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Abstract. Over the last decade, users of the Global Positioning System (GPS) have developed the technology capable of meeting stringent requirements to study the dynamics of tall buildings, towers, and bridges during earthquakes, wind-induced deformation and traffic loading. Dynamic measurements of relative displacements of structures is currently possible using real-time kinematic (RTK) positioning techniques, now advanced to record typically at 10–20 Hz (or higher – e.g., 100 Hz) with an accuracy of ±1 cm horizontally and ±2 cm vertically. With further advances in the technology and improvements in sampling capability, it is possible to meet the needs of real-time displacement information for the structural engineering community. After a decade of great strides in proving the feasibility of the technology, focus is moving to sensor integration and operational systems. Several investigators are now routinely researching the integration of GPS with other sensors (accelerometers, optic fibres, pseudolites, etc.) to utilise the complementary benefits and overcome limitations of the individual systems. Examples of real-time operational systems exist to demonstrate the significance of GPS technology in measuring the dynamic behaviour of large engineering structures.

Keywords Global Positioning System (GPS) ─structural monitoring–RTK

1 Introduction

The last decade has witnessed a rise in the number of investigators demonstrating the feasibility of using the Global Positioning System (GPS) technology to monitor the dynamic behaviour of tall buildings, towers, and bridges due to earthquake, wind or traffic effects. This has occurred for the following major reasons: (1) displacement measurements under static and dynamic conditions are easier to make with GPS; (2) easy and economical access to GPS hardware and software; (3) portability of field equipment; (4) international collaboration; and (5) improvements in both accuracy and sampling capability.

This paper summarises some of the major activities in structural monitoring with GPS. The precision of GPS receivers has improved and the sampling capability has increased by an order of magnitude over the last decade. These improvements have led to advances in applying the GPS technology in structural health monitoring projects and, as such, this document takes on a rather historical perspective.

1.1 Scope of this paper

In order to limit the length of this paper it has been necessary to assume that the reader has already been introduced to GPS and its applications to structural monitoring (Lovse et al., 1995; Ashkenazi et al., 1996, 1997; Teague et al. 1995; Duff and Hyzak, 1997; Guo and Ge, 1997; Celebi et al., 1998; Roberts et al., 1999; Celebi, 2000; Nakamura, 2000; Ogaja et al., 2001; Celebi and Sanli, 2002; Meng 2002; Kijewski-Correa and Kareem, 2003, 2004; Larocca 2004; Larocca and Schaal, 2005; Guo et al., 2005; Chan et al., 2006; Li et al., 2006a, 2006b; and many others). The emphasis is on real-time kinematic (RTK) GPS for fast deformations of tall structures (Figure 1) and long-span bridges; certain topics such as using GPS for tracking slow deformations (dams, embankments), are beyond the scope of this review. Unfortunately, there is insufficient space to discuss the various experiments and scientific results in detail. The reader may find these project-specific topics discussed in papers submitted to conference proceedings and journals.

FIGURE 1

2 Pioneering work: 1993-1997

Early work on the dynamic monitoring of engineering structures with GPS started in the mid-1990s, soon after the advent of the RTK-GPS surveying technique. Prior to this, some limited studies on structural monitoring with GPS were carried out using static (receiver) observations, post-processed using commercial software available at the time. Such studies were limited to detection of slow deformations, as expected on large structures such as dams and embarkments (DeLoach, 1989; Hollmann & Welsch, 1992). In this review the authors restrict their attention to some of the early work that has been carried out for the dynamic monitoring of tall buildings, towers and suspension bridges.

2.1 Tall Buildings and Towers

A field trial on the Calgary Tower (160m high), Alberta, Canada, in 1993 is probably the earliest test of the use of GPS technology for the dynamic monitoring of a tall structure under wind loading. The article by Lovse et al. (1995) outlines the GPS results from that experiment in which tower movements (0.36 Hz) were caused by a 60–100km/h wind.

In 1996, a similar experiment was carried out in China. Guo and Ge (1997) describe using GPS to measure the displacement and frequency signature of the Diwang Tower (68 stories, 325m high) in Shenzhen City, under wind loading from Typhoon York, which was the strongest typhoon in the region since 1983. Post-mission analysis of the GPS records detected the amplitude and frequency of the tower deflections (0.17 Hz) due to the 90-km/h winds caused by the typhoon.

