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Modified Delay Lock Loop Aided by Short Multipath Insensitive Code Loop Discriminator[1]

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BIOGRAPHY

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[1] Some of the materials in this paper were from "Modified code tracking loop aided by short multipath insensitive code loop discriminator" which was presented in the ION ITM 2017, Monterey Bay, CA, US, Jan 2017.

ABSTRACT

The S-curve zero-crossing point of Short Multipath Insensitive Code Loop Discriminator (SMICLD) has no bias in the presence of single short multipath with a delay even less than 0.1 chips (GPS L1 C/A). However, SMICLD outputs zero when the code tracking error is negative, which results in large code tracking biases in noise environment. The proposed Modified DLL Aided by SMICLD improves the S-curve by utilizing a modified early minus late discriminator to guarantee a negative output under a negative code phase error, switching back to SMICLD under a positive or zero code phase error, and adding a correlation channel to distinguish the two cases. Test results at both digital intermediate frequency level and radio frequency level in real multipath environment demonstrate that the proposed method has better single short multipath mitigation performance than SMICLD, high resolution correlator (HRC), and multipath estimating delay lock loop (MEDLL) in noise environment.

Index Terms: Short delay multipath, S-curve, Short multipath insensitive code loop discriminator (SMICLD), Code tracking bias, Early minus late discriminator (EMLD).

1 INTRODUCTION

In a wide range of daily applications of Global Positioning System (GPS), especially the positioning in urban scenes, meter-level even decimeter-level accuracy has become a normal requirement. In addition to further improving GPS and its augmentation systems, a lot of efforts have been put into the research of GPS positioning error sources. As an important error source in GPS, multipath has always been focused on by many researchers all over the world.

Multipath is the interference to user receivers introduced by the reflection of the direct signal on the ground or other objects. The propagation time of multipath is longer than that of the direct signal, which is directly reflected in the code phase delay of the multipath with respect to the LOS (Line of Sight) signal[1]. Unlike thermal noise and atmospheric interference, multipath cannot be eliminated by differential GPS. This is due to the large differences in multipath rays at different locations[2]. Therefore, multipath mitigation techniques are generally based on receiver and new navigation signal designs.

Mainly three kinds of multipath mitigation techniques are employed in GPS receivers: antenna-based, correlator/discriminator-based, and parameter estimation-based techniques. Choke ring antenna, right-hand circularly polarized antenna, and multi-antenna are typical antenna-based multipath mitigation methods designed to isolate the direct signal from the received signal by reducing the strength of multipath signals[3]. Since the antenna is the front part of a GPS receiver, a good multipath mitigation performance of the antenna can greatly reduce the burdens of the follow-up units in the receiver. The antenna-based multipath mitigation technique, nevertheless, increases the size, weight, and cost.

Multipath distorts the curve of correlation function between the received signal and the local replica of the GPS receiver, which results in the zero-crossing point bias of the S-curve of the discriminator in the code loop. This bias will evolve into the pseudo-range bias. Correlator/discriminator-based techniques mitigate multipath by properly reconstructing or modifying the code loop discriminator or the correlators of the receiver. From this standpoint, some classical algorithms have been developed including Narrow Correlator (NC)[4], Strobe correlator[5], High Resolution Correlator (HRC)[6], and so forth. These techniques show good effects on medium and long multipath, and yet little effects on short multipath.

Most parameter estimation-based techniques perform the maximum likelihood estimation of the parameters of the direct signal and multipath signals. As a typical representative of such methodology, Multipath Estimating Delay Lock Loop (MEDLL) can mitigate not only the code tracking bias but also the carrier tracking bias caused by multipath[7, 8, 9]. Other parameter estimation-based techniques, such as Multipath Mitigating Technology (MMT)[10] and Coupled Amplitude Delay Lock Loops (CADLL)[11], also have great performance in multipath mitigation, especially for medium and long multipath. In terms of short multipath, the parameter estimation becomes an ill-conditioned estimation problem. Therefore, this kind of methodology has poor performance in the case of short multipath.

The short multipath mentioned above has a delay less than 0.1 PRN (pseudo-random noise) code chips (for GPS L1 C/A signal), which means the propagation distance of the short multipath is longer than that of the direct signal by less than 30m. Short multipath usually exists in places with small space size, such as urban canyons where large amount of reflective objects may be close to the user receiver. The short multipath with the delay of 0.1 chips can lead to a C/A code range error of more than 10 meters, which is a large error for urban location applications, such as searching for a public bicycle. It is of great significance but very challenging to mitigate short multipath to improve the ranging accuracy in these occasions.

Several short multipath mitigation methods have been proposed so far. A-Posteriori Multipath Estimation (APME) technique proposed by Sleewaegen [2001] is based on the tight relationship between multipath errors and amplitude of received signals and can estimate short-multipath errors by scaling the combination of correlation values with an optimization coefficient[12]. This technique, however, 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][13] and Gao [2014][14] are similar to APME. Zhang [2005] proposed a short multipath mitigation technique based on virtual multipath[15]. This technique performs well when there is a multipath signal stronger than the direct signal and other multipath signals, which greatly restricts its applications in spite of its low computational complexity. Zhou [2006] improved the short delay multipath mitigation performance of the traditional narrow correlator technique by using Teager-Kaiser operator[16]. Wang [2012] proposed a multipath model with the multipath ray number, and combined it with the adaptive genetic algorithm to mitigate short multipath[17]. A multipath mitigation method based on Fast Orthogonal Search (FOS) proposed by Mo [2018] tries to optimally estimate the correlation function distorted by multipath, which is similar but superior to MEDLL[18]. But large computational loads of this method are high demanding for receiver hardware.

Short multipath insensitive code loop discriminator (SMICLD) is a correlator/discriminator-based short delay multipath mitigation algorithm[19]. The code loop using SMICLD is called SMICL. SMICLD modifies prompt correlation values and the code discriminator formula so that the zero-crossing point of its S-curve has no bias in the presence of short multipath.

However, the S-curve of SMICLD is asymmetrical. When the code error is negative, the output of SMICLD is always zero. Therefore, if the code error becomes zero, SMICLD cannot adjust the code phase of the local replica in time, which may cause large code errors in noise environment.

To improve the S-curve of SMICLD and its short multipath mitigation in noise environment, key contributions in this paper are summarized as follows.

(1) We design Modified DLL Aided by SMICLD by combining modified Early Minus Later Discriminator (MEMLD) and SMICLD. It mainly consists of three sections: SMICLD, MEMLD, and the zero-discriminating correlation channel. The proposed code loop will use SMICLD when the code error is positive and use MEMLD when the code error is negative, which integrates the strength of SMICLD (the zero-crossing point without any bias) with the strength of MEMLD (the ability to adjust negative code errors). The zero-discriminating correlation channel is the key to switching the proper discriminator for the proposed code loop.

(2) Modified DLL Aided by SMICLD is implemented in our software-defined GPS L1 C/A Intermediate Frequency (IF) receiver. Its short multipath mitigating performance and anti-noise ability are compared not only with SMICL, but also with conventional code loops including HRC and MEDLL by using the digital IF GPS signal simulator in the following aspects.

- The code errors in time domain.
- The mean and standard deviation of code errors vs different carrier to noise ratio (CN0).
- The multipath code error envelope.

(3) The positioning errors of above code loops in a real short multipath scene are tested by using a GPS RF signal simulator and a broadband high-speed data recording system. Test results indicate that Modified DLL Aided by SMICLD has the best single short multipath mitigation performance in noise environment among above code loops.

The paper is organized as follows. The section 2 and 3 give a brief description of the short multipath model and the assessment of SMICLD, respectively. Section 4 illustrates the principles of Modified DLL Aided by SMICLD in detail. Test results and comparative analysis will be displayed in Section 5. Finally, Section 6 summarizes this study and makes some suggestions for future research.

