Analysis of the Multipath Meter Performance in Environments With Multiple Interferers

by

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BIOGRAPHY

Bryan Townsend received his Master of Science degree in 1993 from the Department of Geomatics Engineering at the University of Calgary. Since then he has worked in several areas of GPS including GPS surveying, GPS receiver design and wide area reference systems. Currently he works as a consultant in the area of GPS augmentation systems.

Jonathan Wiebe received a Bachelors of Mathematics in Applied Mathematics from the University of Waterloo in 1995. He completed his Masters of Science at the University of Calgary in Geomatics Engineering in 1998. His research interests included Synthetic Aperture Radar texture analysis and speckle filtering. He is currently employed at NovAtel Inc. as a GPS Engineer.

Andy Jakab received his B.Sc. in 1997 from the Geomatics Engineering department at the University of Calgary and is currently pursuing a master's degree. After receiving his undergraduate degree, he joined NovAtel and has worked on receiver testing and end user software. Andy is currently GPS Systems Engineer for the Aviation group working on receiver certification and development activities including evil waveform research.

Michael Clayton is a computer systems engineer with over twenty years systems engineering experience. He graduated from the Royal Military College in 1978 with a Bachelor of Engineering (Electrical) and from Carleton University with a Masters of Engineering (Electrical) in 1984. In 1998 he joined NovAtel as Senior Project Manager - Aviation Group. During this period, Michael was the Project Manager for the GNSSA project, a DO-178B Level A effort and the EGNOS RIMS-C PATP project, a DO-178B, Level D effort.

Tony Murfin is the director of the Aviation Group at NovAtel Inc.

ABSTRACT

The Multipath Estimating Delay-Lock-Loop (MEDLL) is a method for mitigating the effects due to multipath within the receiver tracking loops. A previous publication [8] showed how the MEDLL receiver was modified into an instrument for measuring multipath. This instrument is called the Multipath Meter. It outputs the delay, relative amplitude, and phase of the multipath signal along with the residual values for each correlator. The results showed how the Multipath Meter is used for reference station site analysis and real-time signal quality monitoring (SQM).

This paper builds on the previous paper by investigating how the Multipath Meter performs in more severe multipath environments. The most significant of these is the situation where there are multiple multipath signals present. It is known that the performance of the MEDLL is degraded in this situation. Our investigation includes analyzing and quantifying the effect on the MEDLL performance as well as analyzing the ability of the Multipath Meter to detect this situation when it occurs.

A new software tool designed and produced by NovAtel is introduced. The software is called the Multipath Assessment Tool (MAT). MAT graphically displays the Multipath Meter output as well as performing some statistical analysis. It is used for real-time SQM and post-mission analysis.

INTRODUCTION

The Multipath Estimating Delay-Lock-Loop (MEDLL) is a method for mitigating the effects of GPS signal multipath within the receiver tracking loops. The MEDLL does this by separating the signal into its line-of-sight and multipath components. The line-of-sight

component is then used for computing the tracking error. The MEDLL receiver performance, in mitigating the effects of multipath on C/A code pseudorange and carrier phase measurements, has been demonstrated in previous papers [2, 3, and 7].

The MEDLL receiver was modified to output the multipath parameters. The name 'Multipath Meter' comes from the fact that it 'measures multipath'. The parameters outputs include the delay, relative amplitude, and phase of the multipath signal, along with the residual values for each correlator used for multipath estimation. The multipath parameters are estimated by the MEDLL and the residuals indicate the quality of the estimation process.

This paper investigates how the MEDLL performs under conditions where multiple multipath signals are present, and the ability of the MEDLL outputs to indicate such a condition is present. Using a GPS signal simulator, multiple multipaths are introduced and the output of the MEDLL is observed and analyzed. Also, live data was collected in an effort to capture a practical example of the effect of multiple multipath signals on the MEDLL outputs.

