

# High Accuracy Deformation Monitoring Via Multipath Mitigation by Day-To-Day Correlation Analysis

Robert S. Radovanovic

*Department of Geomatics Engineering, The University of Calgary*

## BIOGRAPHY

Robert Radovanovic is a Ph.D. student with the Department of Geomatics Engineering at The University of Calgary. He received a B.Sc. at the same institution in 1998. His current research activities involve applying GPS technology to high-precision deformation monitoring applications.

## ABSTRACT

On baseline lengths commonly encountered in local GPS-based deformation surveys, multipath is the dominant error source, causing errors as large as 5 centimetres. Since multipath is caused by reflections in the receiver environment, it repeats under identical satellite geometries (assuming a static receiver), or once every 23 hr 56 min. The magnitude of the day-to-day correlation is typically around 85% (Radovanovic et al, 1999), depending on how static the reflective environment is.

The day-to-day repeatability of multipath can be exploited to improve positioning accuracies. Given known coordinates of a point on a given day, the multipath error at every epoch can be calculated from the collected phase data. This multipath signature can then be subtracted from data collected the subsequent day. Although this procedure increases the noise of the corrected measurements, it removes multipath almost completely. Furthermore, since multipath is a low-frequency phenomena, time-averaging of the multipath-free coordinate solutions is more effective.

Tests performed on static and slowly deforming baselines indicate that this mitigation technique can improve epoch-to-epoch position accuracies by 35% or to the 5 mm ( $1\sigma$ )

level. By averaging corrected 1 Hz position estimates over 30 seconds, improvements in positioning accuracies of up to 50 % can be realised. Of course, the technique is only applicable under the constraint of slowly moving monitoring stations, which insures that multipath does not significantly spatially decorrelate.

## INTRODUCTION

There exist many applications in which the precise three-dimensional coordinates of slowly deforming structures are required. In addition, many such applications are of small spatial extent (<10 km). These applications include bridge and small dam monitoring projects, pipeline monitoring and machinery alignment. In such scenarios, it is advantageous if the three-dimensional coordinates of target points can be provided at high data rates (~1 Hz). GPS is an attractive system for providing such data since it is weather independent, capable of autonomous operation, and does not require a line-of-sight between target points (although it does require satellite visibility).

Unfortunately, the accuracy requirements of precision deformation monitoring are generally at the sub-centimetre level, which is presently unachievable on an epoch-by-epoch basis with regular, carrier-phase DGPS techniques. The main reason for this is the effect of carrier-phase multipath, which can cause residuals of up to  $\frac{1}{4}$  of the GPS signal wavelength (or ~5cm on L1). Multipath is caused by multiple reflections of GPS signals in the antenna environment, which then combine to create a composite signal at the antenna. Reception of this composite signal results in a phase measurement error (Braash, 1995).

Many techniques have been developed to reduce the effect of multipath on GPS positioning. Improved antenna design with lower gain at low elevations reduces the influence of ground-reflected signals (Lachapelle et al, 1989). This is the principle behind the chokerings and groundplanes now in common use.

As well, significant work has gone into reducing multipath using specialised signal and data processing techniques. Axelrad et al (1994) investigated the correlation of multipath magnitude to carrier SNR to mitigate carrier phase multipath. Comp and Axelrad (1996) further expanded this work. However, both of these methods can only be applied during post-processing, which limits its use in applications where a warning must be issued once deformations exceed a certain limit (i.e. earthquake and volcano eruption prediction).

Ray et al (1998) and Ray (1999) devised a real-time method to determine multipath effects using a closely spaced array of antennas and the spatial correlation of multipath on short distances. Unfortunately, the cost of the multiple antennas required at each station precludes this method's general use in deformation monitoring networks where a great deal of points are monitored.

Interestingly, little research work has focused specifically on removing multipath from scenarios where monitoring points move very slowly (< 1cm per day), which is common in most deformation monitoring applications. Raquet and Lachapelle (1996) investigated the use of multiple reference stations to remove multipath at the base stations, but this method did not reduce multipath at remote (or monitoring) sites.

A novel method described herein exploits the pseudo-static nature of monitoring points and the day-to-day correlation of multipath to effectively mitigate this error source. Field tests indicate that epoch-to-epoch positioning accuracies at the 5 mm level are achievable even under deforming conditions.

## DAY-TO-DAY CORRELATION OF MULTIPATH

On short baselines (<1 km), GPS error sources such as tropospheric and ionospheric delay and orbital errors are highly correlated between receivers and so nearly completely cancel when forming double differences. As well, receiver and satellite clock offsets cancel in the double differencing process. This means that the double differences of carrier phases between receivers a ,b and satellites i,j can be written as :

$$\nabla\Delta\Phi_{ab}^{ij} = \nabla\Delta R_{ab}^{ij} + \nabla\Delta m_{ab}^{ij} + \nabla\Delta n_{ab}^{ij} + \nabla\Delta N_{ab}^{ij} \quad \text{Eq.1}$$

where  $\Phi$  is the measured carrier phase, R is the true range from the receivers to the satellites, m is the multipath at

each receiver for each satellite, n is carrier phase noise and N is the ambiguity for each satellite-receiver pair. The  $\nabla\Delta$  operator of course operates as :

$$\nabla\Delta f_{ab}^{ij} = (f_a^i - f_a^j) - (f_b^i - f_b^j) \quad \text{Eq.2}$$

Since multipath errors are geometry-dependant (Ray and Cannon, 1999), they will repeat under identical satellite-reflector-antenna geometries, assuming no change in the reflective properties of the reflectors. Thus, since GPS orbits repeat every sidereal day, the double differenced multipath term for a static baseline will be identical every 23 hr 56 minutes.

