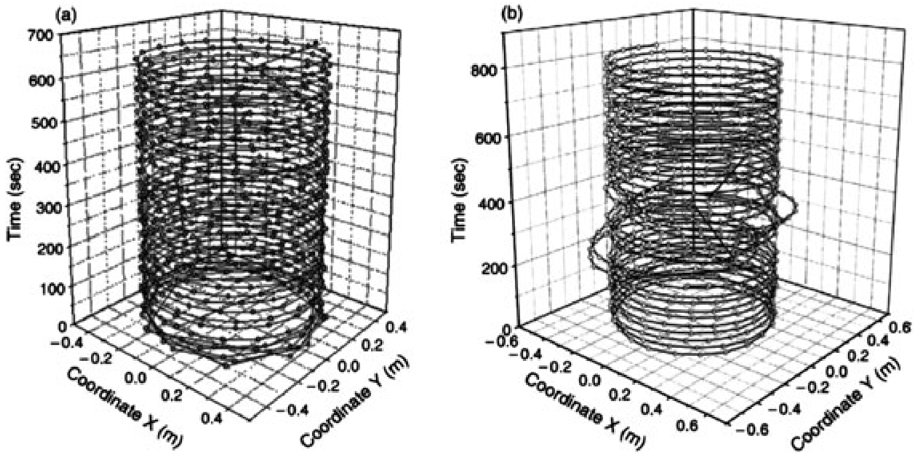

Figure 13. Helix plot of horizontal coordinates of the moving rover versus time. In (a) a nearly ideal cylinder plot is evident, whereas in (b) some outliers are noticed [28].

After the first experiment was carried out in 1998, Breuer *et al*. [29] thought that a regular rotating velocity during the test was not necessary because in reality, the displacement of structures, mainly vibration, did not appear with a linear velocity but with positive and negative acceleration, and they fixed a GPS rover antenna on a rotating arm turning around a fixed center to test the precision of GPS tracing in every direction, as show in Figure 14. Figure 15 displays the results monitoring the track of the GPS rover antenna with two different circle diameters (25 and 49 cm) and different rotating velocity. The mean square deviation from the given course is about 3–4 mm if the monitoring period does not exceed 5 min; otherwise, the possible systematic influences described earlier produce a systematic shift.

4. PROGRESS ON MONITORING THE DISPLACEMENT OF THE HIGH-RISE STRUCTURE CAUSED BY THE AMBIENT EFFECTS

The GPS offers great potential for tall building health monitoring applications. Their significance to health monitoring applications stems from the following facts: (1) There is no intervisibility among stations, and the observation values are independent. (2) All-weather operations. The GPS signal receiver can work continuously at any place and any time, generally free of the impact of weather conditions. (3)

Figure 14. Rover Antenna mounted on a tripod provided with a rotating arm [29].

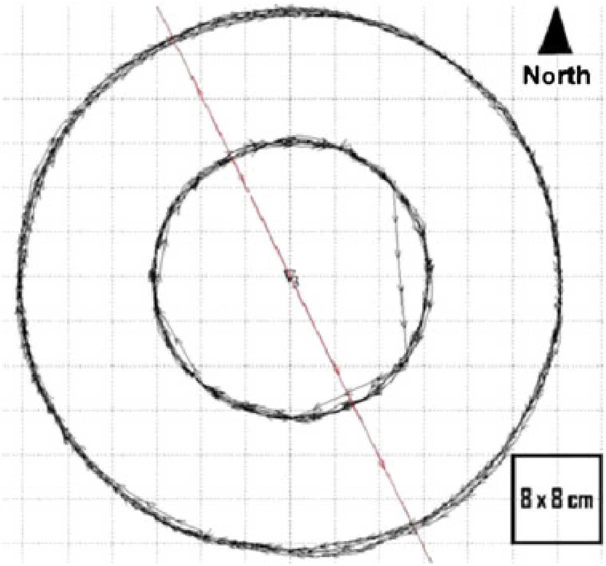

Figure 15. Result of the Rover Antenna’s kinematic GPS tracing applied on two different radii [29].

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High-precision positioning. Real-time positioning accuracy can be up to 10 mm for plane, 20 mm for height. (4) Short observation time. The output time delay of high-precision points is shorter than 0.05 s. (5) The static and dynamic 3D coordinates can be determined simultaneously. (6) The results have no error accumulation and are zero drift. (7) Easy to operate. The GPS measurements have high automation; thus, it is easy to build the automated continuously operating system [30].

