Extended Short Multipath Insensitive Code Loop

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BIOGRAPHY

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ABSTRACT

Short Multipath Insensitive Code Loop Discriminator (SMICLD) can adjust code errors from positive values to zero without any bias in single short multipath ray environment. However, when code errors turn into negative, SMICLD always outputs zero. This kind of asymmetry of SMICLD will induce large code errors when noise exists. Extended Short Multipath Insensitive Code Loop (ESMICL) based on the combination of multiple discriminators is proposed to improve such asymmetry. The superiority of ESMICL has been evaluated against SMICLD, SMICLD's improvement—Modified DLL Aided by SMICLD—and two traditional multipath mitigating methods—Narrow Correlator (NC) delay lock loop and Multipath Estimating Delay Lock Loop (MEDLL). In a set of analysis and simulations, ESMICL demonstrates a higher ability to mitigate single short multipath ray in noise than other four code loops. The lower bound of multipath delay that ESMICL can handle reaches 0.015chips for GPS L1 C/A signal. A real scenario test indicates that the positioning errors of ESMICL are less than those of SMICLD and Modified DLL Aided by SMICLD by more than 80% and 60% respectively. And the anti-noise ability of ESMICL is close to MEDLL.

INTRODUCTION

Multipath is a significant source of errors hard to eliminate in Global Positioning System (GPS), even for the augmented and modernized GPS. Researchers worldwide have proposed many effective multipath mitigating methods, including antenna-based, parameter-estimation-based and correlator/discriminator-based techniques. These methods, however, have little effect on short multipath. Short multipath exists in challenging environments such as urban canyons and indoor positioning, where the relative delays of reflecting rays are short due to the limited space. The shorter the multipath delay is, the more similar the multipath is to LOS signal, which makes the receiver hard to distinguish between them. Although some short multipath mitigating methods have been proposed, they all have some limits and shortcomings.

Sleewaegen [2001] proposed A-Posteriori Multipath Estimation (APME) technique based on the tight relationship between multipath errors and amplitude of received signals. APME can estimate short-multipath errors by scaling the combination of correlation values with an optimization coefficient. However, the optimization coefficient is relevant to the multipath-to-direct ratio (MDR) of amplitude that is unknown to receivers. The optimization coefficient fixed in Sleewaegen[2001] is only suitable for weak multipath of MDR below 0.25, which extremely limits APME's application. The anti-short-multipath methods proposed by Bhuiyan [2010] and Gao [2014] are similar to APME. Zhang [2005] proposed a short multipath mitigating technique based on virtual multipath, which shares the same autocorrelation function (ACF) peak with the received signal. By subtracting the ACF values of virtual multipath from that of the received signal, the peak of the rest ACF will have no multipath bias, corresponding to zero code error. However, the precondition that there has to be a multipath ray stronger than LOS and other multipath signals restricts its applications. Zhou & Huang [2007] improved the short multipath mitigation performance of NC by using Teager-Kaiser operator that can convert the subtle changes of ACF amplitude of received signals into pulses. Thus the multipath delay can be estimated by detecting these pulses. This method ameliorates NC's effect on multipath with delay of less than 0.5chips. However, when multipath delay reduces to 0.1chips or less, the adjacent pulses will get too close to be detected. Mo [2018] proposed a multipath mitigation method based on Fast Orthogonal Search (FOS) that tries to minimize the difference between the correlation measurements and the correlation estimations, which is similar to MEDLL. Even superior to MEDLL and NC, this FOS-based technique still has larger code errors for short multipath than medium and long multipath. Moreover, FOS requires large computational loads, which is high demanding for receiver hardware.

Short Multipath Insensitive Code Loop Discriminator (SMICLD) introduced by Jardak [2007] modifies correlation values and the code discriminator so that the zero-crossing point of its S-curve has no bias in short-multipath environment. However, the S-curve of SMICLD is asymmetrical about the zero-crossing point. When code errors are negative, SMICLD always outputs zero, which results in ambiguous distinction between negative and zero code errors. As a result, SMICLD is sensitive to noise seriously. Moreover, due to its special structure, SMICLD is also sensitive to the number of multipath rays and cannot mitigate long multipath with delay greater than half correlator spacing. Modified Short Multipath Insensitive Code Loop Discriminator (MSMICLD) proposed by Mustafa [2012] and New Modified Short Multipath Insensitive Code Loop Discriminator (New MSMICLD) proposed by Hassan [2018] are respectively the non-coherent envelope and non-coherent dot product power versions of SMICLD. Modified DLL Aided by SMICLD proposed by Weng [2017] has improved the asymmetry of SMICLD. The algorithm uses SMICLD for positive and zero code errors, and switches to the modified early minus late discriminator (EMLD) for negative code errors. This code loop integrates the advantages of SMICLD and EMLD, which can not only mitigate short multipath but also adjust negative code errors in time. However, there's a gap at the zero-crossing point of the S-curve of Modified DLL Aided by SMICLD, which degrades its multipath mitigating performance when noise exists.

In order to further improve the asymmetry of SMICLD, a novel code loop named Extended Short Multipath Insensitive Code Loop (ESMICL) has been proposed in this paper. ESMICL consists mainly of three sections: SMICLD, modified EMLD and multicorrelators. The multicorrelator module is exploited to estimate code errors, which lays the base for the extension of the positive part of SMICLD's S-curve to the region where code errors are negative. The short multipath mitigating performance and anti-noise ability of ESMICL have been compared not only with SMICLD and Modified DLL Aided by SMICLD, but also with conventional code loops including NC and MEDLL. Test results indicate that ESMICL has the best single short multipath mitigation performance in noise environment among these code loops.

The paper is organized as follows. Firstly, a brief description of the short multipath model and the assessment of SMICLD respectively are given. Then the principles of ESMICL are illustrated in detail. Comparative analysis and simulation results will be displayed in the following sections. And then, a real scenario test is implemented. Last section summarizes this study and makes some suggestions for future research.

ASYMMETRY OF SMICLD

The GPS L1 C/A IF signal mixed with multipath can be expressed as

$$r(t) = a_0 p(t - \tau_0) D(t - \tau_0) \cos(wt + \theta_0) + \sum_{i=1}^{M} a_i p(t - \tau_0 - \tau_i) D(t - \tau_0 - \tau_i) \cos(wt + \theta_i) \tag{1}$$

The symbols in (1) and their interpretations are exhibited in Table 1.

