

STEEP WALL MONITORING USING SWITCHED ANTENNA ARRAYS AND PERMANENT GPS NETWORKS

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Abstract

The use of permanent GPS networks for small to medium scale high precision deformation monitoring projects is often discounted due to the high capital cost involved in establishing geodetic GPS receivers at each monitoring point. This paper presents an alternative to the traditional permanent multi-reference GPS network that offers similar levels of precision, at a lower *per point* cost. This is achieved using a *switched GPS antenna array system*, in which multiple GPS antennas are connected to a single GPS receiver at the deformation site. By periodically switching between antennas, it is possible to sample and record GPS observations from different stations quasi-continuously. Moreover, the system has been designed to operate in near real-time, whereby data from all monitoring stations are relayed to a computer, then processed automatically. This enables a cumulative station coordinate time series to be generated 'on-the-fly', from which deformation, such as wall movement, can be assessed.

This paper describes the results achieved using the switched GPS antenna array deformation monitoring system, installed on an unstable wall of an open-pit mine and operating continuously for a total of 8 weeks. Multiple reference stations, on assumed stable ground, have been used to improve the reliability of the resultant coordinate time series from that used using a single baseline approach. Coordinate precisions of 4mm in plan and 10mm in height were obtained, from which three-dimensional deformations of as little as 2mm/week were detected. The proposed configuration has proved to be a viable, much cheaper alternative to using a separate receiver and antenna for each monitoring station.

1. Introduction

In many situations, the measurement of small, superficial displacements on steep slopes can provide the precursors necessary to predict catastrophic failure. Steep slopes are conventionally monitored using theodolites, total stations and geotechnical measurement techniques. Unfortunately, the use of conventional survey techniques can be subject to poor or sporadic observational practices, resulting in inadequate or belated deformation solutions. In recent years, the Global Positioning System (GPS) has provided an alternative method for monitoring the geometrical displacements of surface movement.

When any type of deformation is monitored using GPS, two main techniques are employed (Stewart and Tsakiri, 2001). The first of these is the use of *continuously operating permanent GPS receivers*, which may be used to monitor deformations such as crustal dynamics, subsidence and geotechnical movements (eg. Koivula *et al.*, 1998, Heus, 1997). The second class of GPS technique is the use of *episodic GPS data* (eg Stewart *et al.*, 1999), used commonly for the monitoring of for example dams, open-pit mine walls and landslides, or in any instances when cost and security issues dictate that installation of continuous GPS receivers is unfeasible. The primary differences between the two GPS monitoring classes are the permanency of the GPS receiver locations, and the processing strategies. The advantages of permanent, continuous GPS networks are:

- continuous solutions enable time series of increased temporal resolution, from which deformation motions may be estimated from a shorter data time span and with more confidence than episodic sampling of the deformation signal;

- mitigation of systematic errors (eg. the removal of multipath, and atmospheric delays in the received GPS signal, time decorrelation of the data, removal of antenna set-up error);
- reduction in the likelihood of gross errors and data outliers (due to for example, use of forced centering, elimination of set-up errors);
- lower manpower costs as continuous GPS networks run automatically.

However, the high cost of survey monumentation and individual GPS receivers per station often means that the installation of continuously operating GPS receivers is prohibitively expensive, particularly for small-scale deformation surveys. Episodic monitoring regimes, where monitoring points are revisited at regular intervals ranging from a few days to several months, are frequently applied as a cost-effective alternative, albeit with the resulting degradation in precision of the coordinate time series due to the decreased sample size and resolution, plus potential set up errors.

Consequently, there exists a market for a GPS-based deformation monitoring system that offers the precision offered by continuously operating GPS receivers, but that can be implemented at a hardware cost similar to the episodic monitoring method. Such a solution is proposed and described in this paper, attempting to obtain coordinate time series of a similar quality to those obtained from continuous GPS data, but with similar equipment to that used in episodic GPS monitoring.

