Performance Evaluation of the Multipath Estimating Delay Lock Loop

Bryan R. Townsend[1], D. J. Richard van Nee[2],

Patrick C. Fenton', and Keith J. Van Dierendonck[1]

[1]NovAtel Communications Ltd., 6732 8 Street N.E.
Calgary, Alberta, Canada, T2E 8M4

[2]Faculty of Electrical Engineering, TU Delft, Mekelweg 4,
P.O. Box 5031, 2600 GA Delft, The Netherlands

BIOGRAPHY

Bryan Townsend received his M.Sc. in Surveying Engineering from the University of Calgary in 1993. His master's research was in the area of GPS and Loran-C. He is currently doing research in the area of GPS multipath error reduction at NovAtel Communications Ltd.

Richard D.J. van Nee was born in Schoonoord, the Netherlands. He received an M.Sc. in Electrical Engineering Cum Laude from Twente University in Enschede. the Netherlands in 1990. In May 1994, he will defend his Ph.D. thesis on multipath problems in navigation and communication receivers at Delft Univcrsiry. Since January 1995, van Nee has been working as a consultant to NovAtel Communications Ltd.

Pat Fenton received his B.Sc. in Surveying Engineering from the University of Calgary in 1981. He is currently the Principle Engineer of the GPS Products Group at NovAtel Communications Ltd. Pat specializes in software development and ASIC design.

Keith Van Dierendonck received his B.A. in Mathematics at the University of California, Santa Cruz and is completing his M.Sc. in Geomatics Engineering at the University of Calgary. He is currently Software Test Engineer for the GPS Products Group at NovAtel Communications Ltd.

ABSTRACT

In many differential GPS applications, the positioning errors are mainly caused by multipath propagation. While the C/A-code noise errors are in the order of a decimetre when using Narrow Correlator™ spacing, the errors caused by multipath can be at the metre level.

In a previous paper, the authors demonstrated that it is possible to greatly reduce multipath errors by using a new receiver concept, the Multipath Estimating Delay Lock Loop (MEDLL). The MEDLL estimates both line-of-sight and multipath parameters, thereby reducing the influence of the multipath signals on the code and carrier estimates of the line-of-sight signal.

The basic one-channel MEDLL prototype receiver has been expanded to a multi-channel receiver, which makes it possible to evaluate the performance improvement of pseudorange observables by using double differencing or other techniques that isolate multipath errors. Measurements are performed in various environments in order to compare the MEDLL code and carrier performance as compared to a standard receiver using Narrow Correlator™ spacing.

The improved performance of the MEDLL can be of great help in critical DGPS applications, where the multipath errors associated with using conventional receivers can easily exceed the accuracy requirements.

INTRODUCTION

GPS pseudorange and carrier phase measurements suffer from a variety of systematic biases. The sources of these are:

(i) Satellite Orbit Prediction
(ii) Satellite Clock Drift
(iii) Ionospheric Delay
(iv) Tropospheric Delay
(v) Receiver Clock Offset
(vi) Signal Multipath

The satellite orbit, satellite timing, ionospheric, and uopospheric errors can be removed by differencing techniques or significantly reduced by modeling. The receiver clock offset can also be removed by differencing but is often solved for as an unknown in the position solution.

The measurement bias caused by signal multipath acts differently. Unlike the other error sources, multipath is normally uncorrelated between antenna locations. Hence, the base and remote receivers experience different multipath interference and as a result differencing between them will not cancel the errors. Also, modeling mutlipath for each antenna location is difficult and impractical.

In the presence of multipath. most GPS positioning methods suffer a degradation in accuracy and an increase in processing time. Pseudorange multipath at a real-time differential GPS monitor station will result in errors creeping into the differential corrections causing large position biases for DGPS users.

The most common methods of reducing multipath are by improved antenna design (e.g. choke ring ground planes) and careful site selection. Unfortunately, it is often not possible to change either of these parameters. For example an antenna mounted on an airplane fuselage will not be easily moved or replaced. Therefore the method of reducing multipath that would be most transparent to the user is to remove it at the signal level within the GPS receiver itself.

