Mitigation of Static Carrier Phase Multipath Effects Using Multiple Closely-Spaced Antennas

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BIOGRAPHIES

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ABSTRACT

The effect of carrier phase multipath in static mode is investigated and a system is developed to reduce the effect using multiple closely-spaced antennas. The correlated nature of multipath, along with the known geometry among the antennas, are used with the measured relative carrier phase differences to aid in the extraction of the direct carrier phase from the multipath-corrupted carrier phase measurement.

The mathematical model of the multipath effects on carrier phase measurements and the Kalman filter implemented to estimate these errors are described. The model is first tested on simulated data in which the antenna geometry and reflector parameters were varied. It was then tested on field data collected on a roof whereby the model adaptively estimates the parameters of the composite multipath signal. Initial results demonstrate substantial mitigation of carrier phase multipath signals from multiple sources using this technique under static conditions. The RMS value of the average multipath error on a single differenced carrier phase measurement data is typically reduced by over 70% percent.

This technique estimates the parameters of the composite multipath signal and removes the error due to all multipath signals. It is particularly useful for reference stations which transmit carrier phase data for kinematic positioning applications.

INTRODUCTION

The influence of multipath signals on carrier phase measurements is one of the limitations to achieving high accuracy positions in a wide variety of applications. The problem is especially a concern for GPS reference stations whereby the static environment may induce slowly changing specular effects which do not easily average out.

Significant work has been done to characterize the effects of multipath on a Delay Lock Loop (DLL) in a PRN receiver (e.g. Hagerman, 1973; Breeuwer, 1992; Braasch, 1996) and to reduce these effects using various methods which can be broadly classified as

- Antenna-based mitigation
- Improved receiver technology
- Signal and data processing

Antenna based mitigation involves improving the antenna gain pattern to counter the multipath. A choke ring with a ground plane has been very effective in this regard. By designing an antenna with a very low gain for left hand circularly polarized (LHCP) signals and using an antenna array to have a sharp cutoff below a certain elevation angle, significant improvements can be achieved (Bartone and van Graas, 1998). Moelker (1997) describes various methods to mitigate code multipath by using a Multiple Signal Classification (MUSIC) technique with multiple antennas and an extended Multipath Estimation Delay Lock Loop (MEDLL).

A comprehensive overview of receiver technologies to mitigate multipath is given in van Dierendonck and Braasch (1997). Some of the special techniques are Narrow Correlator Spacing (Fenton et al., 1991; van Dierendonck et al., 1992), the Multipath Elimination Technique (Townsend and Fenton, 1994), MEDLL (van Nee, 1994) and the Strobe Correlator Technique (Garin and Rousseau, 1997).

Multipath mitigation using the signal-to-noise ratio is explored by Axelrad et al. (1994), while Raquet and Lachapelle (1996) investigate the use of multiple reference stations. Carrier phase smoothing is another way to reduce multipath on pseudorange measurements (Hatch, 1982).

The effect of multipath on the carrier phase is characterized by Braasch (1996). Overall, however there is less literature on mitigation strategies (Weill, 1997). One technique, given in Georgiadou et al. (1988), uses L1-L2 measurements to estimate the carrier phase multipath error using the relationship between the frequency of the carrier phase multipath error and the carrier wavelength. Tests showed however, that the performance was not satisfactory due to unmodeled phase center variation and antenna imaging resulting from the attached aluminum box used in the experiment. Another technique called the Enhanced Strobe Correlator, rejects carrier phase multipath, but in a strong and fast-changing multipath environment, it does not completely eliminate the effect (Garin and Rousseau, 1997). These limitations highlight the need for alternative approaches for carrier phase multipath mitigation and thus provides the motivation for this research.

EFFECT OF MULTIPATH ON CARRIER PHASE

A GPS receiver generally receives a number of reflected signals along with the direct signal from the satellite. These reflected signals are called multipath signals and impact the input satellite signal to a GPS receiver. The composite input signal can be expressed as,

$$s(t) = d(t)c(t)A\sum_{i=0}^{n}\alpha_i \cos(2\pi f_L t + \theta_0 + \frac{2\pi d_i}{\lambda}) \qquad (1)$$

where,

$d(t)$	is the navigation data bit
$c(t)$	is the GPS C/A code
A	is the carrier signal amplitude
α_i	are the direct and reflected signal coefficient
f_L	is the GPS carrier frequency (Hz)
d_i	is the signal path delay with respect to direct signal (m)
λ	is the GPS signal wavelength (m) and
θ_0	is the initial phase (rad).