GPS MULTIPATH

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 phenomenon for one reflected signal.
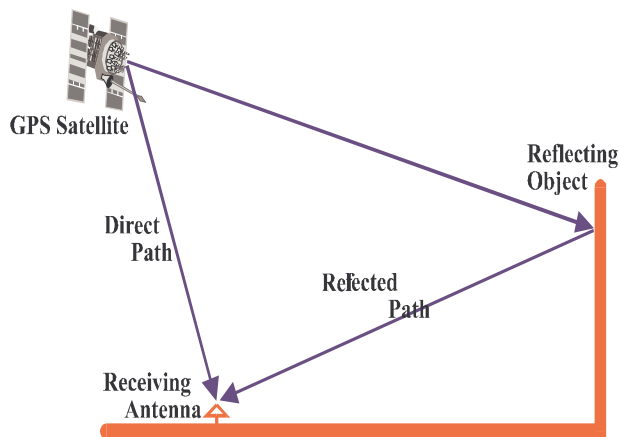

Figure 1: Direct Path and Multipath (Reflected Path) Signals

Some important characteristics of multipath are as follows [4]:

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

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.

MEDLL

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

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

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 decomposition of the correlation function into its direct path and reflected path 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. The result is an estimate of the direct path correlation function. A standard early-late DLL is applied to the direct path component of the correlation function giving a 'multipath free' estimate of the code loop tracking error.

THE MULTIPATH METER

The multipath meter involves taking the signal parameters output from the MEDLL algorithms and using them for quality monitoring of the GPS signal. These parameters are the delay, relative amplitude, and phase of the multipath signal along with the residual values for each correlator.

The multipath meter output is used for real-time signal quality monitoring. It can also be used for reference station site surveys to determine if a location is suitable for a GPS reference station.

Of the signal parameters output, the amplitude of the multipath is of most interest because it will indicate the presences of multipath even if it is not causing any pseudorange error. This would be the case is the relative phase of the multipath is 90 or 270 degrees.

MULTIPLE INTERFERERS

Figure 2 shows a plot of the pseudorange error due to multipath for MEDLL and Narrow Correlator tracking. The light colored line is the MEDLL and the dark colored line is the Narrow Correlator. The multipath signal has an amplitude (a_m) of 0.5 relative to the direct path signal. The delay is varied from 0 to 1.1 chips. The plot appears almost solid because the multipath varies in phase as the delay is varied. One carrier phase cycle is 1/1540 chips and as the delay varies over one cycle the phase of the multipath signal relative to the direct path signal varies over 360 degrees. The multipath error is at its maximum positive value at 0 degrees phase and at its maximum negative value at 180 degrees phase. The error is 0 at 90 and 270 degrees.
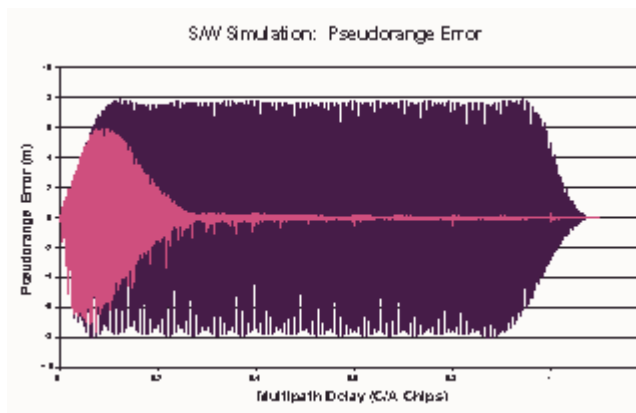

Figure 2: **Theoretical pseudorange multipath error for MEDLL and Narrow Correlator (a_m = 0.5)**

It should be mentioned here that the MEDLL receiver has a pre-correlation bandwidth of 8 MHz and the

Narrow Correlator receiver has a 16 MHz pre-correlation bandwidth. This was done to simulate the NovAtel WAAS receiver that is used in the next section for live signal tests. The MEDLL was implemented in the WAAS receiver using an OEM2 hardware platform and the Narrow Correlator is implemented using an OEM3 hardware platform. The two platforms use different RF decks.

