

Delay Lock Loop Assisted Phase Lock Loop for GNSS Signal Tracking

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Abstract—For positioning with Global Navigation Satellite System (GNSS) in urban canyon area, besides the weak signal power, the satellite signal may also be frequently sheltered and no power can be received. It is a great challenge for the GNSS receiver to keep positioning continuously. If the tracking loop in GNSS receivers can recover locking the signal soon after the signal appears again, it will help a lot for the improvement of the positioning continuity since the acquisition stage is omitted. However, when signal is shortly interrupted, the local frequency estimation error increases during the period without signal. The tradition Phase Lock Loop (PLL) cannot directly lock the signal again. Hence, we propose the Delay Lock Loop (DLL) assisted PLL. In the method, when the signal is detected to be recovered, the DLL is firstly started up. Once the DLL is locked, the code phase measurements are extracted from the DLL to estimate the carrier frequency. Afterwards, it is utilized to correct the initial frequency of the PLL. By making use of the DLL's insensitivity to the frequency variation, it will help the PLL quickly and accurately lock the signal when the signal is shortly sheltered. The theoretical analysis results inform that the accuracy of the carrier frequency estimated from the DLL is sufficient for the PLL to recover locking. The simulation results show that the proposed DLL assisted PLL can recover tracking immediately after the signal is shortly interrupted. And it will help a lot for the positioning availability of GNSS receiver.

Index Terms—Global Navigation Satellite System, Phase Lock Loop, Delay Lock Loop, Urban canyon area, loop recovering

I. INTRODUCTION

The power of the Global Navigation Satellite System (GNSS) signals vary randomly and may be really weak in urban canyon area since it is easily sheltered, scattered and attenuated. In some cases, the signal can be totally sheltered which is unable to be received by the GNSS signal tracking loop. Accordingly, it is a great challenge for the signal tracking loop of GNSS receivers to stably locking the signal in these areas. Considering the tracking stability and continuity of the loop will directly affect the continuity of the positioning, the method to deal with the randomly sheltered signal is in great demand.

In the past few years, several studies have concentrated on the tracking of the weak signal. Ref. [1] analyzes the weak signal tracking performance of different carrier loop

architecture comprehensively. It gives out the conclusion of the signal tracking sensitivity for loops with different parameters. In order to improve the signal tracking sensitivity, some methods are designed based on the traditional Phase Lock Loop (PLL)[2]. Ref. [3] designs a Wiener filter based optimal carrier tracking loop to track the signal in the condition with serious noise. Ref. [4] introduces the Kalman filter to replace the simple two-order or three-order filter to improve the sensitivity. Ref. [5] and [6] propose Kalman Filter based adaptive carrier tracking loops to further improve the ability of weak signal tracking. On the other hand, some methods change the architecture of signal tracking including the vector tracking loop [7], [8] and the open loop tracking method [9], [10]. Ref. [11] introduces the Fast Fourier Transform (FFT) operator to improve the open-loop measurement accuracy. All these methods can indeed enhance the signal tracking sensitivity to some extent. However, in some situations, the signal may be totally sheltered and no power can be received. All the loops listed above can't maintain locking the signal in these cases. Furthermore, the sheltering may last for a short time. Hence, besides high sensitivity, if the loop is able to directly lock the signal without the process of acquisition as soon as the signal power is recovered from the large attenuation, it is of great meaningful for GNSS receivers to continuously position in the urban area.

For traditional GNSS receivers, the incoming satellite signal is processed with the method of Phase Lock Loop (PLL) assisting Delay Lock Loop (DLL) [12], [13]. Along with the momentarily disappearance or power attenuation of the satellite signal, the carrier phase estimation in the tracking loop will be highly distorted and easily over ranges the PLL convergence area. When the signal power recovers, it will lead to incorrect tracking or even unable to lock the signal if the loop is going to lock the signal directly. Although Frequency Lock Loop (FLL) can achieve the frequency locking when the initial frequency error is large, its carrier phase measurement is poor which cannot fulfill the requirement of common application [14]. For the more, it takes an extremely long time for FLL to lock the signal so that it cannot adapt to the instantaneous variation of the signal power if the PLL and FLL are switched between each other. The FLL assisted PLL can more or less solve the problem of the long convergence time compared with FLL but its structure is complex [15]. The stability and

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accuracy are also degraded in contrast with PLL. The dual update-rate FLL-assisted PLL improves the tracking accuracy and stability of the traditional FFL-assisted PLL, but it is even more complex and the tracking accuracy is still worse than PLL [16]. Moreover, for all of the FLL assisted PLL above, the input noise will increase the frequency aviation and the loop will not recover locking when the signal is momentarily vanished.

