Definition and Analysis of WAAS Receiver Multipath Error Envelopes

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BIOGRAPHIES

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ABSTRACT

Multipath is the primary range error constraining the accuracy of differential GPS systems. This has been an important motivating factor in the development of receiver and antenna technologies to mitigate multipath errors. This paper describes the results of a study of GPS receiver multipath error envelopes, measured using a high resolution technique for use with lab environment GPS signal simulators, and their consistency with multipath errors observed at the FAA's Wide Area Augmentation System (WAAS) reference sites.

Using the WAAS reference receiver, the effects of receiver bandwidth, correlator spacing, very short or extended multipath delays, autocorrelation function sidelobes, and multiple specular reflections were explored. Test results showed good agreement between theoretical, experimental, and field observed multipath error estimates and illustrated the characteristics and impact of the variety of multipath mitigating receiver technologies employed in the WAAS receiver. The results are widely applicable to GPS receiver designs in general, and other differential systems like LAAS.

Results confirmed the WAAS reference sites are dominated by close-in multipath. New multipath mitigation techniques such as ultra-narrow correlator spacing and refined receiver algorithms, coupled with new antenna designs, have the potential of further reducing multipath errors at differential reference sites.

INTRODUCTION

GPS receiver tracking loop performance can be adversely affected when weaker, delayed reflections off nearby surfaces interfere with reception and tracking of the direct satellite signal. The degradation resulting from these multipath signals depends on factors including antenna design, spreading code, bandwidth, and the type of correlator technology used in the receiver tracking loop.

Multipath mitigation continues to be an area of great interest and concern, particularly for differential reference stations like those in the FAA's Wide Area Augmentation System (WAAS). Multipath has been determined to be a significant error source at many WAAS Reference Stations (WRS) and additional receiver and antenna enhancements are continuously under consideration to address the problem. The incorporation of multipath mitigation processing techniques was one of the key selection criteria for the WAAS reference receiver.

The WAAS receiver is actually comprised of three GPS receiver subsystems integrated in a single unit, each utilizing distinct measurement and data processing techniques: Multipath Estimating Delay Lock Loop (MEDLL), Narrow, and Wide correlators (Figure 1). The MEDLL and Wide cards are configured as L1-C/A code receivers. The Narrow card is an L1/L2 receiver employing Novatel's proprietary codeless tracking capability. This unique blend of hardware and software offered an interesting opportunity to view and compare the multipath rejection capabilities of these different technologies.

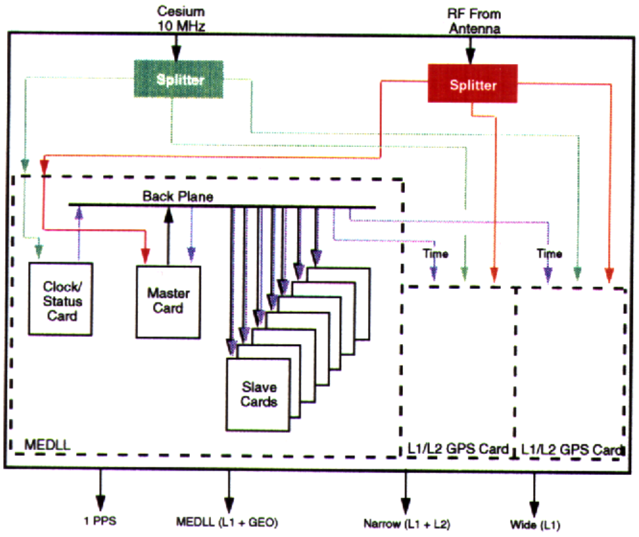

Figure 1. WAAS Receiver Schematic

Receiver multipath errors depend on the magnitude and phase of the reflected signal as it arrives at the antenna, thereby determining the extent to which it will degrade tracking of the direct satellite signal.

The impact of a multipath reflection can be observed in the receiver's correlation function using a WAAS receiver firmware utility that allows the correlation of a single tracked PRN to be simultaneously measured at 48 points (Figure 2). With no multipath present, a well-behaved triangular correlation of the direct signal is observed. When a -3 dB, 30 meter delay multipath signal is added 180 degrees out of phase with the direct signal, the correlation function is distorted and tracking errors result.

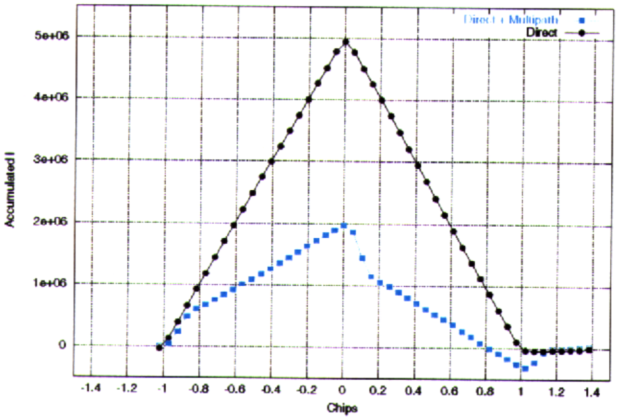

Figure 2. Multipath Distorted Correlation Function

Previous analyses have demonstrated how multipath errors for GPS receivers can be derived theoretically from a few key assumptions about the magnitude, phase, and delay of the reflection, coupled with the code chipping rate, bandwidth and correlator spacing of the receiver. Previous spot checks of envelope points using laboratory simulators and field data observations have confirmed the general accuracy of these theoretical estimates. [1, 2, 3].

These theoretical estimates demonstrate the multipath mitigation potential of narrow correlator designs and how the more sophisticated techniques like Novatel's MEDLL technology can result in performance approaching that of P-code correlators (Figure 3).

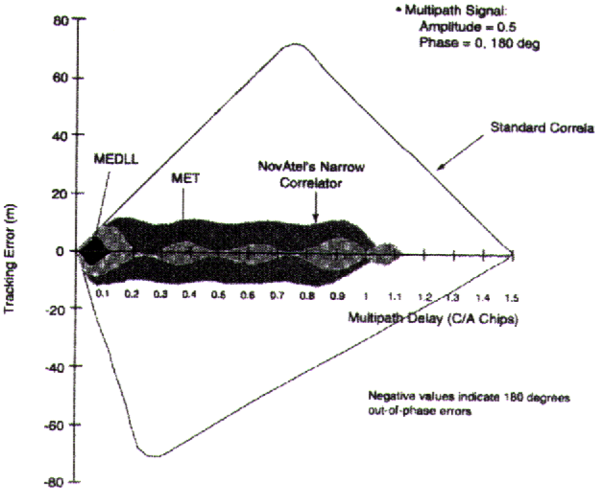

Figure 3. Theoretical Errors for WAAS Receiver

Given sufficient receiver bandwidth, multipath errors are proportional to the correlator spacing. Narrow correlator spacing one tenth that of the standard 1 chip spacing common to wide correlator designs yields a ten-fold improvement in multipath errors. The MEDLL card allows an even more accurate determination of the correlation function peak by using multiple 0.1 chip spaced narrow correlators to estimate the distortion caused by multipath and remove it from the correlation function. P-code error envelopes are even smaller still due to that code's higher chipping rate (10.23 MHz, vice 1.023 MHz for the C/A-code which will thus correlate with multipath at up to 10 times the delay of P-code).

