

# Structural Deformation Monitoring Using *Locata*

Joel BARNES, Chris RIZOS, Mustafa KANLI, David SMALL, Gavin VOIGT,  
Nunzio GAMBALE and Jimmy LAMANCE, Australia

**Key words:**

## SUMMARY

GPS has proven to be a useful tool for precision deformation monitoring applications, in both physical geodesy, and more recently for structural engineering. For continuous structural deformation monitoring (on an epoch-by-epoch basis) it is desirable for the measurement system to deliver equal precision in all position components, all of the time. However, the quality of GPS position solutions are heavily dependent on the number and geometric distribution of the available satellites. Therefore, the positioning precision is not the same in all three components, and during a 24-hour period the positioning precision varies significantly. This situation becomes worse when the line-of-sight to GPS satellites is obstructed due to trees or buildings in urban environments, reducing the number of visible satellites (often to less than 4).

*Locata* is a new positioning technology that uses a network of ground based transceivers which cover a specific area with strong signals. This paper discusses the *Locata* technology and assesses its suitability for use in structural deformation monitoring applications, through an experimental trial at the Parsley Bay suspension footbridge in Sydney, Australia.

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## 1. INTRODUCTION

The Global Positioning System (GPS) has been widely used for measuring crustal motion, surface subsidence and ground deformation due to volcanic activity, etc., and more recently for monitoring the deformation of manmade structures such as bridges, dams and buildings (Ashkenazi *et al.*, 1998; Behr *et al.*; 1998, Celebi *et al.*, 1998; Duffy & Whitaker, 1999; Rizos *et al.*, 1999). In many of these applications position solutions are required on a continuous basis, at least once a second. In the case of monitoring bridges, this allows early detection of changes in the bridge's response to traffic load, temperature and wind load. To achieve cm-level kinematic positioning accuracies with GPS a relative carrier-phase differential technique (using a base station) is almost exclusively used. Differential operation, most commonly using the double-differenced observable, is necessary to reduce orbit errors, spatially correlated errors due to the atmosphere, and to eliminate both receiver and satellite clock biases. For real-time positioning (i.e., RTK), the roving GPS receiver must receive base station data via a radio modem (or other wireless link) from a base station. This, combined with the fact that RTK GPS only works well with a relatively unobstructed and geometrically good satellite constellation, and the operating range of a rover receiver is typically limited to less than 10km due to ionospheric effects, is a significant limitation of the RTK GPS technology. Even if an RTK GPS system can operate successfully, the precision, availability, reliability and integrity of the position solutions is very dependent on the number and geometric distribution of the available satellites. Therefore, a very large variation in positioning accuracy can be expected during a twenty four hour observation period. Moreover, the accuracy in the height component is typically 2-3 times worse than in the horizontal, because of the geometrical distribution of the satellite constellation and the poorer quality of data below approximately 15 degrees elevation (which is typically not used). Additionally, in mid and high latitude areas (>45 degrees) the accuracy in the north component is worse than the east component, due to the 55 degree inclination of GPS satellites (Meng *et al.*, 2002). This situation becomes worse when the line-of-sight to GPS satellites becomes obstructed, such as in urban environments, and there may be insufficient GPS satellites for positioning.

In situations where the GPS satellite signals are obstructed or the geometry is poor, ground-based transmitters of satellite-like signals ("pseudo-satellites", *pseudolites* or PLs) can be used to increase the number of satellite signals. In theory, PLs can be optimally located to provide additional ranging information to improve the positioning geometry and consistency, and thereby improving the positioning accuracy and reducing its variation. In addition, with enough pseudolites it is theoretically possible to replace GPS entirely, though in practice this has been difficult to achieve. Typically pseudolites use cheap crystal oscillators and operate independently (in the so-called "unsynchronised mode"). In this case, double differencing must be used to eliminate the pseudolite and GPS receiver clock biases.

