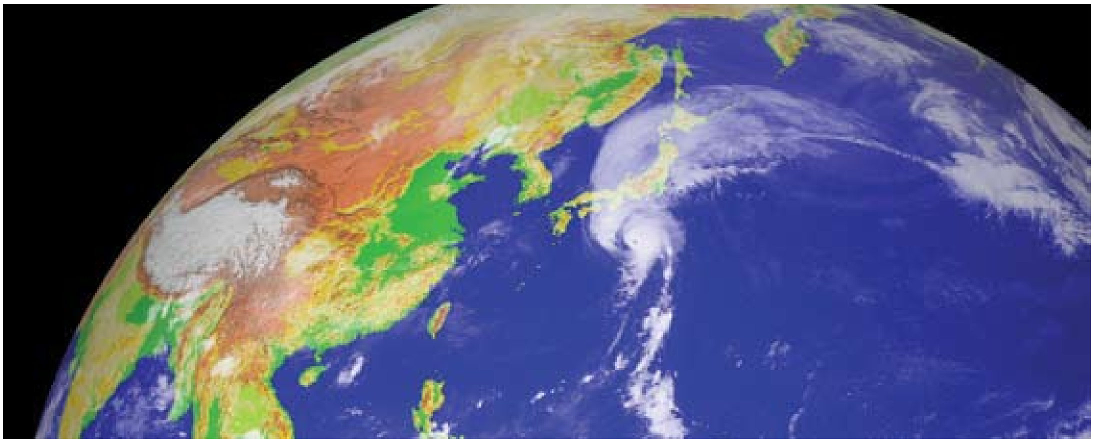
Building Monitors

The Complementary Characteristics of GPS and Accelerometers in Monitoring Structural Deformation



Japan National Institute of Informatics

Typhoon Number 21 approaches Japan, Oct. 1, 2002

The effects of natural phenomena on buildings and other structures have profound engineering and safety implications. For several years, efforts have been under way to use high-precision GPS techniques and, separately or together with, accelerometer technology to monitor these effects in real-time. In this article, researchers from Australia and Japan describe a new technique for converting and combining measurements from an integrated system, as well as the field results from an installation subjected to earthquake and typhoon.

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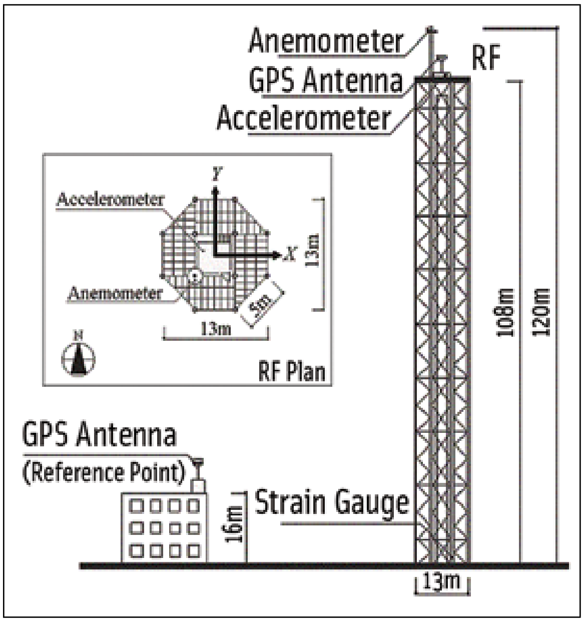
Severe loading conditions such as strong winds and earthquakes acting on modern tall buildings and structures can cause significant loads and vibrations. Recent trends toward slender, flexible, and light-weight buildings have left a large number of buildings susceptible to wind-induced motion. Furthermore, human perception of building motion has become a critical consideration in modern building design.

More complex building shapes and structural systems further accentuate eccentricities between the mass center, the elastic center, and the instantaneous point of application of aerodynamic loads, and consequently will generate significant torsional effects.

Verifying dynamic structural analysis requires the development of direct dynamic measurement tools and techniques in order to determine the natural frequencies, damping characteristics, and mode shapes. Among these tools accelerometers have played the most important part in analyzing structural response due to severe loading conditions. However, they provide only a relative acceleration measurement. The displacement from acceleration measurement cannot be obtained directly by double integration.