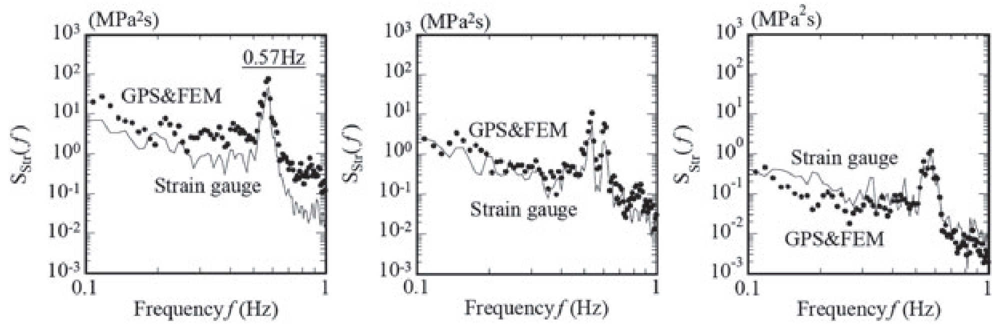
From the aforementioned discussion, it would be correct to believe that the GPS is capable as a useful tool for (1) detecting tall building response in real time to extreme loading events such as windstorms with high velocities and earthquakes of average to high magnitudes, (2) estimating the 'permanent' displacements experienced by tall buildings once the shaking event has stopped, and (3) detecting long-term tall building deformation due to ground subsidence and temperature variation. The integration of the GPS with high-rise structures for the SHM has become an active research field. Although the benefits of GPS long-term structural monitoring are yet to be fully realized, several applications have been demonstrated to date. The rest of this section will review these demonstrations.

4.1. Wind-induced response

The GPS has been successfully applied to high-rise structures for displacement measurement due to winds for a long time. Early in 1995, a NovAtel GPS receiver (Novatel Wireless Inc., San Diego, CA, USA) was installed by Lovse *et al.* [31] on Calgary Tower (160 m above ground level) to measure the structural vibrations. The results showed that Calgary Tower, under wind loading, vibrates with a frequency of about 0.3 Hz in both north–south and east–west directions. The 0.3-Hz vibration frequency measured on the tower is within the range of 0.1 Hz to 10 Hz expected for structures of this type. When the capability of GPS to monitor structural vibrations is verified by further test, it could be adopted as a standard technique.

Ogaja *et al.* [17] mounted two Trimble 4700 receivers on top of the Republic Plaza (280 m, the maximum height of any Singaporean building) sampling at the rate of 1 Hz to measure the vibrations of the building due to winds. The results from the analysis of the experiment data suggested that low-frequency vibrational signature of tall buildings could not be easily recognized in the time and frequency domain of the data sampled at 1 Hz under normal loading conditions. Later in the same year, Ogaja *et al.* [32,33] used a pair of Leica GPS receivers installed on the Republic Plaza building again to generate time series of antenna positions again. The study demonstrated that pre-filtering of the GPS monitoring data with a finite impulse response median hybrid filter (FMH) and developing the calibration model from a set of coefficients obtained from a Haar wavelet transform (FMH) of the FMH-filtered data could produce a monitoring model with better classification features. Chen *et al.* [34] carried out a field experiment to employ two NovAtel Outrider DL RT2 dual frequency GPS receivers to measure the vibrations of the 384-m-tall Di Wang building in Shenzhen, China, under relatively stronger winds. Experimental results demonstrated that when short GPS baselines were used, the GPS multi-path effects were the most dominant error source, which might easily reach the level of several centimeters. They found that the typical periods of the GPS multi-path errors in the Di Wang building is about 72 s or longer, which are much longer than the periods of the building vibrations and therefore can be easily separated by using the techniques such as the wavelet transform. Tamura and Yoshida [19,35] installed an RTK-GPS antenna on the top of a 108-m-high steel tower, and the temporal variation of the wind and the response data during the typhoon 0211 was obtained. By calculation, they found that the GPS system could monitor the stresses calculated from the temporal variation of the tip displacement of the tower in all members during typhoons and could even send out a warning if one of the member stresses exceeded an allowable level. Figure 16 shows the power spectrum of member stresses obtained by the strain gauges and the hybrid use of FEM analysis and GPS. For the power spectrum of stresses in the outer column as shown in Figure 16(a), those by the hybrid use of FEM analysis and GPS showed higher energy in all parts than that by strain gauge. However, for the power spectrums of stresses in the diagonal member (Figure 16(b)) and in the inner column (Figure 16(c)), that by strain gauge and that by hybrid use of FEM analysis and GPS showed good agreement.