Here, d_i and α_i vary with time. Also for the direct signal (i.e. i=0), $d_0 = 0$ and $\alpha_0 = 1$.

In the receiver, the incoming signal is beat with the local carrier in Inphase and Quadraturephase loops after (or sometimes before) the DLL. Neglecting the effect of the navigation data bits, the discriminator output is,

$$\Psi = \arctan\left(\frac{\sum_{i=0}^{n} R(\tau-\delta_i)\alpha_i \sin\left(\psi+\frac{2\pi d_i}{\lambda}\right)}{\sum_{i=0}^{n} R(\tau-\delta_i)\alpha_i \cos\left(\psi+\frac{2\pi d_i}{\lambda}\right)}\right) \qquad (2)$$

where,

$R(\tau)$	is the correlation function
δ_i	is the multipath signal delay (s)
Ψ	is the measured carrier phase (rad), and
ψ	is the true carrier phase (rad).

In the absence of reflected signals, $\alpha_0 = 1$, $\alpha_1 \ldots. \alpha_n = 0$, and $\delta_0 = 0$, so the equation reduces to $\Psi = \psi$; i.e. the measured phase is same as the true phase. In the presence of reflected signals, the carrier phase measurement error due to multipath is $\Delta\Psi = \Psi - \psi$.

It is possible to assume a virtual reflector with time varying parameters (reflection co-efficient and location) as a representation of all the reflectors in the vicinity of the antenna. The effect of all the reflected signals can then be assumed to be due to this single virtual reflector.

The variability of the reflection parameters of the virtual reflector can be expressed as a function of time which gives the error due to multipath as,

$$\Delta\Psi = \arctan\left(\frac{R(\tau)\sin\psi(t) + R(\tau-\delta(t))\alpha(t)\sin(\psi(t)+\gamma(t))}{R(\tau)\cos\psi(t) + R(\tau+\delta(t))\alpha(t)\cos(\psi(t)+\gamma(t))}\right) - \psi(t)$$

$$= \arctan\left(\frac{R(\tau-\delta(t))\alpha(t)\sin\gamma(t)}{R(\tau) + R(\tau-\delta(t))\alpha(t)\cos\gamma(t)}\right) \qquad (3)$$

where, $\gamma(t)$ is the phase of the composite reflected signal.

By dividing the numerator and denominator of equation (3) by $R(\tau)$ and describing $\alpha(t)R(\tau - \delta(t))/R(\tau)$ as $\alpha_1(t)$, the following form results,

$$\Delta\Psi = \arctan\left(\frac{\alpha_1(t)\sin\gamma(t)}{1+\alpha_1(t)\cos\gamma(t)}\right) \qquad (4)$$

which is the relationship between the carrier phase error due to multipath and the reflected signal strength and phase.

In a situation where multiple antennas are placed nearby, a reflected signal on each of the antennas will be highly correlated. The difference in carrier phase error at two closely-spaced antennas due to multipath is then given by,

$$\Delta\Psi_0 - \Delta\Psi_1 = \arctan\left(\frac{\begin{array}{l}\alpha_1(t)\sin\gamma_0(t) - \alpha_1(t)\sin\gamma_1(t) \\ +\alpha_1^2(t)\sin(\gamma_0(t) - \gamma_1(t))\end{array}}{\begin{array}{l}1 + \alpha_1(t)\cos\gamma_0(t) - \alpha_1(t)\cos\gamma_1(t) \\ +\alpha_1^2(t)\cos(\gamma_0(t) - \gamma_1(t))\end{array}}\right) \quad (5)$$

where the subscripts 0 and 1 refer to Antennas 0 and 1. This model is used to develop the multipath mitigation filter described below since it relates the measurement data and the state parameters to be estimated.

MULTIPATH MITIGATION MODEL

The multipath mitigation algorithm is a software suite which processes raw carrier phase measurement data from an antenna array before the data is used for kinematic position determination. Although this technique can be used to correct phase measurements in real-time, it is implemented in post mission in the sequel.

In the mitigation algorithm, the virtual reflector represents the total sum of all the associated reflectors and is modeled as a single reflector. For this reason it is appropriate to analyze the concept using the single reflector case.

The reflection of a satellite signal can be viewed from a geometrical perspective. For example, if the satellite is far away, the GPS signal can be assumed to arrive as parallel rays at two closely-spaced antennas. A plane wavefront, perpendicular to the line of sight, can be assumed to have the same carrier phase. After reflection from a plane reflector, the parallel incident signals remain parallel and thus phase propagation takes place through the advancement of the plane wavefront. Therefore, the phase of the reflected signal at each antenna phase center in a group of closely-spaced antennas is a function of the reflected signal direction (i.e. azimuth and elevation) as well as the relative geometry of the antennas with respect to each other.

