Proceedings, 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.

GPS DATA STACKING FOR SMALL SCALE GPS DEFORMATION MONITORING APPLICATIONS

Troy Forward[1], Michael P Stewart and Maria Tsakiri[2]

Western Australian Centre for Geodesy, Curtin University of Technology, Perth, WA 6845, Australia.
[1]Now at: Defence Science and Technology Organisation, DSTO Stirling, Rockingham, Australia.
[2]Dept. of Rural and Surveying Engineering, National Technical University of Athens, Greece.

Abstract

GPS data stacking techniques have been evaluated for deformation monitoring of an open pit high wall in central Western Australia. GPS stacking techniques proposed in the literature using both observable and coordinate stacking methodologies are based on the assumption that GPS data observed at the same point are well correlated from day to day. Data presented in this paper challenges this assumption by illustrating that GPS data may not be well correlated under conditions where high levels unmodelled systematic error are present due to complex multipath reflectors such as natural and man-made rock structures.

1. Introduction

Engineering-type GPS deformation monitoring schemes are characterised by episodic surveys which may be days, weeks or months apart, short occupation times (usually less than 30 minutes per point) and short baselines. Because of the availability of a small number of deformation observation epochs (in comparison to, say, continuously operating reference stations), interpretation of potential motion is vulnerable to erroneous results caused by the presence of systematic biases in the raw GPS data. In the case of engineering surveys, where GPS antennas are likely to be located on or near the structures to be monitored, the presence of multipath is, more often than not, the dominant error source.

Data stacking approaches have been widely proposed to reduce the effect of multipath-induced systematic errors for high precision positioning applications. There are generally two types of stacking approaches. The first technique uses observable (or residual) stacking, where least squares observations (or residuals) are correlated with respect to the sidereal day to reduce the impact of multipath delay on the positioning results. These techniques have been investigated, for example, by Ma *et al.* (2001), Ding *et al.* (1999), Radovanovic (2000), and Wübbena *et al.* (2001). The second technique uses stacking of the coordinate solutions to reduce the effects of unmodelled systematic error (for example Bock *et al.*, 2000; Alber *et al.*, 2000; Braun *et al.*, 2001).

Both the observable and residual stacking techniques rely on the assumption that a high level of correlation exists in the double difference phase data time-series between successive sidereal days, primarily resulting from a repeating multipath signature. Whilst this may be a largely valid assumption, suitability of data stacking techniques in cases where multipath reflectors are very complex and their surface reflectance/absorption characteristics may vary with time (for example due to variations in temperature and water content) is yet to be proven. This paper tests observable stacking techniques in an operational deformation monitoring environment in an open cut mine in Western Australia.

2. Sample Data and Site Description

Approximately 3 months of continuous data from a baseline which forms part of a GPS deformation monitoring network on an open cut mine site in Western Australia have been recorded for this analysis. The deformation station was located 45m below the surface approximately 5m from the mine wall (Fig. 1) and 1900m from the reference station. The deformation station was susceptible to poor satellite geometry and significant multipath effects due to the nearby high-wall. Furthermore, over 140mm of motion in an easterly direction (caused by the outward bulging of the mine wall) was detected over the 3-month period.

24 solutions have been computed for each day (one per hour) using approximately 15-minute 1Hz data segments measured at the same sidereal time each day using Leica CRS 1000 dual frequency GPS receivers. For more information regarding the data collection strategy and data processing, the reader is referred to Forward (2002).

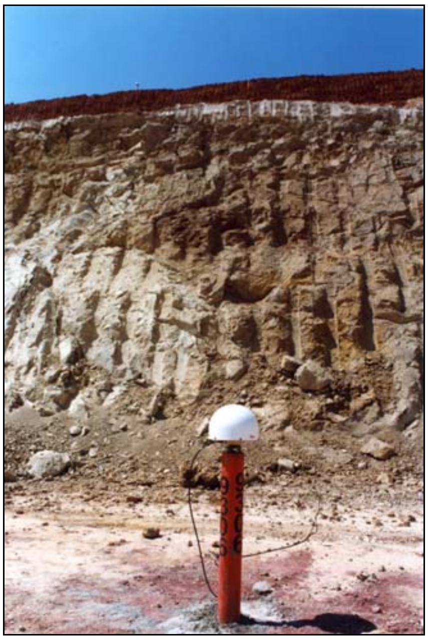

Fig. 1. Deformation station illustrating nearby high-wall which acts as a multipath reflector

3. Observation Stacking

Data collected from satellite pair (satellites 25-17) at the deformation station are plotted in Fig. 2 for 14 successive days of double-difference observed-minus-computed (DDOmC) values (GPS weeks 1085 and 1086). Elevation angles for the satellites 25 and 17 were approximately 13° and 66° respectively. This satellite pair is selected as a representative sample of all satellite pairs over this 14-day data sub-sample. Daily RMS differences range from ±0.033 cycles to ±0.079 cycles with the average RMS being ±0.056 cycles.