The TV tower in Stuttgart was designed and built by Professor Fritz Leonhardt from 1953 to 1955. It was the first television tower in the world, which was constructed as a concrete tube. The concrete shaft is 161 m high. Its diameter is 10.8 m at the bottom and 5.04 m at the end, and the wall thickness



(a) Outer column (b) Diagonal member (c) Inner column

Figure 16. Power spectrum of member stresses during Typhoon 0221 [19,35].

decreases from 60 to 19 cm. At the upper end of the shaft is mounted a steel antenna mast, which is 51 m high. The Stuttgart TV Tower has been temporarily monitored with the RTK-GPS method by the Breuer *et al.* [27] since 1998. Experimental results demonstrated a typical and elliptical movement of the TV tower where the cross-wind displacement was approximately equal to 4 cm and the along-wind displacement was equal to 2.5 cm. The time history of vibrations in the cross-wind direction was very similar to a sine wave with a constant frequency of 0.2 Hz—this value was also measured by Leonhard *et al.* [37]. In the evening of 5 July 2006, a thunderstorm occurred from 22:00 to 23:00 h. The maximum wind velocity of 11 m/s was observed at a distance of 7 km southwest of the Stuttgart TV Tower. Using the power law, an average velocity of 17–18 m/s at the top of the tower was calculated. The upper right-hand corner in Figure 17, which is separately shown as Figure 18, illustrated the response to the wind between 22:00 and 22:30 h, and visualized the trace of vibration for three separated time intervals over 1 min within the two 10-min sessions. Every vibration trace inclines to an elliptical form, whose axis azimuth changes slightly. The graphic design shows two components: (1) The static component = the displacement to the North–East of about 6 cm from the daily temperature path, and about 10 cm from the zero-spot area and (2) the dynamic component = the vibration in the cross-wind direction with the amplitude ±7 cm. The time marks 5–22:00 and 5–22:30 indicates the average position of the tower within the point cloud of 1020 GPS positions. The center of both point clouds is situated about 10 cm northeast of the zero-spot area. The distance of the actual temperature path, that is, between the time marks 5–21:00 and 5–22:00, is 6 cm. It can be concluded that the North–East displacement of 6 cm from the actual temperature course is caused by the static component of wind response [28,36].

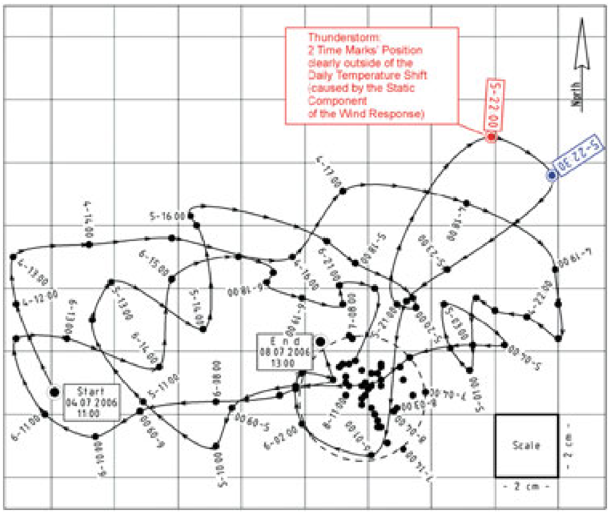


Figure 17. The Stuttgart TV Tower, daily drift of the top due to solar radiation and daily temperature variation with hourly positions and time marks (4–8 July 2006). In North–East of the ground plan two outliers are shown, caused by a thunderstorm with wind from South–West at a velocity of about 1 m/s [36].

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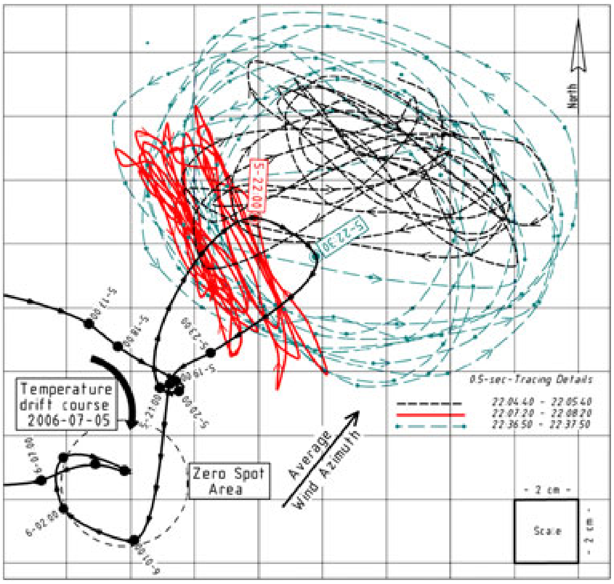

Figure 18. The Stuttgart TV Tower, static and dynamic components of the wind response during a thunderstorm producing an outline of the daily temperature drift. The wind from South–West with a velocity of about 17 m/s causes a North–East displacement of about 6 cm. The main direction of vibration is at a right angle to the wind direction with a displacement of 9–14 cm (5 July 2006) [36].

