An Efficient Method for GPS Multipath Mitigation Using the Teager-Kaiser-Operator-Based MEDLL

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Abstract. *An efficient method for GPS multipath mitigation is proposed. The motivation for this proposed method is to integrate the Teager-Kaiser Operator (TKO) with the Multipath Estimating Delay Lock Loop (MEDLL) module to mitigate the GPS multipath efficiently. The general implementation process of the proposed method is that we first utilize the TKO to operate on the received signal's Auto-Correlation Function (ACF) to get an initial estimate of the multipaths. Then we transfer the initial estimated results to the MEDLL module for a further estimation. Finally, with a few iterations which are less than those of the original MEDLL algorithm, we can get a more accurate estimate of the Line-Of-Sight (LOS) signal, and thus the goal of the GPS multipath mitigation is achieved. The simulation results show that compared to the original MEDLL algorithm, the proposed method can reduce the computation load and the hardware and/or software consumption of the MEDLL module, meanwhile, without decreasing the algorithm accuracy.*

Keywords

GPS, multipath mitigation, TKO-MEDLL, LOS time delay estimation.

1. Introduction

The factors that affect modern Global Positioning System (GPS) receivers to achieve high accurate pseudo-range measurement have been greatly improved. These factors include the frequency drift of the satellite atomic clock and that of the receiver oscillator, time delay error caused by the ionosphere and the troposphere, and the phase center deviation of the receiver antenna and so on. But for the multipaths which originate from the reflection or diffraction of the surroundings around the receiver, it is hard to cancel or remove them by the mathematical modeling or by the Differential GPS (DGPS) method [1], since the surroundings may change quickly and unpredictably. At the same time, the multipath may cause a significant distortion to the ACF's shape, which will accordingly affect the LOS signal time delay estimation and hence the pseudo-range measurement [2]. For these reasons, now it has become a fairly important work to mitigate the multipath of the receiver as much as possible.

In order to mitigate the GPS multipath efficiently, many new approaches have now been presented, and some of them have got widely used in GPS receivers. At the receiving end, according to the place where the multipath is mitigated, the GPS multipath mitigation methods can be roughly categorized into two types: the front-end methods and the back-end methods. For the first type, the multipaths are mitigated at the receiver's antenna. The techniques such as the choke ring antenna [3] and the multi-antenna array [4] are typical of this kind. For the second type, the multipaths are mitigated by processing on the received signal's ACF in the receiver. Based on the number of the correlators used in the receiver, this type can be further classified into two kinds [5]: (a) the conventional techniques such as the narrow Early-Minus-Late (nEML) estimator [6], [7], the Double Delta estimator (ΔΔ) [8] including the High Resolution Correlator (HRC) [9], [10] and the Multiple Gate Delay (MGD) estimator [11], [12] and so on; (b) the advanced techniques such as the Multipath Estimating Delay Lock Loop (MEDLL) technique [5],[13], the Fast Iterative Maximum Likelihood Algorithm (FILMA) [14], the TKO [15], [16] and so on. For this kind of (b), they often use more correlators than those in (a). Besides the techniques mentioned above, the post-processing techniques are also now becoming an important part of the GPS multipath mitigation methods, and these techniques include Wavelet Filter (WF) [17], Adaptive Filter (AF) [18] and so on.

Among the techniques mentioned above, the MEDLL can often get higher accuracy compared with the other techniques, and now has been applied into some advanced GPS receivers [19]. But its high computation load and more hardware and/or software consumption have limited its further applications in conventional GPS receivers [5], [20]. Contrarily, for the TKO, it can offer a simple and efficient estimation of the GPS multipath, moreover, it does not require a high hardware and/or software consumption as the MEDLL does [21], but the Signal-to-Noise Ratio (SNR) and the limited bandwidth are the two limiting factors for its estimate accuracy [7].

The proposed GPS multipath mitigation method, which integrates the Teager-Kaiser Operator with the MEDLL algorithm (TKO-MEDLL), is just for reducing the high computation load and the resources consumption of the MEDLL algorithm, meanwhile, without decreasing the algorithm accuracy. The general implementation process of the TKO-MEDLL is that first we utilize the TKO to get an initial estimate of the multipaths including the path numbers, the time delays, and the amplitudes and so on. Then we transfer these initial estimated results to the MEDLL module for a further estimation. Finally, with a few iterations which are less than those of the original MEDLL algorithm, we can get a more accurate estimate of the LOS signal, and thus the goal of GPS multipath mitigation is achieved.

The rest of this paper is organized as follows. In Section 2, a received signal model is given. In Section 3, the TKO and the MEDLL algorithm are briefly described. Section 4 presents the principle of the proposed TKO-MEDLL and its detailed algorithm implementation, followed by the performance simulations and comparisons of the TKO-MEDLL and the MEDLL in Section 5. Finally, the paper is concluded in Section 6.

2. Signal Model

The received signal of the GPS receiver after down-conversion can be written as

$$r(t)=\sum_{i=0}^{M}a_i d(t-\tau_i)c(t-\tau_i)e^{j(2\pi f_{IF}t+\phi_i)}+n(t) \tag{1}$$

where the subscript $i=0$ denotes the LOS signal, and $1\le i\le M$ denote the Non-LOS (NLOS) signals, a_i, τ_i and ϕ_i are the ith multipath normalized amplitude, time delay and carrier phase respectively, $d(t)$ is the navigation data bit and $c(t)$ is the GPS Coarse/Acquisition (C/A) code with the value of +1 or -1, f_{IF} is the intermediate frequency (IF) containing the Doppler frequency shift, and $n(t)$ is supposed to be the additive noise incorporating all sources of interferences over the channel.