Various spikes within the data can be seen, for example between 0 and 100 seconds for day 1. These spikes represent data outages due to temporary loss of lock caused by the difficult multipath environment in which the GPS receiver was operating. Data outages have been assigned to zero in the matrix/vector form within the subsequent data analysis process. While missing observations are not desirable in the type of correlation analysis presented below, empirical tests have indicated that the correlation coefficient computed is not significantly affected (at the ~0.01 cycle level).

Visual inspection of Fig. 2 reveals some of the expected repeating signatures from data observed on consecutive sidereal days. However, the differences between the daily plots in Fig. 2 are more apparent.

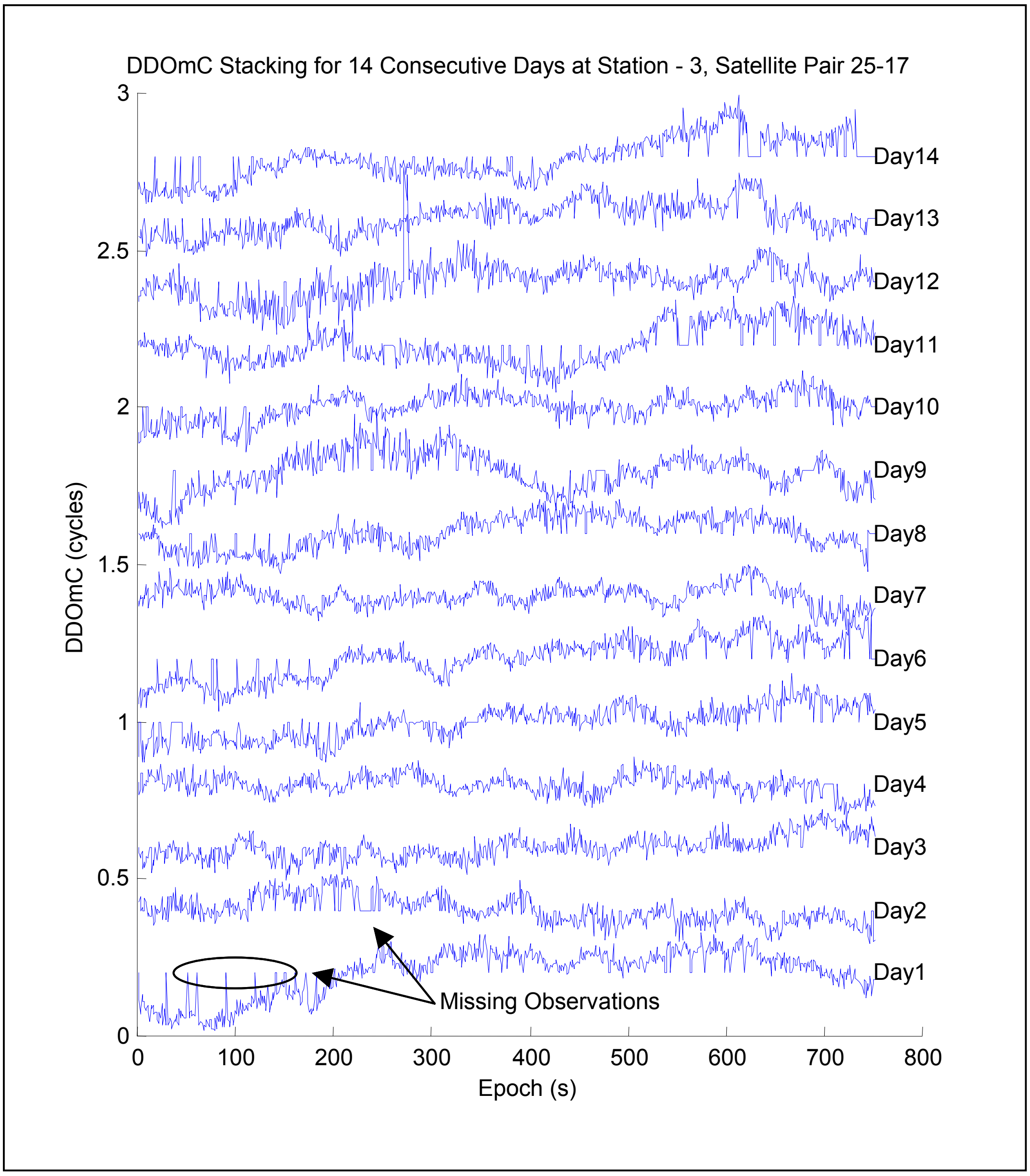

Fig. 2. Daily DDOmC values for 14 successive days (satellite pair 25-27)

Table 1 illustrates the correlation coefficients for the 14-day sample data set. The maximum correlation coefficient occurs between days 5 and 6 where a correlation coefficient of 0.74 is recorded. The lowest correlation coefficient is computed as 0.18 which incidentally occurs between the next two successive days (days 6-7). The average correlation coefficient for the off-diagonal elements presented in table 1 is computed as 0.40 with a standard deviation of 0.15. The low correlation coefficients indicate that, in this case, the observations are not as highly correlated as would be expected. This does not support the use of observable stacking techniques to reduce residual systematic error within the double difference data observed at this site. Decorrelation of the observables appears to be a result of errors that do not necessarily repeat on a daily basis.

Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	1.00	0.27	0.53	0.25	0.64	0.67	0.26	0.69	0.47	0.58	0.56	0.61	0.64	0.51
2		1.00	0.35	0.22	0.32	0.35	0.19	0.38	0.32	0.22	0.38	0.21	0.33	0.35
3			1.00	0.19	0.57	0.49	0.39	0.45	0.26	0.39	0.46	0.36	0.51	0.47
4				1.00	0.19	0.21	0.22	0.21	0.27	0.24	0.26	0.19	0.18	0.20
5					1.00	0.74	0.18	0.57	0.33	0.55	0.38	0.46	0.60	0.53
6						1.00	0.18	0.60	0.25	0.51	0.46	0.48	0.58	0.64
7							1.00	0.28	0.30	0.20	0.22	0.25	0.27	0.24
8								1.00	0.34	0.45	0.53	0.49	0.66	0.46
