Theory and Performance of the Pulse Aperture Correlator

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ABSTRACT

The reduction of multipath biases on GPS measurements has traditionally been achieved through innovative antenna design, such as choke ring ground planes, and careful antenna site selection. These methods, although effective, are not always practical, especially in a kinematic environment. The implementation of Narrow Correlator spacing design in GPS receiver code tracking loops has greatly reduced the multipath bias and the measurement noise on C/A code pseudorange measurements. Even with these advancements the bias due to multipath is still dominant in GPS position calculations. This paper introduces NovAtel's Pulse Aperture Correlator (PAC) tracking loop which takes full advantage of the Narrow Correlator spacing design, but in addition, is much more resistant to multipath effects on the correlation function and thereby reduces the multipath bias on the pseudorange measurements. The theory behind this tracking loop design is identical to that of NovAtel's Multipath Elimination Technology (MET), first introduced in NovAtel's OEM2 GPSCard. The difference in the OEM4 PAC implementation is that the algorithms are implemented in the hardware rather than the software and we see a performance improvement in PAC over MET due to the increased pre-correlation bandwidth of the OEM4. The theory behind PAC and MET will be presented along with its implementation into existing receiver hardware. Test results showing the performance of a PAC receiver compared with a Wide Correlator receiver Narrow Correlator receiver, and MET are also presented.

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 tropospheric 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 multipath for each antenna location is difficult and impractical.

In the presence of multipath, most GPS positioning methods suffer 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.

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 phenomenon for one reflected signal.

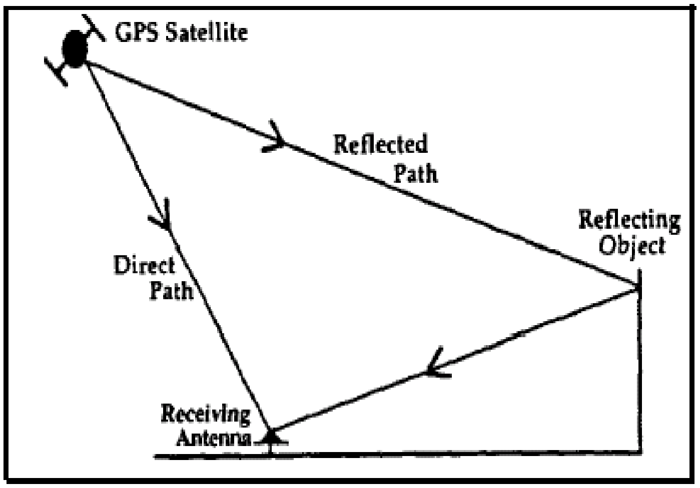

Figure 1: Direct Path and Multipath (Reflected Path) Signals

Some important characteristics of multipath are as follows:

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 [Proakis, 1983].
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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.

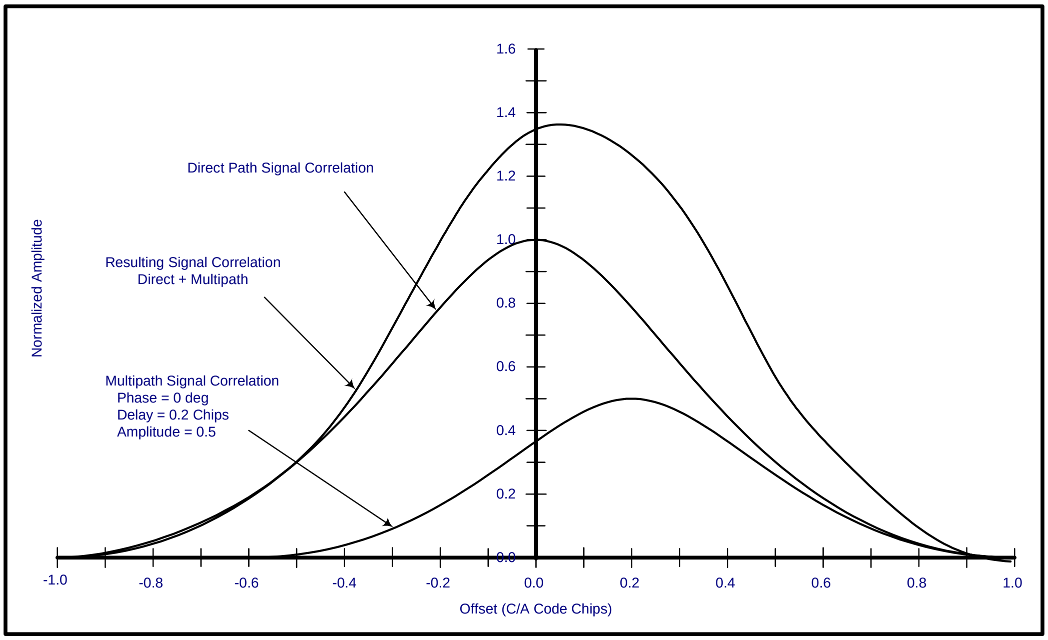

Figure 2: Direct Path, Multipath (In Phase) and Resulting Correlation Functions

In this case the multipath signal has a delay of 0.2 chips, 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 OEM2 GPSCard^{TM} [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.