In this paper, based on the traditional structure of PLL coupled with DLL, we propose the DLL assisted PLL for the high-speed recovery of GNSS signal tracking. After the signal is shortly attenuated or sheltered, the DLL is firstly started up. Then, the carrier Doppler frequency is estimated with the pseudo range rate calculated from the measurements of the DLL. The estimation result is used to correct the carrier frequency initialization of the PLL. The method can highly reduce the time used for the loop to correctly lock the signal when the signal is intermittent. Thus, it will greatly ameliorate the positioning continuity of GNSS receivers in urban canyon area. Theoretical analysis is conducted to evaluate the Doppler frequency estimation accuracy and a simulation is carried out to assess the loop recovery ability of the proposed method in the situation of short signal power sheltering. The results indicate that the method can help the loop quickly recover tracking and extent the locking time in the environments with random short power sheltering.

The following paper is organized as follow. Section 2 gives out the signal model of GNSS signal and reviews the traditional signal tracking loop. The proposed DLL assisted PLL method is illustrated in Section 3. Section 4 evaluates the proposed method by theoretical analysis and Section 5 assesses the total performance of the method by simulation. Section 6 concludes the paper.

II. SIGNAL MODEL

The incoming GNSS signal, after down-converted to intermediate frequency by the receiver, is expressed as below

$$s(t) = \sqrt{2P}c(t)d(t)\cos(2\pi(f_i + f_d)t + \varphi) + n(t) \quad (1)$$

where P is the received signal power, c is the pseudo range noise (PRN) code. d is the binary navigation message data. f_i is the intermediate frequency of the received signal. f_d is the carrier Doppler frequency. φ is the initial carrier phase. n is the Additive Gaussian White Noise (AGWN) with the single band power spectral density of N_0 . After multiplied with the locally generated complex valued carrier, correlated with the local PRN code, the intermediate frequency signal is transformed to be the in-phase and quadrature coherent integration results which are expressed as

$$I_k = \sqrt{P}d_k R_c(\tau) \sin c(\pi \Delta f_d T_c) \cos(\phi) + n_I \quad (2)$$

$$Q_k = \sqrt{P}d_k R_c(\tau) \sin c(\pi \Delta f_d T_c) \sin(\phi) + n_Q \quad (3)$$

where k is the index of the discrete coherent integration results. The interval between two accumulation results is the coherent integration length which is T_c . $R_c(\cdot)$ is the autocorrelation function (ACF) of the PRN code. τ is the code phase delay between the incoming signal and the local replica. Δf_d is the carrier frequency estimation error. ϕ is the carrier phase residual. n_I and n_Q are the accumulated AWGN with the power of $N_0 / 2T_c$.

In the traditional GNSS signal tracking loop, as the tracking accuracy of PLL is high, the Doppler frequency estimation accuracy is perfect. In this way, with the Doppler frequency assistance from the PLL, the code Doppler frequency can be totally compensated. The code phase error of DLL in τ only contains the first order component. However, when the satellite signal is shortly and frequently attenuated or sheltered which is the usual situation in urban canyon area, the PLL may not be able to directly recover locking the signal. During the absence of the signal, the frequency estimation is deviated from the satellite signal due to the motion of the receiver and the disturbance of noise. Therefore, the initial frequency of the PLL may be out of its convergence area but within the transition area. The PLL can still track the signal but lock on the image frequency. The frequency deviation may also be entirely larger than the PLL locking area and the loop loses lock. For both cases, the receiver has to return to the acquisition stage to acquire the signal which will lead to a long time of positioning interruption.