For the same multipath scenario as in Figure 2, the corresponding measured multipath power is shown in Figure 3.
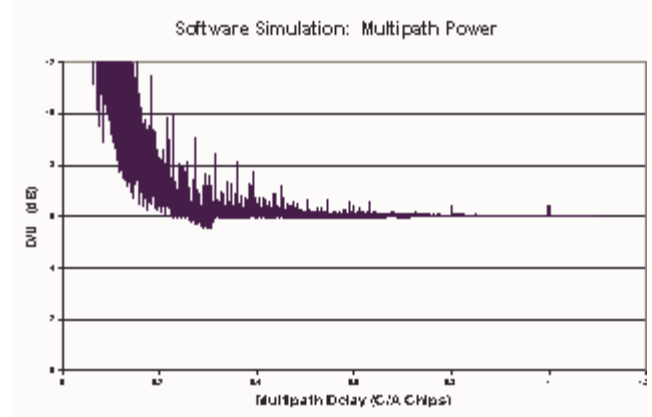

Figure 3: **Theoretical D/U values for 0.5 amplitude signal**

The multipath power is plotted in D/U (desired signal power over undesired signal power) in decibels (dB). The D/U is calculated using the equation,

$$D/U = 20*\log(a_{direct} / a_{multipath}) \qquad (2)$$

The plot shows that the D/U converges to 6 dB as the delay of the multipath is increased. 6 dB corresponds to a relative multipath power of 0.5. For delays less than 0.2 the D/U becomes less accurate. This is expected since the accuracy of the MEDLL is limited by the BW of the GPS receiver RF deck and the GPS signal itself.

Figure 4 shows a plot of the pseudorange error due to multipath for MEDLL and Narrow Correlator tracking in the presence of two multipath signals instead of only one. Again, the light colored line is the MEDLL and the dark colored line is the Narrow Correlator. The two multipath signals have relative amplitudes of 0.5 and 0.3 respectively. The half power multipath signal is varied from 0 to 1.1 chips again with the 0.3 power multipath signal having a constant delay of 0.5 chips. We can see that the Narrow Correlator results are very similar to the single multipath case performance except that the error envelope is offset by approximately 4 meters. The

MEDLL performance is in places worse than the Narrow Correlator for this scenario, but still significantly reduces the effects of the multipath sources on the pseudorange error beyond 0.2 chips.
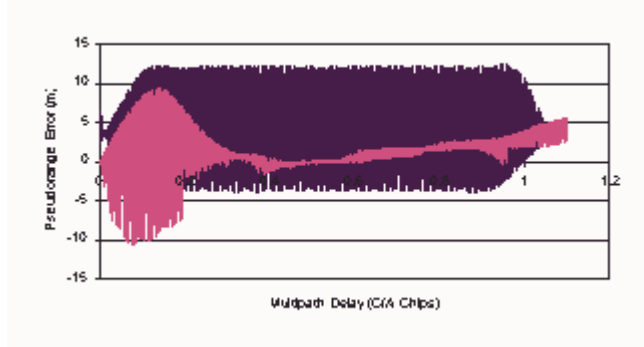

Figure 4: **Theoretical pseudorange multipath error for MEDLL and Narrow Correlator (a_m = 0.5, Standing wave: a_m = 0.3, τ_m = 0.5)**

For the same multipath scenario as in Figure 4, the corresponding measured multipath power is shown in Figure 5. The multipath power is plotted in D/U.
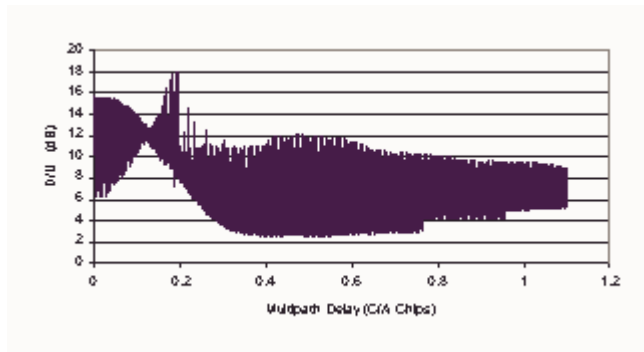

Figure 5: **Theoretical D/U values for a_m = 0.5 plus standing wave with a_m = 0.3 and τ_m = 0.5**

The 0.3 power multipath signal corresponds to an approximate D/U of 10.5 dB. We can see that the estimate of the D/U value is much less accurate that in the single multipath case. There is a large variation in D/U values for delays of all kinds, where only delays less than 0.2 chips were problematic for the single multipath case.