2. The Switched GPS Antenna Array System

2.1 Hardware

The establishment of permanent, continuously operating GPS arrays is expensive, due to the need to install one complete monitoring system per station. Such a system comprises typically one GPS receiver, one GPS antenna, a radio and radio antenna for communications, controlling hardware and software to appropriately store and forward the data back to the base station, and some type of power source (mains or solar).

The concepts of multiple antenna arrays have been discussed previously in Petrovski et al (1999) and Ding et al (2000). The system presented here and shown in Figure 1 utilises a *switched GPS antenna array* design, whereby several antennas are connected to a single GPS receiver which polls each station sequentially.

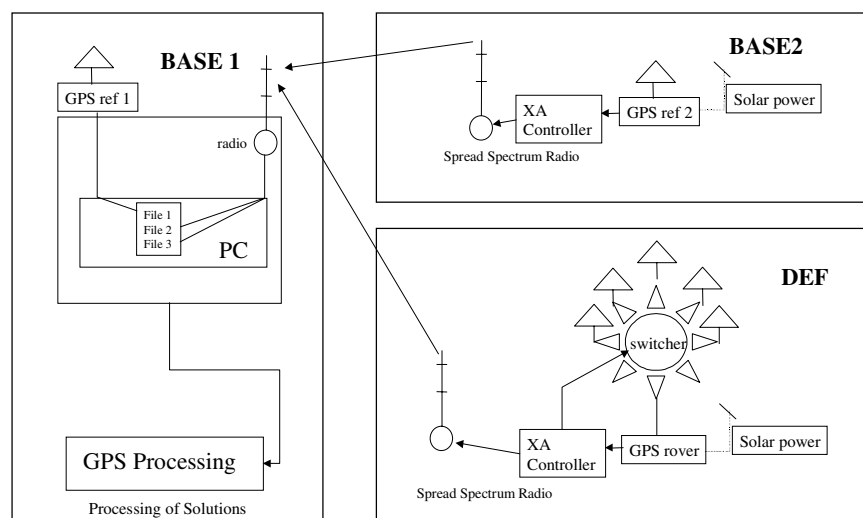


Figure No. 1 – Schematic of System Design

For the study presented in this paper, the hardware comprised Leica AT504 choke ring antennas coupled to geodetic quality Leica CRS1000 GPS receivers, operating at 1Hz. This configuration negates the need for multiple sets of the equipment mentioned above, reducing to just one set, although obviously an antenna is still required per station. In addition, the system utilises a ‘base’ network of two continuous reference GPS stations, termed ‘base 1’ and ‘base 2’ in this paper.

The GPS receiver, switching device and communication radio are all driven by an XA controller (eXtended Architecture), that ensures all components are synchronised appropriately. Furthermore, the *store and forward* capability of the XA controller allows only one radio to be used at the central processing site. The raw code and carrier-phase data are transferred to the main processing station via spread spectrum radios. Once collected, the raw data are binned into appropriate files for processing.

Running from the GPS receiver and antenna switching device to each antenna is low-loss coaxial antenna cable, interspersed with dual frequency line amplifiers and lightning protectors. The longest cable run at present in the system described is approximately 340m.

As installed on the test site, the data are logged at each remote antenna for 15 minute periods. Therefore, for a 4 antenna array, each monitoring point would be sampled hourly. The logging interval can be varied however, to adapt the system to different number of monitoring points, baseline lengths and rates of deformation.

2.2 Software

Operation of the switched antenna array system is controlled by two specifically developed in-house software packages. The first, termed *Gather GPS*, controls the scheduling, antenna switching, download and transmission of the data from deformation site to base. On arrival of the data at the base station computer, the in-house developed GPS processing software ‘engine’, *Multibas*, is executed. This computes a least squares estimate of the coordinate of each antenna, via double differencing relative to the two reference stations.