The Narrow and MEDLL correlator designs also offer additional benefits such as improved receiver measurement noise. However, these techniques require greater signal bandwidths which can result in increased vulnerability to RF interference compared to a conventional wide correlator design using only 2 MHz bandwidth. The WAAS receiver uses an 8 MHz bandwidth in the MEDLL card and 18 MHz for the Narrow/Wide cards (Wide and Narrow cards use the same hardware, resulting in a larger bandwidth than necessary for the Wide card).

Data from WRS and Functional Verification System (FVS) sites have verified the theoretical expectations and demonstrated the substantial multipath mitigation provided by the MEDLL and Narrow correlator cards in the WAAS receiver relative to the receiver's standard 1 chip spaced Wide card. During one satellite pass at the Dayton FVS site, MEDLL errors never exceeded a few meters and Narrow card errors remained below 10 meters while Wide card errors approached 80 meters, as observed in a crossplot of these errors (Figure 4). However, data from these and other sites occasionally showed the Narrow card out-performing the MEDLL.

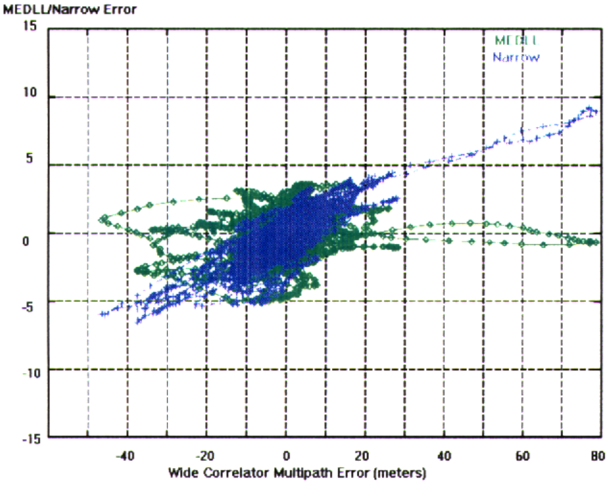

Figure 4. Multipath Errors Observed at Dayton FVS

An overall picture of the WAAS system multipath error environment is obtained by processing data collected from all WRS sites. The multipath errors for all satellite passes during a 24 hour period for each WRS were determined by computing the one sigma error versus elevation angle (Figure 5).

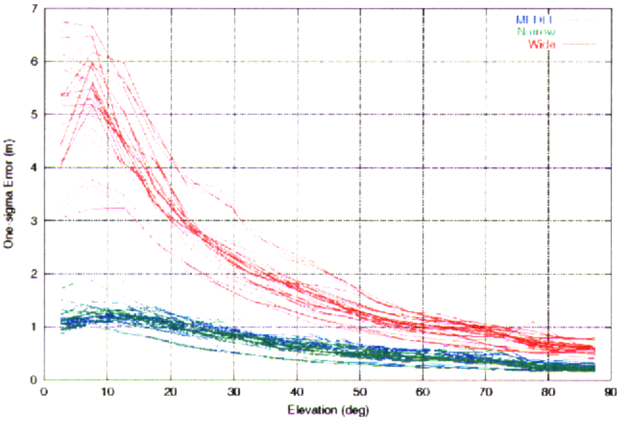

Figure 5. Multipath Errors for All WRS Sites

This data represents the combined effects of the antenna and receiver multipath mitigation measures. Well designed reference site systems couple receiver signal processing techniques with antennas designs to reduce multipath errors. The WRS sites adhere to this concept by marrying the WAAS receiver technologies with antennas that have significantly less gain at low elevations to attenuate multipath signals.

Although the vast improvement in multipath errors produced by the Narrow and MEDLL receiver card outputs relative to the Wide card was apparent in these data, the general equivalence in Narrow and MEDLL performance appeared to indicate the WRS sites are dominated by close-in, short delay multipath (< 30 meter delays), an environment where the MEDLL advantage is minimized. However, it was necessary to confirm individual card performance to rule out the possibility some problem was undermining MEDLL performance.

However, with any performance difference between these cards masked by the antenna error contributions, an accurate isolation of receiver multipath mitigation performance required a high resolution testing procedure which would not be dependent on field test data and its associated measurement and environment errors.

Measuring Multipath Error Envelopes

GPS receiver multipath errors typically have been determined by differencing code pseudorange and integrated carrier phase range measurements and correcting for L1/L2 ionospheric delays.

Given the repeatability of the GPS orbit ground tracks, a stationary receiver sees the same multipath errors 23:56 hours later. Narrow card error data computed from passes of PRN-19 on two consecutive days illustrates this effect (Figure 6). In fact, processing algorithms have been explored in previous studies which attempted to exploit the regularity of these multipath errors to model and then remove them from subsequent passes [4, 5].

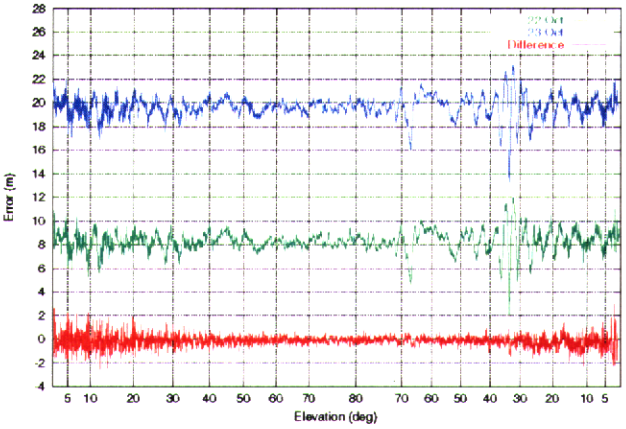

Figure 6. Multipath Errors for Consecutive Passes

Using this procedure, differences in the multipath errors for various receiver designs can be identified. The larger errors for the Wide correlator card were quite apparent in a comparison of data from all three WAAS receiver cards during a single pass of PRN-19 (Figure 7).