In contrast to accelerometers, GPS can directly measure position coordinates, thereby providing an opportunity to monitor, in real-time and full scale, the dynamic characteristics of a structure. GPS used in the real-time kinematic mode (GPS-RTK) offers direct displacement measurements for dynamic monitoring. Earlier studies by the authors and other researchers, referenced in the Additional Resources section at the end of this article, have shown the efficiency and feasibility of structur-



The antenna for the GPS reference receiver (upper left photo), the tower site of the GPS rover receiver (upper right), and a schematic diagram of the overall installation.

al deformation monitoring by combining accelerometer and GPS-RTK.

However, GPS-RTK has its own limitations. For example, the measurement accuracy can be affected by multipath and depends strongly on satellite geometry. Moreover, the typical GPS-RTK 20Hz sampling rate will limit its capability in detecting certain high mode signals of some structures. The new 100Hz GPS-RTK systems need to be further tested in order to ensure the independence of the measurements.

In order to exploit the advantages of both GPS-RTK and accelerometers, two data processing strategies have typically been used, namely to convert GPS measured displacement to acceleration through double differentiation and compare it with the accelerometer measurements (what we refer to as *forward transformation*), or to convert the accelerometer measurements into displacement through double integration and compare it with GPS measured displacement (the *reverse transformation*).

The latter approach is much more challenging because we have to determine two integration constants in order to recover all the components of displacement (static, quasi-static and dynamic). If the structure to be monitored is subject to a quasi-static force, as in the case of a typhoon, this further complicates the analysis.

Although earlier research has proposed a lab-based threshold setting for accelerometers to deal with the quasi-static issue, we believe that avoiding this procedure and developing new ways to recover the false and missing measurements from GPS by acceleration transformation would provide a preferred approach.

This article discusses recent efforts to design such a system based on a new integration approach that employs the

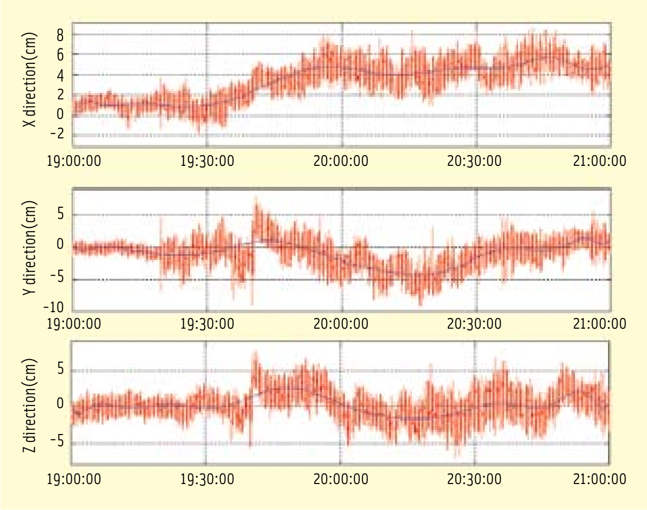


FIGURE 1 Displacement measured by GPS-RTK.

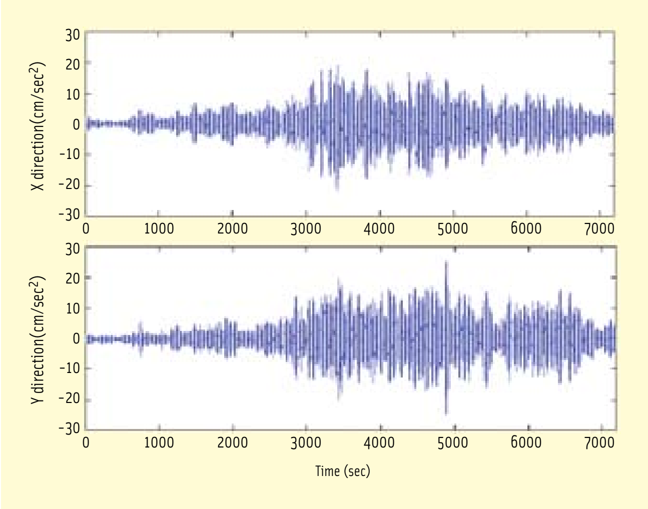


FIGURE 2 Acceleration measured by accelerometer.

correlation signals directly detected from a GPS-RTK system and an accelerometer to transform one form of measurement to the other. The methodology consists of a Fast Fourier Transform (FFT) for correlated signal identification, a filtering technique, delay compensation, and velocity linear trend estimation from both GPS and accelerometer measurements. We also present results derived from its installation on structures in Japan that subsequently experienced the effects of an earthquake and typhoon.

