SLOW STRUCTURAL DEFORMATION MONITORING USING LOCATA - A CASE STUDY AT THE TUMUT POND DAM

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Abstract

A Global Navigation Satellite System (GNSS) is a very popular technology for '24/7' monitoring of slow structural deformation. Unfortunately a GNSS is dependent on the number as well as geometric distribution of the available satellites, and the precision may therefore vary at different observation times. On the other hand, Locata Corporation's positioning technology, known as "Locata", provides centimetre level accurate position solutions with millimetre noise level for static positioning using carrier phase data. This provides an advantage over other technologies for monitoring structural movement in many applications. The Locata network can be deployed around a structure that would ensure optimal network geometry under site constraints. Previous investigations have demonstrated the applicability of Locata for deformation monitoring. This paper describes a deformation monitoring trial conducted at the Tumut Pond Dam near Cabramurra, NSW, Australia. After analysing network geometry for precession, as well as site constraints (such as line-of-sight visibilities, power, security, etc.) a Locata network, composed of four LocataLites (or transceivers) and a Locata receiver, was established. Locata pseudorange and carrier phase measurements, and atmospheric data were collected and post-processed using a sequential least squares estimation technique. Measurement data was used to obtain 3D coordinate solutions, and these coordinate solutions were checked for statistically significant deformation using standard deformation analysis procedures. It was observed that, with 2mm horizontal and 5mm vertical component precision (95% CI), Locata provided position solutions that could identify any statistically significant movement.

1. Introduction

Dams, bridges, and tall buildings are examples of structures that are routinely surveyed and monitored for their stability. Locata Corporation's positioning technology, known as "Locata", provides centimetre level accurate position solutions with millimetre noise level for static positioning using carrier phase measurements. Locata has several advantages over other technologies (such as GNSS) for monitoring structural movement in many applications. The Locata network can be deployed around a structure that would ensure optimal network geometry under site constraints. This paper describes a deformation monitoring case trial conducted at the Tumut Pond Dam near Cabramurra, NSW, Australia.

This paper is organised as follows. In section 2, the Locata positioning system is introduced; in section 3, deformation analysis procedure is described; in section 4, the Tumut Pond Dam case study is presented followed by result and analysis of the case study in section 5. Finally, section 6 presents conclusions and discusses future research directions.

2. Locata positioning technology

Locata Corporation's technology, *Locata*, provides positioning solutions using a number of time-synchronised pseudolite-like transceivers, known as *LocataLites*. These LocataLites form a Locata network (*LocataNet*) and transmit Locata proprietary signals in the licence-free 2.4GHz Industry

Scientific and Medical (ISM) band. According to the Locata system design, in any LocataNet there is one Master LocataLite and other slave LocataLites are time synchronised to it. As soon as the LocataLites are synchronised with the Master, they start transmitting signals. When a Locata receiver tracks four or more signals from four different LocataLites, it can carry out centimetre-level accurate single point positioning, using phase measurements, without any differential methods or transmitted data corrections. However, at the installation of the LocataNet, a precise survey is required. A detail description of the Locata technology can be found in, for example, Barnes *et al*. (2003).

3. Method of deformation analysis

As Locata is based on the same principles as GNSS, Locata position calculations are similar to GNSS position computation methods. However, there are differences in how clock corrections and tropospheric corrections are handled. The mathematical models, as well as the position calculation method, are extensively described in Choudhury *et al*. (2010). Continuous deformation analysis is performed using the results of consecutive epochs. There are different methods (such as shewhart, CUSUM, EWMA etc. algorithms) that can be used for deformation analysis. However, in this paper, the Harvey (2006, pg, 293) method of determining the stability of the monitoring point is used. In this method, instead of using one epoch at a time, two epochs (first epoch as reference and latest epoch) of data are used for the least squares adjustment to ensure that systematic biases will be reduced. This is also necessary for developing the standard deviation as well as the relative error ellipse of the distance between the positions generated by the reference epoch and the latter epoch datasets. It also has the advantage of reducing systematic noises, which is not convenient in other deformation analysis methods.