Kijewski-Correa *et al*. [38,39] established a 'Chicago Full-Scale Monitoring Program' (call windy city) in 2001 to facilitate the monitoring of several tall buildings for validation of performance against the predicted wind tunnel and analytical models in order to calibrate the current state of the art in design. Their findings suggested the need for time–frequency analyses to identify coalescing modes and the mechanisms spurring them. The study also highlighted the effect of this phenomenon on damping values; the overestimates could result due to amplitude dependence, as well as the comparatively larger degree of energy dissipation experienced by buildings dominated by frame action. Li *et al*. [40] also devised an SHM system based on the GPS for a high-rise building. The field data, such as wind speed, wind direction and displacement responses were simultaneously and continuously measured under strong wind conditions. The responses of the high-rise building were investigated using the Periodogram method to conclude that the identified results agreed well with the results computed by the finite element method.

4.2. Thermal variation-induced response

Because the RTK-GPS can measure the static displacement, the deformation of the high-rise structures caused by the solar heating effect might also be detected. Figure 19 shows a 160-m-high steel tower deformation caused by solar heating on a calm and clear day. Each plot indicates the preceding hour's mean displacement with time. Just after sunrise, the tower began to move about 4 cm in the NW direction. The top of the tower moved in an almost circular shape in the daytime and returned to its zero point after sunset [19].

In order to quantify statistically the relation between the environmental conditions and the building movement, Seco *et al*. [41] monitored continuously a 30-m concrete building between 1 March and 3 July 2003 for 125 days. During the observation period, the computed variations in position had standard deviations of 3.1 mm in the *XX*-axis, 6.6 mm in the *YY*-axis, and 9.1 mm in the *ZZ*-axis. These values reveal that the building displacements are very small and that they are masked by the characteristic errors of GPS observations. The correlation between the observed displacements and the weather variables was analyzed, as shown in Table II, and only temperature and direct radiation were significant, but the relationship was weak, with low values of the correlation coefficients. By the visual analysis of the coordinate variations, they observed that the building suffered a negative displacement with respect to the *XX*-axis in the morning up to noon, when the displacements became positive, with an observed variation over the reference position of ±2 mm. With respect to the *YY*-axis, the building

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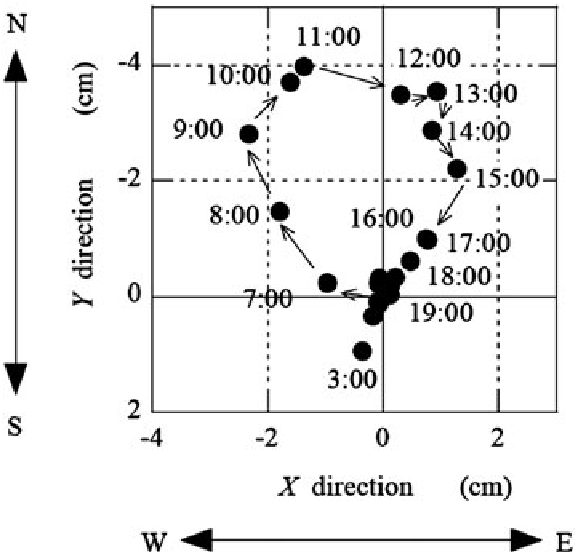

Figure 19. Deformation of the tower caused by heat stress [19].

Table II. Correlation analysis of displacements versus weather variables.

		Temperature	Direct radiation	Wind
Displacement on *XX*-axis	Pearson's correlation	−0.054	−0.059	0.000
	Bilateral significance	0.000	0.000	0.963
Displacement on *YY*-axis	Pearson's correlation	0.199	0.070	0.000
	Bilateral significance	0.000	0.000	0.969
Displacement on *ZZ*-axis	Pearson's correlation	0.099	0.091	0.016
	Bilateral significance	0.000	0.000	0.134

remained fairly stable until afternoon, in which it moved toward to approximately north 2 mm in relation to the reference position. With respect to the *ZZ*-axis, they observed an increase of the height of the building during the central hours of the day of around 1 cm. These displacements observed in the building agree qualitatively with the *a priori* expected displacements as a function of the movement of the sun throughout the day.