Table 1: Parameters of multipath model

a_0	Amplitude of LOS Signal	θ_i	Carrier Phase of Multipath
τ_0	Propagation Time of LOS Signal	M	Number of Multipath Signals
θ_0	Carrier Phase of LOS Signal	w	Carrier Frequency
a_i	Amplitude of Multipath	$p(t)$	C/A Code Sequence
τ_i	Multipath Delay Relative to LOS Signal	$D(t)$	Navigation Message Data

The multipath amplitude a_i that is normalized by LOS signal is also called the multipath-to-direct ratio (MDR). There is no definite standard for short multipath, the delay of which is usually considered less than 1chip by some researchers or within 0.5chips by others. In this paper, multipath with delay of less than 0.1chips will be focused on. In the receiver, the replica C/A code is represented by $p(t-\tau)$, which is delayed by τ relative to the direct signal. θ is the carrier phase of local carrier. After carrier wipe-off and code correlation process, the in-phase prompt correlation value IP can be written as

$$IP = a_0 R(\varepsilon) \cos(\theta_0 - \theta) + \sum_{i=1}^{M} a_i R(\varepsilon - \tau_i) \cos(\theta_i - \theta) \tag{2}$$

In (2), it is assumed that the data sequence doesn't transition during the integration time, so $D(t)$ can be neglected. The code tracking error ε is the code phase difference between the direct signal and the local replica.

$$\varepsilon = \tau - \tau_0 \tag{3}$$

Theoretically, the autocorrelation function $R(\varepsilon)$ is defined as a triangle function

$$R(\varepsilon) = \begin{cases} 1 - |\varepsilon| \ , \ |\varepsilon| \le 1\text{chip} \\ 0 \quad , \text{others} \end{cases} \tag{4}$$

Let's denote the other quadrature prompt, in-phase early, quadrature early, in-phase late, quadrature late correlation values as QP, IE, QE, IL, QL, respectively. By modifying correlation values and the discriminator expression, SMICLD eliminates the zero-crossing point bias of its S-curve distorted by single short multipath with delay less than min(Δ/2, 1-Δ/2), where Δ denotes the correlator spacing. The SMICLD is defined in the following expressions

$$IP' = IP - \frac{\Delta}{2} \frac{IE + IL}{2 - \Delta} \tag{5}$$

$$QP' = QP - \frac{\Delta}{2} \frac{QE + QL}{2 - \Delta} \tag{6}$$

$$D = (IE^2 + QE^2) - ((IP')^2 + (QP')^2) \tag{7}$$

Combined with (2)~(6), the discriminator function can be written as follows.

$$D_{SMICLD} = \begin{cases} 2(2-\Delta)\left[a_0^2\varepsilon + a_1^2\left(\varepsilon-\tau_1\right) + a_0a_1\cos(\theta_0-\theta_1)(2\varepsilon-\tau_1)\right] & 0<\tau_1<\varepsilon\le\min\left(\frac{\Delta}{2},1-\frac{\Delta}{2}\right) \\ 2a_0^2(2-\Delta)\varepsilon + 4a_0a_1\cos(\theta_0-\theta_1)\varepsilon(1+\varepsilon-\tau_1-\frac{\Delta}{2}) & 0<\varepsilon<\tau_1\le\min\left(\frac{\Delta}{2},1-\frac{\Delta}{2}\right) \\ 0 & \tau_1-\min\left(\frac{\Delta}{2},1-\frac{\Delta}{2}\right)<\varepsilon<0<\tau_1\le\min\left(\frac{\Delta}{2},1-\frac{\Delta}{2}\right) \end{cases} \tag{8}$$

The assessments of SMICLD in single short multipath environment have been illustrated by Table 2, the details of which can be found in X Weng & Y Kou [2017]. As it is shown in Table 2, SMICLD can adjust code error from positive to zero without any bias when single short multipath exists. However, when the code tracking error becomes negative (no less than τ_1-min(Δ/2, 1-Δ/2)), SMICLD outputs zero constantly, which leaves code error without any adjustment. This kind of asymmetry of SMICLD's S-curve seriously restricts its application, especially in noise environment. The code loop using SMICLD as the discriminator is called Short Multipath Insensitive Code Loop (SMICL).

Table 2: SMICLD's outputs of different code error

Code Error ε	D_{SMICLD}
τ_1-min(Δ/2,1-Δ/2) < $\varepsilon \le 0 < \tau_1 \le$ min(Δ/2,1-Δ/2)	$D_{\mathrm{SMICLD}}=0$
$0 < \varepsilon \le \tau_1 \le$ min(Δ/2,1-Δ/2)	$D_{\mathrm{SMICLD}}>0$
$0 < \tau_1 < \varepsilon \le$ min(Δ/2,1-Δ/2)	$D_{\mathrm{SMICLD}}>0$

EXTENDED SHORT MULTIPATH INSENSITIVE CODE LOOP

Architecture of ESMICL

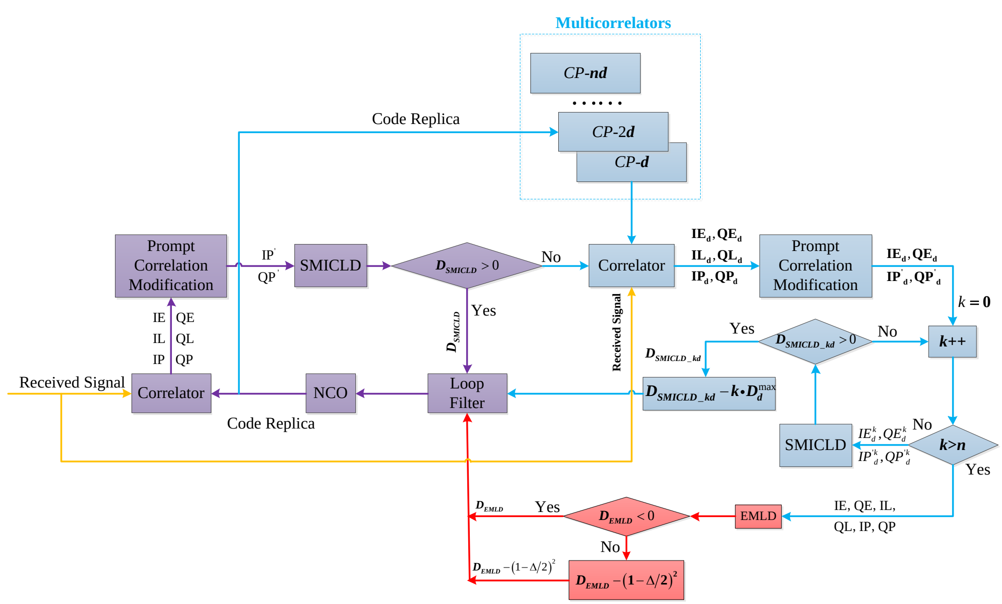


Fig.1 Block Diagram of ESMICL

The main idea of ESMICL is to extend the S-curve of positive code errors of SMICLD that is located in the first quadrant of εD-plane to the third quadrant where code errors are negative, considering SMICLD can adjust code errors from positive values to zero. Its architecture is illustrated by the block diagram in Fig.1. As shown in Fig.1, Extended SMICL mainly consists of three sections: modified EMLD (the red section), SMICLD (the purple section) and the multicorrelator module (the blue section). By default, the code loop discriminator is set to SMICLD. If the output of SMICLD is positive, the code error will be considered as positive correspondingly. Thus, SMICLD will continue to be used. If SMICLD outputs zero, the code error may be zero or negative. In this case, the multicorrelator module is activated to estimate current code error, whereby the extension of SMICLD or modified EMLD will be switched on.

