

Research Article

An Adaptive Multipath Mitigation Filter for GNSS Applications

Chung-Liang Chang and Jyh-Ching Juang

Department of Electrical Engineering, National Cheng Kung University, Tainan 70101, Taiwan

Correspondence should be addressed to Chung-Liang Chang, ngj567.liang@msa.hinet.net

Received 27 June 2007; Revised 15 November 2007; Accepted 5 January 2008

Recommended by Jonathon Chambers

Global navigation satellite system (GNSS) is designed to serve both civilian and military applications. However, the GNSS performance suffers from several errors, such as ionosphere delay, troposphere delay, ephemeris error, and receiver noise and multipath. Among these errors, the multipath is one of the most unpredictable error sources in high-accuracy navigation. This paper applies a modified adaptive filter to reduce code and carrier multipath errors in GPS. The filter employs a tap-delay line with an Adaline network to estimate the direction and the delayed-signal parameters. Then, the multipath effect is mitigated by subtracting the estimated multipath effects from the processed correlation function. The hardware complexity of the method is also compared with other existing methods. Simulation results show that the proposed method using field data has a significant reduction in multipath error especially in short-delay multipath scenarios.

Copyright © 2008 C.-L. Chang and J.-C. Juang. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

1. BACKGROUND AND MOTIVATION

In recent years, the Global navigation satellite system (GNSS) has been extensively used in navigation services to provide users with information of positioning accuracy and integrity. However, the performance of GNSS in navigation and survey is subject to several errors, such as ionosphere delay, troposphere delay, and receiver noise and multipath. Among these errors, multipath is the major error source in precision-oriented GNSS applications. The multipath effect is caused by extraneous reflections of the satellite signal from nearby objects, such as buildings, the ground, trees, and water surfaces that reach the receiver by way of multiple paths. For GNSS, the multipath initiates tracking errors in the receiver and may lead to ranging error of up to 100 m. The influence of multipath as an error source has resulted in the development of different multipath mitigation techniques. These techniques are typically categorized in terms of antenna design, improved receiver internal architecture, and postprocessing of discernible objects. The drawback of antenna design lies in the extra hardware cost. The effectiveness of postprocessing may be limited in accordance with short-delay multipath. The paper thus focuses on the design of receiver internal architecture for multipath mitigation.

A survey of multipath mitigation techniques is presented as follows to serve as a comparison reference of performance and complexity. Hagerman [1] and Spilker Jr. [2] analyzed the effect of multipath error by using a conventional receiver tracking loop which contains phase lock loop (PLL) and delay lock loop (DLL). The conventional correlation encompasses the 70–80 m tracking error that employs the DLL with one chip of early-late spacing in multipath environment.

Van Dierendonck et al. [3] first proposed the narrow correlation to effectively mitigate multipath effects and decrease the tracking error to about 8–10 m. The narrow correlation employs a DLL by narrowing the spacing between early and late correlators. However, as described by van Nee [4, 5] and Braasch [6], multipath can lead to an offset in the measured time delay that cannot be erased by either smoothing or narrowing correlator receivers. Townsend and Fenton [7] proposed a multipath estimation technique (MET) by using the slope of the autocorrelation function to estimate the code phase offset delay of the direct signal. Yet, this technique has been utilized to reduce only code-phase error in DLL and the effect of PLL carrier-phase error is not considered. From these reasons, van Nee et al. [8] employed a multipath estimation delay lock loop (MEDLL) to estimate multipath signals and mitigate code and carrier-phase errors. To achieve this, the incoming signal is separated into its line-of-sight

(LOS) and multipath components in MEDLL. The adoption of the LOS component has made possible the unbiased measurement of code and carrier phase. Performance evaluation of conventional correlation, narrow correlation, and the MEDLL, regarding multipath mitigation capability, was conducted by Townsend et al. [9] for GPS C/A code. The MEDLL presents better performance than the conventional correlation and narrow correlation. Nevertheless, it does not completely cancel out all multipath errors. This is due to multipath signals with short delays being difficult to eliminate. In addition, the MEDLL depends on a maximum likelihood search, which is an extensive computation load.

Garin et al. [10] utilized strobe and edge correlators to achieve discriminator function shaping through the combination of two different narrow correlation discriminators. This method modified the DLL design by employing the narrow early-late spacing and expanding the correlation bandwidth. However, a disadvantage is that the tracking capability of the DLL is reduced. Afterwards, the enhanced strobe correlator has been proposed and adopted to mitigate both code and carrier-phase errors and decrease the error to 24 meters, which is about 0.08 chip [11]. Laxton and DeVilbiss [12] also employed a modified rake DLL (MRDLL) technique to estimate the LOS signal along with those of all multipath components. Even though the MRDLL reduces the code-phase error in DLL and the carrier-phase error in PLL, it would take a large number of correlators for estimation and consume a great deal of hardware resources.

An Early1/Early2 (E1/E2) tracker has also been proposed by van Dierendonck and Braasch [13]. In this method, two correlators with chip spacing are located on the early slope of the autocorrelation function. The major advantage of this approach lies in the fact that non-pseudorange errors are caused by multipath signals arriving after this (early) tracking point. Nevertheless, as the distance of the tracking point from the correlation peak increases, the noise performance decreases. In other words, the noise performance degrades when the E1 and E2 are shifted to the left slope of the correlation. Apparently, each method consists of not only advantages but also inherent limitations as addressed by Braasch [14] who investigated the theory behind each multipath mitigation technique and offered a performance comparison.

Chaggara et al. [15] proposed the multicorrelator technique for multipath parameters estimation. Though this technique enhances the performance of multipath mitigation in DLL and PLL, it requires a great number of correlators for estimation and consumes a great deal of hardware resource. Irsigler and Eissfeller [16] provided a survey of current multipath mitigation techniques that are able to minimize code and/or carrier multipath. The optimal code multipath mitigation is achieved by adopting a linear combination of several correlators or equivalently correlated the incoming signal with a code-tracking reference function [17]. This technique is utilized in BPSK(1) and BOC(1,1) signals for infinite, 16 MHz and 8 MHz bandwidths. An analysis of the influence of coherent and noncoherent GPS receiver code tracking architecture on the carrier phase multipath error including a thorough validation of carrier phase multipath theory was presented [18, 19]. This research provided a theo-

retical structure which served as reference for simulation of multipath mitigation techniques.