Batch processing of one complete cycle of the switching device means that station coordinate solutions can be available within a few minutes of the last observation in the current switching cycle. This would mean that typically, the deformation solutions are updated to the geotechnical engineer approximately every hour. However, in more dynamic situations, where the slip or failure may be moving at an increased velocity, the individual station(s) monitoring the failure can be monitored more regularly, even providing near-to real time deformation solutions (for example, every few seconds).

3. The Test Site

A suspected deforming wall of an operating open-pit nickel mine, Mount Keith, Western Australia, was selected as the switched antenna array deformation system test site. The nature of wall movement was suspected relaxation following its recent cut-back. Figures 2 and 3 illustrate schematic plans of the system, featuring two reference stations located on assumed stable ground, and four monitoring points along the deforming wall, at which data are collected quasi-continuously via the antenna switching device.

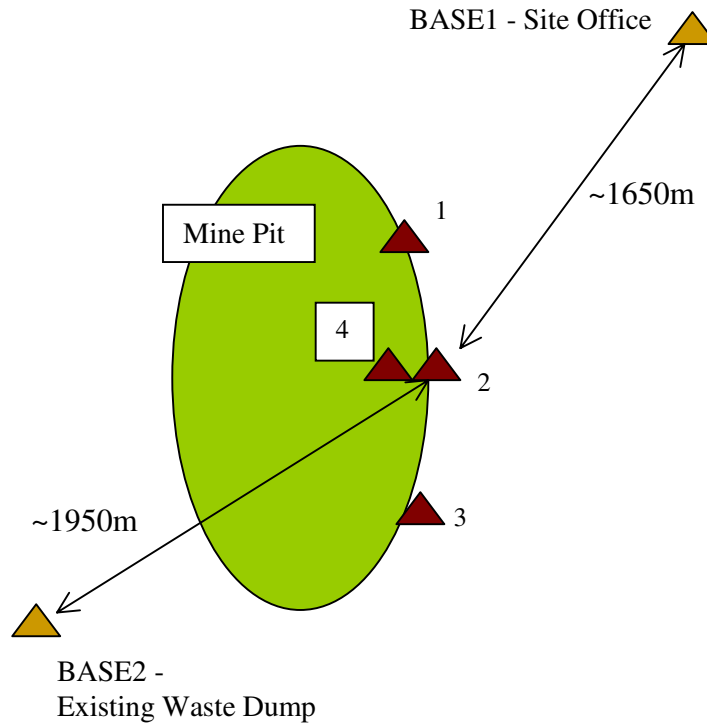


Figure No. 2: Schematic of the equipment as installed to monitor the deforming wall.