Code Error Estimation

The estimation of code errors is fundamental to the extension of SMICLD. Let *CP*, *n* and *d* respectively represent the current values of the replica code phase, the number of correlation channels and the spacing between adjacent correlators in the multicorrelator module. The code phase of the k^{th} correlator in the multicorrelator module falls behind the prompt correlator by *kd*, which increases the code error of the k^{th} correlator to $\varepsilon + kd$. The correlation values in the k^{th} channel are represented by IE_d^k, QE_d^k, IL_d^k, QL_d^k, IP_d^k, QP_d^k, $IP_d^{'k}$, $QP_d^{'k}$. All correlation values in the multicorrelator module can be written in the form of vectors: $\mathbf{IE}_d$, $\mathbf{QE}_d$, $\mathbf{IL}_d$, $\mathbf{QL}_d$, $\mathbf{IP}_d$, $\mathbf{QP}_d$, $\mathbf{IP}_d^{'}$, $\mathbf{QP}_d^{'}$ which will be utilized to update SMICLD. As soon as the multicorrelator module is activated, SMICLD will be firstly updated by the correlation values of the 1st channel. If the output of SMICLD (D_{SMICLD_d}) is positive at this time, the code error ε will be considered to lie in [-*d* 0]. However, if SMICLD still outputs zero, which means the code error ε is less than -*d*, the correlation values of the 2nd correlator will be used to update SMICLD again. Such operations will be repeated until SMICLD outputs a positive value. Assuming the k^{th} channel meets above requirements ($D_{SMICLD\_kd}>0$), we can determine that the code error ε is located in the interval of [-*kd*, -(*k*-1)*d*] (*k* is a positive integer and no more than *n*). If SMICLD still outputs zero in terms of the n^{st} channel, the code error ε will be considered less than -*nd*.

Extension of SMICLD

The discriminator of ESMICL can be called Extended Short Multipath Insensitive Code Loop Discriminator (ESMICLD), which is composed of three kinds of discriminator. If it is determined that the code error is located in the interval of [-*kd*, -(*k*-1)*d*], the following discrimination values will be used.

$$D_{ESMICLD} = D_{SMICLD}\left(\varepsilon + kd\right) - k \bullet D_d^{max} \tag{11}$$

D_d^{max} represents the maximum value of SMICLD in the interval of [0 *d*] in the presence of single short multipath ray. As illustrated in Fig.2, when the code error ε lies in the interval of [-*kd*, -(*k*-1)*d*], the code error of k^{th} correlation channel $\varepsilon+kd$ must be located in the interval of [0 *d*]. Therefore, the output of SMICLD $D_{SMICLD}(\varepsilon+kd)$ is less than D_d^{max}. Moreover, in order to guarantee the monotonous increase of the S-curve, D_d^{max} is multipled by *k* and then subtracted from $D_{SMICLD}(\varepsilon+kd)$. Thus, the discriminating result D_{E_SMICLD} is negative and instructs the code loop to diminish the replica code phase, which promotes the code loop to converging to the right direction. The whole process of extension, as illustrated in Fig.2, can be described as moving the S-curve of SMICLD in the interval of [0 *d*] to the left by *kd* and then downwards by kD_d^{max} to extend the positive part of the S-curve of SMICLD to the third quadrant. However, it will be difficult to determine D_d^{max} if the multipath delay is less than *d*. Thus, Extended SMICLD is designed to handle the multipath with relative delay greater than *d*. In this case, we can get the expression of D_d^{max}:

$$D_d^{max} = 4d\left(2 - \Delta - \tau_1 + d\right) \tag{12}$$

The details of calculating the maximum discriminating value D_d^{max} can be referred to Appendix. As you can see from Fig.2, there is a subtle gap at the zero-crossing point of the S-curve of ESMICL. The smaller the correlator spacing *d* is, the smaller the maximum value of SMICLD and the gap at the zero-crossing point are. Nevertheless, the computational complexity will intensify with the increase of correlators that is the result of decreasing *d*. Taking into account the smaller gap at the zero-crossing point and the computational complexity, we choose six correlators spaced consecutively by d=Δ/64 to extend the positive S-curve of SMICLD to the range of [-6Δ/64 0] (approximately [-0.1 0] chips with Δ=1 chip) of code errors. Under these conditions, ESMICL can mitigate the short multipath delayed by more than Δ/64 chip (approximately 0.015 chips with Δ=1 chip). According to (12), the maximum discriminating value of SMICLD in the interval of [0 Δ/64] can be calculated:

$$D_{d=\Delta/64}^{max}=\left(2\text{-}\frac{63}{64}\Delta\right)\bullet\frac{\Delta}{16} \tag{13}$$

If SMICLD still outputs zero until the nth correlation channel, modified EMLD will be activated.

$$D_{ESMICLD}=D_{modified\ EMLD}\left(\varepsilon\right)=\begin{cases} D_{EMLD}\left(\varepsilon\right) & D_{EMLD}\left(\varepsilon\right)<0 \\ D_{EMLD}\left(\varepsilon\right)-\left(1-\dfrac{\Delta}{2}\right)^2 & D_{EMLD}\left(\varepsilon\right)\geq 0 \end{cases} \tag{14}$$

As shown in Fig.3, the S-curve of ESMICLD consists of three sections: the positive part of the S-curve of SMICLD ($\varepsilon \geq 0$), the negative part of the S-curve of modified EMLD (where $\varepsilon <$ -6Δ/64) and the extension of the S-curve of SMICLD near the zero-crossing point (where -6Δ/64<ε <0).

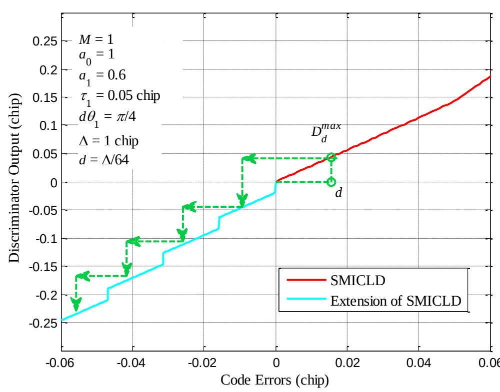


Fig.2 Extension of SMICLD

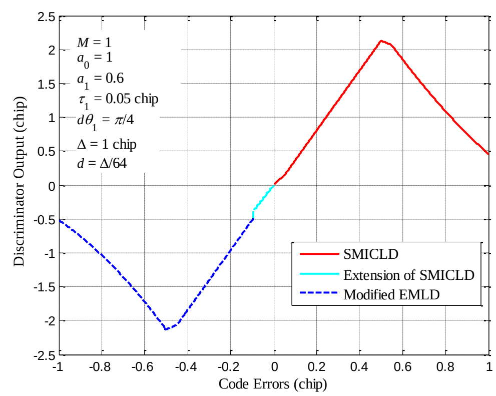


Fig.3 S-curve of ESMICLD

It can be seen from equation (11) that the maximum gap at the zero-crossing point of ESMICLD's S-curve is -D_d^{max} (about -0.06 chip with d=Δ/64 and Δ=1), less than that of Modified DLL Aided by SMICLD (about -0.25 chip with Δ=1 chip) by 76% according to Weng [2017].