The case of multiple multipath signals has been investigated in [9] and overall, these cases are quite troublesome for any correlation method chosen.

ANALYSIS OF CORRELATOR RESIDUALS

In addition to D/U, delay, and phase measurements of the multipath signals, another check of how well the MEDLL algorithms are performing is to look at the size of correlator residuals. A correlator residual is calculated by taking the measured correlator value and subtracting off the computed direct path and multipath correlator values. The direct path and multipath correlator values are calculated using a pre-determined reference correlation function. Based on equation (1) the correlator residual is represented by,

$$C_{\text{res}} = C_{\text{meas}} - \sum_{m=0}^{M-1} a_m C_{\text{ref}}(x - \tau_m)\cos(\theta_m) \qquad (3)$$

where,

$$
\begin{aligned}
C_{\text{res}} &= \text{correlator residual} \\
C_{\text{meas}} &= \text{measured correlator value} \\
C_{\text{ref}} &= \text{reference function correlator value} \\
M &= \text{number of signals} \\
x &= \text{correlator position} \\
a_m &= \text{component signal amplitude} \\
\tau_m &= \text{component signal delay} \\
\theta_m &= \text{component signal phase}
\end{aligned}
$$

For the single multipath case using the signal simulator, with a half power multipath signal of varying delay, the correlator residuals are shown in Figure 6. As expected, the RMS of the normalized residual values are quite low, with the majority of the values less than 1%. This shows that the MEDLL algorithms are converging and the modeling is good.
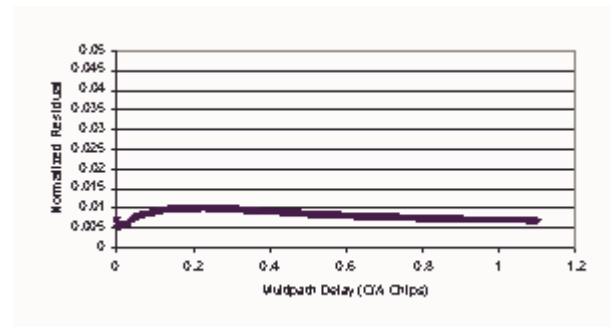

Figure 6: **RMS of correlator residuals, GPS simulator, a_m = 0.5**

For the multiple multipath case, with two signals: one at half and the other at one third power, the correlation residuals in Figure 7 show a lesser ability of the MEDLL to estimate the correct multipath signal. The correlator residuals are much higher, as expected, since we are only modeling one multipath signal in the MEDLL while there are two multipath signals present. The MEDLL

algorithms are having difficulty converging on a good estimate of the multipath signal with the RMS of the normalized correlator residuals greater than 2% in most cases.
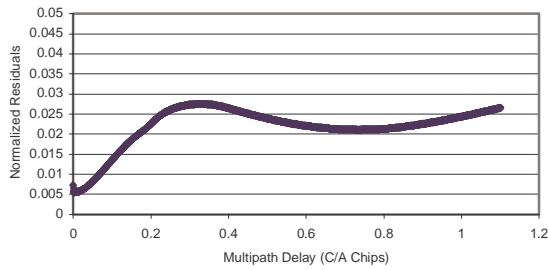

Figure 7: **RMS of correlator residuals, GPS simulator, $a_m = 0.5$, standing wave with $a_m = 0.3$ and $\tau_m = 0.5$**

GPS SIMULATOR TESTS

Using a GPS signal simulator several tests with involving multiple multipath signals were performed. The test setup consisted of the Global Navigation Satellite System (GSS) GPS signal simulator and NovAtel EGNOS receiver.