Given two points with known coordinates, the  $\nabla\Delta m$  term can be calculated once ambiguities have been resolved and then plotted over two successive days. This has been done for two Trimble 4000 SSI receivers separated by 15m. Figure 1 shows resulting residuals for two satellites PRN 25 and 29. Note that the residual plots have been shifted off zero for clarity and that the same base satellite was used on both days. As well, the antennas used did not have groundplanes or chokerings.

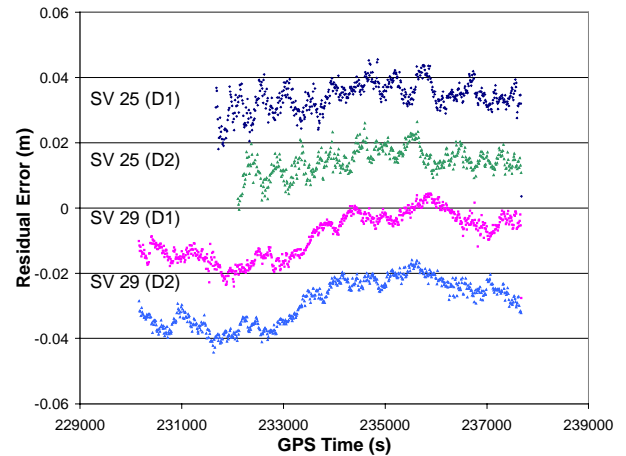


Figure 1. Double Differenced Multipath Errors – Day 1 vs. Day 2.

As can be seen, the multipath errors are highly correlated between days. As well, the error plots on subsequent days are shifted by ~ 4 minutes. The standard deviations of the errors are identical for both days to within 0.3 mm, although different for different satellites. This is expected, since satellite-reflector-antenna geometries are different for various satellites, so the corresponding multipath effects should vary. For example, the multipath trace for SV 25 is predominantly dominated by high frequency components, whereas SV 29 shows low frequency variations.

To better quantify the day-to-day correlation of multipath, the cross-correlation function for two multipath error

traces for two successive days was calculated for all satellites. The resulting plots for SV 24 and SV 29 are shown in figure 2. The peak of both graphs occur within 5 seconds of 4 minutes 12 seconds. Thus the correlation time of two successive days is 23 hr 55 min 48 s (1 sidereal day). Analysis of subsequent days of data indicates that this correlation period is stable to  $\pm 10$ s.

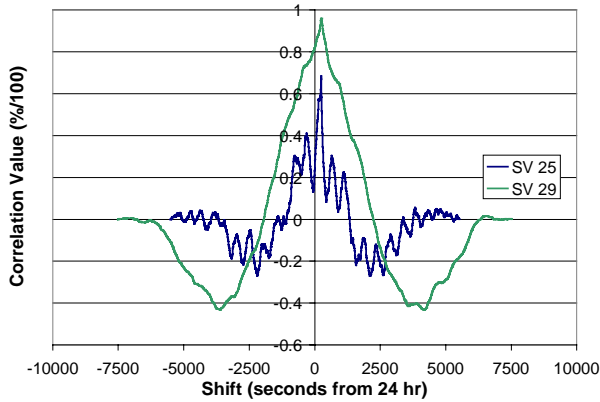


Figure 2. Multipath Inter-Day Cross-Correlation

The shape of the two correlation functions, however, is not the same. The plot for SV 29 shows a high peak (92%) and a slow decay, whereas the plot for SV 25 shows a lower peak (67%) and a much faster decay, as well as periodic features. The reason for this is that, as indicated by figure 1, the signal from SV 29 is corrupted by low frequency multipath of large amplitude. As a result, the long-period component is strongly correlated over long time shifts. On the other hand, the signal from SV 25 is dominated by small amplitude, high-frequency multipath. Thus, the components quickly decorrelate over time. Finally, the periodic nature of the multipath error manifests itself as a periodic trend in the cross-correlation function.

It is well known that chokerings significantly reduce multipath by attenuating signals arriving from low elevation angles (i.e. ground-reflected signals). However, the cross-correlation analysis described above can illustrate some further effects chokerings have on the nature of the residual multipath remaining in the acquired carrier phases.

In the experiment described above, the conventional antennas used were replaced by chokeringed antennas. All other parameters, such as receiver location, time-of-day, base satellite, etc., were held fixed. On average, the presence of the chokering reduced the RMS value of the residuals to the 3 mm level, or from 15% to 75% depending on the satellite. The resulting cross-correlation plot of the multipath errors for SVs 25 and 29 are shown in figure 3.

