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Analysis of Multipath and CW Interference Effects on GNSS Receivers with EMLP Discriminator

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ABSTRACT

Multipath and continuous wave (CW) interference may cause severe performance degradation of global navigation satellite system (GNSS) receivers. This paper analyzes the code tracking performance of early-minus-late power (EMLP) discriminator of GNSS receivers in the presence of multipath and CW interference. An analytical expression of the code tracking error is suggested for EMLP discriminator, and it can be used to assess the effect of multipath and CW interference. The derived expression shows that the combined effects include three components: multipath component; CW interference component and the combined component of multipath and CW interference. The effect of these components depends on some factors which can be classified into two categories: the receiving environment and the receiver parameters. Numerical results show how these factors affect the tracking performances. It is shown that the proper receiver parameters can suppress the combined effects of multipath and CW interference.

Keywords: Multipath; Interference; GNSS; EMLP; Discriminator

1. Introduction

GNSS signal is very susceptibility to receiving environment [1-2]. Multipath is the dominant error source in most GNSS applications. Therefore, multipath performance analysis plays a significant role in the analysis of the code tracking performance of GNSS receivers. The multipath error envelope (MEE) is a common way of assessing the multipath performance of a given signal/receiver combination [3]. CW interference is typical radio frequency interference (RFI) which is another error source for GNSS receivers [4, 5]. The post-correlati on effects of narrowband interference and partial-band interference have been analyzed in [4, 6]. Reference [7] suggested analytical expressions for GNSS receiver performance such as the effective carrier-to-noise density ratio, the code tracking error and the carrier phase tracking error for the receiver affected by CW interference. Reference [8] presented the analytic expressions of the code tracking error bound for the EMLP discriminator and the dot-product (DP) discriminator. The definition of new families of curves named interference error envelope (IEE) and interference running average (IRA) was presented, and these tools are able to assess the impact of RF interference on different GNSS receivers [9].

The effects of multipath or interference have been analyzed in the articles above. However, if multipath and interference exist at the same time, their effects on the code tracking performance with EMLP discriminator are not independent. However, the combined effects of multipath and CW interference haven't been analyzed in other papers. This paper analyzes the effects of multipath and CW interference on the code tracking performance of GNSS receivers. An analytical expression of the code tracking error is suggested for EMLP discriminator, and it can be used to assess the combined effect of multipath and CW interference.

The rest of this paper is organized as follows. Signal models are provided in Section 2. The analytical expression of the code tracking error for EMLP discriminator is derived in Section 3. Section 4 shows how the receiving environment and the receiver parameters affect the code tracking error. This paper concludes in Section 5.

2. Signal Models

As defined in [10], the direct signal is denoted as equation(1):

$$r_0(t) = a_0 s(t-\tau_0)\cos(2\pi f_c t + \varphi_0) \tag{1}$$

with a_0 being the amplitude of the direct signal, $s(t)$ being the pseudo random noise (PRN) code, τ_0 being the time delay, f_c being the carrier frequency, and φ_0 being the carrier phase.

With the increase in the number of reflections, the amplitudes of reflected signals are becoming smaller and smaller. Without loss of generality, one reflected signal with the maximum amplitude is taken into consideration to simplify the received signal model, so the reflected signal can be simplified as follow:

$$r_N(t) = a_1 s(t-\tau_1)\cos(2\pi f_c t + \varphi_1) \tag{2}$$

where a_1 is the amplitude of a reflected signal, τ_1 is the time delay of a reflected signal, φ_1 is the carrier phase of a reflected signal.

The CW interference can be considered to be a sine wave which can be expressed as:

$$l(t) = c_l \cos(2\pi f_c t + 2\pi f_l t + \varphi_l) \tag{3}$$

where c_l is the amplitude of CW interference, f_l is the frequency offset from the carrier frequency f_c, and φ_l is the phase of CW interference.