In previous papers, the authors demonstrated that it is possible to greatly reduce multipath errors by using a new receiver concept, the Multipath Estimating Delay Lock Loop or MEDLL (pronounced 'meddle') [van Nee et. al., 1993 and 1994]. The MEDLL estimates both line-of-sight and multipath parameters, thereby reducing the influence of the multipath signals on the code and carrier estimates of the line-of-sight signal, This paper will investigate the performance of MEDLL in reducing code multipath errors,

MULTIPATH CHARACTERISTICS

The term multipath is derived from the fact that a signal transmitted from a GPS satellite can follow a 'multiple' number of propagation 'paths' to the receiving antenna. This is possible because the signal can be reflected back to the antenna off surrounding objects, including the earth's surface. Figure 1 illustrates this phenomena for one reflected signal.

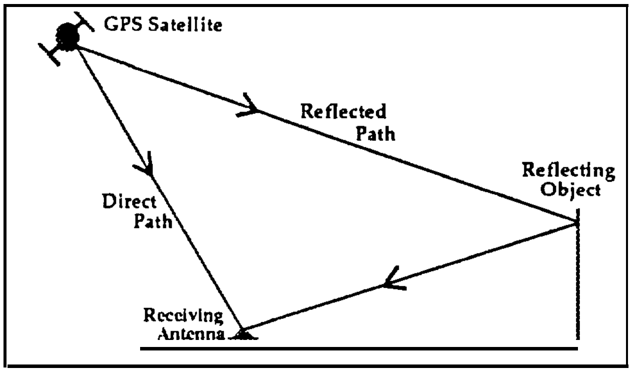

Figure 1: Direct Path and Multipath (Reflected Path) Signals

Some important characteristics of multipath are as follows [Townsend and Fenton, 1994]:

i) The multipath signal will always arrive after the direct path signal because it must travel a longer propagation path.

ii) The multipath signal will normally be weaker than the direct path signal since some signal power will be lost from the reflection. It can be stronger if the direct path signal is hindered in some way.

iii) If the delay of the multipath is less than two PRN code chip lengths, the internally generated receiver signal will partially correlate with it. If the delay is greater than 2 chips the correlation power will be negligible.

For this paper it is assumed the direct path signal is present and is stronger than the multipath signals.

THE EFFECT OF MULTIPATH ON EARLY-LATE DLL

Since GPS is a ranging system it is desirable to perform measurements on the direct path signal. The presence of multipath signals corrupts this process because the receiver tries to correlate with both signals. Figure 2 shows the plots of the correlation functions for a direct path signal, multipath signal, and the resulting composite signal.

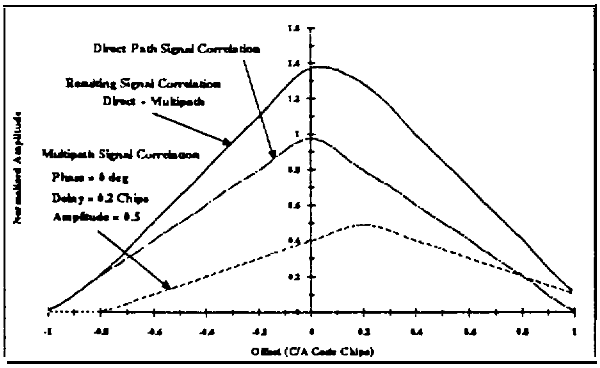

Figure 2: Direct Path, Multipath (In Phase) and Resulting Correlation Functions

In this case the multipath signal has a delay of 0.2 chips, an amplitude of 0.5 relative to the direct path signal and is in phase with the direct path signal. These curves were calculated assuming a pre-correlation bandwidth (BW) of 8 MHz and a 'brickwall' filter. An 8 MHz bandwidth is similar to that used in the GPSCard™ [Fenton et al, 1991]. Figure 3 shows the resulting correlation function when the same multipath signal is 180 degrees out-of-phase with the direct path and therefore has a negative correlation.