Breuer *et al*. [29,36] also studied the daily drift and seasonal drift of the Stuttgart TV Tower due to the solar radiation and daily air temperature variation. After carefully studying the monitoring date, he recognized that the temperature distribution on the external surface of a TV shaft varied with environmental conditions. During the sunny day, the enlightened surface of the tower shaft was subjected to thermal expansion due to nonsymmetrical warming. As a result of changes in temperature gradient within the cross section of the shaft of the tower, additional stresses and horizontal deformations of the tower were induced. During a sunny day, the path of the top of the tower described an ellipse related to the position of the sun. The side exposed to the sun would be extended, and the tower and its top would incline away from the sun. Because during the day, the sun moved from the East, via the South, to the West, the top of the tower described an elliptical path West–North–East. The size of the displacement depended on the temperature difference between the exposed side and the shaded side, that is, the intensity of direct sun irradiation. During the night, the temperature differences between the two sides were balanced and the tower returns to a certain zero area. Figures 17 and 18 shows the typical time-dependent records of daily drift of the top tower during 4 days of measurements (4–8 July 2006).

4.3. Earthquake-induced response

Because the GPS satellites are not affected by earthquakes, the GPS constellation may be considered as an 'ideal pendulum'. Thus, a GPS receiver on the Earth may be used as a seismometer to recover the signature of the antenna displacement very well. This new ‘GPS seismology’ application is greatly simplified thanks to the freely available International GPS Service (IGS) orbit/clock products and the data from its globally distributed network of high-rate GPS tracking stations. The 5-min sampling of the IGS satellite clocks appears to be sufficient even for the high-frequency position solutions with centimeter resolution, which is required for this application, although this demanding application would likely benefit from a more frequent clock sampling. The GPS is able to observe predominantly horizontal components of surface seismic waves generated by large earthquakes with magnitude 7 or greater, provided that the network spacing and data sampling be sufficient. The standard 30-s GPS data sampling (decimated or smoothed) cannot be used for this purpose. For very large earthquakes, such as the Denali Fault earthquake, GPS 1-s data can observe seismic waves nearly continent-wide. The GPS can detect seismic waves with periods as short as a few seconds and amplitudes of a few centimeters. Such GPS seismic wave measurements may supplement and even enhance the standard seismic observations, which frequently saturate near the epicenter of a very large earthquake [42].

The feasibility of the GPS to record seismic movements is depicted in the record of a Ms = 7.0 earthquake, which excited a 108 m high, 13 m × 13 m wide steel tower in Tokyo. The fast Fourier transform (FFT) spectra of the GPS data recorded at the top of the tower at a frequency of 10 Hz revealed a main peak corresponding to the dominant frequency of 0.57 Hz and a secondary peak (2.16 Hz) for both easting and northing coordinate components, corresponding to the second mode of the structure, in agreement with accelerometer-derived spectra. Such seismic movement corresponded to a horizontal oscillation with amplitude 2–4 cm, whereas the vertical oscillation was below the noise level (1–2 cm) [43].

5. RECENT PROGRESSES OF AUGMENTING GPS MONITORING TECHNOLOGY

Although the GPS offers real-time solutions, it has its own limitations. For example, the GPS satellite signals are susceptible to many kinds of error sources, such as ionospheric and tropospheric errors, orbital errors, clock errors, and multi-path effects. Even though the double-differencing technique could be used for constructing the functional model as it can eliminate or reduce many of the troublesome GPS biases. But two unmodeled biases still remain that have not been well eliminated even after data differencing by past research efforts. The first is the dilution of precision error that results from suboptimally oriented satellites. This error is inherent in the technology and can only be practically remedied through the addition of more satellites. The other error source is the multi-path effect that occurs when duplicate satellite transmissions are received by the GPS antenna. Moreover, the typical RTK-GPS 20 Hz sampling rate will limit its capability in detecting certain high mode signals of some structures. In addition, the prices of the GPS receivers are very high, which will hinder the application of the GPS monitoring technology in practice. Thus, an integrated sensor system consisting of the GPS receivers, accelerometers, displacement transducers, or even ground-based pseudo-satellite (pseudolite) transmitters can greatly increase the accuracy, reliability, and productivity of the overall monitoring system.

5.1. Integrating GPS receiver and conventional instruments

As aforementioned, in civil engineering, the accelerometers are more accurate for higher frequencies and higher sampling rates than displacement sensors. Thus, supplementing accelerometers with the GPS receivers measuring at high frequencies, both the static and dynamic components will be quite useful. Celebi *et al.* [15] deployed a GPS unit and a tri-axial accelerometer at two diagonal corners of the roof of a 34-story San Francisco building. The real-time displacement and acceleration responses were collected synchronously. The GPS solutions were confirmed by the acceleration data, and both approaches showed that GPS monitoring of long-period structures could provide sufficiently accurate measurements of relative displacements. A monitoring system on a chimney of the power plant of Piacenza (Italy), 120 m high, was installed by Cazzaniga *et al.* [44]. The system acquired data at a frequency of 10 Hz from three Leica GRX1200 GPS receiver (one rover on the chimney, connected to the acquisition and processing unit by a Wi-Fi system, and two references) and at 100 Hz from two Crossbow CXL02LF3 tri-axial accelerometers (Crossbow Technology, Inc., Milpitas, CA, USA),