Normalization of ESMICL

The theory about ESMICL above is based on the assumption that the amplitude of the direct signal is 1. In practice, the normalization of the discriminators in ESMICL has to be done to deal with received signals with different power. Firstly, SMICLD is normalized according to the following equation.

$$D_{SMICLD}=\frac{(IE^2+QE^2)\text{-}((IP^{'})^2+(QP^{'})^2)}{(IE^2+QE^2)+(IL^2+QL^2)} \tag{15}$$

Modified EMLD is normalized as follows, the details of which can be found in Weng [2019].

$$D_{modified\ EMLD}(\varepsilon) = \begin{cases} D_{norEMLD}(\varepsilon) & D_{norEMLD}(\varepsilon) < 0 \\ D_{norEMLD}(\varepsilon) - \dfrac{2-\Delta}{\sqrt{2\left[1+(1-\Delta/2)^2\right]}+2-\Delta/2} & D_{norEMLD}(\varepsilon) \geq 0 \end{cases} \tag{16}$$

Where $D_{norEMLD}$ is

$$D_{norEMLD} = \frac{\left(IE^2+QE^2\right)-\left(IL^2+QL^2\right)}{\left(IE^2+QE^2\right)+\left(IP^2+QP^2\right)} \tag{17}$$

The normalization of ESMICLD is implemented with the help of the forward correlation channel. If the code tracking error is estimated in the interval of [-*kd*, -(*k*-1)*d*], the code phase of the forward correlation channel will be greater than that of the k^{th} channel in the multicorrelator module by 1 chip. In this case, the correlation values of the forward correlation channel are not interfered by the short multipath ray. The correlation values of the forward correlation channel are shown as follows.

$$\begin{aligned} IF &= a_0 R(\varepsilon + k \bullet \Delta/64 - 1)\cos(\theta_0 - \theta),\ \varepsilon \in \left[-kd, -\left(k-1\right)d\right] \\ QF &= a_0 R(\varepsilon + k \bullet \Delta/64 - 1)\sin(\theta_0 - \theta),\ \varepsilon \in \left[-kd, -\left(k-1\right)d\right] \end{aligned} \tag{18}$$

Additionally, the forward late correlation channel, delayed by d_f relative to the forward correlation channel, is utilized to calculate the amplitude of the direct signal. The correlation values of the forward late correlation channel are given as follows.

$$\begin{aligned} IF_d &= a_0 R(\varepsilon + k \bullet \Delta/64 - 1 + d_f)\cos(\theta_0 - \theta),\ \varepsilon \in \left[-kd, -\left(k-1\right)d\right] \\ QF_d &= a_0 R(\varepsilon + k \bullet \Delta/64 - 1 + d_f)\sin(\theta_0 - \theta),\ \varepsilon \in \left[-kd, -\left(k-1\right)d\right] \end{aligned} \tag{19}$$

In order to obtain the pure amplitude of the direct signal without interfered by the multipath ray, the value of d_f should be as small as possible. In this paper,

$$d_f = \frac{d}{2} = \frac{\Delta}{128} \tag{20}$$

ESMICLD is normalized as follows.

$$D_{E\_SMICLD} = \frac{D_{SMICLD}\left(\varepsilon + k \bullet \Delta/64\right)}{\left[\left(IF_d - IF\right)^2 + \left(QF_d - QF\right)^2\right]/d_f^2} - k \bullet \left(2 - \frac{63}{64}\Delta\right) \bullet \frac{\Delta}{16} \tag{21}$$

COMPARATIVE ANALYSIS OF DISCRIMINATORS IN SHORT-MULTIPATH ENVIRONMENT

In this section, ESMICL has been compared with the discriminators of SMICL, Modified DLL Aided by SMICLD and NC to demonstrate its superiority in short-multipath environment. S-curves of these loops distorted by single short multipath ray and its parameters have been displayed in Fig.4. The correlator spacing of SMICL, Modified DLL Aided by SMICLD and ESMICL is 1chip. The correlator spacing of NC is 0.2chips. The correlator spacing of the multicorrelator module in ESMICL is 1/64chips. Fig.4 illustrates that the zero-crossing point of NC's S-curve has a certain bias. When the code error ranges from positive values to zero, the S-curves of ESMICL and Modified DLL Aided by SMICLD keep the same as that of SMICL, the zero-crossing point of which has no bias. Compared with Modified DLL Aided by SMICLD, ESMICL not only improves the asymmetry of SMICLD, but also has a much smaller gap at the zero-crossing point of its S-curve. Not until the code error is less than -6Δ/64 (about -0.1chip with Δ=1 chip) will modified EMLD be activated. Therefore, it can be considered that ESMICL moves the large gap introduced by modified EMLD from origin point to the point (-6Δ/64, 0).

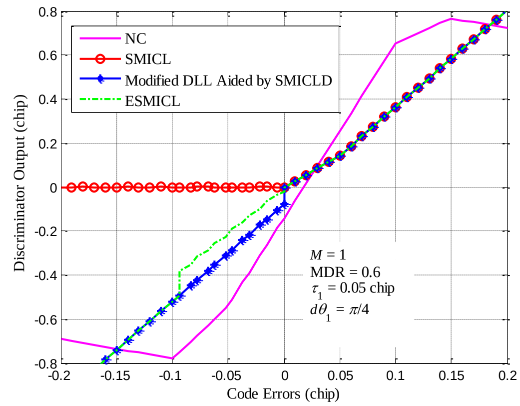


Fig.4 S-curves of SMICL, Modified DLL Aided by SMICLD, ESMICL and NC in short-multipath environment

A converging process of code errors in above loops has been simulated in Fig.5, and the multipath and loop parameters stay the same. An initial code error of 0.1 chips and an abrupt code error change of -0.03 chips at the 5th second are set. This abrupt code error change is used to simply simulate the interference from noise or signal blocking, which should be a gradually-changing process in real circumstances.