Table 1
List of the Key Acronyms and Abbreviation

CN0	Carrier to Noise Ratio
DLL	Delay Lock Loop
EMLD	Early Minus Late Discriminator
GPS	Global Positioning System
IF	Intermediate Frequency

LOS	Line of Sight
MDR	Multipath-to-Direct Ratio
MEDLL	Multipath Estimating Delay Lock Loop
MEMLD	Modified Early minus Late Discriminator
MoSMICLD	Discriminator of Modified DLL Aided by SMICLD
HRC	Narrow Correlator
RF	Radio Frequency
S-curve	Discriminator Curve
SMICL	Short Multipath Insensitive Code Loop
SMICLD	Short Multipath Insensitive Code Loop Discriminator

2 SHORT MULTIPATH MODEL

The received GPS L1 C/A IF signal $r(t)$ can be expressed as

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

Equation (1) ignores the navigation message considering its period is much longer than that of the C/A code sequence. The parameters in equation (1) are explained in Table 2.

Table 2
Parameters of Short Multipath Model

a_0	Amplitude of the LOS Signal
τ_0	Propagation Time of the LOS Signal
θ_0	Carrier Phase of the LOS Signal
a_i	Amplitude of the i^{th} Multipath
τ_i	Delay of the i^{th} Multipath Relative to the LOS Signal
θ_i	Carrier Phase of the i^{th} Multipath
M	Number of Multipath Signals
w	Carrier Frequency
t	Time
$p(t)$	C/A Code Sequence

If the received signal is normalized by the amplitude of the LOS signal a_0, a_i will be called the multipath to direct ratio (MDR) of amplitude. The definition of short multipath depends on the specific positioning scenarios. This paper focuses on the multipath with delay of less than 0.1 chips (about 30 m for GPS L1 C/A signal).

After the carrier wipe-off, the signal is correlated with the local code replica to obtain the correlation values. The local code replica is $p(t-\tau)$, which is delayed by τ relative to the transmitted signal. The code error ε is defined as the code error between the LOS signal and the local replica.

$$\varepsilon = \tau - \tau_0 \tag{2}$$

Thus, the in-phase prompt correlation value IP can be obtained as follows.

$$IP = a_0 R(\varepsilon)\cos(\theta_0 - \theta) + \sum_{i=1}^{M} a_i R(\varepsilon - \tau_i)\cos(\theta_i - \theta) \tag{3}$$

The autocorrelation function $R(\varepsilon)$ in equation (3) is expressed as an ideal triangle function for the convenience of calculation.

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

3 ASSESSMENT OF SHORT MULTIPATH INSENSITIVE CODE LOOP DISCRIMINATOR

By modifying the prompt correlation values and the discriminator function, SMICLD eliminates the zero-crossing point bias of its S-curve in the presence of single short multipath ray with the delay of less than min(Δ/2, 1-Δ/2), where Δ denotes the correlator spacing in SMICLD.

Like equation (3), we can denote the quadrature prompt, in-phase early, quadrature early, in-phase late, quadrature late correlation values as *QP*, *IE*, *QE*, *IL*, *QL*, respectively. SMICLD is defined as

$$D_{SMICLD} = (IE^2 + QE^2) - ((IP^{'})^2 + (QP^{'})^2) \tag{5}$$

$IP^{'}$ and $QP^{'}$ are the modified prompt correlation values:

$$IP^{'} = IP - \frac{\Delta}{2}\frac{IE + IL}{2 - \Delta} \tag{6}$$

$$QP^{'} = QP - \frac{\Delta}{2}\frac{QE + QL}{2 - \Delta} \tag{7}$$

The discriminator function of SMICLD can be written as

$$D_{SMICLD}(\varepsilon) = \begin{cases} 2(2-\Delta)\left[a_0^2\varepsilon + \sum_{i=1}^{M} a_i^2(\varepsilon - \tau_i) + \sum_{i=0}^{M-1}\sum_{j=i+1}^{M} a_i a_j \cos(\theta_i - \theta_j)(2\varepsilon - \tau_i - \tau_j)\right] & 0 < \tau_{i,j} < \varepsilon \le \min(\frac{\Delta}{2}, 1 - \frac{\Delta}{2}) \\ 2a_0^2(2-\Delta)\varepsilon + 4\sum_{i=1}^{M} a_0 a_i \cos(\theta_0 - \theta_i)\varepsilon(1 + \varepsilon - \tau_i - \frac{\Delta}{2}) & 0 < \varepsilon < \tau_i \le \min(\frac{\Delta}{2}, 1 - \frac{\Delta}{2}) \\ 0 & \tau_i - \min(\frac{\Delta}{2}, 1 - \frac{\Delta}{2}) < \varepsilon < 0 < \tau_i \le \min(\frac{\Delta}{2}, 1 - \frac{\Delta}{2}) \end{cases} \tag{8}$$

Additionally, to remove amplitude sensitivity, SMICLD is normalized by its early and adjusted prompt correlation values, which is given by:

$$D_{norSMICLD} = \frac{(IE^2 + QE^2) - ((IP^{'})^2 + (QP^{'})^2)}{(IE^2 + QE^2) + ((IP^{'})^2 + (QP^{'})^2)} \tag{9}$$

The characteristics of SMICLD can be illustrated by Table 3.

Table 3
SMICLD Outputs with Different Numbers of Multipath Rays

Code Error	Number of Multipath Rays		
	$M = 0$	$M = 1$	$M \ge 1$
$\tau_i - \min(\Delta/2, 1-\Delta/2) < \varepsilon < 0 < \tau_i \le \min(\Delta/2, 1-\Delta/2)$	$D_{SMICLD} = 0$	$D_{SMICLD} = 0$	$D_{SMICLD} = 0$
$0 < \varepsilon < \tau_i \le \min(\Delta/2, 1-\Delta/2)$	$D_{SMICLD} > 0$	$D_{SMICLD} > 0$	D_{SMICLD} is not always greater than zero
$0 < \tau_i < \varepsilon \le \min(\Delta/2, 1-\Delta/2)$	$D_{SMICLD} > 0$	$D_{SMICLD} > 0$	D_{SMICLD} is not always greater than zero

In the case of only one short multipath ray, when the code error is positive, the output of SMICLD is positive. When the code error is zero or negative (no less than τ_1-min(Δ/2, 1-Δ/2)), the output of SMICLD is always zero. Therefore, SMICLD cannot handle negative code errors.

Table 3 also illustrates that, in the presence of more than one multipath ray, when the code tracking error is positive, the output of SMICLD is not always greater than zero. In this case, the S-curve of SMICLD may have zero-crossing points on the positive axis of the code error, which will cause false lock. Additionally, SMICLD cannot mitigate the medium and long multipath because the equation (10) is based on the premise that the multipath delay is less than or equal to min(Δ/2, 1-Δ/2).

This paper focuses on the problem of SMICLD’s zero outputs for negative code errors in the presence of single short multipath. To solve it, Modified Delay Lock Loop Aided by SMICLD is proposed in this paper.

4 MODIFIED DLL AIDED BY SMICLD

The discriminator of Modified DLL Aided by SMICLD (MoSMICLD) consists of SMICLD and modified EMLD (MEMLD). When the code error is positive or zero, the code loop uses SMICLD; when the code error is negative, the code loop uses MEMLD. A zero-discriminating correlation channel is designed to determine when to use SMICLD and when to use MEMLD.