In the following diagram two antennas are placed at Antennas 0 and 1. Each of the antennas receives a direct signal from the satellite and a reflected signal from a nearby plane object. A wavefront perpendicular to the indirect signal at Antenna 0 will have the same phase for all the other parallel reflected rays from the same object. Therefore the phase of the signal at Antenna 1 is given by,

$$\gamma_1 = \gamma_0 + \frac{2\pi}{\lambda}\frac{a_{01}\cos(\varphi_0 - \phi_{01})}{\cos\theta_0} \quad (6)$$

where,

γ_0	is the phase of the signal at Antenna 0
a_{01}	is the distance between 0 and 1
φ_0	is the azimuth of the reflected signal
ϕ_{01}	is the azimuth of the vector 0-1, and
θ_0	is the elevation of the reflected signal.

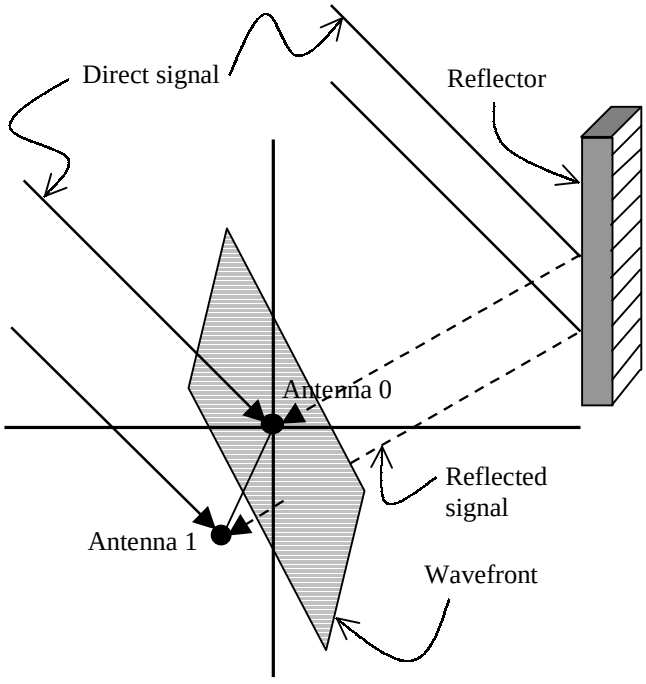

Figure 1: Correlated multipath errors can be related to each other through signal direction and known geometry between the antennas.

If the phase and direction of the reflected signal at Antenna 0 are known, the phase at Antenna 1 can be computed from the known geometry between the two antennas. This relationship is exploited to estimate the reflected signal phase at each of the antennas in the array thereby reducing the number of unknowns in the system.

The parameters of the reflected signal are estimated using an Extended Kalman Filter (Gelb, 1979; Brown and Hwang, 1992; Maybeck, 1994). Multiple antennas are placed close together to ensure correlated multipath signals. Generally at least five antennas would be used and a typical layout would be (for the six antenna case) as shown in Figure 2.

One of the antennas (normally the center one) would be defined as the reference antenna (A0 in this case). All the parameters of the reflected signal and the placement of other antennas are defined with respect to this reference antenna.

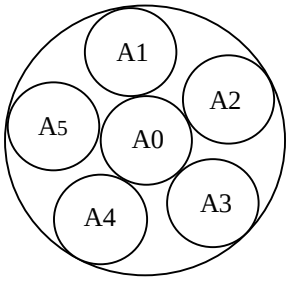

Figure 2: Typical antenna assembly for six antennas.

The state vector for the estimator is,

$$\begin{bmatrix} \alpha \\ \gamma_0 \\ \theta_0 \\ \varphi_0 \end{bmatrix} = \begin{bmatrix} \text{Reflection coefficient} \\ \text{Reflected signal phase at the reference antenna} \\ \text{Reflected signal elevation} \\ \text{Reflected signal azimuth} \end{bmatrix}.$$

The measurement vector for the estimator is

$$\begin{bmatrix} \Delta\Psi_{0,1} \\ : \\ : \\ \Delta\Psi_{0,m-1} \end{bmatrix}$$

where,

m is the number of antennas, and

$\Delta\Psi_{0,1}$ is the difference in phase between Antennas 0 and 1.