Therefore, the received signal can be expressed as:

$$\begin{aligned} r(t) &= a_0 s(t-\tau_0)\cos(2\pi f_c t + \varphi_0) \\ &+ a_1 s(t-\tau_1)\cos(2\pi f_c t + \varphi_1) \\ &+ c_l \cos(2\pi f_c t + 2\pi f_l t + \varphi_l) \end{aligned} \tag{4}$$

Before processing the received signal and beginning the code tracking, the received signal needs to be down-converted. In the down converting process, the estimated carrier phase is provided by the phase locked loop (PLL) and a replica carrier is generated by the receiver. The replica carrier is expressed as $2\cos(2\pi f_c t + \hat{\varphi}_0)$, where $\hat{\varphi}_0$ is the estimated carrier phase. After down converting and filtering the received signal, the received signal can be expressed by the in-phase component and the quadrature component. The in-phase component can be expressed as follow:

$$\begin{aligned} s_I(t) &= a_0 s(t-\tau_0)\cos(\varphi_0 - \hat{\varphi}_0) \\ &+ a_1 s(t-\tau_1)\cos(\varphi_1 - \hat{\varphi}_0) + c_l \cos(2\pi f_l t + \varphi_l - \hat{\varphi}_0) \end{aligned} \tag{5}$$

The quadrature component can be expressed as follow:

$$\begin{aligned} s_Q(t) &= a_0 s(t-\tau_0)\sin(\varphi_0 - \hat{\varphi}_0) \\ &+ a_1 s(t-\tau_1)\sin(\varphi_1 - \hat{\varphi}_0) + c_l \sin(2\pi f_l t + \varphi_l - \hat{\varphi}_0) \end{aligned} \tag{6}$$

In the delay lock loop, the code generator usually generates two types of PRN codes: early replica code $s^*(t-\hat{\tau}_0 + d/2)$, late replica code $s^*(t-\hat{\tau}_0 - d/2)$, where $\hat{\tau}_0$ is the estimated time delay, * denotes the conjugate operation, and d is the correlator spacing. In the code tracking process, the replica codes are multiplied and integrated with the in-phase component and the quadrature component.

The early in-phase output I_E can be expressed as follow:

$$\begin{aligned} I_E &= a_0 \cos(\hat{\varphi}_0 - \varphi_0) R(\varepsilon_\tau - \frac{d}{2}) \\ &+ a_1 \cos(\varphi_1 - \hat{\varphi}_0) R(\varepsilon_\tau - \hat{\tau}_1 - \frac{d}{2}) \\ &+ \frac{c_l}{T_p}\int_{-T_p/2}^{T_p/2} \cos(2\pi f_l t + \varphi_l - \hat{\varphi}_0) s_l^*(t - \hat{\tau}_0 + \frac{d}{2}) dt \end{aligned} \tag{7}$$

Similarly, the late in-phase output I_L, the early quadrature output Q_E and the late quadrature output Q_L can be expressed respectively as follow:

$$\begin{aligned} I_L &= a_0 \cos(\hat{\varphi}_0 - \varphi_0) R(\varepsilon_\tau + \frac{d}{2}) \\ &+ a_1 \cos(\varphi_1 - \hat{\varphi}_0) R(\varepsilon_\tau - \hat{\tau}_1 + \frac{d}{2}) \\ &+ \frac{c_l}{T_p}\int_{-T_p/2}^{T_p/2} \cos(2\pi f_l t + \varphi_l - \hat{\varphi}_0) s^*(t - \hat{\tau}_0 - \frac{d}{2}) dt \end{aligned} \tag{8}$$

$$\begin{aligned} Q_E &= a_0 \sin(\hat{\varphi}_0 - \varphi_0) R(\varepsilon_\tau - \frac{d}{2}) \\ &+ a_1 \sin(\hat{\varphi}_0 - \varphi_1) R(\varepsilon_\tau - \hat{\tau}_1 - \frac{d}{2}) \\ &- \frac{c_l}{T_p}\int_{-T_p/2}^{T_p/2} \sin(2\pi f_l t + \varphi_l - \hat{\varphi}_0) s^*(t - \hat{\tau}_0 + \frac{d}{2}) dt \end{aligned} \tag{9}$$