From a review of the above mentioned techniques, it is implied that almost all of the techniques are based on two key concepts. The first is discriminator function shaping and the second is correlation function shaping. The advantage of the discriminator function shaping technique is the reduced complexity of hardware and software. One of the benefits of correlation function shaping, both the MEDLL and the MRDLL, is the decrease of carrier phase multipath. The lack of performance improvement for short-delay multipath signals is by far the most prominent feature of every receiver. This matters a great deal in the application of multipath mitigation. If a technique involves only short-delay multipath, then the best correlation function shaping receiver will not outperform a traditional one.

In this paper, an adaptive filtering approach application is proposed in the GPS multipath mitigation. The approach is based on the correlation function shaping technique which estimates the direct plus multipath signal parameters, then separates the delayed signal from the received signal simultaneously. The processed output signal is then subtracted from the measured autocorrelation value of received signal. Simulation results in multipath environments are presented to compare the performance of the proposed method with some of the recently developed high-performance multipath mitigation techniques. It is confirmed that the method is well suited in the multipath environment, especially in the short-delay multipath environment where the computation load and complexity are low with the best performance. In addition, this method is also effective in eliminating both code-phase error and carrier-phase error. However, the latter is neglected in some of the reviewed techniques detailed above.

The remainder of this paper is organized as follows. Section 2 gives an overview of how multipath affects GPS receivers. Section 3 describes how the proposed adaptive filtering method is applied in multipath mitigation. Performance analysis and simulation results are given in Section 4. Then conclusions are provided in Section 5.

2. MULTIPATH OVERVIEW

Most communicative systems are subject to multipath. The multipath phenomenon can degrade the system performance and reduce the range of measurement accuracy from centimeters to several meters [20]. Multipath is caused by reflections of satellite signals from such objects as the ground or nearby buildings. The reflected signal takes more time to reach the receiver of the direct or LOS signal. In GPS, the desired signal is only the direct path signal. All other signals distort the desired signal and cause errors in ranging measurement. With the presence of multipath, the incoming code, discriminator functions, and correlation function are all distorted. Analytically, the direct-path and multipath components can be managed in separate ways.

Figure 1 shows the tracking errors of the early-late discriminator output caused by multipath in DLL. The tracking errors primarily come from distortion of the correlation function with the received IF signal. In the direct-path

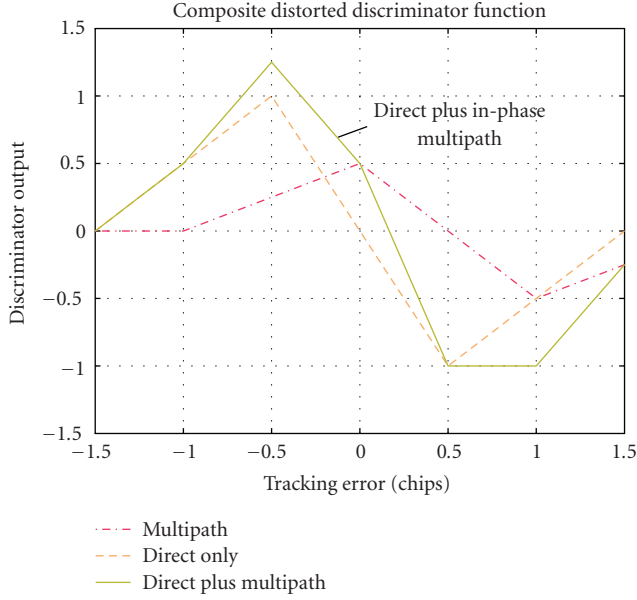


FIGURE 1: Composite distorted of early-late discriminator.

case, the ideal case is when the discriminator function passes through zero while the code tracking error is zero. Nevertheless, with the presence of multipath, the distorted function has a zero-crossing at a nonzero code tracking error. With the direct signal, when the relative multipath phase is 0 radians, the multipath component is *in phase* and with π radians, the multipath component is *out of phase*. Therefore, multipath error analysis is related to simulation of direct and indirect path signals and is the determination of the zero crossing of distorted discriminator function. Three multipath parameters must be considered: strength, delay, and phase. The absolute value of each parameter is independent.

Figure 2 shows the example result for the theoretical multipath error envelope versus the multipath delay. This simulation is provided in the case of infinite bandwidth receiver filter, one-chip early-late spacing and unchanged multipath amplitude. In addition, the code autocorrelation sidelobes have been ignored.

The multipath error can be determined, for a given multipath to direct ratio, by fixing the upper bounds relative multipath phase at 0 radians, the lower bounds at π radians, and by adjusting the relative multipath delay. At each delay point, the distorted discriminator curve is decided, while the zero-crossing point and multipath error are calculated. The error will fall somewhere between the bounds shown in the error envelope, if the multipath has any phase other than 0 or π radians. Based on the influence of multipath on GPS receiver, a solution method is proposed in the following section.

3. MULTIPATH MITIGATION METHODOLOGY

3.1. System description

The block diagram of the multipath mitigation system is shown in Figure 3. The received signal is processed in a RF

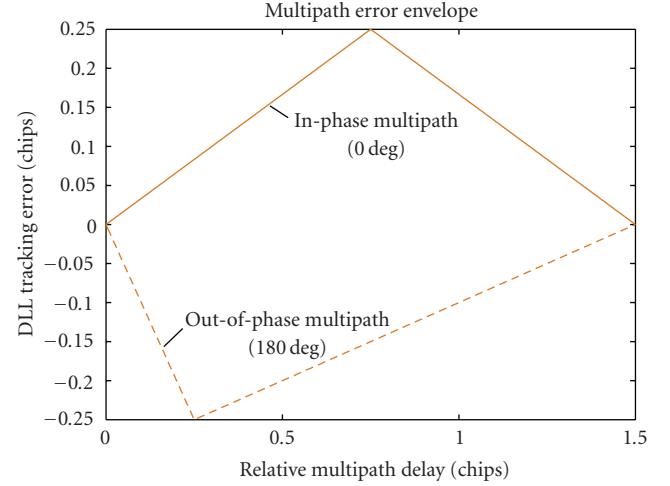


FIGURE 2: Multipath error envelope for a conventional, one-chip early-to-late DLL receiver. Multipath component is half the strength of the direct signal.

filter, then downconverted and sampled to a digital IF signal. The tracking module performs the correlation algorithm in the PLL and DLL from the IF signal. The tracking module acquires the GPS signal, the output of the code phase and the carrier phase of the PLL and DLL is obtained. The multipath estimator is used to estimate the correlation parameter of multipath, based on the modified adaptive filter by employing duplicated signal and digital IF signal. As shown in Figure 3, the estimated signal parameters are then sent to the correlation decomposer and the correlation value of multipath signal is determined in the multipath cancellation area. The estimated delayed signal is recreated at the modified adaptive filter and is subtracted from the correlation value of the received signal. The detailed process of the multipath estimator, the correlation value decomposer, and the multipath cancellation will be addressed in the following subsections.