The relationship between the state variables and the measurements is given by the following design matrix:

$$H = \begin{bmatrix} \frac{\delta(\Delta\Psi_{0,1})}{\delta\alpha} & \frac{\delta(\Delta\Psi_{0,1})}{\delta\gamma_0} & \frac{\delta(\Delta\Psi_{0,1})}{\delta\theta_0} & \frac{\delta(\Delta\Psi_{0,1})}{\delta\varphi_0} \\ --- & --- & --- & --- \\ --- & --- & --- & --- \\ \frac{\delta(\Delta\Psi_{0,m-1})}{\delta\alpha} & \frac{\delta(\Delta\Psi_{0,m-1})}{\delta\gamma_0} & \frac{\delta(\Delta\Psi_{0,m-1})}{\delta\theta_0} & \frac{\delta(\Delta\Psi_{0,m-1})}{\delta\varphi_0} \end{bmatrix} \quad (7)$$

The above filter is used to estimate the reflection parameter of a virtual reflector affecting the carrier phase measurement of a particular GPS satellite signal. One such filter per satellite is required to correct the carrier phase from each of the satellite signals in the receiver.

After the filter estimates the reflected signal phase at the reference antenna, it is possible to compute the phase at all the other antennas by using the relationship given in equation (6). The reflected signal strength at all the antennas are assumed to be the same and is also estimated. After all the above mentioned parameters are estimated, the carrier phase error due to the composite multipath signal can be computed using equation (5).

By using the above model, it is possible to estimate the carrier phase error due to multipath signals. This method is valid only if the reflected signals are correlated across the antennas, hence the need for closely-spaced antennas on a rigid platform.

TEST DESCRIPTION

A Multipath Simulation and Mitigation software program (MultiSiM) was first developed to study the behavior of simulated multipath signals and their mitigation. The multipath simulation module of MultiSiM allows the simulation of various multipath environments by placing reflectors and antennas at a desired geometry with respect to each other. In the multipath mitigation module of MultiSiM, different experimental multipath-countering models were incorporated to study their effectiveness in estimating the multipath effect. After having successfully demonstrated the mitigation of multipath using the above model on simulated multipath; the same approach was applied to real data as described below.

In order to test the concept, a special antenna array was assembled whereby a thick aluminum plate was used to rigidly mount six antennas close together. Novatel Model 521 antennas were used, as they are small with a diameter of approximately 5.6 cm. The assembly is shown in Figure 3.

Figure 3: Antenna array assembly.

NovAtel BeeLine™ receivers were used for data collection (Ford et al., 1997). The BeeLine™ is an 8+8 channel (L1-L1) receiver generally used for the attitude determination. Three BeeLines™ were used together with six antennas where all receivers were driven by an external rubidium oscillator. Data was collected for

several sessions spread over successive days on the roof of the Engineering building at the University of Calgary.

The antenna assembly was placed on a surveyed pillar where there are concrete sidewalls of approximately 3 m in height on the east side and 1 meter in height on the south side (Figure 4). It is expected that these walls, along with the aluminum plate, would cause the most significant multipath signals.

Figure 4: Test environment

By using Semikin™, a software package developed at the University of Calgary (Cannon, 1993), the position of each of the antennas in the array was determined and their relative geometry established.

The modified carrier phase of single differences between antennas are used as measurements in the estimator. The single difference removes most of the errors except receiver clock bias, multipath and carrier phase noise. For example,

$$\Delta\Psi_{0,i} = \Delta\rho_{0,i} + \Delta N_{0,i}\lambda + c\Delta t_{0,i} + \varepsilon_{\varphi 0,i} + \varepsilon_{MP0,i} \qquad (8)$$

where,

- $\Delta\Psi$ is the measured carrier phase single difference between antennas 0 and i (m)
- $\Delta\rho$ is the range difference due to spatial separation between antennas
- $c\Delta t$ is the receiver clock bias difference
- ΔN is the integer ambiguity difference
- ε_{φ} is the carrier phase noise difference, and
- ε_{MP} is the carrier phase multipath error difference.

In the present case, since the receivers are driven by a single external stable clock, the receiver clock bias difference is negligible. In addition, since the phase difference due to the spatial separation of the antennas is known, the range difference then can be eliminated from equation (8) to give,

$$\Delta\Psi'_{0,i} = \Delta N_{0,i}\lambda + \varepsilon_{\varphi 0,i} + \varepsilon_{MP0,i} \qquad (9)$$

As the multipath induced error is less than a quarter of a cycle, the phase difference due to the relative integer ambiguity can be removed and the residual phase error can be obtained. This residual phase is due to the receiver carrier phase noise and the multipath between the receivers.