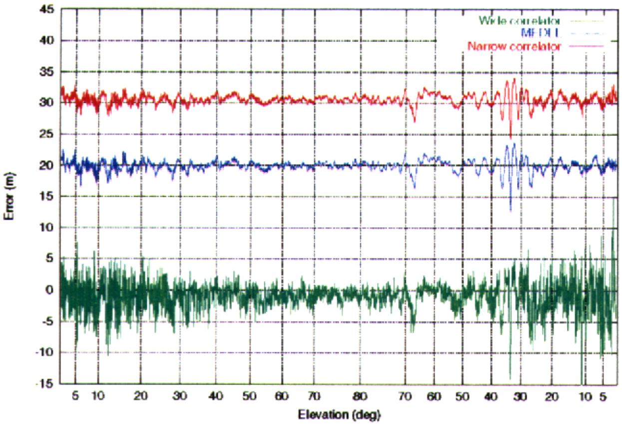

Figure 7. Receiver Multipath Errors (Single Pass)

However, the differences between MEDLL and Narrow cards were not significant and isolating the performance of either receiver card is difficult without an exact knowledge of the multipath environment, knowledge which is virtually impossible to obtain through field measurements or site modeling.

To minimize the dependency on field site data and its potential ambiguity when making relative receiver evaluations, isolation and mapping of the WAAS receiver multipath error envelopes required the use of "known" direct and multipath signal inputs, for which the signal levels and relative delays and phase could be carefully set and monitored in a controlled laboratory environment.

The laboratory setup for the multipath tests consisted of a multi-channel L1-C/A and P-code GPS signal simulator, preamplifier, the receiver under test, and a computer to log the signal strength, pseudorange, and phase data from the receiver at a 1 Hz rate. One channel of the GPS signal simulator was configured to generate a direct path PRN-1 satellite signal at the ICD-200 specified minimum signal level (-130 dBm). A second channel generated a multipath signal with the same PRN code, but at a lower level and with a variable delay relative to the direct path signal. A third channel was sometimes configured to generate a non multipath corrupted PRN-2 to serve as a reference.

To account for polarization and reflection losses, the multipath signal level was set at -4 dB relative to the direct signal. The delay was systematically increased in 1 cm steps every second up to a maximum of 450 meters delay (1.5 C/A-code chips). Some tests used 1 mm/sec step rates for even higher resolution.

With the receiver and simulator both phase locked to the same cesium frequency reference, multipath pseudorange errors were usually determined from a direct examination of the un-smoothed pseudorange data. However, some errors, particularly phase data, were computed by differencing the multipath corrupted PRN-1 signal track with a non-corrupted reference PRN-2 track to subtract out long term, temperature sensitive drift characteristics of the simulator and receiver phase lock loops.

Simulator controls did not allow direct control of the multipath signal phase. As a result, the phase of the multipath signal was strictly a function of the relative path delay. However, the small delay step sizes used (0.05 λ) resulted in a good statistical definition of the envelope boundaries. To simplify analysis, zero Doppler signals were produced by using a simulated satellite in a circular, zero inclination (equatorial) orbit with a polar observer.

These tests were lengthy, overnight procedures that required an automatic test execution setup. Fortunately, many GPS signal simulators can be configured in this manner. For example: Global Simulation Systems (formerly Nortel) 2760/4760 simulators (v5.04 software) have a replay mode in which user-defined action text files containing command sequences can be executed, Other makes of simulators may have comparable automatic test scripting facilities. These scripts or command action files can be lengthy (200,000 lines), but very simple programs can be composed to quickly generate them off-line.

Observations

The controlled and limited nature of these tests resulted in a straightforward, although simplified characterization compared with real world conditions for roof-top antennas mounted in noisy, complex multipath environments, receiving signals from a full GPS satellite constellation. Nevertheless, this testing procedure does offer a useful insight into receiver design and performance and represents a valuable development tool.

Tests conducted using the WAAS receiver illustrated the effects of various receiver design features and multipath signal characteristics on the receiver measurements and performance. These included receiver precorrelation bandwidth, correlator spacing, very short or extended multipath delays, autocorrelation function sidelobes, and multiple reflections.

Correlator Spacing

Correlator spacing is one of the most important elements in multipath mitigating receiver designs. Distortion in the correlation function is smaller near the peak and multipath tracking errors can be reduced by positioning correlators as close to the peak as possible.

Tests confirmed the dramatic impact reduced correlator spacing has on receiver multipath errors and code tracking accuracy. The measured multipath envelopes for the three WAAS receiver cards for zero to 450 meter delays (1.5 chips) showed the substantial multipath mitigation contributions of the Narrow correlator card (Figure 8). These results agreed closely with the theoretical envelope (Figure 3).

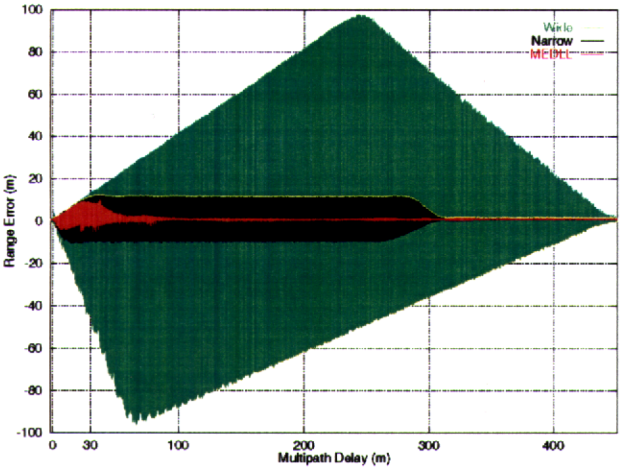

Figure 8. WAAS Receiver Multipath Error Envelopes

Results for the MEDLL card, which uses multiple narrow correlators to estimate the distortion caused by multipath and remove it from the correlation function, showed the even greater reductions in multipath errors provided by that technique (Figure 9).

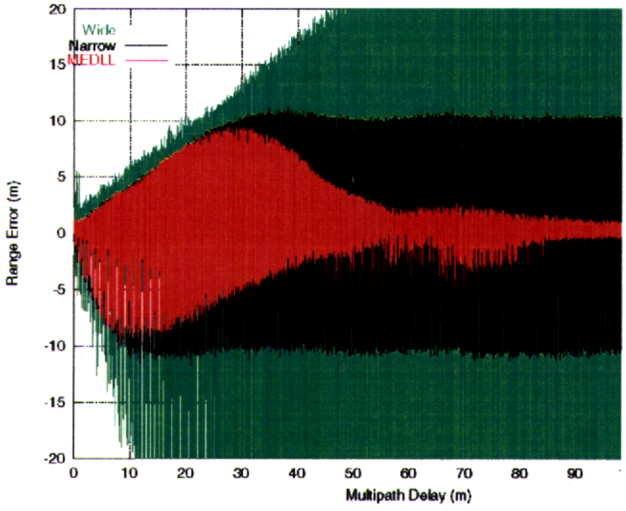

Figure 9. WAAS Receiver Card Error Envelopes

For delays greater than 0.1 chips (30 meters), the MEDLL error envelope shrinks dramatically. However, for close-in multipath delays of less than 0.1 chips, the differences in the multipath errors for each of the three WAAS receiver cards become much smaller, although the Narrow and MEDLL cards still provide a clear edge over the Wide card (Figure 10).