In (1), since the data bit $d(t)\in\{+1,-1\}$ and its duration (20 ms) is far longer than that of C/A code (977.5 ns), its effect on the received signal can be attributed to ϕ_i, thus we can neglect $d(t)$ in (1). At the same time, we can correlate $r(t)$ with the local replica $c(t-\tau)e^{-j2\pi f_{IF}t}$, suppose that $r(t)$ is tracked perfectly by the Phase Locked Loop (PLL) of the receiver and that the initial phase of local generated carrier equals 0, then the received signal's ACF can be written as

$$R_x(\tau)=\sum_{i=0}^{M}a_i R(\tau-\tau_i)e^{j\phi_i}+N(\tau) \tag{2}$$

where τ is the local C/A code time delay or phase, $N(\tau)=\left[\int_0^{LT_c} n(t)c(t-\tau)e^{-j2\pi f_{IF}t}dt\right]\Big/LT_C$ is the correlation function of C/A code with the noise, $R(\tau-\tau_i)=\left[\int_0^{LT_c} c(t-\tau_i)c(t-\tau)dt\right]\Big/LT_C$ is the normalized ACF of C/A code, and its ideal result is

$$R(\tau-\tau_i)=\begin{cases}1-\dfrac{|\tau-\tau_i|}{T_c}, & |\tau-\tau_i|\le T_c\\ 0, & \text{elsewhere}\end{cases} \tag{3}$$

where T_c is the C/A code interval and L is the accumulation time expressed in the multiples of T_c.

In (2), the estimate of the received signal's ACF corresponding to $R_x(\tau)$ is

$$R_M(\tau)=\sum_{i=0}^{M}a_i R(\tau-\tau_i)e^{j\phi_i}. \tag{4}$$

For the convenience of our study, we make two hypotheses on (4) as follows.

(i) The propagation time of the NLOS signal is longer than that of the LOS signal, that is, $\tau_i>\tau_0$ for all $i=1,2,\cdots,M$.

(ii) The amplitude attenuation of the NLOS signal is heavier than that of the LOS signal. Though in some special occasions such as indoors or in an LOS signal sheltered environment, this result may get reversed, but for these special cases, the multipath mitigation cannot be solved solely by the algorithm, it needs some other means for assistance, and it is out of the scope of this paper. Based on this point, if we set $a_0=1$, we can get $0<a_i<1$ for all $i=1,2,\cdots,M$.

3. TKO and MEDLL Algorithm

3.1 TKO

TKO is a non-linear quadratic operator initially used for measuring the instantaneous-varying signal's energy, and it can also be used for the GPS multipath mitigation [15]. For a continuous-time complex signal $x(t)$, its TKO can be written as [22]

$$\psi_c[x(t)]=\frac{dx(t)}{dt}\frac{dx^*(t)}{dt}-\frac{1}{2}\left[\frac{d^2x(t)}{dt^2}x^*(t)+x(t)\frac{d^2x^*(t)}{dt^2}\right] \tag{5}$$

where $x^*(t)$ is the complex conjugate of $x(t)$.

The discrete-time TKO of (5) can be written as [21]

$$\psi_c\left[x(n)\right]=x(n)x^*(n)-\frac{1}{2}\left[\begin{matrix}x(n-1)x^*(n+1)+\\x(n+1)x^*(n-1)\end{matrix}\right]. \tag{6}$$

In (5), if we replace $x(t)$ with $R_x(\tau)$ given in (4), then we can obtain

$$\begin{aligned}&\psi_c[R_x(\tau)]=\\&\frac{1}{T_c^2}\left[\begin{matrix}\left(\sum_{i=0}^{M}a_i\cos(\phi_i)\operatorname{sign}(\tau-\tau_i)\Pi(\tau-\tau_i,T_c)\right)^2\\+\left(\sum_{i=0}^{M}a_i\sin(\phi_i)\operatorname{sign}(\tau-\tau_i)\Pi(\tau-\tau_i,T_c)\right)^2\end{matrix}\right]\\&+\frac{1}{2T_c}\left[\begin{matrix}R_x^*(\tau)\left(\sum_{i=0}^{M}a_i\delta(\tau-\tau_i)e^{j\phi_i}\right)\\+R_x(\tau)\left(\sum_{i=0}^{M}a_i\delta(\tau-\tau_i)e^{-j\phi_i}\right)\end{matrix}\right]+\Delta_n'(\tau)\end{aligned} \tag{7}$$

where sign(t) is the sign function, $\delta(t)$ is the impulse Dirac function, $\Delta_n'(\tau)$ is the result of $\psi_c(\cdot)$ operating on the component $\Delta_n(\tau)$, and $\Pi(t,T_c)$ is the rectangle pulse function with time interval T_c.

From (7) we can see that the TKO of $R_x(\tau)$ is sensitive to the time delay of the multipath component, besides, it can also offer us a good estimation of the multipath amplitude which has a moderate or high strength when SNR is high, as can be clearly seen in Fig. 1.

