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Publication details:
FIG Working Week

Event details:
FIG Working Week
Hong Kong

Publication Date:
2007

DOI:
https://doi.org/10.26190/unsworks/728

Long term performance analysis of a new ground-transceiver positioning network (*LocataNet*) for structural deformation monitoring applications.

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Key words: *Locata*, Pseudolites, High-precision positioning, Structural monitoring

SUMMARY

The Global Navigation Satellites Systems (GPS, GLONASS) have proven to be a useful tool for precision deformation monitoring applications in structural engineering. For continuous structural deformation monitoring on an epoch-by-epoch basis it is desirable for a measurement system to deliver equal precision in all position components, all the time. However, the quality of GNSS position solutions is heavily dependent on the number and geometric distribution of the available satellites. Therefore, the positioning precision varies significantly and is typically three times worse in vertical than in the horizontal component. This situation becomes worse when the line-of-sight to GNSS satellites is obstructed, as can be the case for monitoring dams in step sided valleys, or large suspension bridges, often reducing the number of visible satellites to less than four.

Locata's solution to difficult GNSS environments is to deploy a network of terrestrially based transceivers (*LocataLites*) that transmit ranging signals. These transceivers form a positioning network (*LocataNet*) that today can operate in combination with GNSS or entirely independent of GNSS. One special property of the *LocataNet* is that it is time-synchronous, allowing single point positioning with potentially cm-level accuracy. The *LocataLites* transmit their own proprietary signal structure in the 2.4GHz ISM band (license free) to ensure complete interoperability with GNSS.

The *Locata* technology is becoming part of Leica Geosystems solution for the structural monitoring application. This paper assesses the performance of the *Locata* technology using a test *Locata* network (*LocataNet*) established at the University of New South Wales. Using this network a long term static tests and a simulated deformation movment test were conducted. This paper describes the *LocataNet* established at UNSW and presents the results and analysis of the tests conducted. Overall the paper demonstrates the suitability of *Locata* for structural deformation monitoring type applications (such as dams) where there is reduced or unavailable satellite coverage.

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1. INTRODUCTION

The monitoring of structural engineering infrastructure is important for the prevention of disasters resulting from structural failure. There are two common scenarios for structural failure: one during construction and the other due to ageing of the structure. In the case of failure as a result of ageing materials, Australia has been fortunate (in terms of loss-of-life), but there have been nevertheless some incidents. In October 1996 a 60 year old dam near Albury-Wodonga developed a structural fault. In order to prevent a major disaster the flood gates were opened, flooding farmland and meadows along the Murray River all the way to South Australia. This dam had been monitored periodically using traditional surveying techniques (distance & angle measurement). This incident alone highlights the importance of regular measurement monitoring.

Ideally the movement of man-made engineering structures should be monitored on a continuous basis and with high accuracy, in order that departures from the expected movements of a structure can be detected quickly and necessary action taken. In the past few years Global Navigation Satellite Systems (GNSS) have been applied to monitoring the structural deformation of bridges, dams and buildings (Roberts *et al.*, 2004), by permanently installing GNSS receivers at key locations on the engineering structure so as to provide cm-level positioning information on a 24/7 basis. However, the major problem with such GNSS receiver installations is that, the accuracy, availability, reliability and integrity of position solutions is very dependent on the number and geometric distribution of the available satellites. This means that the precision of positioning solutions will vary by typically up to 3 times during the day in Sydney, Australia (from an analysis of PDOP values). The large variation in positioning precision obtained with GNSS is undesirable for a continuous deformation monitoring system. More-over, the accuracy of the height component is typically 2-3 times worse than for the horizontal (because of the geometrical distribution of the satellite constellation and the poorer quality of data at low elevation angles). This situation becomes worse when the line-of-sight to GNSS satellites becomes obstructed, as on a bridge, and there may be insufficient GNSS satellites for positioning.