The single differenced residual carrier phase error for a particular satellite is input to the multipath mitigating software to adaptively estimate the parameters of the composite multipath signal due to all reflectors affecting the carrier phase. After the parameters are estimated by the filter, it is possible to determine the multipath error in the carrier phase at each of the antennas by using equations (5) and (6). The estimated multipath error at each antenna can be differenced and then subtracted from the single differenced phase residual (which was input) to observe a multipath-reduced phase measurement. The signature of the residual phase difference with the multipath error correction (which should be white due to receiver phase noise) can be analyzed to assess the performance of the technique.

TEST RESULTS

The single differenced residual described in the previous section contains the carrier phase noise and multipath error. Carrier phase noise is random in nature, while the multipath error is oscillatory where the amplitude depends upon the material and surface structure of the reflector as well as the distance between the reflector and antenna. The frequency of the multipath error is a function of the carrier cycle wavelength and the antenna reflector geometry (Georgiadou and Kleusberg, 1988).

In order to demonstrate the multipath mitigation technique, the single differenced residual phase was computed for satellite 21 from data collected on August 25, 1998 and is shown in Figure 5. Each plot has a distinct trend, which is different for each antenna. Some oscillatory errors of varying amplitude are also evident. Data collected on the subsequent two days (at 4 minutes earlier than the previous day) also show a similar trend and oscillation pattern. The residual phase for the same satellite from the data collected on August 26 is shown in Figure 6.

The day-to-day repeatability of the residual errors indicates that it is due to multipath. An average correlation of 85% was observed between data collected on August 25 and 26.

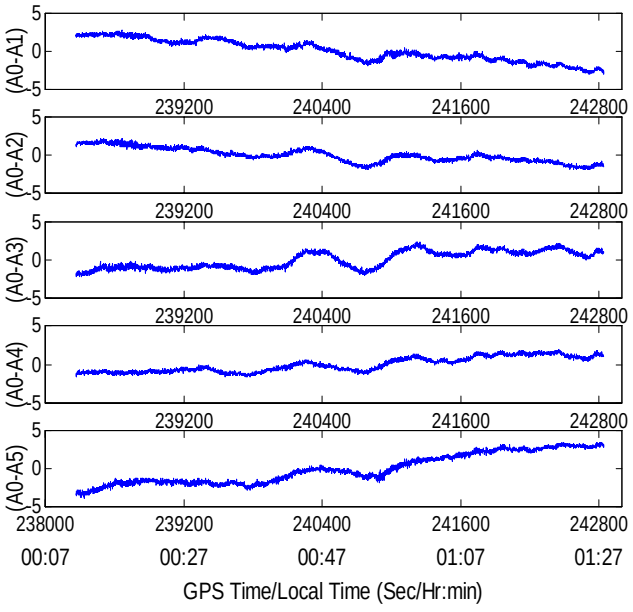

Figure 5: Single difference residual carrier phase error before applying multipath correction for SV 21 on August 25, 1998 (Y-axis units in cm; A0-A*n* denotes single difference between antennas 0 and *n*).

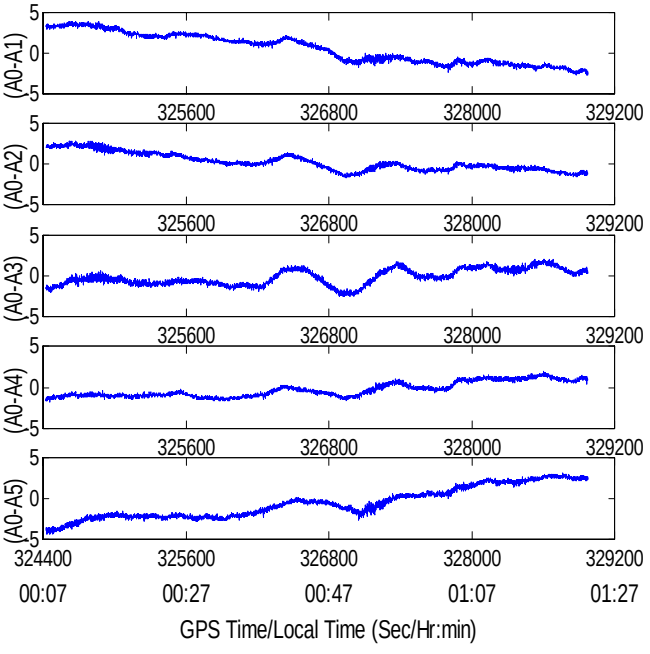

Figure 6: Single difference residual carrier phase error before applying multipath correction for SV 21 on August 26 for the same time of day (shifted by 4 minutes) as in Figure 5 (Y-axis in cm; A0-A*n* denotes single difference between antennas 0 and *n*).