In urban application, along the direction of the line from the satellite to the receiver, the acceleration of the receiver cannot exceed $a=1.6\text{m/s}^2$ (the angle between the line from the satellite to the receiver and the receiver movement direction is 30° , the accelerating time for the receiver velocity ranging from 0 to 100km/h is 15s). As a result, when the signal is disappeared for t second, the carrier Doppler frequency shift variation f_e is

$$f_e = f_r \cdot at/c \quad (4)$$

where f_r is the signal radio frequency, c is the light velocity. Taking the GPS L1CA signal as an example, the variation of the carrier Doppler frequency during the time period of $T=5\text{s}$ is around 40Hz. As the stably tracking bandwidth of PLL is usually 15Hz, the variation exceeds the frequency locking area of the PLL with the updating duration of 1ms. When the signal power is recovered, the loop cannot directly recover locking the signal without acquisition. Nevertheless, the DLL still can lock the signal as soon as the signal power is recovered since the code phase deviation doesn't exceed the DLL locking area. Taking the situation above as an example again, during the period of 5s, the code Doppler frequency deviation $f_{c,e}$ is only 0.026Hz. The corresponding accumulated code phase error τ_e during the time is

$$\tau_e = f_{c,e} \cdot T = 0.026 \times 5 = 0.13 \quad (5)$$

The accumulated code phase error in the time length of 5s is 0.13chip which is much less than the edge of the DLL convergence area which is ± 1 chip. In addition, the code phase measurement contains the information of frequency residual. Regardless of the noise, the code phase delay between two adjacent coherent integration results is expressed as

$$\tau_n = \Delta f_{c,d} T_c + \tau_{n-1} \quad (6)$$

where $\Delta f_{c,d}$ is the PRN code Doppler frequency estimation error that is $\Delta f_{c,d} = \Delta f_d \cdot f_c / f_r$. In consideration of the fact the code chip rate is much smaller than the carrier frequency, such as GPS L1CA signal in which $f_c / f_r = 1/1540$, although the frequency estimation deviation induced by the sheltering or attenuation will cause the carrier loop to lose lock, the corresponding code Doppler frequency estimation error is a little. Thus, the effects of the frequency estimation deviation brought by the signal attenuation on the DLL can be ignored and the DLL can lock the signal again as soon as the signal is recovered without the process of acquisition.

III. DLL ASSISTED PLL METHOD

A. Frequency Estimation Method

As DLL can quickly recover locking the signal without acquisition when the satellite signal is shortly sheltered, in this section, we give out the carrier Doppler frequency estimation method. Assuming the signal carrier frequency estimation deviation is inherent within the interval of the signal power attenuation, the relationship between the carrier Doppler frequency estimation error and code phase deviation is as below according to (6)

$$\tau_n - \tau_{n-1} = \Delta f_d T_c \cdot f_c / f_r \quad (7)$$

When the satellite signal is normally received by the receiver, the carrier tracking loop is stably tracking the signal. With the help of the carrier assistance, the code Doppler frequency estimation residual is really small. Only the first order code phase error is need to be corrected by DLL. When the signal is shortly sheltered, the feedbacks of both the PLL and DLL are stopped so as to retard the dispersion of the PLL and DLL brought by noise. Owing to the dynamic of the receiver and satellites, clock drift, etc., the carrier Doppler frequency estimation error is continuously increased that leads to the increment of the difference between the locally generated signal and the incoming satellite signal. As soon as the signal is recovered, the DLL will begin to lock the signal. Because of the code Doppler frequency deviation between the incoming signal and local replica, the difference between τ_n and τ_{n-1} is increased. As a result, the code Doppler frequency error is contained in the output of the loop filter which is expressed as

$$f_{c,e} = \Delta f_{d,c} + f_e + n_f \quad (8)$$

where f_e is the frequency component to compensate the error brought by other sources such clock error, clock

drift and ionospheric delay. n_f is the noise component in the code Doppler frequency estimation. Obviously, the code Doppler frequency deviation can be calculated from the code tracking results. Then, based on the relationship between the code Doppler frequency and carrier Doppler frequency, the carrier frequency error can be estimated from the code tracking results. Hence, considering the code deviation after the short signal power attenuation is within the locking area of DLL, the DLL can correctly lock the signal. The carrier frequency deviation can be calculated according to the DLL outputs. With the help of the frequency correction according to the DLL tracking result, the carrier tracking loop can be quickly recovered without the acquisition.