In the state of California, due to the high risk of earthquakes, researchers at the US Geological Survey (USGS) successfully tested the feasibility of using GPS technology to monitor the dynamic response of buildings to earthquakes (Celebi et al., 1997, 1998; Celebi, 1998).

2.2 Suspension Bridges

In 1996, Ashkenazi et al. (1996) reported real-time GPS monitoring of the Humber Bridge in the United Kingdom. In the USA, Duff and Hyzak (1997) were probably the first to measure the short-term motion of a suspension bridge under wind and traffic loading with the GPS technology. They generated a bridge deck surface profile of the Hartman Bridge in Houston (Texas) and the Blackwater River Bridge in Florida, from a GPS kinematic survey. Around the same time, Ashkenazi et al. (1997) demonstrated that RTK-GPS could monitor the movements of large bridges in real-time. Successful tests were carried out at strategic points on three different bridges in the UK; the Humber Bridge, the Nottingham Clifton Bridge and the Dee Bridge. Since then, researchers at the Institute of Engineering Surveying and Space Geodesy (IESSG), University of Nottingham, have followed with a series of other trials (reviewed in a later section). In Australia, Watson and Coleman (1998) measured the dynamic movement of the Batman Bridge in Tasmania using GPS.

3 GPS Receiver Technology: From 10 Hz to 100 Hz

High-accuracy dynamic monitoring with GPS demands the best of both hardware and software as well as innovative methodologies. Geodetic receivers, ranging in cost between US$10,000 and US$20,000, are readily available. Over 100 manufacturers are marketing receivers and magazines such as *GPS World, Inside GNSS* and *Professional Surveyor* regularly publish information on the latest receiver models. Figure 2 is an extract from the *GPS World* Receiver Surveys of 1997 to 2006, indicating the trends in the sampling capability of some of the most common GPS receivers. In terms of accuracy, there is notable improvement in some receiver models [e.g., Leica MC1000 was capable of 1 cm + 2 ppm at 10 Hz sampling rate in the 1997 *GPS World* Receiver Survey; a comparable model (MC500) was capable of sub-centimetre resolution (5 millimetres + 2.0 ppm dynamic RMS accuracy) in the 2004 *GPS World* Receiver Survey].

FIGURE 2

Historically, accelerometers have been used to monitor structures through the double integration of acceleration measurements to derive the displacement measurements (see e.g., Celebi, 1993, 1994). Accelerometers can record at up to 1,000 Hz or higher (Chan et al., 2006), however displacement results are not obtainable in real-time and instrument drift is undesirable. Unlike accelerometers, high rate GPS directly measures displacements, however, until recently, the maximum data rate was typically 10–20 Hz. The complementary features of the two technologies (Table 1) are important for an integrated GPS-accelerometer system. Furthermore, advances in the GPS sampling capability will enable researchers to expand the measurable frequency with the integrated approach.

TABLE 1

While 10–20 Hz receivers have been used for some time, e.g., as GPS seismometers (Ge 1999; Ge et al., 2000, 2002; Ogaja 2001; Turner 2002), some manufacturers have introduced receivers with much higher sampling rates (e.g., up to 100 Hz, as shown in Figure 2). The introduction of 50–100 Hz GPS receivers is an important development for GPS-based structural monitoring as it increases the GPS frequency bandwidth compared to that of accelerometers. Early trials have shown that such receivers are quite capable of performing as well as the known high quality 10–20 Hz receivers. For example, Roberts et al. (2004a, 2004b) have published results from zero-baseline and actual bridge trials. A newsletter article by the Institute of Geophysics and Planetary Physics (IGPP), University of California, San Diego, describe a trial with 50 Hz GPS receivers on a 7-storey building ["IGPP geodesists Yehuda Bock & Fan Yang apply 50 Hz GPS to outdoor shake table tests of a 7-story building at Camp Elliott", *IGPP News*, January 30, 2006]. Genrich and Bock (2006) also confirm that instantaneous positioning using 10–50 Hz geodetic GPS receivers is comparable in accuracy with lower-frequency (1 Hz) sampling.

4 Field Trials and Innovations: 1997-2006

Concurrent with the above developments in GPS receiver technology was the increase in the number of investigators publishing their research activities. The following is a summary of the major field trials and research activities which have occurred within the last decade.