$$\begin{aligned} Q_L &= a_0 \sin(\hat{\varphi}_0 - \varphi_0) R(\varepsilon_\tau + \frac{d}{2}) \\ &+ a_1 \sin(\hat{\varphi}_0 - \varphi_1) R(\varepsilon_\tau - \hat{\tau}_1 + \frac{d}{2}) \\ &- \frac{c_l}{T_p}\int_{-T_p/2}^{T_p/2} \sin(2\pi f_l t + \varphi_l - \hat{\varphi}_0) s^*(t - \hat{\tau}_0 - \frac{d}{2}) dt \end{aligned} \tag{10}$$

where T_p is the integration time, $\varepsilon_\tau = \hat{\tau}_0 - \tau_0$ is the code tracking error, and $\hat{\tau}_1 = \tau_1 - \tau_0$ is the extra delay of the reflected signal with respect to the direct signal, $R(\cdot)$ is the autocorrelation function defined as follow:

$$R(\tau) = \frac{1}{T_p}\int_{-T_p/2}^{T_p/2} s(t) s^*(t-\tau) dt \tag{11}$$

When CW interference is multiplied with the replica PRN signal, the CW interference is spread by the PRN code. Since the code tracking loop is an equivalent low-pass filter, when the interference locates at zero frequency (this occurs when $f_l = n/(N_c T_c)$), it causes the most serious degradation of the code tracking performance. Then the interference term of I_E can be expressed as follow [8]:

$$I_{E\_l} = c_l \left|C(n)\right| \cos(\alpha + \pi d n / N_c T_c) \tag{12}$$

where $C(n) = S_p(n)\sum_{m=0}^{N_c-1} c_m e^{-j2\pi mn/N_c} / N_c T_c$

is the Fourier transform of the PRN signal, $S_p(n)$ is the transform of the pluse shape,

$$\alpha = \varphi_l - \hat{\varphi}_0 + \beta + 2\pi(n / N_c T_c)\hat{\tau}_0 ,$$

and β is the phase of $C(-n)$. Similarly, we can obtain the interference term of I_L, Q_E, and Q_L.

3. Code Tracking Performance Analysis

The EMLP discriminator is a typical noncoherent discriminator which can mitigate the effect of the phase difference between the carrier phase and the estimated carrier phase. The output of EMLP discriminator is denoted as follow:

$$D_{EMLP} = (I_E^2 + Q_E^2) - (I_L^2 + Q_L^2) \tag{13}$$

Assuming that the carrier tracking loop tracks the carrier phase of the received signal perfectly, we can obtain $\varphi_0 = \hat{\varphi}_0$. Substituting (7)-(10) into (13) and simplifying the expression, we can obtain the following expression.

$$\begin{aligned} D_{EMLP}(\varepsilon_\tau) &= D_{Direct}(\varepsilon_\tau) + D_{Mult}(\varepsilon_\tau) \\ &\quad + D_{Infer}(\varepsilon_\tau) + D_{Mult\_Infer}(\varepsilon_\tau) \end{aligned} \tag{14}$$

The output of EMLP discriminator includes four components: the direct signal component $D_{Direct}(\varepsilon_\tau)$, the multipath component $D_{Mult}(\varepsilon_\tau)$, the CW interference component $D_{Infer}(\varepsilon_\tau)$, and the combined component $D_{Mult\_Infer}(\varepsilon_\tau)$ of multipath and CW interference.

The direct signal component $D_{Direct}(\varepsilon_\tau)$ can be expressed as follow:

$$D_{Direct}(\varepsilon_\tau) = a_0^2 \left[R^2(\varepsilon_\tau - \frac{d}{2}) - R^2(\varepsilon_\tau + \frac{d}{2}) \right] \tag{15}$$

The direct signal component has relation to the amplitude of the direct signal a_0, the correlator spacing d, and the autocorrelation function of the navigation signal. The direct signal component is the output of EMLP discriminator without the effects of multipath and CW interference.