The Satellite Navigation & Positioning Group (SNAP) in the School of Surveying and Spatial Information Systems at UNSW have been actively conducting research into high precision positioning with combined GPS and PL technologies since 1999. Although the PL technology has been used since the 1970s, for receiver equipment testing before the launch of GPS satellites (Harrington & Dolloff, 1976), PLs have not been widely adopted. However, the technology has been applied to niche applications such as the precision approach of aircraft (Soon *et al.*, 2003; Hein *et al.*, 1997; Bartone, 1996; Cobb *et al.*, 1995). Integrated GPS and PL systems developed for such purposes are expensive (of the order of US\$100K) and custom-built for a particular installation. Stand-alone PLs can be purchased, but the majority of off-the-shelf (OTS) GPS receivers do not have the capability to use their signals. Of the few OTS GPS receivers that are able to track PLs, they can only record PL data for post-processing, and cannot use the signals in real-time. Because of these difficulties PLs are not yet a mainstream OTS technology.

Research by the SNAP group has led to the development of carrier-phase single-epoch software that can process both GPS and PL data. Due to the comparatively small separation between PLs and user receivers, there are some challenging modelling issues which must be addressed, such as non-linearity, PL location errors, tropospheric delays, multipath and noise. These issues have been discussed in a series of papers by SNAP researchers (Barnes *et al.*, 2002a; Wang *et al.*, 2001, 2000; Dai *et al.*, 2000). These earlier studies were conducted using OTS GPS receivers and commercial PLs from IntegriNautics and Global Simulation Systems (now Spirent). Despite the operational difficulties of the hardware used, the benefits and feasibility of PLs in application areas such as deformation monitoring, machine guidance and aircraft landing has been demonstrated (Barnes *et al.*, 2002a,b; Soon *et al.*, 2003; Tsujii *et al.*, 2002).

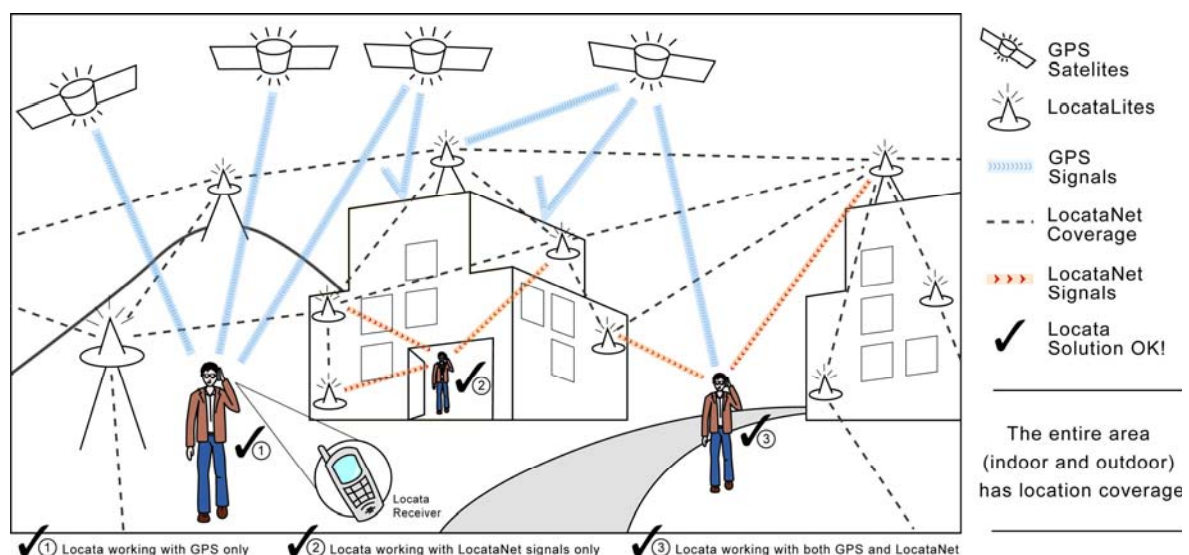
More recently for structural deformation monitoring applications, the SNAP group together with the IESSG at Nottingham University (UK), have been conducting research into the use of PLs for the monitoring of suspension bridges and conducted tests on bridges in the UK and Australia (Barnes *et al.*, 2003d,e; Meng *et al.*, 2003a,b). The results of these trials have been encouraging and demonstrated proof-of-concept for the augmentation of GPS with PLs for deformation monitoring. However, the location of pseudolites is a critical consideration, not only from a geometric perspective (in terms of strengthening the solution), 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 due to 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.