3.2 MEDLL Algorithm

The MEDLL algorithm is a Most-Likelihood (ML) estimation method for GPS multipath mitigation. For $R_x(\tau)$ given in (2), the estimates of the ith multipath based on the MEDLL algorithm can be given as [13]

$$\hat{\tau}_i=\max_{\tau}\Re\left[\left(R_x(\tau)-\sum_{\substack{m=0\\m\neq i}}^{N}\hat{a}_mR(\tau-\hat{\tau}_m)e^{j\hat{\phi}_m}\right)e^{-j\hat{\phi}_i}\right], \tag{8}$$

$$\hat{a}_i=\Re\left[\left(R_x(\hat{\tau}_i)-\sum_{\substack{m=0\\m\neq i}}^{N}\hat{a}_mR(\hat{\tau}_i-\hat{\tau}_m)e^{j\hat{\phi}_m}\right)e^{-j\hat{\phi}_i}\right], \tag{9}$$

$$\hat{\phi}_i=\arg\left(R_x(\hat{\tau}_i)-\sum_{\substack{m=0\\m\neq i}}^{N}\hat{a}_mR(\hat{\tau}_i-\hat{\tau}_m)e^{j\hat{\phi}_m}\right). \tag{10}$$

where N is the estimated multipath numbers, and the notation $\Re(\cdot)$ means to take the real part of a complex value.

The general steps of the MEDLL algorithm are as follows [23].

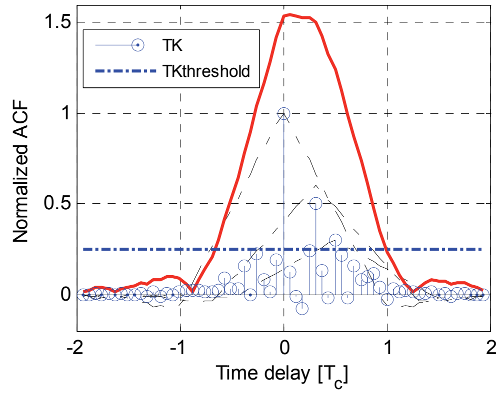
(a) Find the highest peak of $R_x(\tau)$ and regard it as the peak of the LOS ACF, then estimate the peak parameters and get the estimated ACF of the LOS.

(b) Remove the estimated LOS ACF from $R_x(\tau)$ and find the highest peak of the residual signal and take it as the second path peak, then estimate its corresponding parameters and get the estimated ACF of the second path.

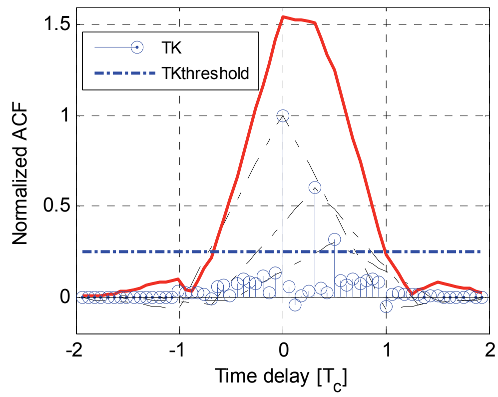
(c) Repeat the process similarly as in step (b) until all N NLOS paths are estimated or a termination condition is met.

(d) Based on the estimates of N NLOS paths, remove them from $R_x(\tau)$ and utilize the residual of $R_x(\tau)$ to estimate the LOS again as in (a).

In most cases, the whole process above may need many times of iterations so that a more accurate estimation of each multipath can finally be got.



(a)



(b)

Fig. 1. Simulation results of the TKO on the received signal's ACF with different SNR. The normalized amplitudes and the respective time delays of the multipaths are set to [1, 0.6, 0.3] and [0, 0.3, 0.5]T_c, their incident angles are all set to 0°. The accumulation time of ACF is set to 1 ms and the SNR in each simulation is set to (a) SNR = -10 dB, and (b) SNR = 0 dB. The "TKthreshold" in the figure is a threshold used for limiting the effect of the noise on the TKO estimation.

4. TKO-MEDLL Algorithm

4.1 Principle of the TKO-MEDLL

From the implementation of the MEDLL algorithm we can see that it is an extremely time and resources consuming process, because there is not any prior knowledge of the multipath components. On the other hand, if we can offer some prior information of the multipaths such as the path numbers, the initial amplitude estimates and/or the initial time delay estimates for the algorithm, then we can speed up the iteration process and improve the algorithm's efficiency.

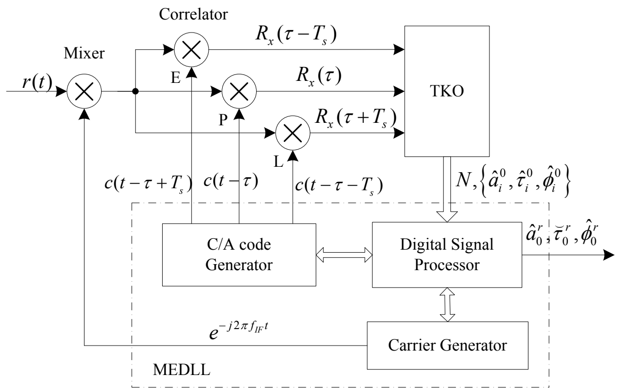


Fig. 2. Principle block diagram of the TKO-MEDLL. The E, P and L denote the Early correlator, the Prompt correlator and the Late correlator respectively, and T_s is the sample interval.

Given this consideration, the proposed TKO-MEDLL algorithm is just to utilize the TKO to get an initial estimate of the path numbers N and the corresponding estimates $(\hat{a}_i^0,\hat{\tau}_i^0,\hat{\phi}_i^0)$ of each multipath (the detailed meaning of the superscript and subscript can be referred to in the subsequent Subsection 4.2). Then these initial estimated results are transferred to the subsequent MEDLL module so that a further estimation of the acquired multipaths can be got. Finally after several iterations, more accurate estimates $(\hat{a}_0^r,\tilde{\tau}_0^r,\hat{\phi}_0^r)$ of the LOS signal can be obtained from the final estimated results. The principle block diagram of the proposed TKO-MEDLL is shown in Fig. 2.