The multipath error consists of two distinct components in this case, i.e. the slow trend is due to multipath from a nearby strong reflector while the smaller oscillatory errors (or higher frequency multipath) are due to weaker reflectors from objects further away. The non-uniformity of the oscillatory pattern suggests multiple reflectors in the vicinity of the antenna assembly. All other satellites show similar trends and oscillatory patterns, which repeat day-to-day.

In Figures 5 and 6 it can also be observed that the higher frequency multipath error is correlated among the antennas. In contrast, the lower frequency multipath has a different trend for different antennas. This is because the lower frequency multipath changes its phase very slowly and has a different phase at each antenna depending upon the antenna reflector geometry. Since trends of a similar nature were found in other satellites as well, they are most likely due to the aluminum plate on which the antennas are mounted. Such a high correlation of multipath across antennas is due to the close antenna spacing in the assembly and is critical to the estimation of composite reflected signal parameters using the algorithms described in the previous sections.

The multipath-corrupted carrier phase measurement residuals are used as input to the mitigating filter. Figure 7 shows the parameters of the composite reflected signal estimated by the filter for SV 21 on August 25. The parameters of the virtual reflector vary with time to track the effect of the composite multipath error.

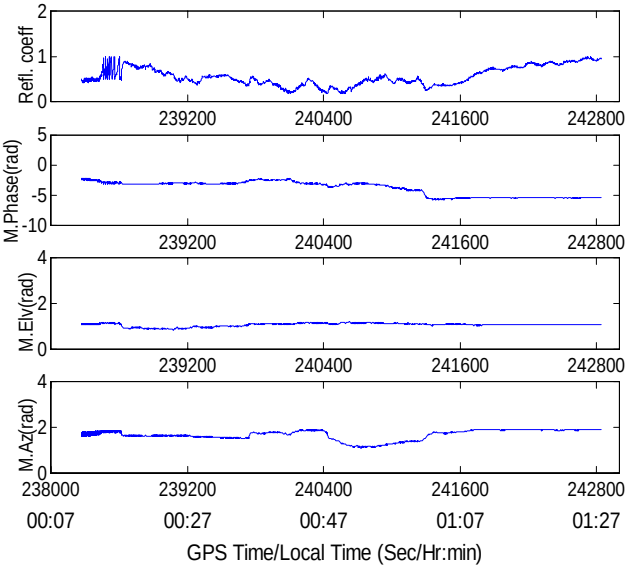

Figure 7: Estimated composite reflected signal parameters for SV 21 on August 25

Figure 8 shows the estimated multipath error at each antenna computed from the estimated parameters of the composite reflected signal. The estimated multipath shows a trend and oscillations corresponding to low and high frequency multipath, respectively, and this demonstrates the capability of the system to estimate a composite reflection effect, rather than a single reflector.

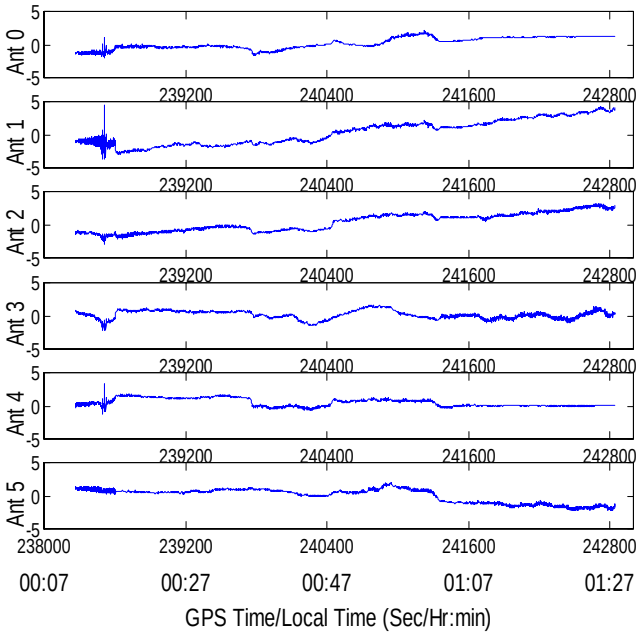

Figure 8: Estimated carrier phase multipath error for SV 21 on August 25 for each antenna (Y-axis in cm).

The carrier phase measurement from each antenna can be corrected by the estimated multipath error at that antenna. Figure 9 shows the single differenced residual with the corrected measurement data. It is clear from the figure that the residuals are more random in nature and that phase error due to multipath is nearly eliminated.