Another limitation of the GNSS technology for precise (cm-level) real-time continuous positioning is the requirement for differential corrections or measurements from a single reference station or Continuously Operating Reference Station (CORS) Network. Acceptable performance from GNSS in structural deformation monitoring type applications is therefore heavily dependent on the reliability of the wireless data link used, and on a relatively unobstructed sky-view, where there are at least five satellites with good geometry available. To address these significant limitations of GNSS *Locata* has developed a novel positioning technology.

2. *LOCATA* POSITIONING TECHNOLOGY

Locata's solution to "difficult" GNSS environments is to deploy a network of terrestrially-based transceivers (*LocataLites*) that transmit positioning signals. These transceivers form a positioning network called a *LocataNet* that can operate in combination with GNSS (such as in urban environments) or entirely independent of GNSS (for indoor applications). One special property of the *LocataNet* is that it is time-synchronous, potentially allowing single point positioning (no differential corrections and data links required) with cm-level accuracy.

In the current system design the *LocataLites* transmit their own proprietary signal structure in the 2.4GHz ISM band (license free). This ensures complete interoperability with GNSS and allows enormous flexibility due to complete control over both the signal transmitter and the receiver. Details of the current system design have been detailed previously in Barnes *et al.* 2005.

On the 19th July 2006 Leica Geosystems announced publicly on their website the signing of a co-operation agreement between Leica Geosystems and *Locata* Corporation for the distribution and support of *Locata* technology in two key market areas, namely:

- open cast mining – for machine automation and mine monitoring operations, and
- structural deformation monitoring – for structures such as bridges, dams and buildings.

In addition, Leica Geosystems will develop the first integrated GNSS/*Locata* receiver.

As a first step in assessing the suitability of the *Locata* technology for deformation monitoring applications the University of New South Wales has conducted tests to assess the *Locata* network stability and the level of movement that can be detected by the system. The remainder of this paper describes the *LocataNet* established at UNSW and some of the tests conducted.

3. UNSW LOCATANET AND SYSTEM TESTING

To test and evaluate the performance of *Locata* technology for the purpose of structural deformation monitoring, a small temporary network was set up at the University of New South Wales (UNSW). For security purposes, the network's components were placed in limited-access zones restricted to select university personnel.

The *LocataNet* established at UNSW is illustrated in Figure 1, comprised of 10 *LocataLite*s situated on top of three buildings. The *Locata* receiver (or rover) was situated on the roof of the School of Surveying building (Elec. Eng), and the distance from the *Locata* receiver to *LocataLites* ranged from approximately 5 to 80 metres. The *Locata* receiver's omni-directional antenna was mounted on a tripod, and the *Locata* receiver was located in an office below via a 30m low-loss coaxial antenna cable. Each *LocataLite* was assigned consecutive PRN codes, starting from the Master, in a clockwise direction.

Each of the *LocataLite* sites consists of three main components: a pole with three antennas attached, a *LocataLite* transceiver, and a power source. For a fully operational *LocataLite* utilising spatial diversity, two transmitting antennas and one receiving antenna are required. In the UNSW setup, directional patch antennas with beam width of 70 degrees were used for both transmission and reception. The transmitting antennas were positioned towards the rover antenna and attached to a vertical pole with a separation of approximately 75cm; the receiving antenna was directed towards the Master location and mounted in-between the transmitters, approximately 15cm below the top transmitting antenna (see Figure 2).

The *LocataLites* were enclosed in customised weatherproof boxes, allowing for external connections to the antennas, data communication ports and power sources. The external interface is then wired to the *LocataLite* inside, as shown in Figure 2.

