

Combined Tracking Strategy Based on UKF for GPS L2C CM/CL Signal

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Abstract: In a Global Positioning System (GPS) receiver, the tracking algorithm plays a dominant role since the code delay and Doppler frequency shift need to be accurately estimated as well as their variation over time need to be continuously updated. In this paper, we propose to combine Unscented Kalman Filter (UKF) with CM/CL signal to improve the signal tracking precision. The main idea is to allow weighting assignment between CM code and CL code incoming signal, masked by a mass of noise, and to describe a UKF tracking loop aiming at decreasing numerical errors. UKF here involves state and measuring equations which calculate absolute offsets to adjust initial code and carrier phase then dramatically decrease the tracking error. In particular, the algorithm is implemented in both open space and jammed environment to highlight the advantages of tracking approach, by comparing single code and combined code, UKF and EKF tracking loop. It proves that signal tracking based on UKF, with low energy dissipation as well as high precision, is particularly appealing for a software receiver implementation.

Keywords: GPS receiver; tracking algorithm; Unscented Kalman Filter; CM/CL signal; weighting assignment

1. INTRODUCTION

The last decade has seen the trial sub stage of GPS satellite based on L2 frequency band for civilian applications. Opening up a new band mainly aims at improving the quality of the positioning services in low signal-to-noise ratio environment since the long length code (CL code) included here can realize more precise coherent integration than C/A code or CM code¹. So the usable signal, drowned in the noise, can be extracted thus enlarging GPS applications.

The first operation performed by GPS receiver is signal acquisition, which provides a coarse estimation of the code delay and Doppler frequency shift². Then tracking procedure, involved in this paper, mainly offers an accurately estimation and continuously updated.

However, L2C signal includes moderate length code (CM code) as well as long length code (CL code) which based on time division multiplexing³. The former is modulated by navigation data and the latter is for pilot frequency according to its signal structure. In this case, conventional single code tracking inevitably wastes the other half acquired energy⁴. Meanwhile, the high-complexity and nonlinearity of the L2C signal in jammed environment make the precise tracking of traditional methods become unattainable, since they usually adopt approximate linear filter if possible⁵. By consequence, these approaches become weak performers when facing with CL code and relatively complicated computation.

The contribution of this work is to propose a CM/CL combined signal tracking strategy that makes use of the goodness of UKF nonlinear measuring equations. We describe a UKF iterative algorithm of tracking loop to decrease tracking error of nonlinear data as well as we take the weighting assignment between CM code and CL code into consideration for maximum energy utilization. Then prove and discuss them.

2. STRATEGY OF CM/CL CODE COMBINATION

In present GPS L2C signal receiver architecture, the operation of tracking mainly copies the expert model of traditional C/A code tracking, which uses single code tracking algorithm. But either single CM or single CL code, only half received energy resource is utilized because of the time division multiplexing. Meanwhile, single CM code cannot gain enough navigation information in jammed environment and single CL code needs much more time for acquisition, which increases the computational load⁶. In this context, these problems force receiver to carry out an efficient algorithm to combine advantages of both codes and to avoid the adverse factors. So, a block diagram of the combination frame is put forward in Figure 1(a).

Notice that, I (In-phase) and Q (Quadrature phase) baseband signals are separated from the digital intermediate frequency (IF) signal. Then single CM and CL tracking loops are used to track these branches with Costas or phase lock loop independently. But in the L2C signal, Costas is not the most appropriate solution since its tracking result may be affected by the long integration time, about 1.5s. After that, the weighting assignment algorithm between CM code and CL code is implemented before UKF processing.