3.2. Multipath model and modified adaptive filter

In the case of a global positioning system (GPS), it is difficult to describe the statistical model of the received signal in the presence of multipath. Nevertheless, many hypotheses can be made. One hypothesis is that the multipath signals are delayed with respect to the direct GPS signal. From this, consider only these reflected signals that have a delay with less than one chip. This is due to signals with a code delay larger than one chip are uncorrelated with the direct signals. Otherwise, the multipath signal is assumed to have lower power than the direct one. Then, the baseband signal model can be represented as follows:

$$y(n) = \sum_{i=0}^M A_i g(n - \tau_i) \cos(\omega n + \varphi_i) + \eta(n), \quad (1)$$

where A_i , φ_i , and τ_i are the amplitude, carrier phase, and code delay of i th delayed signal. M is the number of multipath component. $g(n)$ is the spread-spectrum code. ω is the

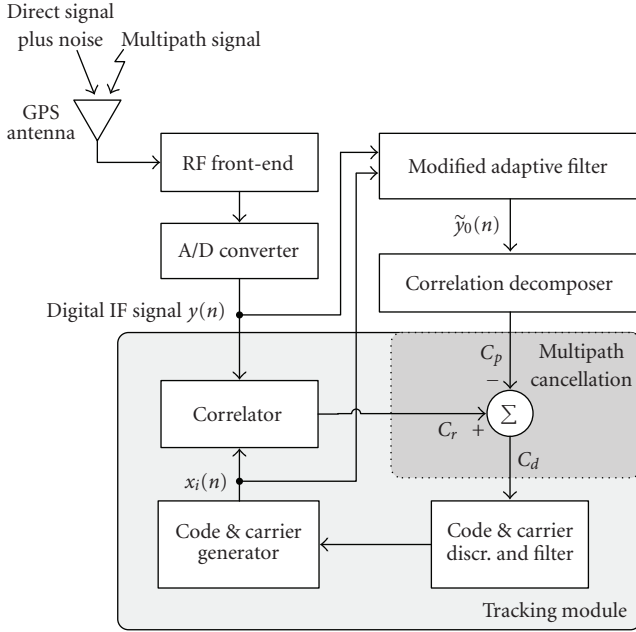


FIGURE 3: Multipath mitigation system block diagram.

IF angular frequency. n is the discrete time index. The 0th delayed signal corresponds to the direct signal. $\eta(n)$ is usually modeled as white Gaussian noise distribution.

The task of a multipath estimator is to estimate the multipath delay profile through the use of a modified adaptive filter, which is illustrated in Figure 4. It employs the tap-delay line with an Adeline network to create this structure without a nonlinear element [21, 22]. An adaptive algorithm such as the LMS algorithm or the backpropagation (BP) learning algorithm is often utilized to adjust the weights of the Adeline so that it responds accurately to as many patterns as possible in a training set. In this paper, the BP with an adaptive learning rate algorithm is utilized as a substitute for the LMS algorithm. This is to avoid inherent limitations in the LMS and to improve filter convergence rate [23]. Thus, the BP is the simplest self-learning algorithm that adapts itself to achieve an optimal solution [24, 25]. The multipath estimator mainly provides the multipath delay profile. This utilizes reference signals in the estimation process. A reference signal is a replica of code and carrier obtained from the output of the DLL and the PLL and is mathematically expressed as follows:

$$x_i(n) = g(n - i\tau^d - \tau_{\text{err}}) \cos(\omega n - \varphi_{\text{err}}) \quad (i = 0, \dots, K), \quad (2)$$

where τ_{err} and φ_{err} are the measured group delay and carrier phase that includes multipath error. τ^d is the sample period of the delay of the multipath signals and $K\tau^d$ is the maximum delay of multipath signals. It is assumed that the estimated digital IF signal can be defined as

$$\tilde{y}(n) = \sum_{i=0}^{\tilde{M}} \tilde{A}_i g(n - \tilde{\tau}_i) \cos(\omega n + \tilde{\varphi}_i) + \eta(n), \quad (3)$$

where the parameter with the symbol “ \sim ” denoted the estimated parameter. Because the parameters are impossible to be determined directly without any assumption about multipath signals, we employ (2) in estimation process. Thus, (3) is modified by using the reference signal and replacing \tilde{M} with \tilde{K} , the output signal of the filter is given by

$$\tilde{y}(n) = \sum_{i=0}^{\tilde{K}} w_i x_i(n) + w_b x_b + \eta(n), \quad (4)$$

where $w_i = \tilde{A}_i \cos(-\tilde{\varphi}_i)$ is the adjustable weight. The filter weight is used to minimize the cost function, which is also called the squared error energy function and is defined by using (1) and (3):

$$L(n) = \|y(n) - \tilde{y}(n)\|^2. \quad (5)$$

The filter that minimizes the cost function must be chosen by its tap weights to be the optimal solution to the normal equation [26],

$$C w_{\text{opt}} = p, \quad (6)$$

where C is the autocorrelation, $E[x_i(n)x_i^H(n)]$, of two reference signals ($x_l(n)$ and $x_i(n)$). p is the crosscorrelation, $E[y(n)x_l^H(n)]$, of the digital IF signal $y(n)$ and reference signal $x_l(n)$. Where $E[\cdot]$ is an expectation operator, the filter solves (6) recursively by using the BP with the adaptive learning rate algorithm. This learning rule performs a gradient descent on the energy function in order to achieve a minimum

$$\begin{aligned} w_i(n+1) &= w_i(n) - \mu \frac{\partial L(n)}{\partial w_i(n)}, \\ w_b(n+1) &= w_b(n) - \mu \frac{\partial L(n)}{\partial w_b(n)}. \end{aligned} \quad (7)$$