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one on the top of the chimney and another in the middle of the chimney span, to complement the GPS data and monitor higher order modes of vibration. The gathered results agreed with each other very well, except that the static component was missing from the accelerometer-derived results. Safak and Hudnut [45] thought that the damage could be detected more accurately if engineers investigated not only the changes in natural frequencies, but also the changes in the propagation characteristics of seismic waves in the structure and any permanent changes in the structural configuration. They monitored a 17-story, moment-resisting steel frame building at the UCLA campus in Los Angeles, in real time with a very dense downhole-surface-structural array of accelerometers, plus three GPS sensors on the roof. By adaptive signal processing and system identification tools, and statistical decision-making tools, the changes in the building due to real damage from those due to environmental factors were identified. An integrated system comprising of the RTK-GPS and accelerometers were installed on a 108-m-tall steel tower by the Li *et al*. [46], with the objective of assessing full-scale structural responses by exploiting the complementary characteristics of GPS and accelerometer sensors. The system successfully collected the structural responses during a typhoon on 1 October 2002 and an Ms 7.0 earthquake on 26 May 2003. The monitored results showed that the general GPS could pick up signals at the low-frequency end (0–0.2 Hz), probably affected by the GPS-specific noise such as the multi-path, whereas it is easier for the accelerometer to record high-frequency signals (2 Hz and above). Therefore, the two sensors were complementary. On the other hand, the two sensors did have some overlapping capability in the band between 0.2 and 2 Hz, that is, whatever was picked up by the accelerometer would also be picked up by the RTK-GPS. This overlap could provide redundancy within the integrated system, which enabled robust quality assurance. Park *et al*. [24] measured an actual 66-story high-rise building’s horizontal and torsional responses to yellow dust storm and typhoon by two accelerometers and three GPS receivers. The results showed that GPS-measured displacement and acceleration were similar in cases of vibration amplitude greater than 1 cm. The torsional mode shapes of the tallest TV tower—Guangzhou New TV Tower (610 m)—in China during the Nuri typhoon were precisely analyzed for the first time by using an integrated network made of a GPS receiver and several uni-axial accelerometers [47,48]. Two torsional parameters were calculated as a function of time: the angle of rotation of the oval cross section and the twist angle of the inner shaft cylinder. Their dependence on the sensors measurements and their locations was also in-depth investigated. They found that the effects due to the integration process of the acceleration measurements, and the nonsynchronization among the sensors could be removed by using several GPS sensors. This important finding of the experimental results can be used to enhance the performance of GPS technology. In order to exploit the advantages of both RTK-GPS and accelerometers, two data processing needs to be developed, namely to convert GPS-measured displacement to acceleration through double differentiation or to convert the accelerometer measurements into displacement through double integration. The later approach is much more challenging because its two integration constants must be determined in order to recover all the components of displacement (static, quasi-static, and dynamic). Li *et al*. [49] designed a methodology overcoming the problem, which consisted of an FFT for correlated signal identification, a filtering technique, delay compensation, and velocity linear trend estimation from both GPS and accelerometer measurements. Smyth and Wu [50] proposed a Kalman filtering and smoothing technique, which was capable of dealing with multi-rate estimates, had been investigated to accurately estimate the velocity and displacement from noise contaminated measurements of acceleration and displacement, which were gathered by accelerometer and GPS receivers, respectively. Casciati and Fuggini [51,52] made an interesting study for the ability of GPS sensors to detect the response of a steel structure to pulse actions (short-duration actions) as the movements of the bridge-crane inside the building. The potential offered by the GPS approach for monitoring the dynamic displacements was emphasized by comparing, both in the time and the frequency domains, the displacements measured by the GPS units with the displacements re-elaborated from tri-axial accelerometers data. A numerical simulation using an FEM of the building was developed, and the elaborations from the GPS position readings are compared with the simulation results. This unique research outlines a suitable way for processing GPS data toward structural monitoring and offer special values to practicing engineers and researchers.