4.1 Architecture of Modified DLL Aided by SMICLD

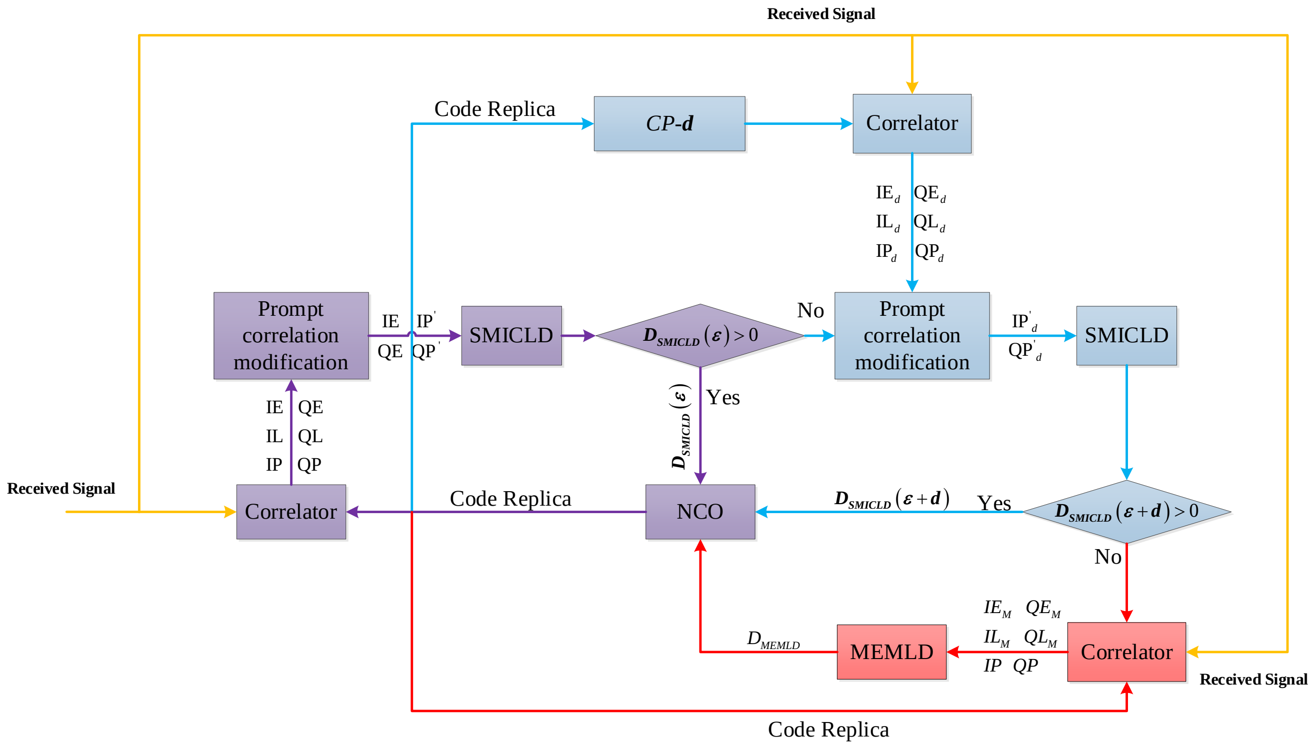

Fig. 1 Architecture of Modified DLL Aided by SMICLD

As shown in Fig. 1, Modified DLL Aided by SMICLD consists of three sections: SMICLD (the purple section), MEMLD (the red section), and the zero-discriminating correlation channel (the blue section). Initially, the code loop discriminator, i.e. MoSMICLD, 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 might be zero or negative. In this case, the zero-discriminating correlation channel is used to distinguish zero from negative values and determine whether to switch to MEMLD.

4.2 Zero-discriminating Correlation Channel

Let *CP* and *d* respectively represent the local replica code phase of the prompt correlation channel and the zero-discriminating resolution. When SMICLD outputs zero, the code phase of the zero-discriminating channel is reduced to *CP-d*, which means that its code tracking error is increased to $\varepsilon + d$ (ε is the code error of the prompt correlation channel). If the SMICLD output calculated in the zero-discriminating correlation channel is still zero, ε will be considered as negative. Then the code loop is switched into the MEMLD mode.

4.3 Modified EMLD (MEMLD)

EMLD's S-curve is symmetrical around its zero-crossing point, which allows EMLD to work stably in noise environment. From this standpoint, EMLD is used to adjust negative code errors that SMICLD cannot deal with. However, the zero-crossing point of the traditional EMLD's S-curve might be located on the negative axis, which will cause a false lock onto a negative code error. To avoid such false lock, we modify the traditional EMLD to guarantee a negative discriminating output. Firstly, a normalized non-coherent EMLD is defined as follows.

$$D_{nor\_non-coherent\_EMLD}\left(\varepsilon\right)=\frac{\left(IE_M{}^2+QE_M{}^2\right)-\left(IL_M{}^2+QL_M{}^2\right)}{\left(IE_M{}^2+QE_M{}^2\right)+\left(IP^2+QP^2\right)} \tag{11}$$

where IE_M, QE_M, IL_M, QL_M respectively represent its in-phase early, quadrature early, in-phase late, quadrature late correlation values.

$$\begin{aligned}
IE_M &= a_0R(\varepsilon-\Delta_M/2)\cos\left(\theta_0-\hat{\theta}\right)+a_1R(\varepsilon-\tau_1-\Delta_M/2)\cos\left(\theta_1-\hat{\theta}\right)\\
QE_M &= a_0R(\varepsilon-\Delta_M/2)\sin\left(\theta_0-\hat{\theta}\right)+a_1R(\varepsilon-\tau_1-\Delta_M/2)\sin\left(\theta_1-\hat{\theta}\right)\\
IL_M &= a_0R(\varepsilon+\Delta_M/2)\cos\left(\theta_0-\hat{\theta}\right)+a_1R(\varepsilon-\tau_1+\Delta_M/2)\cos\left(\theta_1-\hat{\theta}\right)\\
QL_M &= a_0R(\varepsilon+\Delta_M/2)\sin\left(\theta_0-\hat{\theta}\right)+a_1R(\varepsilon-\tau_1+\Delta_M/2)\sin\left(\theta_1-\hat{\theta}\right)
\end{aligned} \tag{12}$$

It is noted that the correlation spacing Δ_M used in this normalized non-coherent EMLD differs from Δ used in SMICLD. However, its in-phase prompt and quadrature prompt correlation values are same as those of SMICLD.

The global maximum of $D_{nor\_non-coherent\_EMLD}(\varepsilon)$ is denoted as $D_{nor\_non-coherent\_EMLD}\,(\varepsilon_e)_{\max}$.

$$D_{nor\_non-coherent\_EMLD}\left(\varepsilon_e\right)_{\max}=\frac{2-\Delta_{\mathrm{M}}}{\sqrt{2\left[1+(1-\Delta_{\mathrm{M}}/2)^2\right]}+2-\Delta_{\mathrm{M}}/2} \tag{13}$$

Hence, MEMLD can be acquired by subtracting $D_{nor\_non-coherent\_EMLD}\,(\varepsilon_e)_{\max}$ from $D_{nor\_non-coherent\_EMLD}\,(\varepsilon)$.

$$D_{MEMLD}\left(\varepsilon\right)=\frac{\left(IE_M{}^2+QE_M{}^2\right)-\left(IL_M{}^2+QL_M{}^2\right)}{\left(IE_M{}^2+QE_M{}^2\right)+\left(IP^2+QP^2\right)}-\frac{2-\Delta_M}{\sqrt{2\left[1+(1-\Delta_M/2)^2\right]}+2-\Delta_M/2} \tag{14}$$

4.4 Discussion

To conclude, the algorithm exhibited in Table 4 will be used in Modified DLL Aided by SMICLD.

Table 4

Discriminating Algorithm of Modified DLL Aided By SMICLD

✧ If $D_{SMICLD}(\varepsilon) \geq 0$, which means the code error is positive, the code loop will continue using SMICLD

$$D_{MoSMICLD} = D_{norSMICLD}(\varepsilon)$$

✧ If $D_{SMICLD}(\varepsilon) \leq 0$ & $D_{SMICLD}(\varepsilon+d) \geq 0$, which means the code error is located in [-d , 0], the code loop will continue using SMICLD

$$D_{MoSMICLD} = D_{norSMICLD}(\varepsilon)$$

✧ If $D_{SMICLD}(\varepsilon) \leq 0$ & $D_{SMICLD}(\varepsilon+d) \leq 0$, which means the code error is less than -d chip, MEMLD will be used.

$$D_{MoSMICLD} = D_{MEMLD}(\varepsilon)$$

Fig. 2 simply demonstrates the code phase tracking process of Modified DLL Aided by SMICLD. The zero-discriminating resolution d is 0.01 chips. The code error of the initial state A is negative and less than –d chips. In this case, SMICLD outputs zero both in the prompt correlation channel and the zero-discriminating correlation channel. Therefore, the code error is considered as negative. And MEMLD will be employed to adjust the negative code error. Thus, the current state of the code loop is switched to point B. Then, MEMLD outputs a negative value to adjust the code error towards the positive direction, which switches the state of the code loop to point C. Now, SMICLD outputs a positive value that will adjust the code error to zero.