For example, at time (t), position of a point is POS_t (E_t, N_t, H_t,) with covariance matrix Q_t whereas at time (t+Δt), the position of the same point is $POS_{t+\Delta t}$ ($E_{t+\Delta t}$, $N_{t+\Delta t}$, $H_{t+\Delta t}$) with covariance matrix $Q_{t+\Delta t}$. Displacement ($\Delta E, \Delta N, \Delta H$) can be obtained by differencing the estimated coordinates at time (t) and (t+Δt) which, as a result, is the distance (d) between POS_t , $POS_{t+\Delta t}$:

$$d = \sqrt{\Delta E^2 + \Delta N^2 + \Delta H^2} \tag{1}$$

and the variance of *d* can be determined by:

$$\sigma^2_{t,t+\Delta t} = J * Q_{t,t+\Delta t} * J' \tag{2}$$

J matrix is called Jacobian matrix (Harvey, 2006):

$$J = \left(\frac{\partial d}{\partial E_t} \quad \frac{\partial d}{\partial N_t} \quad \frac{\partial d}{\partial H_t} \quad \frac{\partial d}{\partial E_{t+\Delta t}} \quad \frac{\partial d}{\partial N_{t+\Delta t}} \quad \frac{\partial d}{\partial H_{t+\Delta t}} \right) \tag{3}$$

where

$$\frac{\partial d}{\partial E_t} = \frac{E_t - E_{t+\Delta t}}{d} \qquad \frac{\partial d}{\partial N_t} = \frac{N_t - N_{t+\Delta t}}{d} \qquad \frac{\partial d}{\partial H_t} = \frac{H_t - H_{t+\Delta t}}{d}$$

$$\frac{\partial d}{\partial E_t} = -\frac{E_t - E_{t+\Delta t}}{d} \qquad \frac{\partial d}{\partial N_t} = -\frac{N_t - N_{t+\Delta t}}{d} \qquad \frac{\partial d}{\partial H_t} = -\frac{H_t - H_{t+\Delta t}}{d}$$

Next, $Q_{t,t+\Delta t}$ of equation (2) is the covariance matrixes of POS_t , $POS_{t+\Delta t}$:

$$Q_t = \begin{bmatrix} \sigma^2_{E_t} & \sigma_{E_t N_t} & \sigma_{E_t H_t} \\ \sigma_{E_t N_t} & \sigma^2_{N_t} & \sigma_{N_t H_t} \\ \sigma_{E_t H_t} & \sigma_{N_t H_t} & \sigma^2_{H_t} \end{bmatrix} \qquad Q_{t+\Delta t} = \begin{bmatrix} \sigma^2_{E_{t+\Delta t}} & \sigma_{E_{t+\Delta t} N_{t+\Delta t}} & \sigma_{E_{t+\Delta t} H_{t+\Delta t}} \\ \sigma_{E_{t+\Delta t} N_{t+\Delta t}} & \sigma^2_{N_{t+\Delta t}} & \sigma_{N_{t+\Delta t} H_{t+\Delta t}} \\ \sigma_{E_{t+\Delta t} H_{t+\Delta t}} & \sigma_{N_{t+\Delta t} H_{t+\Delta t}} & \sigma^2_{H_{t+\Delta t}} \end{bmatrix}$$