The main limitations of the GPS are requirement for an unobstructed view of satellites and the avoidance of surfaces on which the satellite signal is reflected and distorted before reaching the GPS antenna. The principle of operation of RTS on the contrary is very different because it is based on a wave emitted by the instrument, reflected on a reflector, and received back and analyzed by the robotic theodolite. The limitations in this case are the requirements for a stable position for the RTS and for an unobstructed view of the reflector. The later should be at a distance of up to a few hundred meters from the RTS, and the emitted ray should pass through clear air; dust and mist, for instance, highly disturb this signal, reducing the range of measurements and their quality. Concerning with these, Psimoulis and Stiros [25] explored the possibility of using the GPS and RTS together for measurements of oscillations of relatively rigid structures (modal frequencies up to 3–4 Hz). Experimental results showed that these two geodetic instruments were compatible, even supplementing each other. The GPS and RTS have a much broader possible range of applications than what was previously believed, but still, there are limits in their use. Yigit *et al.* [53] assessed the dynamic measurement quality and reliability of inclinometers for a 30-story high reinforced concrete building monitoring applications, and discussed the strengths and weaknesses of the GPS vis-a-vis the use of inclination sensors for monitoring the dynamic response of tall buildings under wind load. From the analyses in the frequency domain, the first-mode natural frequency of the building determined from both sensors agreed very well with each other. The discrepancy of the measured first-mode natural frequency compared with that derived from the FEM prediction was 7%.

5.2. Pseudolite-based positioning system

It is well known that, for such satellite-based deformation monitoring systems, the accuracy, availability and reliability of the GPS-derived position solution are highly dependent on the number of tracked satellites. However, in some situations, such as the monitoring of high-rise structures in built up urban environments, the availability of GPS satellites may be insufficient for positioning requirements. Furthermore, because of the limitations of satellite geometry, the accuracy of the height component is generally two or three times worse than the horizontal components.

Pseudolites, which are ground-based instruments that transmit the GPS-like signals, can improve the satellite-receiver geometry [54,55]. Hence, in principle, they may be used as additional range observations to improve the performance of a GPS-based deformation monitoring system, with enough devices, could replace the GPS constellation entirely. There are three general scenarios for the use of pseudolites in deformation monitoring systems: (1) The first case is the *GPS augmentation* with pseudolites, which is suitable where the geometry of the existing GPS constellation is insufficient for positioning requirements. (2) In the second case, a *pseudolite-only system* replaces the GPS constellation entirely. This may extend satellite-based deformation monitoring applications indoors, into tunnels or underground, where the GPS signals cannot be tracked. (3) The final case is an *inverted pseudolite-based* deformation monitoring system, where a 'constellation' of GPS receivers tracks a mobile pseudolite. Many civil engineers have been conducting researches into the use of pseudolites for the monitoring of slender structures [56]. The results of these trials have been encouraging and have demonstrated the proof-of-concept for the augmentation of GPS with pseudolites for deformation monitoring. However, the location of pseudolites is a critical consideration, not only from a geometric perspective, but also in terms of reliable signal tracking at both the 'stable' reference receiver and the 'kinematic' rover positions on the structure being monitored. Furthermore, these are constrained because of the near-field pseudolite constellation. As a result, the reference and rover positions must be at similar distances from the pseudolites, and in practice, satisfying this condition can be a significant limitation of the technology. Additionally, for real-time deformation monitoring, radio modems are required to allow differential processing of the reference and rover data together.

Locata is a kind of pseudolite-based positioning system (PPS) operating in the license-free 2.4 GHz Industrial Scientific and Medical frequency band [57]. Unlike its predecessors, Locata utilizes time-diversity methods to overcome the near–far problem. The concept Locata positioning is using a network of ground-based transmitters that cover a chosen area with strong signals, together with signals from the GPS. Thereby, Locata is able to operate over larger regions than the previous PPSs. Barnes *et al.* [58] conducted a trial to assess the suitability of the Locata positioning technology for the structural deformation monitoring type applications. Through a temporary LocataNet positioning network installed at Parsley Bay bridge in Sydney, the kinematic positioning precision at the sub-centimeter level has been clearly demonstrated. Experimental results showed that the Locata technology could continuously deliver very high positioning precision, independently of GPS and without the need for a base station and data link and, thus, had enormous potential for structural deformation monitoring type applications.

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5.3. GPS multi-antenna system

Although an effective tool for the deformation monitoring of large structures, one of the major drawbacks of continuous GPS is the high capital cost of the GPS equipment required at each site [59]. Each installation will include a receiver, antenna, communications hardware and software, power supply, and security fixtures. Thus, it is desirable to moderate this expense, which may be achieved using the episodic GPS in the form of a switched multi-antenna array. In this case, the multiple GPS antennae are connected to a receiver, which records data continuously while switching between antennae periodically [60]. This will, of course, reduce the overall capital cost of the whole monitoring process significantly because of the reduction in the number of receivers used compared with the continuous GPS. Although the number of GPS antennae is unchanged, these have significantly lower unit costs. Each antenna is mounted at the required test location, and the signal from each antenna is multiplexed to the receiver through a switch mechanism, which consists of multiple input channels and a single output channel, as shown in Figure 20. This allows the receiver to sample sequentially the signals from each antenna for a certain time interval, producing periodic GPS data for the network of fixed monitoring stations.