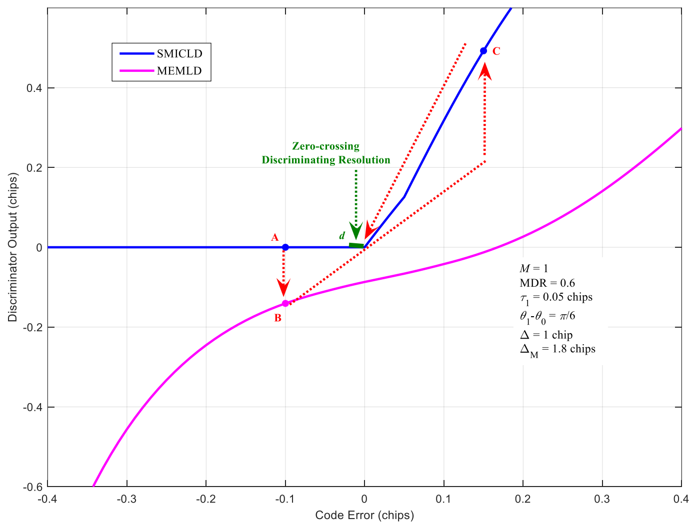

Fig. 2 Code Phase Tracking Process of Modified DLL Aided by SMICLD

As shown in Fig. 2, however, the S-curve of MEMLD has a gap when code error is zero. This gap is related to the correlation spacing used in MEMLD, which can be explained by equation (15).

$$D_{norEMLD}\left(\varepsilon_e\right)_{\max} = \frac{2-\Delta_M}{\sqrt{2\left[1+(1-\Delta_M/2)^2\right]}+2-\Delta_M/2} = \frac{2}{\sqrt{2\left[1+\frac{1}{(1-\Delta_M/2)^2}\right]}+\frac{1}{1-\Delta_M/2}+1} \tag{15}$$

Therefore, the gap can be diminished by increasing the correlation spacing Δ_M of MEMLD, which is proven in Fig. 3.

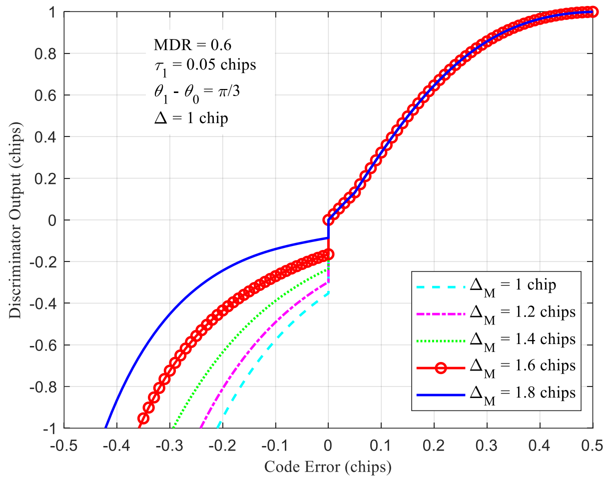

Fig. 3 S-curves of Modified DLL Aided by SMICLD in the Presence of Single Short Multipath Ray with Different Δ_M

Fig. 4 illustrates the S-curves of Modified DLL Aided by SMICLD, SMICLD and HRC in the presence of single multipath ray. The related parameters are shown in Fig. 4.

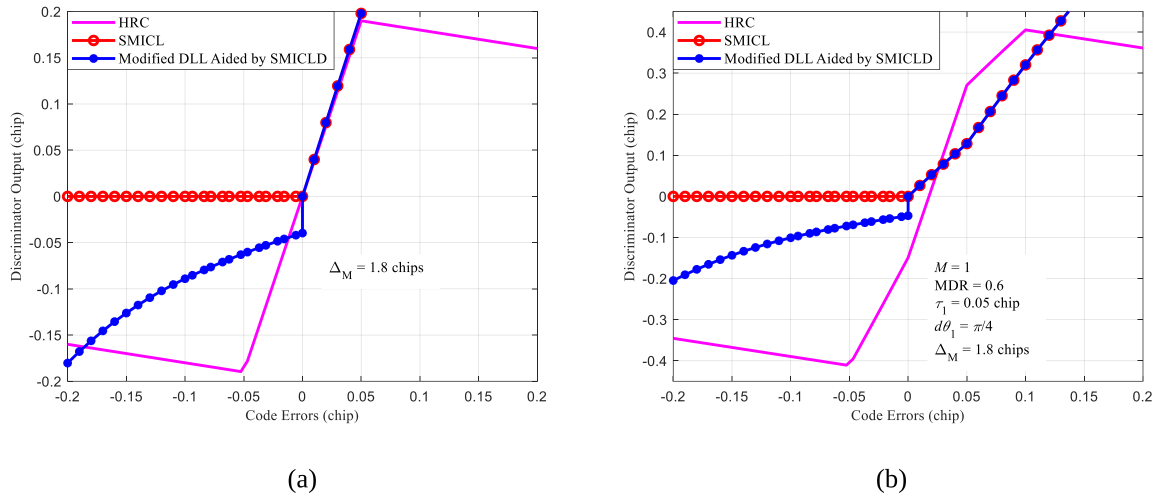

Fig. 4 S-curves of Modified DLL Aided by SMICLD, SMICLD and HRC (a) without multipath and (b) with multipath

Fig. 4 (a) shows that, in ideal non-multipath scene, Modified DLL Aided by SMICLD can discriminate negative code errors while SMICLD cannot. However, the S-curve of Modified DLL Aided by SMICLD has a gap at the zero point, which will degrade its anti-noise performance as shown in Section 5. Fig. 4 (b) shows that, in single short multipath scene, the S-curve of

HRC has a zero-crossing bias that will result in code errors while Modified DLL Aided by SMICLD can adjust code errors to zero without bias with the help of SMICLD.

In Fig. 5, the tracking process of SMICL, Modified DLL aided by SMICLD and HRC are simulated in the presence of single short multipath. The related parameters are shown in Table.

Table 5
Parameters Related to the Simulation of the Tracking Process of SMICL, Modified DLL aided by SMICLD and HRC

a_0	1
θ_0 - θ_1	π/4
a_1	0.6
τ_1	0.05 chips
M	1
Δ_{SMICLD}	1 chip
$\Delta_{\text{Modified DLL Aided by SMICLD}}$	1 chip
Δ_{HRC}	0.1 chips
Δ_{M}	1.8 chips

The initial code error for the three code loops are all 0.03 chips. At the time of 5 second, the code error jumps to -0.01chips. This sudden 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.

