A COMPARATIVE STUDY OF ADVANCED MULTIPATH MITIGATING GLOBAL POSITIONING SYSTEM RECEIVER ARCHITECTURES

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This thesis addresses the problem of multipath in spread spectrum ranging systems. In particular, the thesis deals in multipath with respect to the Global Positioning System (GPS). The scope of this thesis is within the realm of receiver processing techniques. GPS, or the NAVSTAR GPS, refers to a ranging system set up by the US DoD (The Department of Defense). This was initially setup for military purposes, but in the recent past its impact on the civilian community has been immense.

The core of this thesis starts with a brief introduction to the Global Positioning System (GPS) and goes on to give a description of the major source of error in Differential GPS. Its adverse effects are pointed out and, a description of the techniques used to mitigate multipath is explained in the fourth chapter. Also stated is the theoretical basis for these techniques, supported by MATLAB based simulations. The fifth chapter deals with the carrier phase multipath limiting capabilities of the techniques discussed in chapter three. The sixth and seventh chapters given an idea about the relative performance of these multipath mitigating architectures which leads to some ineluctable conclusions as shown in chapter seven.

References are included at the end of the report, after the section on comparisons and conclusions. Plots illustrating the performance of each receiver architecture are found
in the respective appendices. Some plots are also included with the theoretical exposition. Much of the material contained in this thesis was originally presented in a report to Rockwell Collins [22].
CHAPTER 2

OVERVIEW OF THE GLOBAL POSITIONING SYSTEM

This section describes the satellite constellation, the ranging equations using four satellites and gives a basic idea about the signal structure.

2.1.1) SATELLITE CONSTELLATION

GPS, as stated before, was a DoD venture. It is a constellation of 24 satellites. The orbits of this satellite constellation are inclined at 55 degrees to the equator, with four satellites in each of six orbital planes. These satellites are not placed in a uniform manner and are positioned in their respective orbits based on the type of signal coverage they need to provide. The satellites are used for positioning in three dimensions. The operating logic is to find out the time of transmission of the signal from the satellite, which can be obtained from the received signal, and find out the time of reception using a reference clock at the receiver. Based upon these two times, travel time can be estimated. The travel time is proportional to the distance between the satellite and the receiver.

The received signal provides the satellite ephemeris data that allows the user to compute the satellite position. So, the user has an idea of where the satellite is. Hence, the user position is given to be in the locus of all points that are at the computed satellite receiver distance. It may be noted that this is a sphere. Similarly, with two
more satellites the user can tell the distance from each of the satellites and there are three spheres to deal with. From basic geometry, it follows that that the user position in three dimensions is given by the point of intersection of the three spheres.

The implementation of the receiver algorithms generally requires a minimum of four satellites to obtain a position fix. This goes back to the well-known problem of timing inaccuracies in spread spectrum ranging systems. So, the receiver takes the clock bias that arises due to inaccurate time measurements at the receiver and solves for it as an unknown. Using an additional number of satellites is helpful when it comes to improving accuracy and integrity monitoring.

If there were three satellites, the above technique would result in trying to solve for four unknowns \((x, y, z\) position and \(c_B\), the clock bias) with three equations. In order to meet the mathematical requirement, the minimum is four satellites. This would give four equations with four unknowns. The equations concerning this solution are on the next page. The equations given below are an absolute minimum to obtain a position solution when the clock used at the receiver end is not of atomic standard. If more satellites are used to obtain the position solution, then the user could perform integrity monitoring.

2.1.2) THE RANGING EQUATIONS USING FOUR SATELLITES

\[(x_1 - u)(x_1 - u) + (y_1 - v)(y_1 - v) + (z_1 - w)(z_1 - w) = (R_1 - C_b)(R_1 - C_b)\]
(x2 - u) \times (x2 - u) + (y2 - v) \times (y2 - v) + (z2 - w) \times (z2 - w) = (R2 - Cb) \times (R2 - Cb)

(x3 - u) \times (x3 - u) + (y3 - v) \times (y3 - v) + (z3 - w) \times (z3 - w) = (R3 - Cb) \times (R3 - Cb)

(x4 - u) \times (x4 - u) + (y4 - v) \times (y4 - v) + (z4 - w) \times (z4 - w) = (R4 - Cb) \times (R4 - Cb)

Where:

u, v, w are the user's position coordinates

and, "Cb" is the clock bias.

x1, x2, x3, x4, y1, y2, y3, y4, z1, z2, z3, z4 are the co-ordinates of the four satellites which could be determined from the ephemeris data. R1, R2, R3, R4 are the measured data.

This system, like any other, is not immune to errors. A multitude of error sources affects the basic GPS measurements of pseudo range and integrated doppler. Among these are the URE (user range error like the unintentional clock and ephemeris errors), intentional satellite clock and ephemeris errors (SA – Selective Availability), ionospheric delay, tropospheric delay, receiver tracking, multipath and noise. Most of these errors can be eliminated using code and carrier differential techniques.

Many GPS errors can be reduced through a technique known as differential GPS (DGPS). The technique requires a reference station to be sited at a known location. The reference receiver computes corrections by taking the difference between the measured pseudo-range and the true range from the satellite to the receiver.
The corrections are then data linked to a mobile user. This eliminates errors that are common to the reference and mobile receivers. Multipath is the dominant source of error in DGPS because it is not common to spatially separated users.

However, even while performing DGPS, thermal noise, multipath, and dynamic tracking error are not eliminated since they are not common to the user and the surveyed reference station [20]. Dynamic tracking errors typically are small (i.e., well under a meter) and code-phase noise levels are of the order of one meter. Multipath levels can exceed 50 meters, but are normally on the order of 10 meters. Filtering can reduce code-phase noise errors. Finally, multipath remains, as this source of error is not common to the receiver sites. High accuracy applications like precision approach and landing require tight multipath error control. More literature on this is available in various books dedicated to GPS and spread spectrum ranging systems [10].

2.1.3) GPS SIGNAL STRUCTURE

In order to gain a better understanding of the system it would help to take a look at the signal structure. The GPS signal is transmitted at two frequencies. These are called the L1 and L2 signals. The L1 signal has a center frequency of 1575.42 MHz, and the L2 signal has a center frequency of 1227.6 MHz. The L1 signal has two pseudo random codes on it. They are called the C/A code and the P code. These codes are called pseudo random because they resemble a random binary sequence.
The C/A code is generated using shift registers. Actually, two 10 bit shift registers generate a sequence of codes. These codes are modulo two added to give a C/A code (this code has interesting cross-correlation properties). The P code is generated in a slightly different way using twelve bit shift registers. Each satellite keeps transmitting a unique C/A sequence. This helps identify the satellite for tracking.

The C/A code has a lower chipping rate when compared to the P code. Actually, its chipping rate is one-tenth of that of the P code. The P code has a chipping rate of 10.23 MHz. The P code has a period of one week. (i.e. it repeats the same sequence exactly after one week). In comparison the C/A code has a very short period. It has a period of one millisecond and a chipping rate of 1.023 MHz. [10]

Originally, when the signal structure was decided upon, the C/A code was used to acquire the more precise P code. The innate capabilities of the C/A code had not been exploited. Since the C/A code uses a 10 bit register it repeats the sequence after every $2^{10} - 1$ states. (i.e. 1023 states).