The multipath component $D_{Mult}(\varepsilon_\tau)$ can be expressed as follow:

$$\begin{aligned} D_{Mult\_EMLP}(\varepsilon_\tau) &= a_1^2 \left[R^2(\varepsilon_\tau - \hat{\tau}_1 - \frac{d}{2}) - R^2(\varepsilon_\tau - \hat{\tau}_1 + \frac{d}{2}) \right] \\ &\quad + 2a_0 a_1 \cos(\hat{\varphi}_1) \left[R(\varepsilon_\tau - \frac{d}{2}) R(\varepsilon_\tau - \hat{\tau}_1 - \frac{d}{2}) \right. \\ &\quad \left. - R(\varepsilon_\tau + \frac{d}{2}) R(\varepsilon_\tau - \hat{\tau}_1 + \frac{d}{2}) \right] \end{aligned} \tag{16}$$

In addition to the amplitude of the direct signal a_0, the correlator spacing d and the autocorrelation function of the navigation signal, equation (16) shows that the multipath component $D_{Mult}(\varepsilon_\tau)$ has relation to the amplitude a_1 of the reflected signal, the phase difference of the reflected signal and the direct signal, and the extra delay of the reflected signal with respect to the direct signal $\hat{\tau}_1$. When only multipath signal exists in the receiving environment, the output of EMLP discriminator is the sum of the multipath component $D_{Mult}(\varepsilon_\tau)$ and the direct signal component $D_{Direct}(\varepsilon_\tau)$.

The CW interference component $D_{Infer}(\varepsilon_\tau)$ can be expressed as follow:

$$\begin{aligned} D_{Infer}(\varepsilon_\tau) &= 2a_0 A_{cw} \cos(\alpha)\cos(\pi dn / N_c T_c) \\ &\quad \times \left[R(\varepsilon_\tau - \frac{d}{2}) - R(\varepsilon_\tau + \frac{d}{2}) \right] \\ &\quad + 2a_0 A_{cw} \sin(\alpha)\sin(\pi dn / N_c T_c) \\ &\quad \times \left[R(\varepsilon_\tau - \frac{d}{2}) + R(\varepsilon_\tau + \frac{d}{2}) \right] \end{aligned} \tag{17}$$

CW interference component $D_{Infer}(\varepsilon_\tau)$ has relation to the phase $\alpha = \varphi_l - \hat{\varphi}_0 + \beta + 2\pi(n / N_c T_c)\hat{\tau}_0$, the amplitude and the frequency of CW interference beside the amplitude of the direct signal a_0, the correlator spacing d and the autocorrelation function of the navigation signal. It is easy to know that the output of EMLP discriminator is the sum of the CW interference component $D_{Infer}(\varepsilon_\tau)$ and the direct signal component $D_{Direct}(\varepsilon_\tau)$ in the case that only CW interference exists in the receiving environment.

The combined component $D_{Mult\_Infer}(\varepsilon_\tau)$ of multipath and CW interference can be expressed as equation (18).

$$\begin{aligned} & D_{Mult\_Infer\_EMLP}(\varepsilon_\tau) \\ &= 2a_1 A_{cw} \cos(\hat{\varphi}_1 + \alpha)\cos(\pi dn / N_c T_c) \\ &\quad \times \left[R(\varepsilon_\tau - \hat{\tau}_1 - \frac{d}{2}) - R(\varepsilon_\tau - \hat{\tau}_1 + \frac{d}{2}) \right] \\ &\quad + 2a_1 A_{cw} \sin(\hat{\varphi}_1 + \alpha)\sin(\pi dn / N_c T_c) \\ &\quad \times \left[R(\varepsilon_\tau - \hat{\tau}_1 - \frac{d}{2}) + R(\varepsilon_\tau - \hat{\tau}_1 + \frac{d}{2}) \right] \end{aligned} \tag{18}$$

The combined component $D_{Mult\_Infer}(\varepsilon_\tau)$ has relation to not only the multipath factors but also the CW interference factors. Because of the combined component $D_{Mult\_Infer}(\varepsilon_\tau)$, the effects of multipath and CW interference are not independent.