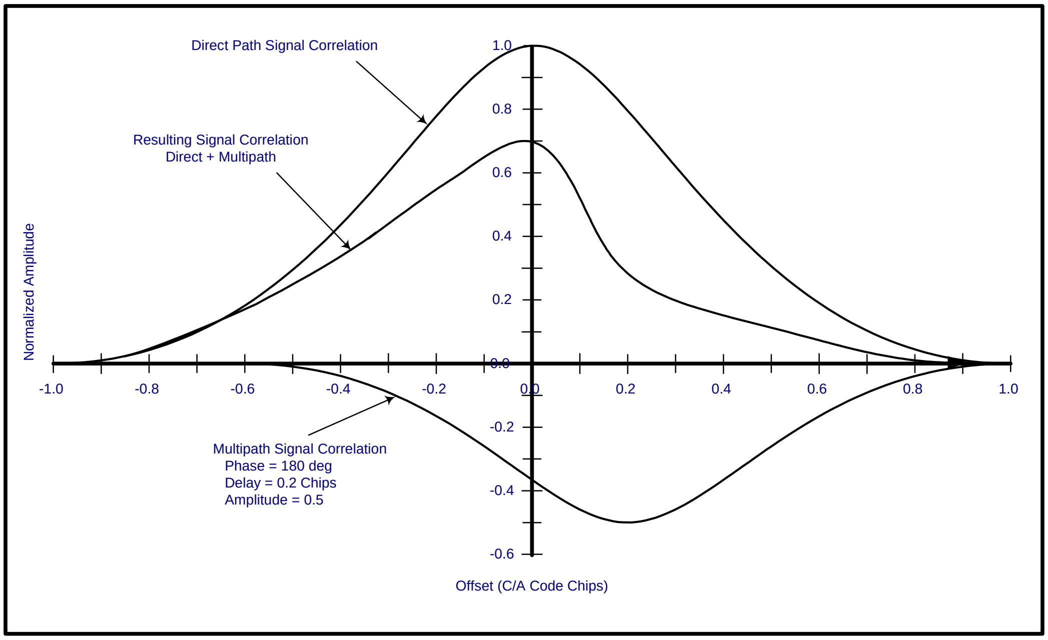

Figure 3: Direct Path, Multipath (out of phase) and Resulting Correlation Functions

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 of the early and late correlators equal, a distorted correlation function will **bias** this process.

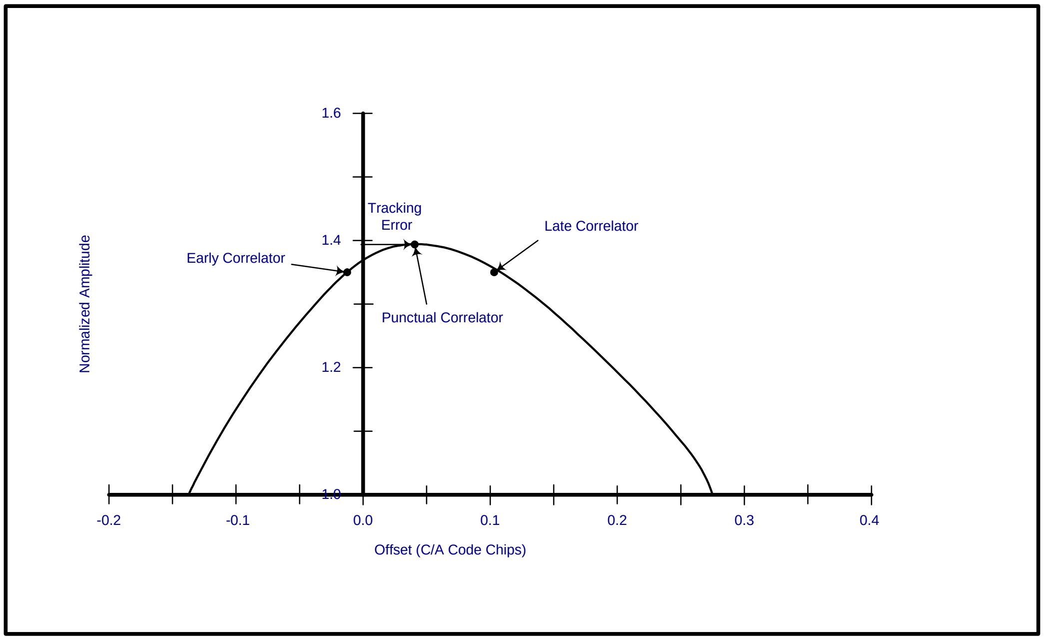

Figure 4: Tracking Error Due to Multipath

Since the multipath signal causes distortion in the correlation function it should be possible to measure distortion in the correlation function and derive a correction for multipath.