For this deformation analysis, it is assumed that POS_t and $POS_{t+\Delta t}$ are uncorrelated. As a result, the covariance matrix for both POS_t and $POS_{t+\Delta t}$ (i.e. $Q_{t,t+\Delta t}$) becomes:

$$Q_{t,t+\Delta t} = \begin{bmatrix} \sigma^2_{E_t} & \sigma_{E_t N_t} & \sigma_{E_t H_t} & 0 & 0 & 0 \\ \sigma_{E_t N_t} & \sigma^2_{N_t} & \sigma_{N_t H_t} & 0 & 0 & 0 \\ \sigma_{E_t H_t} & \sigma_{N_t H_t} & \sigma^2_{H_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{E_{t+\Delta t}} & \sigma_{E_{t+\Delta t} N_{t+\Delta t}} & \sigma_{E_{t+\Delta t} H_{t+\Delta t}} \\ 0 & 0 & 0 & \sigma_{E_{t+\Delta t} N_{t+\Delta t}} & \sigma^2_{N_{t+\Delta t}} & \sigma_{N_{t+\Delta t} H_{t+\Delta t}} \\ 0 & 0 & 0 & \sigma_{E_{t+\Delta t} H_{t+\Delta t}} & \sigma_{N_{t+\Delta t} H_{t+\Delta t}} & \sigma^2_{H_{t+\Delta t}} \end{bmatrix} \qquad (4)$$

In this deformation analysis, the congruency test (Caspary, 2000) is used, where the null hypothesis is that there is no displacement between the epochs, and the alternative hypothesis is the opposite to null hypothesis. As a result:

Null hypothesis H_o : d = 0,

Alternative hypothesis H_a : d ≠ 0.

The test statistic is:

$$T = \frac{d}{\sigma^2_{t,t+\Delta t}}$$

The value of T can be determined by using the above equations (1,2, 3 and 4).

H_o is true when *T* has Student's t-distribution:

$$|T| < t_{df,\propto/2}$$

where *df* is the degrees of freedom and α is the significance level.

If H_a is true, further investigation of the epochs is needed. In this Locata trial, the deformation calculation is continuous which means the first epoch's data is used as reference and all other epochs are compared with the reference epoch. If H_a is true for more than ten consecutive epochs, then a deformation alert is generated.

4. Tumut Pond Dam

Tumut Pond Dam is a dam that forms a reservoir on the upper reaches of the Tumut River near Cabramurra in the Snowy Mountains of New South Wales, Australia (Figure 1). The dam and reservoir are parts of the Snowy Mountains Scheme. This dam collects the inflow from the Tumut River to form the Tumut Pond Reservoir which is diverted through the Tooma-Tumut and the Eucumbene-Tumut tunnels to provide the head pondage for the Tumut-1 Power Station. The dam is 86.3m high and 217.9m long. The crest and base width are 3.7m and 29.6m respectively (Snowy Hydro Limited, 2003).