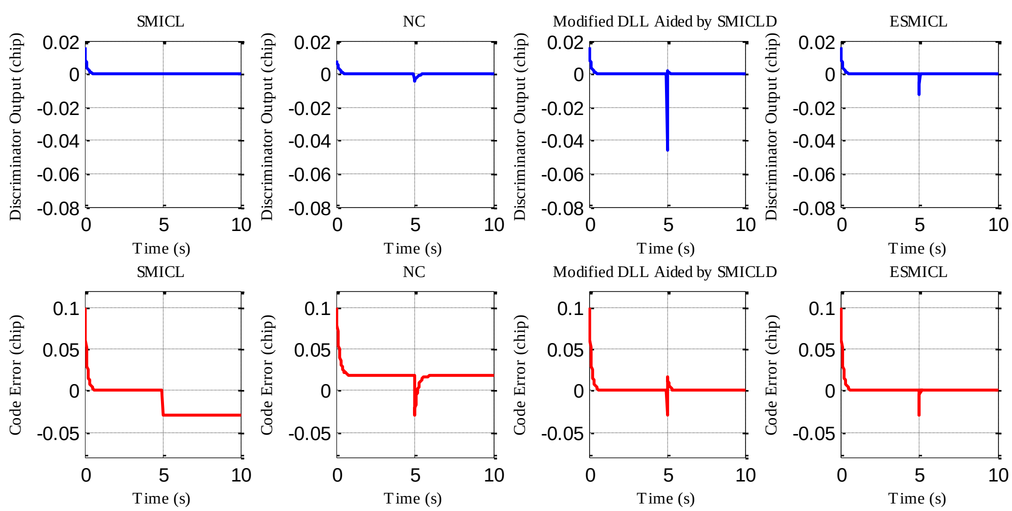


Fig.5 Discriminator outputs and code errors of SMICL, NC, Modified DLL Aided by SMICLD and ESMICL

Fig.5 shows that the initial positive code error prompts positive output of the discriminators in the four loops to adjust replica code. Before the 5th second, the code error of NC converges to a nonzero value, a bias caused by short multipath. By contrast, the other three code loops can mitigate this kind of bias. At the 5th second, SMICLD produces zero when the code error turns into negative value, which leaves the replica code exceeding the LOS signal by 0.03 chips. In contrast, NC can respond to the abrupt mutation and pull the code error back with the same bias as before. Even better, Modified DLL Aided by SMICLD and ESMICL can timely rectify the negative error without any bias. At the time of the abrupt code error change, however, Modified DLL Aided by SMICLD yields the largest discriminating value among the four loops, which adjusts the code error towards positive direction excessively. As a result, a positive pulse of its code error appears at the 5th second. In comparison, ESMICL outputs a much smaller discriminating value in response to the negative variation to tune up the replica code more temperately. The above four code loops have been implemented in software-defined GPS L1 C/A receivers. Their code tracking performance has been tested in terms of short multipath and thermal noise using the software-defined GPS L1 C/A simulator, the results of which will be particularized in the next section.

COMPARISON OF SHORT MULTIPATH MITIGATION PERFORMANCE

This section will focus on the means and standard deviation of code errors, which can be employed to assess the bias induced by multipath and the fluctuation caused by noise respectively. Moreover, as a classic multipath parameter estimating technique, MEDLL has been included in the comparison.

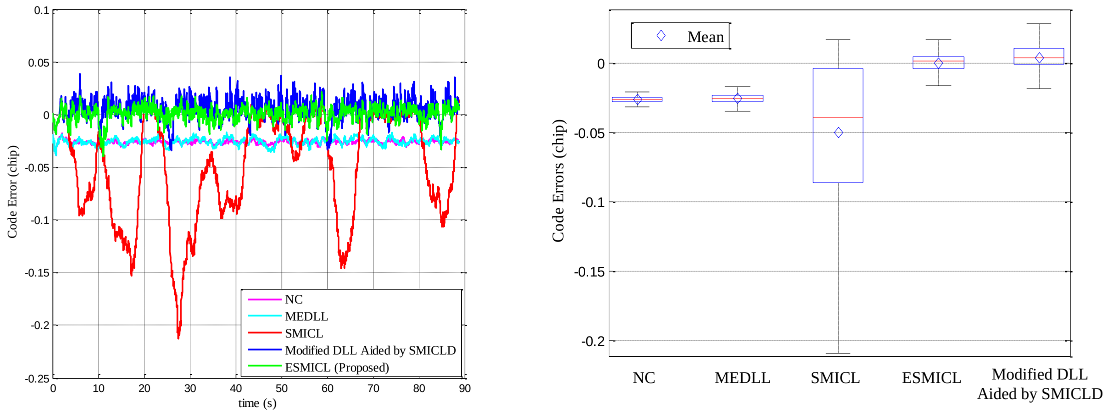
Code Errors in the Presence of Single Multipath Ray

To compare the short multipath mitigation performance in time domain, Fig.6 (a) shows the code errors of NC, MEDLL, SMICL, Modified DLL Aided by SMICLD and ESMICL. The parameters used in this simulation are exhibited in Table 3. The boxplots are exploited to analyze the distribution of code errors of the five loops, which is exhibited in Fig.6 (b). For a quantitative comparison, means and standard deviations of code errors are summarized in Table 4.

Table 3: Parameters used in the simulation

Parameters	Values
MDR of Amplitude a_1	0.6
Multipath Delay τ_1	0.05chips
Difference of Carrier phase between multipath and LOS $d\theta_1$	0.75π
Sampling Frequency f_s	100MHz
Intermediate Frequency f_{IF}	1.405MHz
Carrier to Noise Ratio CN0	45dB•Hz
Multicorrelator Spacing d	Δ_{ESMICL} /64
Correlator Spacing Δ	$\Delta_{\text{SMICL, Modified DLLAided by SMICLD, ESMICL}} = 1\text{chip}$, $\Delta_{\text{NC, MEDLL}} = 0.2\text{chips}$

Fig.6 and Table 4 show that the mean of code error of ESMICL is smaller than that of Modified DLL Aided by SMICLD by an order of magnitude. Compared with the other three loops, ESMICL has diminished the code error (absolute value) to a much greater extent, by more than two orders of magnitude. It can also be seen from Fig.6 (a) that the code error of SMICL fluctuates seriously towards negative values as the result of its asymmetrical S-curve and noise. In contrast, ESMICL and Modified DLL Aided by SMICLD have better anti-noise ability that owes to their improvement on asymmetry of SMICLD's S-curve. Moreover, compared with Modified DLL Aided by SMICLD, the code error of ESMICL has a smaller standard deviation and distributes around zero more evenly according to Table 4 and Fig.6 (b). Among the all five code loops, NC has the best anti-noise ability.