The cross-correlation plots show once again a peak correlation of  $\sim 80\%$  at 4 min 12 s shift, which indicates that residual multipath still remains in the signal. However, the functions decay very rapidly and show definite periodic trends, so one can conclude that only high frequency multipath remains. Since multipath frequency is directly proportional to the reflector-antenna separation (Radovanovic et al, 1999), the results indicate that chokerings are very effective at attenuating multipath reflections from nearby reflectors. Also, since low frequency components are removed from the residuals, averaging over time (equivalent to high-pass filtering using a sinc function) becomes more effective.

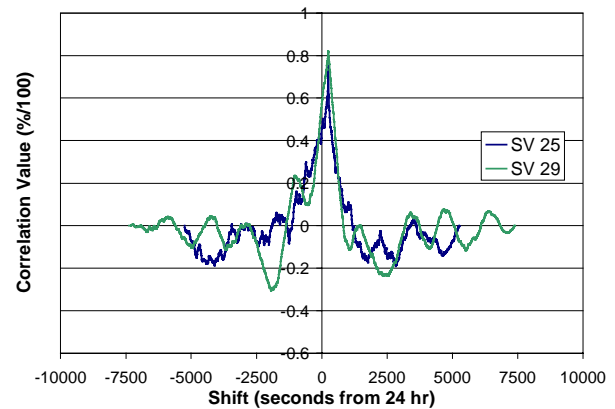


Figure 3. Multipath Inter-Day Cross-Correlation – Chokeringed Example.

## MULTIPATH MITIGATION METHOD

The multipath mitigation method developed is based upon the premise that the monitoring antennas do not move than a few centimetres per day. This is an acceptable assumption in most deformation monitoring situations and is critical in that it ensures that the reflector-antenna geometries do not change significantly between days. Assuming that the reflectivities of the reflectors in the environment do not change, then the multipath effect at each monitoring station will repeat each sidereal day.

Furthermore, if the coordinates of the monitoring stations are known on one day (from a day-long GPS processing campaign, for example), then these reference positions can be used to calculate theoretical ranges to observed satellites. These can then be used in equation (1) to solve for  $\nabla\Delta m$  and thus determine a “multipath signature” for the day. Since this signature repeats every day, it can be used to correct double differences produced on the next day. The corrected double differences then yield position estimates for the monitor stations on the second day which then can be used to repeat the correction procedure on subsequent days.

The multipath reduction system was implemented as a pre-processor that would operate on individual raw data files and output “clean” data in a standard format. The advantages of this strategy include :

- Any commercial GPS processor can be used to process the cleaned data. This makes integration of the system into existing GPS-based deformation monitoring systems simpler.
- Future development of the system as a real-time system is simplified.
- The number of remote receivers that can be used is unlimited.
- No assumptions about data collection rates, data spans or satellite constellations are required.

An important constraint on developing the system as a pre-processor is that no assumptions about base satellites or double difference combinations can be made, as these are package specific. As a result, the pre-processor works on a satellite-by-satellite and station-by-station basis. The basic algorithm is described below in figure 4:

This procedure described can be analysed using the standard model for carrier phases, namely:

$$\Phi = R + \frac{c}{\lambda} \delta t_{sat} - \frac{c}{\lambda} \delta t_{rec} + m + n + N \quad \text{Eq. 3}$$

where  $\delta t_{sat}, \delta t_{rec}$  are the satellite and receiver clock offset, respectively,  $c$  is the speed of light, and  $\lambda$  is the wavelength of the GPS carrier (19 cm for L1). By denoting quantities measured on different days by their superscripts, the resulting clean phases can be written as :

$$\begin{aligned} \Phi_{clean} &= \Phi^2 - (\Phi^1 - R - \delta t_{rec}^{est1}) \\ &= \left( R^2 + \frac{c}{\lambda} \delta t_{sat}^2 - \frac{c}{\lambda} \delta t_{rec}^2 + m^2 + n^2 + N^2 \right) \\ &\quad - \left( R^1 + \frac{c}{\lambda} \delta t_{sat}^1 - \frac{c}{\lambda} \delta t_{rec}^1 + m^1 + n^1 + N^1 \right) \\ &\quad - \left( -R^1 - \frac{c}{\lambda} \delta t_{rec}^{est1} \right) \\ &= R^2 + \frac{c}{\lambda} (\partial \delta t_{sat} - \partial \delta t_{rec} + \partial \delta t_{rec}^{est}) + \partial n + \partial N \end{aligned} \quad \text{Eq.4}$$