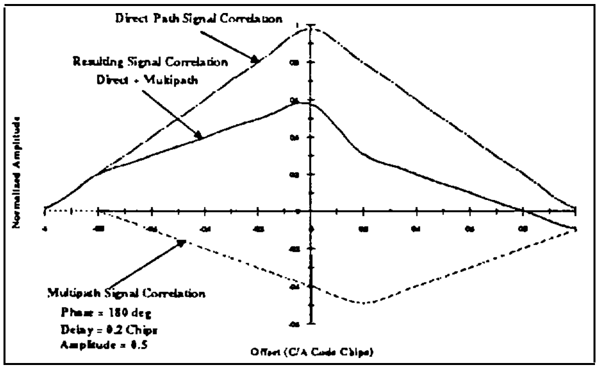

Figure 3: Direct Path, Multipath (Out of Phase) and Resulting Correlation Functions

It is important to note that in both the cases shown in Figures 2 and 3 the resulting correlation function is skewed and non-symmetric.

The effect multipath has on a normal dot-product or early minus late delay-lock-loop (DLL) is illustrated in Figure 4. Since a normal DLL is designed to feedback to the hardware in such a way to keep the power at the early and late correllators equal, a distorted correlation function will bias this process.

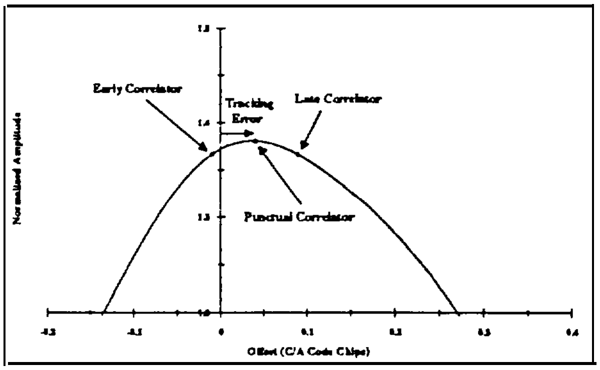

Figure 4: Early-Late DLL Tracking Error Due to Multipath

As shown earlier the correlation function is really the composite of one or more correlation functions. This being the case, it should be possible to measure the correlation function and deconvolve it into its direct path and multipath components. One such method for doing this is described in the following section.

MULTIPATH ESTIMATING DELAY LOCK LOOP (MEDLL)

In the presence of multipath propagation, the received signal at the input of a direct-sequence spread-spectrum receiver can be written as:

$$r(t)=\sum_{m=0}^{M-1} a_m p(t-\tau_m)\cos(\omega t+\theta_m)+n(t) \tag{1}$$

where,

M = number of signals.
t = time.
$p(t)$ = the spread-spectrum code
$n(t)$ = white Gaussian noise.
a_m = component signal amplitude.
τ_m = component signal delay.
θ_m = component signal phase.

For a positioning system like GPS, the parameters of interest are the direct path signal delay and phase. In order to estimate these parameters, the direct path correlation function needs to be determined. The MEDLL approach used here involves the deconvolution of correlation function into its direct and multipath components.

The MEDLL estimates the amplitude, delay, and phase of each multipath component using maximum likelihood criteria. Each estimated multipath correlation function component is in turn subtracted from the measured correlation function. Once this process is complete estimate of the direct path correlation function is left Finally, a standard early-late DLL is applied to the direct path component and an optimal estimate of the code loop tracking error is obtained.

MEDLL - THEORETICAL PERFORMANCE

In theory there can be an infinite number of multipath signals present at any given time. In practice there is rarely more than one or two dominant multipath signals present at one time. Therefore in normal operation the MEDLL configured to solve for three signals -- the direct path plus up to two multipath signals.

To investigate the performance of MEDLL in the presence of a strong multipath a simulation experiment was performed. The 8 MHz band-limited correlation function from Figures 2 and 3 was used to estimate the multipath error envelopes for a standard E-L DLL with both narrow and wide correlator spacing similar to one used in NovAtel's GPSCard™, along with the MEDLL and a P-code receiver [Van Dierendonck et. al., 1993]. The error envelopes were calculated by taking the DLL equations and solving for the tracking error as 0.5 amplitude multipath signal is varied in delay from 0 to 1.5 chips. The error is calculated at the maximum points when the multipath signal is at 0” in phase or 180” out of phase with respect to the direct path signal. The results are shown in Figure 5.