THE EARLY LATE SLOPE TECHNIQUE

The early late slope technique is the basis for NovAtel's MET technology. In deriving the early-late slope (ELS) technique it is convenient to consider the ideal situation where the pre-correlation BW is infinite and the resulting correlation function is triangular. Figures 5 and 6 show the resulting correlation functions for the same situations as in Figures 2 and 3 respectively. The resulting correlation functions in Figures 5 and 6 share two important common characteristics. Firstly, the desired tracking point is at maximum power in both cases. Secondly the slopes of the functions on either side of the peak are not equal.

Figure 7 is a close-up of a similar correlation function peak with two correlators placed on the early and late side. In Figure 7, y_1 and y_2 are the amplitudes of early and late correlators respectively. The slope of the correlation function on the early side of the peak is a_1, and a_2 is the slope on the late side of the peak. The spacing between the early and late correlators is d.

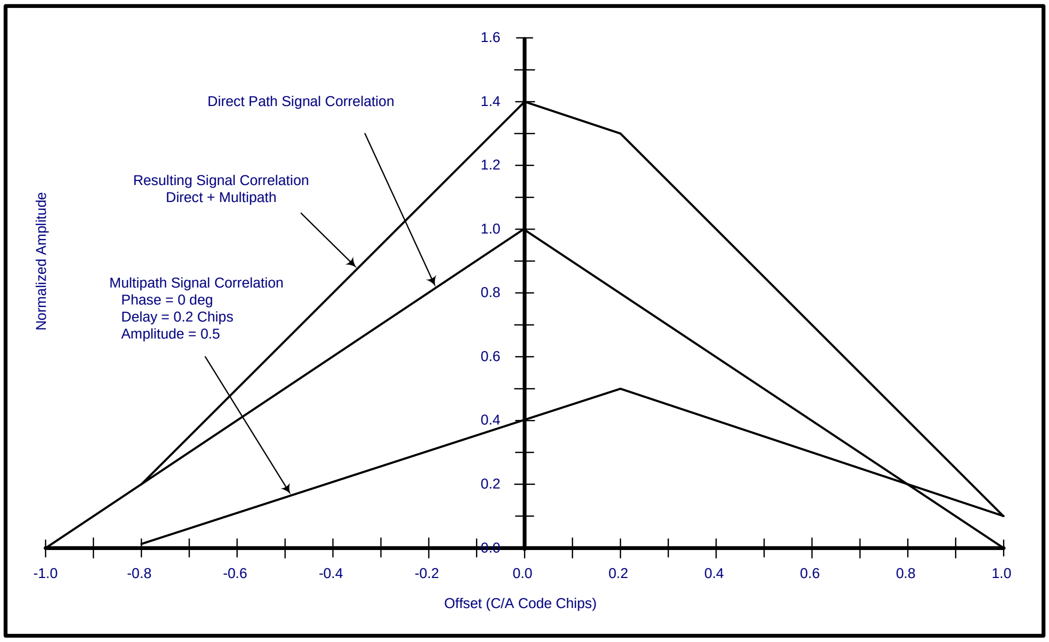

Figure 5: Direct Path, Multipath (in phase) and Resulting Correlation Functions

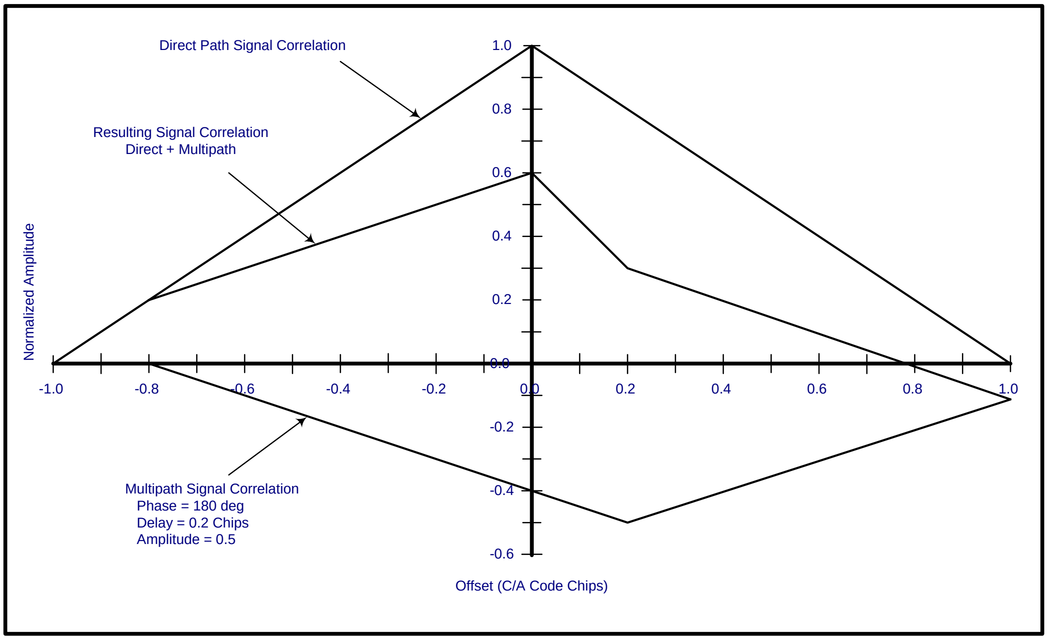

Figure 6: Direct Path, Multipath (out of phase) and Resulting Correlation Functions