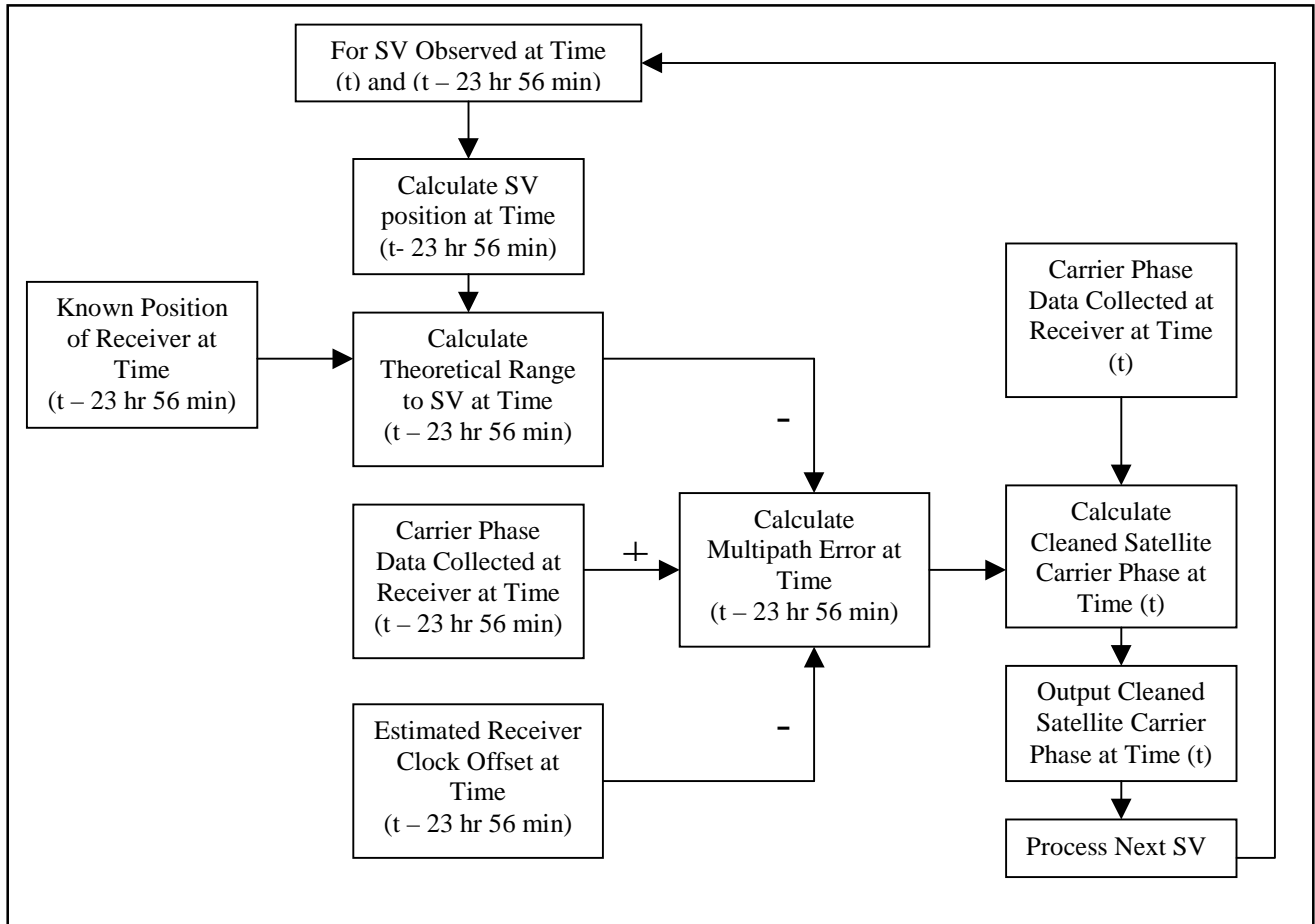


Figure 4. Flowchart Diagram of Multipath Mitigation Technique.

where  $\delta t_{res}^{est1}$  is the estimated receiver clock offset on day one. Since  $m^2 = m^1$  due to the day-to-day correlation of multipath, these terms cancel. As well, since receiver clock offsets are identical for all satellites (although different between epochs), the between-satellite single-difference will cause the  $\partial\delta_{rec}$  term to cancel. The same holds true for the  $\partial\delta_{sat}$  term when between-receiver differences are applied. In addition, since the ambiguity term is constant and integer for both epochs, the between-day differenced ambiguity term will be constant and integer as well. Finally, the noise of the clean observable is higher by approximately 1.414.

The  $\delta t_{res}^{est1}$  term is included such that the pseudorange receiver clock error of the clean observation will be approximately the same as that of the Day 2 observation. This ensures compatibility with most packages that use this value to calculate the satellite orbits required in the positioning solution. Again, it will cancel out in a single-difference between satellites and can be solved for using a single-point solution.

### TEST OF THE MITIGATION SYSTEM

The first test of the mitigation system was to gauge its success in removing multipath on very short, static baselines. Three stations were set up on the roof of the offices of Challenger Surveys and Services Ltd (CSSL), as shown in figure 5. Trimble 4000SSI receivers were used. Stations BASE and CONT were equipped with groundplanes, while station MULT was equipped with a standard antenna mounted onto a precise translation stage (figure 6). Note that station MULT was located near metallic heating cooling units, thus placing it in a high multipath environment. Conversely, station CONT was placed in a relatively clear area to ensure minimal multipath corruption. The translation stage at MULT allowed movements to be induced into the point with a precision of 0.01 mm.