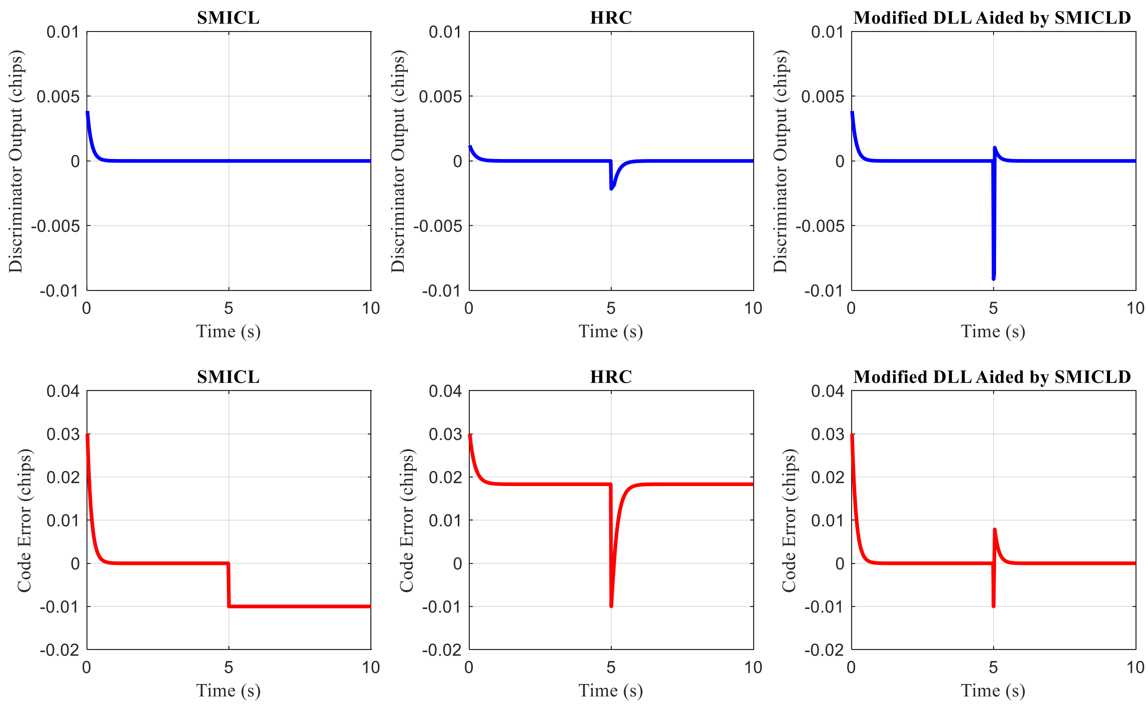

Fig. 5 Discriminator Outputs and Code Tracking Errors of SMICL, HRC and Modified DLL Aided by SMICLD

As shown in Fig. 5, all the three discriminators can work stably in the first five seconds. The code errors of SMICL and Modified DLL Aided by SMICLD are zero, whereas HRC is affected by short multipath and has a certain tracking bias. After the abrupt code error change at the 5th second, SMICLD cannot discriminate this negative code error and thus locks to it with a bias of -0.01chips. HRC discriminates this code error change and adjusts the code phase of the local replica promptly to track the received signal, but with the same bias as before. Modified DLL aided by SMICLD can not only discriminate the code error jump, but also adjust it to zero without any bias.

5 EXPERIMENTAL RESULTS

In this section, the proposed Modified DLL Aided by SMICLD is compared with HRC, MEDLL, and SMICL, in terms of means and standard deviations of code errors, to assess the bias induced by multipath and the fluctuation caused by noise respectively. All these code loops have been implemented in the software-defined GPS L1 C/A IF receiver developed by our groups at Beihang University. The software-defined and hardware GPS L1 C/A signal simulator (Pseudolite) developed by us are also used in the following experiments. The front-end bandwidth is not considered as its influence on the code loop is a fixed bias of code errors which can be collaborated in advance according to [19].

5.1 Tests Results at Digital IF level

Firstly, the software defined IF GPS L1 C/A signal simulator is used to evaluate Modified DLL Aided by SMICLD, SMICL, HRC, and MEDLL in short multipath and noise environment from the following aspects: code errors in time domain, noise performance, and multipath code error envelope.

5.1.1 Code errors in Time Domain

In this section, the following four scenarios are simulated. The related parameters are shown in Table 6.

- Scenario A. 65 dB•Hz noise environment with single in-phase short multipath ray.
- Scenario B: 45 dB•Hz noise environment with single in-phase short multipath ray.
- Scenario C: 65 dB•Hz noise environment with single out-phase short multipath ray.
- Scenario D: 45 dB•Hz noise environment with single out-phase short multipath ray.

It is noted that 65 dB•Hz noise environment is simulated for the evaluation of SMICL's short multipath mitigation.

Table 6
Related Parameters

a_1 (MDR)	0.6
τ_1	0.05 chips
M	1
Δ_{HRC}	0.1 chips
Δ_{MEDLL}	0.2 chips
Δ_{SMICLD}	1 chip
$\Delta_{\text{Modified DLL Aided by SMICLD}}$	1 chip
Δ_{M}	1.5 chips
f_{IF} (Intermediate Frequency)	1.405 MHz
f_s (Sampling Frequency)	100 MHz

Code errors of SMICL, Modified DLL Aided by SMICLD, HRC and MEDLL in the four scenarios are displayed in Fig. 6. For a quantitative comparison, means and standard deviations of code errors of above code loops in the four scenarios are summarized in Table 7.

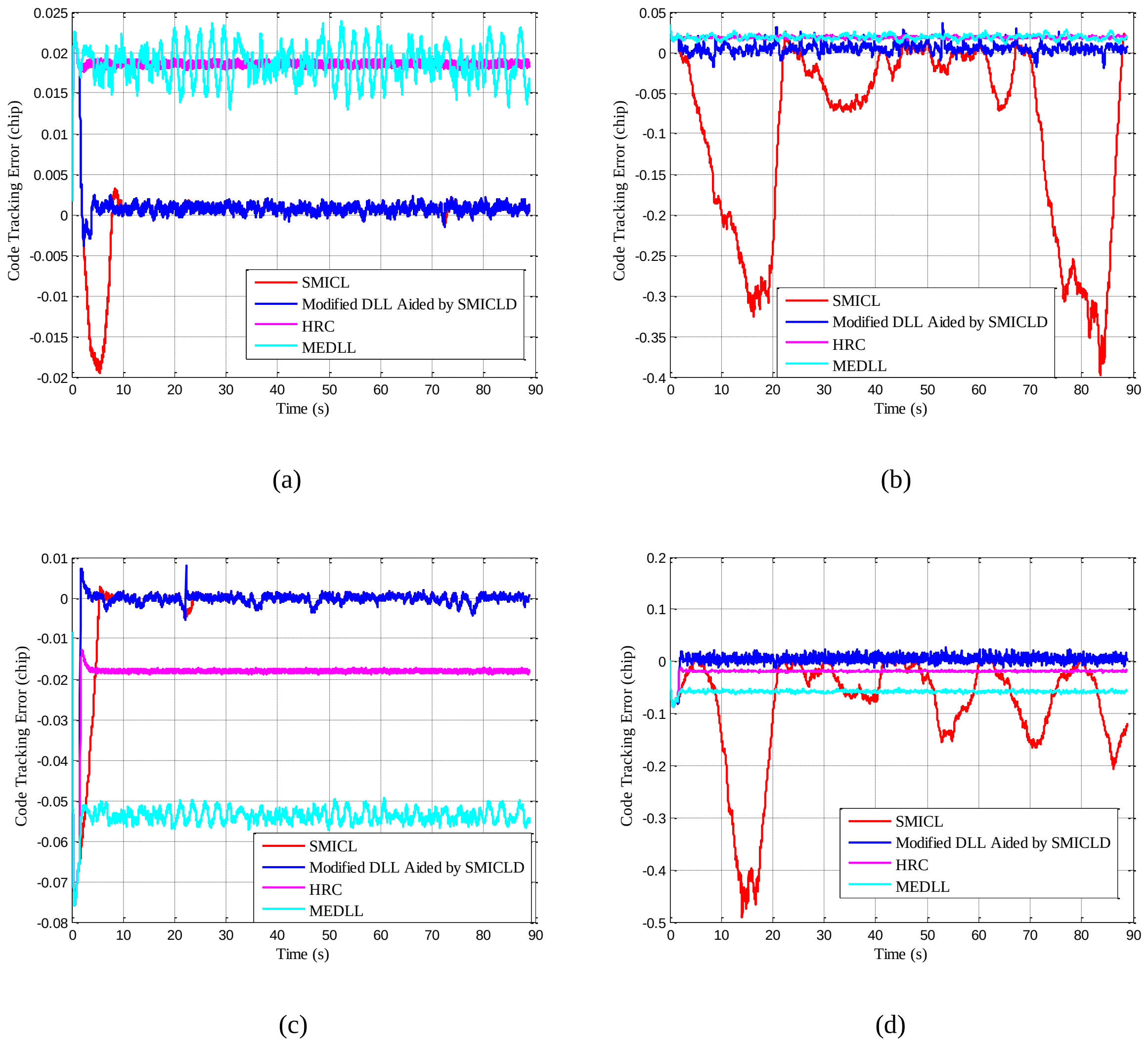

Fig. 6 Code Errors of SMICL, Modified DLL Aided by SMICLD, HRC and MEDLL in (a) scenario A, (b) scenario B, (c) scenario C and (d) scenario D

Because the practical correlation function is not the same as the ideal correlation function expressed by equation (4), SMICLD outputs about -0.001chips rather than zero when the code error is negative. Thus, SMICL can still converge its negative code error to zero but very slowly, as Fig. 6 (a) and (c) illustrate that the code error of SMICL fluctuates in the beginning.