However, the code Doppler frequency can't be directly estimated from the filter output since it may be highly disturbed by noise. As huge jitters induced by the noise is existed in the filter outputs, the carrier Doppler frequency is designed to be estimated from the pseudo range rate that is calculated from the code phase measurements. The frequency of PLL is corrected by the estimation results. Hence, it is named as DLL-assisted PLL. According to the pseudo range of the two adjacent epochs, the pseudo range rate is calculated as

$$v_\rho = (\rho_{t_1} - \rho_{t_2}) / (t_1 - t_2) \quad (9)$$

where ρ_{t_1} is the pseudo range of t_1 epoch, ρ_{t_2} is the pseudo range of t_2 epoch. The relationship between the pseudo range rate and carrier Doppler frequency is

$$f_d = f_{IF} \cdot v_\rho / f_c \quad (10)$$

Based on the pseudo range rate, the carrier Doppler frequency can be calculated. Since the noise components vastly disturb the pseudo range calculating result derived from the single epoch measurements, the carrier Doppler frequency is estimated by using the average of several epochs' pseudo range measuring results. If N pseudo range measurements are utilized, the pseudo range rate is

$$v_\rho = \sum_{i=1}^N (\rho_{t_{1,i}} - \rho_{t_{2,i}}) / (t_{1,i} - t_{2,i}) \quad (11)$$

In consideration of the estimation accuracy of the pseudo range measurement, N is usually chosen to be 10 and the time between each two adjacent epochs used for the estimation is 50ms.

B. Frequency Correction and Loop Recovery

The DLL assisted PLL for GNSS receiver is illustrated in Fig. 1. In the architecture, the correlation channel is the same as the traditional tracking loop. The outputs of the correlators are the in-phase and quadrature branch coherent integration results. Based on the correlation outputs, the carrier frequency and the code delay are estimated and feedback to adjust the local generated signal. In the module of the code phase storage, the code phase measurement of last epoch is stored. When the code phase measurement of the present epoch is extracted,

the two code phase measurements are put together to estimate the code rate. With the help of the noise statistic channel, the noise power is estimated. Together with the correlation outputs, the carrier to noise ratio (C/N_0) of the signal is calculated. Based on the C/N_0 estimation, the presence or absence of the signal can be judged. When the satellite signal is normally received and loop is in the stable state, the two switches are closed, the code delay estimation result calculated from the present epoch is feedback to the loop. The carrier frequency result is feedback to control the generation of the local carrier as well. When the C/N_0 decreases to a threshold, the loop is detected to lose lock and the two switches are open to stop the loop feedback. The C/N_0 threshold for the

switches of DLL and PLL are different. As the sensitivity of DLL is higher than PLL, the C/N_0 threshold for DLL is lower. Then, the DLL can start to work earlier when the signal is recovered. In this way, the frequency error is just that induced by the movement of the receiver and the PLL will not lead to extra frequency error. Although the carrier frequency error still exists, the corresponding code Doppler frequency error is little so that the DLL will probably recover locking the signal. When DLL works for some time, the code rate is estimated based on the pseudo range rate and the carrier frequency Doppler frequency is calculated according to the code rate. Finally, the switch of PLL is closed and the carrier frequency is corrected by the estimation result.