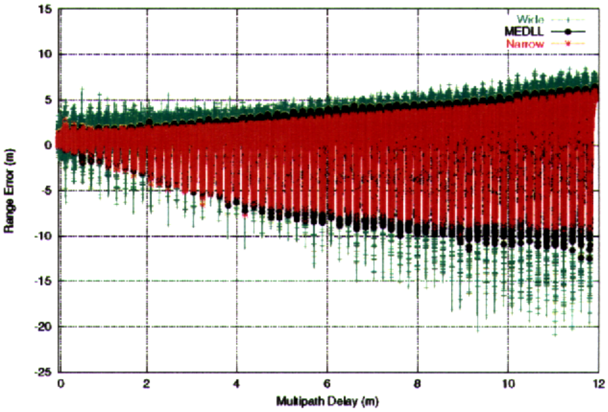

Figure 10. Close-in Multipath Errors

Although the Narrow card provides less multipath mitigation than the MEDLL at delays exceeding 0.1 chips, it does tend to out-perform the MEDLL in lower C/No environments. Initial MEDLL receiver designs included a provision to automatically switch to narrow correlator spacing in low C/No conditions. However, this feature sometimes resulted in excessive toggling back and forth between the two modes and it was not included in the WAAS receiver firmware. [3]

The MEDLL performance approaches that of a P-code receiver, as illustrated in the P-code multipath error envelope measured for the WAAS Verification Receiver (WVR) using this same laboratory procedure. This test also showed the WVR L1-C/A-code envelope reflects the use of narrow correlator technology (Figure 11).

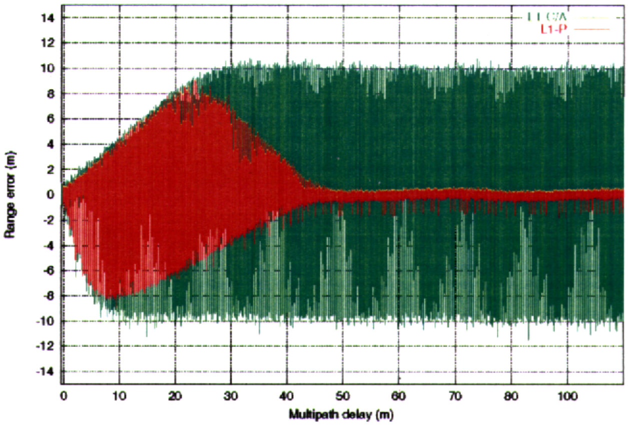

Figure 11. WVR Receiver Error Envelopes

Receiver tracking accuracy also improves in narrow correlator designs since, unlike most conventional one chip correlator receivers, the noise in the early and late channels becomes partially correlated and cancels out. The WAAS receiver pseudorange measurement noise with no multipath present was measured to be about 25 cm (1-σ) for the WAAS receiver Narrow and MEDLL cards for a -130 dBm signal, vice 87 cm for the Wide correlator card (Figure 12).

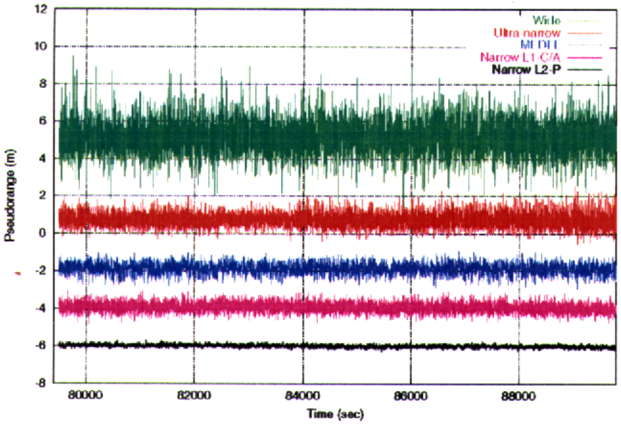

Figure 12. WAAS Receiver Tracking Channel Noise

While measurement noise is proportional to the square root of the correlator spacing, it is inversely related to the square root of C/No and thus measurement noise levels improve as the signal level is raised. With GPS satellites typically transmitting at levels 5 dB or more higher than the ICD-200 minimum guaranteed signal level, better measurement noise figures are usually available. Receiver lab tests with a GPS simulator signal input systematically varied about the minimum -130 dBm level (43 dB-Hz) show this improvement (Figure 13).

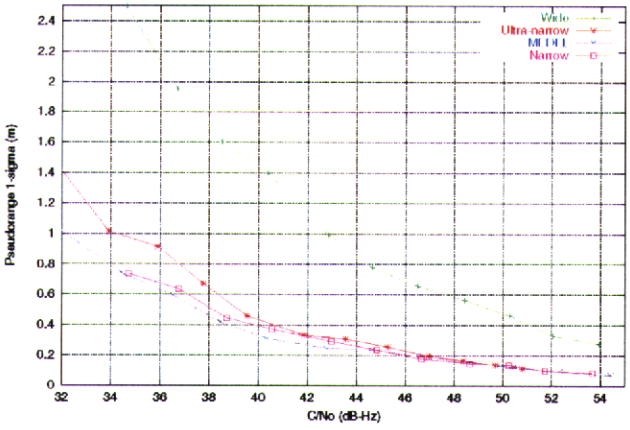

Figure 13. Receiver Measurement Noise vs. C/No

Although the narrow correlator technology used in the WAAS receiver results in significant multipath mitigation compared to the standard 1 chip correlator spacing, further decreases in correlator spacing appeared to offer the potential of additional reductions in receiver multipath error envelopes without resorting to the more sophisticated and expensive MEDLL techniques.

The effects and utility of ultra-narrow correlator spacing were investigated using experimental firmware for the Narrow card configured with 0.05 chip correlator spacing. The same GPS signal simulator procedure was used to map out the error envelope and some improvement in multipath mitigation was indeed observed (Figure 14).