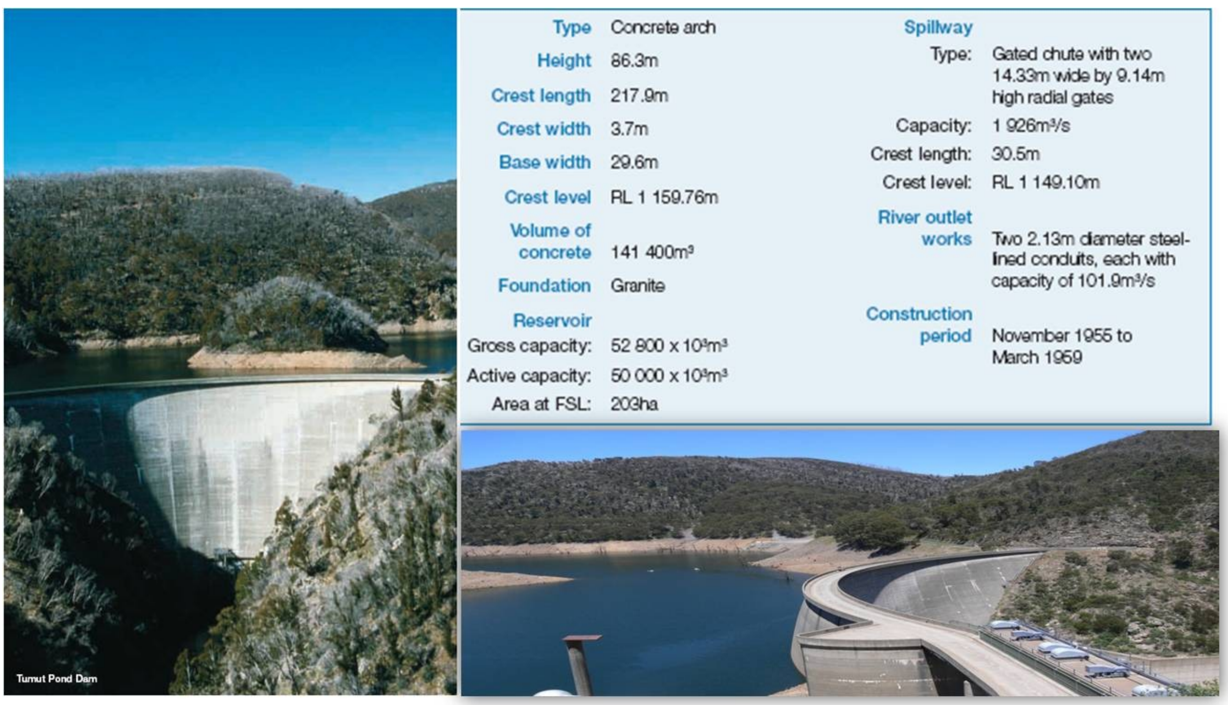

Figure 1. Tumut Pond Dam

This dam is used to evaluate the Locata system for slow structural monitoring as there are extensive past deformation survey measurements for comparison. In this experiment a Total Station was also used for movement detection and cross-checking against the Locata results. Although the surveying prism and Locata receiver could not be placed at the same point due to collocation problems, the Total Station data were used as truth data as it was assumed that the monitoring points' movement would be similar.

4.1 Total Station setup

A "survey robot" Total Station (Leica TCRP1201) was used for comparison with the Locata system. The instrument measured horizontal and vertical angles and distances to a 25mm prism near the Locata receiver. It was used in "lock" mode from a single setup, recording every minute interval over a distance of 176m. See Figure 2.

Figure 2. Experimental setup

4.2. Locata Setup

A Locata network, composed of four LocataLites, was been established after analysing the network geometry for precision and LocataLites line-of-sight visibilities (Figure 3). The Locata "rover" receiver antenna was mounted at the top centre of the dam, approximately on the middle part of the TPD because this point has the highest probability of movement, according to earlier high precision surveys. The antenna was mounted in such a way that it increased the visibility to the LocataLites as well as reduce the effects of multipath. The distances from the Locata "rover" to the four LocataLites were 174.983, 186.602, 273.349 and 141.557 metres. The lowest and highest points differ by 20.61 metres in height. For this experiment, a known point ambiguity resolution method was used for carrier phase positioning. The monitoring point, where the Locata receiver was mounted, was surveyed using a Total Station (Leica TCRP1201) with ± 5mm accuracy. Data was logged onto an internal memory card for post-processing.