The unique property of this code is that, if we try to cross correlate this code with a copy of itself, it will give us a peak when it is aligned with itself and gives negligible cross correlation when the shift is more than one chip. This helps when it comes to tracking the code and recovering timing information. It also gives negligible cross-correlation when it is cross-correlated with a different C/A code.
The L1 signal has both the C/A and the P code on it, along-with the navigation data that is modulo 2 added to the C/A and P codes. The transmission mode for both L1 and L2 signals is RHCP (Right hand circular polarization). The L2 signal either has the P code on it or the C/A code on it. These signals are bi-phase modulated. (i.e. PRN codes are present on both in-phase and quadri-phase components of the carrier).

In the L1 signal, the in-phase component carries the P code and the quadri-phase component has the C/A code on it. In addition to this there is a 50 bps data stream modulated (X-OR) onto both the in-phase and quadri-phase components. In our case one is more concerned about the C/A code.

Ranging can be done in the code as well as the carrier domain. Also, the carrier phase is used to smooth the code phase readings. This has helped reduce the adverse influence of noise on ranging in the code domain. At L1 frequency the carrier has a wavelength of 19.05 cm.
CHAPTER 3

MULTIPATH FUNDAMENTALS

When the incoming signal takes more than one path to reach the receiver, it is termed multipath. The direct signal takes the shortest path. (This is the line-of-sight signal that comes direct from the satellite). All other reflected signals that arrive later are termed as multipath signals as shown in figure 1. In spread spectrum ranging systems, one is interested in the direct signal. But, the copies of this signal that arrive with different delays cause the received signal to become corrupted.

Figure 1: Illustration of Multipath [23]
This affects pseudo-range and carrier measurements, as will be shown. The sole purpose of this thesis is to investigate different receiver techniques that help combat multipath.

3.1) MULTIPATH PARAMETERS

The incoming signal can be characterized as follows:

\[ s(t) = \cos(\omega t + p(t)\pi/2) \quad - (1) \]

where, \( \omega \) is the frequency of the received signal in radians per second (this includes the Doppler shift) and \( p(t) \) is the PRN code. (It is either 1 or -1). The amplitude of the incoming signal has been normalized to one.

This may be rewritten as:

\[ s_1(t) = -p(t)\sin(\omega t); \quad - (2) \]

Once inside the receiver, multipath is characterized by four parameters [2]:

1) Amplitude
2) Delay
3) Phase
4) Phase rate
A stable multipath scenario is assumed and the relative phase rate of change is assumed to be zero. Here, the case of a single multipath ray is considered. The incoming signal could be written as:

\[ s_{1m}(t) = s_1(t) + \text{amp}*s_1(t - \delta) \]  

- (3)

Where, "amp" is the amplitude of the multipath relative to the direct, "\(\delta\)" is the multipath relative time delay.

Substituting (2) in (3),

\[ s_{1m}(t) = -p(t)*\sin(\omega*t) - \text{amp}*p(t-\delta)*\sin(\omega*t + \theta) \]  

- (4)

Where, "\(\theta\)" is the phase of the multipath relative to the direct.

In the cases where the phase of the multipath is taken into account and is neither zero nor \(\pi\) radians, it has been anchored to the time delay. In a real life situation, the phase is dependent upon other factors apart from the time delay.

### 3.2) CROSS-CORRELATION FUNCTION

The receiver cross correlates the incoming code with a locally generated code. The tracking is performed after signal acquisition. This gives the cross-correlation function \(R(\lambda)\) as shown in figure 2. If there is multipath, theoretically, one can assume an auto-correlation function for the multipath signal \((R(\lambda-\delta))\), where \(\delta\) is the delay of the multipath with respect to the direct) as in figure 3. This has a peak at a delay of "\(\delta\)". This peak is of a different amplitude (This is a function of the strength
Figure 2: Plot of the Cross-correlation Functions (Direct and multipath)
Figure 3: Ideal Auto-correlation Function
of the multipath to direct signal (M/D)). This ratio is denoted by "amp" in the following sections and in the MATLAB code.

The system being linear, the composite function is the sum of these two functions, the direct and the reflected (multipath). This may very well cause the function to be distorted, depending upon the amplitude of the multipath as shown in figure 4. In most GPS receivers the code-tracking loop is mechanized with a phase detector known as the discriminator. Taking the difference between the received code and the early and late versions of the locally generated code forms this discriminator.

3.3) THE DISCRIMINATOR

Figure 5 illustrates an ideal discriminator function while figure 6 shows a discriminator function that could result when multipath is present. In the ideal case, the incoming signal and the locally generated code are kept in lock by tracking the zero crossing of the discriminator function. However, multipath distorts the discriminator function in such a manner that the zero crossing of the discriminator function is shifted figure 6. The pseudo-range multipath error is given by scaling the difference between the zero crossings of the ideal and distorted discriminator functions by the chip size in meters.
Total cross correlation function (Direct plus reflected components), delay = 0.5 chips, amp = 0.5

Figure 4: Plot of the Cross-correlation Functions (Direct plus Multipath)
Figure 5: Plot of an ideal discriminator function
Figure 6: Plot of the composite distorted discriminator function

(Direct plus Multipath)
MDR is the multipath to direct ratio in dB. Also seen from the plots of the discriminator function for the two cases (on the next page, with and without multipath), the zero crossing of the discriminator function is offset due to multipath. The degree to which the zero-crossing of the distorted discriminator function is offset in comparison to the discriminator function formed from the cross-correlation function that is unfettered by multipath, is proportional to the code tracking error discussed earlier.

All of the above mentioned functions are performed in a DLL (Delay Locked Loop). There are two categories of delay locked loops, the Coherent and non-coherent DLL’s. In the coherent DLL the system keeps track of the phase of the incoming signal, while in the non-coherent DLL the received signal is processed in such a way that its phase is discarded. As an example, the standard 1 chip Early-to-late spacing DLL is discussed below.
3.4) THE STANDARD ONE CHIP DLL

Here, one comes across the concept of chip spacing. Referring to The auto-correlation function of the C/A code, it is triangular in shape. Geometrically speaking, this function is shifted half a chip (in time) to the left and the right. This results in the early and late version of the correlation function. In the receiver this is implemented by having an early and a late correlator on either side of the auto-correlation peak, which is locked onto by the receiver. The following sections assume that one is using a coherent DLL. In addition, the coherent DLL has a phase locked loop that aids in recovering the phase information from the signal using a Phase Locked Loop (PLL).

The functions thus obtained (the early and late versions) are used to form a discriminator function. "Early – late" gives the discriminator function. When the auto-correlation function is unfettered by multipath, the discriminator function should have its zero crossing at zero delay. If the signal has been distorted by multipath, then the discriminator function does not cross zero at zero delay (as shown in the figure). The zero crossing is shifted by some amount. This is called the tracking error as shown in figure 7. This is the tracking error in chips. The code tracking error in meters is given by the negative of the tracking error in chips scaled by the chip size (1 C/A chip = 293.3 meters).