Real-World Installation

As part of the collaborative research between the Tokyo Polytechnic University and the University of New South Wales (UNSW), our team deployed a combined GPS-RTK and accelerometer system atop a 108-meter steel tower in Tokyo owned by the Japan Urban Development Corporation. This was done in order to monitor its deformation on a continuous basis and to test methodologies such as those suggested by our research.

A GPS antenna together with accelerometers and an anemometer were installed at the top of the tower. Another GPS antenna was set up on top of a 16-meter high rigid building, as a reference point 110 meter away from the tower. The GPS-RTK sampled at 10Hz while the accelerometer was making measurements at 20Hz. See the accompanying schematic illustration on page 41.

In addition to this instrumentation, strain gauges were set in the base of the tower to measure member stresses. For more details about the monitoring system setup see the article by Xiaojing Li (2004) in the Additional Resources section. We obtained results from two different datasets: from 19:00 to 21:00 Japan Standard Time (JST) on October 1, 2002 during Typhoon No. 21 and another collected from 18:00 to 19:00 JST when an earthquake occurred on May 26, 2003.

Real-World Results

Figures 1 and 2 show the displacement and acceleration of the steel tower measured during the typhoon by GPS-RTK and accelerometer respectively. In order to identify the correlated signals, a Fast Fourier Transform (FFT) was applied to the two sets of time series. Although the GPS spectra are noisy at the low frequency end and the accelerometer spectra have a few peaks above 1Hz, correlated signals between the two are clearly identifiable around 0.5Hz.

Zoom-ins on the overall FFT spectra are shown in **Figures 3 and 4** for GPS and accelerometer data, respectively. A 0.57Hz component in the Y direction (blue peak in Figure 3) can clearly be seen. However, in the X direction (red) two peaks appear, at 0.54Hz and 0.61Hz. No clear peak shows up in the Z direction at the expected frequencies. In the 0–0.20Hz range, static and quasi-static responses and noise such as multipath are contributing to all three directions.

Accelerometer data in Figure 4 appear to be very clean at the lower frequency end (0 to 0.20Hz). As with the GPS-RTK data, an obvious 0.57Hz component shows up in the Y direction (green peak). However, by further zooming in on the X direction (blue peaks) we see two peaks, at 0.54Hz and 0.61Hz, which are identical to what GPS-RTK has detected. *Therefore, we can identify the 0.57Hz component in the Y direction and 0.54Hz and 0.61Hz centered at 0.57Hz in the X direction as the correlated signals.* The 0.57Hz component has been confirmed as the first mode natural frequency by finite element modeling (FEM) based on the design documents.

Transformation of Signals

In order to convert the GPS measured displacement to acceleration, a straight forward approach would be to differentiate the GPS-RTK time series twice (that is, double differentiation), without any filtering of the GPS-RTK data. Take the X component as an example. In **Figure 5** the upper plot is the GPS-RTK time series. The GPS-derived acceleration through the double differentiation (mid plot) is then compared with the acceleration measured by accelerometer (bottom plot).

Any similarities between the two time series are hard to find. Moreover, the amplitude of the converted accelera-

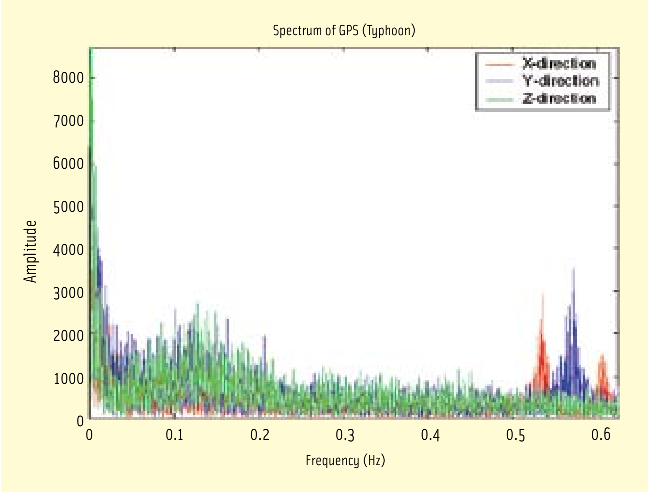


FIGURE 3 Zoom-in of the FFT spectrum of GPS-RTK.