4.1 Tall Buildings and Towers

Since the occurrence of Northridge (17 January 1994, M_W=6.7) and Kobe (17 January 1995, M_W=6.8) earthquakes, studies of susceptibility to damage of tall buildings have become more important. Early studies by USGS scientists in California have discussed concepts and the technical feasibility of using GPS technology to monitor the response of buildings to such earthquakes (Celebi et al., 1997; Celebi, 1998; Celebi et al., 1999). Simulation studies with a model structure demonstrated the technical feasibility, and recent papers have discussed actual deployment of GPS receivers on tall buildings. For example, Celebi and Sanli (2002) describe developmental work in which GPS receivers were deployed on two 44-storey buildings in Los Angeles and one 34-storey building in San Francisco. The buildings were also instrumented with accelerometers to allow comparison of GPS-measured displacements with the displacements calculated by double integration of acceleration measurements. Results showed the great potential for GPS application to monitor structures during earthquakes and wind-induced deformation.

In Singapore, the Republic Plaza (Figure 3) has been instrumented with accelerometers and anemometers since 1996, in order to measure its response to distant earthquakes and wind forces (Ogaja, 2002; Brownjohn et al., 2004). Despite the city being relatively far from the earthquake zones in Indonesia and without strong cyclonic weather systems, the Republic Plaza (280 m tall) was built with earthquake-proof features and designed to improve its stability to wind loading (i.e., it tapers as it rises). In February 2000 a pilot experiment was carried out to test the feasibility of incorporating GPS to the existing monitoring system (Ogaja et al., 2000, 2003). Both the GPS and accelerometer data successfully captured the building response to strong winds. In another paper, Brownjohn et al. (2003) looked into the challenges of implementing GPS and fibre optics for the continuous monitoring of the building. Problems such as overheating, power failures, and landline reliability prevented continuous GPS operation, but data collected in early 2003 and in the first half of 2004 showed that GPS is capable of monitoring the dynamic response (Brownjohn et al., 2004).

FIGURE 3

In Malaysia, a case study was conducted on the tallest building in Penang, KOMTAR Plaza (245m high, 65 floors) at two different epochs, in October 2000 and February 2001 (Wan Aziz et al., 2001). A follow-up experiment was carried out on the Sarawak Business Tower (30 stories) in Johore, during December 2004 (Wan Aziz et al., 2005). In static tests, both studies showed stability of the structures, however no significant events (such as earthquakes and strong wind episodes) occurred to enable dynamic stability tests. However, the suitability of RTK-GPS for continuous monitoring was demonstrated.

As part of a collaborative research project, investigators at the Tokyo Polytechnic University and the University of New South Wales, Australia, have described a series of tests on a 108 m steel tower in Tokyo using GPS, accelerometer and optical fibre sensors (Tamura et al., 2002; Li et al., 2003; Li, 2004; Li et al., 2004, 2005a, 2005b, 2006a, 2006b). Actual data has been collected during typhoons and earthquakes [for example, Typhoon No. 21 on 1 October 2002 (Tamura et al., 2002) and M_S=7.0 earthquake on 26 May 2003 (Li, 2004)], and analysed in both time and frequency domains for wind and earthquake-induced deformation. The benefits of sensor integration have been highlighted.

Kijewski-Correa (2003) described comprehensive GPS configuration and validation tests in Chicago, where instrumentation deployed on three tall buildings included high-accuracy GPS, accelerometers and anemometers. The observed responses were compared to predictions from wind tunnel tests and analytic models developed in the design phase. Following these initial tests, a full-scale monitoring system has been in operation since mid-2002 (Kijewski-Correa and Kareem, 2003, 2004; Kijewski-Correa et al., 2005).

During November 2005–January 2006, investigators at the Institute of Geophysics and Planetary Physics (IGPP), University of California, San Diego, deployed seven 50 Hz GPS receivers in shake-table tests of a 7-storey building. They compared instantaneous 50 Hz GPS displacements with accelerometer data and induced earthquake motions. Results demonstrated consistent mm-level accuracy for the measured displacements and the usefulness of high-rate GPS for seismic monitoring of structures. This experiment was reported in the *IGPP News* of January 30, 2006.

4.2 Suspension Bridges

IESSG researchers at the University of Nottingham have been active in monitoring suspension bridges in the UK since the first trials by Ashkenazi et al. (1996). There have been numerous studies ranging from GPS/accelerometer integrations (Ashkenazi and Roberts, 1998; Roberts et al., 1999, 2000, 2001, 2004a, 2004b; Meng, 2002; Cosser et al., 2003) to GPS/pseudolite integrations (Meng et al., 2002). Starting early 2002, collaboration with investigators at the University of New South Wales, Australia, have led to further systematic studies on GPS/pseudolite integration and methodologies (Barnes et al., 2003, 2005). The trials on Wilford Suspension Footbridge in Nottingham, UK (Barnes et al., 2003), and the Parsley Bay Suspension Footbridge in Sydney, Australia (Barnes et al., 2005), have demonstrated that pseudolite augmentation is one solution in situations of poor GPS geometry.