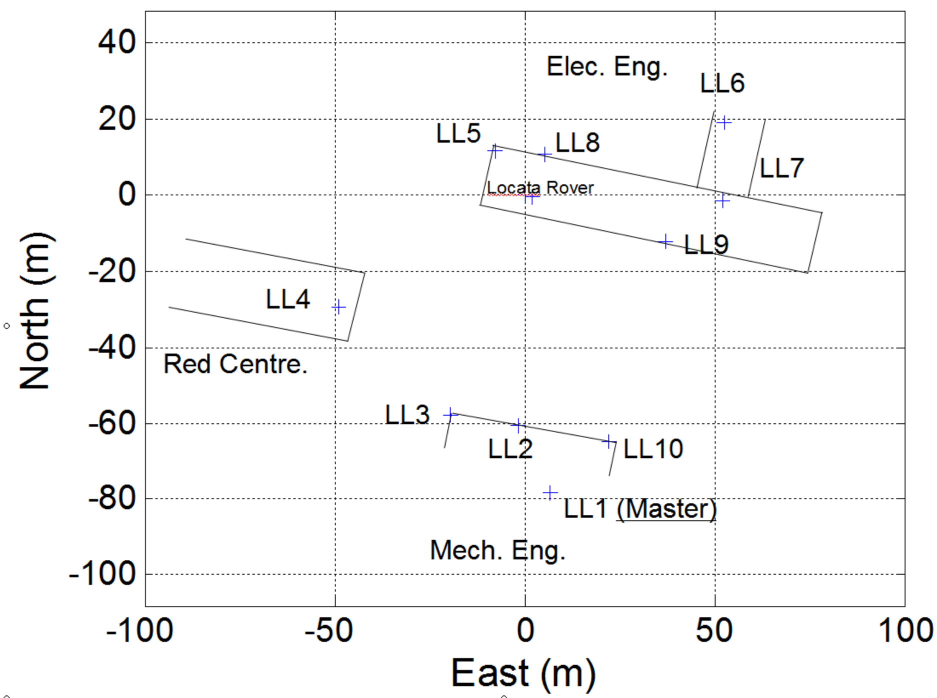

Figure 1 *LocataNet* of 10 *LocataLites* established on the roof-tops at UNSW.

Figure 2 Example *LocataLite* (5) antenna setup and weatherproof enclosure.

With the exception of the “master” *LocataLite*, which operates on mains power source, the *LocataLite* locations at UNSW were powered by 12V/55AH batteries, which allowed a continuous run time of over 24 hours per battery. Y-splitters were connected to the power cables, which enabled the connection of a replacement battery in parallel to the exhausted one before disconnecting the latter, thus providing uninterrupted power to the *LocataLites*.

The coordinates of the transmitting antennas were surveyed using a combination of carrier-phase differential GPS (using Leica System 500 processed using Leica Geo-Office) and a reflectorless total station.

3.1 Long term static test

In deformation monitoring applications (such as dams), the monitored structures are generally in a static state, and it is the deviation from this status quo that requires early detection. The long term stability of a positioning solution is therefore critical for deformation monitoring applications. For the purposes of this test, the network setup described in section 2 was used and Figure 3 shows the setup of the *Locata* receiver antenna on the tripod.

Figure 3 *Locata* receiver antenna setup.

The *Locata* receiver in the office was connected to a laptop computer via two serial ports. After powering up the receiver the *LocataLite* signals are acquired and tracked within 10s of seconds. For a single point carrier-phase solution the receiver requires initialising at a known point (as discussed previously in Barnes *et al.* 2005). The coordinates of the *Locata* receiver was surveyed using differential GPS, at the same time the *LocataNet* survey was conducted. The receiver was initialised via a command through the laptop and then the receiver output single point carrier-phase solutions at a 1Hz rate in an NMEA format, which was logged and visually displayed. In addition to the real-time position raw data (containing pseudorange and carrier-phase) was logged. Data in this test was collected for approximately 13.5 hours and the results and analysis are given in Section 4.

3.2 Simulated deformation movement test

Ideally a positioning system used in structural deformation monitoring applications (such as dams) must be able to detect centimetre to millimetre level movements. The purpose of this test was to establish if the accuracy of the *Locata* technology allowed one centimetre level movements of the *Locata* receiver's antenna to be detected.

For the purpose of this test, the rover antenna was required to move accurately over a small distance in pre-defined directions. The process needed to be automated and repetitive in order to test the system over a long term period. To address these requirements, the rover antenna was mounted on top of the printing-head of a Roland DXY-980A plotter as shown in Figure 4. The use of such a plotter enabled control of the device using a parallel port connection to a laptop. The plotter supports the HPGL graphic language and thus by creating appropriate computer scripts allowed the automation, repetition and accuracy of movement.