The learning rate coefficient μ determines stability and convergence rate; and a BP trained reference signal is utilized in order to obtain the minimum of (5) (see, e.g., [27–29]). If the learning rate is too large, the search path will oscillate about the desired path and converge more slowly than a direct descent. However, the descent will progress in small steps if the learning rate is too small, which significantly increases the total time to convergence. Thus, an adaptive coefficient in which the value of μ is a function of the error derivation is utilized as the solution [25]. To simplify the laws used in the filter computation, the following is updated:

$$\begin{aligned} w_i(n+1) &= w_i(n) + \mu \varepsilon(n) x_i(n), \\ w_b(n+1) &= w_b(n) + \mu \varepsilon(n) x_b, \end{aligned} \quad (8)$$

where $\varepsilon(n)$ is the output layer error term. \tilde{A}_i , $\tilde{\varphi}_i$, and $\tilde{\tau}_i$ are estimated as the absolute value of weight $|w_i|$, the phase angle of weight $\arg(w_i)$, and the value of delay element $i\tau^d$. The bias weight w_b , which is connected to a constant input $x_b = +1$, effectively controls the input signal level of the filter. The digital IF signal given in (1) is used as the desired signal; and the output of the DLL and the PLL is utilized as the filter input signal. The reference signal is determined by (2) which

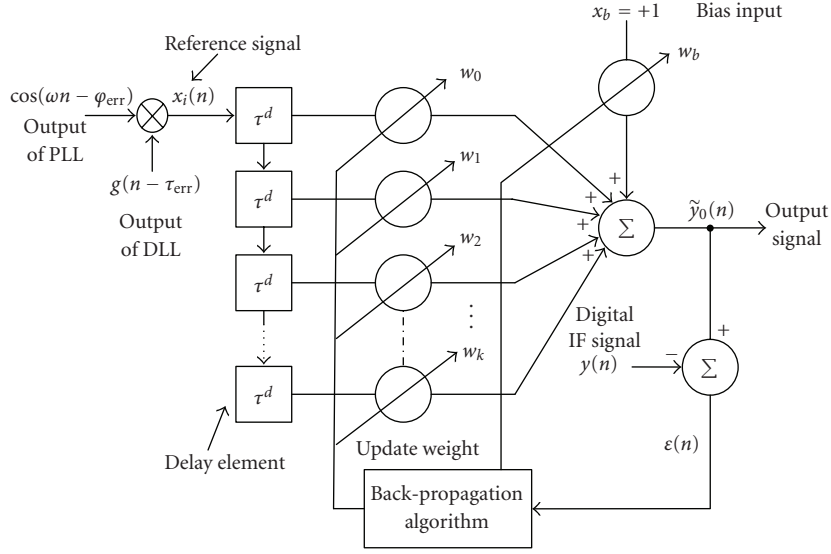


FIGURE 4: Structure of the modified adaptive filter used in the multipath estimator.

generates the output of each delay element. Thus, the estimated delay parameters from the filter weights and the delay element can be obtained, if the learning algorithm has converged.

3.3. Correlation value decomposer

After proceeding with the adaptive filter, the estimated parameters can be obtained and the correlation decomposer divides the estimated parameters into multipath and direct signal. In addition, the autocorrelation function of multipath signals is subtracted from analog-to-digital (A/D) converter output of the received signal. In the decomposer process, it is assumed that the values of the first peak amplitude tap weight are the direct signal and the remainders are multipath signals. Figure 5 shows an example in which the direct signal refers to the first peak $i = l$ and the multipath signal amplitude as the remnants $l < i \leq K$. It is assumed that the multipath channel has a decreasing power delay profile. Finally, the multipath signal parameter is then used to calculate the correlation value. The correlation equation of estimated multipath signals with amplitude \tilde{A}_i , delay $\tilde{\tau}_i$, and carrier phase $\tilde{\varphi}_i$ is given by

$$C_i(\tau) = \tilde{A}_i C(\tau - \tilde{\tau}_i) \cos(\tilde{\varphi}_l - \tilde{\varphi}_i), \quad (9)$$

where $C(\tau)$ is the autocorrelation function, $E[g(n)g(n - \tau)]$, of the GPS pseudorandom noise (PRN) code signal. Thus, the entire correlation value of the estimated multipath signal $C_i(\tau)$ is written as

$$\begin{aligned} C_p(\tau) &= C_{l+1}(\tau) + C_{l+2}(\tau) + \dots + C_K(\tau) \\ &= \sum_{i=l+1}^k C_i(\tau). \end{aligned} \quad (10)$$

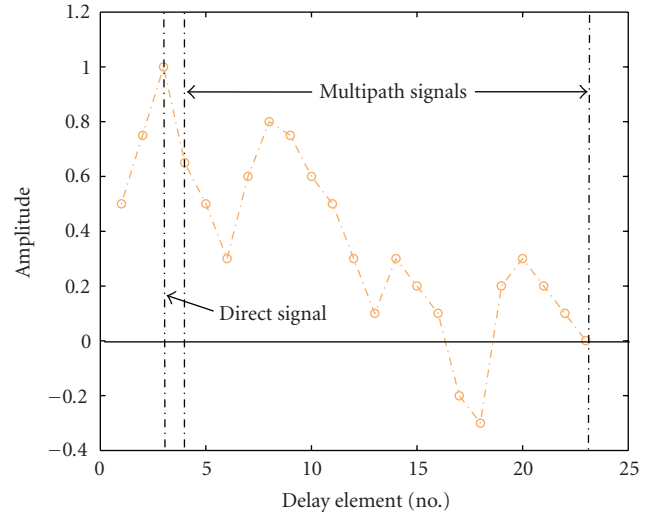


FIGURE 5: Decomposition of estimated parameters divided into direct signal and multipath signal. (The first peak is the direct signal and the others are multipath signals.)