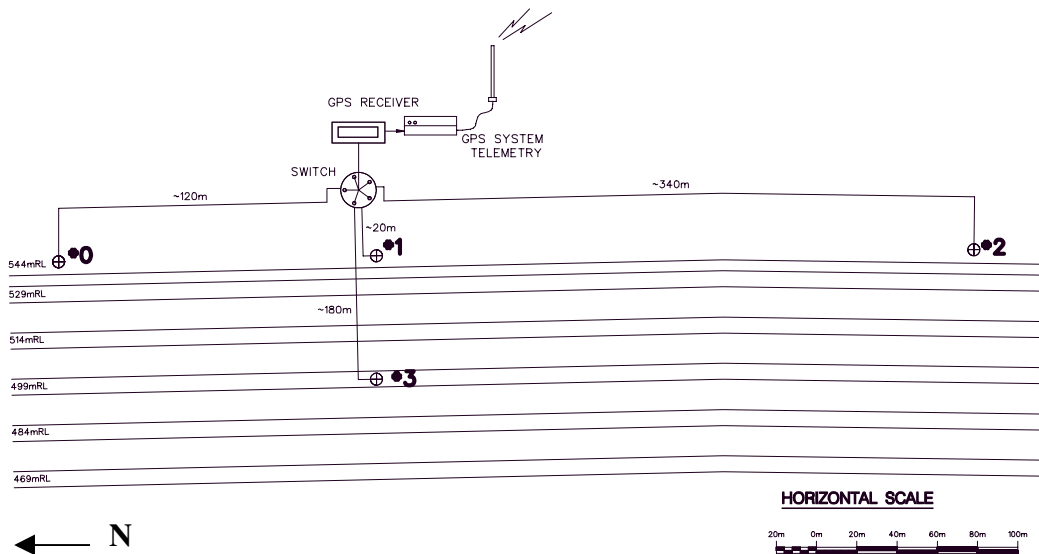


Figure No. 3: Plan view of monitoring station locations

The locations of the monitoring stations (stations 0 to 3 in Figure 3) were selected, in consultation with geotechnical experts, to monitor the deformation and stability of the wall in both plan and profile components. Stations 0, 1 and 2 are located along the wall at the top of the pit, and station 3 is located at an excavation depth of 45m below stations 0, 1 and 2. The location of station 3, well below the top of the pit, is illustrated in Figure 4.



Figure No. 4: Deformation station 3 situated near to the mine wall and below top excavation level

As can be seen from Figure 4, the station (number 3) is optimally located in the middle of the berm with regards to monitoring geotechnical movement of the wall structure, and also to minimise signal multipath effects and poor satellite geometry effects caused by locating the receiver close to the wall. Localised slips can also be seen in the wall both above and below the berm. Ground cracks indicate further localised failure.

4. Results

At present, approximately 8 weeks of continuous data have been collected and processed. For the first three weeks, the system comprised one reference station (BASE1) and four deformation monitoring stations. During the latter five weeks, a second reference station (BASE2) also became operational.

4.1 Positioning Results

Figures 5-7 illustrate the observed displacement at monitoring station 0 that was located along the top of the mine wall, with an unobstructed view of the sky in all directions. As this station is situated at the northern end of the pit, where the cut-back operation begins, minimal station deformation was expected (constrained by surrounding rock mass).