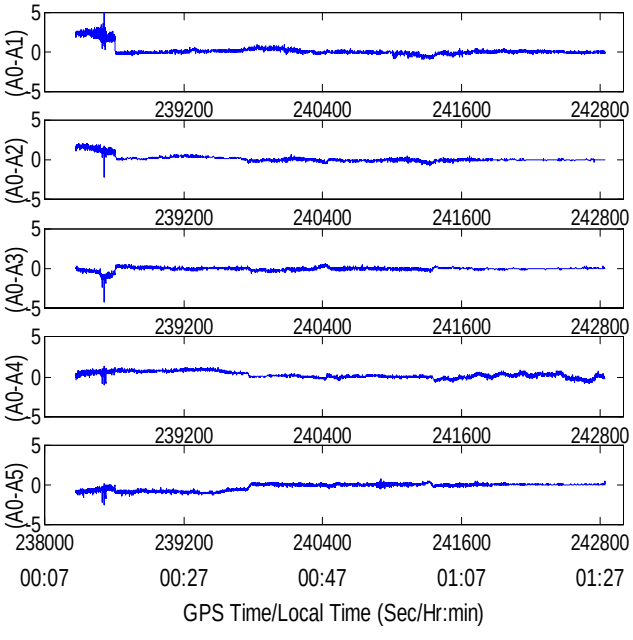

Figure 9: Single difference residual carrier phase error after removing estimated carrier phase multipath for SV 21 on August 25 (Y-axis in cm; A0-A*n* denotes single difference between antennas 0 and *n*).

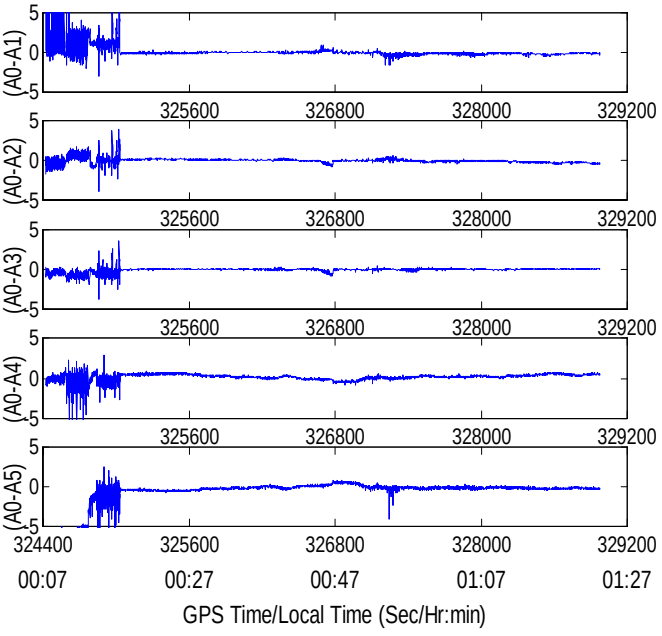

Figure 10: Single difference residual carrier phase error after removing estimated carrier phase multipath for SV 21 on August 26 (Y-axis in cm; A0-A*n* denotes single difference between antennas 0 and *n*).

Figure 10 shows the multipath corrected measurement data for the same satellite on August 26. As in the previous case, the multipath correction is nearly eliminated except during the filter convergence period.

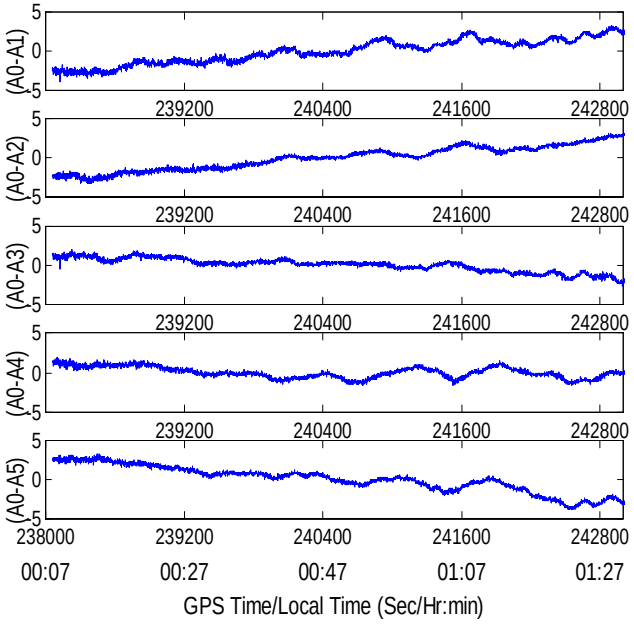

Figure 11: Single differenced residual carrier phase error before applying multipath correction for SV 31 on August 25 (Y-axis in cm; A0-A*n* denotes single difference between antennas 0 and *n*).