4.2 Implementation of the TKO-MEDLL Algorithm

According to Fig. 2, a detailed implementation process of the proposed TKO-MEDLL algorithm can be given as follows.

Step 1. First in (6), substitute $x(n)$ with the discrete ACF $R_x(n)$ to get an initial estimate of each multipath. In fact, $\hat{a}_i^0$ and $\hat{\tau}_i^0$ are just the amplitude and the corresponding time delay of the competitive peak of TKO operating on $R_x(n)$ [7], so we can obtain them by finding the competitive peak of TKO operating result; for $\hat{\phi}_i^0$, after we get $\hat{a}_i^0$ and $\hat{\tau}_i^0$, it can be directly obtained by (10), here $\hat{\phi}_0^0$ for the LOS signal is regarded as 0. Then, from the estimated results, choose those whose amplitudes exceed the preset TKO threshold. After that, sort the chosen multipaths in descending order and select the first N competitive peaks for the subsequent further estimation, here N is the number preset in advance. If N is larger than the actual path numbers got by the TKO, let N equal the actual path numbers.

Step 2. Take the amplitudes, the time delays and the carrier phases of the N estimated multipaths into (4) to get their respective estimated ACFs. Then the estimated ACF of the ith multipath can be written as

$$R_i^0(\tau)=\hat{a}_i^0 R(\tau-\hat{\tau}_i^0)\exp(j\hat{\phi}_i^0) \tag{11}$$

where the subscript i denotes the ith estimated multipath, $i\in\{0,1,2,\cdots,N\}$. Here $i=0$ is for the LOS signal and $1\le i\le N$ are for the NLOS signals. The superscript denotes the iteration times, and it means the initial TKO estimation when its value equals 0.

Step 3. Transfer the initial TKO estimated results to the MEDLL module to perform a more accurate estimation on each path. For the ith multipath, its primary MEDLL estimates can be written as follows based on (8) to (10),

$$\begin{cases}\hat{\tau}_i^1=\max\limits_{\tau}\Re\left[R_i^0(\tau)\exp(-j\hat{\phi}_i^1)\right],\\ \hat{a}_i^1=\Re\left[R_i^0(\hat{\tau}_i^1)\exp(-j\hat{\phi}_i^1)\right],\\ \hat{\phi}_i^1=\arg[R_i^0(\hat{\tau}_i^1)].\end{cases} \tag{12}$$

Due to the parameters in (12) coupling each other, it is hard to get their analytical results, and their practical implementations are often got by the iteration method which can be given as follows.

(a) Based on the previous $i-1$ estimated multipaths ($1\le i\le N$), get the residual signal of $R_x(\tau)$ and its energy according to the following formulas:

$$v_i^1(\tau)=R_x(\tau)-\sum_{k=0}^{i-1}R_k^0(\tau)=R_x(\tau)-\sum_{k=0}^{i-1}\hat{a}_k^0R(\tau-\hat{\tau}_k^0)\exp(j\hat{\phi}_k^0), \tag{13}$$

$$E_i^1=\frac{1}{T}\int_0^T\left|v_i^1(\tau)\right|^2d\tau. \tag{14}$$

(b) Based on the $v_i^1(\tau)$ given in (13), get the estimates of time delay, phase and amplitude of the ith multipath according to the formulas given as follows [23]:

$$\hat{\tau}_i^1=\max_{\tau}\left\{\left[\Re\left(v_i^1(\tau)\right)\right]^2+\left[\Im\left(v_i^1(\tau)\right)\right]^2\right\}, \tag{15}$$

$$\hat{\phi}_i^1=\begin{cases}\operatorname{atan}\left[\dfrac{\Im\left(v_i^1(\hat{\tau}_i^1)\right)}{\Re\left(v_i^1(\hat{\tau}_i^1)\right)}\right], & if\ \Re\left(v_i^1(\hat{\tau}_i^1)\right)>0\\ \operatorname{atan}\left[\dfrac{\Im\left(v_i^1(\hat{\tau}_i^1)\right)}{\Re\left(v_i^1(\hat{\tau}_i^1)\right)}\right]+\pi, & if\ \Re\left(v_i^1(\hat{\tau}_i^1)\right)<0\\ \pi/2, & if\ \Re\left(v_i^1(\hat{\tau}_i^1)\right)=0\ and\ \Im\left(v_i^1(\hat{\tau}_i^1)\right)>0\\ -\pi/2, & if\ \Re\left(v_i^1(\hat{\tau}_i^1)\right)=0\ and\ \Im\left(v_i^1(\hat{\tau}_i^1)\right)<0\ ,\end{cases} \tag{16}$$

$$\hat{a}_i^1 = \Re\left[v_i^1(\hat{\tau}_i^1)\exp(-j\hat{\phi}_i^1) \right] \tag{17}$$

where atan(t) is the arctangent function, and the notation $\Im(\cdot)$ means to take the image part of a complex value.

(c) Remove the phase rotation from $v_i^1(\tau)$, that is,

$$\bar{v}_i^1(\tau) = \Re\left[v_i^1(\tau) \right]\cos\hat{\phi}_i^1 + \Im\left[v_i^1(\tau) \right]\sin\hat{\phi}_i^1. \tag{18}$$

Then for a given peak delay τ_0, the normalized C/A code phase discriminating function can be given as [1], [23]

$$D(\varepsilon_i) = \frac{\bar{v}_i^1(\tau_0 - \varepsilon_i - \frac{d}{2}) - \bar{v}_i^1(\tau_0 - \varepsilon_i + \frac{d}{2})}{\left|\bar{v}_i^1(\tau_0 - \varepsilon_i - \frac{d}{2})\right| + \left|\bar{v}_i^1(\tau_0 - \varepsilon_i + \frac{d}{2})\right|} \tag{19}$$

where d is the correlator spacing of E and L of the MEDLL discriminator, $D(\varepsilon_i)$ is a function of the discriminating error ε_i and it takes the monotonic part of the right term of (19) around τ_0.