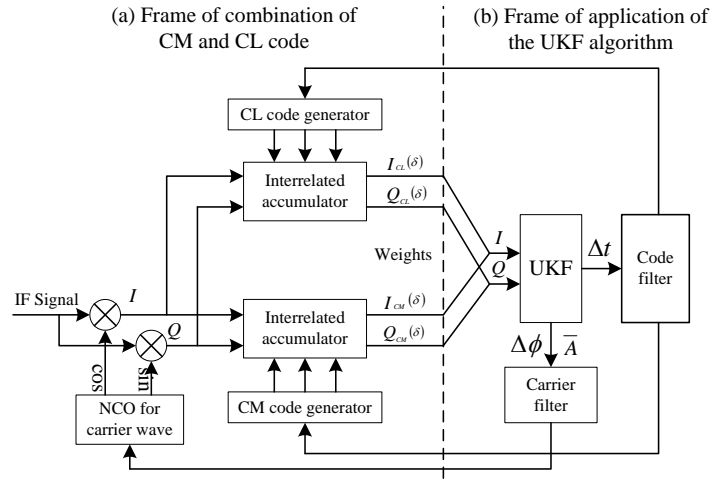


Figure 1. Combination of CM/CL code based on UKF

The details of signal process are shown as follows. First, the feature of incoming IF signal is:

$$y_k = A[D(t_k)CM(t_k - t_0) + CL(t_k - t_0)]\cos[2\pi(f_l + f_d)t_k + \Phi_0] + v(t_k) \quad (1)$$

Where A is the amplitude of L2C signal. f_l : the frequency of the IF signal; f_d : the Doppler frequency shift; Φ_0 : the initial carrier phase; $CM(t)$: CM code with 20ms period; $CL(t)$: CL code with 1.5s period; t_0 & t_k : the starting & present time of input signal; $D(t)$: the navigation data with 20ms pulse width; $v(t)$: the white Gaussian noise.

Given these parameters, the integration time of the CL code is 1.5s, 75 times of CM code. So the CM code utilizes the Costas tracking loop to track the carrier phase, while CL code need to adopt the Phase Locking Loop (PLL) to avoid accuracy loss. Specific details of tracking scheme are described in next three steps.

Step 1. Split I as well as Q signals in each time interval of the CM code and CL code. Outputs of separated signals during $20ms^{3,4}$, a CM code period, are shown in Eqn (2) and CL code signal possesses the similar separated forms.

$$\begin{aligned} I_{CM}(\delta) &= \sum_{k=mn}^{(m+1)n-1} y_k CM(t_k + \delta - t_s) \times \cos[(\omega_{L2} - \omega_d)t_k] \\ Q_{CM}(\delta) &= \sum_{k=mn}^{(m+1)n-1} y_k CM(t_k + \delta - t_s) \times \sin[(\omega_{L2} - \omega_d)t_k] \end{aligned} \quad (2)$$

Where n is sampling number of an integration period. m : the reference index; Subscripts CM : CM code signal; δ : the time difference between early and prompt code; t_s : the time

difference between received code and local code; ω_{L2} : the frequency of L2C signal; ω_{dt_k} : the carrier phase of the receiver. Outputs of equation get the split value of in-phase and quadrature phase during the number m coherent integrating range, which begins at the number mn point and involves n points.

Step 2. Accurately estimate the code delay and Doppler frequency shift of split signals and their variations. The tracking loop is designed as a Delay Locked Loop (DLL), which generates the prompt (P), early (E) and late (L) code as the observed value of tracking loop⁷. Figure 2 shows the structure of CM code tracking loop. CL code tracking provides a similar framework expect the PLL loop.

During CM code tracking, the Figure 2 indicates the Costas discriminator applies the difference between early and late energy to adjust the initial signal until locally generated copy matches the input signal⁸. The offset produced by the discriminator, called “discrimination factor (D)”, is shown in Eqn (3).

$$D = \frac{(I_e^2 + Q_e^2) - (I_l^2 + Q_l^2)}{(I_e^2 + Q_e^2) + (I_l^2 + Q_l^2)} \quad (3)$$

Where I_e, Q_e are the early in-phase and quadrature phase signals and I_l, Q_l are the late signals. Then, repeat the tracking step in Step 2 until GPS receiver get maximum of I and minimum of Q , both in CM code and CL code.