(a) **(b)**

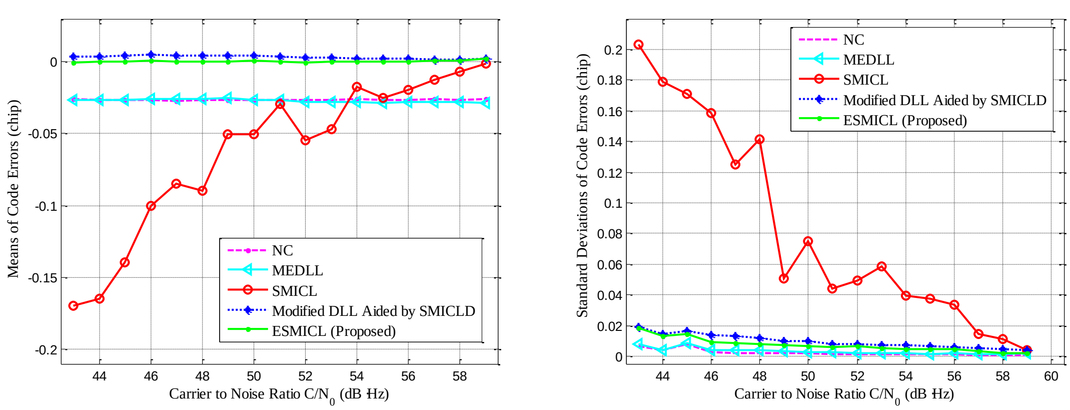
Fig.6 (a) Code errors and (b) their boxplots of NC, MEDLL, SMICL, Modified DLL Aided by SMICLD and ESMICL

Table 4: Means and standard deviations of code tracking errors

Multipath Mitigation Methods	Code tracking errors	
	Mean (chip)	Standard Deviation (chip)
NC	-0.0260	0.0019
MEDLL	-0.0254	0.0034
SMICL	-0.0501	0.0504
Modified DLL Aided by SMICLD	0.0044	0.0101
ESMICL	4.0917e-4	0.0071

Multipath Code Errors in Different Noise Environment

With a much smaller gap at the zero-crossing point of the S-curve, ESMICL keeps a subtle code error in thermal noise of both high and low CN0, which has been illustrated in Fig.7. Except for CN0, other parameters are the same as those in Fig.6.



(a) **(b)**

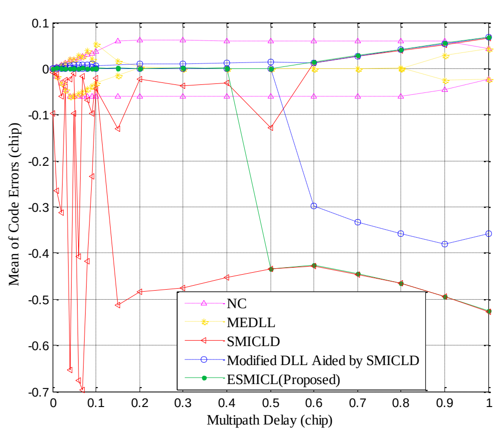
Fig.7 (a) Means and (b) standard deviations of code errors of SMICL, Modified DLL Aided by SMICLD, ESMICL, NC and MEDLL

It can be seen from Fig.7 that ESMICL confines code error means to 10^{-4} order of magnitude under diverse noise background, even in strong noise environment. The code error of SMICL possesses the similar stochastic characteristic that the noise has. With the rise of CN0, the code error of SMICL becomes smaller and smaller. It is the higher CN0—the weaker noise—that allows the code error to lock to zero stably without drafting to the negative value. Thus, if there is no noise, Modified DLL Aided by SMICLD and ESMICL will degrade to single SMICL. Moreover, with the rise of CN0, the standard deviations of code errors in above loops all converge to zero. The anti-noise ability of ESMICL is superior to that of SMICL and Modified DLL Aided by SMICLD. NC and MEDLL can track the code phase of the received signal more stably but with a certain bias. In terms of short multipath mitigation performance and anti-noise ability, ESMICL outperforms other four code loops.

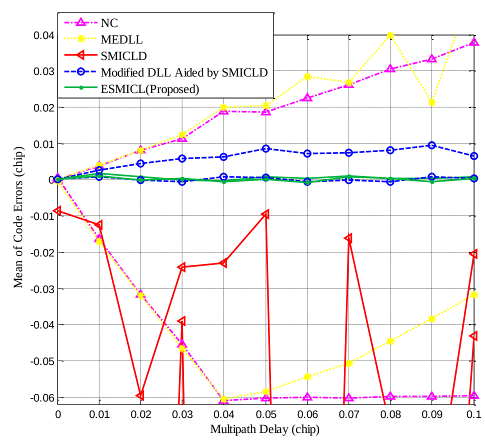
Multipath Code Error Envelope

Multipath code error envelope can illustrate the disparate influence of multipath rays with different delays on code loops. S-curves of ESMICL and Modified DLL Aided by SMICLD have a gap at the zero-crossing point that brings about an excessive adjustment towards positive values. Constant noise invokes constant positive fluctuation of code errors, which evolves into a positive bias ultimately. Therefore, for these two code loops, the upper and lower boundaries of multipath code error envelope just appear when the gap reaches the maximum and minimum respectively.

Fig.8 exhibits multipath code error envelopes of the five loops, where the multipath delay varies from 0 to 1 chip. Except for multipath delay and the difference of carrier phase between multipath and LOS, the other relevant parameters are showed in Table 3. The front-end bandwidth is not considered in the simulation as its influence on the code loop is a fixed bias of code errors which can be amended in advance according to Jardak [2007]. When multipath delay is less than 0.5 chips, the upper and lower boundaries of ESMICL’s multipath code errors correspond to out-of-phase and in-phase multipath respectively. On the contrary, when multipath delay is larger than 0.5 chips, its upper and lower boundaries correspond to in-phase and out-of-phase multipath respectively.



(a)



(b)

Fig.8 Measured multipath code error envelopes of NC, MEDLL, SMICL, Modified DLL Aided by SMICLD and ESMICL in noise environment (CN0=45dB•Hz) with respect to multipath delay of (a) [0, 1] chip and (b) [0, 0.1] chips

Fig.8 indicates that ESMICL can almost eliminate short multipath with delay of less than 0.5 chips, with the smallest code error mean of 10^{-4} orders of magnitude among these five code loops. However, the multipath code error envelope of SMICL fluctuates seriously towards negative direction as the result of noise, which conforms to the analysis before. The upper boundary of the multipath code error envelope of Modified DLL Aided by SMICLD is about 0.01 chips because of the larger gap at the zero-crossing point. As it is well-known, NC cannot thoroughly eliminate the code error induced by multipath with any delay. MEDLL can mitigate medium and long multipath effectively but useless for short multipath whose delay is less than 0.18chips in this simulation test. Therefore, ESMICL has the best short multipath mitigation performance among these code loops. Nevertheless, when the multipath delay is larger than $\Delta/2$, SMICL doesn't work normally, the weakness its derivatives—ESMICL and Modified DLL Aided by DLL—have too.

REAL SCENARIO TEST

To further test the short multipath mitigation performance of ESMICL, we use GPS RF signal simulator and UWB high-speed data recording system to set up a real short multipath scene displayed in Fig.9.