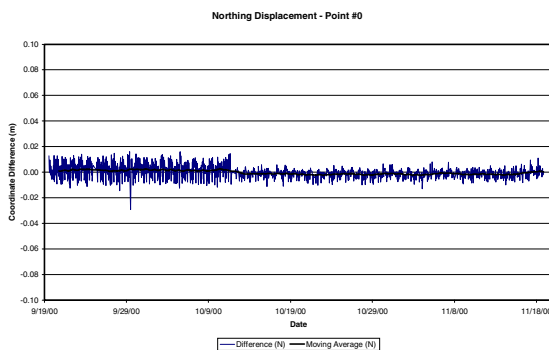


Figure No. 5: Northing Time Series - Point #0

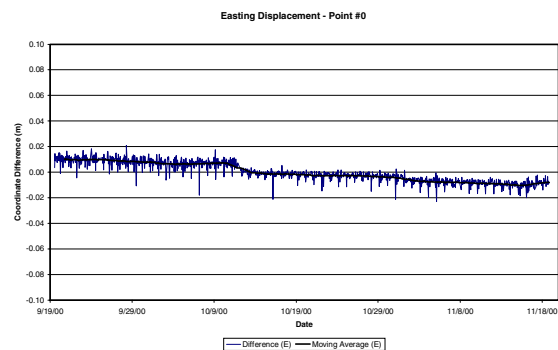


Figure No. 6: Easting Time Series - Point #0

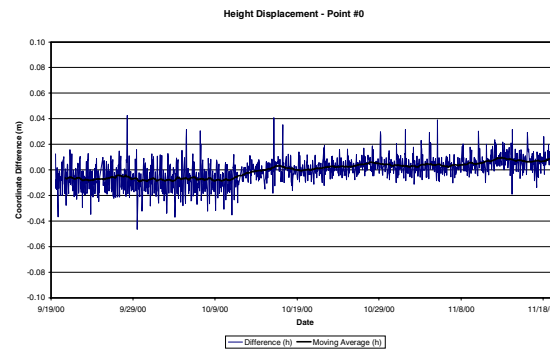


Figure No. 7: Height Time Series - Point #0

From the coordinate time series shown in Figures 5-7, it can be seen that an appreciable reduction in the noise level occurs from 12 October 2000 onwards, when the second reference station (BASE2) is included in the data processing network. The solid lines shown in Figures 5-7 represent the moving average of the data set, with a period of 30 15 minute epochs (approximately 30 hours) and is plotted to illustrate the smoothed time series that may be used to determine/monitor gross geometrical wall shift. The RMS of the differences between the moving average and the unfiltered data points provide an indication of the precision of the coordinate time series, being 4.7, 3.1 and 8.8mm for the north, east and height components respectively.

The coordinate time series for station 3, 45m below the top level of the pit, are shown in Figures 8-10. The RMS of the differences between the moving average and the unfiltered data points provide are 5.3, 5.4 and 12.1mm for the north, east and height components respectively. An increased noise level compared with station 0 located along the top of the pit wall occurs as expected, because the mine wall obstructs the satellite signals, reducing the number of visible satellites, and also causes likely signal multipath. From visual inspection of Figure 9, significant deformation of about 70mm in an east-west direction has occurred. This indicates that the wall has relaxed at a rate of about 1cm per week, moving to fill the void created by the wall cut-back, and follows the expected geotechnical movement. Little motion is observed in the northing component, whilst an upward motion of approximately 2mm/week can be observed in the height component.

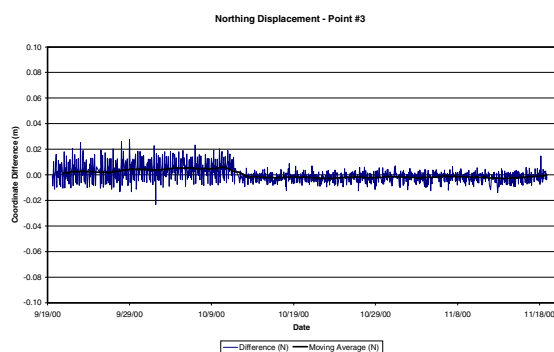


Figure No. 8: Northing Time Series - Point #3

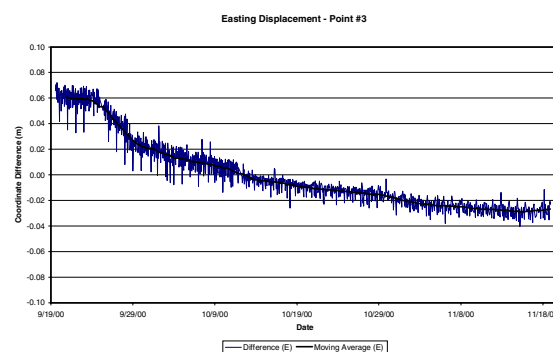


Figure No. 9: Easting Time Series - Point #3

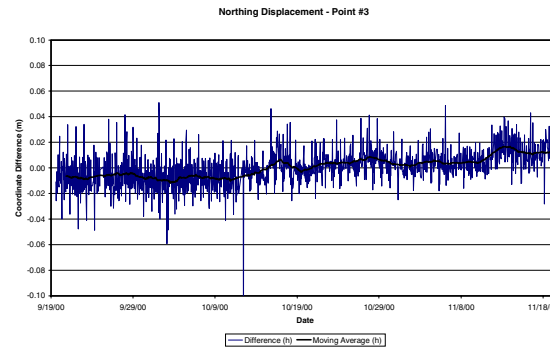


Figure No. 10: Height Time Series - Point #3

If the coordinate time series shown in Figures 8-10 are considered further, it is of interest that a visible reduction in the noise of the northing time series occurs on introduction of the second reference station, BASE2, on 12 October 2000. The time series were subsequently analysed both when a single reference station was used (BASE1) and when both BASE1 and BASE2 were used as reference stations, with the statistics shown in Table 1.