9									1.00	0.47	0.59	0.43	0.24	0.44
10										1.00	0.48	0.46	0.41	0.41
11											1.00	0.52	0.50	0.66
12												1.00	0.50	0.39
13													1.00	0.45
14														1.00

Table 1. Correlation coefficients calculated between 14 successive days of DDOmC data for satellite pair 25-17

The results presented for table1 indicate that the dominant systematic error components that are expected to repeat every sidereal day (for example signal multipath, diffraction and antenna phase centre variations), in fact decorrelate from day to day. This could be due to the motion of the antenna location itself as approximately 12.2mm of motion were detected over the two weeks of data presented. Such motion will result in a different daily multipath signature. However, if deformation of 1mm per day was the cause for signal decorrelation, one would expect to find that days which are temporarally further apart would be less correlated than, for example, adjacent days. This, apparently, is not the case.

4. Coordinate Solution Stacking of Time-series for Multipath Mitigation

The second stacking technique for GPS observations involves the use of the processed coordinate solution time-series in a stacking process to reduce the impact of signal multipath on solution quality. The method presented by Bock *et al.* (2000), stacks instantaneous solutions (one solution computed every second) at the same sidereal time each day.

Fig. 3 illustrates coordinate solutions at the deformation station for a 50-day period commencing on 9 October 2000. A single line represents one 15-minute solution per day over 50 days, with the 15-minute data having been taken from the same sidereal time period each day. Each line represents the sidereal 15-minute time span taken from a different hour of the day. Therefore, 24 50-day solutions can be seen, the first showing solutions for each day from a 15 minute sidereal period from the first hour of the day, the second showing solutions for each day from a 15 minute sidereal period from the second hour of the day etc. Additionally, each line has been offset by 20mm for clarity. Each hourly time series has been smoothed using a moving average window of length 2 days. This is a similar approach to that adopted in Bock *et al.* (2000).