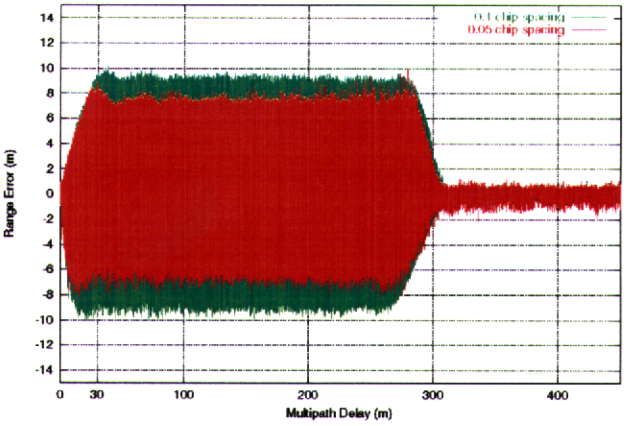

Figure 14. Ultra-narrow (0.05 chips) Firmware Test

The impact of the ultra-narrow correlator spacing on the combined WRS receiver/antenna system was measured by calculating the multipath errors for all satellites passes during a 24 hour period over Zeta and computing a one sigma for the observed error versus elevation angle. This data shows the improvement in multipath mitigation offered by the ultra-narrow technology relative to the Narrow and MEDLL receiver cards (Figure 15) in a relatively benign multipath environment.

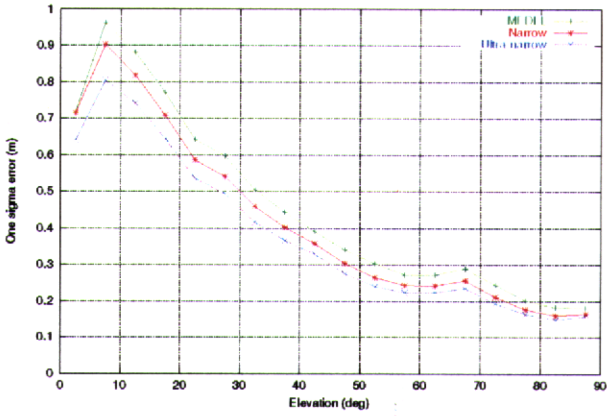

Figure 15. WAAS Antenna/Receiver Multipath Errors

However, the ultra-narrow fiirmware's demonstrated improvement in multipath mitigation came at the expense of increased measurement noise (Figures 12 & 13). The pseudorange one sigma increased to 37 cm from 24 cm for the 0.05 and 0.1 chip spacings, respectively, for a -130 dBm signal level. The ultra-narrow firmware measurement noise is even worse at the tracking threshold, however it approaches that of the 0.1 chip narrow card at typical GPS signal levels (48 dB-Hz).

This increased noise effect is attributed to the different discriminator algorithm used for this ultra-narrow firmware, as well as the bandwidth constraint of the front-end in the current Narrow card hardware design. A receiver designed to optimally exploit the 0.05 chip spacing might deliver better results.

Precorrelation Bandwidth

The use of narrow correlator spacing requires increased precorrelation bandwidth in order to sharpen the correlation function peak and keep the correlators in a linear operating region. The greater the bandwidth, the closer the correlators can be spaced together and the higher the resulting tracking accuracy. Tests comparing the 18 MHz bandwidth Narrow correlator card with an 8 MHz bandwidth card illustrated the effect of a bandwidth difference on the multipath error envelope (Figure 16).

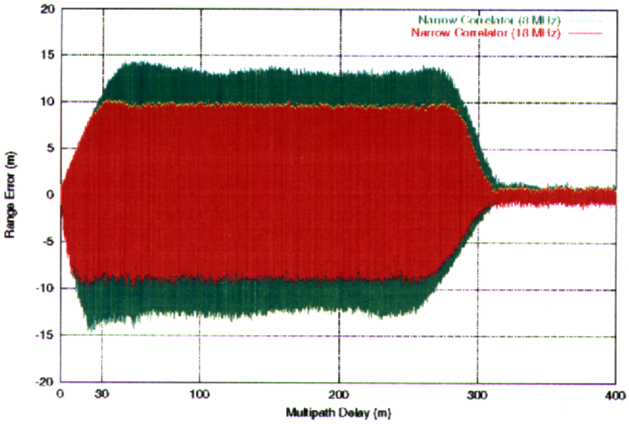

Figure 16. Precorrelation Bandwidth Effects (Narrow)

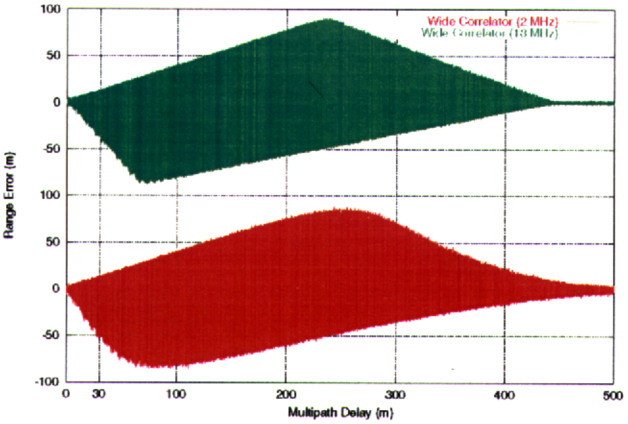

Figure 17. Precorrelation Bandwidth Effects (Wide)

The effects of greater bandwidth are also apparent in a comparison of the measured multipath envelope for a commercial 2 MHz bandwidth GPS receiver with the WAAS receiver 18 MHz bandwidth Wide correlator card (Figure 17). The narrower bandwidth of the 2 MHz receiver results in a rounding of the correlation function.

Multipath Signal Magnitude

The magnitude of multipath errors is a function of the level and phase of the multipath signal relative to the direct signal. Stronger reflections result in greater distortion of the correlation function and increased errors. This effect is illustrated for the WAAS receiver Wide and Narrow cards in tests generating simulated reflected signal levels of -4, -7, -10 and -13 dB relative to the direct path signal (Figures 18 & 19).