Three hours of 0.5 Hz single-frequency data was collected at the same time of day during the period of November 22-25, 1998 at all stations. On the last two days, known deformations were induced into the MULT station. All processing was done using GrafNav™, a processing package developed by WayPoint Consulting Inc. The coordinates of BASE were available from a previous GPS campaign.

#### Static Test Results

Figures 7 and 8 show the variation in epoch-by-epoch position solutions for the MULT station on day 1 and day 2 of data collection, respectively. The standard deviations of the position solutions are at the 4 mm level in the horizontal and 8 mm in height. The periodic variations of the position solutions about the mean are correlated

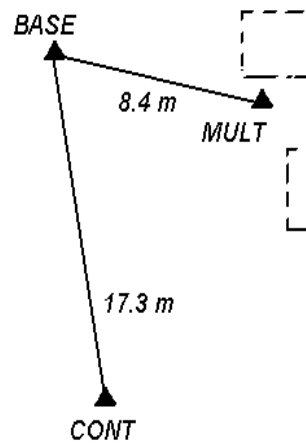


Figure 5. CSSL Test Set-up showing baselines.



Figure 6. Station MULT showing precise translation stage and presence of heating/cooling units.

between the two days and are, as a result, mainly due to multipath. The fact that the standard deviations of the position estimates for both days are within 0.2 mm indicates that no significant deformation has occurred over the two days, unless the deformation has a period of 24 hours.

The Day 2 data was then corrected using the multipath mitigation technique using the two days' worth of data. Station coordinates for Day 1 were assumed static and

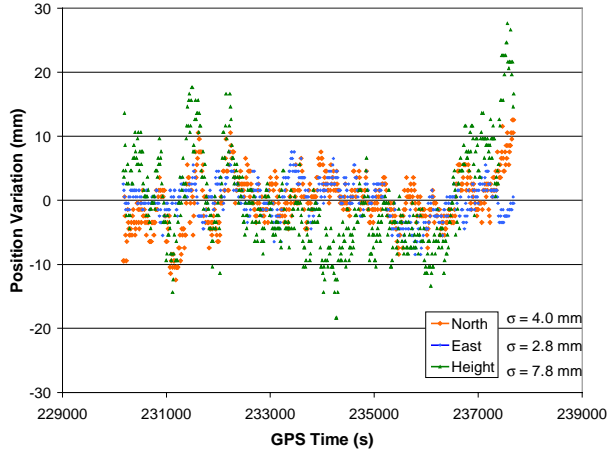


Figure 7. Position Variation for MULT – Day 1

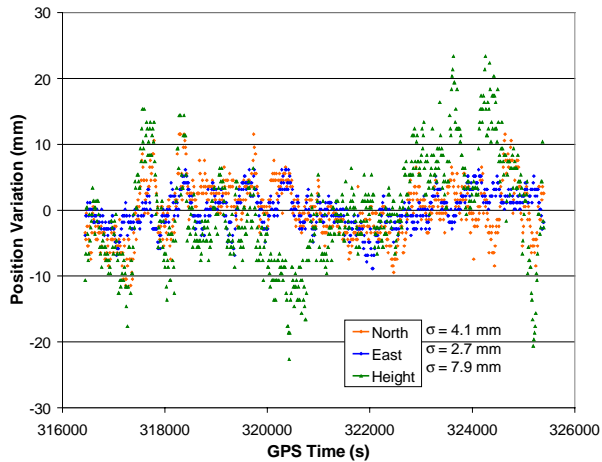


Figure 8. Position Variation for MULT – Day 2.

obtained from a full-day GPS survey of the station points. Processing 6000 epochs on a Pentium III 450 MHz desktop required an average of 25 seconds. The corrected data was then used to calculate epoch-by-epoch coordinates of the MULT point on Day 2. The resulting position trace is shown in figure 9. As can be seen, the position errors are reduced by 34 % in the horizontal and 47 % in the vertical. In addition, most of the periodic signal in the variations has been removed. This is important since it means that the position variations are now more like white noise and can be more easily smoothed.

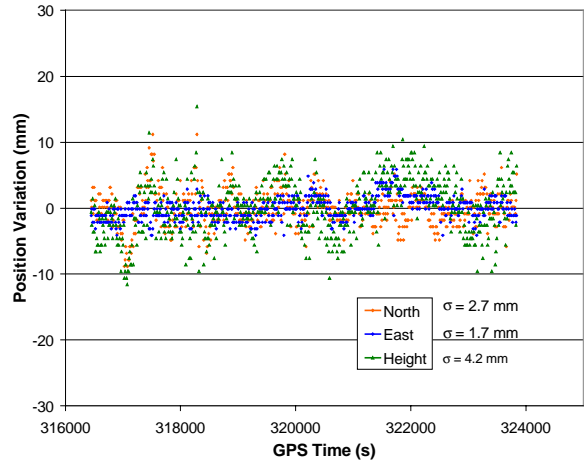


Figure 9. Position Variations for MULT – Cleaned.