Based on the $\hat{\tau}_i^1$ given in (15), we can get $\bar{v}_i^1(\hat{\tau}_i^1 - d/2)$ and $\bar{v}_i^1(\hat{\tau}_i^1 + d/2)$ from (18), where $\hat{\tau}_i^1 = \breve{\tau}_i^1 - \varepsilon_i^1$ and $\breve{\tau}_i^1$ is the ideal or theoretical value of $\hat{\tau}_i^1$. Take them into (19), we can get the corresponding result $D(\varepsilon_i^1)$.

(d) Since $D(\varepsilon_i)$ in (19) is a monotonic function, we can get ε_i from the inverse function of $D(\varepsilon_i)$, that is, we can get ε_i^1 by the value $D(\varepsilon_i^1)$. Then the time delay of the ith multipath can be updated as

$$\breve{\tau}_i^1 = \hat{\tau}_i^1 + \varepsilon_i^1. \tag{20}$$

(e) Recalculate the residual signal and the residual energy of $R_x(\tau)$ as in (a) for the subsequent (i+1)th multipath estimation.

Step 4. Repeat the process of *Step 3* until all the N multipaths are estimated. At the same time, compare E_N^1 with the preset energy residual E_{th} to determine whether the process is terminated. If $E_N^1 > E_{th}$, take the N estimated results above into the MEDLL module again for the next iteration as in *Step* 3. Repeat this iteration process until the final termination condition $E_N^r \le E_{th}$ ($r \ge 1$) is met, here r is the iteration times.

Step 5. Choose the first multipath estimated results ($\hat{a}_0^r, \hat{\tau}_0^r, \hat{\phi}_0^r, \varepsilon_0^r$) or ($\hat{a}_0^r, \breve{\tau}_0^r, \hat{\phi}_0^r$) as the estimates of the LOS signal and output them for the further GPS ranging or for other purposes.

5. Simulation Results and the Discussions

To verify the performance of the proposed method, simulations of the TKO-MEDLL algorithm and the corresponding MEDLL algorithm used for comparison are conducted. In Subsection 5.1, simulations with different multipath setups are offered. In Subsection 5.2, simulations on the LOS time delay estimation with the varying second path time delay are provided. In Subsection 5.3, simulations on the LOS time delay estimation with the varying SNR are supplied.

The common parameter setups used in following simulations are as follows.

- TKO threshold is set to 0.25 (normalized) according to the reference [7] for the GPS BPSK modulation.
- The number of competitive peaks is chosen to be 5 [7].
- C/A code accumulation time is set to 5 ms for gaining a higher SNR.
- Sample frequency $f_s = 1/T_s$ is set to 16.36328 MHz.
- The correlator spacing of E and L is set to 0.2 T_c.
- The valid time range of the received signal's ACF is limited to [-2, 2] T_c, which takes the ideal LOS time delay as the center. Here T_c. is the C/A code interval and T_c.= 1/1.023 μs $\approx$ 977.5 ns.

Based on the setups given above, if we take the start of the ACF valid time range as the time origin, we can easily get the ideal LOS time delay relative to the time origin is $2T_c$, or $16.36328 \times 2 \div 1.023 \approx 31.99077$ expressed in samples. We will take this theoretical value as the performance comparison criterion in the following simulations.

5.1 Performance Simulations with Different Multipath Setups

For simplicity, here we only present two scenarios for verification. According to the setups given in Tab. 1, the simulation results of the TKO-MEDLL and the corresponding MEDLL are shown in Figs. 3 and 4. In the simulations, for the convenience of comparison, we give the estimated LOS time delay expressed in samples.

Paths	Amplitudes (normalized)	Time delays (in chip)	Incident angles (in rad)
2	[1, 0.5]	[0, 0.3]	[0, $\pi/4$]
3	[1, 0.6, 0.4]	[0, 0.2, 0.5]	[0, $\pi/6$, $\pi/5$]

Tab. 1. Multipath setups for different scenarios.

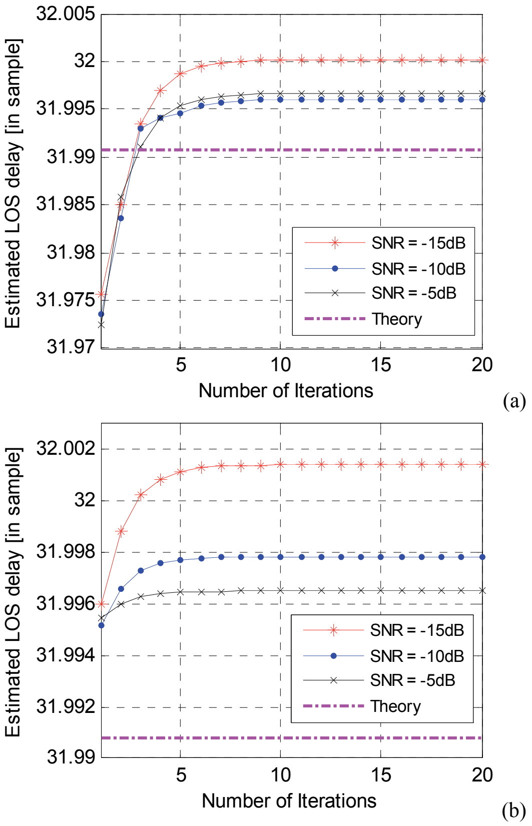


Fig. 3. Simulation results of 2 paths scenario of (a) MEDLL and (b) TKO-MEDLL under the conditions of different SNR.