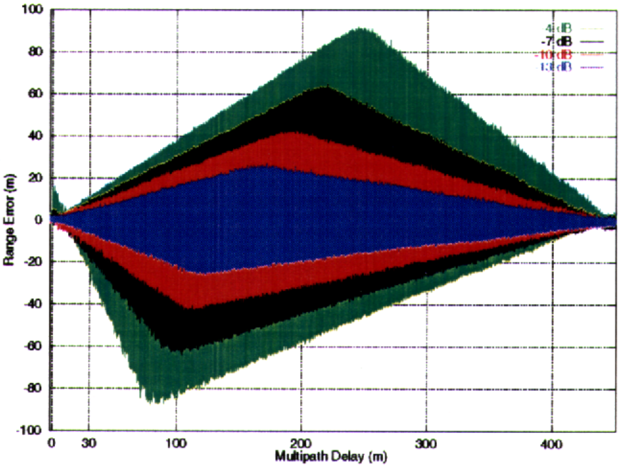

Figure 18. Wide Correlator Multipath Error Levels

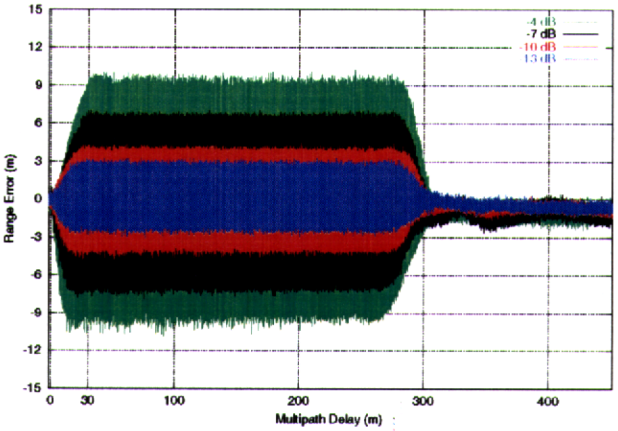

Figure 19. Narrow Correlator Multipath Errors

Signal Strength

Multipath signals will adversely impact the receiver signal-to-noise ratio depending on whether the direct and reflected signal components reaching the receiver combine constructively or destructively. When they add out of phase, the receiver C/No values can be seriously degraded to the point where the receiver can lose lock on the signal or suffer cycle slips.

C/No values are most adversely affected at short delays (Figure 20). The degradation in C/No for the Wide card approaches 8 dB-Hz at near zero delays for multipath signals -4 dB relative to the direct path. Signal to noise losses decrease in a somewhat linear fashion out to 1 chip delay. Losses are correspondingly lower for smaller amplitude multipath signals and are less than 2 dB-Hz low for -13 dB signals.

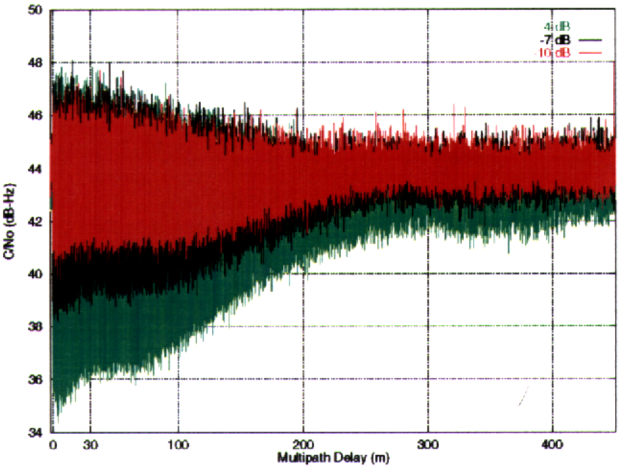

Figure 20. Wide Receiver C/No Comparison

The results are similar for the WAAS receiver MEDLL and Narrow cards, but, as predicted, with slight differences and decreases in the envelopes due to the more narrow 0.1 chip correlator spacing (Figure 21). [6]

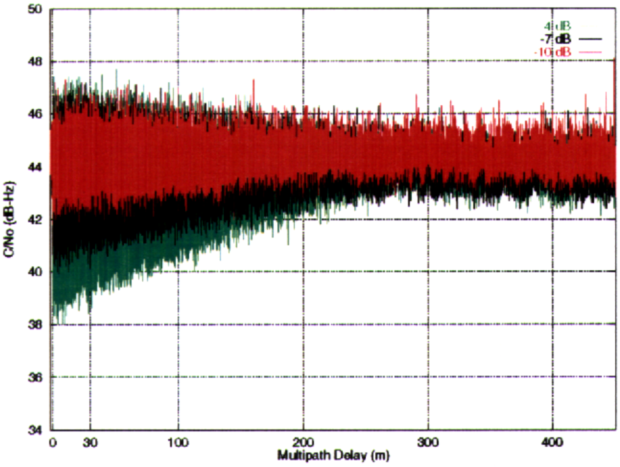

Figure 21. Narrow Receiver C/No Comparison

A close-up examination of the Narrow correlator simulator test data (-4 dB multipath signal) shows multipath-induced C/No changes are in phase with the multipath pseudorange errors (Figure 22). Carrier phase range errors are 90 degrees out of phase with C/No [6]. Nonlinear elements in the receiver design result in the distorted sinusoidal character of the measurements for multipath signals this large.

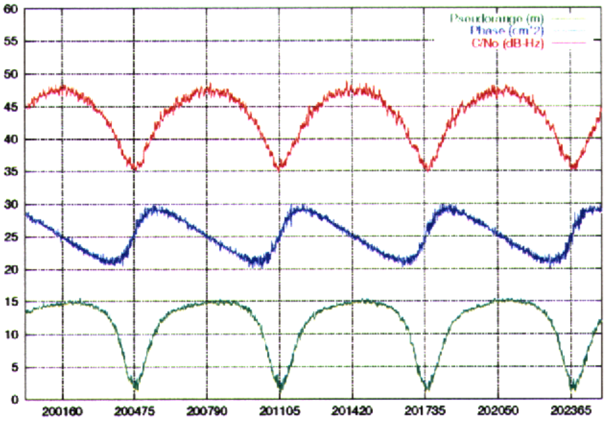

Figure 22. Phase Relation of Multipath Errors

Data collected during a GPS satellite pass shows the same correlation between C/No and the calculated pseudorange multipath error (Figure 23). Data from the WAAS FVS sites have shown C/No degradations sufficiently severe in some locales to result in loss of lock and/or carrier tracking cycle slips.

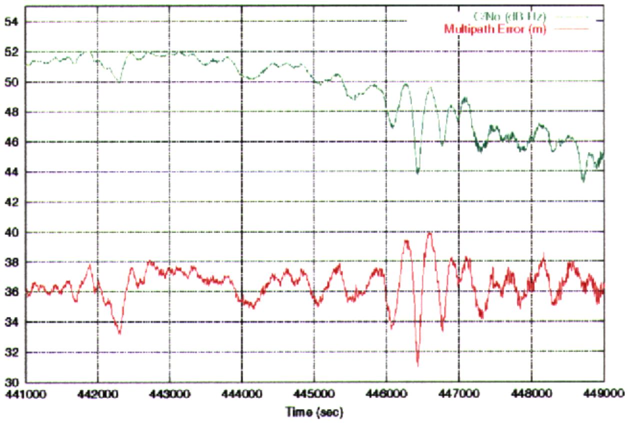

Figure 23. WAAS Receiver C/No (Antenna)

Receiver processing algorithms have been proposed which exploit the C/No and multipath error correlation in an attempt to model and correct for multipath-induced phase errors [7].