The plotter, with rover antenna attached, was placed on a levelled table on the roof of the School of Surveying building near the *Locata* rover antenna used in the static test. This location had a clear line-of-sight to all surrounding *LocataLites*. The coordinate of the *Locata* receiver antenna at the centre of the plotter table was surveyed using a reflectorless total station. In addition the plotter table was orientated so the X and Y axis was closely aligned with truth North/South and East/West. Conducting the test in a similar way to the static test the *Locata* receiver was first initialised at the know point, the receiver then output positions at a 2Hz rate. After one minute the *Locata* receiver antenna was moved 1cm in an East direction. After one minute of static data was collected, the antenna was moved a further 1cm to the East. This procedure was repeated until the antenna was 15 cm to the East of the initial position. The antenna was then moved 1cm to the West repeatedly until the antenna was 15cm West of the initial position. The antenna was then moved by 1cm in the East direction again until the antenna was back at the initial start location. The procedure described above was then repeated giving a total of 150 static points with the test running approximately 2.5 hours.

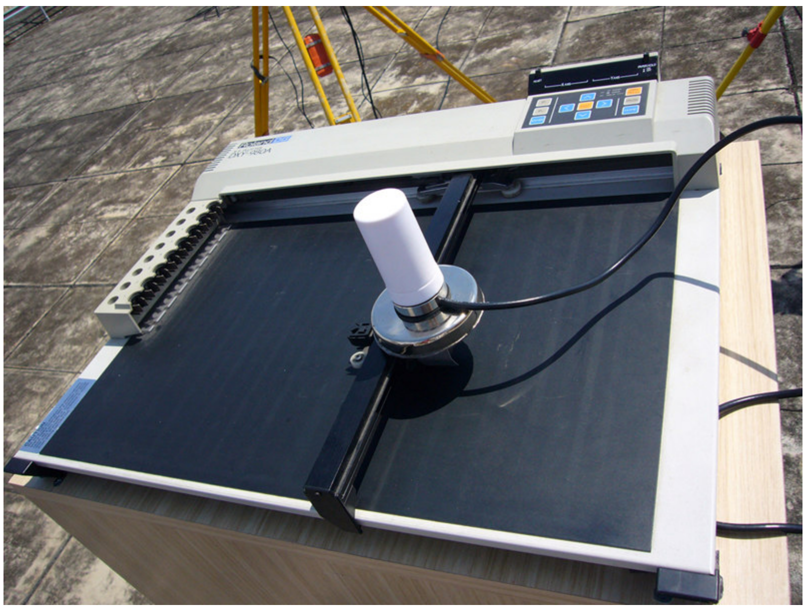

Figure 4 *Locata* receiver antenna setup using Roland DXY-980A plotter table.

4. TEST RESULTS AND ANALYSIS

In the *LocataNet* established at UNSW the elevation angles from the *Locata* receiver location to all the *LocataLites* are less than 8 degrees. This means that the vertical dilution of precision is poor therefore the following results will concentrate on the horizontal.

4.1 Long term static test

In the long term static test, data was collected for approximately 13.5 hours to assess the long term stability of the *Locata* receiver's position solution. Figures 5 and 6 show the horizontal scatter plot of the position error (with respect to the true position surveyed using GPS) and the individual East and North positioning error components. The mean position error in both East and North are less than 1mm and the standard deviation in East and North was 2.1 and 1.5mm respectively. The slightly larger standard deviation in the East component is due to the fact that the dilution of precision in the East-West (0.543) component is slightly worse than the geometry in the North-South (0.530). Visually from Figures 5 and 6 it is clear that the overall precision and stability of the position solution is very good over the 13.5 hour period with no long term drifts. However, there are approximately 7 positions (out of ~48600) that could be considered as outliers, and the largest with a maximum error of 2 cm in the North. The cause of these outliers is under investigation but since they are "single events", they could be easily removed using a filter or using data snooping techniques.