Figure 3. LocataLite installations

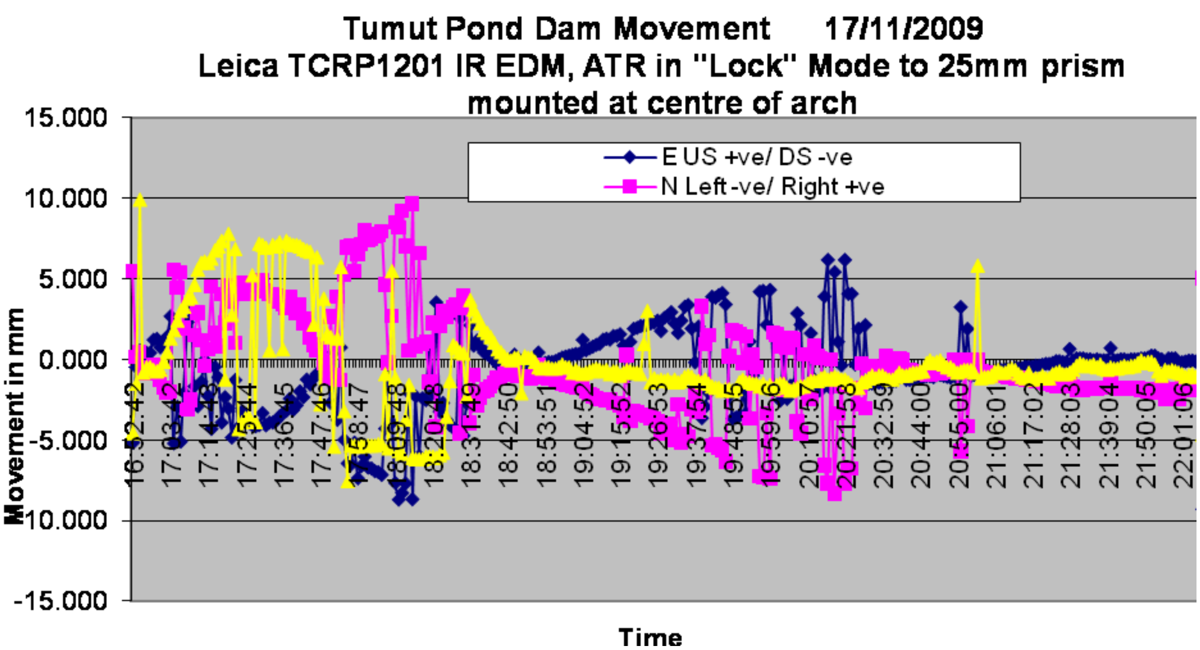

Figure 4. "Movement detection" by Total Station

5. Results

5.1. Total Station

The Total Station was operated to log for 24 hours. However, battery power only lasted for four hours. The detected "movements" are presented in Figure 4. It can be observed that the maximum horizontal and vertical displacements are 12.99mm and 9.95mm respectively, whereas maximum position displacement is 14.35mm. Although the system showed horizontal “movement” at the 5mm level, the standard deviation of these coordinates was +/- 6mm and hence was difficult to compare with the Locata results.

5.2. Locata

The Locata network at the Tumut Pond Dam was configured to operate for 24 hours. However, battery power only lasted for 22 hours. Data definition for each epoch has been defined as sixty seconds of accumulated Locata observations. The Master LocataLite’s measurements were used for single-differencing for removing clock error. The other three LocataLites formed a plane that is almost horizontal, the lowest and highest points differing by about 20.61 metres in height. The rover lies very close to that plane which prevents the reliable determination of the height of the rover. Therefore, one possible solution would be to hold the height of the rover fixed at the known survey coordinates. Alternatively, solve for the height though the estimates might absorb some distance errors. In the following section a 3D method is analysed.

For a 3D position solution only the coordinates of the LocataLites were held fixed, at values determined by reliable Total Station surveying with ± 5mm, and the three coordinate components were estimated. The monitoring point’s position differences from the mean value are shown in Figure 5(a), and the coordinate solution time series are presented in Figure 5(b).