Phase Errors

Phase errors caused by multipath behave in a manner somewhat similar to C/No. In laboratory tests, phase errors were observed to peak at 25 mm for short delays and decrease somewhat linearly to the receiver phase noise level (1.9 mm 1-σ) by one chip delay (Figure 24).

In these single reflection tests, the peak phase error is reduced as the reflection signal magnitude is decreased and is under 1 cm by -13 dB (the phase errors shown are artificially low since they were computed by differencing the multipath-corrupted PRN phase data with that of a reference PRN).

These phase errors are much smaller than the 100 meter error magnitudes potentially obtainable in the code range data, but would be large enough to cause phase ambiguity resolution problems in high dynamic applications. The phase errors for the Narrow card are similar (Figure 25).

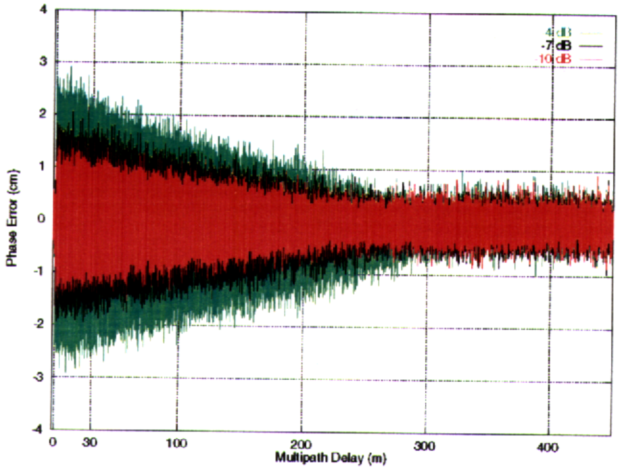

Figure 24. Wide Receiver Phase Errors

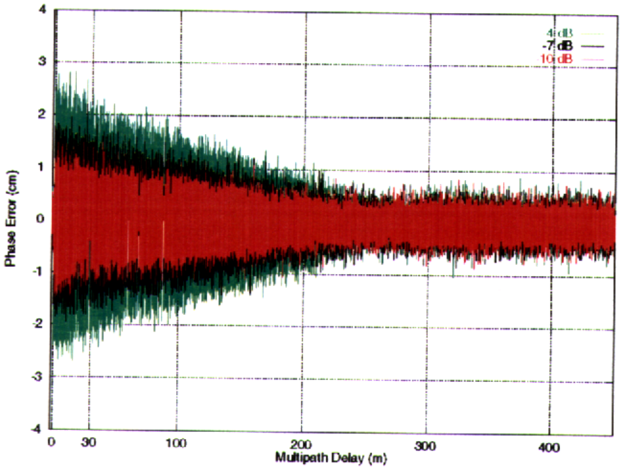

Figure 25. Narrow Receiver Phase Errors

MEDLL card phase errors were nearly identical to those of the Narrow card, although previous studies have demonstrated the feasibility of phase multipath error mitigation improvements for the MEDLL which result in a significant improvement in phase error relative to wide correlators. Using this technique, phase errors became small at delays of 0.2-0.4 chips in the MEDLL, vice the 1 chip delay required in the wide correlator. However, this technique remains a developmental procedure and is not present in the WAAS receiver firmware. [8]

Long Delay Autocorrelation Sidelobe Errors

Multipath error analyses typically simplify the problem by assuming errors are negligible at long path delay values. However, mapping of the error envelope at extended delays demonstrates this is not always the case because of the significant sidelobe levels common to some PRN code autocorrelation functions.

Previous studies of this effect have shown codes like PRN-8 can yield substantial multipath errors at delays greater than one chip plus half the correlator spacing (Figure 26). Other codes like PRN-1 are relatively multipath error-free out to 8 chips delay (2.4 km). GPS PRN codes 31 & 32 have the best long delay characteristics (flat to 9 chips) and the best WAAS PRN (131) is flat out to 18 chips delay. [9]

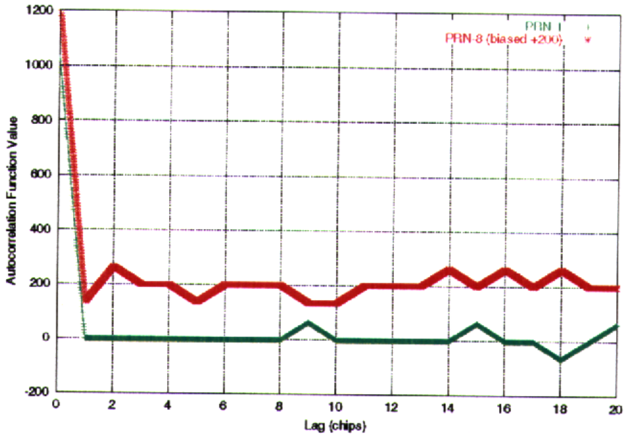

Figure 26. PRN-1/PRN-8 Autocorrelation Functions

A laboratory simulator test mapping the PRN-8 error envelope using the WAAS WRS receiver cards shows the significant errors that remain at extended delay values (Figure 27). The bulges in the error envelope at longer delays for the Wide correlator card correspond to areas in the PRN-8 autocorrelation function where the function is not invariant and thus some correlation occurs. In contrast, the envelope for a code with minimal sidelobe levels, like PRN-1, approaches the receiver noise level at long delays (Figure 28).