Table 1 shows the standard deviations of the position variations for Day 1 and Day 2 for the MULT and CONT points, as well as for the cleaned data. Finally, the standard deviation of the position variations when averaged over 30 seconds for the MULT station cases are also included.

From Table 1, it is clear that on short, static baselines, the multipath reduction system can improve epoch-by-epoch position accuracies from 25% to 40%. The improvement in accuracy mainly depends on the magnitude of the

Table 1. Standard Deviations of Position Variations for Static Experiment

Stn	MULT					CONT		
	Day 1	Day 2	Cleaned	Day 1 Av.	Clean Av.	Day 1	Day 2	Cleaned
<b>N (mm)</b>	4.0	4.1	2.7	<b>3.9</b>	<b>2.1</b>	3.2	3.1	2.4
<b>E (mm)</b>	2.8	2.7	1.7	<b>2.6</b>	<b>1.4</b>	1.9	2.2	1.3
<b>H (mm)</b>	7.8	7.9	4.2	<b>7.5</b>	<b>3.3</b>	5.0	6.2	3.3

multipath effect in the raw data. For example, the CONT station is in a relatively low multipath area and is equipped with a groundplane. As a result, the data collected at CONT is relatively multipath-free and thus the multipath-reduction system does little to improve accuracy. However, in the case of a high-multipath situation, such as at MULT, removing multipath results in significant accuracy improvement.

The most striking effect of removing multipath using this method can be seen when data is averaged. Since multipath is a low-frequency phenomenon, averaging data over a short interval is ineffectual. This can be seen in the case of MULT, where averaging position estimates over 30 seconds only improves results by about 5%. However, if the data is first corrected and then the position estimates are averaged, the final accuracy improves by about 50%.

**Deformation Test Results**

Since the purpose of this multipath mitigation system is to improve the accuracy of deformation monitoring systems, an important test is to induce known deformations into a point and gauge the improvement realised in detecting the deformations. To do this, the MULT station was precisely moved using a translation stage while the receiver was collecting data on Day 3. Figure 10 shows the raw position solutions with the known deformations superimposed. The standard deviation of the difference between the induced movement (known) and the detected movement is 4.8 mm in the north direction and 3.2 mm in the east direction (1σ). Periodic deviations are readily apparent in the stable periods and are caused by multipath.

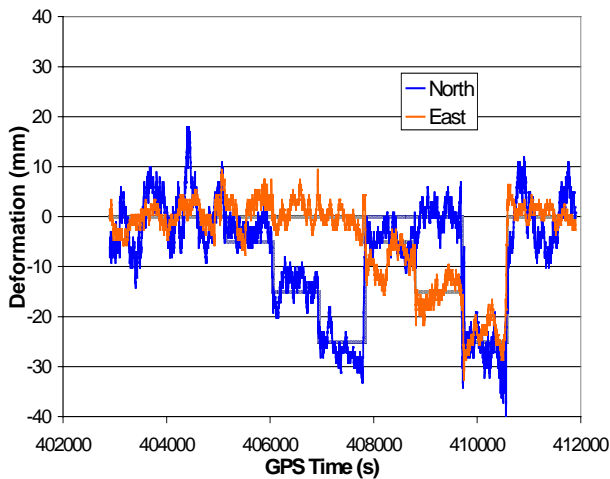


Figure 10. Deformation Detection at MULT Station.

Figure 11 shows the effect of performing the multipath mitigation technique prior to processing the collected data. Static data from Day 2 was used to generate the predicted multipath signal. The accuracy of the deformation detection improves to 3.8 mm in the north

direction and 2.0 mm in the east (1σ). A large source of error was a cycle slip occurring at 406560 seconds, GPS Time. This slip caused position accuracies to degrade until the correct ambiguities were resolved. As before, the noise of the position solutions has been increased (due to noise propagation), but the periodic trends have been removed.

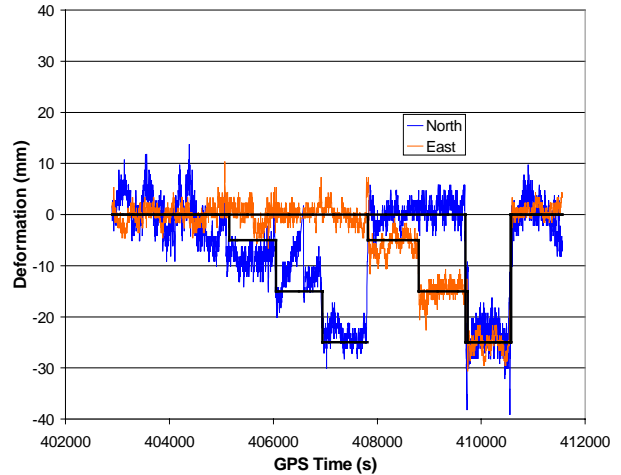


Figure 11. Deformation detection after applying multipath mitigation.

As discussed previously, the strength of the mitigation technique lies in its ability to remove low frequency errors from the data and improve the effectiveness of averaging. Table 2 shows the accuracies achieved in deformation detection for uncorrected and corrected data, for no averaging and using an averaging period of 30s. As can be seen, accuracies below 5 mm in height are possible, indicating the system has the potential to allow extremely precise monitoring of vertical displacements using GPS.