3.4. Multipath removal

The entire correlation values of multipath signal C_p are subtracted from the correlation value of received signal C_r and the output of correlation value C_d is given by

$$C_d(\tau) = C_r(\tau) - C_p(\tau). \quad (11)$$

The tracking error occurred in the DLL and the PLL because of the multipath effect. The effect principally comes from the distortion of the correlation function receiving the IF signal, as shown in Figure 6. The figure shows the normalized correlation function with multipath effect. It is observed that the symmetry is lost and that the propagation delay is difficult to estimate. Therefore, the range measurement accuracy is

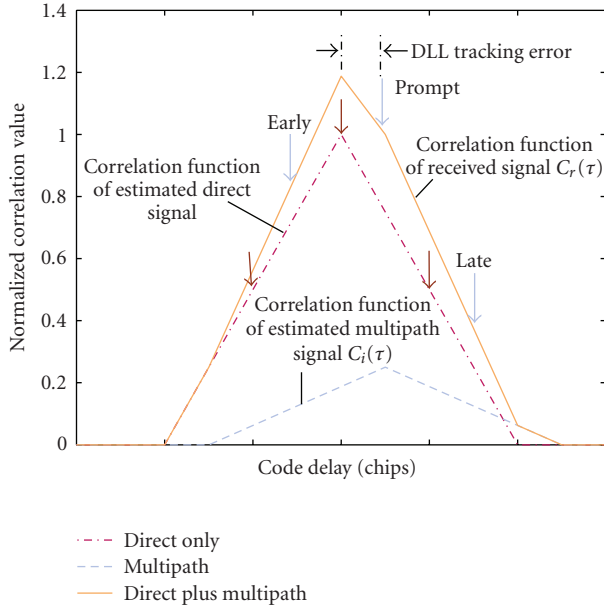


FIGURE 6: Normalized correlation functions, with and without multipath, respectively (plot in phase).

diminished. However, using a subtractive method provides multipath mitigation in the tracking loop and the output $C_p(\tau)$ enables the tracking loop to track direct signal accurately.

The above processes, the estimating process, the correlation decomposer, and the cancellation method, can reduce the multipath effects concerning the autocorrelation function of the received signal since the tracking errors in DLL and PLL are not completely removed. Given that the reference signal acquires the multipath error, the estimated parameters do not reflect correctly that of the real multipath. In order to achieve the ideal estimated parameters, the BP learning process is recursively utilized.

4. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

In this section, computer simulations are conducted to assess the performance of the proposed method. To make an easy comparison in performance with other published methods, the multipath tracking error envelopes in code and carrier phase for a multipath signal amplitude of half the LOS amplitude are represented as $A_0 = 1.0$ and $A_1 = 0.5$. A GPS multipath model consists of one direct signal and one delayed signal. It is assumed that a high signal-to-noise ratio (SNR) of 10 dB is located in this model. Simulation results are demonstrated in infinite bandwidth situation.

4.1. Simulation parameter

The digital IF frequency of a GPS signal is $\omega/2\pi = 1.25$ MHz and the sampling rate is 5 MHz. The delay chip of the multipath signal is varied from 0 to 1.5 chips with the phase of 0 and π radians relating to the direct signal. In conventional

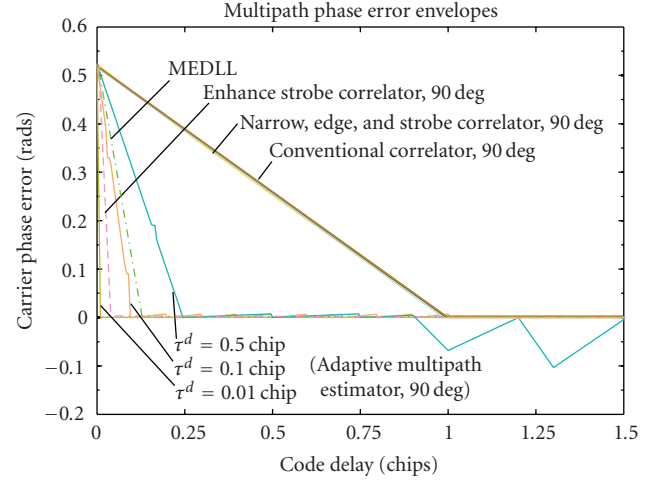


FIGURE 7: Carrier-phase error simulation results. ($A_0 = 1.0$, $A_1 = 0.5$, $\tau_0 = 0$ chip, $\tau_1 = 0 \sim 1.5$ chip, $\phi_0 = 0^\circ$, $\phi_1 = 90^\circ$; delay element $\tau^d = 0.01$ chip, 0.1 chip, and 0.5 chip is compared with other existing methods.)

correlator simulations, code-phase error and carrier-phase error are computed with 1 chip of an early-late discriminator. The chip spacing of a narrow correlator is less than 1 chip. Usually, a spacing of 0.2 chips is used to build up the discriminator functions. Two different narrow correlator discriminators are employed in a strobe correlator and the chip spacing of the two narrow correlators can be adjusted to 0.1 and 0.2 chips. The same parameters are also utilized in both enhanced strobe and edge correlators. The E1/E2 tracker of the two correlators is located at E1 = -0.55 and E2 = -0.45 with 0.1 chip spacing [16]. The modified adaptive filter method under the parameter of tap delay $\tau^d = 0.01$ chip, 0.1 chip, 0.5 chip and its 5-delayed tap are used as the input to the filter. The initial learning rate is 0.05, the number of training samples is 5000 at 1 ms C/A code period and the weights are initialized to 1. The performance is evaluated on a separate test set of 100 ms samples measured at intervals of 1 ms samples during the adaptive process.

4.2. Performance comparison

The multipath performance of these correlation techniques will be compared with each other, including the proposed method of this paper. To achieve this, the envelopes of all techniques described above are plotted into the same diagram to allow for a comprehensive comparison of multipath mitigation performance.