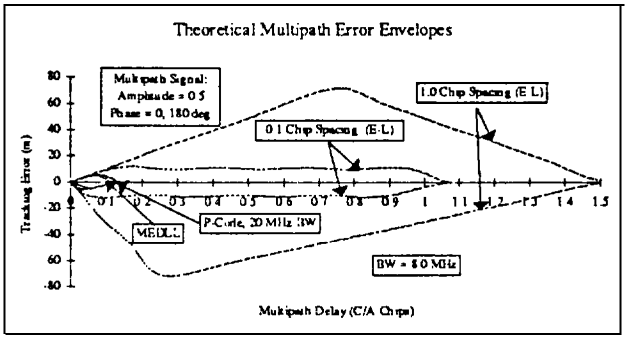

Figure 5: Multipath Error Envelopes For Wide Correlator Spacing (1 chip) and Narrow Correlator Spacing (0.1 chip) Early-Late DLL's, and the MEDLL

Figure 5 shows a plot of the multipath error envelopes. It shows that the MEDLL has as good as or better multipath rejection then the P-code DLL and significantly better than standard GPSCard receivers. It virtually eliminates any multipath biases for delays greater than 0.1 chips.

MEDLL - RECEIVER ARCHITECTURE AND DESIGN

The MEDLL algorithms require that the complete correlation function be measured in order to detect distortions caused by multipath. This is achieved by multiple correlator sampling of the correlation function as shown Figure 6.

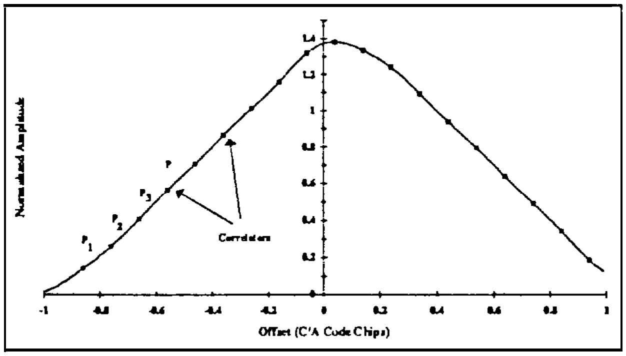

Figure 6: Multiple Correlator Sampling of the Correlation Function

A traditional GPS receiver dedicates only two, possibly three, correlators to each satellite tracking channel. The MEDLL algorithms require 10 or more. Theoretically, the MEDLL only requires three correlators per direct path or multipath signal. In reality more correlators are required in order to obtain the initial estimates of each signal.

The extra correlators require that more hardware be used. This was achieved at NovAtel by grouping some of the standard GPSCards into a multi-card system. The cards are linked to the same RF deck and OCXO to minimizes cross channel biases. The OCXO also gives better clock stability then the TCXO used on the standard GPSCard. The interfaces to the MEDLL receiver is tailored after the GPSCard 3951R receiver presently sold by NovAtel. Figure 7 show a block diagram of the MEDLL receiver design.

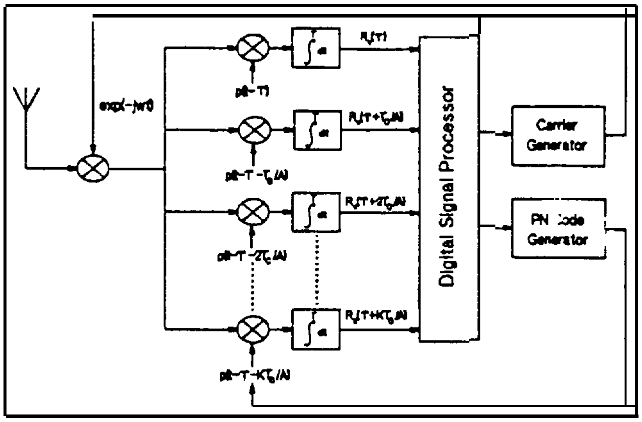

Figure 7: MEDLL Block Diagram, K-l is the Number of Correlators, T_c/A is the Delay Spacing.

SHORT BASE LINE TEST RESULTS

As a first test, an experiment system was set up as shown in Figure 10. The monitor and remote antennas, named A and B respectively, were located on the roof of the NovAtel building in Calgary. Antenna A located in the centre of the roof and is expected to be experiencing a low multipath environment. Antenna B is located at the edge of the roof and is expected to experience strong ground mutlipath. Neither antenna had a chokering ground plane.