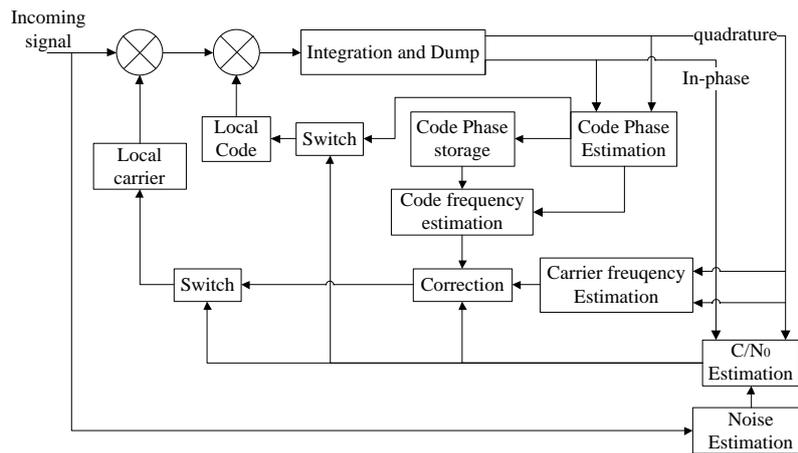


Fig. 1. DLL assisted PLL

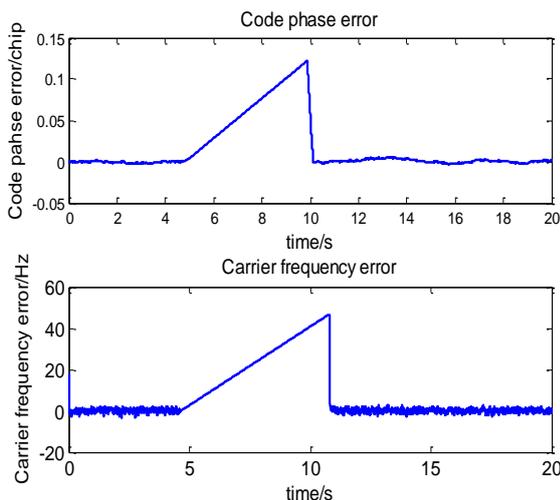


Fig. 2. The tracking error of the DLL assisted PLL

In fact, when the signal is shortly sheltered, for the usual application in urban area, the carrier frequency variation is little. If the carrier tracking loop stops working, the frequency error will be really small. When the signal is recovered, it is easy for the loop to detect the signal power. Afterwards, the DLL can lock the signal and compensate the frequency error itself. As a result, when the signal is recovered, the DLL is firstly restarted.

If the estimation value of C/N_0 continuously increases, the signal is considered to be recovered. The carrier frequency is calculated based on the DLL tracking results so as to compensate the initial frequency error for carrier tracking. Then, the switch of PLL is closed and the PLL start to work. Taking the GPS L1CA signal as an example, Fig. 2 shows the carrier Doppler frequency tracking error of PLL and the code tracking error of DLL for the DLL assisted PLL in the test case that the signal is shortly sheltered and quickly recovered. In the figure, the acceleration of the receiver is $1.6m/s^2$, the signal sheltering length is 5s, the signal power is $-125dBm$.

It shows that, on one hand, the variation of the error of DLL is smaller than that of the PLL. On the other hand, by firstly starting the DLL and starting PLL afterwards, the DLL can successfully lock the signal again. With the help of the frequency correction derived from the DLL, the carrier frequency error sharply reduces. Accordingly, the PLL can successfully recover tracking and lock the right phase. In the next section, the performance of different methods is evaluated and compared.

IV. PERFORMANCE EVALUATION

In this section, the convergence area of the DLL assisted PLL is calculated. Hereafter, the DLL based carrier frequency estimation accuracy is evaluated

With the DLL's assistance, the frequency convergence area of PLL is extended compared with the traditional PLL. However, it is still limited by the convergence area of DLL. Taking the GPS L1CA signal as an example, the loop convergence area of the DLL using the early minus late power discriminator is ± 1 chip. Assuming that the code tracking error of DLL when stably tracking is zero, the relationship between the loop losing time and the frequency convergence area is as blow

$$|\Delta f_d T_l \cdot f_c / f_r| < 1 \quad (12)$$

where T_l is the loop losing time. For GPS L1CA signal, the relationship between the loop losing time and the frequency convergence area is shown in Fig. 3.

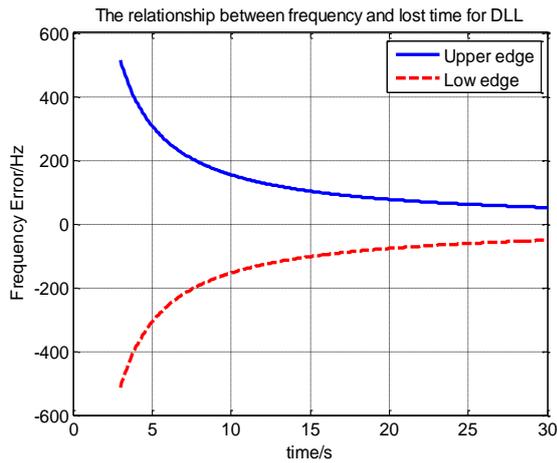


Fig. 3. Relationship between the loop losing time and frequency convergence area

As the losing time extends, the frequency convergence area is reduced. The up and down edge are symmetry to the error of zero. When the loop losing time reaches 30s, the ability of the frequency convergence is identical with the traditional PLL. However, when the loop losing time is smaller than 10s, the frequency locking area is as large as 100Hz which is much larger than the traditional PLL. The other factor which has influence on the frequency convergence ability is the frequency estimation accuracy. Because the frequency is estimated from the pseudo range estimation, its accuracy is derived from that of the pseudo range measurements. The standard deviation of the pseudo range estimation is