It would be expected that in the presence of only multipath and geometric-dependant error sources, each line in Fig. 3 should display the time-series in a relatively smooth manner (as the multipath/geometrical error contribution should be consistent for each sidereal time period). Under this condition, any remaining trends should be due to surface deformation. However, this does not appear to be the case for the data presented in Fig. 3, where some of the deviations that appear, as highlighted on the figure, are not consistent in each hourly time series. In these time series, there is evidence of non-sidereal systematic error which is biasing the final coordinate solutions.

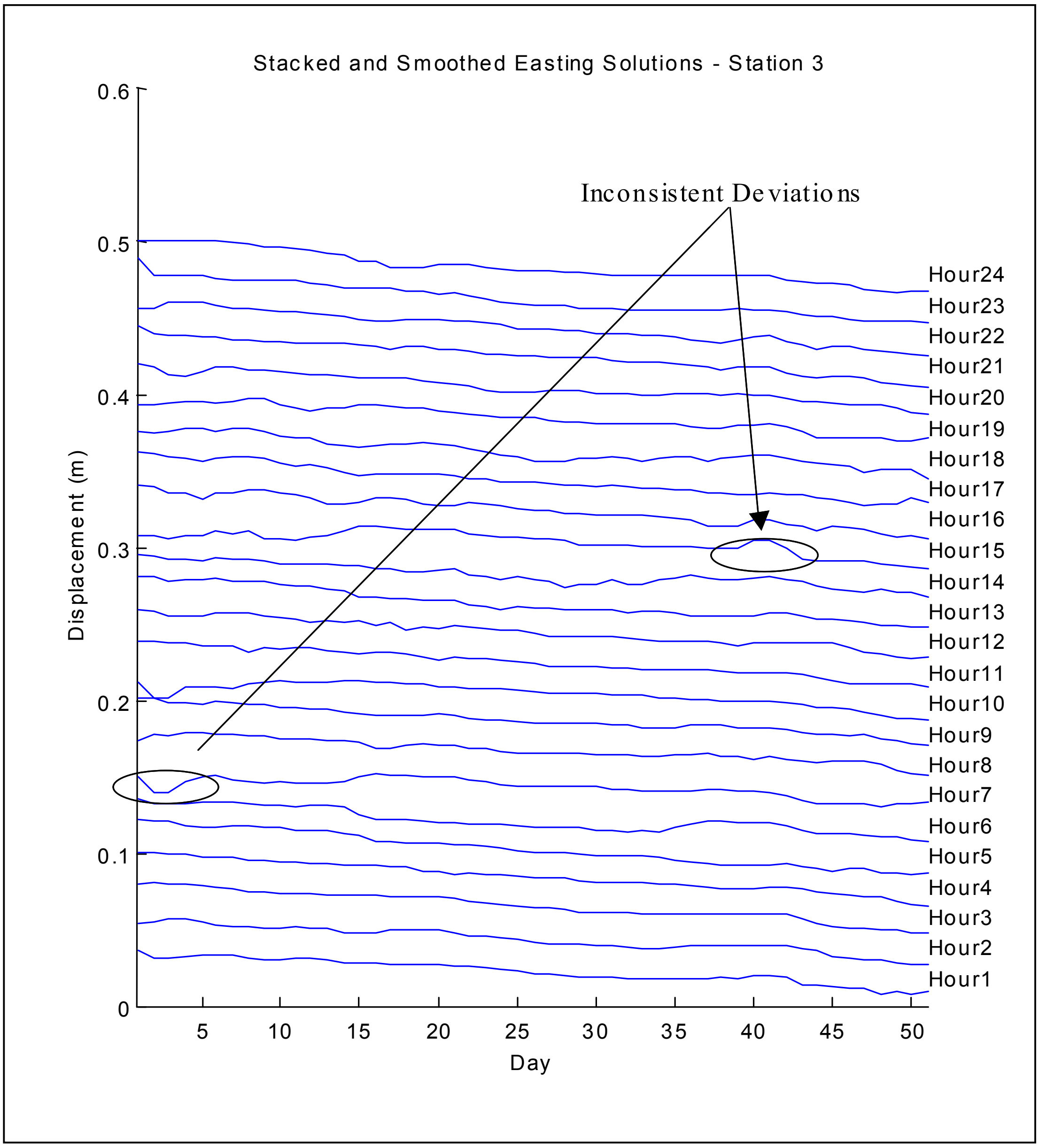

Fig. 3. Stacked and smoothed coordinate solutions for easting component at deformation station

5. Data Averaging Techniques to Display Multipath Affected GPS Data for Deformation Monitoring

Another method of coordinate stacking could involve the daily averaging of coordinate solutions. In this case, 24 hourly coordinate solutions from each sidereal day are binned and averaged. This method, illustrated in Fig. 4, also allows for the computation of dispersion estimates (standard deviation or RMS error) for each day that can then be represented by error bars.