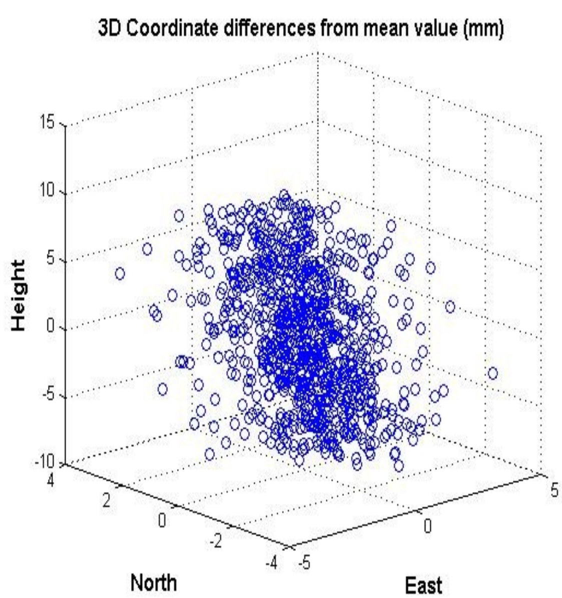

Figure 5(a). Position differences from mean value

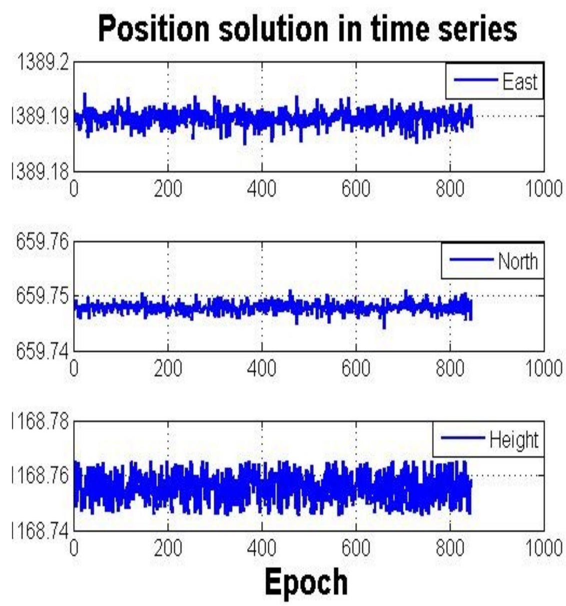

Figure 5(b). Position solution time series

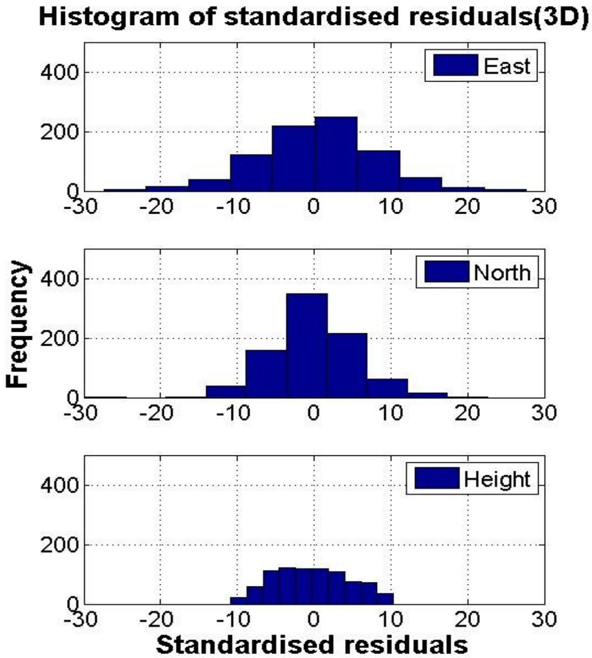

Figure 6. Histogram of standardised residuals

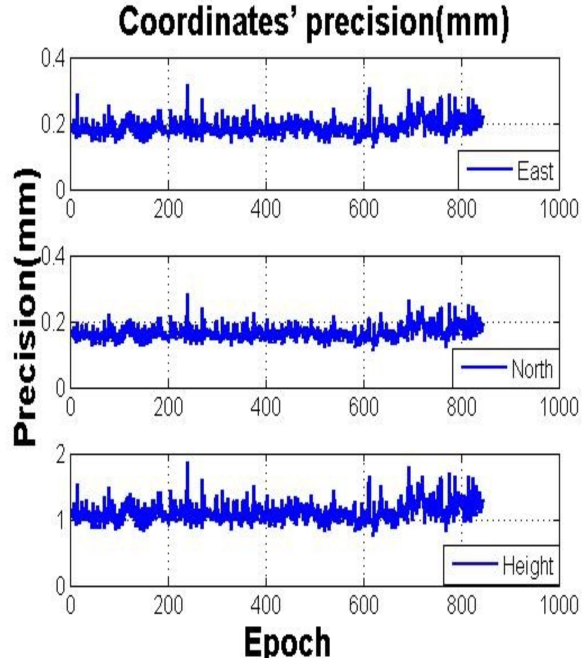

Figure 7. Coordinates' precision

Histogram of standardised residuals (i.e. coordinate component differences from ground truth divided by the standard deviation of coordinate components) is presented in Figure 6. It can be easily seen that the standardised residuals have normal distribution which suggests that the LSE modelling of systematic errors, gross errors, biases and observation quality are acceptable (Harvey, 2006). On the other hand from coordinates' precision is presented in Figure 7.

5.3. Deformation Analysis

Observable "movement" of the monitoring point is presented in Figure 7(a). It can be seen that the detected horizontal and vertical movement was 5mm and 10mm. As the vertical component had weaker vertical network geometry, there are larger variations of height position component. And this weaker vertical network geometry absorbs some distance errors. However, most importantly, these movements are not continuous (Figure 7(b)). This experiment was only conducted for one day, and different trends might be observed from a longer experiment (i.e. weeks or months).