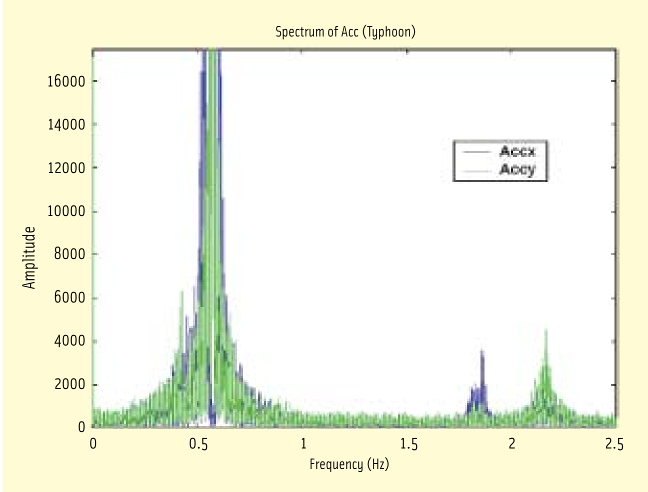


FIGURE 4 Zoom-in of the FFT spectrum of accelerometer.

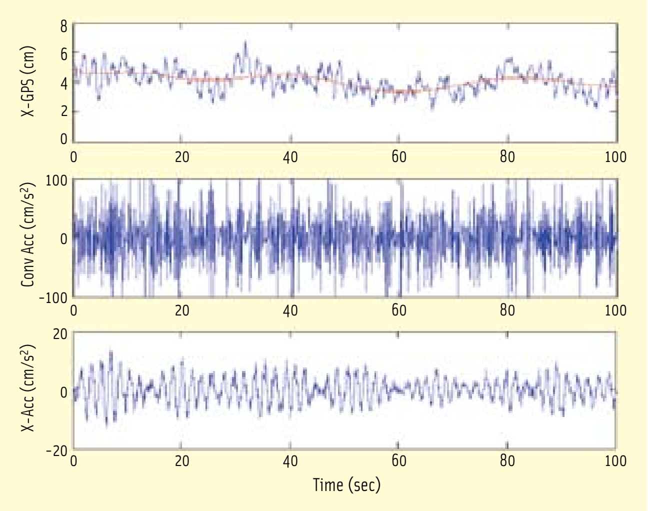


FIGURE 5 Result of direct forward transformation.

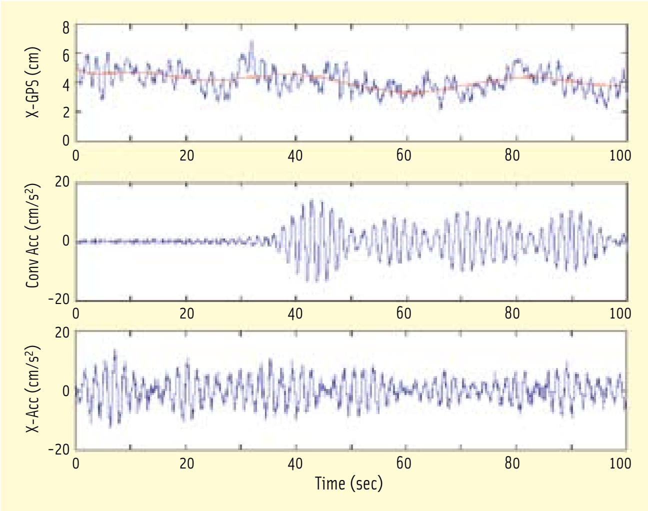


FIGURE 6 Result of transformation of extracted signals.

tion is 100 cm/s2, more than five times the acceleration measured by the accelerometer, due to degradation of GPS-RTK specific noise. *In fact, these spikes of much larger magnitude are the false measurements in the GPS-derived acceleration.*