Therefore, the code error of SMICL is doomed to have large fluctuations in noise environment because SMICLD cannot promptly adjust negative code errors caused by noise, which has been proved in Fig. 6 (b) and (d). By contrast, Modified DLL aided by SMICLD can promptly adjust the code phase of the local replica to be aligned with the received signal.

Table 7
Means and standard deviations of code errors of HRC, MEDLL, SMICL and Modified DLL Aided by SMICLD

Multipath Mitigation Methods	Code Errors							
	Mean (chip)				Standard Deviation (chip)			
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario A	Scenario B	Scenario C	Scenario D
HRC	0.0186	0.0187	-0.0180	-0.0197	5.05e-4	0.0013	3.14e-4	0.0075
MEDLL	0.0187	0.0190	-0.0537	-0.0579	0.0022	0.0029	0.0015	0.0034
SMICL	7.38e-4	-0.0969	-2.49e-4	-0.0853	5.12e-4	0.1151	0.0011	0.1059
Modified DLL Aided by SMICLD	7.44e-4	0.0053	-1.83e-4	0.0028	5.05e-4	0.0064	0.0010	0.0123

Table 7 indicates that, compared with SMICL, the means of code errors of Modified DLL Aided by SMICLD in scenario B and D decrease by more than 94% and 96% respectively[2]. Compared with HRC and MEDLL, the mean of code errors of Modified DLL Aided by SMICLD decreases by more than 71% and 72% respectively in scenario B, and more than 85% and 95% respectively in scenario D. Therefore, Modified DLL Aided by SMICLD has the best short multipath mitigation performance in noise environments among the four code loops.

Table 7 also shows that, compared with SMICL, the standard deviations of Modified DLL Aided by SMICLD are also reduced by 2 and 1 order of magnitude in scenario B and D, respectively. However, HRC and MEDLL have smaller standard deviations than Modified DLL Aided by SMICLD due to their continuous S-curves, which means they have better anti-noise performance.

5.1.2 Noise performance

Fig. 7 provides means and standard deviations of code errors in noise environments with different CN0. The CN0 configured in the simulator varies from 38dB•Hz to 59dB•Hz. The difference of carrier phase between the short multipath and LOS signal is 0.75π. Other settings are the same as those in Table 6. The measured CN0 in different receivers are shown in Fig. 7 (c).

Fig. 7 shows that SMICL has large code error means and standard deviations. With the rise of CN0, however, 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 will degrade to SMICL.

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[2] Absolute values of means and standard deviations of code errors are used for the calculation and comparison.

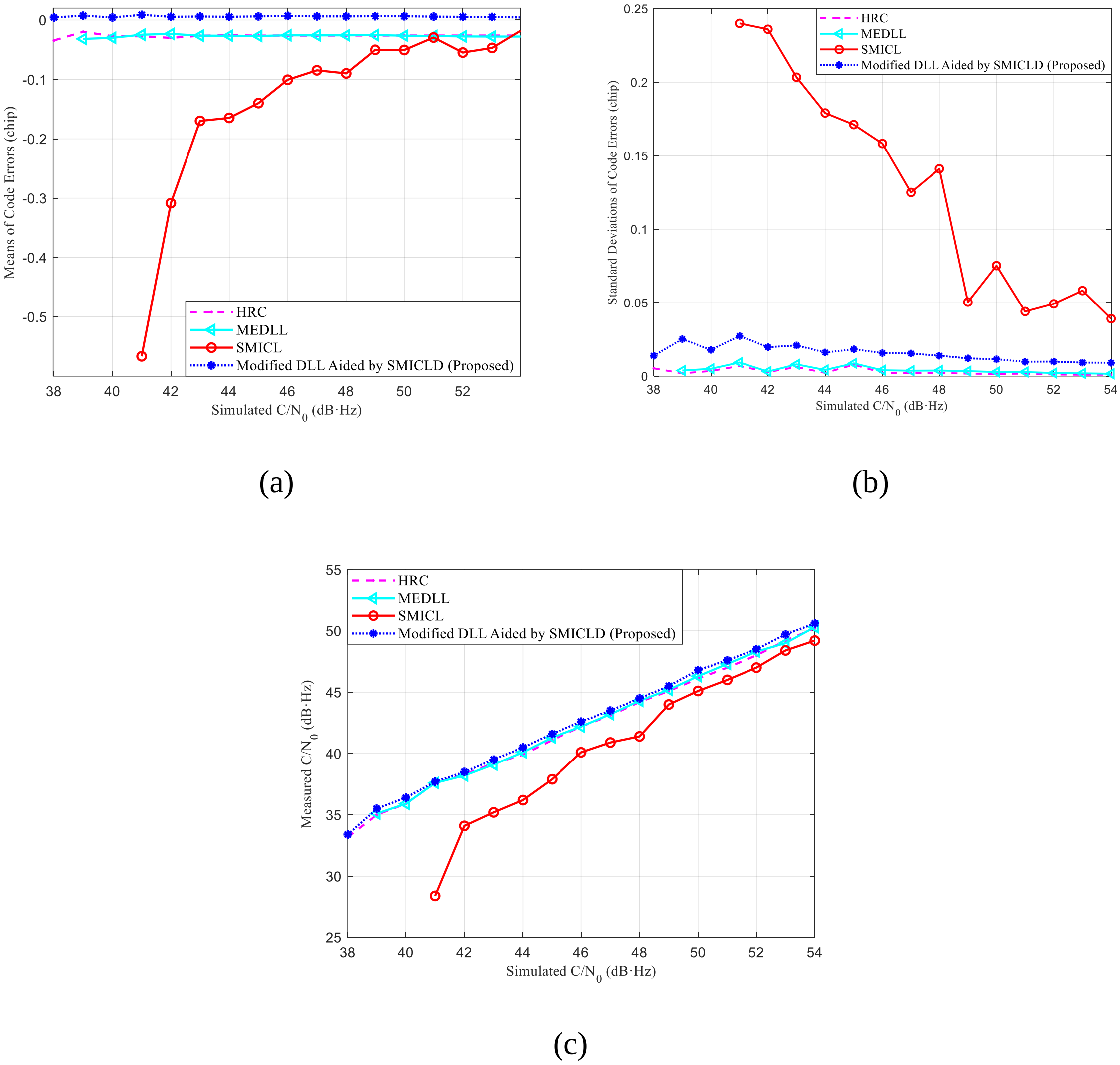


Fig. 7 (a) Means of Code Errors, (b) Standard Deviations of Code Errors, and measured CN0 of SMICL, Modified DLL Aided by SMICLD, MEDLL and HRC in Noise Environments

Fig. 7 (a) shows that, compared with the other three code loops, Modified DLL Aided by SMICLD has the minimum code errors and keeps the code error mean less than 0.01 chips. It is because MEMLD adjusts its negative code error induced by noise and helps SMICLD work normally. The smaller code error corresponds to higher CN0, which is proven in Fig. 7 (c). Fig. 7 (b) indicates that its standard deviation of the code error is also much smaller than that of SMICL, but still little higher than that of HRC and MEDLL (no more than 0.02 chips). It is the discontinuous S-curve of MoSMICLD that results in the worse anti-noise performance than HRC and MEDLL.

In terms of multipath mitigation performance, we are more concerned about the bias of code errors. Therefore, Modified DLL Aided by SMICLD has the best short multipath mitigation capability among these four code loops.