## 2. LOCATA TECHNOLOGY OVERVIEW

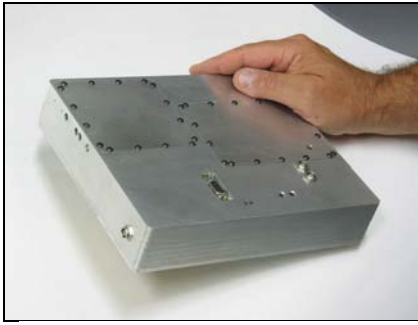
*Locata* is a new positioning technology, developed to address the limitations of existing technologies for precise, reliable, ubiquitous (outdoor and indoor) positioning. The *Locata* positioning concept uses a network of ground-based transmitters that cover a chosen area with strong signals, together with signals from GPS. As illustrated in Figure 1, a *Locata* receiver can track both GPS and *Locata* signals, thereby providing a seamless transition between environments where a user can utilise *Locata* signals, GPS signals, or both. A GPS receiver can only give precise reliable positioning with a relatively unobstructed sky view, which allows enough satellites (4 or more for 3D positioning) with good geometry to be tracked (scenario 1 in Figure 1). *Locata* is designed to improve GPS positioning, extending its capability into difficult indoor and urban environments (scenarios 2 & 3 in Figure 1). Additionally *Locata* can operate entirely independently of GPS (as demonstrated in this paper).

There are two core components of the *Locata* technology (see Barnes *et al.*, 2003a for further details):

- *LocataLite* – A transceiver which generates a GPS-like signal. The prototype device shown in Figure 2 transmits a GPS L1 signal and C/A code pseudorange, and incorporates the same receiver hardware as the *Locata*.
- *Locata* – A stand-alone low cost GPS-like receiver that can track both GPS and *LocataLite* signals. The prototype hardware, shown in Figure 3, is based on an existing GPS chipset. When four or more *LocataLite* signals are tracked the *Locata* receiver is capable of 3-dimensional positioning with sub-centimetre precision.



**Figure 1:** The *Locata* technology positioning concept.



**Figure 2:** Prototype *LocataLite* (transceiver) hardware.



**Figure 3:** Prototype *Locata* (receiver) hardware.

When four or more *LocataLites* are deployed they cooperate to form a positioning network called a *LocataNet*. This positioning network is time-synchronous, which means a stand-alone *Locata* receiver can compute its position without any additional information or correctional data. The time synchronisation procedure is called *Time-Loc*, and is a key innovation of the *Locata* technology. This innovation and other special characteristics of the *LocataNet* are detailed in Barnes *et al.*, 2003a & 2003b.

Using the prototype hardware described above several studies have been conducted to demonstrate proof-of-concept for the *Locata* positioning technology, and verify key system methodologies and algorithms, including:

- Time-synchronised positioning network (*LocataNet*) – using *Locata's Time-Loc* methodology *LocataLites* (ranging signal transceivers) can be time synchronised to better than approximately 30 pico-seconds to form a *LocataNet* (Barnes *et al.*, 2003c). This is done without any hard-wires or external data links.
- Network propagation - the *Time-Loc* methodology allows a *LocataNet* to autonomously propagate into difficult environments and over wide areas, covering many kilometres (Barnes *et al.*, 2003a).
- Signal penetration - In comparison to GPS signals, *LocataLite* signals are orders of magnitude stronger. Because of this, signals from a *LocataNet* can penetrate buildings (Barnes *et al.*, 2003b)
- Outdoor positioning - At an outdoor test network, a *Locata* receiver using only *LocataLite* signals performed as good as if not better than RTK GPS with cm-level positioning precision (Barnes *et al.*, 2003c).
- Indoor positioning with non line-of-sight signals - At a test network located outside a two-storey office building, *LocataLite* signals penetrated the building (brick walls and a metal roof) and allowed real-time static positioning inside with sub-cm precision for a *Locata* receiver (Barnes *et al.*, 2003b). Also, using the same test network, a *Locata* receiver was tracked in real-time as it moved around the office building with sub-metre

level precision. This level of precision is at least ten to one hundred times better than can currently be achieved using high sensitivity GPS receivers indoors.