In 1999, the California Department of Transportation (Caltrans) launched a GPS-based project on the Vincent Thomas Bridge in Los Angeles Harbour, the San Francisco Bay Bridge, and the Golden Gate Bridge in San Francisco, to evaluate the feasibility and capability of GPS technology for monitoring long-span bridges (Turner, 2003). Caltrans demonstrated that networked RTK-GPS is a good tool for monitoring differential movements that may indicate potential problems in a post-disaster situation. Following this initial success, a new project focussed on the Carquinez Bridge in California, in early 2004, for monitoring real-time displacement under traffic, wind, and seismic loads.

The late 1990's also saw the introduction of GPS for the monitoring of suspension bridges in Japan. Fujino et al. (2000) describe the monitoring system on the Akashi Kaikyo Bridg,e and one of the first trials of displacement measurement using GPS. Nakamura (2000) compares GPS results to wind velocities and acceleration data of suspension bridge girder displacements under wind forces. The field measurements were carried out during a strong wind season, and the displacements of the girders obtained agreed well with the numerically-predicted values and wind tunnel test results.

Trials in Brazil have occurred since circa 2001 (Schaal and Larocca, 2002; Larocca, 2004; Schaal et al., 2005; Larocca and Schaal, 2005). Most notably, the Brazilian investigators have developed an innovative methodology for low-cost high-accuracy bridge monitoring with single-frequency GPS receivers. In their methodology, there is no data adjustment and bridge oscillations can be seen directly from data collected from two satellites, one close to the zenith and the other in the direction of the horizon. The reference satellite is chosen according to the direction of bridge movements (e.g., close to horizon for vertical oscillations). The satellite geometry constraint requires that trials be conducted when the constellation has one highest and one lowest satellite. This challenge can be overcome with proper trial planning.

In July 2004, the IESSG researchers conducted zero-baseline, short-baseline and bridge trials to assess the performance of JNS100 receivers, capable of gathering data at up to 100 Hz (Roberts et al., 2004b). Previously, the highest GPS data rate used in experiments had been 10 – 20 Hz, which means that only bridge dynamics lower than 10 Hz could be detected. At the IESSG, most previous work had included the integration of 10 Hz GPS with accelerometers, typically gathering data at up to 200 Hz. In the JNS100 trials, comparisons were made with Leica SR510 single-frequency receivers sampling at 10 Hz. Standard deviations of the JNS100 data at 50 Hz and 10 Hz (resampled) were compared with those of the Leica receivers in a local coordinate system. The results showed that the Leica receivers performed slightly better than the JNS100 in the static trials, but the difference was small. In the bridge kinematic trials, the JNS100 receivers performed as well as the Leica receivers. The JNS100 results, measured at 50 Hz, also compared well to a triaxial accelerometer measuring at the same data rate.

5 Operational Systems

Real-time monitoring systems with GPS receiver array systems have been commissioned in many parts of the world. The GPS components are based on RTK software developed by various commercial vendors and research institutions.

5.1 Major RTK Software Systems

The following is an alphabetically ordered list of major RTK software systems, which are in routine use today and are capable of real-time monitoring of manmade structures. The inclusion of the names herein does not imply endorsement of the products by the authors.

3D TRACKER by Condor Earth Technologies Inc. (www.condorearth.com) is a commercial software package for real-time 3D monitoring of large engineered structures. In 2002, Trimble and Condor announced a joint venture to use Trimble's survey-grade GPS receivers.

GOCA (GPS-based Online Control and Alarm) software system by the University of Applied Sciences in Karlsruhe (Kalber et al., 2000) for a centralised network adjustment of baseline solutions to detect motions of receivers between observation epochs. It uses both single- and dual-frequency GPS receivers.

INTETRAK by Orion Monitoring Systems Inc. for real-time displacement monitoring and the comprehensive management of continuous GPS monitoring systems. InteTrak supports receivers and raw data formats from a wide range of GPS manufacturers.

RTK Extend™ by NavCom Technologies Inc. (NavCom, 2006) for RTK positioning. NavCom integrated StarFire with RTK to introduce RTK Extend™.