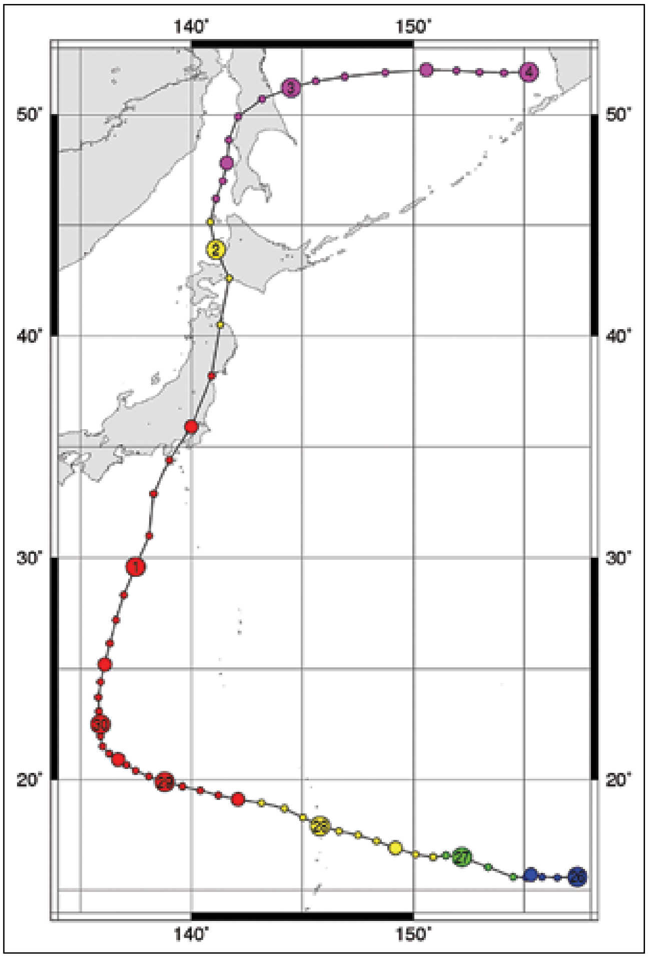
Transformation of Extracted Signals. From the preceding processing result we see that it is important to apply some "quality control" measures before the double differentiation. One such measure is to identify the correlated signal based on FFT and then carefully design the filter parameters so that the filter can extract the signal, while suppressing noise. **Figure 6** gives the double differentiation result of the signal extracted from GPS-RTK displacement measurements. The axes are the same as Figure 5.

By using filtering techniques, the GPS converted acceleration (mid plot in Figure 6) is now very similar to the accelerometer time series (bottom plot). But a delay of more than 35 seconds is clearly visible due to the nature of the FIR filter. Because filtering is a convolution process, the filtered signal is time shifted. And the filter also alters the output signal phase, leading to phase delay, although the filter can be designed with linear phase.

Therefore, the extracted signal obtained by filtering contains time delay, phase delay, and amplitude distortion. Although careful filter design can ensure constant magnitude and linear phase, we also need to compensate for the delay caused by filtering in order to match converted results from one sensor with the direct measurements from another sensor for the purpose of direct and real-time comparison.

Result after Delay Compensation. The delay between the converted and measured accelerations was accurately calculated using cross-correlation. After compensating for the estimated delay (**Figure 7** mid plot) a clear similarity now exists between the two time series (mid and bottom plots). Note also that the GPS-derived acceleration is smoother than that measured by the accelerometer because the derived acceleration is based primarily on the first mode. This demonstrates the success in removing the spikes in the GPS-derived acceleration as shown in Figure 5.

The advantage of multi-sensor integration can be further exploited after



Typhoon Number 21 storm track, September 27–October 4, 2002.

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this synchronization between converted and measured acceleration. For example, by averaging the two acceleration time series, we can obtain a final measurement that is higher in accuracy than using either single sensor.

Results from the Typhoon Event

How do we apply the framework described earlier in a reverse transformation? We try to convert the acceleration measured by the accelerometer into displacement. This is much more challenging than the forward transformation because a double integration process is involved and the two integration constants (velocity and displacement) are not available from the accelerometer measurements alone.

Therefore, we first assume that both the velocity and displacement constants are zero and simply integrate twice the acceleration from the accelerometer. Even this did not prove to be easy because of the drift in the accelerometer (more details later). In **Figure 8** the blue line in the lower plot represents the converted displacement from acceleration through double integration. The red line in the lower plot is the correlated displacement extracted from GPS-RTK measurements.

The displacements from the two sensors appear close to each other, oscillating at 0.57Hz frequency, although some differences can be observed in the first 30 seconds because the detected vibration amplitude was less than two centimeters, the limit of the GPS-RTK sensitivity. In this case the GPS-RTK measured displacement is significantly affected by the inherent noise of the GPS.

However, if we compare the accelerometer-derived displacement (blue line in the lower plot) with the GPS measured displacement (red line in the upper plot), both the static (represented by the offset between the two plots) and the quasi-static (represented by the pink least-square fitted line) components of displacement are missing in the converted result. This is due to the fact that both the velocity and displacement constants had

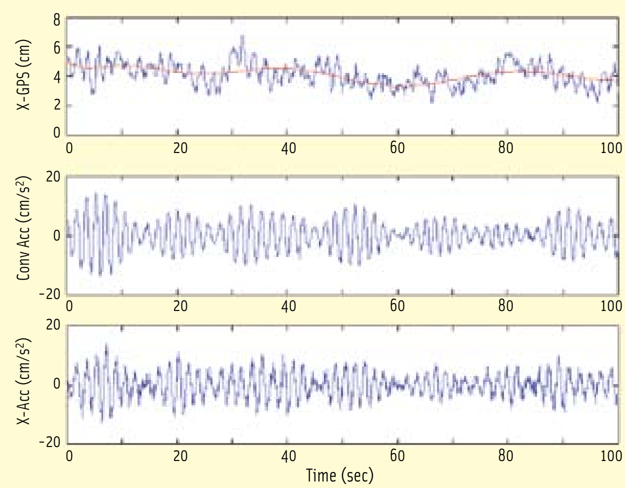

FIGURE 7 Result of transformation after delay compensation.