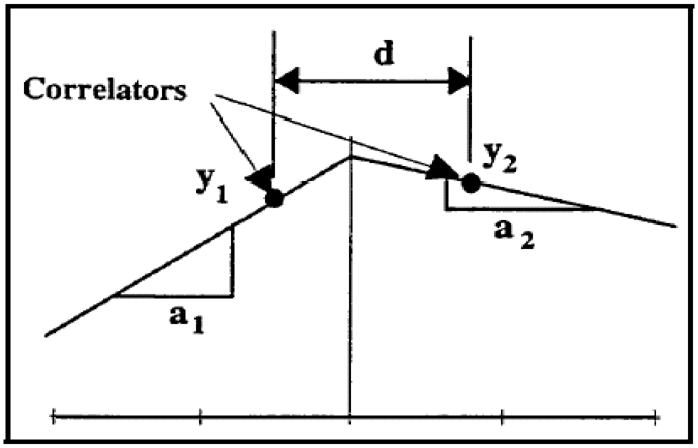

Figure 7: Early Late Slope Technique -- Ideal Case

Applying this discriminator to the bandlimited case is straightforward. Figure 8 shows how this can be accomplished.

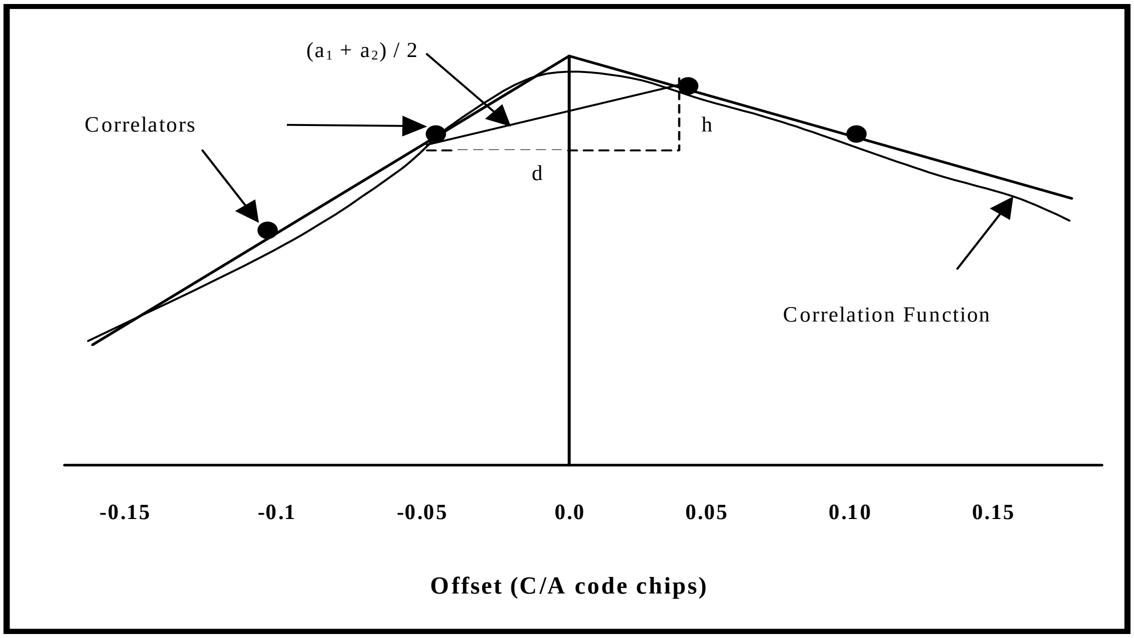

Figure 8: Early Late Slope Technique – Band Limited Case

Two additional correlators are added at a wider spacing so that the early and late slopes can be calculated. The inside two correlators are spaced wide enough apart so that they are not affected by flatness at the peak of the correlation function. In a multipath free signal, the correlation function would be symmetrical and maximum correlation would occur when our early minus late measurement equals zero, therefore classical early minus late correlators try to drive this value to zero. However for maximum correlation with the direct plus multipath signal, the correlators must be located on the line with slope shown in Figure 8 resulting in a non-zero early minus late measurement. Since this slope is an average of the early and late slopes, we can compute this value and then compute the power difference required for maximum correlation:

$$h = d / 2(a_1 + a_2)$$

where h = the ideal early minus late value

We can then compute the difference between our early minus late measurement and the ideal early minus late value:

$$\text{Early – late error} = (y_1 - y_2) + h$$

Now by translating this value into horizontal error by dividing out the slope of our correlation function, the following DLL discriminator can be derived to accurately estimate how much the correlators need to be moved so that they are centered on the peak:

$$T = \frac{[(y_1 - y_2) + d / 2(a_1 + a_2)]}{(a_1 - a_2)}$$

where T = the tracking error.