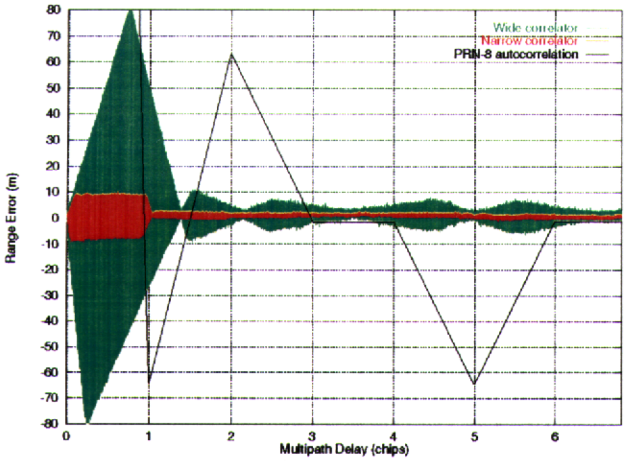

Figure 27. PRN-8 Multipath Error Envelope

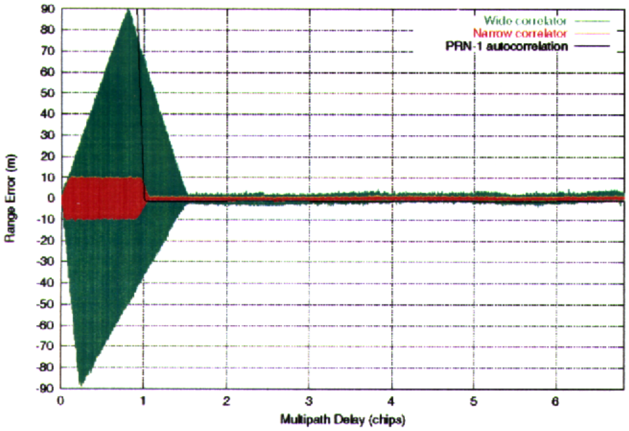

Figure 28. PRN-1 Multipath Error Envelope

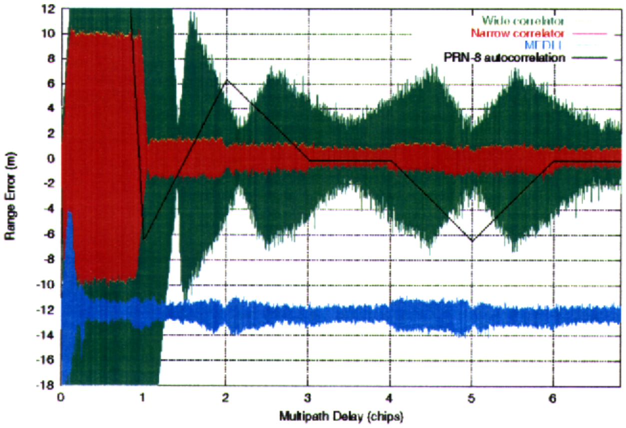

Figure 29. Narrow Correlator Errors at Long Delays

The Wide card shows errors rebounding beginning at 1.5 chips (450 meters), with errors reaching a magnitude of 10 meters. MEDLL and Narrow cards show similar effects at 1.05 chips delay (308 meters), peaking as high as 1.5 meters at long delays (Figure 29). Although code errors can be significant, phase and C/No measurements are not noticeably affected at these long delays for any PRN code.

Multiple Reflection Sensitivity

Receiver multipath error envelopes are typically characterized using only a single, strong refleciton. To explore the WAAS receiver's response to multiple reflections, the simulator was configured to generate a second reflection fixed at 21.1 meters delay and at a level -18 dB relative to the direct signal, in addition to the -4 dB variable delay signal. The MEDLL receiver was designed to handle two strong multipath reflecitons and no significant change in the MEDLL or Narrow error envelopes was observed using this pair of reflections.

However, additional distortion in the multipath error envelope became evident when a third reflection at -7 dB and 30 meters delay was added (Figure 30). Peak Narrow card errors increased from 10 up to 15 meters. When yet a fourth fixed reflection was added at -20 dB and 199.12 meters delay, the MEDLL error envelope actually exceeded that of the Narrow card in a narrow delay window and frequent cycle slips occurred in all cards at short delays (although performance at long delays remained superior). Peak Wide card errors increased only slightly and peak Narrow card errors remained 15 meters.

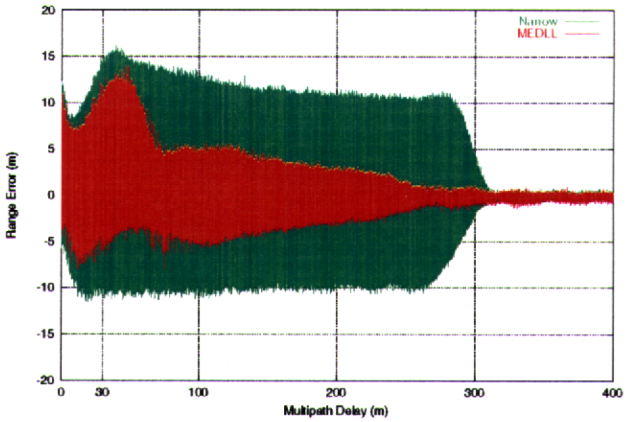

Figure 30. Error Envelopes with Multiple Reflections

They confirm the general equivalence in Narrow and MEDLL multipath mitigation at short delays and the potential for the Narrow card performance to occasionally exceed that of the MEDLL. This is consistent with field test data indicating the WRS sites are dominated by close-in, short delay multipath (< 30 meter delays), an environment where the MEDLL advantage is minimized.

These tests demonstrated the value of testing with multiple reflections to more carefully characterize the performance of receiver multipath technologies and to project their response in real world deployed antenna environments.

Antenna Effects

Like receiver technology advances, WAAS and LAAS antenna experiments provide evidence that additional multipath mitigation at the WRS locations can be incorporated into future antenna designs which can impact the close-in multipath problem.

An evaluation of data collected using the WAAS receiver with an integrated multipath limiting antenna---a design combining a linear dipole array (MLA) with a high zenith element (HZA)---showed significant reductions in multipath errors at low elevations could be achieved compared to the WAAS Micropulse WRS antenna (Figure 31). Other proposed designs offer the potential for similar reductions [10, 11].

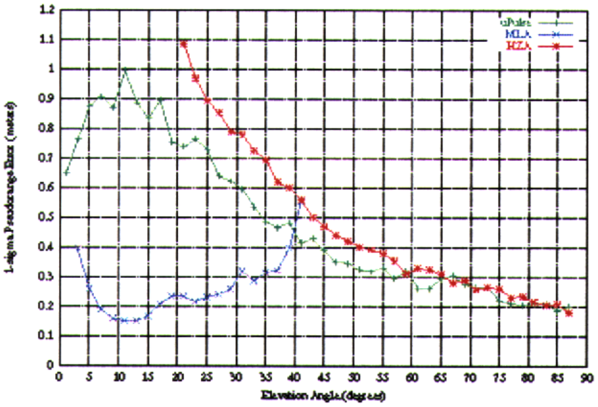

Figure 31. WAAS Receiver/MLA Antenna Errors

SUMMARY

This paper has illustrated the effects of receiver bandwidth, correlator spacing, very short or extended multipath delays, autocorrelation function sidelobes, and multiple specular reflections on GPS receiver multipath error envelopes using a high resolution lab mapping procedure. This procedure allows rapid and automatic evaluation of multipath errors in support of receiver development and improvement cycles.

The results illustrate the characteristics and impact of the variety of multipath mitigating receiver technologies employed in the WAAS receiver. The laboratory measurements are consistent with multipath errors observed at WAAS reference sites. The combined effect of receiver and antenna mitigation technologies at the WAAS reference sites indicates errors are being kept at or below the 1-2 meter level.

Multipath mitigation techniques like ultra-narrow correlator spacing and new antenna designs demonstrate the potential value of these techniques in differential GPS systems like the FAA's WAAS and LAAS where multipath is one of the primary errors constraining the accuracy of the system.

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