The total number of Locata observations used for each epoch position solution was 1200 observations resulting from 60 seconds observations at 2Hz data from 12 different channels. In addition, two channels were used for single-differencing to eliminate clock error (60*2*10 = 1200 observations).

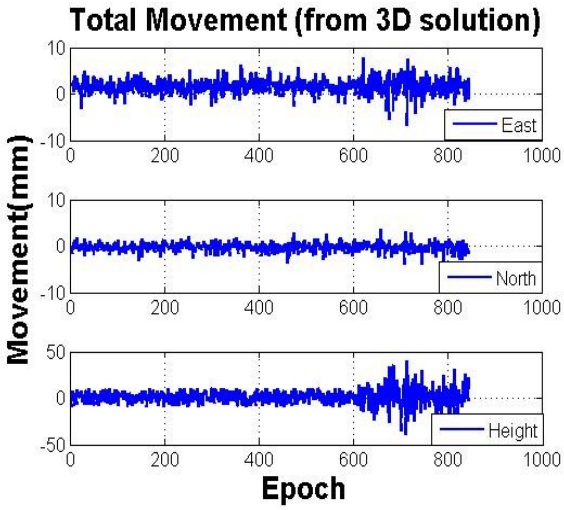

Figure 7(a). Movements

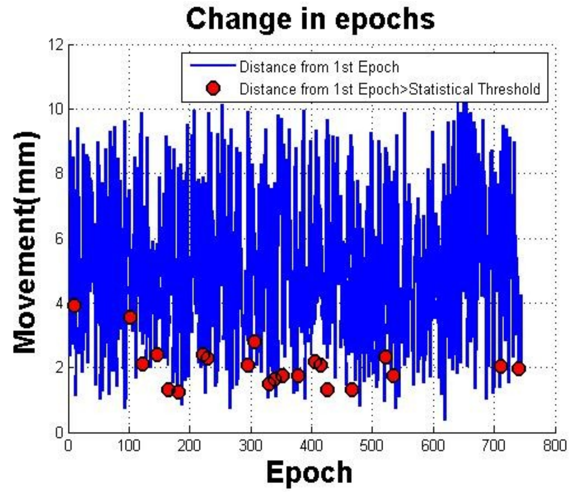

Figure 7(b). Deformation analysis

6. Concluding remarks

In this paper a deformation trial using Locata technology was carried out at Tumut Pond Dam. This trial ran for 22 hours and provided millimetre level precision for both horizontal and vertical position components throughout all the epochs without any signal outage. The accuracy of the position solution is also at the millimetre level with standard deviation of 5mm. The position solutions in this trial were generated through a sequential Least Squares procedure based on sixty seconds Locata carrier phase observations. Standard deformation calculation methods were applied in order to simulate the detection of millimetre to centimetre level movement. No significant movement had been observed during this trial, though longer experiment would need to be conducted in order to verify this conclusion.

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