Number of Reference Stations	Operating Date	Number of Observations	Northing RMSE (mm)	Easting RMSE (mm)	Height RMSE (mm)
1	9 th Sept. – 11 th Oct. 2000	512	7.4	7.1	14.0
2	12 th Oct. – 18 th Nov. 2000	806	3.6	4.1	9.9
Combined	9 th Sept. – 18 th Nov. 2000	1318	5.3	5.4	12.1

Table No. 1: RMSE of Station #3 data (compared to the moving average time series)

It can be seen from Table 1 that, for station 3, the addition of the second reference station reduces the RMS coordinate difference from the moving average by approximately 45% in plan, and 30% in the height component.

4.2 Influence of Long Antenna Cables

As described above, the system includes some long antenna cable lengths from the sole monitoring GPS receiver to the multiple antennas. This leads to concerns over the resultant signal strength and quality degradation due to their use. This was assessed by analysing the signal-to-noise (C/N0) values obtained at stations 1 and 2, involving the shortest (20m) and longest (340m) cable lengths in the system respectively. Arbitrarily, for satellite 19, each 15 minute period of data throughout GPS week 1084 was selected for analysis, with the signal-to-noise ratios illustrated in Figure 11.

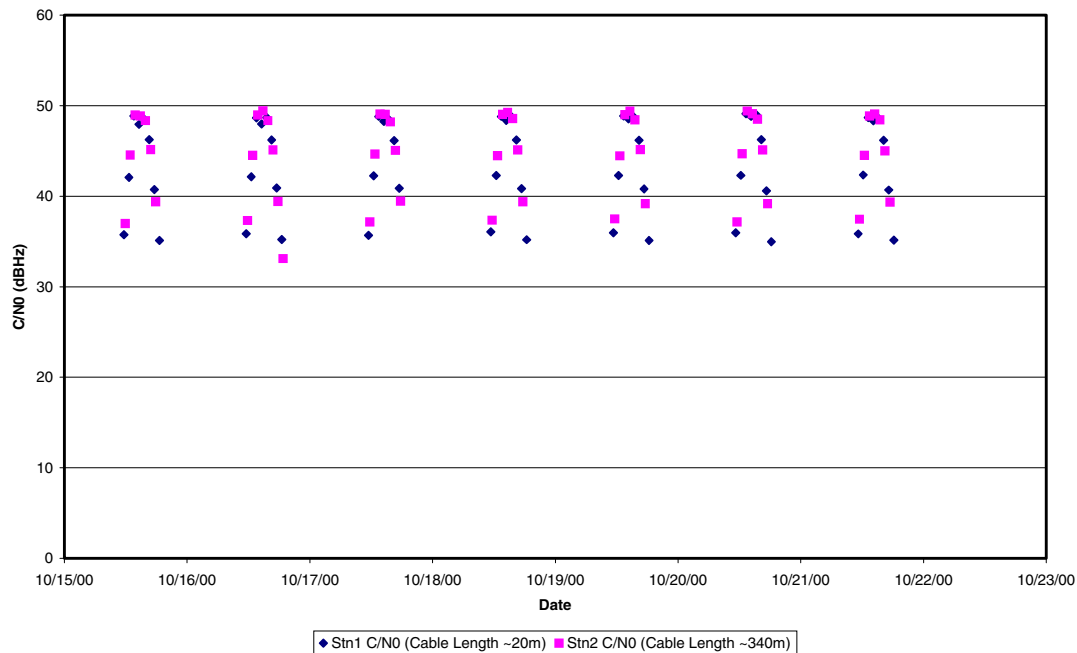


Figure No. 11: Average C/N0 values for satellite 19, GPS week 1084

The average value of all satellites for station #1 is 43.0dBHz, with a minimum of 33.3dBHz, and a maximum of 50.7dBHz. The average value of the received signal for station #2 in this case is 43.1dBHz, with minimum and maximum values of 32.5dBHz and 50.7dBHz respectively. This indicates that, on average, the C/N0 ratio observed is higher for the station with the longer cable length, which is unexpected. One possible cause of this effect is that the line may be over amplified for the signal loss.