The tracking error is usually small, so $D_{EMLP}(\varepsilon_\tau)$ can be linearly expressed as follow:

$$D_{EMLP}(\varepsilon_\tau) \approx D_{EMLP}(0) + \varepsilon_\tau D'_{EMLP}(0) \tag{19}$$

The tracking error ε_τ can be expressed as

$$\varepsilon_\tau = -\frac{D_{EMLP}(0)}{D'_{EMLP}(0)} \tag{20}$$

In order to simplify the mathematic derivation of the tracking error, some functions are defined as equations (21)-(24).

$$RA(\hat{\tau}_1, d) = R(\hat{\tau}_1 + \frac{d}{2}) + R(\hat{\tau}_1 - \frac{d}{2}) \quad (21)$$

$$RM(\hat{\tau}_1, d) = R(\hat{\tau}_1 - \frac{d}{2}) - R(\hat{\tau}_1 + \frac{d}{2}) \quad (22)$$

$$DRA(\hat{\tau}_1, d) = R^{'}(-\hat{\tau}_1 - \frac{d}{2}) + R^{'}(-\hat{\tau}_1 + \frac{d}{2}) \quad (23)$$

$$DRM(\hat{\tau}_1, d) = R^{'}(-\hat{\tau}_1 - \frac{d}{2}) - R^{'}(-\hat{\tau}_1 + \frac{d}{2}) \quad (24)$$

where $R^{'}(\tau)$ is the derivative of $R(\tau)$.

Substituting equations (14)-(18) into equation (20), the analytical expression of the code tracking error can be derived, which is denoted as equation (25):

$$\varepsilon_{EMLP}(\hat{\varphi}_1, \alpha) = \frac{\begin{bmatrix} a_1^2 RA(\hat{\tau}_1, d) RM(\hat{\tau}_1, d) + 2a_0 a_1 \cos(\hat{\varphi}_1) R(\frac{d}{2}) RM(\hat{\tau}_1, d) - 4a_0 A_{cw} \sin(\alpha) \sin(\pi dn / N_c T_c) R(\frac{d}{2}) \\ +2a_1 A_{cw} \cos(\hat{\varphi}_1 + \alpha) \cos(\pi dn / N_c T_c) RM(\hat{\tau}_1, d) - 2a_1 A_{cw} \sin(\hat{\varphi}_1 + \alpha) \sin(\pi dn / N_c T_c) RA(\hat{\tau}_1, d) \end{bmatrix}}{\begin{bmatrix} -4a_0^2 R(\frac{d}{2}) R^{'}(\frac{d}{2}) + a_1^2 \left[RA(\hat{\tau}_1, d) DRM(\hat{\tau}_1, d) - RM(\hat{\tau}_1, d) DRA(\hat{\tau}_1, d) \right] \\ +2a_0 a_1 \cos(\hat{\varphi}_1) \left[-R^{'}(\frac{d}{2}) RA(\hat{\tau}_1, d) + R(\frac{d}{2}) DRM(\hat{\tau}_1, d) \right] - 4a_0 A_{cw} \cos(\alpha) \cos(\pi dn / N_c T_c) R^{'}(\frac{d}{2}) \\ +2a_1 A_{cw} \cos(\hat{\varphi}_1 + \alpha) \cos(\pi dn / N_c T_c) DRM(\hat{\tau}_1, d) + 2a_1 A_{cw} \sin(\hat{\varphi}_1 + \alpha) \sin(\pi dn / N_c T_c) DRA(\hat{\tau}_1, d) \end{bmatrix}} \quad (25)$$

Equation (25) shows that the tracking error has relation to the phase α and the phase difference $\hat{\varphi}_1$. The phase difference $\hat{\varphi}_1$ depends on the carrier phase of the reflected signal, and the phase α has relation to the spectrum of the PRN code signal, the phase and the frequency of the CW interference. We can make use of the maximum and the minimum values of the tracking error to evaluate the effects of the reflected signal and the CW interference. The interference and multipath error envelope (IMEE) is defined as the maximum and the minimum values of the tracking error, which can be expressed as equation (26).

$$\varepsilon_{Envelope} = \begin{cases} Max\left[\varepsilon_{EMLP}(\hat{\varphi}_1, \alpha)\right] \\ Min\left[\varepsilon_{EMLP}(\hat{\varphi}_1, \alpha)\right] \end{cases} \quad (26)$$

Because the expression of the code tracking error includes not only the term $\cos(\hat{\varphi}_1)$, $\sin(\alpha)$ and $\cos(\alpha)$, but also $\cos(\hat{\varphi}_1 + \alpha)$ and $\sin(\hat{\varphi}_1 + \alpha)$, it is hard to obtain the analytical expression of IMEE. Fortunately, IMEE can be obtained by numerical methods for its evaluation.