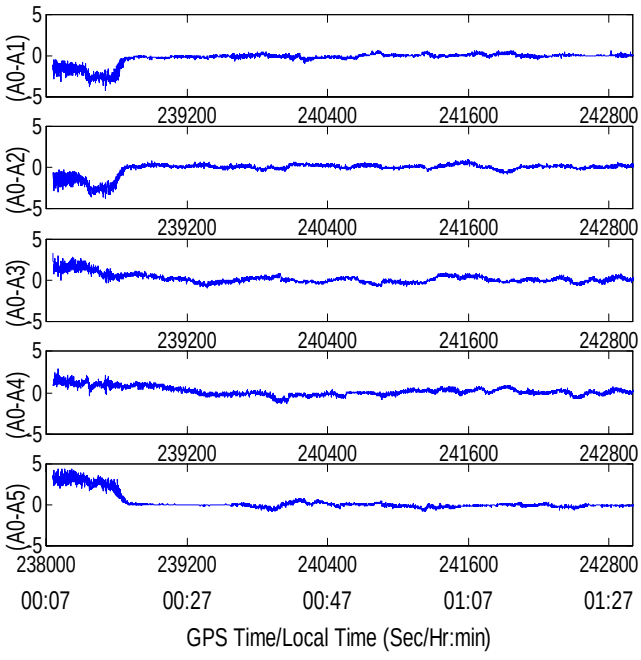

Figure 12: Single differenced residual carrier phase error after removing carrier phase multipath for SV 31 on August 25 (Y-axis in cm; ; A0-A*n* denotes single difference between antennas 0 and *n*).

Figures 11 and 12 show the single differenced residual before and after applying the multipath mitigation technique for satellite 31 on August 25. These results are in agreement with SV 21.

This method was applied to other satellites available during the data collection period and the improvement of residuals is observed in all cases. Table 1 gives an overview of statistics before and after multipath mitigation. These statistics were compiled from approximately 4000 samples excluding the convergence period and were averaged over all the antennas.

The RMS values of the multipath-corrected measured phase differences are significantly lower than the values before correction. On average, there was a 73% improvement, which clearly demonstrates the effectiveness of this method to mitigate carrier phase multipath in this environment.

CONCLUSIONS AND FUTURE WORK

The effect of multipath on GPS carrier phase measurement data is investigated using field data. Tests were carried out on the roof of the Engineering building at the University of Calgary. Six closely-spaced antennas and three Novatel BeeLine™ receivers were used for the experiment and the carrier phase multipath signature was found to be highly correlated across the antennas.

A method to estimate the total effect of multipath from all sources on GPS carrier phase data was developed and consists of a filter which estimates the reflection coefficient, multipath signal phase and direction using the single difference phase measurements between antennas as input. Initial results show that the proposed technique is capable of estimating the composite multipath effect on the carrier phase, which can be easily removed from the measurement. On average, 73% of the carrier phase multipath was removed.

The technique shows promise to effectively remove static multipath. In particular, it has application to reference stations which transmit carrier phase data for kinematic positioning applications.

Further investigations with a better ground plane and in different multipath environments are needed to further assess the performance of the system. The estimator also needs to be further tuned for superior performance. The applicability of the system to real time application will also be analyzed to exploit the potential of this system.

Table 1: Carrier phase error before and after applying the multipath mitigation technique.

SV ID	August 25					August 26					Correlation coefficient before correction
	Before correction		After Correction		Improve-ment	Before correction		After correction		Improve-ment	
	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)	%	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)	%	
17	0.14	1.77	0.00	0.40	77.4	0.08	1.68	0.01	0.37	78.0	0.84
21	0.01	1.26	0.02	0.30	76.2	-0.08	1.28	-0.01	0.23	82.0	0.94
23	-0.19	1.70	0.26	0.59	65.3	-0.17	1.67	0.26	0.67	60.0	0.83
31	0.02	1.30	0.04	0.28	78.5	0.00	1.26	0.03	0.46	63.5	0.78

ACKNOWLEDGMENTS

Thanks to Waldemar Kunysz of NovAtel Inc. for technical support and logistics. One of the first authors (J.K.R) thanks Nesbitt Burns Inc. and Canadian Natural Resources Limited for their financial support during his graduate program.

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