SPIDER by Leica Geosystems is an integrated software suite for centrally controlling and operating single GPS reference stations or networks of GPS stations. This is probably the most widely used system in operational structural monitoring systems today.

5. 2 Examples of Operational RTK-Based Monitoring Systems

5.2.1 Tall Buildings in Chicago, Illinois

Chicago (Figure 4) has the tallest building in the United States, the Sears Tower – consisting of at least 100 floors (New York City had 3 such buildings from 1973-2001). A full-scale monitoring program was established for three tall buildings in Chicago in 2003 (Kijewski-Correa and Kareem, 2003). The program integrates high-accuracy GPS with a suite of traditional sensors in a comprehensive and robust sensor array. Each building is equipped with four force-balance accelerometers, mounted in orthogonal pairs at opposite corners of the highest possible floor, to capture both sway and torsional responses. The instrumentation was installed on two buildings in June 2002 and on a third in April 2003. The latter was supplemented by two ultrasonic anemometers atop masts at opposite corners of the rooftop, 41 metres above roof level, to measure the wind field characteristics above downtown Chicago.

FIGURE 4

5.2.2 Latitude Tower in Sydney, Australia

Latitude Tower (Figure 5) is a 46-storey office building in the Sydney Central Business District, Australia. Completed in late 2004, it stands at a height of 192 m above street level (222m to the tip of a spire). A test bed has been set up by the University of New South Wales in collaboration with the University of Sydney to study the structural response of the building to local wind effects. The test bed is equipped with GPS sensors, accelerometers and an anemometer, installed since early 2006. The monitoring system is intended to measure sway and torsional response hence GPS is installed on the rooftop, and the two accelerometers are mounted at the highest accessible level of the tower. The anemometer is installed on the rooftop to measure both wind speed and direction.

FIGURE 5

5.2.3 Tsing Ma Bridge, Hong Kong

The Tsing Ma Bridge is an internationally known engineering achievement, and a major Hong Kong landmark (Figure 6). It is part of the Lantau Link, which comprises the Tsing Ma suspension bridge, viaducts crossing Ma Wan and the Kap Shui Mun cable-stayed bridge. With a clear span of 1377 m, it is 97 m longer than San Francisco’s Golden Gate Bridge. The *Wind and Structural Health Monitoring System* for the Tsing Ma Bridge consists of 774 sensors (of seven major types: anemometers, temperature sensors, dynamic weigh-in-motion sensors, accelerometers, displacement transducers, level sensing stations, and strain gauges) and 31 GPS receivers (Wong et al., 2001; Svitil, 2002). The GPS receiver array system, referred to as "the real-time GPS On-Structure Instrumentation System (GPS-OSIS)", monitors the motions of the main suspension cables, decks and bridge towers.

FIGURE 6

5.2.4 Akashi Kaikyo Bridge, Japan

The Akashi Kaikyo Bridge (Figure 7) is the world’s longest suspension bridge, with a centre span length of 1991 metres. It has a state-of-the-art structural health monitoring system (operational since 1999) comprising three GPS receivers, and several seismometers, accelerometers, and anemometers. Two of the GPS antennas are mounted on the tall bridge towers at either end of the bridge, and the third is at the midpoint of the bridge. Through the continuous measurement of bridge positions, temperatures at representative points, and other sensory data, the bridge performance is monitored in real-time, and a network of GPS reference stations enables mm-level accuracy. The Akashi Strait has rapid currents and the region is at risk from high winds and earthquakes.

FIGURE 7

5.2.5 Jiangyin Bridge, China

The Jiangyin Yangtze River Highway Bridge (Figure 8) spans more than one kilometre (Leica, 2007). It is the longest steel box girder suspension bridge in China, and the fourth longest in the world. It services a major highway, which is the national key trunk route crossing the Yangtze River, between Jiangyin and Jingjiang in Jiangsu Province. An upgrade and modification of the Jiangyin bridge health monitoring system was recently completed using a Leica Geosystems GPS monitoring system which focusses on the monitoring of the girder geometric form and the displacement of the bridge towers. The system has provided a cost-effective and innovative solution for delivering 3D positioning information at 20 Hz from several GPS sensors, including the advanced analysis application software (Leica 2007).