Table 2. Deformation Detection Accuracy (1σ) at MULT

Stn	MULT			
	Day 3	Cleaned	Day 3 Av.	Cleaned Av.
N (mm)	4.8	3.8	4.5	3.2
E (mm)	3.2	2.0	3.1	1.6
H (mm)	8.0	5.6	4.4	3.4

## LIMITATIONS OF THE MITIGATION SYSTEM

The effectiveness of day-to-day differencing in improving deformation detection depends largely on two factors – the strength of the day-to-day correlation of multipath and the accuracy of the reference coordinates used to generate the multipath signature.

The main premise of the mitigation technique is the day-to-day repeatability of multipath at a station. If the multipath does not repeat, then a false correction is applied and positioning accuracies can become worse than if no correction was applied. This can occur for two reasons. Firstly, if the station environment changes, then the location and number of multipath reflectors varies, which results in differing multipath signatures between days. This would typically happen in areas where large machinery moves near the station, or where earthwork and construction is ongoing.

The second reason for multipath decorrelation is receiver motion. If the receiver moves more than a few centimetres per day, the receiver-reflector geometry may change sufficiently for multipath to decorrelate. However, in typical deformation monitoring scenarios, point motion is expected to be very slow.

A second source of error in the system is the accuracy of the reference coordinates. Since the multipath signature is calculated using the reference coordinates as knowns, any error in these coordinates will cause a direct error in the calculation of multipath at a particular epoch. In particular, if the station moves on Day  $i$  and this motion is not detected, then the multipath error calculate on Day  $i$  will falsely image the motion of the point. This error will then propagate into the cleaned data for Day  $(i+1)$ .

Propagating positional errors are a particular concern if long deformation monitoring campaigns are processed. For a given Day  $i$ , the main error sources are noise and multipath assuming short baseline lengths. As a result, the uncorrected position accuracy can be written as :

$$\sigma_i^2 = \sigma_{mi}^2 + \sigma_{ni}^2 \quad \text{Eq.5}$$

where  $\sigma_{mi}$  is the standard deviation of the multipath error and  $\sigma_{ni}$  is the standard deviation of the noise mapped into the position domain. If we assume that errorless coordinates on Day $(i-1)$  are available, then the multipath signature on Day $(i-1)$  can be determined to within the level of noise, or :

$$\sigma_{m(i-1)}^2 = \sigma_{n(i-1)}^2 \quad \text{Eq. 6}$$

Also, assuming that multipath is perfectly correlated between two days, the corrected positioning accuracy of Day  $i$  becomes :

$$\sigma_i^2 = \sigma_{ni}^2 + \sigma_{n(i-1)}^2 \quad \text{Eq. 7}$$

since the multipath is removed from the measurements to the accuracy of  $\sigma_{m(i-1)}$ , or effectively  $\sigma_{n(i-1)}$ .

The corrected Day  $i$  position estimates are then used to calculate the multipath profile on Day  $i$ , which in turn is used to correct data on Day $(i+1)$ . The corrected Day $(i+1)$  position accuracy then becomes :

$$\sigma_{(i+1)}^2 = \sigma_{n(i+1)}^2 + \sigma_{ni}^2 + \sigma_{n(i-1)}^2 \quad \text{Eq. 8}$$

Thus, the system noise accumulates until the positional accuracies of the corrected data become *worse* than those of the uncorrected data. This is a classical example of a positive feedback system.

However, it must be realised that the corrected positional accuracy is dominated by noise (instead of multipath), which is easily averaged out. Since monitoring points are slowly moving, long averaging times (~10 minutes) can be used on the reference position estimates. The Day $(i+1)$  corrected accuracy then becomes :

$$\sigma_{(i+1)}^2 = \sigma_{n(i+1)}^2 + \overline{\sigma_i^2} \quad \text{Eq. 9}$$

where the overbar indicates an averaged quantity. This means that as long as the averaged positional accuracies of the reference coordinates are smaller than the multipath errors, the system aids in deformation detection.

A final limitation of the mitigation system lies in the fact that it must be applied to *all* receivers. For example, the system will not work if only applied to the reference station. Referring to equation 4, day-to-day differencing creates new combined receiver and satellite clock offsets. However, since satellite clock offsets are common to measurements made at all receivers, the day-to-day differenced satellite clock offsets will be common to all receivers. This further means that it will be eliminated in subsequent between-receiver differences only if both receivers have been differenced between-days.

## FUTURE WORK

Further work to be completed will focus on the long-term performance of the system. As discussed, the performance of the system may deteriorate over time due to the amplification of noise in the system. A simple test to perform will be to obtain static data for a series of days and process them sequentially using the multipath

mitigation technique discussed herein. One can then analyse the degradation in accuracy of the positions (which should be constant) over the test period.

However, one limitation to be overcome is that it is difficult to assess the stability of existing monumentation at the millimetre level. Thus one cannot be certain if a reported movement at the millimetre level is merely noise (and thus true error), or if the monument actually occurs. This can occur due to variations in solar heating over the course of a day, for example.