Figures 7–9 compare the error envelopes of the code phase and carrier phase for all of the multipath mitigation techniques considered. Simulation results show that the proposed method for the $\tau^d = 0.01$ chip case has both the best overall code multipath and the best carrier multipath performance. The conventional PLL has a maximum 0.52 radians in carrier-phase error. Therefore, the use of the conventional correlator results in very large maximum multipath errors and shows the worst multipath performance. The same

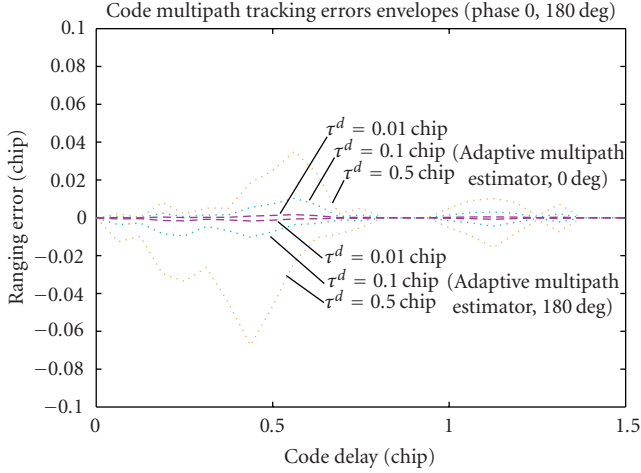


FIGURE 8: Code-phase error simulation results of proposed method. ($A_0 = 1.0$, $A_1 = 0.5$, $\tau_0 = 0$ chip, $\tau_1 = 0 \sim 1.5$ chip, $\phi_0 = 0^\circ$, $\phi_1 = 0^\circ, 180^\circ$; delay element $\tau^d = 0.01$ chip, 0.1 chip, and 0.5 chip.)

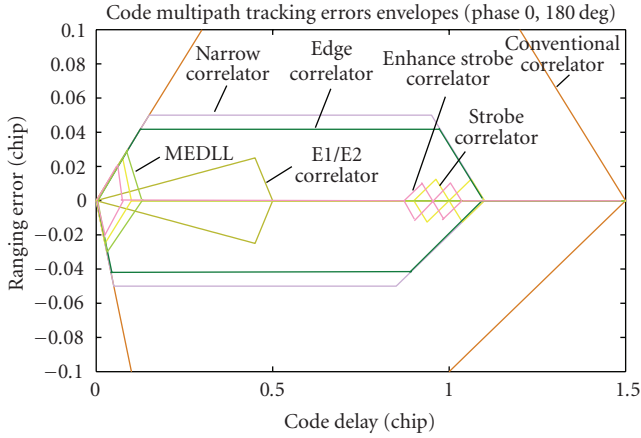


FIGURE 9: Code-phase error simulation results of existing methods. (Conventional correlator, edge, E1/E2, narrow, strobe, enhanced strobe, and MEDLL correlator; $A_0 = 1.0$, $A_1 = 0.5$, $\tau_0 = 0$ chip, $\tau_1 = 0 \sim 1.5$ chip, $\phi_0 = 0^\circ$, $\phi_1 = 0^\circ, 180^\circ$.)

results are in both narrow and edge correlators. It must be taken into consideration that since the narrow, the MEDLL, and the edge and strobe correlators do not offer any carrier-phase elimination, their sensitivity to multipath is almost the same as the one-chip conventional correlator. Only slight differences can be observed on account of differences in their code multipath mitigation.

From these figures through the use of the proposed method with a delay element $\tau^d = 0.01$ chip, both code- and carrier-phase errors are reduced in the range of delay from 0 through 1.5 chip. In contrast, through the adoption of the proposed multipath mitigation approach with a tap delay $\tau^d = 0.01$, the code- and carrier-phase error decrease dramatically in the range of delay from 0 to 1.5 chip. In the case of the tap delay $\tau^d = 0.1$, multipath mitigation performance degrades in comparison with the case of $\tau^d = 0.01$. This is due to the accuracy of the estimated delay profile in

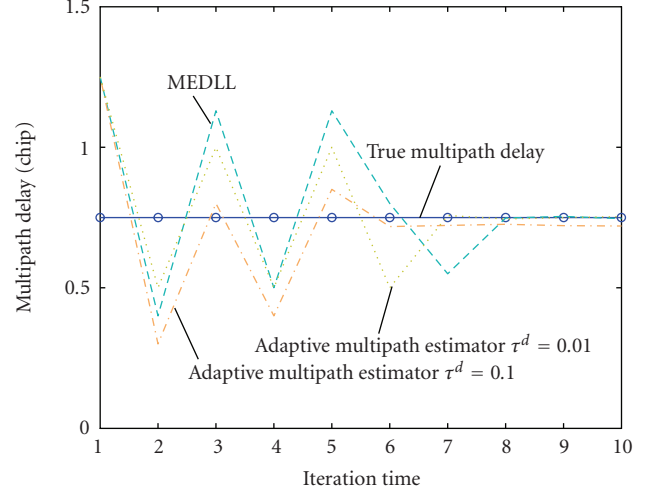


FIGURE 10: Delay estimated by MEDLL and adaptive multipath estimator.

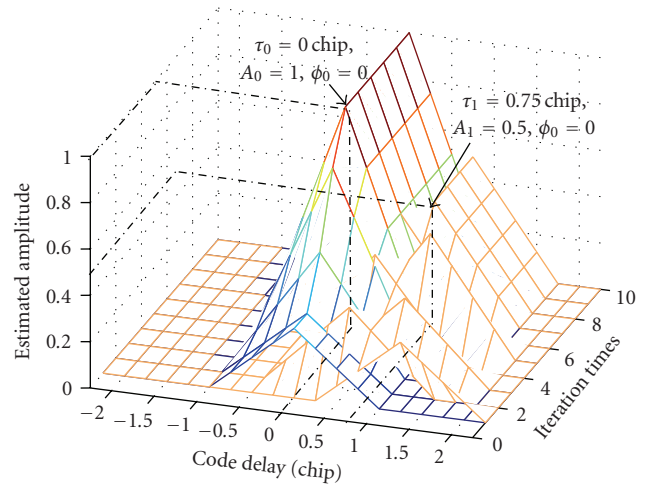


FIGURE 11: An example of estimated parameters. ($A_0 = 1.0$, $A_1 = 0.5$, $\tau_0 = 0$, $\tau_1 = 0.75$, $\phi_0 = 0^\circ$, $\tau^d = 0.01$.)

the adaptive filter relying on the tap delay τ^d . The smaller τ^d is, the better the performance of multipath mitigation will be. In the case of the $\tau^d = 0.5$ chip, the multipath mitigation performance degrades in code-phase error simulation and the carrier-phase error also exceeds that of the conventional tracking loop. Though the use of a small tap delay is suitable to achieve high performance in multipath mitigation, it also takes high computation cost to estimate delay profiles. Thus, there is a tradeoff between the performance of multipath mitigation and computational load.