$$\begin{aligned} \sigma_F &= \sqrt{\text{var}((\rho_{t_1} - \rho_{t_2}) / (t_1 - t_2))} \\ &= \frac{1}{(t_1 - t_2)} \sqrt{\text{var}(\rho_{t_1} - \rho_{t_2})} \end{aligned} \quad (13)$$

As the pseudo range estimation results of instant t_1 and t_2 are independent of each other, the standard deviation is rewritten as below

$$\sigma_F = \frac{1}{(t_1 - t_2)} \sqrt{\text{var}(\rho_{t_1}) + \text{var}(\rho_{t_2})} \quad (14)$$

Assuming that the frond-end bandwidth of receiver is infinite, the result is [17]

$$\text{var}(\rho_{t_1}) = \text{var}(\rho_{t_2}) = \frac{B_L}{2 \cdot C/N_0} D \left(1 + \frac{2}{(2-D)T_{coh} \cdot C/N_0} \right) \quad (15)$$

where B_L is the loop bandwidth, D is the correlation space between the early and late branch correlation result, T_{coh} is the coherent integration length, the code frequency estimation error standard deviation is

$$\sigma_F = \frac{1}{(t_1 - t_2)} \sqrt{\frac{B_L}{C/N_0} D \left(1 + \frac{2}{(2-D)T_{coh} \cdot C/N_0} \right)} \quad (16)$$

After N times average calculation, the carrier frequency estimation error standard deviation is

$$\sigma_F = \frac{f_{IF}}{N(t_1 - t_2)f_c} \sqrt{\frac{B_L}{C/N_0} D \left(1 + \frac{2}{(2-D)T_{coh} \cdot C/N_0} \right)} \quad (17)$$

Still taking the GPS L1CA signal as an example, if the pseudo range measuring interval between two epochs is $t_1 - t_2 = 0.05s$, the coherent integration length is 20ms, the loop bandwidth B_L is 0.5Hz, for different C/N_0 and different correlation space, the frequency estimation error standard deviation is drawn in Fig. 4. It is clear that, for the usual C/N_0 of GNSS signal which is higher than 40dBHz, the error is within 5Hz which is much smaller than the frequency convergence area of simple PLL without FLL assisted. In this case, the PLL with the bandwidth of that at the stably working state can quickly lock the signal and the positioning will be recovered immediately after the signal power is increased.

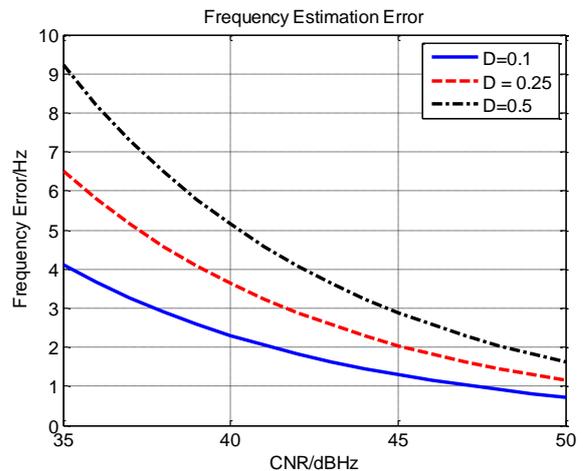


Fig. 4. Frequency estimation error of different CNR

V. TEST AND VERIFICATION

In order to verify the loop quickly recovering locking performance of the proposed DLL assisted PLL method, taking the GPS L1CA signal as an example, simulation is carried out and the result is compared with the traditional PLL. The simulation parameters are listed in Table I.