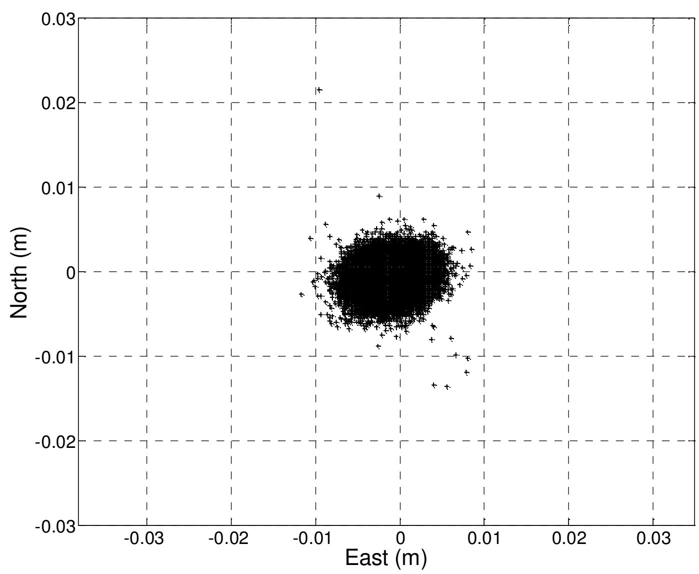

Figure 5 Horizontal error scatter plot for long term (13.5 hour) static positioning test.

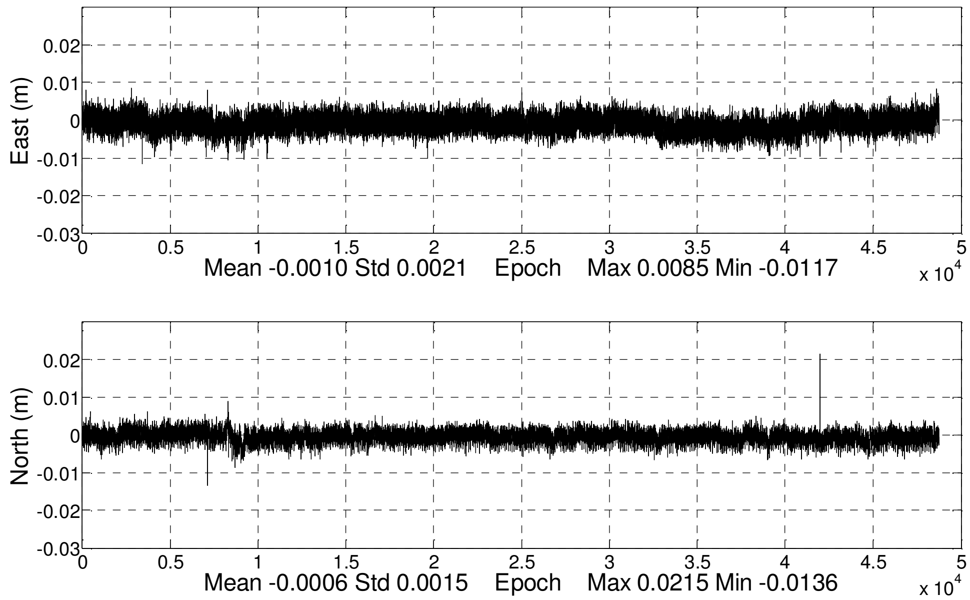

Figure 6 East and North error for long term (13.5 hour) static positioning test.