The concept of a multiple-antenna array has been discussed previously in several investigations with different perspectives. One of the earliest was by Santerre and Beutler [61], who linked the multiple antennae to a GPS receiver with the aim of improving height determination for baselines of few kilometers in length. Ding *et al*. [62] tested a GPS multi-antenna system (GMS), which was near to the typical accuracy achieved using the conventional GPS surveying systems, to monitor deformations such as landslides or unstable slopes. Forward *et al*. [63] developed a GPS-switched antenna array system comprising four switched antennae, in addition to two continuously operating reference stations recording at 1 Hz. Three-dimensional deformations of 2 mm/week were detected. He *et al*. [64] developed a prototype of GMS with eight channels, called GMAS (GMS), as shown in Figure 21. The average precision of baselines over the whole observation period may reach around 1–2 mm.

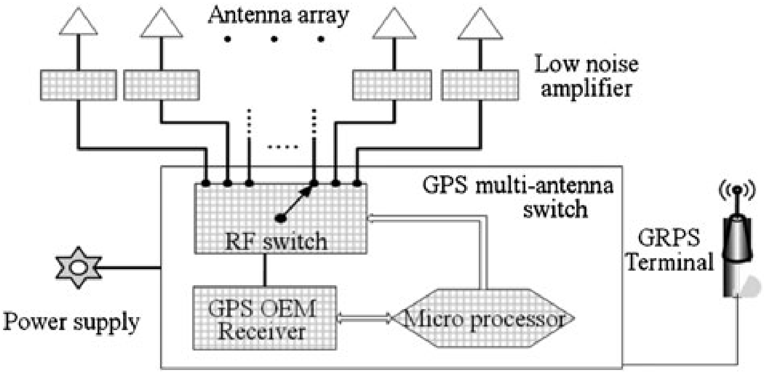

Figure 20. Schematic diagram of antenna array connections [60].

Figure 21. GPS multiple-antenna switching device [64].

The GMS provides a cost-effective and precise technique for deformation monitoring especially for high-density networks [65]. However, the GPS data are not collected continuously but for a certain time interval at fixed antennae connected to one receiver; that is, switching between antennae will result in some poor epochs of data at the start of each session until the lock is regained on sufficient healthy satellites for reliable positioning. The number of these transitional epochs was discovered to be about 30–50 regardless of the switching interval, for the tested hardware and environment [66]. That means that this kind of technique can only be used in the near-static situation, such as the thermal variation-induced response of the high-rise structures.

6. CONCLUSIONS AND RECOMMENDATIONS

The displacement is a key parameter when assessing the safety of tall and flexible engineering structures. Civil engineers require precise and reliable instruments to resolve their concerns with angular movements, displacements and structural vibrations. Although the progress of the GPS health monitoring technology for measuring the static, quasi-static, and dynamic displacement responses is impressive, it is yet to reach its full potential. The existing problems and promising research efforts at least include the following aspects.

1. For the field measurements being able to validate a computational model, the sampling rate is a key index needed to be considered. However, to date, the highest GPS data rate used in experiments has been 20 Hz, which means that only structure dynamics of lower than 10 Hz could be detected, taking other error budgets into account. The new 100 Hz or higher sampling RTK-GPS systems have emerged, but further test still needs to be carried out to ensure the independence of the measurements, as well as effectively resolve the data overrun problems.
2. The quality of the GPS measurements depends on many factors, mainly the satellite visibility, availability and geometry, the quality of the signal sent, and the delays caused by the GPS waves crossing the ionosphere and the troposphere. After adopting the double-differencing technique, the primary concern for the GPS tracking, particularly in urban zones, is the multi-path effect. Thus, the selection of receiver location, the duration of measurements, and the proper design of software to filter multi-path signals should arouse enough attention.
3. Undoubtedly, an integrated sensor system consisting of the GPS and other sensors can greatly increase the accuracy, reliability, and productivity of the overall monitoring system. This leads to the challenge of having to gather additional data, requiring more communication bandwidth. Thus, all the measurements should be collected independently in real time and reliably transformed into a uniform coordinate system.
4. Long time monitoring will lead to the challenge of having to deal with potentially vast amounts of data, requiring heavy computational loads. Efficient data reduction techniques therefore become necessary tools for handling the data system generated. On the other hand, a filtering and smoothing technique that is capable of dealing with multi-rate estimates is necessary. Therefore, a proper software package needs to be developed to synchronize the different time series from the sensors during post-processing, which may permit each sensor type to play to its inherent strengths.

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