Conventional GPS receivers have used a 1.0 chip spacing in the implementation of the delay locked loop (DLL). However, there are distinct advantages to narrowing
Figure 7: Code tracking error for the standard one chip early – to – late spacing
this spacing in C/A code tracking applications [15]. These are the reduction of tracking errors in the presence of noise and multipath. The flip side is the high pre-correlation bandwidth coupled with high sampling and signal processing rates.

However, generally speaking, the desired code spacing determines the amount by which the correlators are placed on either side of the peak. For an early-late spacing of “d” chips, the shift is “d/2” chips to the left and the right respectively (geometrically speaking).

The multipath effects dominate the error budget while the receiver utilizes the C/A code to obtain a position fix. The effect of multipath around the peak of the direct component of the correlation function is less severe than that on other regions of the correlation function.

The simulation for the one chip early late version and the narrow correlator version is done for a range of delays from 0-1.5 chips. The tracking error is computed and the plot of code tracking error in meters versus delay in chips is shown. This is done for different values of “amp”. Here, “amp” is the relative amplitude of the multipath relative to the direct. This is generally referred to in units of decibels.

The performance of a DLL is highly influenced by the pre-correlation bandwidth. The C/A code has a bandwidth of 2.046 MHz. The pre-correlation bandwidth is generally in the range of 8-20 MHz. The degree of band limiting has a direct relation to the
sharpness of the auto correlation peak. The greater the bandwidth, the sharper the auto correlation peak. The sharper the peak, lesser the chance of committing an error while tracking the peak. Hence, the trade-off involved is obvious. The effect of band limiting on the code tracking error can be seen from the plots.

The plots at the end of this section (figures 7 and 8) are the code and phase tracking errors for the standard one chip early-to-late spacing respectively over a range of 0-1.5 chips in delay. A comprehensive list of plots is given in Appendix (A) for the standard correlator (one chip spacing). These plots are for the bandlimited case.

The next section discusses other techniques that mitigate multipath at the receiver level. At this moment it would be interesting to note that receiver level techniques are not the only way by which multipath can be mitigated. Antennas with excellent gain patterns in the direction of the direct signal have been developed. The same antennas let in negligible amounts of signal in a different direction. In this manner, the strength of the multipath that corrupts the direct signal is reduced and causes lesser tracking errors, as the multipath generally takes a different route to the receiver. The concept of phase multipath will be dealt with in detail in a later section. But, it would be helpful to have an understanding of what it means while we discuss code multipath.

In a coherent receiver, the code and the carrier tracking loops aid each other. For the sake of simplicity, let the phase of the direct incoming signal be zero. Let the phase of
Figure 8: Phase tracking error for the standard one chip early – to – late spacing
the multipath be \( \theta_m \). Then, the composite phase of the signal the receiver is tracking will be \( \theta_c \), where \( \theta_c \) is given by:

\[
\theta_c = \text{atan} \left( \frac{R(\lambda - \delta) \sin(\theta_m)}{R(\lambda) + R(\lambda - \delta) \cos(\theta_m)} \right)
\]

- (1)

Where:

\( \lambda \) is the code tracking error (in units of chips).
CHAPTER 4

MULTIPATH MITIGATION ARCHITECTURES

IMPACT ON PSEUDORANGE

This section reviews the different types of correlator techniques used to track the signal and recover timing information from the received signal. There are different correlator techniques in the market that mitigate the effect of code and carrier phase multipath. Some techniques mitigate both code and carrier multipath to a very good extent while the others mitigates code multipath only. The Standard one chip spacing correlator was reviewed in the last section and will not be dealt with in this section.

The correlator techniques under review in this section are given below:

1) Narrow correlator spacing (Early to Late spacing is 0.1 chips)
2) Strobe Correlator
3) e1e2 Tracker
4) Edge correlator
5) Multipath elimination technology (MET or, the Early late slope technique)
6) Enhanced Strobe Correlator (ESC)
7) Leica’s type A and B multipath mitigation techniques
8) Correlator reference waveform design techniques
9) The Multipath mitigating delay locked loop (MEDLL)
This section concentrates on the code tracking error. The following section deals with the carrier phase errors. In the following sections, “in phase” refers to an angle zero radians and “out of phase” is an angle of pi radians. In the following sections the MEDLL has been included for reference but it has not been simulated.

In order to determine the effects of multipath and multi-transmitter interference, it is necessary to have a model of a direct sequence spread spectrum receiver. In general, there are two different systems that are used in spread-spectrum receivers to estimate delays and phases; the coherent and non-coherent delay locked loop and the carrier-tracking loop. Here, the coherent delay locked loop is used extensively. To start with, the narrow 0.1 chip spacing delay locked loop (DLL) is considered. The underlying logic for the standard and the narrow chip spacing techniques are the same. Plots for techniques 1-8 are given in the Appendices (A) and (B). “Amp” in the plots refers to 0.5 as a ratio and -6dB in terms of decibels. The plots in the appendices follow a particular order. The order is as follows:

1) Code tracking error for multipath delays ranging from 0 to 1.5 chips. The phase of the multipath is held constant at 0 and pi radians.

2) Code tracking error for multipath delays ranging from 0 to 1.5 chips. The phase of the multipath is anchored to the time delay.

3) Code tracking error for multipath delays ranging from 5 to 10 nanoseconds. The phase of the multipath is anchored to the time delay.
4) Phase tracking error for multipath delays ranging from 5 to 10 nanoseconds. The phase of the multipath is anchored to the time delay.

5) Phase tracking error for multipath delays ranging from 0 to 1.5 chips. The phase of the multipath is anchored to the time delay.

4.1) THE NARROW 0.1 CHIP DLL

Referring to the auto-correlation function of the C/A code, it is triangular in shape. Geometrically speaking, this function is shifted half the chip spacing (in time) to the left and the right. This results in the early and late version of the correlation function. In the receiver this is implemented by having an early and a late correlator on either side of the auto-correlation peak, which is locked onto by the receiver. The following sections assume that one is using a coherent DLL. In addition, the coherent DLL has a phase locked loop that aids in recovering the phase information from the signal using a Phase Locked Loop (PLL).

The functions thus obtained (the early and late versions) are used to form a discriminator function, which was discussed earlier. “Early – late” versions give the discriminator function.

The desired code spacing determines the amount by which the correlators are placed on either side of the peak. For an early-late spacing of “d” chips, the shift is “d/2”
chips to the left and the right respectively (geometrically speaking). So, for a narrow correlator spacing of 0.1 chips, the shift is 0.05 chips on either side.

Although the narrow correlator spacing provides superior noise performance in a DLL, the multipath effects dominate the error budget while the receiver utilizes the C/A code to obtain a position fix. The manner in which the narrow correlator reduces the effect of multipath is quite simple [15]. The narrow Correlator tracks near the peak of the correlation function. And, the effect of multipath around the peak of the direct component of the correlation function is less severe than that on other regions of the correlation function.

The simulation for the narrow correlator version (Figure 9) is done for a range of delays from 0-1.5 chips. The tracking error is computed and the plot of code tracking error in meters versus delay in chips is shown. This is done for different values of “amp”. Here, “amp” is the relative amplitude of the multipath relative to the direct. This is generally referred to in decibels.