- Indoor positioning with line-of-sight signals - With a *LocataNet* installed inside a large metal warehouse at BlueScope Steel, a *Locata* receiver tracked a crane with cm-level positioning accuracies in a severe multipath environment (Barnes *et al.*, 2004).

This paper focuses on the suitability of using *Locata* for structural deformation monitoring type applications, through a trial on a suspension footbridge at Parsley Bay in Sydney.

### 3. PARSLEY BAY SUSPENSION FOOTBRIDGE TRIAL

The suspension footbridge at Parsley Bay (Figure 4) crosses a narrow inlet on the east side of Sydney Harbour, and has been used in a previous GPS augmented pseudolite trial (see Barnes *et al.*, 2003d). It was constructed in 1910 to improve pedestrian access between the two shores of Parsley Bay, and cost 500 pounds to build. The bridge towers, deck walkway and handrails are constructed from wood, whilst the cabling and rail fencing are steel. The bridge is approximately 55 metres long and 2 metres wide.

On 5<sup>th</sup> May 2004 a trial was conducted at Parsley Bay to assess the performance of the prototype *Locata* technology for detecting movements in a suspension footbridge. A *LocataNet* positioning network comprising of four *LocataLite* devices was established in an area around the bridge. When establishing a *LocataNet* there are two basic considerations. First, each *LocataLite* must be able to receive signals from at least one other *LocataLite*, and secondly they must be located such that the network geometry is sufficient for positioning precision.

For the temporary *LocataNet* installation at Parsley Bay possible locations for the *LocataLites* were severely restricted by surrounding natural features, existing infrastructure, and time constraints for the entire experiment (8 hours, including installation/removal). This meant



**Figure 4:** Parsley Bay suspension footbridge trial using *Locata*.

that it was necessary to position all the *LocataLites* below the bridge at relatively low elevation angles. The elevation angles to the bridge ranged from -1.8 to -18.2 degrees as given in Table 1, and Figure 5 shows the installation of each *LocataLite* antenna. Three of the *LocataLite* antennas were mounted on tripods, while the fourth was mounted at the bottom of one of the bridge pillars. *LocataLite* antennas 12 and 14 had a severely restricted view of the sky and could not quickly and reliably be surveyed using GPS. Therefore, the positions of all the *LocataLite* antennas were manually surveyed using a total station (theodolite and electronic distance measurement) instrument. The coordinate system of the *LocataNet* was established such that it was approximately in line with true north.

<i>LocataLite</i>	Elevation (Deg.)	Azimuth (Deg.)	Distance (m)
12	-1.8	3.0	108.3
14	-8.3	101.3	25.8
21	-1.8	168.8	105.6
29	-18.2	255.7	18.5

**Table 1:** *LocataLite* geometry with respect to *Locata* receiver antenna on bridge



**Figure 5:** Locations of the four *Locatalites* (12, 14, 21 and 29 from left to right)

After deploying the *LocataLite* network, time-synchronisation of the *LocataNet* was established within a few minutes. The *LocataNet* was established in an autonomous synchronisation mode (*TimeLoc*), entirely independent of GPS. Figure 7 shows the configuration of the time-synchronisation (*TimeLoc*) between the *LocataLites*, where devices 12, 14 and 29 time-synchronise to 21. It should be noted that it is not a requirement for *LocataLite* devices to time-synchronise to a single device in the *LocataNet*, and the *LocataLites* may propagate using *Cascaded TimeLoc* methodology (see Barnes *et al.*, 2003a for details).