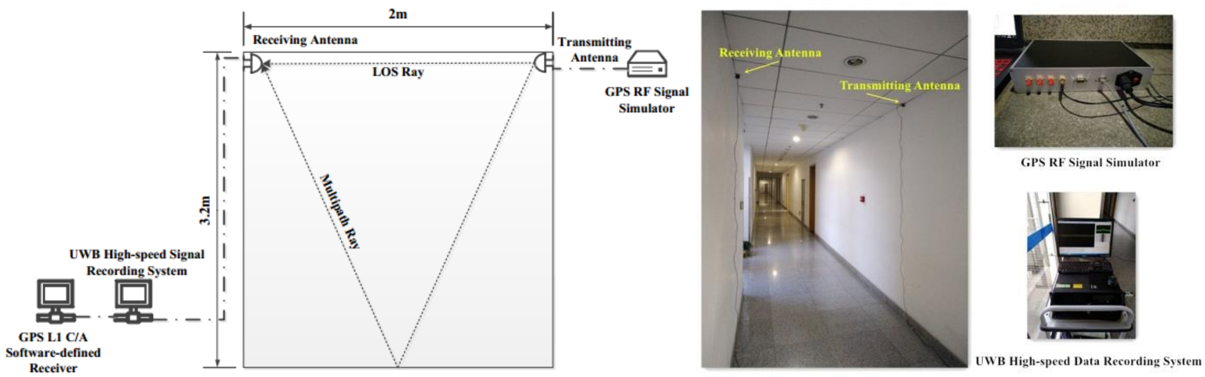


Fig.9 Real short multipath scenario

The GPS RF signal simulator developed by our research group can generate GPS L1 C/A RF signal based on pre-set time, user's location and velocity information. The simulated signal power is adjustable. The UWB high-speed data recording system, a workstation based on the TG-X3600 high-speed data acquisition card and the disk array constituted by solid state disks, can continuously record GPS RF signal with high sampling rate. A real short delay multipath scenario is set up in the corridor, the length of which is about 280 meters, much longer than the width and the height, so only the following four reflectors are considered: the ground, the ceiling and two walls alongside the corridor. The transmitting antenna connected to the GPS RF signal simulator is closely attached to the ceiling and the right wall. The receiving antenna connected to a UWB high-speed data continuous system is closely attached to the ceiling and the left wall. Therefore, the ground becomes the solitary reflection surface without considering multiple reflections whose power has been attenuated seriously. After measurement and calculation, the multipath delay is about 0.016chip (4.7m). The parameters of signal simulated by the GPS RF signal simulator are displayed in Table 5. The UWB high-speed data recording system stores the collected signal as ".dat" format with sampling frequency of 100MHz. GPS L1 C/A software receivers based on NC, MEDLL, SMICL, Modified DLL Aided by SMICLD and ESMICL have been used to process the ".dat" files. The correlator spacing of SMICL, Modified DLL Aided by SMICLD and ESMICL is 1chip. The correlator spacing of NC and MEDLL is 0.2chips. The correlator spacing of the multicorrelator module in ESMICL is 1/64chips.

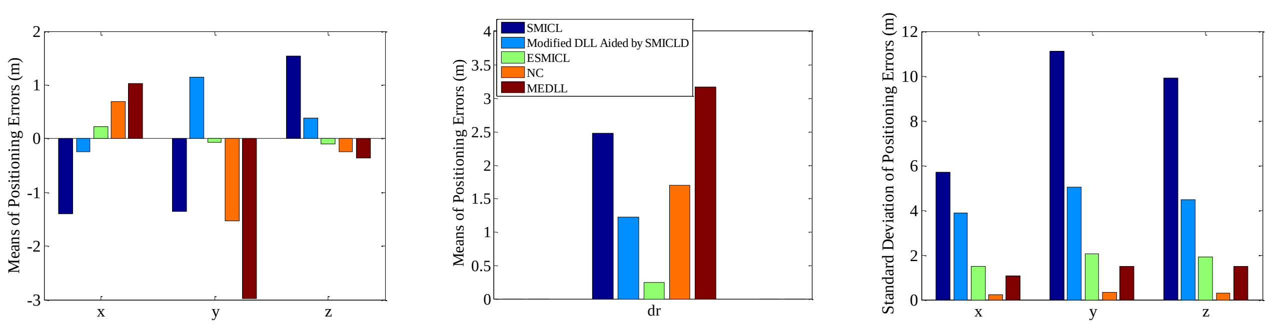
Table 5: Parameters used in the GPS RF signal simulator

Parameters	Values
Signal Power	9dBm
Radio Frequency f_{RF}	1575.42MHz
Longitude	116° E
Latitude	40° N
Height	100m

The positioning results of these receivers are compared with the position coordinates set in the GPS RF signal simulator, from which we can get the positioning errors calculated in xyz-coordinate system. The positioning errors of the five receivers have been exhibited in Fig.10. The relative distance dr between the position acquired from the receiver and the position set in the simulator can be calculated as follows (10).

$$dr=\sqrt{dx^2+dy^2+dz^2} \tag{10}$$

where dx, dy, dz represent means of positioning errors of three axes. As shown in Fig.10, ESMICL receiver has the smallest positioning errors of each axis among the five receivers. Therefore, the relative distance between its positioning result and real location is also the minimum among these receivers. Compared with SMICL and Modified DLL Aided by SMICLD, the relative distance of ESMICL has been diminished by more than 80% and 60% respectively. The positioning precision of ESMICL receiver reaches the level of decimeter in single short multipath environment. In terms of NC and MEDLL, code errors induced by short multipath have evolved into positioning errors displayed in Fig.10 (a) and (b).



(a) **(b)** **(c)**

Fig.10 Positioning errors of SMICL, Modified DLL Aided by SMICLD, ESMICL, NC and MEDLL: (a) means of positioning errors of xyz-axes; (b) relative distance; (c) Standard deviations of positioning errors of xyz-axes

Fig.10 (c) shows that ESMICL receiver has the smallest standard deviation of positioning errors among the three receivers based on SMICLD, which means the anti-noise performance has been improved. However, because of the discontinuity at the zero-crossing point of the S-curve, the standard deviation of ESMICL is still larger than that of NC and MEDLL, which implies that ESMICL is more sensitive to noise than traditional code loops. Moreover, the anti-noise performance of ESMICL is close to MEDLL receiver. The goal of multipath mitigation techniques is to eliminate the positioning bias caused by multipath. Therefore, ESMICL receiver is the best choice in above five receivers considering both the short multipath mitigation performance and the anti-noise ability.

CONCLUSION

By improving the asymmetry of SMICLD's S-curve, ESMICL proposed in this paper can be a practical solution to the problem of mitigating single short multipath ray whose delay is even less than 0.1chips (GPS L1 C/A) in noise environment, which propels the SMICLD from the theory to the application in real scenario. The novel code loop can be used in the scene where single multipath reflection exists from nearby objects, such as the road with buildings on single side. However, ESMICL cannot mitigate multiple multipath rays and have no effect on long multipath, the delay of which is larger than min (Δ/2, 1-Δ/2). Overcoming these two problems will be a challenging topic in the future research.