Figure 10 shows the tracking error for short-range delays (Standard and narrow correlators, 0-0.35 chips). The upper curve represents the in-phase component of the multipath and the lower envelope shows the out of phase component of the multipath. The phase of the multipath is held constant in this plot at zero and pi radians respectively. The plots in the appendices also show the tracking error when the phase is anchored to time delay.
The above plot shows the standard and the narrow correlator envelopes superimposed upon each other. Here "amp" is 0.5 (i.e. – 6 dB). A comprehensive list of plots is given in Appendices – (A) and (B) for the narrow and the standard cases. These plots are for the bandlimited case.
Figure 10: Zoomed in version of the Multipath Error envelopes for the Standard and Narrow correlators.
The short delay multipath envelope shows that the error envelope is the same for all the different schemes for a particular range of delays. As an example, the zoomed in version of the envelopes was shown for the standard and the narrow correlators. The delay till which the error envelope is common for the standard and the narrow correlator types is different for the in-phase and the out of phase components. This number is different for the out of phase multipath as seen before (figure 10). It should be kept in mind that 1 C/A chip is equal to 977.5 nanoseconds.

The performance of a DLL is highly influenced by the pre-correlation bandwidth. The C/A code has a bandwidth of 2.046 MHz. The pre-correlation bandwidth is generally in the range of 8-20 MHz. The degree of band limiting has a direct relation to the sharpness of the auto correlation peak. The greater the bandwidth, the sharper the auto correlation peak. The sharper the peak, lesser the chance of committing an error while tracking the peak. Hence, the trade-off involved is obvious. The effect of band limiting on the code tracking error can be seen from the plots.
4.2) STROBE CORRELATOR - BOTH TYPES:

The strobe correlator was a totally new development in correlator techniques [4,5]. It uses a simple hardware structure and only one extra correlator for a better code tracking. The very idea is to reduce the size of the function in question. Instead of coping with a situation where both correlator responses are super-imposed, they are kept separate. The tracking is done around the peak, but with spacing close enough to hit only the slope of the line of sight correlation curves (LOS).

It is important that the correlation technique reduces the sensitivity of the system to short delay multipath. One way of achieving this is to shorten the correlation pattern. The strobe correlator forms two discriminator functions as shown in figure 11. The discriminator functions are formed by using two early-late correlator pairs. The equation used in the implementation logic is:

\[ \text{Composite function} = \text{disc1} \times \left( \frac{\text{Elsp2}}{\text{Elsp1}} \right) - \text{disc2}; \]

Where, “disc1” is the first discriminator, “disc2” is the second discriminator, “Elsp1” and “Elsp2” are the early late spacings for the first and second discriminators. Here, Elsp1 is the smaller of the two Early-Late spacings. In the above figure, “discriminator 1” is the smaller of the two. (Due to its smaller early to late spacing).
The combination of the two discriminator-like functions is plot in figure 12. The two small discriminator-like functions at one chip distance on either side of the zero crossing of the main discriminator function gives the parasitic effects in the code tracking error plots at one chip delay. The code tracking error is plot as a function of delay in chips.
Figure 12: Composite discriminator function - Strobe Correlator
The presence of these parasitic effects in the tracking error plot can be explained when one considers the shift of the small discriminator to be equal to one chip (the one on the left). This will align with the narrow discriminator whose zero crossing is being tracked. At this point the tracking error goes to zero. But before and after it aligns, the code tracking error ramps up and peaks, to half its maximum value over a delay of 1.5 chips, and ramps down to zero as seen in the plots.

Taking a closer look at the composite discriminator function for the strobe correlator, one could see that there are three discriminator like functions. The normal technique is to track the middle discriminator like function. On the contrary, the first discriminator like function that appears one chip earlier than the middle discriminator like function can be used for tracking purposes. The idea is that one tracks the zero crossing of the small discriminator like function that appears one chip earlier. The reference strobe would be generated one whole chip earlier. The “late” secondary strobe response then aligns with the punctual code and will be used for tracking, whereas the “secondary early” and “main” responses are shifted one chip to the early side, which does not pose a problem. In this manner no parasitic effects are observed at one chip delay.

The flip side to this technique is that the first discriminator like function that the receiver is tracking is half the amplitude of the previous one, which results in 3db degradation in SNR. Hence, it is more susceptible to noise. The plots shown in Appendices C and D were observed when tracking is done at an offset of one chip.
and around the middle discriminator like function respectively. The plots are for the finite Bandwidth case. The effects of band limiting are observed in the tracking error plot. The pre-correlation bandwidth is 20 MHz.
4.3) THE E1E2 TRACKER:

The e1e2 tracker uses two early correlators [9,16]. Its main purpose is to track at a point on the auto-correlation function that is relatively undistorted by multipath. Figure 2 in chapter 2 gives the sum of the direct and reflected component of the auto-correlation function. One can see that, in general, the part of the function near –0.9 chip delay is not badly affected by multipath. This technique strives to reduce the effect of multipath by tracking along the early side of the slope of the auto-correlation function. This concept utilizes a predetermined ratio to detect tracking error. The technique is explained below.

The primary disadvantage in this technique is the low signal level compared to the early minus late techniques that track around the peak of the auto-correlation function. This makes the system more susceptible to noise. The unfettered auto correlation function (without multipath) has a peak normalized value of one. The ideal ratio depends on the signal conditions and the separation of the tracking points and the distance from the peak, as tracking further from the peak means that the multipath is less, but, so is the SNR. For example, if the ratio of the value of the correlation function at 0.9 chips and 0.8 chips ahead of the peak were taken, it would be $0.2/0.1 = 2$. These points are selected because they are less affected by multipath. The values of the composite auto correlation function are taken at these two points. The tracking error is computed by the formula given below. For the normalized cross correlation function, the slope on either side is one. If there is multipath, the slope is
not going to be one and will deviate from this value. This component of this deviation along the amplitude axis is considered equal to twice the tracking error that would result along the x-axis (delay in chips). From this one could easily arrive at the following formula:

\[ \text{Error} = A_2 - \text{ratio} \times A_1, \]

where:

"Error" is the code tracking error in meters, "A1" is the value of the correlation function at 0.9 chips away from the peak (on the earlier side), "A2" the value at 0.8 chips away from the peak.

The logic in this technique is quite clear. If there is no multipath, the value of "Error" immediately goes to zero. In the presence of multipath, there is a difference in the value of the auto correlation function (when compared to its ideal value). This discrepancy gives rise to a non-zero "Error". The error is a discrepancy in terms of the amplitude of the composite auto correlation function (normalized). This is proportional to an error in units of chips. As a result, the tracking error is taken to be a fraction of half a chip. This, when scaled by half the chip size (in meters) gives the code tracking error in meters. However on the practical side, the minimum long delay mitigation this tracker offers would not be as good as the MEDLL or the strobe techniques. The code tracking error is computed for this tracking algorithm.