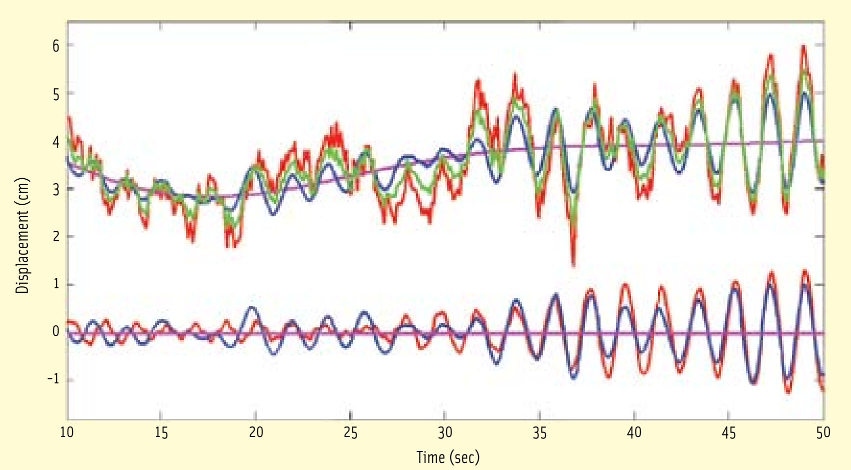

FIGURE 8 Acceleration to displacement transformation: intermediate and final results.

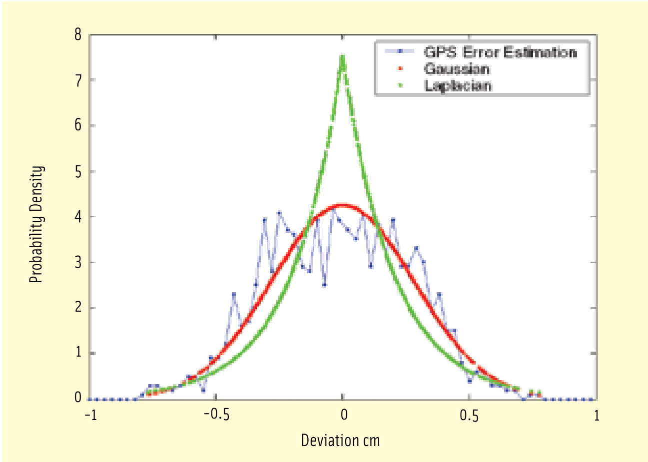

FIGURE 9 GPS deviation distribution analysis.

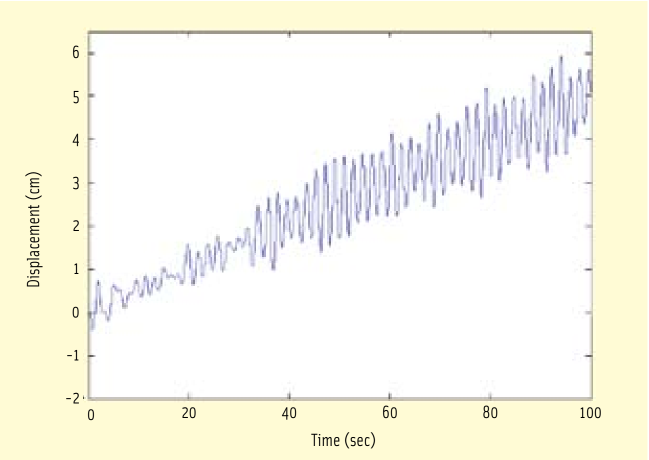

FIGURE 10 Direct double integration of acceleration

been assumed zero in the double integration while in fact they were not.

By extracting the static and quasi-static components from the GPS measurements and adding them to the accelerometer-derived displacement (the dynamic component), the blue line in the upper plot gives the final displacement converted from acceleration. We can see that the displacement is now very close to the original GPS-RTK measurement (red line in the upper plot). The green line in the upper plot is the average of two displacement time series, one derived and the other directly measured.