4.2 Simulated deformation movement test

In the simulated deformation movement test the *Locata* receiver was moved by 1cm at a time in an East-West direction using an XY plotter table for approximately 2.5 hours. A total of 151 static points with 1 minute of data was collected during the tests. Figure 7 shows the horizontal trajectory of the antenna over the period of the test centered at the initial 'true' position, and Figure 8 shows the component East and North values. From the East plot in Figure 8 visually the 1cm moves can clearly be seen, and from the North plot there is a repetitive pattern of movement in the North direction (as the antenna moves East-West), with a maximum deviation of about 5mm (see Figure 9). The repetitive movement in the North-South could be due to multipath error. In an RF-based terrestrial positioning system the multipath error at a particular position in the network will have a similar multipath error if the same position is reoccupied. This is assuming the transmitter locations and environmental factors (buildings etc) do not change. In this particular test the results indicate that the multipath error could be calibrated and reduced. The mean static position of each location was computed (from each 1 minute of static data) and these are plotted in Figure 9 for East and North components. In addition the East and North standard deviation of each static point is shown in Figure 10. The worst standard deviation in the East and North was 2.6 mm and 1.5 mm respectively, with the smaller North component being due to better geometry (lower DOP as previously discussed in 4.1). The distance traveled from each 1cm move was computed based on the mean position values and the error computed, assuming a 'true' move value of 1cm. Figure 11 shows the error in the distance moved with a maximum error of 1.3 mm, and therefore indicating that 1 cm moves of the *Locata* antenna can easily be detected. From Figure 11 it can be seen that this error is correlated with the displacement in the North direction previously discussed.

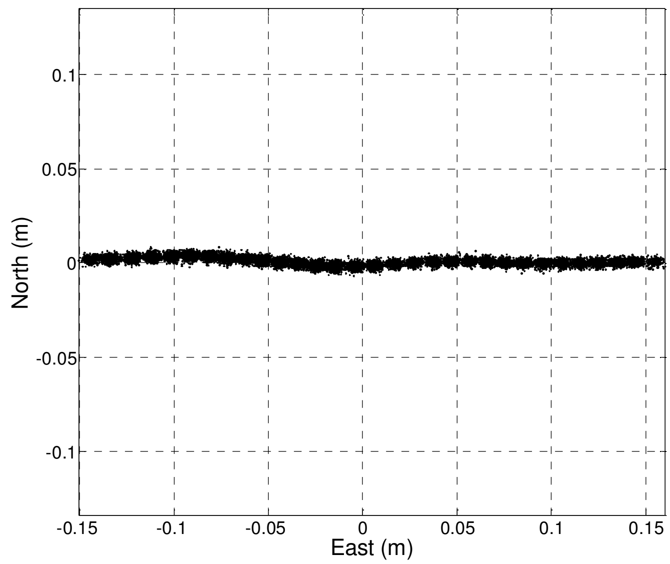

Figure 7 Horizontal trajectory plot (simulated deformation movement test).

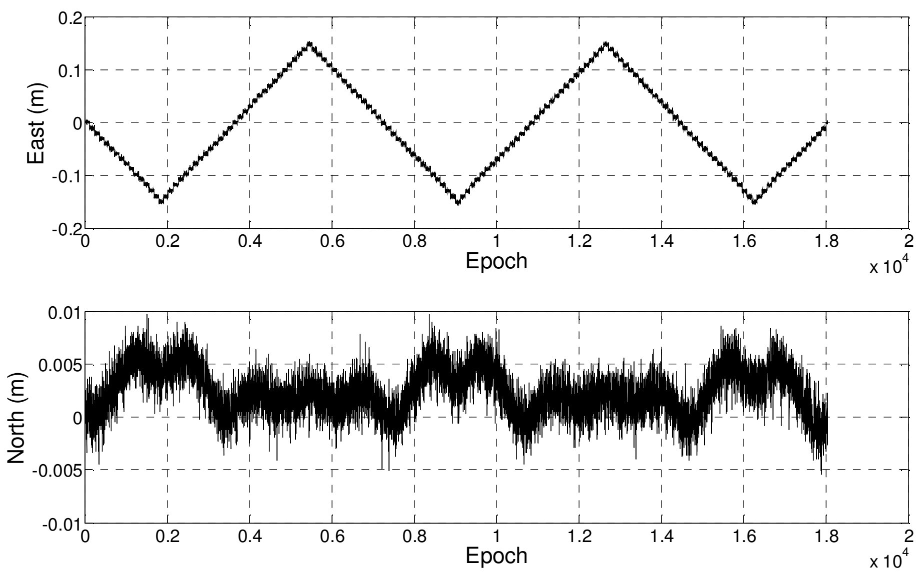

Figure 8 East North time series (simulated deformation movement test).