The relevant plots are given in Appendix – E.
4.4) THE EDGE CORRELATOR:

The edge correlator has been patented by Ashtech [4,16]. It has an error envelope that is very similar to the narrow correlator (0.1 chip narrow correlator). In this section, it has been simulated along the same lines as the e1e2 tracker. Here, the tracking points are on both sides of the peak. It should be noted that this architecture uses a ratio tracking system that is different from the method used to implement the narrow correlator which uses the Early-Late technique.

It had been suggested that the edge correlator could be simulated by placing the tracking points on either side of the peak, with the distance of the tracking points (in units of chips) from the peak being unequal [16]. But, by placing it on both sides of the peak in a symmetric fashion, it gives a constant amplitude error envelope which, after a particular delay, narrows down toward zero at a distance of “1 + d/2”. This envelope is similar in shape to the narrow correlator, but it is supposed to give better code tracking performance. This should yield less than 0.5-dB pre-detection power degradation with respect to the narrow correlator [16].

The plots in Appendix – F give the edge correlator’s code tracking error envelope. Its performance in the presence of filtering has been indicated. The pre-correlation bandwidth is twenty-megahertz (20 MHz).
4.5) MET (THE ELS TECHNIQUE):

The MET (Multipath elimination technology) or the Early-late slope as it is called, presents a novel and interesting way to solve the problem of multipath [12]. In deriving the "early – late" slope technique (ELS) it is convenient to consider the ideal situation where the auto-correlation function is triangular.

The slopes are calculated on both sides of the peak. The amplitudes on both sides of the peak are found out at these two points. They are denoted by two variables, \texttt{amplitude}_1 and \texttt{amplitude}_2. \texttt{"d"} is the spacing between these two correlators. Based on these values one can find out how much the correlators have to be moved so as to be centered around the peak. The following formula gives the code tracking error in units of meters:

\textbf{FORMULA FOR THE ELS TECHNIQUE}

\[ T = \frac{\texttt{amplitude}_2 - \texttt{amplitude}_1 - \texttt{d} \times (\texttt{slope}_1 + \texttt{slope}_2)}{\texttt{slope}_1 - \texttt{slope}_2}; \]

With, slopes \texttt{"1 and 2"} as the slopes on either side of the peak of the auto-correlation function [12].

Theoretically, in the infinite bandwidth case, this principle would eliminate any long delay multipath, assuming that the multipath remains a constant between the correlator positions and the peak. The plot next page (figure 13) shows the correlator positions on the correlation curve.
Figure 13: Plot of the distorted correlation function for the MET technique and the positions of the four correlators.
The performance degrades in the band-limited case because of the flatness of the peak. The same principle holds well when we track the peak for the band limited case. Here, one uses two extra correlators. One of the extra correlators is placed on the early side and the other is placed on the late side. These are used to compute the slope on both sides of the peak. The inside two correlators are placed wide apart so that they are not affected by the flatness at the peak of the correlation function. The relevant plots are shown in Appendix- (G). The plots are given for the bandlimited case.

4.6) THE ENHANCED STROBE CORRELATOR:

The enhanced strobe correlator (ESC) represents a significant improvement on the strobe correlator [5]. This technique also provides better carrier tracking. This technology follows some basic principles that are deeply rooted in its implementation. They are: -

1) The method does not estimate any of the multipath parameters.
2) It does not depend on any multipath model.
3) Independent correction of every channel at the tracking level.
4) Works well in any kind of multipath environment, specular or diffuse

The operating logic is to blank out the latter part of the incoming PRN code by about ninety percent. The code, thus obtained, is cross-correlated with a similar reference
code. This nulls all medium and long delay multipath. This cross correlation gives a narrow auto correlation function. The amplitude of this function is reduced in addition to its width. These reductions are in proportion to the extent of blanking involved. In this case, it would be optimal to blank the pulse by ninety percent (90%). Effectively, the pulse will be gated by a particular amount (This can be a ratio between 0 and 0.5, In this case it is taken to be 0.10). Gating the C/A code can occur either during a chip transition or when the chip maintains the same level (1 or -1). The cross-correlation function when the C/A code is gated over a chip transition is given by:

\[
Ra (\lambda) = \begin{cases} 
-\lambda & -w \leq \lambda \leq -w/2 \\
-(w/2) + 3*\lambda & -w/2 \leq \lambda \leq 0 \\
w - 3*\lambda & 0 \leq \lambda \leq w/2 \\
-(w/2) + 3*\lambda & w/2 \leq \lambda \leq w 
\end{cases}
\]

And, if the gating occurs when the chip stays at the same level its cross-correlation function is given by:

\[
Rb (\lambda) = w*(1 - abs(\lambda)/w) \quad -w \leq \lambda \leq w
\]

Now, there is an equal probability of the C/A code to be gated when there is transition and otherwise. Hence, the total cross-correlation function is given as the average of the above shown cross-correlation functions. This gives us:
\[ R(\lambda) = \text{w}^*(1 - \text{abs}(2*\lambda/w)) \quad \text{abs}(\lambda) \leq \text{w}/2 \]

As a result, the auto-correlation function extends from −0.05 to 0.05 chips in width (private communication with Dr. Gary A. Mc Graw)[24].

Blanking the code also reduces the performance of the system in the presence of noise. Blanking by a greater extent causes the performance of the system to reduce drastically, which is not acceptable. Using this narrowed cross correlation function a 0.1 chip early – late spacing coherent DLL is implemented. The plots in Appendix – H depict the performance of the ESC for the bandlimited case. The pre-correlation bandwidth is 20 MHz. A plot of the cross-correlation function for the C/A code (unfettered by multipath) is shown on the next page (figure 14).
Figure 14: Plot of the Narrow correlation function - Enhanced strobe correlator
4.7) LEICA'S CODE MULTIPATH MITIGATION TECHNIQUES:

Leica GPS has come up with two correlator based multipath mitigation techniques [6]. They are called “type A and type B MM techniques”. Based upon the theoretical error curves, it can be concluded that the type A MM technique is similar (in performance) to the strobe correlator and type B MM is similar (in performance) to the Enhanced strobe correlator.

4.8) CORRELATOR REFERENCE WAVEFORM DESIGN:

The present methods of processing against multipath usually involve cross-correlating the received signal with an ideal replica of the GPS PRN code, followed by special processing of the resultant function to remove ranging error caused by the distortion of the auto-correlation function due to a secondary path signal.

In this technique, instead of using the conventional ideal code waveform as a reference for the correlation, a correlator reference waveform specifically designed to produce a much narrower correlation function is used [19].
The approach has some distinct advantages:

1) The improved range resolution does not require any additional signal processing.

2) The gains are achieved with a single correlator dedicated to code tracking and just one more correlator for acquisition. An example of this technique is the second derivative correlator, which is explained below.

The technique was developed by Dr. Lawrence Weill [19]. The underlying idea is to reduce the width of the correlator function. As in the previous technique, the ESC, narrowing the width of the cross correlation function is very important to reducing code-tracking error due to multipath.

When the filtered cross correlation function is differentiated twice, (with respect to time), and is subtracted from zero, it gives a narrow triangle like function which is similar in shape to the original cross correlation function. Mathematically speaking, this would be equivalent to differentiating the reference waveform twice and then cross-correlating this with incoming code. This function is smaller in size, much narrower and has visible side lobes one chip away from its peak. This function is used as a reference to form the discriminator. A 0.1 chip early-late correlator pair is used.