We must point out that delay compensation once again plays a very important role in ensuring the success of this reverse transformation. Some of the challenging issues involved are discussed in the following sections.

In order to assess the benefit of combining measurements from two sensors, we use the average of the two measurements from the two sensors as true values. We then analyze the data probability density function (PDF) of any measurement from a single sensor against the average.

In **Figure 9** the blue line is the PDF result of GPS displacement measurement (red line in Figure 8) at 0.03cm interval. The calculated variance value is 0.28 and the spreading of the measurement away from the average (green line in the upper plot of Figure 8) is in the range of -0.8cm to 0.8cm. The red and green lines in Figure 9 are, respectively, the mathematically expected Gaussian and Laplacian distribution with variance of 0.28.

We can see that the deviation of GPS measurement from the average fits the typical Gaussian distribution. Meanwhile, it gives us other information, for example, the GPS displacement deviation from the average is bounded within ±0.3cm mostly. Therefore, averaging the measurements from different sensors is one way of exploiting the complementary characteristics of the multi-sensor system.

Reverse Transformation Step by Step

Displacement measurement is theoretically possible using an accelerometer by double integrating the acceleration. However, an accelerometer has a natural drift due to the unknown local gravity value and the behavior of certain system components. Consequently, displacement results cannot be obtained by simple double integration without pre-processing of the acceleration data. **Figure 10** shows the result of a direct double integration with a clear drift of large rate, no matter whether the drift is negative or positive. The converted displacement contains such a drift that the mean is increasing by 5 centimeters in 100 seconds. Because of the filter's die-away characteristics the output window length is limited to 100 seconds only in this example.

In order to overcome this problem we need to find the correct velocity constant from both the accelerometer measured acceleration and GPS-RTK measured displacement. In this way, the lab-based threshold setting for accelerometers can be avoided. In our new approach very low frequency components were filtered out first from the raw acceleration data, taking into account clear signals located in the lower end of the GPS measurement spectrum. Then the acceleration

We need to compensate for the delay caused by filtering in order to match converted results from one sensor with the direct measurements from another sensor for the purpose of direct and real-time comparison.

is converted to velocity measurements through a single integration. Therefore, the velocity constant from the accelerometer data can be calculated from the derived data.

In the same way, the GPS velocity constant can be obtained, but only the extracted correlation signal was used in the single differentiation. Once both velocity constants were obtained, velocity trend was removed from the velocity

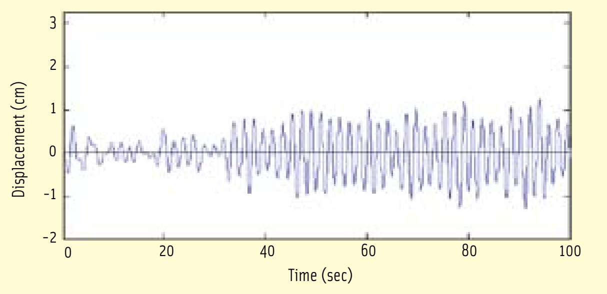

FIGURE 11 Double integration of acceleration with velocity constant correction

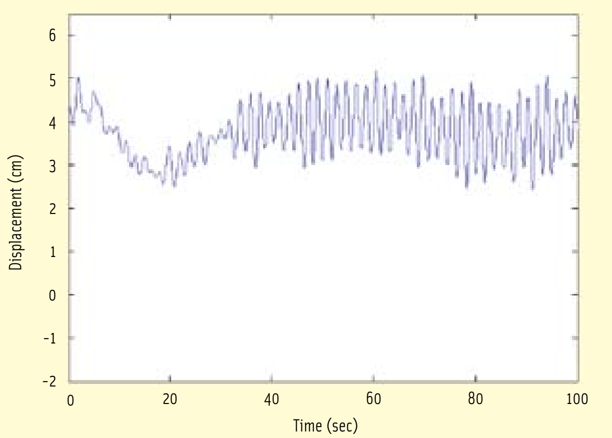

FIGURE 12 Accelerometer-derived displacement after incorporating the static and quasi-static components from GPS-RTK.