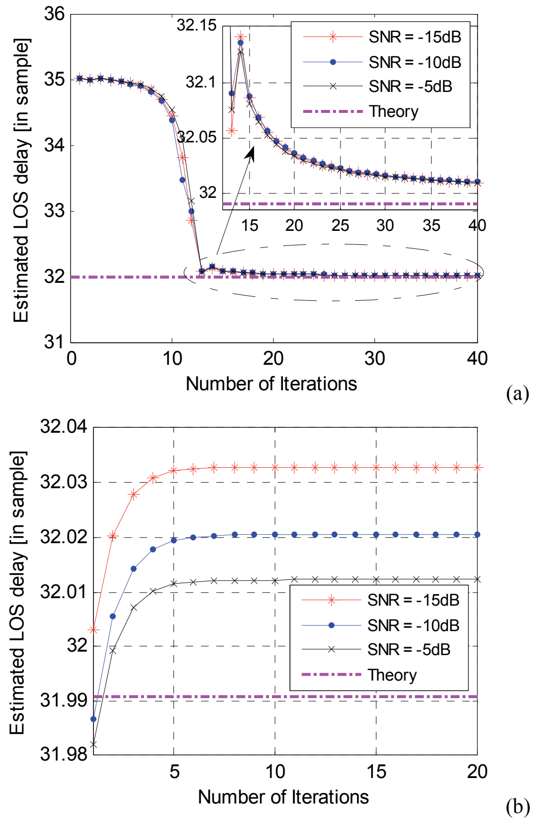


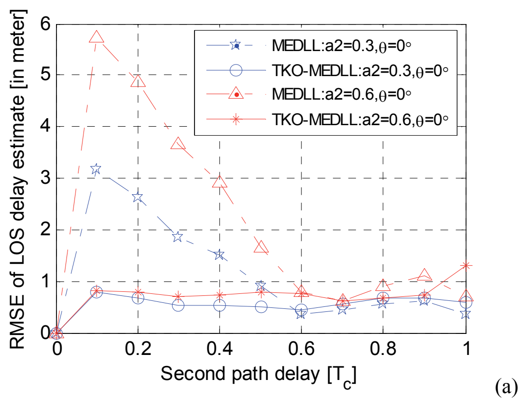
Fig. 4. Simulation results of 3 paths scenario of (a) MEDLL and (b) TKO-MEDLL under the conditions of different SNR.

Based on the simulation results shown in Figs. 3 and 4, we can get 2 points. (1) The iterations of the MEDLL algorithm before converging to the final stable value will increase with the increasing of the multipath components. For example, in Fig. 3(a), there are about 8 iterations, while for the 3 paths scenario shown in Fig.4(a), the iterations will increase to about 35. At the same time, when there are more multipaths with the similar strength, there may give rise to a slight oscillation before the algorithm converges to the final stable LOS time delay, as can be seen in Fig. 4(a). While for the TKO-MEDLL algorithm, as shown in Figs. 3(b) and 4(b), it needs only about 10 iterations at most before converging to the stable LOS time delay estimate, the efficiency of the TKO-MEDLL improves about 4 times than that of the MEDLL in the case of 3 paths. (2) The accuracy of both algorithms will decrease with the decreasing of SNR, as can also be seen in Figs. 3 and 4. This is because that at low SNR, the received signal's ACF becomes more irregular and this will decrease the estimate accuracy of the multipath.

But there is also a limitation on the TKO-MEDLL just as that mentioned in Subsection 3.1, it is sensitive to the SNR, the final result of the TKO-MEDLL is slightly less accurate than that of the MEDLL when SNR is low, as can be seen in both Figs. 3 and 4. For this problem, it can be improved by increasing the accumulation time of the incoming signal's ACF.

5.2 Effect of the Second Path Time Delay on the LOS Time Delay Estimation

The simulation setup for this scheme is that we change the second path time delay within the scope of one chip to calculate the Root-Mean-Square discriminating error (RMSE) of the LOS time delay estimate. Besides, we carry out the simulations according to the different SNR and the different second multipath amplitude, and we repeat the simulation 100 times at each given second path time delay. For simplicity, here we only present two cases of the simulation results corresponding to SNR = -15 dB and SNR = -5 dB which are shown as in Fig. 5.



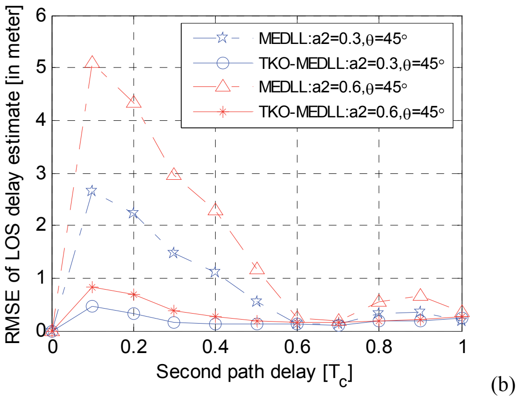


Fig. 5. RMSE simulations of the LOS time delay estimation with the varying second path time delay. The value of a2 in the legend box is the normalized second path amplitude, and the θ followed it is the corresponding incident angle. The correlaotr spacing of E and L in both simulations is set to $0.2T_c$, and the SNR is set to (a) SNR = -15 dB , and (b) SNR = -5 dB , respectively.