For all practical purposes, this new function is equivalent to the original cross correlation function. The reason will become clear if we keep in mind that we are interested in tracking the peak of the cross correlation function. On differentiating twice, the function thus obtained (direct path only) has its peak at the same point as
the original cross correlation function. Hence it does not make a difference if one tracks this function or its precursor (based upon the logic of implementation). On the other hand, there is a lot to gain. The reduced width of the function makes it less susceptible to multipath as seen in figure 15.

However, the side lobes at a distance of one chip from the tracking point play an important role in determining the code tracking error envelope as seen in the plots below. The effect of these side lobes are negligible considering the fact that multipath with such delays is generally weak (in terms of signal power).

Another method of implementing this logic is the signal shaping technique. The incoming signal is shaped to meet the needs using filters. This is accomplished before cross-correlation. This is equivalent to the above mentioned correlator reference waveform design. An advantage in this method is that the signal-shaping filter is common to all channels and hence, only one such filter is required.

4.8.1) SUPERRESOLUTION TECHNIQUE:

A generalized implementation of the above-mentioned technique is explained under the title of super-resolution. Instead of generating a correlation function in the usual way and attempting to measure its shape one can pre-process the received signal so that it produces a correlation function with a higher range resolution (super-resolution).
Figure 15: Plot of the Narrow correlation function - Second derivative correlator
This technique offers important advantages:

1) Preprocessing the signal requires only one filter, which is common to all satellite channels.

2) Only one punctual correlator is needed for the code tracking.

3) Improved range resolution reduces the distortion of the correlation function, which permits use of the standard tracking loops.

4) For path lengths of more than 20 meters, code and carrier bias is completely removed.

Contextually speaking, resolution is the ratio of the negative of the second derivative of the original cross correlation function at zero lag, to that of the original function at zero lag [21]. This gives a measure of how well one can mitigate multipath in that system.

If "R" denotes the auto-correlation function, then, resolution is given by:

$$\Lambda = - \frac{((d/dt) (d/dt) (R(0)))}{(R(0))}$$

Taking a look at the frequency domain representation, one finds that the sharpness of the peak of the cross correlation function determines the width of the first zero crossing of the \((\text{sinc})^2\) function. The sharper the peak (in time domain), the wider it is in the frequency domain. But, a sharp peak is absolutely necessary to track the code and obtain timing information. This leads to the inescapable conclusion that high frequency components should exist in the cross correlation function. It would not be enough to have high frequency components, but they need to have a good deal of energy at these higher frequencies. To achieve this, a
pre-emphasizing filter is used. This filter pre-emphasizes the high frequency components in the incoming signal. In this simulation, such a filter was not used. However, this has been accounted for by generating the narrow correlation function.

Super-resolution can be implemented by correlator reference waveform design or by using a signal-shaping filter. All GPS receivers need to have a method to track the peak of the correlation function. That is, in the code-tracking loop, an error signal must be generated to track the peak of the correlation function. In the signal-shaping model, the signal-shaping filter is multiplied by a \( j\omega \) component, which is equivalent to differentiation in the time domain. Thus, one arrives at the model shown in [21], that incorporates all the transfer functions into one single entity. This holds good for the signal-shaping model. This single filter is common to all satellite channels. The relevant plots are given in Appendix - I.

4.9) MULTIPATH ESTIMATING DELAY LOCKED LOOP (MEDLL):

The received signal at the input of the direct sequence spread spectrum receiver can be written as [13]:

\[
R(t) = \sum a_m p(t-t_m) \cos (\omega t + \theta_m) + n(t)
\]

Where:

"\( \Sigma \)" Ranges from 0 to M-1;

"\( a_m \)" is the component signal amplitude
"t" is the time

"p(t)" is the spread spectrum code

"t_m" is the component signal delay

"θ_m" is the component phase delay

"n(t)" is the white gaussian noise

In a positioning system like GPS, the parameters of interest are the direct path signal phase, delay and amplitude. The direct path correlation function needs to be determined in order to acquire this data. The MEDLL approach involves the decomposition of the correlation function into its direct and multipath components.

The MEDLL estimates the amplitude, delay, and phase of each multipath component using maximum likelihood criteria [14]. The estimated multipath correlation function is subtracted from the measured function. Once this process is complete, an estimate of the direct path correlation function is obtained. A standard early – late DLL is applied to the direct path component and an optimal estimate of the code tracking error is obtained.

Theoretically speaking, an infinite number of multipath signals can be present at any given time. But, in practice there are rarely more than one or two dominant multipath signals present at one time. Hence, the MEDLL is configured to solve for three signals-the direct plus two multipath signals.
The performance of the MEDLL was investigated in a strong multipath environment. The traditional GPS receiver dedicates only two or at the most three correlators to each satellite tracking channel. The MEDLL algorithm requires 10 or more correlators. Theoretically speaking, the MEDLL requires only three correlators per direct or multipath signal. But, more correlators are required to obtain initial estimates of each signal. The MEDLL is also used to mitigate carrier phase multipath.
CHAPTER 5

PHASE TRACKING ERRORS

This section deals with carrier phase errors. While tracking the carrier of the incoming signal, which is contaminated by multipath, one ends up tracking the composite phase of the incoming signal. The composite phase of the signal is determined from the phase of the direct and the phase of the multipath relative to the direct.

In a coherent receiver, the code and the carrier tracking loops aid each other. It is a closely-knit system. For the sake of simplicity, let the phase of the direct incoming signal be zero. Let the phase of the multipath be \( \theta_m \). Then, the composite phase of the signal the receiver is tracking will be \( \theta_c \), where \( \theta_c \) is given by:

\[
\theta_c = \text{atan} \left( \frac{R(\lambda - \delta) \sin(\theta_m)}{R(\lambda) + R(\lambda - \delta) \cos(\theta_m)} \right)
\]

(1)

Where:

\( \lambda \) is the code tracking error (in units of chips).

The direct component is assumed to have a phase of zero radians. This is the \( R(\lambda) \) component. The multipath that contaminates the direct component is said to have a phase of \( \theta_m \) with respect to the direct. This is the \( R(\lambda - \delta) \) component. The \( R(\lambda - \delta) \) component.

\[
\theta_m
\]

\[
\theta_c
\]
vector can be resolved along two directions. One direction is along the direct and the other is at an angle of $\pi/2$ radians to the direct. Thus there are two components, $R(\lambda - \delta) \cos (\theta_m)$ along the direct and $R(\lambda - \delta) \sin (\theta_m)$ in quadrature. The resultant angle would give the composite phase. This is the angle the composite signal (direct plus multipath) is going to make with respect to the direct signal. Since the direct signal had an incoming phase of zero radians, any non-zero angle made by the resultant vector is termed as the carrier phase error.

From equation (1), it is quite clear that if the magnitude of $R(\lambda - \delta)$ is small or zero, the carrier phase error will be very less and the carrier phase multipath is very small. Thus, if the $R(\lambda)$ function is narrow in nature, the $R(\lambda - \delta)$ component vanishes after a particular delay "\(\delta\)". This is what happens in the case of the ESC and Weill’s technique [19,20], which reduce the width of the correlation function in order to obtain code and carrier phase multipath mitigation. Plots of the phase tracking error for the ESC and Weill’s techniques are shown at the end of this section.