Fortunately, using a precision theodolite can provide an independent assessment of the accuracy of GPS positions obtained using this method on short baselines. In particular, it is possible to automatically perform measurements to targeted points at regular intervals by using a robotic theodolite with automatic targeting. Initial testing of the theodolite shows that accuracies at the sub-millimetre level are possible using special prism reflectors. The baseline length computed from GPS-derived positions can then be compared to those obtained from the theodolite data.

Finally, an exciting feature of the mitigation system developed is the fact that the remaining errors affecting the carrier phase observations are only slightly correlated in time. Several authors including Wang, 1998 and Han and Rizos, 1995 have noted that neglecting the temporal correlations of GPS carrier phases in the observation variance-covariance matrix input into a least-squares adjustment can cause the resulting a posteriori-variance factor to be optimistic by an order of magnitude. This has serious consequences in the analysis of deformations, which typically rely on the confidence regions of observed points to determine if a given movement is significant. Since most commercial GPS-packages do not take into account the temporal correlation of carrier phases, reducing these correlations in the input data via multipath mitigation may be able to improve the accuracy estimates returned by such packages. However, this hypothesis must be verified by further testing.

## CONCLUSIONS

An approach to mitigate multipath by exploiting its day-to-day correlation was presented. The approach is effective only under slowly deforming conditions, since multipath decorrelates spatially. As well, the approach requires that the antenna environment be static, since multipath is purely dependent on the reflectivities of signal reflectors in the environment and their geometries with respect to the satellites and antenna. Fortunately, both these requirements can be met in most deformation monitoring scenarios.

The main strength of the mitigation method presented lies in the fact that, once multipath is removed, the resulting positional errors are predominantly due to noise. This means that time averaging becomes extremely effective, even on short time intervals (~30s).

Under deforming situations, the multipath mitigation technique was able to deliver epoch-to-epoch accuracies at the 5 millimetre level, and better accuracies were achieved by averaging the position estimates over 30 seconds. As well, the performance of the system under deformation seemed only slightly worse than under static conditions, reaffirming the theory that multipath is sufficiently correlated on small distances (< 1cm) for the method to be effective. As a result, the author feels that an effective, low-cost solution to acquiring precise positions with GPS has been developed.

## ACKNOWLEDGEMENTS

The author would like to thank Challenger Surveys and Services Ltd. for providing the research funding and equipment necessary to develop this mitigation technique. As well, Ryan Fox and Scott Crawford are also acknowledged for aiding in the data collection and preliminary analysis of multipath effects on short baselines.

## REFERENCES

- Axelrad, P., C. Comp, and P. MacDoran (1994), Use of Signal-To-Noise Ratio for Multipath Error Correction in GPS Differential Phase Measurements : Methodology and Experimental Results, Proceedings of ION GPS-94, Salt Lake City, September 20-23, pp. 655-666.
- Braasch, M. (1995), Multipath Effects. In Global Positioning System : Theory and Applications, American Institute of Aeronautics and Astronautics, Vol. 1, Ch 14, pp. 547-568.
- Comp, C. and P. Axelrad (1996), An Adaptive SNR-Based Carrier Phase Multipath Mitigation Technique, Proceedings of ION GPS-96, Kansas City, September 17-20, pp. 683-697.
- Han, S. and C. Rizos (1995), Standardization of the Variance-Covariance Matrix for GPS Rapid Static Processing, Geomatics Research Australia, No. 62, June, 1995, pp. 37-54.
- Lachapelle, G., W. Falkenberg, D. Neufeldt, and P. Keilland (1989), Marine DGPS Using Code and Carrier in Multipath Environment, Proceedings of ION GPS-89, Colorado Springs, September 27-29, pp. 343-347.

- Radovanovic, R., W.F. Teskey, R. Fox, and S. Crawford (1999), Development of a Precision GPS Monitoring System : Short Baseline Deformation Detection, Technical Report, Department of Geomatics Engineering, The University of Calgary. 40 pp.
- Raquet, J., and G. Lachapelle (1996), Determination and Reduction of GPS Reference Station Multipath Using Multiple Receivers. Proceedings of ION GPS-96, Kansas City, September 17-20, pp. 673-681.
- Ray, J. K. (1999), Use of Multiple Antennas to Mitigate Carrier Phase Multipath in Reference Stations, Proceedings of ION GPS-99, Nashville, September 14-17.
- Ray, J.K. and M.E. Cannon (1999), Characterization of GPS Carrier Phase Multipath, Proceedings of ION National Technical Meeting, San Diego, January 25-27, pp. 343-252.
- Ray, J.K., M.E. Cannon and P. Fenton (1998), Mitigation of Static Carrier Phase Multipath Effects Using Multiple Closely-Spaced Antennas, Proceedings of ION GPS-98, Nashville, September 15-18, pp. 1025-1034.
- Wang, J. (1998), Stochastic Assessment of the GPS Measurements for Precise Positioning, Proceedings of ION GPS-98, Nashville, September 15-18, pp. 81-89.