T will equal zero when the two correlators are positioned equidistant on each side of the peak. When T is non-zero it can be used to feed back to the hardware to keep the early and late correlators centered on the peak.

In the ideal case this DLL discriminator will estimate exactly the amount the correlators have to be moved.

CHARACTERISTICS OF PAC DISCRIMINATOR

The MET formula derived above can be used by software to feedback corrections to the hardware but this correction could also be done right in the hardware itself. This is the idea behind PAC and it can be shown that PAC is just a simple hardware implementation of MET. We know that we are trying to drive the tracking error to zero, therefore in the hardware we want to drive the numerator of our tracking error equation to zero. So the PAC discriminator becomes:

$$y_1 - y_2 + d/2(a_1 + a_2)$$

As shown in Figure 9, PAC uses a second set of correlators that are spaced at exactly double the width of the first correlator set.

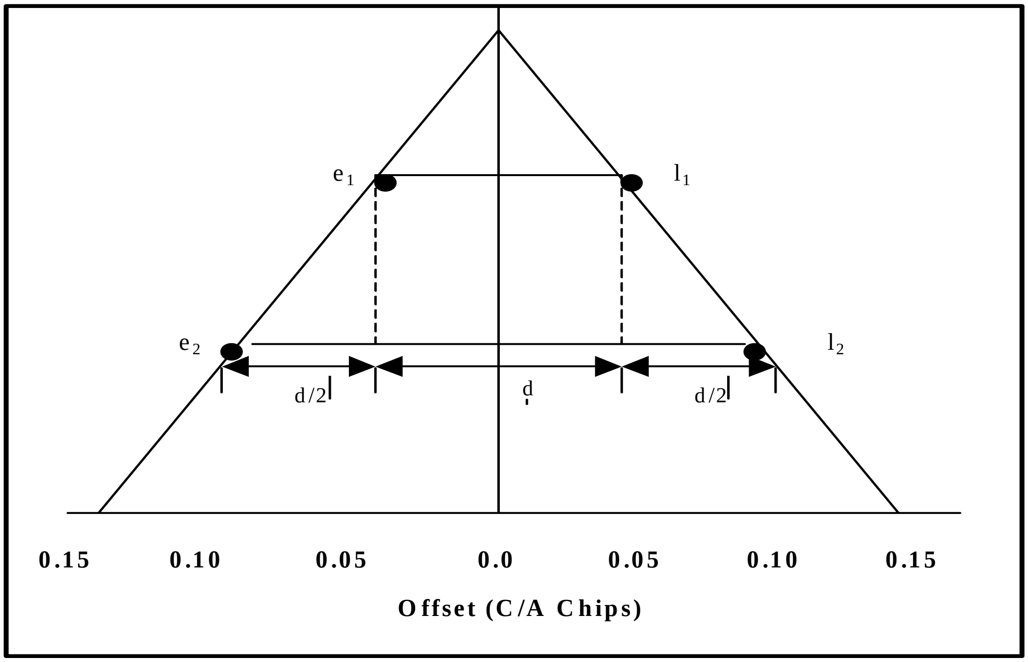

Figure 9: PAC correlator layout

Using this information, the above discriminator can be rewritten as a function of early and late measurements:

Since:

$a_1 = (e_1 - e_2)/(d/2)$

$a_2 = (l_1 - l_2)/-(d/2)$

$y_1 = e_1$

$y_2 = e_2$

The PAC discriminator can be rewritten as:

$$e_1 - l_1 + (d/2)\left[\frac{(e_1 - e_2) + (l_2 - l_1)}{d/2}\right]$$

Then simplified to:

$$2(e_1 - l_1) - (e_2 - l_2)$$

Now, by considering the PAC discriminator function to be simply a linear function of two early minus late narrow correlators, its correlation function can be derived. It is helpful to examine the correlation functions of various correlator types to understand how multipath errors are related to correlation patterns. Multipath signals with delays exceeding the outside envelope of our correlation function will be rejected. Therefore as the correlation function narrows, the more multipath we can reject by eliminating shorter delays. PAC implements this concept to reduce the sensitivity of the correlators to multipath delays. Figure 10 shows the infinite bandwidth correlation patterns for two early minus late narrow correlators with spacing of 0.1 chips and 0.2 chips.