4. Numerical Results

The IMEE expression shows that it depends on the extra delay of the reflected signal with respect to the direct signal, the frequency of CW interference, the correlator spacing, the amplitude ratio of the multipath signal and the direct signal (MDR), and the amplitude ratio of the direct signal and CW interference (SIR). The role of MDR and SIR is evident in the determination of the IMEE, so the effects of three other factors are analyzed in the following figures.

In the following analysis, we assumed that the received signal is the GPS L1 signal in which the PRN code is C/A code and the front-end bandwidth is 20.46MHz. The expression of $|C(n)|$ depends on the chip sequence and pulse shape. If the real chip sequence is taken into account, $|C(n)|$ fluctuates around the sinc(x) envelope. In order to show the IMEE clearly, the spectral lines are assumed to match the sinc(x) envelope exactly. The chipping rate Rc of C/A code is 1.023×10^6 chip/s, and the chip duration Tc is 1/Rc.

The effects of different frequencies of CW interference on the code tracking error are shown in **Figure 1**. The correlator spacing is 0.1 Tc, the amplitude ratio a_1/a_0 is -10 dB, and a_0/c_I is -15 dB. The path delays are respectively 7.5 m, 15 m, 30 m. The effect of CW interference on the code tracking error is fluctuating and decreasing with the frequency of CW interference. When the frequency of CW interference locates at half of the C/A code rate, the code tracking error reaches the worst value. When the frequency of CW interference is the integral multiple C/A code rate, the effect of CW interference on the code tracking error is negligible.

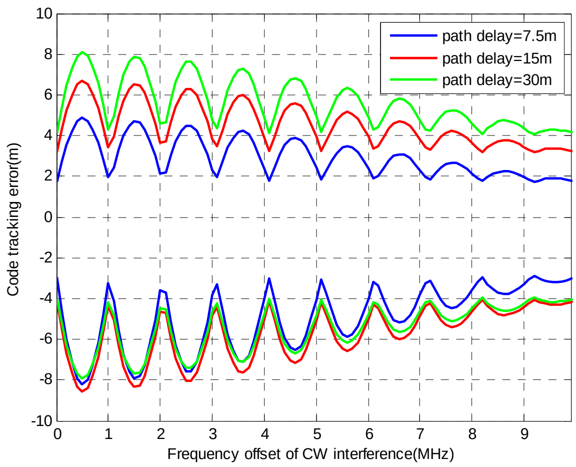

Figure 1. Code tracking error versus f_I.

The effects of different path delays on IMEE are shown in **Figure 2**. The correlator spacing is 0.1 Tc, the amplitude ratio a_1/a_0 is -10 dB, and a_0/c_l is -15 dB. The frequencies of CW interference are respectively 0MHz, 0.5 MHz, 1 MHz, 1.5 MHz. The impact of multipath on tracking error increases, when the time delay of multipath signal increases from 0m. However, when the IMEE reaches the corresponding value, around which IMEE fluctuates slightly. Since the chipping duration of C/A code is 1/Rc and the path delay of 1 Tc is approximately 293 m. When the time delay of multipath is larger than 293 m, the multipath effect is suppressed due to the autocorrelation of C/A code.

The effects of the correlator spacing on the code tracking error are shown in **Figure 3** and **Figure 4**. The amplitude ratio a_1/a_0 is -10 dB, a_0/c_l is -15 dB, and the correlator spacing are respectively 0.1 Tc, 0.3 Tc, and 0.5 Tc.