Another focal point is that the proposed method (Figure 8) can better enhance the performance in short-delay multipath scenario as opposed to almost every DLL structure (Figure 9). If a given application involves only the short-delay multipath, then the best correlation techniques such as the enhanced strobe correlator will not perform any better than the proposed method of this paper.

TABLE 1: Comparative performance of multipath mitigation techniques.

| | Conventional correlator | Narrow | Strobe | Enhanced strobe | Edge | E1/E2 | MEDLL | Modified adaptive filter |
|-----------------------------------|-----------------------------|-------------------------|----------------------------|-----------------------------|-------------------------|-----------------------------|------------------------------|-------------------------------------|
| Noise performance (SNR = -10 dB) | Poor (above 0.2 chip error) | Good (0.034 chip error) | Poor (0.2~0.25 chip error) | Poor (below 0.2 chip error) | Fair (0.054 chip error) | Fair (0.04~0.06 chip error) | Fair (below 0.18 chip error) | Fair (0.05~0.1 chip error) |
| Code multipath performance | Poor | Fair | Fair | Good | Fair | Good | Good | Best |
| Carrier multipath performance | Poor | Poor | Poor | Fair | Poor | Poor | Good | Best (count on number τ^d) |
| Short-delay multipath performance | Poor | Poor | Poor | Fair | Poor | Good | Good | Best |
| A priori information | Needed (coarse delay) | Needed (coarse delay) | Needed (coarse delay) | Needed (coarse delay) | Needed (coarse delay) | Needed (coarse delay) | Needed (reference function) | None |
| Hardware complexity | Easy | Easy | Fair | Fair | Fair | Fair | High | Fair (count on number of iteration) |
| Software complexity | Easy | Easy | Easy | High | Fair | Easy | Fair | Low to moderate |

In order to achieve the estimated performance in the proposed method, the desired multipath correct delay profiles are $A_0 = 1.0$, $A_1 = 0.5$, $\tau_0 = 0$, $\tau_1 = 0.75$, $\phi_0 = 0^\circ$, and $\phi_1 = 0^\circ$. The delay element number is five. An estimated multipath delay versus the true multipath delay curve for two considered algorithms, the MEDLL and the modified adaptive filter, is shown in Figure 10. As determined, the proposed method of $\tau^d = 0.01$ has faster convergence rate than the MEDLL. The modified adaptive filter is rapid in convergence rate with $\tau^d = 0.1$. However, it is subject to a steady state error of 0.03 chips in delayed estimation.

Figure 11 shows how the estimate improves over time. The estimated parameters are computed from 1 to 10 times with multipath mitigation iteration. The time of iteration is 5 ms. As observed, during the first iteration time, the delay parameters have a large estimated error caused by the multipath error of the reference signal. When the iteration time increases to 5 or 6 ms, the estimated error is reduced and the correct estimated delay profiles are obtained. The same result is observed in all simulations.

Table 1 shows the evaluation of these architectures such as: noise performance, code versus carrier performance, *a priori* information needed as an input, short-delay performance and hardware/software complexity. With regard to the noise mitigation performance, when SNR = -10 dB, the simulation result shows that the narrow correlator is the best in performance with the code tracking error of about 0.034 chip. The proposed method in this paper is medium in performance with the tracking error of around 0.05~0.1 chip, which is equal to the medium noise performance of the edge and E1/E2 correlator. In contrast, the conventional correlator,

strobe, enhanced strobe correlator, and the MEDLL are inferior in noise performance, with the tracking error around 0.2 chips.

Regarding the GPS mobile applications, very good accuracy is needed even at the expense of slightly increased complexity. In this context, the best options are the enhanced strobe correlator and the modified adaptive filter. The modified adaptive filter method has the best performance in multipath mitigation. However, its hardware complexity, such as the number of the required multiplications per delay estimate is on the order of $O[N_{\text{iter}}(K\tau^d)^3]$. Where N_{iter} is the number of filter iterations and $K\tau^d$ is an estimate of the maximum delay spread of the channel in the samples. The high complexity of this method is principally due to the matrix inversion operations. However, in short-delay multipath environments, the number of delay samples $K\tau^d$ is smaller and therefore the complexity of the modified adaptive filter is not very high. The enhanced strobe correlator has lower complexity on the order of $O[(K\tau^d)^2]$, but its performance is not as good as the modified adaptive filter performance. From the design point of view, the best tradeoff between accuracy and complexity should be chosen according to the estimated maximum delay spread of the channel.

4.3. Brief summary

As indicated previously, there are inherent limitations in almost every technique. The combined characteristics of these studies proposed method prevail over those of other techniques. In addition, the prerequisite of short-delay multipath

causes the influences of hardware complexity in the modified adaptive filter to be insignificant. Therefore, the proposed method is a well-suited and well-balanced application in multipath mitigation.

5. CONCLUSION

Multipath is the dominant error source in high precision-based GPS applications and is also a significant error source in nondifferential applications. Many receiver architectures have been on the market and claim various multipath mitigation characteristics. Most of these techniques can be characterized either as discriminator function shaping or correlation function shaping. In this study, a modified adaptive filter method is applied in multipath mitigation for GNSS application. A simplified GPS plus multipath signal model is utilized in this simulation. This approach improves the performance of the code-phase and carrier-phase errors compared with all other published methods. Simulation results also show that the proposed method is a viable solution to increase the positional accuracy for GNSS navigation in the presence of a short-delay multipath environment.

ACKNOWLEDGMENT

The authors would like to thank the National Science Council of Taiwan for their support of this work under NSC 96-2628-E-006-246-MY2.