This section strives to make clear the fact that all the aforementioned code multipath mitigating techniques do not help in mitigating carrier phase multipath.

For example, there is a significant reduction in code multipath errors in a narrow chip coherent DLL when compared to the standard one chip DLL. But, on the other hand there is not much difference between the narrow and the standard DLL when it comes to carrier phase multipath mitigation. The degree of carrier
Phase multipath mitigation seems to be a function of the width of the cross-correlation function and is also a function of the phase of the multipath relative to the direct.

So, the Enhanced strobe correlator and Leica’s type B MM techniques achieve carrier phase multipath mitigation. This is because the correlation function that is formed after cross correlating with the reference code is narrower in width when compared to the standard correlation function. The plots at the end of this section give the phase errors for the Enhanced strobe correlator and the second derivative correlator (figure 16 and 17). The plots in the respective appendices in the next section give the complete phase error plots for the different multipath mitigation techniques for multipath delays ranging from 0 – 1.5 chips. Here, it should be noted that the phase of the multipath is anchored to the time delay.
Figure 16: Plot of the phase tracking error - Enhanced Strobe correlator
Figure 17: Plot of the phase tracking error - Second derivative correlator
6.1) COMPARISON OF THE DIFFERENT MULTIPATH MITIGATING TECHNIQUES

From the plots in the appendices, it is readily apparent that all of the receiver architectures (except the standard correlator) reduce or eliminate medium and long delay multipath. It is important, however, to point out the various tradeoffs involved.

When the narrow correlator was introduced in the early 1990’s, it was shown to reduce noise as well as multipath. This results from the fact that the noise in the early and late correlators is not independent. The impact, however, is felt in the implementation. Narrow correlator spacing requires higher sampling rates, faster digital processing and a wider front-end bandwidth to preserve the correlation peak.

As with the narrow correlator, the strobe correlator, edge correlator and e1e2 tracker all yield a reduction in multipath error through judicious manipulation of the discriminator function. The strobe correlator combines two narrow correlator discriminator functions to produce a new discriminator which, is zero at all points except near the tracking point. This yields zero multipath error for medium and long
delay cases. The e1e2 tracker reduces multipath by tracking very early on the correlation functions and in doing so is penalized by a significant reduction in C/No. The edge correlator has been surmised to be similar to the e1e2 in its formation of a discriminator function but since it yields narrow correlator performance, its correlators are likely placed close to the correlation peak.

The multipath-elimination technology (MET) is a variation of the above. Four correlators are required (as with the strobe) and the correlation peak is estimated through computation of early and late slopes and the resulting intersection. As with the narrow correlator, the strobe, edge and MET all require wide front-end bandwidths, high sampling rates and fast digital processing. Unlike those mentioned so far, the multipath-estimating delay-lock-loop (MEDLL) is not a discriminator-based technique. The MEDLL attempts to form the maximum likelihood estimate of the direct and multipath signal parameters (amplitude, delay and phase). The MEDLL may also be viewed as an image processing or pattern recognition problem (i.e., what combination of direct and multipath components yields the distorted correlation function). This technique requires multiple correlators per channel (on the order of 10). It is thus a significantly more complicated hardware design and also requires more computational power. The MEDLL promises to reduce (optimally) noise and multipath but it can do so only when these are the sole error sources present. Specifically, the MEDLL has not been formulated to include interference in its channel model and anecdotal field test results have indicated poor performance
accordingly. In addition, the MEDLL assumes a model of the multipath and this generally will not be valid in the field.

The recent work of Dr. Weill and the introduction of the enhanced strobe correlator (ESC) represent a new approach to the multipath problem. Dr. Weill has pointed out that it is far better to manipulate the correlation function itself rather than form more favorable discriminator functions. By narrowing the basic correlation function, both code and carrier-phase multipath are reduced. Implementation, however, is the key issue. The ESC seems to be a practical application of Dr. Weill’s theory. It has been surmised that it is accomplished via gating or blanking out ninety- percent or so of the local and incoming codes. This can achieve a narrowed auto-correlation function but the peak value is reduced accordingly and thus the technique is plagued by loss of C/No (about 10 dB). Again, it has been surmised that this limitation is overcome by heavy carrier aiding from an unblanked code/carrier-tracking loop. The heavy carrier aiding allows for an extremely narrow code tracking loop and thus noise mitigation.

The table on the next page (table 1) gives us a good idea about the performance of each technique and how it compares to the others.
<table>
<thead>
<tr>
<th>S.No</th>
<th>Technique</th>
<th>Chip spacing</th>
<th>Width of the error Envelope (Code Multipath/ Carrier Multipath)</th>
<th>Comments</th>
<th>Carrier Phase Multipath Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Standard</td>
<td>1.0</td>
<td>1.5 / 1.10</td>
<td>Does not reduce the amplitude of the multipath as well as the others, error envelope extends to a delay of 1.5 chips.</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Narrow</td>
<td>0.1</td>
<td>1.05 / 1.0</td>
<td>Reduces the amplitude of the envelope as a function of chip spacing, error envelope extends to a delay of 1.05 chips.</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Strobe 1</td>
<td>.05&amp;.1</td>
<td>0.05 / 1.0</td>
<td>Reduces the amplitude of multipath and beyond 0.05 chips, the code tracking error envelope goes to zero. Suffers</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Strobe 2</td>
<td>.05 &amp; .1</td>
<td>0.05 and 1.05 \ / 1.0</td>
<td>Reduces the amplitude, but does not eliminate multipath entirely till a delay of 1.05 chips.</td>
<td>No</td>
</tr>
<tr>
<td>---</td>
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<td>----------------------</td>
<td>-------------------------------------------------</td>
<td>----</td>
</tr>
<tr>
<td>5</td>
<td>E1E2</td>
<td>0.1</td>
<td>0.20 / 1.0</td>
<td>Reduces amplitude as a function of chip spacing and beyond 0.20 chips, the code tracking error envelope goes to zero. Since the tracking points are placed very early on the early side of the correlation function, it suffers from a loss of signal strength</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Edge</td>
<td>0.1</td>
<td>1.05 / 1.0</td>
<td>Performance is similar to that of the narrow correlator</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>MET</td>
<td>0.1</td>
<td>0.25 and 1.15 \ / 1.0</td>
<td>Eliminated multipath entirely between 0.25 and 0.85 chips and the multipath error envelope goes to zero after a delay of 1.15 chips. Needs a wide pre-correlation</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Method</td>
<td>Bandwidth</td>
<td>Multipath Rejection</td>
<td>Result</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>----------------</td>
<td>------------</td>
<td>---------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>ESC</td>
<td>0.1</td>
<td>0.10 / 0.15</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Extremely good code and carrier multipath rejection is achieved. The technique might suffer from a loss of signal to noise ratio.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Leica’s type A MM technique</td>
<td>0.05 &amp; .1</td>
<td>0.05 and 1.05 / 1.0</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Similar in code and carrier multipath rejection performance, as compared to “strobe 2”.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Leica’s type B MM technique</td>
<td>0.1</td>
<td>0.10 / 1.0</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Similar to the Enhanced Strobe Correlator in terms of multipath rejection (code as well as carrier)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Second Derivative Correlator</td>
<td>0.1</td>
<td>0.15 and 1.05 / 0.15 and 1.0</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dr. Weill’s technique</td>
<td></td>
<td>Quite a promising concept, offers good multipath rejection (code and carrier), has a non-zero error envelope at delays around 1 chip. Dr. Weill claims that this would not affect the performance in the field. Yet to be tested and</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In all the cases shown above the pre-correlation bandwidth has been set at 20 MHz (double sided). Here, “strobe 1” is the case where one tracks the first discriminator like function and “strobe 2” is the case where we track the middle discriminator like function as seen in figure 12. A “No” in terms of carrier phase rejection would mean that the technique does not offer any advantages in terms of rejecting carrier phase multipath in comparison to the other regular architectures. It does not mean that the technique does not mitigate carrier phase multipath. The SMR used for the purpose of simulation was six dB.