FIGURE 8

6 Concluding Remarks

This paper summarises some of the developments in structural health monitoring (SHM) based on the use of GPS technology. Advances in the GPS technology are making the application of real-time SHM systems ever more a feasible solution to SHM of tall buildings or long slender bridges. Recent papers report trials with complementary technologies such as accelerometers and fibre optic sensors. The benefits of such sensor integrations cannot be overemphasised. Further improvements to the GPS technology are possible, including the ability to gather data at very high sampling rates and the tracking of other satellite constellations (e.g. GLONASS).

Other areas of development include (1) additional software tools to deal with the large volumes of data generated by real-time systems, and (2) incorporating wireless technologies in the SHM systems. Most operational real-time SHM systems are Internet-based, designed such that data is transferred to an Internet server through an appropriate telecommunicatiosn link. SHM systems have to date been based on wire-line instrumentation where sensors placed at critical points on a structure are connected to a central data system with cables of various types (coaxial, serial, optical fibre, etc). However emerging wireless technologies provide an opportunity to overcome cabling problems in large monitoring networks.

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Table 1 The complementary features of GPS technology and accelerometer.

	GPS	Accelerometer
Dynamic Displacement	Measures directly, real-time	Requires double integration
Frequency Bandwidth	Currently up to 100 Hz	Up to 1,000 Hz
Portability, Deployment	Portable, requires sky visibility, hence can only be deployed on the outside of structures e.g. on rooftops, bridge decks and towers	Portable, can be deployed both inside and outside of structures, can recover dynamic response at different structural floor levels
Position Accuracy	Sub-cm to cm-level No instrument drift errors	Very accurate Instrumental drift errors
Tolerance	All-weather system	Low temperatures

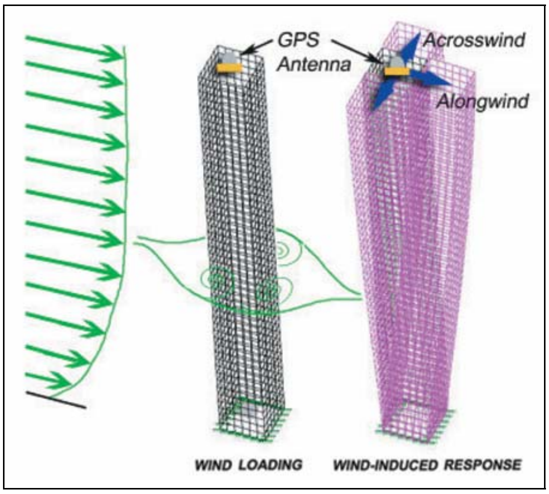

Fig. 1 A schematic of wind-induced deformation (Kijewski-Correa and Kareem, 2003).

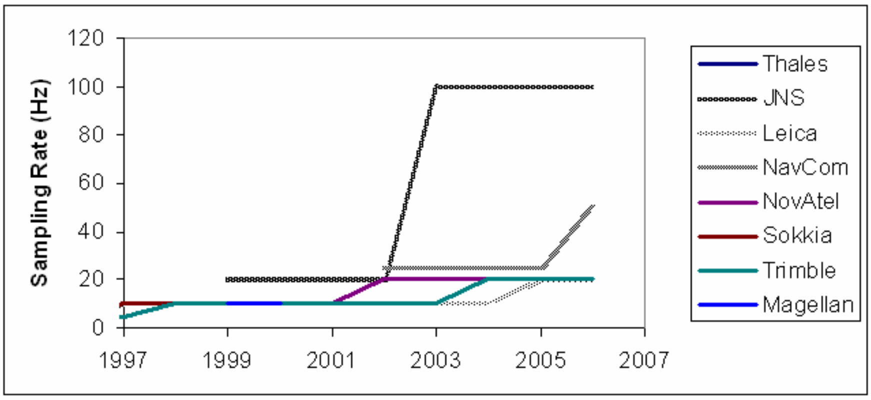

Fig. 2 Trends of GPS receiver sampling rates from the *GPS World* Receiver Surveys of 1997-2006.

Fig. 3 Republic Plaza, Singapore

Fig. 4 Downtown Chicago (Kijewski-Correa and Kareem, 2003).

Fig. 5 Latitude Tower in Sydney, Australia.

Fig. 6 GPS antenna on Tsing Ma Bridge, Hong Kong. The bridge has over 800 sensors of which 31 are GPS. The GPS sensors continuously monitor motion caused by high winds and traffic.

Fig. 7 Akashi-Kaikyo Bridge, Japan. In the bottom image is a GPS antenna on one of the bridge towers.

Fig. 8 GPS monitoring station at Jiangyin Bridge, China.