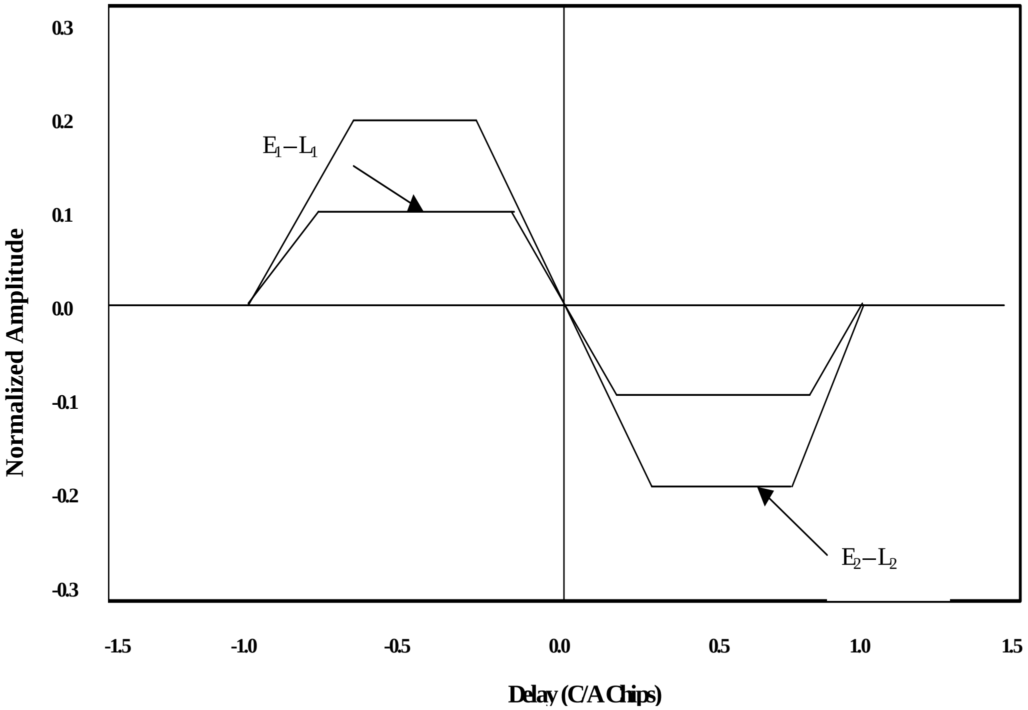

Figure 10: Correlators of spacing 0.1 and 0.2 chips

The linear function of these two correlators according to our PAC discriminator function will produce the narrowed and therefore more multipath resistant correlation pattern shown in Figure 11.

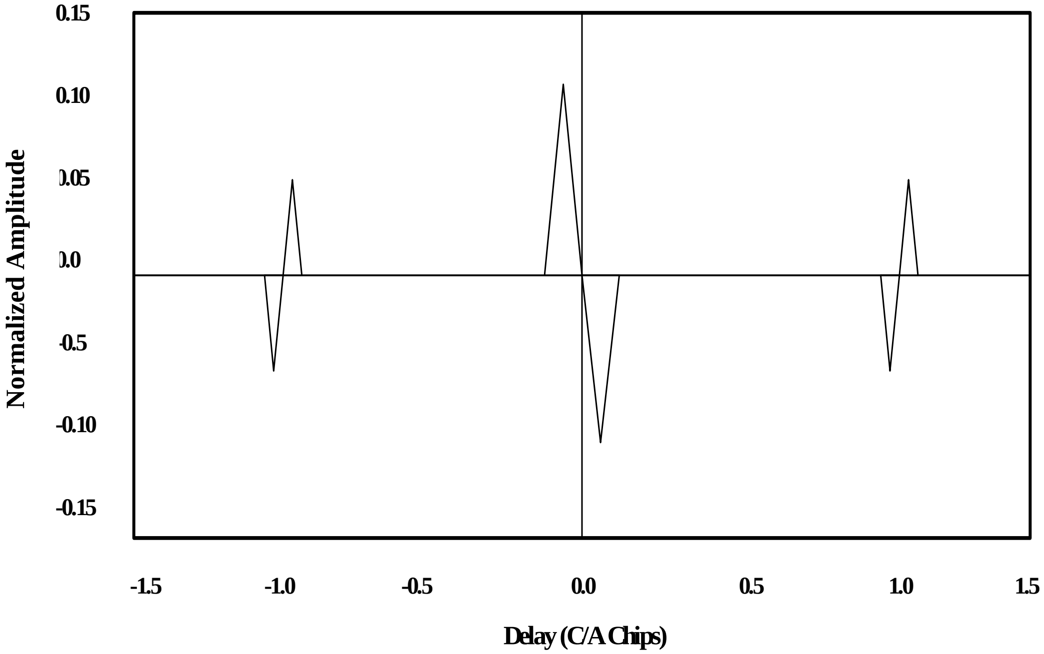

Figure 11: PAC correlation pattern

As can be seen from the figure, any multipath with delay between ±(0.1-0.9) chips will be rejected since it lies outside of the correlation function envelope. However, not all multipath greater than ±0.1 chips is rejected because some correlation occurs around ±1.0 chip. Therefore the PAC discriminator will be susceptible to multipath at these delays. However, this is a vast improvement over the narrow correlator early minus late discriminator correlation function shown in Figure 10 that is susceptible to any multipath less than 1.1 chips.