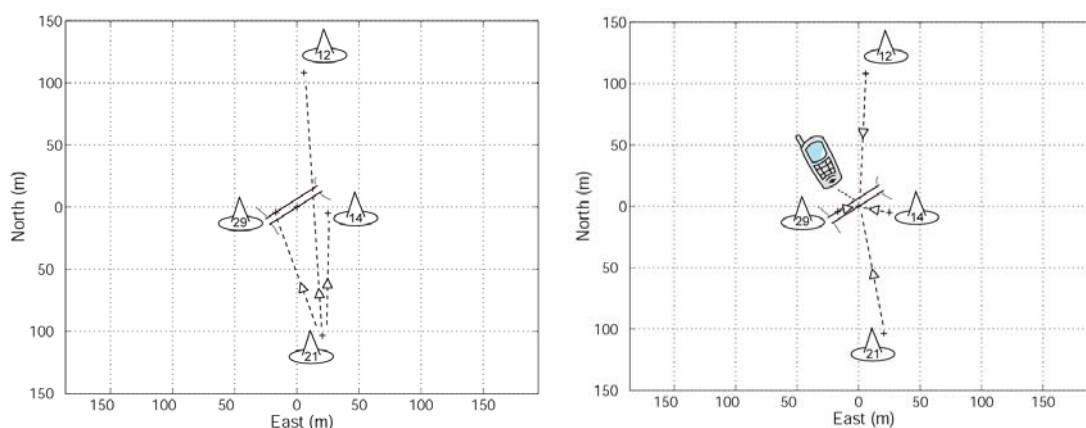
The *Locata* receiver antenna was mounted on a pole at the centre of the bridge on the southern side below the walkway pointing down (Figure 6). The antenna was mounted in this way to increase visibility to the *LocataLites*, and to minimise signal obstructions caused by people walking across the bridge walkway. With this configuration of *LocataNet* the dilution of precision in east north and vertical at the *Locata* receiver was 0.9, 0.7 and 5.4 respectively. The lack of a *LocataLite* ranging signal at a high elevation angle results in the relatively poor positioning geometry in the vertical component. For a permanent *LocataNet* installation greater effort would be taken to ensure optimal geometry in the vertical positioning component. For example, by moving *LocataLite* 14 from the position shown in Figure 6 down to the base of the bridge pillar (similar to *LocataLite* 29 on the opposite side), the VDOP would improve from 5.4 to 3.6 with the same 4 *LocataLites*. Four *LocataLites* is the minimum required for 3-D positioning. Typical monitoring applications would use more *LocataLites* to provide improved geometry, redundancy, reliability, and integrity.



**Figure 6:** *Locata* receiver antenna position

In the current prototype, the *Locata* receiver first requires a static initialisation at a known point before carrier phase point-positioning can begin (see Barnes *et al.*, 2003c for further details). The initialisation position of the *Locata* receiver antenna was measured using a total station, and the test began with an initialisation command issued to the *Locata* receiver. The *Locata* receiver then computed carrier phase point-positions once a second, which were logged to a laptop computer situated on the bridge walkway, together with raw carrier phase and pseudorange measurement data. In this trial the *Locata* receiver computed position solutions entirely independent of GPS using only the four *LocataLite* ranging signals. The test was conducted for approximately 67 minutes and on four occasions the bridge was intentionally ‘rocked’ from side to side to induce movement. On one of these occasions the bridge was ‘rocked’ very lightly (by one person) to see if the *Locata* positioning precision was high enough to detect the small movement. At other times during the trial a variety of pedestrians used the bridge but the bridge movement appeared to be less than the induced movements. During the trial the movement of the bridge in the vertical direction appeared to be very small. It should also be noted that data from a standard GPS RTK was not recorded simultaneously for comparison purposes because of interoperability issues with the current prototype. Moreover, there was no ‘truth’ positioning system available that could deliver 3D millimetre kinematic positioning accuracies.