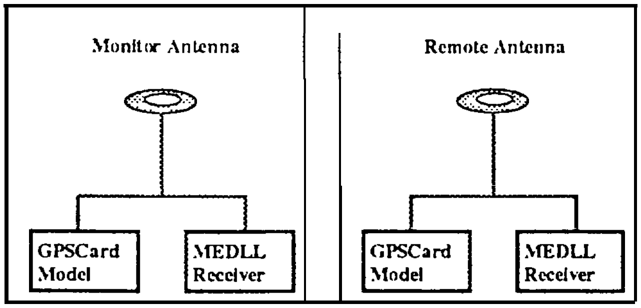

Figure 8: Equipment Setup

The signal from each antenna was split so that it could be connected to one Model 3951R GPSCard™ (Narrow Correlator™ receiver) and one MEDLL™ as shown in Figure 8. With this set up both types of receivers are receiving the same signals and direct comparison can be made.

Data was collected at 1 Hz and double difference residuals (DDR's) where calculated using the pair of 3951R receivers. DDR's where also computed for the pair of MEDLL receivers. Since the baseline between antenna A and B was known it could removed from the DDR's. The resulting DDR's **only contained** measurement noise and the combined multipath bias for the four pseudoranges used to calculate them. Figures 9 and 10 show DDR plots from the 3951R and MEDLL receivers respectively.

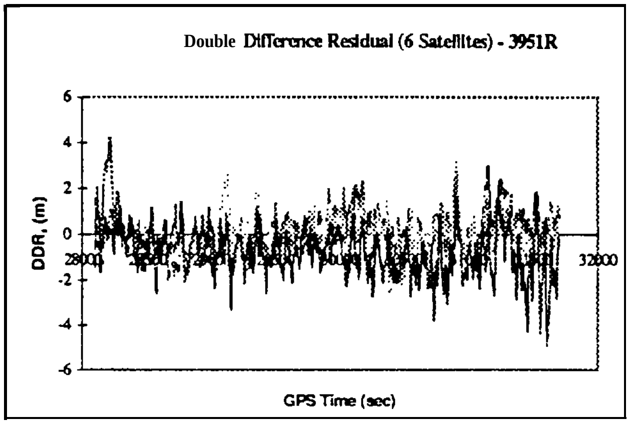

Figure 9: Double Difference Residuals -- Model 3951R GPSCards

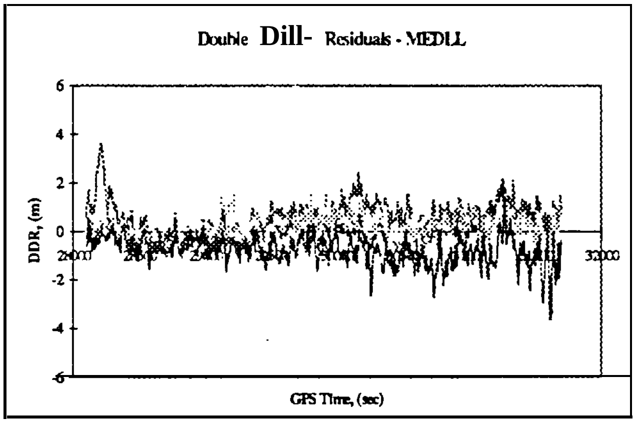

Figure 10: Double Difference Residuals -- MEDLL

Table 1 shows a comparison of the RMS statistics for each receiver and satellite pair. These values were calculated by computing the RMS of each set of DDR's. The RMS was divided by 2 so that it reflects the value that could be expected of one pseudorange measurement. The results show a 10 to 40 % improvement with the MEDLL. These results were not as significant as expected given the theoretical values shown in Figure 5. The reason for this is simply there was not much multipath present. The results do however confirm that the MEDLL receiver is operating properly.