From the simulation results we can get 3 points. (**1**) For the same SNR and the same second multipath amplitude, the TKO-MEDLL shows a more superior performance in mitigating the short time delay multipath than that of the MEDLL under the same conditions. For example, in Fig. 5(a), for $a2 = 0.3$, the performance of the TKO-MEDLL outperforms that of the MEDLL about 4 times for the maximum RMSE and this result becomes about 6 times when $a2 = 0.6$, there are also the similar results in Fig. 5(b). When the time delay of the second multipath is more than about $0.6T_c$, both algorithms almost have the same performance, as can be seen either in Fig. 5(a) or in Fig. 5(b). (**2**) For the same SNR, the RMSE performances of both algorithms will deteriorate with the increasing of the second multipath amplitude. But for the TKO-MEDLL, the effect of the second multipath amplitude is not as dramatic as that of the MEDLL for the short time delay multipath. For example, in Fig. 5(a), when a2 changes from 0.3 to 0.6, the maximum RMSE of TKO-MEDLL almost remains unchanged, while for the MEDLL, its maximum RMSE nearly doubles, in Fig. 5(b) we can also get the similar results. When the second multipath time delay is more than about $0.6T_c$, both algorithms are not sensitive to the second multipath amplitude. (**3**) The SNR also has an important effect on both algorithms, as will be shown in detail in the following Subsection 5.3.

5.3 Effect of SNR on the LOS Time Delay Estimation

The simulation setup for this scheme is that we fix the second path time delay and change the SNR within a given scope to calculate the RMSE of the LOS time delay estimate. Besides, we change the second path amplitude for more evaluations and repeat the simulation 100 times at each given SNR. For the same reason of simplicity, we only present two cases of the simulation results corresponding to the second path time delay $\tau = 0.4\ T_c$ and $\tau = 0.6\ T_c$. The simulation results are shown as in Fig. 6.

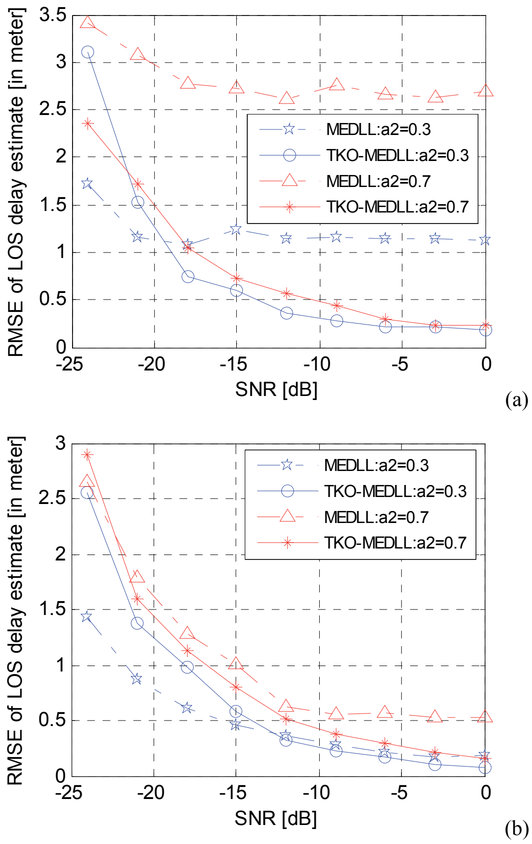


Fig. 6. RMSE simulations of the LOS time delay estimation with the varying SNR. The value of a2 in the legend box is the normalized amplitude of the second path. The correlaotr spacing of E and L in both simulations is set to $0.2T_c$, and the second path time delay is set to (a) $\tau = 0.4T_c$, and (b) $\tau = 0.6T_c$, respectively.

From the simulation results we can also get 3 points. (1) For both the TKO-MEDLL and the MEDLL, the LOS time delay estimate will become more accurate with the increasing of SNR, as can be clearly seen from Fig. 6. (2) For both the TKO-MEDLL and the MEDLL, the RMSE of the LOS time delay estimate will rise with the increasing of the second multipath amplitude, but the effect of the second multipath amplitude on the TKO-MEDLL is not as dramatic as it on the MEDLL, as can also be seen in Figs. 6. (3) Under the conditions of the same SNR and the same a2, for the short time delay multipath, as shown in Fig. 6(a), the TKO-MEDLL will outperform the MEDLL when SNR is high, but for the low SNR, for example, SNR is under -20 dB, the result will be reversed. While for the medium or long time delay multipath, as shown in Fig. 6(b), the TKO-MEDLL has approximately the same performance as the MEDLL when SNR is high. Conversely, when SNR is low, the TKO-MEDLL will show a poor performance, especially when a2 is relatively small, and this can be explained by that the TKO is more susceptible to the noise when SNR is low.

6. Conclusions

In this paper we present an improved MEDLL algorithm by integrating with the TKO to mitigate the GPS multipath efficiently. By the comparisons of the two algorithms in computation efficiency and RMSE performance of LOS time delay estimate, we can get that the proposed TKO-MEDLL outperforms the MEDLL when SNR is high. In fact, we can gain a higher SNR by increasing the coherent and non-coherent accumulation time of the received signal's ACF as long as possible. Based on these results, we can conclude that the TKO-MEDLL is more preferable to the MEDLL in GPS multipath mitigation applications.

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References

[1] KAPLAN, E. D., HEGARTY, C. J. *Understanding GPS: Principles and Applications*. 2nd ed. Norwood: Artech House, 2006.

[2] CHEN, H. H., JIA, W. M., YAO, M. L. Cross-correlation-function-based multipath mitigation method for Sine-BOC signals. *Radioengineering,* 2012, vol. 21, no. 2, p. 659 - 665.