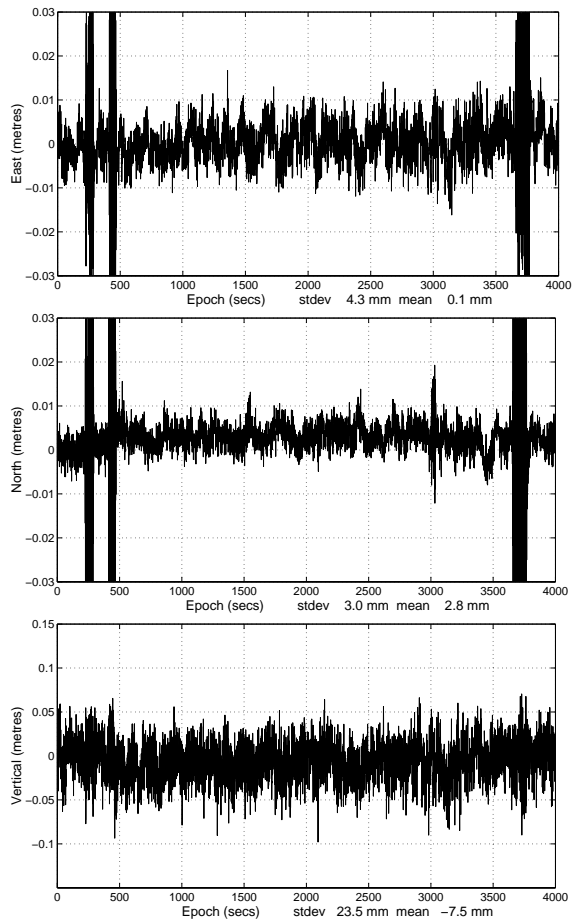
**Figure 7:** Configuration of *LocataNet* time synchronisation (left) and *Locata* positioning (right).

### 3.1 Results

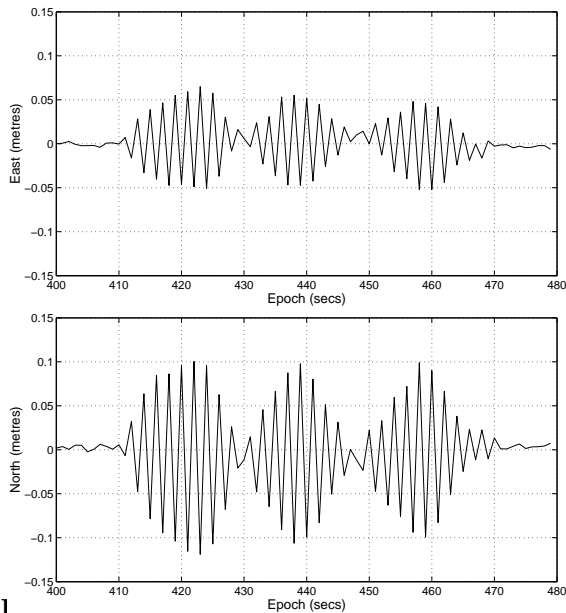
		Move 1 Epoch 210-300	Move 2 Epoch 400-480	Move 3 Epoch 2980-3060	Move 4 Epoch 3640-3800
East	Max (m)	0.039	0.065	0.013	-0.044
	Min (m)	-0.039	-0.052	-0.014	0.048
North	Max (m)	0.066	0.101	0.019	0.076
	Min (m)	-0.072	-0.119	-0.012	-0.078