In the table shown above, an entry that is of the form “a” and “b” under the section “Width of the error envelope” means that the multipath is eliminated for delays beyond point “a”, but the envelope exhibits a symmetric non-zero code tracking error around the
one chip delay point. Again, the multipath envelope goes to zero at a delay of “b” (in units of chips). Also, “x/y” indicates that it is the width of the code tracking error envelope and the carrier phase multipath error envelope with “x” for the code tracking error envelope and “y” for the carrier phase multipath error envelope.
CHAPTER 7

CONCLUSIONS

This section comprises of the conclusions drawn as a result of investigating the above-described multipath mitigating techniques.

This study has considered a variety of receiver-based multipath mitigation architectures. With the exception of the standard correlator, all receiver architectures either reduce or eliminate medium and long delay multipath. In all cases, however, receiver complexity is increased. The techniques showing the greatest multipath reduction are invariably paying the price by a loss of C/No. Clever carrier aiding may reduce this problem. The most impressive performance has been achieved by manipulating the signal in order to reduce the width of the auto-correlation function. This is the only technique (aside from MEDLL) which reduces carrier multipath as well as code.

There are two techniques that reduce the width of the auto-correlation function, one of which is the correlator reference waveform design. The correlator reference waveform design technique reduces the width of cross-correlation function along-with increasing the sharpness of the correlation peak which is an advantage when it comes to tracking the peak of the cross-correlation function. Another method of increasing the sharpness of the peak would be to use a high frequency pre-
emphasizing filter. The other technique is the Enhanced Strobe correlator, which is quite simple and promising.
CHAPTER 8

REFERENCES


(7) Holmes, J. K., “Non-coherent Late Minus Early Power Code Tracking Performance With Front End Filtering”, Proceedings of the 10th International Technical Meeting of
the Satellite Division of The Institute of Navigation, ION GPS-97, Kansas City, Missouri, September 1997.


(22) Kalyanaraman, S. and Braasch, M. “GPS Multipath Mitigation Studies”, Technical


APPENDIX – A

STANDARD CORRELATOR

CHIP SPACING = 0.1
Multipath error envelope for a relative amplitude of -6dB
Multipath error envelope for a relative amplitude of -6 dB

Phase anchored to time delay
Multipath error envelope for a relative amplitude of amp

Code tracking error in meters

Delay in nanoseconds
Plot of the phase error in metres
Plot of the phase error in metres

Delay in chips

Phase error in metres

0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
0
0.5
1
1.5
APPENDIX – B

NARROW CORRELATOR

CHIP SPACING = 0.1
Multipath error envelope for a relative amplitude of -6 dB
Multipath error envelope for a relative amplitude of -6 dB
Multipath error envelope for a relative amplitude of amp.
Plot of the phase error in metres

Delay in nanoseconds

Phase error in meters
Plot of the phase error in metres
APPENDIX – C

STROBE CORRELATOR

CHIP SPACING = 0.05 AND 0.1
Multipath error envelope for a relative amplitude of -6 dB
Multipath error for an amplitude of -6dB

Phase anchored to time delay
Multipath error envelope for a relative amplitude of amp

Code tracking error in meters

Delay in nanoseconds
Plot of the phase error in metres
Plot of the phase error in metres
APPENDIX – D

STROBE CORRELATOR

NORMAL MODE

CHIP SPACING = 0.05 AND 0.1
Multipath error envelope for a relative amplitude of -6 dB
Multipath error for an amplitude of -6dB

Phase anchored to time delay

Delay in chips

Code tracking error in meters
Multipath error envelope for a relative amplitude of amp
Plot of the phase error in metres
Plot of the phase error in metres
APPENDIX – E

E1E2 TRACKER

CHIP SPACING = 0.1
Multipath error envelope for a relative amplitude of -6 dB

Delay in chips

In phase component

Out of phase component
Multipath error envelope for a relative amplitude of -6 dB

Phase anchored to time delay
Multipath error envelope for a relative amplitude of amp

Delay in nanoseconds

Code tracking error in meters

-3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1

4 5 6 7 8 9 10
Plot of the phase error in metres
Plot of the phase error in metres

Phase error in meters

Delay in chips
APPENDIX – F

EDGE CORRELATOR

CHIP SPACING = 0.1
Multipath error envelope for a relative amplitude of -6 dB

In phase component

Out of phase component

Delay in chips

Code tracking error in meters
Multipath error envelope for a relative amplitude of amp
Plot of the phase error in metres
Plot of the phase error in metres

Phase error in meters

Delay in chips
APPENDIX – G

EARLY LATE SLOPE (ELS/MET)

CHIP SPACING = 0.1
Multipath error envelope for a relative amplitude of -6 dB

In phase component

Out of phase component
Multipath error for a relative amplitude of -6dB

Code tracking error in meters

Delay in chips
Phase error for a relative amplitude of -6 dB
Phase error for a relative amplitude of -6dB
APPENDIX – H

ENHANCED STROBE CORRELATOR

BLANKING FACTOR = 90 %

RATIO = 0.9

CHIP SPACING = 0.1
Multipath error envelope for a relative amplitude of -6 dB

In phase component

Out of phase component
Multipath error envelope for a relative amplitude of -6 dB

Phase anchored to time delay
Multipath error envelope for a relative amplitude of amp

Delay in nanoseconds

Code tracking error in meters
Plot of the phase error in metres

Delay in nanoseconds

Phase error in meters

-0.02  -0.015  -0.01  -0.005  0  0.005  0.01  0.015  0.02
Plot of the phase error in metres
APPENDIX – I

CORRELATOR REFERENCE

WAVEFORM DESIGN

CHIP SPACING = 0.1
Multipath error envelope for a relative amplitude of -6 dB
Multipath error envelope for a relative amplitude of -6 dB
Multipath error envelope for a relative amplitude of amp

Delay in nanoseconds

Code tracking error in meters
Plot of the phase error in metres

Delay in nanoseconds

Phase error in meters

-0.02
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
0.02
4
5
6
7
8
9
10

Delay in nanoseconds
Plot of the phase error in metres

Delay in chips

Phase error in metres