Table 1: **Simulator scenarios**

MP	Description	Start	End
1	Delay = 0.68, Amp = -10, Fixed offset	357253	357533
2	Delay = 1.02, Amp = -12, Fixed offset	357422	358022
3	Delay = 0.34, Amp = -12, Fixed offset	357637	358229
4	Delay = 0.41, Sinusoidal 0.5 Hz, Peak 5 dB	358185	358485
5	Delay = 0.29, Amp = -10, Fixed offset	358375	358975
6	Delay = 0.73, Amp = -9, Fixed offset	358622	359216
7	Delay = 0.31, Sinusoidal 0.05 Hz, Peak 8 dB	359064	359300
8	Delay = 0.51, Amp = -15, Fixed offset	359532	359839
9	Delay = 0.19, Amp = -10, Fixed offset	359695	359989

From Table 1, we can see that for the majority of the test, two multipath signals were present. The introduction of each successive multipath signal was timed so that as one multipath signal stopped, another was started.

Figure 8 shows the Code-Carrier plot for the entire multipath scenario described in Table 1. For conditions of multiple multipath signals, there is significant error introduced into the system. The Code-Carrier has specific jumps in it that correspond to the introduction or removal of one or all of the multipath sources. However, not all multipath conditions introduced a noticeable error above that of the ambient noise.
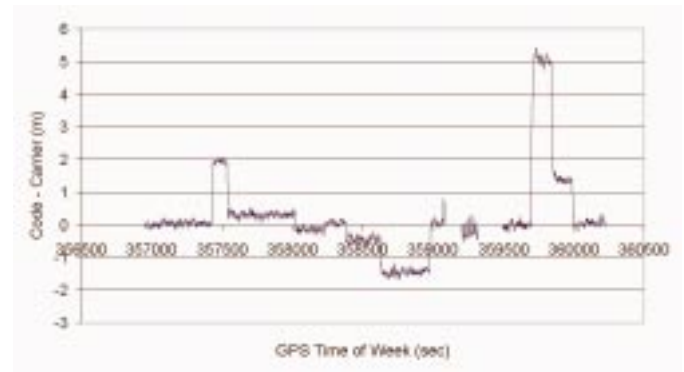

Figure 8: **Code-Carrier for Multipath Scenario**

Figure 9 shows the output of the desired to undesired signal ratio from the MEDLL. This plot more accurately announces the arrival and departure of the multipath sources. Each jump in D/U can be directly traced to the multipath signal state described in Table 1.
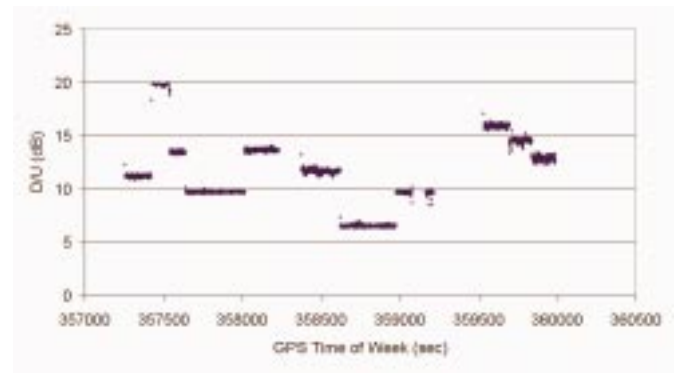

Figure 9: **D/U for Multipath Scenario**

In addition to the D/U values, the RMS of the correlator residuals shown in Figure 10 show precisely when there are multiple multipath signals present. Nominally, and when only one multipath signal is present, the correlator residual are less than 0.5%. This shows a good fit of the MEDLL algorithms to the environment. When additional multipath sources are present, the RMS of the correlator residuals jumps up beyond 2% in some cases.
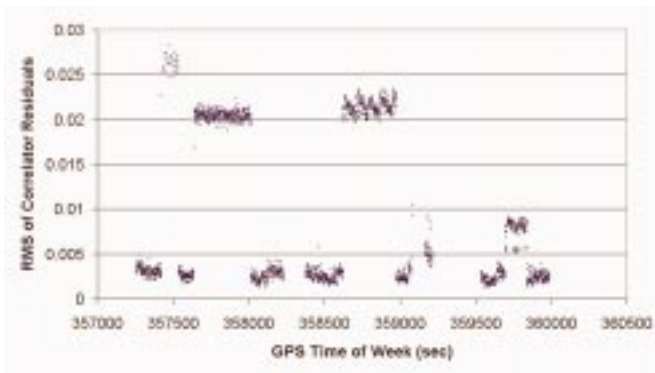
Figure 10: RMS of correlator residuals for Multipath Scenario