APPENDIX

In order to calculate the maximum discriminating value of SMICLD in the interval of [0 d] when the multipath delay exceeds d, we firstly study the expression of SMICLD. If $0 \le \varepsilon \le d < \tau_1 <$ min (Δ/2, 1-Δ/2), SMICLD can be illustrated by an quadratic function

$$D(\varepsilon) = 4a_0 a_1 \cos(\theta_0 - \theta_1)\varepsilon^2 + \left[2a_0^2(2-\Delta) + 4a_0 a_1 \cos(\theta_0 - \theta_1)(1-\tau_1-\frac{\Delta}{2})\right]\varepsilon \tag{A1}$$

The axis of symmetry of this parabola is located at εs, which can been expressed as

$$\varepsilon_s = -\frac{a_0(2-\Delta) + a_1(2-\Delta-2\tau_1)\cos(\theta_0-\theta_1)}{4a_1\cos(\theta_0-\theta_1)} \tag{A2}$$

A. If $\cos(\theta_0\text{-}\theta_1) > 0$, the maximum value of SMICLD can be calculated as $D(d)$

$$D(d) = 4a_0 d\left[a_1\left(1-\tau_1+d-\frac{\Delta}{2}\right)\cos(\theta_0-\theta_1) + a_0\left(1-\frac{\Delta}{2}\right)\right] \tag{A3}$$

Providing that $a_0 = 1$, $a_1 \le 1$, $0 \le \cos(\theta_0\text{-}\theta_1) \le 1$, the upper bound of $D(d)$ can be written as

$$D(d) \le 4d(2-\tau_1-\Delta+d) \tag{A4}$$

B. If $\cos(\theta_0\text{-}\theta_1) < 0$, the maximum value of SMICLD may be $D(d)$ or $D(\varepsilon_s)$, which depends on whether the axis of symmetry is located in the interval of [0 d]. When the axis of symmetry is out of [0 d], the maximum value of SMICLD is $D(d)$, the same as case A. In the other situation, the maximum of SMICLD is given by

$$D(\varepsilon_s) = -\frac{4a_0\left[a_0(2-\Delta) + a_1(2-\Delta-2\tau_1)\cos(\theta_0-\theta_1)\right]^2}{16a_1\cos(\theta_0-\theta_1)} \tag{A5}$$

In this respect, ε_s is within d, from which we can get

$$0 < a_0(2-\Delta) + a_1(2-\Delta-2\tau_1)\cos(\theta_0-\theta_1) < -4a_1 d\cos(\theta_0-\theta_1) \tag{A6}$$

Combining the condition of $a_0 = 1$, $a_1 \le 1$, $-1 \le \cos(\theta_0\text{-}\theta_1) \le 0$, we can get the upper limit to $D(\varepsilon_s)$ as follows

$$D(\varepsilon_s) < 4d^2 \tag{A7}$$

Given the multipath delay is less than min (Δ/2, 1-Δ/2), the following relationships can be get easily

$$D(\varepsilon_s) < 4d^2 < 4d(2-\Delta-\tau_1+d) \tag{A8}$$

To conclude, the maximum value of SMICLD in the interval of [0 *d*] is given by

$$D^{max}(\varepsilon) = 4d\left(2 - \Delta - \tau_1 + d\right) \tag{A9}$$

If the spacing of multi-correlators *d* is equal to Δ/64, the maximum value is computed as follows

$$D^{max}_{d=\Delta/64}(\varepsilon) = \left(2\text{-}\frac{63}{64}\Delta - \tau_1\right)\bullet\frac{\Delta}{16} \leq \left(2\text{-}\frac{63}{64}\Delta\right)\bullet\frac{\Delta}{16} \tag{A10}$$

REFERENCE

[1] Mustafa, A. I., El-Sheikh, S. S., *et al.*, "Modified short multipath insensitive code loop discriminator," *Proceedings of IEEE International Conference on Informatics & Systems, Cairo, Egypt, 2012*, pp. NW-60-NW-67.

[2] Dierendonck, A. J. V., Fenton, P. and Ford, T., "Theory and Performance of Narrow Correlator Spacing in a GPS Receiver," *NAVIGATION*, vol. 39, no. 3, 1992, pp. 265-284.

[3] Kaplan, E. D. and Hegarty, C., *Understanding GPS: Principles and Applications*, 2nd ed., 2006.

[4] Hassan, E. S., Mustafa, A. I., Awadalla, K. H., *et al*., "A New Modified Short-Multipath-Insensitive Code Loop Discriminator," *Wireless Personal Communications*, 2018, pp. 1-17.

[5] Zhou, F., Huang, S., "Multi-Path Mitigation Based on Teager-Keiser Operator," *Journal of University of Electronic Science and Technology of China*, 2007, 36(4), pp. 692-695.

[6] Mo, J., Deng, Z., Jia, B., *et al*., "A Novel Multipath Mitigation Method Based on Fast Orthogonal Search (FOS) for Short-Delay Multipath with Zero Doppler Shift Difference," *Proceedings of China Satellite Navigation Conference, Harbin, China, 2018*, pp. 289-299.

[7] Sleewaegen, J. M. and Boon, F., "Mitigating short-delay multipath: a promising new technique," *Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation, Salt Lake City, UT, USA, 2001*, pp. 11-14.

[8] Weill, L. R., "Conquering mutlipath: The GPS accuracy battle," *GPS World*, 1997, 4, pp. 59-66.

[9] Bhuiyan, M. Z. H., Lohan, E. S. and Renfors, M., "A Slope-Based Multipath Estimation Technique for Mitigating Short-Delay Multipath in GNSS Receivers," *Proceedings of IEEE International Symposium on Circuits and Systems, Paris, France, 2010*, pp. 3573-3576.

[10] Jardak, N., Samama, N., "Short Multipath Insensitive Code Loop Discriminator," *IEEE Transactions on Aerospace & Electronic Systems*, 2010, 46(1), pp. 278-295.

[11] Van Nee, R. D. J., "Multipath and multi-transmitter interference in spread-spectrum communication and navigation systems," *Ph.D. dissertation, Department Electrical Engineering, Technical University of Delft, Netherlands, 1995.*

[12] Weng, X., Kou, Y. H., "Modified Code Tracking Loop Aided by Short Multipath Insensitive Code Loop Discriminator," *Proceedings of the 2017 International Technical Meeting of The Institute of Navigation*, pp. 1316-1329.

[13] Weng, X., Kou, Y. H., "Improvement on Short Multipath Insensitive Code Loop Discriminator," *NAVIGATION*, under submission.

[14] Gao, Y., Li, Q., "Modified Narrow Correlator Spacing Method for Mitigation Short-Delay Multipath," *Measurement and Control Technology*, 2014, 33(1), pp. 43-46.

[15] Zhang, Z., Law, C. L., "Short-delay Multipath Mitigation Technique Based on Virtual Multipath," *IEEE Antennas & Wireless Propagation Letters*, 2005, 4, pp. 344-348.