5.1.3 **Multipath code error envelope**

Multipath code error envelope can illustrate the influence of multipath with different delays on code loops. Fig. 8 exhibits multipath code error envelopes of the above four loops, where the multipath delay varies from 0 to 1 chip. Except for τ_1 and θ_0 - θ_1, other relevant parameters are same as those in Table 6. To more clearly show the performance of each code loop vs short multipath with delay of less than 0.1 chips, the multipath code error envelope within 0.1 chips is zoomed in by Fig. 9.

It is noted that the S-curve of MoSMICLD has a gap at the zero point that results in an excessively positive adjustment in noise environments. Thus, constant noise causes constant positive fluctuation of code errors, which ultimately evolves into a positive bias. Therefore, for Modified DLL Aided by SMICLD, in noise environments, the upper and lower boundaries of multipath code error envelope appear when the gap (absolute value) reaches the maximum and minimum, respectively. The gap (absolute value) reaches the maximum and minimum when the multipath is in-phase and out-of-phase, respectively. The details about the calculation of the relationship between multipath carrier phase and boundaries of the multipath code error envelope can be found in Appendix.

The multipath code error envelope of SMICL fluctuates seriously towards negative direction, which conforms to the analysis before. Although HRC can eliminate multipath with delay greater than 0.1 chips, it cannot mitigate multipath with delay of less than 0.1 chips. MEDLL can mitigate medium and long multipath effectively but useless for short multipath whose delay is less than 0.18chips in this simulation test.

Compared with the above three code loops, the lower boundary of the multipath code error envelope of Modified DLL Aided by SMICLD is maintained near zero. Additionally, its maximum code error is less than 0.01 chips, which is the smallest among the four code loops. For the multipath with delay of 0.1chips~0.5chips, Modified DLL Aided by SMICLD keeps its code error less than 0.015chips. However, it is less effective for medium and long delay multipath with delay over 0.5chips, which is caused by the biased zero-crossing point of SMICLD's S-curve.

Therefore, Modified DLL Aided by SMICLD has the best short multipath mitigation performance among these code loops.

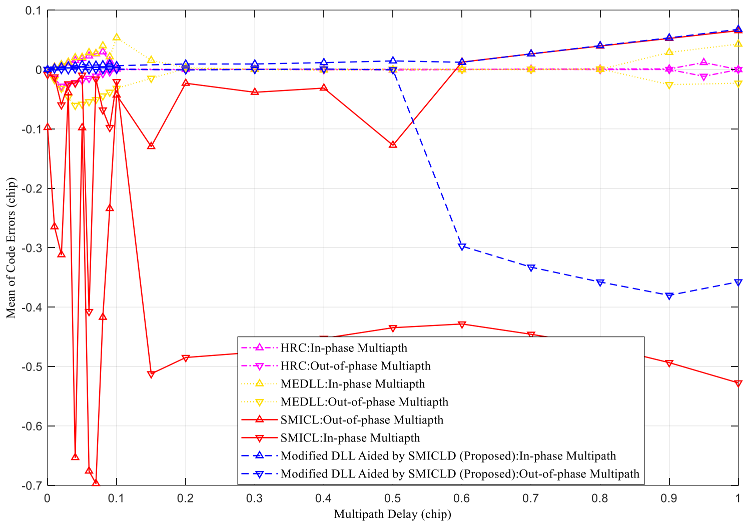


Fig. 8 Measured Multipath Code Error Envelopes for SMICL, Modified DLL Aided by SMICLD, HRC and MEDLL

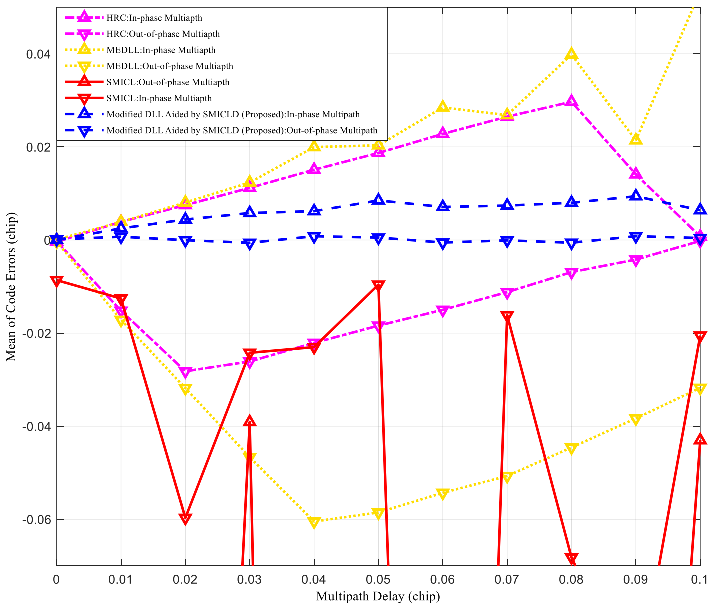


Fig. 9 Measured Multipath Code Error Envelopes for SMICL, Modified DLL Aided by SMICLD, HRC and MEDLL with respect to the multipath delay of [0, 0.1chips]

5.2 Real Multipath Environment Test at RF Signal Level

The GPS Radio Frequency (RF) signal simulator and broadband high-speed data recording system are used to further test the short multipath mitigation performance of Modified DLL Aided by SMICLD in a real short multipath scene displayed in Fig. 10.

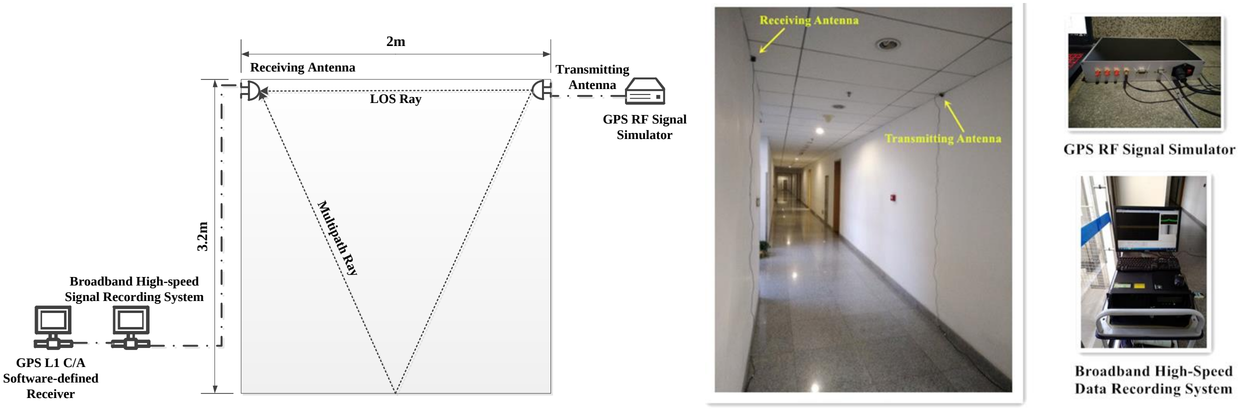


Fig. 10 Real Short Multipath Scene

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 broadband 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. These two devices have been shown in Fig. 10.

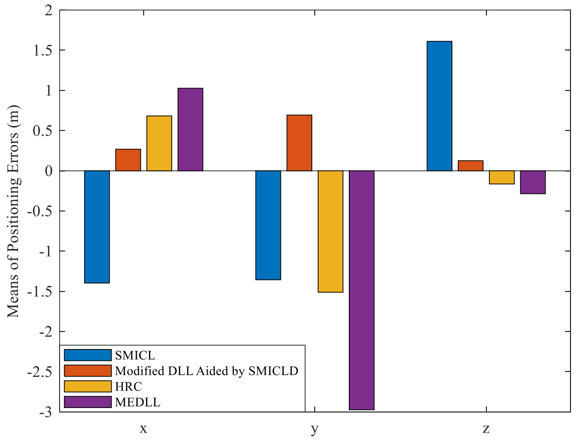
As shown in Fig. 10, a real short delay multipath scenario is set up in the corridor of the New Main Building of Beihang University. The length of the corridor is about 280 meters, much longer than the width and the height, so only the following four reflectors are considered: the ground, the ceiling and two walls alongside the corridor. The transmitting antenna connected to the GPS RF signal simulator is attached to the ceiling and the right wall. The receiving antenna connected to a broadband high-speed data continuous system is 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 0.016 chips (4.7m). The parameters of signal simulated by the GPS RF signal simulator are displayed in Table 8.