**Table 2.** Change in east and north position detected by *Locata* from induced bridge movement.

Figure 8 shows the positioning time series in east, north and vertical, from the ‘stationary’ bridge position. The three large spikes in the east and north position time series at epochs 210-300, 400-480 and 3640-3800 correspond to three of the induced bridge movements. Additionally, the small spikes in the north position times at epoch 2980-3060 are due to the smallest induced bridge movement tested. Table 2 details the maximum deviation from the ‘stationary’ bridge position for each of the four bridge ‘rocks’. The largest bridge movement detected in east and north was approximately 7 cm and 12 cm respectively (epoch 400-480, see Figure 9), while in the smallest move 2 cm was detected in the north. Some other fluctuations in the east and north position time series could be due to pedestrians on the bridge. For the position time series data where there was no intentional bridge movement the standard deviations in east, north and vertical are 4.3, 3.0 and 23.5 millimetres (mm) respectively. The positioning precision (standard deviations) in the positioning components are as expected, and highly correlated with the positioning geometry. The very high positioning precision in the east and north components are both less than 5 mm. The vertical geometry (VDOP) is approximately five and a half times worse than the horizontal components, and therefore the vertical position precision reflects this with a standard deviation of 23.5 mm. In the vertical positioning time series no vertical bridge movements can be detected. However, as noted in section 3, movement of the bridge in the vertical direction appeared to be small during the trial.



**Figure 8:** Locata positioning result in East, North and Vertical.



**Figure 9:** Locata east and north positioning for induced move for between epoch 400-480

### 3.2 How Does the Positioning Precision Compare with GPS and Pseudolite Augmented GPS Systems?

Even though it was not possible to use differential GPS or differential GPS augmented with pseudolites simultaneously during the trial, the *Locata* position solutions can be compared with a previous trial at Parsley Bay bridge. During the trial there were between 4-7 GPS satellites available and two unsynchronised pseudolites were used. Both these solutions were post-processed using double differencing GPS/pseudolite software developed at UNSW (for further details see Barnes *et al.* 2003d). Tables 3 and 4 give the dilution of precision and standard deviations in the east, north and vertical for *Locata*, standard GPS, and GPS augmented with two pseudolites. It should be noted that the GPS-only values are based on when there were at least 5 satellites available for positioning. This is because with only 4 satellites the GPS-only positioning geometry was extremely poor with DOP values greater than 800, and would typically be rejected by most GPS processing software or RTK systems. This very poor GPS geometry occurred for approximately fifteen minutes during the two and a half hour trial. For the *Locata* solution the DOP values are almost constant because the movement of the bridge is small, whereas for the GPS-only and GPS augmented PL solutions the DOP values vary. Therefore, the positioning precision varies, which is undesirable for a deformation monitoring system. The variation in positioning geometry for the GPS-only and GPS-PL solutions are as large as 5.9 times (EDOP 3.51/0.60) and 3.6 times (NDOP 1.93/0.54) respectively. For the *Locata* and GPS/PL solutions the geometry in the east component (EDOP) is similar, and this results in similar positioning precision (east standard deviations of ~4mm). Therefore, the basic measurement precision of the *Locata* technology is as good as GPS and standard pseudolites. Additionally, with a minor change in the *LocataNet* geometry (as described in section 3 by moving *LocataLite* 14), the VDOP would improve to 3.6. With this new *LocataNet* configuration the expected vertical standard deviation is approximately 15 mm, and comparable to the GPS-only solution. However, there are some significant advantages of the *Locata* solution over the GPS/PL solution including:

		<i>Locata</i>	GPS-only	GPS-PL
EDOP	Max		3.51	0.83
	Min		0.60	0.56
	Mean	0.9	0.77	0.64
NDOP	Max		2.89	1.93
	Min		0.74	0.54
	Mean	0.7	1.29	1.02
VDOP	Max		8.46	2.30
	Min		1.99	1.19
	Mean	5.4	2.69	1.54

**Table 3:** Summary of DOP values for *Locata*, GPS-only and GPS augmented with pseudolites.

	<i>Locata</i>	GPS-only	GPS-PL
East (m)	0.0043	0.0053	0.0039
North (m)	0.0030	0.0069	0.0050
Vertical (m)	0.0235	0.0131	0.0054

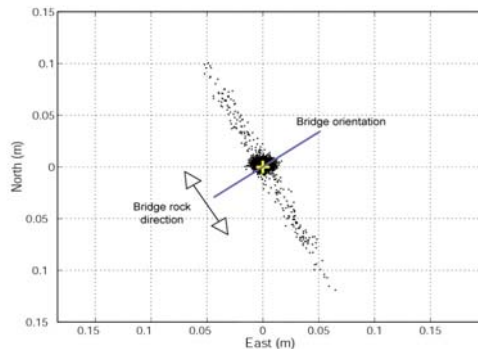
**Table 4:** Positioning standard deviations for *Locata*,