ANALYSIS OF LIVE SIGNAL DATA

The next step is our analysis was to look at data collected from tracking live satellites. For this purpose the NovAtel EGNOS receiver was set up to collect data at NovAtel's facility in Calgary, Alberta, Canada. Figure 7 shows a picture of part of the antenna array on the roof of the NovAtel building. The roof was designed to be a low multipath environment and, as can be seen, the area is reasonably clear of objects that could reflect multipath signals. For the data collection, a non-chokering antenna was used in order to try to induce more multipath. In addition, the antenna was placed at the edge of the roof near some of the reflective glass surfaces and elevated on a range pole.

Figure 11: Antenna array on the roof at NovAtel Inc.

Figure 12 shows a plot of the code minus carrier residuals for all satellites in view and Figure 13 shows the corresponding code minus carrier plot for PRN2 only. Both plots show data from a Narrow Correlator receiver. The data was collected for a 24 hour period starting from approximately 6:00 in the evening. L1 and L2 carrier phase measurements were used to remove the ionospheric trend and the initial bias has been removed so that the plot is centred about zero.

For most part the code minus carrier residuals are small indicating a low multipath environment. There are, however, some large excursions. Figure 13 shows one of these excursions for PRN2. The excursion is visible in the center of the data set when the Code-Carrier value jumps to above 2 meters from a nominal value of less than one meter.
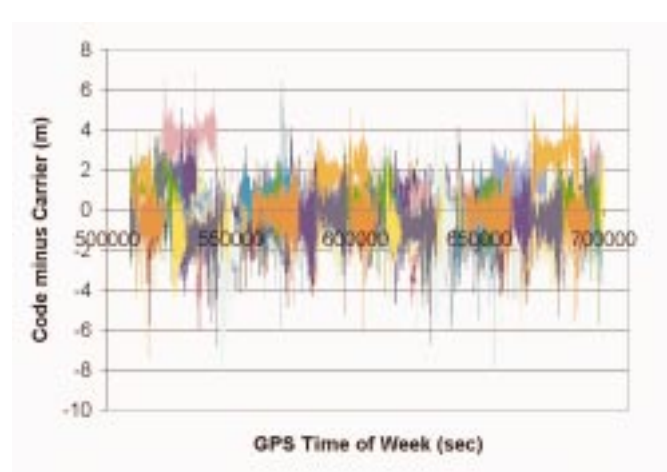

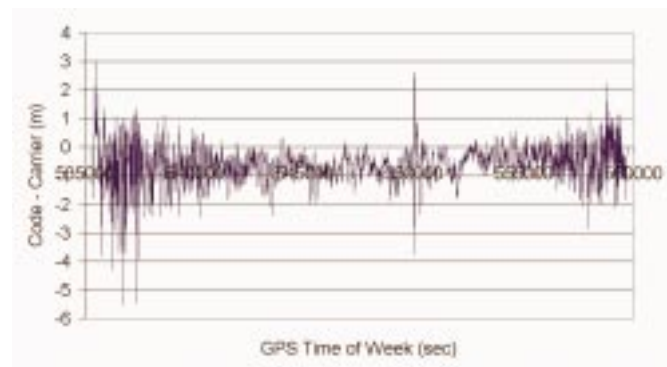**Figure 12: Code minus carrier**

Figure 13: Code minus carrier PRN 2

When examining the RMS of the correlator residuals from the MEDLL for the same period of time, we can vaguely see that the event is present. The event is still

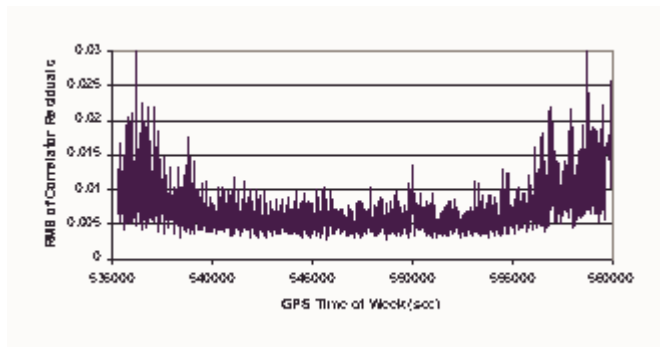within the ambient noise of the measurements, and would not necessarily be detected.