TABLE I: LOOP SIMULATION PARAMETERS

Loop	DLL assisted PLL	Traditional PLL
PLL bandwidth	15Hz	15Hz
DLL bandwidth	0.5Hz	0.5Hz
Coherent integration	20ms	20ms
Correlation space	0.1chip	0.1chip
Signal sheltering length	5s,10s	5s,10s
Simulation times	1000	1000
Signal power	133dBm	133dBm
Velocity	0m/s	0m/s
Acceleration	2m/s ²	2m/s ²

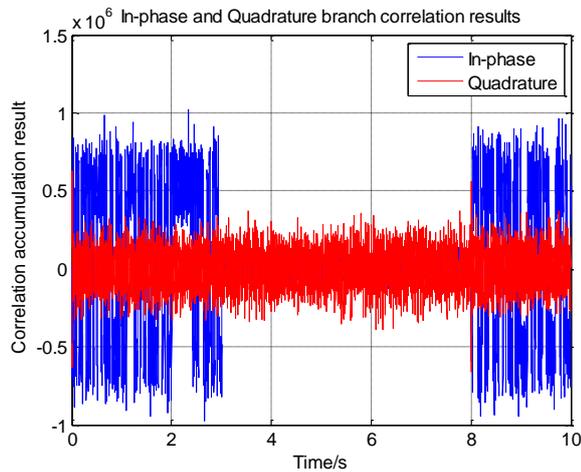


Fig. 5. In-phase and Quadrature branch correlation results for one time of test when the signal is sheltered for 5s

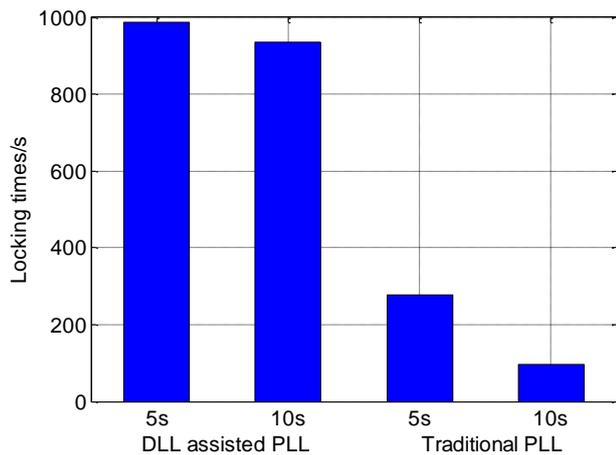


Fig. 6. Simulation statistic results

The simulation process is as follow. Firstly, the GPS L1CA signal is normally broadcasted. When the loop falls into the stable state, the broadcasting of the signal is stopped for the corresponding time. And then, the signal is recovered to broadcast. The In-phase and Quadrature branch correlation results for one time of tests when the signal is sheltered for 5s are shown in Fig. 5. In this test, at the time instant of 3s, the signal disappears and, at the time instant of 8s, the signal power is recovered. It is clear that the loop rapidly lock the signal as soon as the signal power is increased.

For each of the testing scenarios listed in the table, 1000 times tests are carried out and the number of the tests that the loop successfully recovers tracking is recorded. The histogram of the test statistic result is shown in Fig 6. According to the simulation results, it is clear that the proposed DLL assisted PLL is outstanding compared with the traditional PLL for the loop recovery when the signal is shortly sheltered and immediately recovered. Therefore, it will highly improve the vehicle position performance with GNSS in the urban area with large amount of power attenuation and sheltering.

VI. CONCLUSIONS

In this paper, we propose a DLL assisted PLL for the satellite signal tracking in the GNSS receiver. Based on the fact that the DLL is insensitive to the frequency variation induced by the acceleration of the receiver, the pseudo range measurements calculated from the code tracking results of DLL are utilized to compute the carrier frequency residuals and correct the PLL after the satellite signal is shortly sheltered or attenuated. The theoretical analysis verifies that the estimation accuracy of the carrier Doppler frequency calculated from the code phase measurements derived from the DLL is within the locking area of PLL. As a result, the carrier frequency can be corrected with the help of the code phase measurements. The simulation result indicates that the proposed DLL assisted PLL is outstanding in the signal locking recovery compared with the traditional PLL when the signal shortly disappears and it can greatly improve the continuity and serviceability of positioning with GNSS in urban canyon area.

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