TEST RESULTS

By utilizing PAC tracking techniques, the receiver is capable of pseudorange measurement improvements better than 4:1 when compared to standard wide correlator techniques and 2:1 when compared to narrow correlation techniques.

Figure 12 illustrates relative multipath-induced tracking errors encountered by the different correlation technologies. The chart shows the theoretical multipath error envelopes for receivers using various correlator types including wide, narrow, MET, and PAC in a noise-free environment.

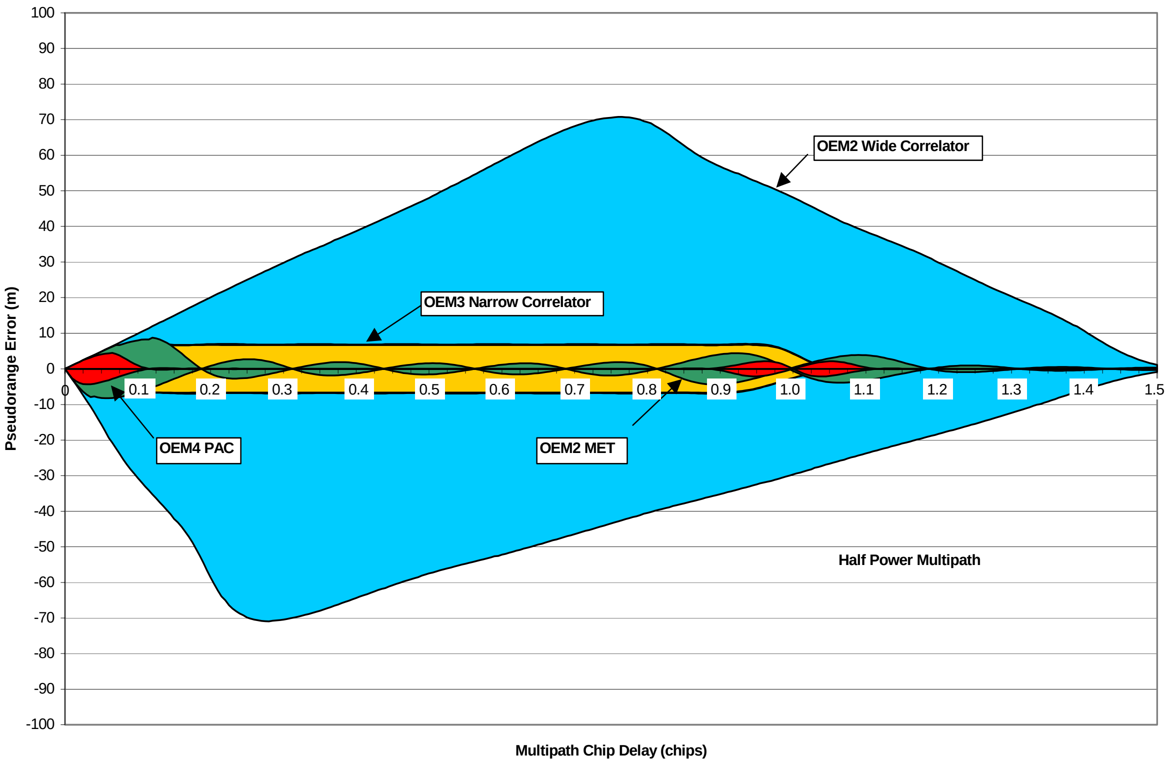

Figure 12: Comparison of multipath error envelopes

Figure 13 shows actual measured test results for the PAC correlator versus its theoretical counterpart. We can see the effect that noise has on the measured pseudorange but the results agree quite closely with our theoretical expectations. The error envelopes were plotted from data collected on each receiver connected to a GPS simulator outputting signals with an induced multipath with amplitude of 0.5. The multipath was cycled through a delay range from 0 to 1.6 chips at 0.2 intervals, collecting for 5 minutes in each interval while varying the phase from 0 degrees in phase to 180 degrees out of phase with respect to the direct signal.