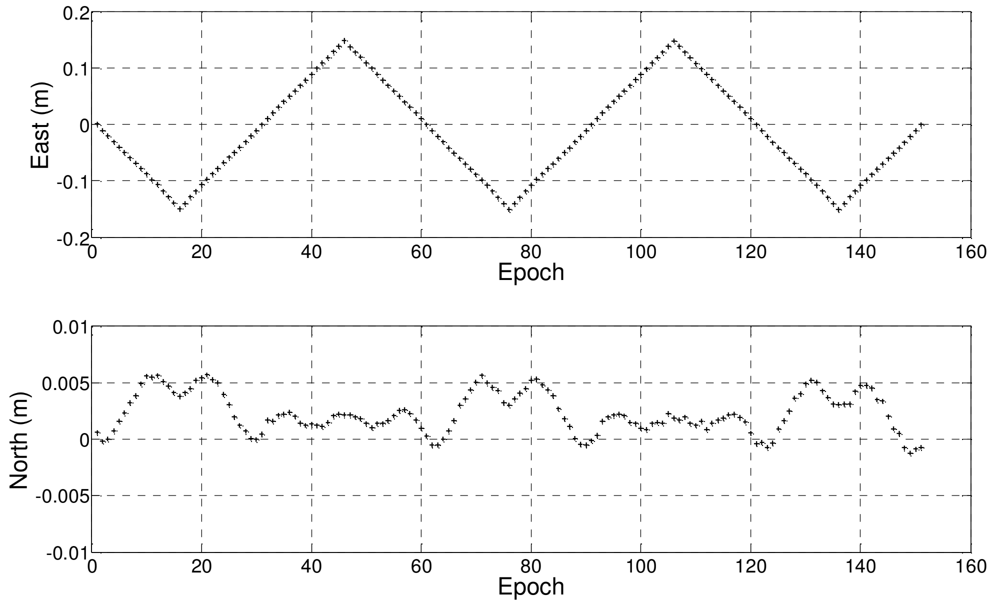

Figure 9 Mean static East North positions (simulated deformation movement test).

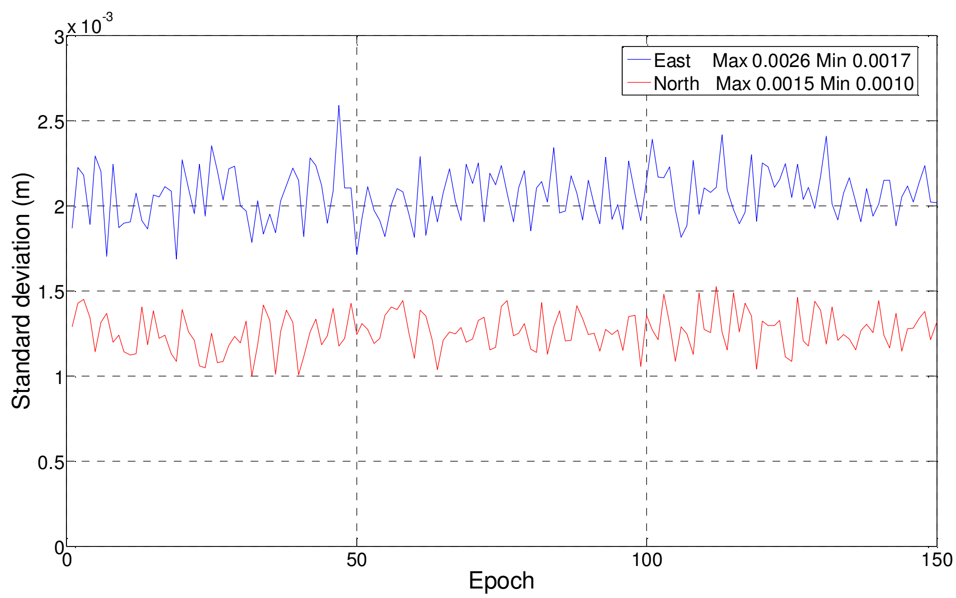

Figure 10 Standard deviation of static East North positions (simulated deformation movement test).