It can be seen from Fig. 4 that when plotted in this manner, the daily averaged solution offers a reasonably smooth representation of the data set, whilst also giving a running indication of the precision of the coordinate solutions. One other advantage of plotting the coordinate time-series in this way is that the (sidereal) daily bins of coordinate solutions should capture the same satellite geometry and multipath signatures every day. This should result in a more consistent computation of the dispersion estimates for each daily solution.

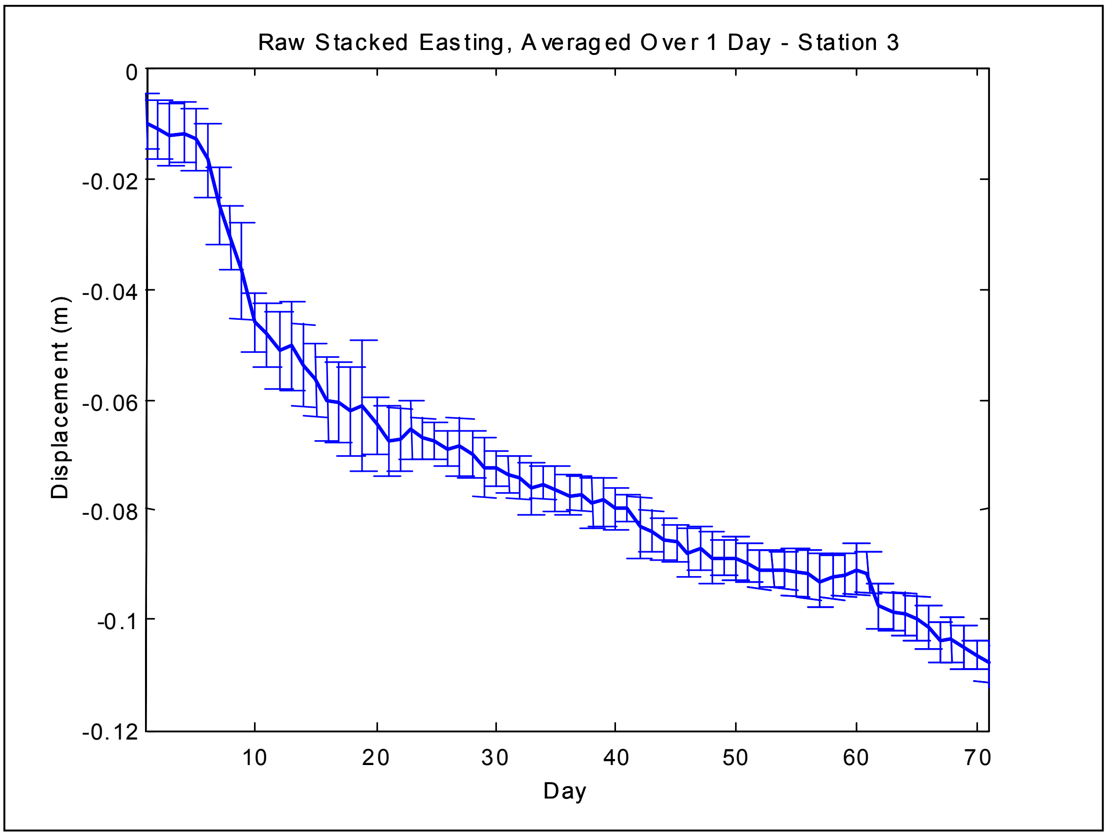

Fig. 4. Mean daily solution of stacked easting component at deformation station

It should be noted, however, that in periods of high station movement, as is experienced in some parts of this time-series set, the precision indicator may be biased by the deformation signal itself. For example, if the high-wall position changes significantly throughout the day, the computed variance or dispersion estimate will increase artificially (because the dispersion estimate assumes stationarity of the mean).