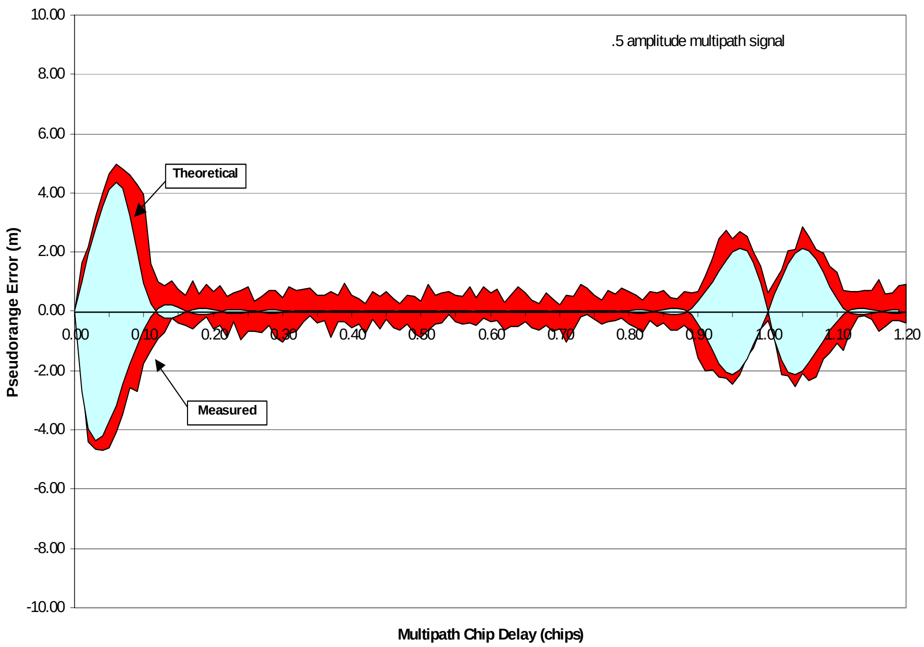

Figure 13: Measured vs. theoretical PAC multipath error envelopes

As shown in Figure 12, standard correlators are susceptible to substantial multipath biases for C/A code chip delays of up to 1.5 chips, with the most significant C/A code multipath bias errors occurring at about 0.75 chips (approaching 80 m error). The Narrow Correlator tracking technology multipath susceptibility peaks at about 0.1 chips (about 10 m error) and remains relatively constant out to 0.95 chips, where it rapidly declines to negligible error after 1.1 chips. The MET tracking method, peaks at about 10 m near 0.1 chips and has some larger effects of about 5 m surrounding 1 chip and some smaller effects in between 0.2 and 0.8 chips. The PAC correlator's multipath susceptibility peaks at about 0.05 chips (about 5 m error) then reduces to a negligible amount at about the 0.1 chip mark until there are some smaller effects around 1.0 chip.

As can be seen from the plot, there is a significant improvement in pseudorange accuracy of the PAC technology over MET technology. So, the next question is – how can this be if PAC is based on the same theory as MET? The answer is that MET was implemented on NovAtel's OEM2 GPSCard that had an 8 MHz bandlimited correlation function, but PAC is implemented on the OEM4, which has a 20 MHz bandlimited correlation function. This increased bandwidth allows for a sharper correlation function, making the ELS slope technique more effective, thereby reducing the tracking error due to multipath. As discussed earlier, if we had an ideal case with infinite bandwidth, where the correlation function is perfectly triangular, we could completely eliminate the multipath. So if we were to implement the MET technology on a 20MHz bandlimited OEM4, we would see the exact same results as for the PAC technology.

The improvement in pseudorange accuracy delivered by PAC technology will then translate into an improvement in position accuracy. While positioning in single point mode, the multipath and ranging improvement benefits of a PAC technology receiver versus MET, narrow, or standard correlators, are overridden by a multitude of GPS system biases and errors. In any case, the positioning accuracy will be in the order of 3 to 10 meters (SA off). However the benefits of PAC technology becomes most significant during pseudorange DGPS operation where the GPS system biases are largely removed.

Receivers operating DGPS with standard correlators typically achieve positioning accuracies in the 2 to 5 m CEP range (low multipath environment and using choke ring or GPS 600 antenna). NovAtel's Narrow Correlator tracking technology receivers are able to achieve accuracies in the order of 0.75m CEP, while PAC technology receivers are able to achieve accuracies in the 0.35 to 0.5 m CEP range.

SUMMARY

Any localized propagation delays or multipath signal reception causes biases to the GPS ranging measurements that cannot be differenced out by traditional DGPS single or double differencing techniques. When SA is inactive, multipath and ionospheric errors are the largest source of errors for single point positioning systems. Multipath is also recognized as the greatest contributor to errors in a system operating in differential mode. It has been discussed that careful site selection and improved antenna design are an effective means of reducing multipath reception, however this is not always possible, especially in kinematic positioning. Therefore internal receiver solutions for multipath elimination have been developed and can be achieved through various types of correlation techniques, where the standard correlator is the reference by which all other techniques can be compared.

It has been shown that PAC technology has a distinct advantage over the standard and narrow correlators. Through the use of a narrower and sharper correlation function, reduced susceptibility to multipath has been achieved with the rejection of C/A code delays of greater than 1.0 chip and reducing multipath to negligible levels for delays between 0.1 and 0.9 chips. This translates into a four-fold improvement over standard correlators and a two-fold improvement over narrow correlators.

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