REFERENCES

- [1] L. L. Hagerman, "Effects of multipath on coherent and non-coherent PRN ranging receiver," Aerospace Report TOR-0073 (3020-03)-3, The Aerospace Corporation, Development Planning Division, Los Angeles, Calif, USA, 1973.
- [2] J. J. Spilker Jr., "GPS signal structure and performance characteristics," *Journal of the Institute of Navigation*, vol. 25, no. 2, pp. 121–146, 1978.
- [3] A. J. van Dierendonck, P. J. Fenton, and T. J. Ford, "Theory and performance of narrow correlator spacing in a GPS receiver," *Journal of the Institute of Navigation*, vol. 39, no. 3, pp. 265–283, 1992.
- [4] D. J. R. van Nee, "Reducing multipath tracking errors in spread-spectrum ranging systems," *Electronics Letters*, vol. 28, no. 8, pp. 729–731, 1992.
- [5] R. D. J. van Nee, "Spread-spectrum code and carrier synchronization errors caused by multipath and interference," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 29, no. 4, pp. 1359–1365, 1993.
- [6] M. S. Braasch, "Isolation of GPS multipath and receiver tracking errors," *Journal of the Institute of Navigation*, vol. 41, no. 4, pp. 415–434, 1994.
- [7] B. R. Townsend and P. C. Fenton, "A practical approach to the reduction of pseudorange multipath errors in all GPS receiver," in *Proceedings of the 7th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION-GPS '94)*, vol. 1, pp. 143–148, Salt Lake City, Utah, USA, September 1994.
- [8] R. D. J. van Nee, J. Sierveld, P. C. Fenton, and B. R. Townsend, "The multipath estimating delay lock loop: approaching theoretical accuracy limits," in *Proceedings of the IEEE Position Location and Navigation Symposium*, pp. 246–251, Las Vegas, Nev, USA, April 1994.
- [9] B. R. Townsend, R. D. J. van Nee, P. C. Fenton, and K. J. V. Dierendonck, "Performance evaluation of the multipath estimating delay lock loop," in *Proceedings of the Annual National Technical Meeting of the Institute of Navigation (ION-NTM '95)*, pp. 277–283, Anaheim, Calif, USA, January 1995.
- [10] L. Garin, F. van Diggelen, and J. Rousseau, "Strobe and edge correlator multipath rejection for code," in *Proceedings of the International Technical Meeting of the Institute of Navigation (ION-GPS '96)*, pp. 657–664, Kansas City, Mo, USA, September 1996.
- [11] L. Garin and J. Rousseau, "Enhanced strobe correlator multipath rejection for code & carrier," in *Proceedings of the International Technical Meeting of the Institute of Navigation (ION-GPS '97)*, vol. 1, pp. 559–568, Kansas City, Mo, USA, September 1997.
- [12] M. C. Laxton and S. L. DeVilbiss, "GPS multipath mitigation during code tracking," in *Proceedings of the American Control Conference (ACC '97)*, vol. 3, pp. 1429–1433, Albuquerque, NM, USA, June 1997.
- [13] A. J. van Dierendonck and M. S. Braasch, "Evaluation of GNSS receiver correlation processing techniques for multipath and noise mitigation," in *Proceedings of the National Technical Meeting of the Institute of Navigation (ION-NTM '99)*, pp. 207–215, Santa Monica, Calif, USA, January 1997.
- [14] M. S. Braasch, "Performance comparison of multipath mitigating receiver architectures," in *Proceedings of the IEEE Aerospace Conference*, vol. 3, pp. 1309–1315, Big Sky, Mont, USA, March 2001.
- [15] R. Chaggara, C. Macabiau, and E. Chatre, "Using GPS multicorrelator receivers for multipath parameters estimation," in *Proceedings of the International Technical Meeting of the Institute of Navigation (ION-GPS '02)*, pp. 477–486, Portland, Ore, USA, September 2002.
- [16] M. Irsigler and B. Eissfeller, "Comparison of multipath mitigation techniques with consideration of future signal structures," in *Proceedings of the International Technical Meeting of the Institute of Navigation (ION-GPS/GNSS '03)*, pp. 2584–2592, Portland, Ore, USA, September 2003.
- [17] T. Pany, M. Irsigler, and B. Eissfeller, "S-curve shaping: a new method for optimum discriminator based code multipath mitigation," in *Proceedings of the International Technical Meeting of the Institute of Navigation (ION-GPS/GNSS'05)*, vol. 2005, pp. 2139–2154, Long Beach, Calif, USA, September 2005.
- [18] J. M. Kelly, M. S. Braasch, and M. F. DiBenedetto, "Characterization of the effects of high multipath phase rates in GPS," *GPS Solutions*, vol. 7, no. 1, pp. 5–15, 2003.
- [19] S. K. Kalyanaraman, M. S. Braasch, and J. M. Kelly, "Code tracking architecture influence on GPS carrier multipath," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 42, no. 2, pp. 548–561, 2006.
- [20] M. S. Braasch and F. van Graas, "Guidance accuracy considerations for real time GPS interferometry," in *Proceedings of the International Technical Meeting of the Institute of Navigation (ION-GPS '91)*, pp. 373–386, Albuquerque, NM, USA, September 1991.
- [21] B. Widrow and M. E. Hoff, "Adaptive switch circuits," in *IRE WESCON Convention Record*, vol. 55, part 4, pp. 96–104, New York, NY, USA, 1960.
- [22] B. Widrow and M. A. Lehr, "30 years of adaptive neural networks: perceptron, madaline, and back propagation," *Proceedings of the IEEE*, vol. 78, no. 9, pp. 1415–1442, 1990.

- [23] R. J. Schalkoff, *Artificial Neural Networks*, McGraw-Hill, New York, NY, USA, 1997.
- [24] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, "Learning internal representations by error propagation," in *Parallel Distributed Processing: Explorations and Microstructures of Cognition*, vol. 1, pp. 318–362, MIT press, Cambridge, Mass, USA, 1986.
- [25] S. Haykin, *Neural Networks: A Comprehensive Foundation*, Prentice Hall, Englewood Cliffs, NJ, USA, 1999.
- [26] S. Haykin, *Adaptive Filter Theory*, Prentice Hall, Englewood Cliffs, NJ, USA, 1995.
- [27] B. Widrow and S. D. Stearns, *Adaptive Signal Processing*, Prentice Hall, Englewood Cliffs, NJ, USA, 1985.
- [28] R. A. Jacobs, "Increased rates of convergence through learning rate adaptation," *Neural Networks*, vol. 1, no. 4, pp. 295–307, 1988.
- [29] D. P. Mandic and J. A. Chambers, "Towards the optimal learning rate for backpropagation," *Neural Processing Letters*, vol. 11, no. 1, pp. 1–5, 2000.