Table 8
Parameters Used in the GPS RF signal simulator

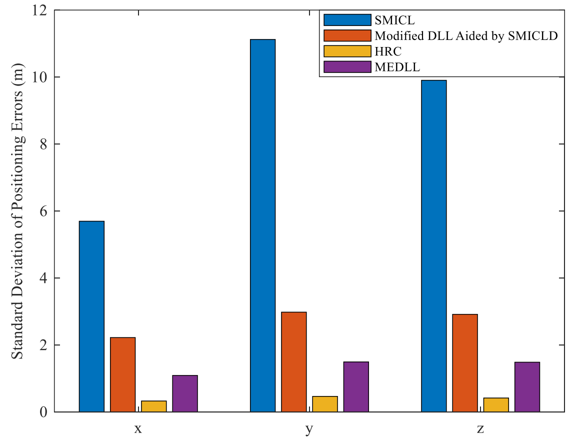
Parameters	Values
Signal Power	9dBm
f_{RF}	1575.42MHz
Longitude	116º E
Latitude	40º N
Height	100m

The broadband 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 HRC, MEDLL, SMICL and Modified DLL Aided by SMICLD have been used to process the “.dat” files. The settings of these receivers are the same as before.

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 four code loops are displayed in Fig. 11.



(a)



(b)

Fig. 11 Positioning errors of SMICL, Modified DLL Aided by SMICLD, HRC and MEDLL: (a) means of positioning errors of three axes; (b) standard deviations of positioning errors of xyz-axes

Fig. 11 shows that Modified DLL Aided by SMICLD has the smallest positioning errors of each axis among the four receivers. Compared with SMICL, the positioning errors on the x, y and z axes of Modified DLL Aided by SMICLD have been diminished by more than 80%, 49% and 90% respectively, which is the contribution from improvement in the S-curve. In terms of HRC and MEDLL, code errors induced by short multipath have evolved into positioning errors.

Modified DLL Aided by SMICLD also has much smaller standard deviations of positioning errors than SMICL, which means the anti-noise performance has been improved. However, due to the discontinuity at the zero-crossing point of its S-curve, the standard deviations of Modified DLL Aided by SMICLD’s positioning errors are still larger than the HRC and MEDLL, which implies that Modified DLL Aided by SMICLD is more sensitive to noise than these two code loops.

The goal of multipath mitigation techniques is to eliminate the positioning bias caused by multipath. Therefore, Modified DLL Aided by SMICLD is the best choice in above receivers considering both the short multipath mitigation performance and the anti-noise ability.

6 CONCLUSIONS

This paper has assessed the multipath mitigation performance of SMICLD. Although the zero-crossing point of SMICLD's S-curve has no bias in the presence of single short multipath ray, SMICLD outputs zero when the code tracking error is negative. Such asymmetry of its S-curve can result in large code tracking biases in real noise environment. Additionally, SMICLD cannot deal with two or more multipath rays or with medium and long multipath.

Aiming at improving the S-curve of SMICLD, this paper has proposed a novel code tracking loop called Modified DLL Aided by SMICLD. Instead of using SMICLD, this new code loop utilizes MEMLD to adjust the loop under negative code tracking errors. And a correlation channel that is later than the prompt correlation channel is added to switch the code loop to the proper discriminator. Simulation results show that Modified DLL Aided by SMICLD keeps the short multipath mitigation performance of SMICL while overcoming its disadvantages of instability under severe signal phase fluctuations.

Modified DLL Aided by SMICLD, SMICL, HRC and MEDLL have been implemented in our software receiver and their short multipath mitigation performances have been compared by using the digital IF GPS signal simulator in the following aspects: (1) The code tracking errors with single in-phase or out-of-phase short multipath ray; (2) The mean and standard deviation of code phase errors with respect to different CN0; (3) The multipath code error envelope. Moreover, their positioning errors in a real short multipath scene are tested by using a GPS RF signal simulator and a broadband high-speed data recording system.

Test results show that Modified DLL Aided by SMICLD can not only mitigate the code tracking biases caused by short multipath, but also promptly adjust the local replica code phase to track the received signal. Compared with SMICL, HRC and MEDLL, the proposed Modified DLL Aided by SMICLD has better single short multipath ray mitigation performance in noise environment.

Future work will focus on reducing the gap at the zero-crossing point of the S-curve of Modified DLL Aided by SMICD. The cases with more than one multipath ray will also be investigated.

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APPENDIX

(1) $\tau_1 \leq$ min ($\Delta_M/2$, 1-$\Delta_M/2$)

Calculate the derivative of equation (14) with respect to cos(θ_0- θ_1) when the code error is zero:

$$\frac{\partial D_{MEMLD}(0)}{\partial \cos(\theta_0-\theta_1)} = -4(1-\Delta_M/2)\frac{\left[1+(1-\Delta_M/2)^2\right]a_0a_1\tau_1\left(a_0^2-a_1^2\right)+2a_0a_1^3\tau_1^3}{\left(2k\varepsilon^2+2\left[(2-\Delta_M/2)k-2b\right]\varepsilon+\left[(1-\Delta_M/2)^2+1\right]k-2(2-\Delta_M/2)b+2a_1{}^2\tau_1{}^2\right)^2} < 0 \quad (16)$$

According to Equation (16), $D_{MEMLD}(0)$ reaches its minimum value when cos(θ_0- θ_1) equals to 1 or (θ_0- θ_1=0), which results in the largest gap and the upper boundary of the multipath code error envelope of Modified DLL Aided by SMICLD. $D_{MEMLD}(0)$ reaches its maximum value when cos(θ_0- θ_1) equals to -1 (θ_0- θ_1=π), which results in the smallest gap and the lower boundary.

(2) min ($\Delta_M/2$, 1-$\Delta_M/2$) $\leq \tau_1 \leq$ min ($\Delta/2$, 1-$\Delta/2$)

In this case, the discriminator function of MEMLD is written as

$$D_{MEMLD}(0)=\frac{-a_1^2(1-\Delta_M/2+\tau_1)^2-2a_0a_1(1-\Delta_M/2)(1-\Delta_M/2+\tau_1)\cos(\theta_0-\theta_1)}{a_0^2\left[(1-\Delta_M/2)^2+1\right]+a_1^2(1-\tau_1)^2+2a_0a_1(1-\tau_1)\cos(\theta_0-\theta_1)} \quad (17)$$

Thus, the derivative of equation (17) with respect to cos(θ_0- θ_1) is

$$\frac{\partial D_{MEMLD}(0)}{\partial \cos(\theta_0-\theta_1)} = \frac{2a_0a_1(1-\Delta_M/2+\tau_1)\left\{a_1^2(2-\Delta_M/2)(1-\tau_1)\tau_1-a_0^2(1-\Delta_M/2)\left[(1-\Delta_M/2)^2+1\right]\right\}}{\left\{a_0^2\left[(1-\Delta_M/2)^2+1\right]+a_1^2(1-\tau_1)^2+2a_0a_1(1-\tau_1)\cos(\theta_0-\theta_1)\right\}^2} \quad (18)$$

The MDR of the multipath ray is 0.6. And the correlation spacing Δ_M in MEMLD is 1.8 chips. In this case, equation (18) is negative, which means the largest gap and the upper boundary of the multipath code error envelope appear when cos(θ_0- θ_1) equals to 1 or (θ_0- θ_1=0). On the contrary, the smallest gap and the lower boundary are reached when cos(θ_0- θ_1) equals to -1 or (θ_0- θ_1=π).

(3) $\tau_1 \geq$ min ($\Delta/2$, 1-$\Delta/2$)

In this case, the multipath code error envelope of Modified DLL Aided by SMICLD only depends on SMICLD. The carrier phase differences between the multipath and the direct signal corresponding to the upper and lower boundaries are the same as situation (2). The details can be referred to [20].