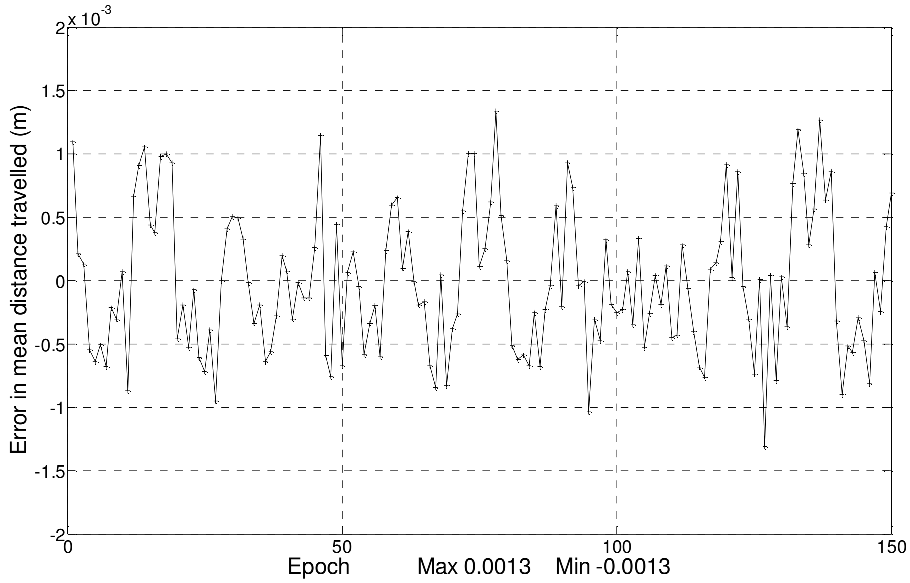

Figure 11 Error in 1cm moves from mean static positions (simulated deformation movement test).

5. CONCLUSIONS

In this paper a *LocataNet* was successfully established at the University of New South Wales for assessing the suitability of *Locata* technology for structural deformation monitoring applications. Using this network a long term static test and a simulated deformation movement test were conducted. The static test over approximately 13.5 hours verified the long term stability of the *LocataNet*. The resulting position standard deviation of the test was aprroximately 2mm and there were no long term drifts. The position solutions in this test were computed on an epoch-by-epoch basis with no filtering or smoothing once a second. Work is now focused on methods to combine several epochs of data to generate solutions with higher precision and integrity.

In the simulated deformation movement test the *Locata* receiver antenna was repeatedly moved by 1cm and static data was collected for one minute after each move (151 static points in total). The maximum error in distance moved computed from the mean *Locata* static positions was 1.3 mm. These results show that the *Locata* technology can easily detect movements of 1cm. Work is now under investigation to remove multipath error via calibration and improve the positioning results further. In addition tests will now focus on larger *LocataNet* installations (where tropospheric effects are greater), and at real structural deformation monitoring sites.

Overall the tests conducted have demonstrated the suitability of *Locata* for structural deformation monitoring type applications (such as dams) where there is reduced or unavailable satellite coverage, and the technology is ready for investigations to begin at real structual monitoring test sites (dams, bridges etc).

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BIOGRAPHICAL NOTES

Dr Joel Barnes is one of the senior researchers within the Satellite Navigation and Positioning (SNAP) group, at the School of Surveying & SIS, the University of New South Wales (UNSW) in Sydney, Australia. He obtained a Doctor of Philosophy in satellite geodesy from the University of Newcastle upon Tyne, UK. He is chairperson of Task Force 6.4.2 – Terrestrial-Based RF Positioning Technologies. Joel has assisted in the development of the *Locata* receiver and testing of the *Locata* technology. Other current research interests include pseudolites, GPS receiver firmware customisation and high precision kinematic GPS positioning.

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