Table I: Comparison of Double Difference Residuals

	Model 3951 GPS Receiver				
#	1	2	3	4	5
Mean (m)	-0.1671	0.1431	-0.0531	-0.1961	-0.758
Stdev (m)	0.863	0.9681	0.875	0.7141	0.991
RMS of i (m)	0.4401	0.489	0.4381	0.3701	0.624
	MEDLL GPS Receiver				
Mean (m)	-0.006	0.569	0.213	0.079	-0.757
Stdev (m)	0.580	0.677	0.507	0.429	0.598
RMS of 1 (m)	0.290	0.442	0.275	0.218	0.482
Improvement	34.04%	9.64%	37.30%	41.10%	22.64%

SIMULATOR RESULTS

To properly evaluate the performance of the MEDLL range measurements under worst-cast multipath, laboratory tests were conducted for comparison with the theoretical multipath error envelopes in Figure 5. As shown in Figure 11, a Northern Telecom STR2760 GPS signal simulator was connected to two NovAtel receivers, the MEDLL and the GPSCard model 3951R which uses the Narrow Correlator™ spacing.

Multipath simulation scenarios were created where for a given satellite signal, a second simulator channel is used to produce a “reflected” signal with a specified relative power and delay as a function of time. The reflected signal was generated with nominal delays between 0.025 and 1.1 C/A Code Chips and 0.5 relative amplitude. Each time, the delay was ramped over a 5 minute interval from one L1 wavelength before the nominal to one after. In this way, the multipath response near that delay could be measured with the reflected carrier at 0” and 180° phase relative to the direct carrier.

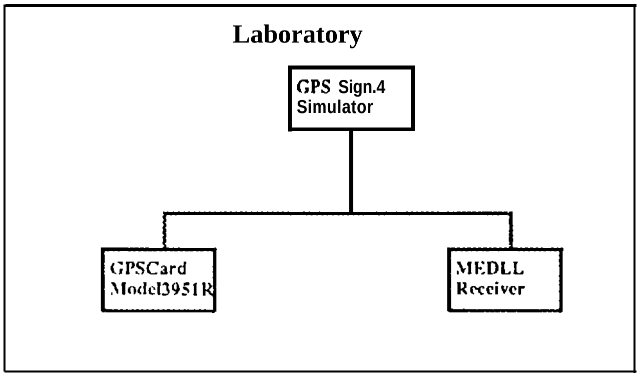

Figure 11: Simulator Test Equipment Set Up

The range error induced by multipath was calculated for each receiver using a double difference between the receiver range and truth data provided by the simulator and between the range that had a reflected signal and a second range free of multipath. Effectively, this is a double difference zero baseline test except that the truth data represents a receiver totally unaffected by multipath.

The error induced when two signals are at 0° and 180” phase was used to create the multipath error envelope in Figure 12. The MEDLL tracking accuracy represents a considerable improvement over the Narrow Correlator™ technology.

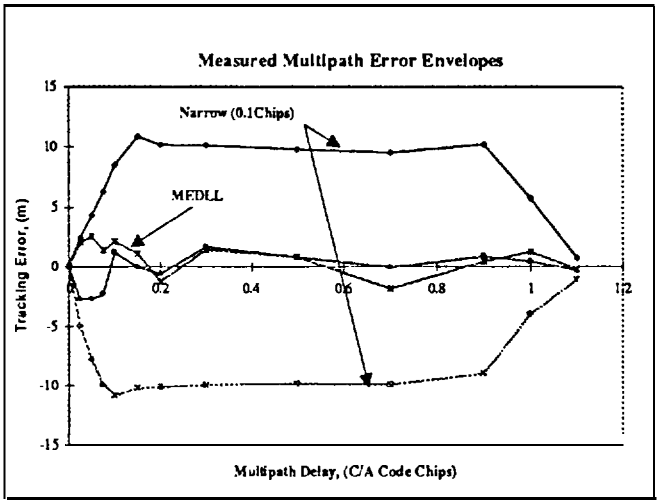

Figure 12: Measured Multipath Error Envelopes For the Narrow **Correlator DLL and MEDLL**

CONCLUSIONS AND FUTURE DEVELOPMENTS

The results show that the MEDLL receiver performance is close to the theoretical performance expected. The MEDLL receiver reduces DLL multipath error by up to 90% over the Narrow Correlator™ receiver.

The improved performance of the MEDLL can be of great help in critical DGPS applications. where the multipath errors associated with using conventional receivers can easily exceed the accuracy requirements.

In future developments on the MEDLL the multipath corrections currently computed for corrections to the pseudorange will be extended to develop corrections for the carrier phase measurements.

ACKNOWLEDGEMENTS

The MEDLL GPS Receiver development team at NovAtel is acknowledged for their effort in getting the product completed on schedule.

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