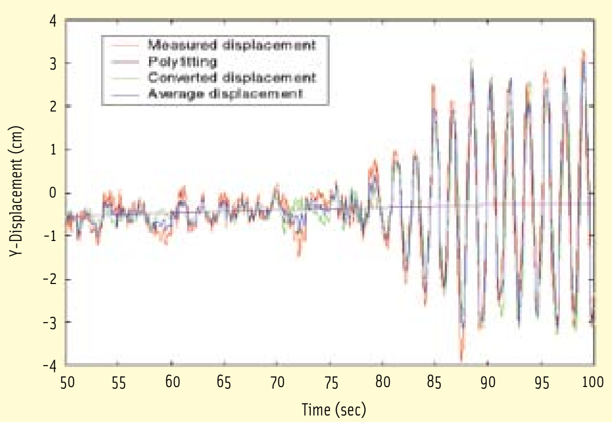

FIGURE 13 Comparison of reverse transformation results for the earthquake event.

time series derived from accelerometer measurements. Finally, the corrected velocity was integrated again to become displacement. **Figure 11** is the result after this de-trending (Note: the scale has been kept the same as Figure 10 for the purpose of easy comparison). This time series was also represented as the blue line in the lower plot of Figure 8, which was overlaid on the extracted correlation signal from GPS measurements (red line in the lower plot of Figure 8).

Wind-induced response, however, consists of a static component— a mean value or displacement constant — as well as a dynamic fluctuating component. It is a challenge to develop a method to estimate and compensate for the missing static component in the displacement derived from the accelerometer data, because the converted displacement can be extremely useful in identifying the false measurements from GPS-RTK (or interpolating for missing data).

Our previous studies have shown the advantage of GPS for measuring static and quasi-static movements. Therefore, we computed the static and quasi-static components from the GPS data and added them to the displacement derived from the accelerometer data. The result after incorporating the static and quasi-static components is shown in **Figure 12**. Both this result and its average with the GPS-measured displacement have been compared to the original GPS displacement measurement as indicated in Figure 8 (upper plot).

Earthquake Displacement: Converted versus Measured

As we mentioned at the outset, another set of data was collected by the combined GPS-RTK and accelerometer system during an earthquake of magnitude Ms 7.0 that occurred on May 26, 2003. We used the same procedures outlined previously to analyze the earthquake dataset. In **Figure 13** the red line represents the GPS-RTK measured displacement; the pink line, its polyfitting; the green line, the displacement derived from accelerometer measurements; and the blue line, the average of the two displacements.

From the figure it can be seen that the converted displacement follows the GPS-measured displacement at the quake waves (right-hand portion) very closely. But before the arrival of the seismic waves, obvious differences between displacements from the two sensors (left-hand portion). This agrees with our earlier study suggesting that GPS-RTK can follow movements better when they are larger than two centimeters. By taking the average of displacements from the two sensors the blue trace gives the most robust result that the combined system could deliver.

Displacement results cannot be obtained by simple double integration without pre-processing of the acceleration data.

Conclusion

In order to exploit the complementary characteristics of the GPS-RTK and accelerometer sensors, a new integration approach has been developed that employs the correlation signals directly detected from GPS-RTK and accelerometer to transform one form of measurement to another. That is, the forward transformation from displacement to acceleration, as well as the reverse transformation from acceleration to displacement.

Because the drift of the accelerometer can be estimated precisely, lab-based threshold setting for the accelerometer has been avoided. On one hand, the false and missing measurements from GPS can be recovered by double integrating the accelerometer measurements. On the other hand, the weakness of lacking static and quasi-static components for the acceleration-derived results is also resolved by incorporating the linear trend detected in the GPS-measured displacement. Therefore, successful forward and reverse transformations can be used as a robust quality assurance for monitoring structural deformation.

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Additional Resources

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Manufacturers Credits

The GPS receiver used in the Japan installation was an MC1000, **Leica Geosystems,** Heerbrugg, Switzerland. Other equipment included a servo type accelerometer, JA-24MA03, **Japan Aviation Electronics Industry,** Limited, Tokyo, Japan; a three-cup AF860 anemometer and vane, **Makino Applied Instruments**, Japan; and an FLA-5-11-5LT strain gauge, **Tokyo Sokki Kenkyujo Co., Ltd.,** Tokyo, Japan.

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Yukio Tamura is a professor of the Tokyo Polytechnic University, and the director of the 21st Century Center of Excellence (COE) Program named "Wind Effects of Buildings and Urban Environment (WEBUE)" authorized by the Ministry of Education, Culture, Sports, Science and Technology of Japan. He currently holds several responsible positions in the wind engineering society, including president of the Japan Association for Wind Engineering, chairman of the Committee on Wind Loading of the Architectural Institute of Japan, and convener of WG-E (Dynamic Responses) of the Codification Working Group of the International Association for Wind Engineering.

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