6. Remarks on Stacking Techniques for Multipath Mitigation

The underlying assumption for much of the work presented in the literature on data stacking techniques is that the multipath signature is well correlated on a daily (sidereal) basis. While this may be a largely valid assumption, it has been shown that in the presence an irregular signal reflecting surface, a strong daily correlation does not necessarily exist between GPS double difference observations. In some instances, the double difference observables appear to decorrelate on a day-to-day basis, bringing the effectiveness of data stacking techniques into question in such environments. For the data presented in this paper, there is evidence of the presence of significant non-sidereal systematic biases. These biases are of a sufficient magnitude to result in erroneous conclusions being drawn regarding the detection of deformation. In an operational situation, this could result in undesirable false alarms for a GPS-based system. In this case, the surface reflector of the station experiencing high levels of signal multipath was predominantly a nearby mine wall. It may be speculated that the irregularities existing within the wall face (the exposed rock) contribute to decorrelation of the multipath signature on successive days.

On such a short baseline (1900m), the presence of unaccountable biases is troublesome. The differencing procedure would be expected to remove the majority of atmospheric error. However, temperature variations within the mine, as opposed to the reference station which was located at the site office, could be an issue. Temperatures in the Australian outback can range from –5°C to +50°C. Although GPS signal errors caused by temperature (and height) differences between the deformation station and the reference station are theoretically insignificant, some thermal effect on hardware cannot be ruled out.

The issue of the variability of multipath reflector characteristics requires further attention, in terms of the level of decorrelation between multipath delay errors with changing surface and environmental characteristics, such as the effect of rainfall, dust and snow on the reflecting surface on the multipath signature.

Acknowledgements

This research was conducted while the first author was a PhD student at Curtin University. The first author was the recipient of a Curtin University Divisional Postgraduate Award. The hardware system and fieldwork was funded by the Australian Research Council Large Grant no. A39803892.

References

Alber, C., Ware, R.H., Rocken, C. and Braun, J.J. (2000) Obtaining Single Path Delays from GPS Double Differences, *Geophysical Research Letters*, Vol, 27, No. 7, pp. 2661-2664.

Bock, Y., Nikolaidis, R.M., de Jonge, P. and Bevis, M. (2000) Instantaneous Geodetic Positioning at Medium Distances with the Global Positioning System, *Journal of Geophysical Research*, Vol. 105, No. B12, pp. 28223-28255.

Braun, J., Rocken, C. and Ware, R. (2001) Validation of Line-of-Sight Water Vapour Measurements with GPS, *Radio Science*, Vol. 36, No. 3, pp. 459-472.

Brunner, F.K., Hartinger, H. and Ritcher, B. (2000) Continuous Monitoring of Landslides using GPS: A Progress Report, in: *Proceedings of the Geophysical Aspects of Mass Movements*, *Bauer, S.J. and Weber, F.K.* (ed.), Austrian Academy of Sciences, Vienna, Austria, pp. 75-88.

Ding, X., Chen, Y., Zhu, J. and Huang, D. (1999) Surface Deformation Detection Using GPS Multipath Signals, *Proceedings of the 12th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GPS-99*, Nashville, Tennessee, September 14-17, pp. 53-62.

Forward, T.A. (2002) Quasi-Continuous GPS Steep Slope Monitoring: A Multi-Antenna Array Approach, Ph.D Thesis, Curtin University of Technology, 211pp.

Grenrich, J.F. and Bock, Y. (1992) Rapid Resolution of Crustal Motion at Short Ranges with the Global Positioning System, *Journal of Geophysical Research*, Vol. 97, No. B3, pp. 3261-3269.

Ma, E., Chen, Y. and Ding, Z. (2001) Monitoring of Slope Stability by using Global Positioning System (GPS), *Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation - KIS2001*, Alberta, Canada, June 5-8, pp. 298-310.

Radovanovic, R.S. (2000) High Precision Deformation Monitoring by Multipath Mitigation via Day-To-Day Correlation Analysis, *Proceedings of the 13th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GPS-2000*, Salt Lake City, Utah, USA, September 19-22, pp. 35-44.

Wübbena, G., Bagge, A., Bettcher, G., Schmitz, M. and Andree, P. (2001) Permanent Object Monitoring with GPS with 1 Millimeter Accuracy, *Proceedings of the 14th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GPS-2001*, Salt Lake City, Utah, USA, September.