Figure 14: RMS of correlator residuals

However, once the RMS of the correlator residuals has been corrected for the carrier to noise (C/No) of the signal, we see that most of the noise at the edges of the graph have been removed. The event at 550000 seconds into the week is more visible in Figure 15 than in Figure 14. With the correction due to C/No of the RMS of the correlator residuals, we should use a constant threshold for multipath indication. There are still additional multipath indicated at the edges of the graph and this is expected since these correspond to the rise and fall of the satellite in the sky.
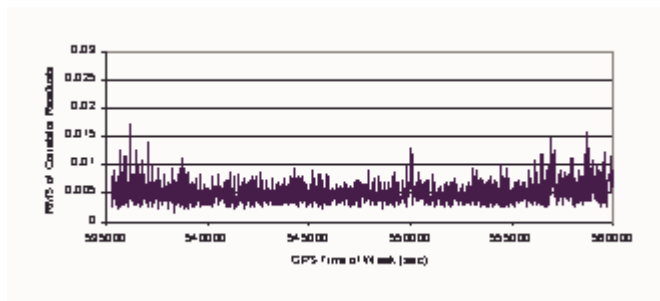

Figure 15: RMS of correlator residuals corrected for C/No

Upon examination of the D/U values output from the MEDLL for the same period, we can see that the PRN 2 event is also visible here in Figure 16. With un-normalized D/U values, it is expected that the measured

output will have a curved path as indicated in Figure 16. By using a using a detection threshold that follows the center of the curved path, the PRN2 event would be detected as excessive multipath. To aid in the detection and reduce the noise, applying a short time constant data smoother would likely increase the ability to detect such events.
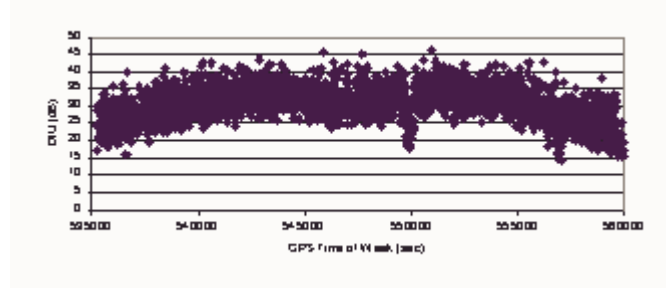

Figure 16: D/U for PRN2 during live data collection

MULTIPATH ASSESSMENT TOOL (MAT)

The Multipath Assessment Tool is shown in Figure 17. This figure shows the software in a file playback mode, replaying the scenario of GPS Simulator results previously shown in figures 8, 9, and 10. The software is capable of both real time data analysis and plotting or post mission file playback.

When the data from the effected satellite is played back with another satellite in the same plots, it is easily discernable that there is something happening to PRN2. The D/U value is significantly less than those of PRN24 and PRN20. Also, the standard deviation of the RMS of the residuals and the RMS of the residuals themselves show uncharacteristically large values indicating the inability of the MEDLL to accurately model the multipath signals.