[3] TRANQUILLA, J. M., CARR, J. P., AI-RIZZO, H. M. Analysis of a choke ring ground plane for multipath control in global positioning system applications. *IEEE Transactions on Antennas and Propagation,* 1994, vol. 42, no. 7, p. 905 - 911.

[4] DANESHMAND, S., BROUMANDAN, A., NIELSEN, J, LACHAPELLE, G. Interference and multipath mitigation utilising a two-stage beamformer for global navigation satellite systems applications. *IET Radar, Sonar and Navigation,* 2013, vol. 7, no. 1, p. 55 - 66.

[5] BHUIYAN, M. Z. H., LOHAN, E. S. Advanced multipath mitigation techniques for satellite-based positioning applications. *International Journal of Navigation and Observation,* 2010, article ID 412393, p. 1 - 15.

[6] VAN DIERENDONCK, K. J., FENTON, P. C., FORD, T. J. Theory and performance of narrow correlator spacing in a GPS receiver. *Journal of the Institute of Navigation,* 1992, vol. 39, no. 3, p. 265 - 283.

[7] BHUIYAN, M. Z. H., LOHAN, E. S., RENFORS, M. Code tracking algorithms for mitigating multipath effects in fading channels for satellite-based positioning. *EURASIP Journal on Advances in Signal Processing,* 2008, article ID 863629, p. 1 -17.

[8] IRSIGLER, M., EISSFELLER, B. Comparison of multipath mitigation techniques with consideration of future signal structures. In *Proceedings of the 16th International Technical Meeting of the Institute of Navigation*. Portland (USA), 2003, p. 2584 - 2592.

[9] MCGRAW, A., BRAASCH, M. GNSS multipath mitigation using gated and high resolution correlator concepts. In *Proceedings of the 1999 National Technical Meeting of the Institute of Navigation*. San Diego (USA), 1999, p. 333 - 342.

[10] ROUABAH, K., CHIKOUCHE, D., BOUTTOUT, F., HARBA, R., RAVIER, P. GPS/Galileo multipath mitigation using the first side peak of double delta correlator. *Wireless Personal Communications*. 2011, p. 321 - 333.

[11] BELLO, P. A., FANTE, R. L. Code tracking performance for novel unambiguous M-code time discriminators. In *Proceedings of the 2005 National Technical Meeting of the Institute of Navigation*, San Diego (USA), 2005, p. 293 - 298.

[12] BHUIYAN, M. Z. H., ZHANG, J., LOHAN, E. S. Analysis of multipath mitigation techniques with land mobile satellite channel model. *Radioengineering,* 2012, vol. 21, no. 4, p. 1067 - 1076.

[13] VAN NEE, R. D. J., SIEREVELD, J., FENTON, P. C., TOWNSEND, B. R. The multipath estimating delay lock loop: approaching theoretical accuracy limits. In *Proceedings of the 1994 IEEE Position Location and Navigation Symposium*. Las Vegas (USA), 1994, vol. 1, p. 246 - 251.

[14] SAHMOUDI, M., AMIN, M. G. Fast iterative maximum-likelihood algorithm (FIMLA) for multipath mitigation in next generation of GNSS receivers. *IEEE Transactions on Wireless Communications*, 2008, vol. 7, no. 11, p. 4362 - 4374.

[15] HAMILA, R., RENFORS, M. Nonlinear operator for multipath channel estimation in GPS receivers. In *The 7th IEEE International Conference on Electronics, Circuits and Systems, 2000*. Jounieh (Lebanon), 2000, p. 352-356.

[16] SHAMSI, K. R., YANG, D., SIDDIQUI, A. A. Experimental evaluation of Teager-Kaiser discriminator under multipath environment for GPS signal. In *The 6th IEEE International Conference on Industrial Electronics and Applications, 2011*. Beijing (China), 2011, p. 991 - 995.

[17] ZHONG, P., DING, X. L., ZHENG, D. W., CHEN, W., HUANG, D. F. Adaptive wavelet transform based on cross-validation method and its application to GPS multipath mitigation. *GPS Solutions*, 2008, vol. 12, no. 2, p. 109 - 117.

[18] YEDUKONDALU, K., SARMA, A. D., SATYA SRINIVAS, V. Estimation and mitigation of GPS multipath interference using adaptive filtering. *Journal of Progress in Electromagnetics Research-M*, 2011, vol. 21, p. 133 - 148.

[19] TOWNSEND, B. R., FENTON, P. C., VAN DIERENDONCK, K. J., VAN NEE, R. D. J. Performance evaluation of the multipath estimating delay lock loop. *Navigation*, *Journal of the Institute of Navigation*, 1995, vol. 42, no. 3, p. 503 - 514.

[20] REN, J. W., CHEN, H. H., JIA, W. M., YAO, M. L. Linear-combined-code-based unambiguous code discriminator design for multipath mitigation in GNSS receivers. *Radioengineering*, 2012, vol. 21, no. 4, p. 1140 - 1146.

[21] LOHAN, E. S., HAMILA, R., LAKHZOURI, A., RENFORS, M. Highly efficient techniques for mitigating the effects of multipath propagation in DS-CDMA delay estimation. *IEEE Transactions on Wireless Communications*, 2005, vol. 4, no. 1, p. 149 - 162.

[22] HAMILA, R., ASTOLA, J., ALAYA CHEIKH, F., GABBOUJ, M., RENFORS, M. Teager energy and the ambiguity function. *IEEE Transactions on Signal Processing*, 1999, vol. 47, no. 1, p. 260 - 262.

[23] VAN NEE, R. D. J. Method of estimating a line of sight signal propagation time using a reduced multipath correlation function. *U.S. Patent*, no. 5615232, March 25, 1997.

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