- No base station and data-links – Centimetre level positioning precision can only be achieved with GPS in a differential operating mode. A base station is used along with a wireless link (radio modem or GSM) to communicate data to the user receiver. The base station concept is meaningless in the *LocataNet* approach, and no radio modem is required at the *Locata*. Additionally there are no radio modems or hard-wires connecting any of the *LocataLite* devices.
- Time solution – In differential GPS the double-differencing procedure eliminates the clock biases and hence time information is lost. For certain applications precise time is important, and the *LocataNet* approach allows time to be estimated along with position (as is the case of standard GPS single-point positioning).
- Reduced latency – In a differential-based navigation system, the highest positioning accuracies are achieved when a user waits for time-matched base station data (with no interpolation). There is therefore latency associated with base station data transmitted on the communication link. The *Locata* receiver does not have to wait for any additional data in order to compute a position and therefore has less latency. Furthermore, the data link bandwidth in a differential-based positioning system limits the maximum rate for time-matched position solutions. Point positioning in *Locata* allows fast real-time positioning, which is useful for detecting high frequency oscillations in applications such as structural deformation monitoring.
- Theoretically greater precision – In differential GPS the double-differenced observable is formed from four carrier-phase measurements. Assuming all measurements have equal precision and are uncorrelated, the precision of the double-differenced measurement is two times worse than a single carrier-phase measurement (the basic measurement used by the *Locata* receiver).
- Fewer measurements are required with the *Locata* system to achieve the same precision - In the above comparisons, the GPS-only solution involved measurements to at least five satellites, and in the GPS-PL solution there were two pseudolites and at least four satellites. The *Locata* position solutions were achieved with measurements to 4 *LocataLites*, and even better positioning precision can be achieved by optimising the *LocataNet* geometry. In addition, using more *LocataLites* will further improve positioning precision, as well as redundancy, reliability and integrity.

### **3.3 Does the GPS-PL Solution Time Series Correctly Depict the Actual Movements of the Bridge?**

There was no ‘truth’ positioning system available that could deliver three dimensional kinematic positioning precision at the millimetre level. However, it is useful to consider the orientation of the bridge with respect to the horizontal positioning components. Figure 10 shows the horizontal positioning time series in relation to the orientation of the bridge. The centre line of the bridge runs approximately in a NE-SW direction and the distribution of the horizontal position time series are perpendicular to this direction. The horizontal position

time series distribution correlates well with what is expected from intentionally ‘rocking’ the bridge from side-to-side.



**Figure 10:** Orientation of bridge with respect to *Locata* horizontal position.

#### 4. CONCLUSION

In this paper a trial has been conducted to assess the suitability of the *Locata* positioning technology for structural deformation monitoring type applications. Through a temporary *LocataNet* positioning network installed at Parsley Bay bridge in Sydney, kinematic positioning precision at the sub-cm level has been clearly demonstrated. This very high positioning precision allowed the detection of cm-level movements, intentionally induced by ‘rocking’ the bridge. The *Locata* position solutions were computed independently of GPS with very consistent positioning geometry, due to the almost static nature of the trial. Consistent positioning geometry is highly desirable for deformation monitoring systems, which cannot easily be achieved through GPS or GPS augmented with standard pseudolites. This trial shows that the *Locata* technology can continuously deliver very high (sub-cm) positioning precision, independently of GPS and without the need for a base station and data link, and thus has enormous potential for structural deformation monitoring type applications.

#### ACKNOWLEDGMENTS

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## CONTACTS

Joel Barnes, Chris Rizos, Mustafa Kanli  
School for Surveying and Spatial Information Systems  
The University of New South Wales  
Sydney 2052  
AUSTRALIA

David Small, Gavin Voigt, Nunzio Gambale, Jimmy Lamance  
Locata Corporation Pty Ltd.  
AUSTRALIA