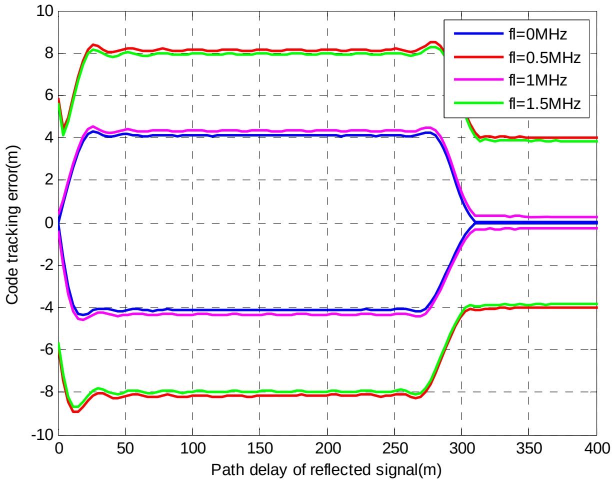

Figure 2. Code tracking error versus the path delay.

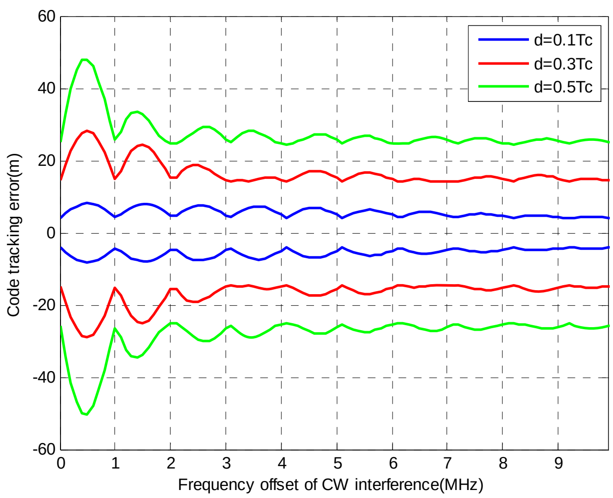

Figure 3. Code tracking error versus f_l with different correlator spacings.

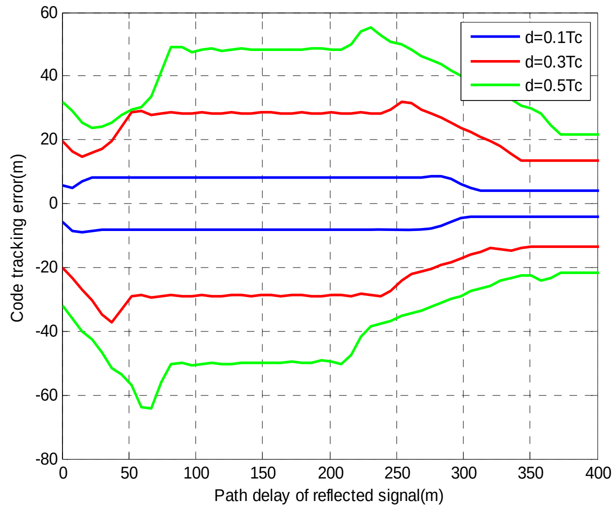

Figure 4. Code tracking error versus the path delay of the reflected signal with different correlator spacings.

5. Conclusions

The effects of CW interference and multipath on EMLP discriminator are analyzed in this paper. In the analysis, an analytical expression of the code tracking error is suggested for the EMLP discriminator, and it can be used to assess the combined effect of multipath and CW interference. The analytical expression of the code tracking error shows that the code tracking performance can be improved by shortening the correlator spacing for the receiver. Further, the analytical expression shows that the combined effects of CW interference and multipath on code tracking performance depend on many factors. When the frequency of CW interference locates at integral times of PRN code rate, the CW interference can be suppressed. When the frequency of CW interference is the sum of half of the C/A code rate and integral times of PRN code rate, the code tracking error reaches the worst value. The effects of multipath on EMLP increases as the time delay of the reflected signal increases, and then it fluctuates with a value until the time delay is larger than the sum of half of the correlator spacing and the chipping duration. When the time delay is larger than the sum of half of the correlator spacing and the chipping duration, the effect of multipath is suppressed by the code tracking loop.

6. Acknowledgements

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