The CRS1000 carrier tracking loop threshold is 32dBHz under normal operating conditions, indicating that successful tracking should be possible in most cases. The repeat pattern in Figure 11 is due to the fact that observations at each site are logged at the same sidereal time each day. The signal strength is correlated strongly to the rise, fall and subsequent elevation angle of the satellite.

5. Conclusions and Further Work

In this paper, a system of near-continuous monitoring of an open pit mine wall, using switched GPS antenna arrays and continuously operating GPS reference stations, has been demonstrated. The use of the switching antenna array reduces the need for multiple sets of receiver hardware and communication systems, thereby reducing the *per station* cost of small- to medium-scale GPS monitoring networks.

The use of continuous monitoring strategies further offers the ability to mitigate systematic biases that result from multipath delays, tropospheric delay errors and other temporal considerations such as thermal expansion of the survey pillars. These issues are currently under further investigation.

The system presented in this paper used high quality dual frequency geodetic GPS receivers and choke ring antennas, purely due to the resources available to the research team. Cheaper antennas and receivers (single frequency) will be tested in the forthcoming months where possible, to evaluate the precision trade-off between receiver/antenna quality versus system cost.

6. Acknowledgments

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References

Ding X., Y. Chen, D. Huang, J. Zhu, M. Tsakiri and M. Stewart (2000). Slope Monitoring Using GPS- A Multi-Antenna Approach. *GPSWorld*, Vol. 11, No. 3, pp. 52-54.

Ding, X., Chen, Y., Zhu, J., and Huang, D. (1999) Surface Deformation Detection Using GPS Multipath Signals, *Proceedings of ION GPS-99*, Nashville, Tennessee, Sept. 14-17, pp. 53-62.

Heus, H. de, (1998), Subsidence monitoring with GPS in the Netherlands, In: Proc. of the International Symposium on: Current Crustal Movement and Hazard Reduction, Wuhan, China, 4-11-1997, Seismological Press, Beijing, China, pp.184-195.

Koivula, H., Ollikainen, M., and M. Poutanen, (1998), Use of the Finnish Permanent GPS Network (FINNET) in Regional GPS Campaigns, *Advances in Positioning and Reference Frames*, Vol. 118, IAG Scientific Assembly, Rio de Janeiro, Springer-Verlag, Berlin. pp. 137-142.

Petrovski, I., Kawagushi, S., Torimoto, H., Asako, M., Chachin, T. and Okano, K., (1999), LAMOS-BOHSAI: Landslide Monitoring System Based On High-speed Sequential Analysis for Inclination. *Proc. ION-GPS99, Nashville, 14-17 September*.

Seeber, G. Menge, F., Volksen, C. (1997) Precise GPS positioning improvements by reducing antenna and site dependent effects. *Advances in Positioning and Reference Frames*, IAG Symposia Vol. 118, pp. 237-244.

Stewart M P, M Tsakiri (2001). Long Term Dam Surface Monitoring using the Global Positioning System. *Geotechnical Engineering* , (under review).

Stewart M P, M Tsakiri and R Duckrell (1999). Dam Deformation Monitoring with Episodic GPS, *Proceedings of 6th South East Asian Surveyors Congress*, Fremantle, WA, November, pp. 477-485

Wanninger, L and M May (2000). Carrier Phase Multipath Calibration of GPS Reference Stations, *Proceedings of ION GPS-2000*, Salt Lake City, Utah, Sept. 19-22.