The MAT also allows you to jump to any portion of the file to playback a specific portion of the file that may be of interest for signal quality monitoring.
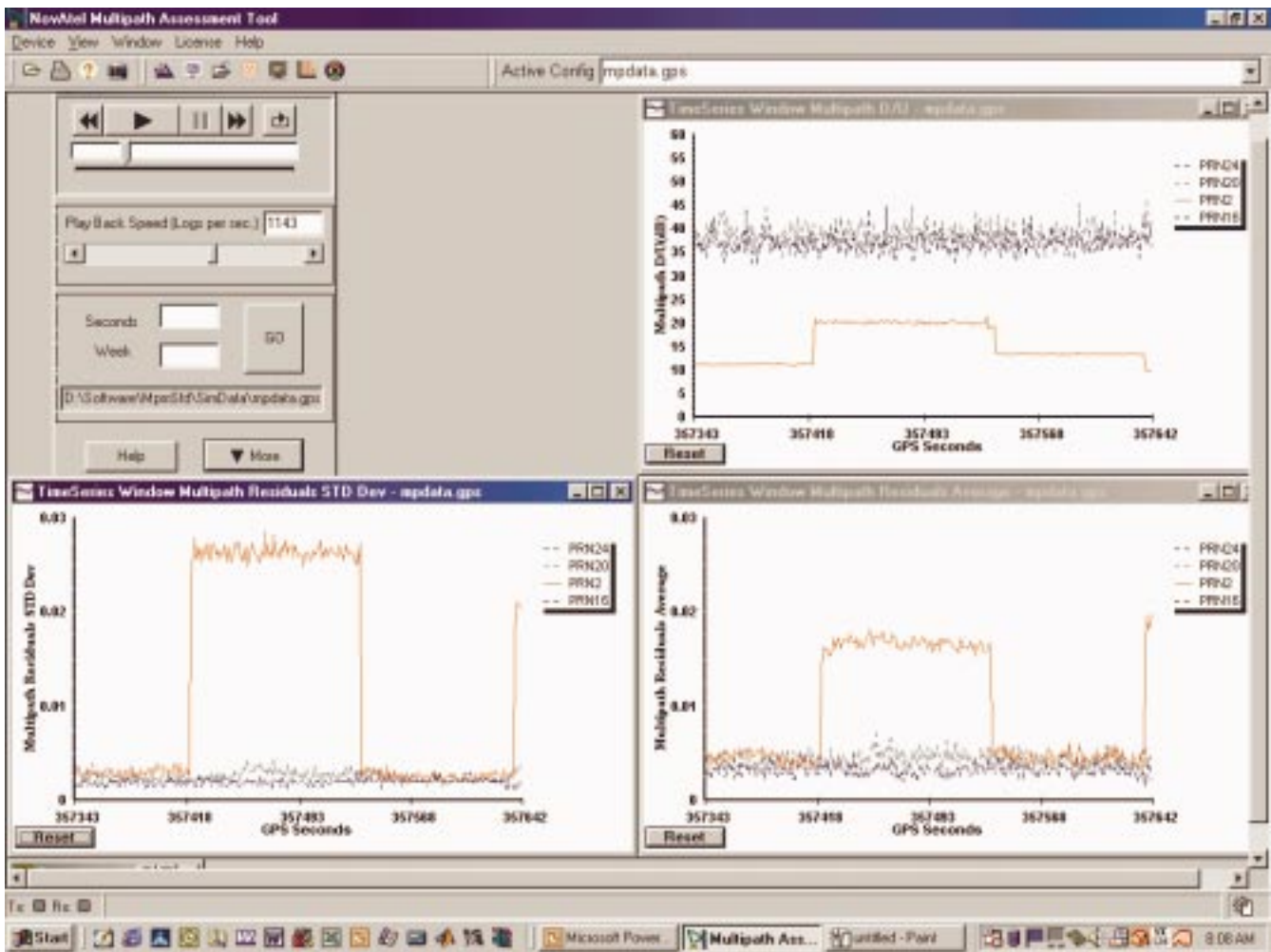
Figure 17: MAT Software window

CONCLUSIONS

The results of the analysis shows that Multipath Meter can be effective in detecting measurement biases caused by multiple multipath environments. Although these results are based on relatively small data set, it is clear that the D/U measurements in combination with analysis of the correlator residuals will detect a broad range of signal failures. In many cases the correlator residuals give a more stable result then the D/U.

The Multipath Meter combined with Multipath Assessment Tool is a valuable tool for site assessment and real-time SQM.

Future work will investigate the Multipath Meter performance in detecting satellite failures.

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