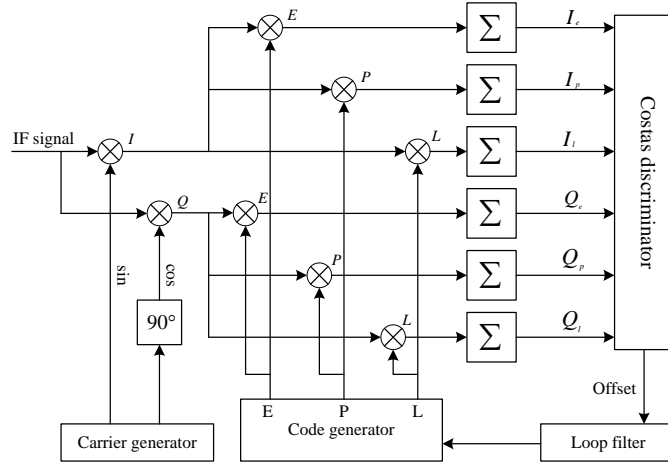


Figure 2. Frame of CM code tracking loop

Unfortunately, either single CM or CL code tracking loop, mentioned above, is only for half energy utilization since it is quite enough for tracking in an ordinary way. Meanwhile, CL code's acquisition needs much more time and computational load than CM code. However, the time-frequency dual folding technique⁹, involved in our previous work, can effectively short the CL code sequence length, relax the computational burdens and make the implementation of combination algorithm possible.

Step 3. Make a combination and weighting assignment between two codes. In the conventional architecture, the methods inevitably include code and carrier phase errors, which will certainly affect tracking accuracy. These errors are related to their variance formulas, listed as follows:

$$\begin{aligned} \sigma_{\tau 1}^2 &= \frac{B_n d}{2aC/N_0} \left[1 + \frac{1}{aC/N_0 T_1} \right] \\ \sigma_{\tau 2}^2 &= \frac{B_n d}{2bC/N_0} \left[1 + \frac{1}{bC/N_0 T_2} \right] \end{aligned} \quad (4)$$

Where B_n is the noise bandwidth of a carrier loop. C/N_0 : the signal-to-noise ratio; $T_1 = 20\text{ms}$ & $T_2 = 1.5\text{s}$: navigation data period; d : the gap between two correlators;

$a = 0.5$: the energy share of CM code; b also equals 0.5 meaning the occupied energy of CL code.

Then a weighting assignment strategy is taken into consideration for combination in this paper according to Tran & Hegarty (2002)¹⁰. When weighting parameters $\alpha = \sigma_{\tau_2}^2 / (\sigma_{\tau_1}^2 + \sigma_{\tau_2}^2)$ and $\beta = \sigma_{\tau_1}^2 / (\sigma_{\tau_1}^2 + \sigma_{\tau_2}^2)$, the code phase variances will get minimum value. Last but most important operation is to allocate I and Q phase signals between CM code and CL code tracking loop. It means that Q_X & I_X in Step 2 are replaced by $I_Y = \alpha I_{CM} + \beta I_{CL}$ & $Q_Y = \alpha Q_{CM} + \beta Q_{CL}$ each iteration. Easy to find that Step 2 is a special case of Step 3 when weighting parameters change to zero, if ignore the utilized energy.

3. DESIGN OF UKF ALGORITHM

The Unscented Kalman filter (UKF), suggested by Julier and Uhlman, has become a popular alternative to the Extended Kalman filter (EKF) during the last decade¹³. Since the high-complexity, nonlinearity of the received L2C signal as well as the autocorrelation function of GPS pseudo code is akin to a triangular wave in low signal-to-noise ratio environment, the tracking error based on EKF is not ignorable. In (12) and (13), although the modified EKF algorithm improves the accuracy of tracking loop, they don't overcome this inherent defect. In (14), GPS signal tracking involves in the UKF algorithm, but its signal-to-noise ratio limitation is 27dbHz because of the improper mathematical model and they just applied UKF in GPS L1 signal obsolete, which cannot reflect the superiority of algorithm. So a block diagram representation of UKF application is shown in Figure 1(b). During each iteration stage, UKF algorithm is used to adjust the feedbacks I and Q phase signal thus improving tracking accuracy.

UKF tracking loop estimates as well as updates code phase and carrier frequency by observing the value of I_e, Q_e, I_l, Q_l and I_p, Q_p at the same time to build state equation and measuring equation. The state equations based on choosing state quantities, shown in Eqn (5), are seen as the index state of incoming $I(\delta)$ & $Q(\delta)$ signal above.

$$X_m = [(X_\phi)_m \quad (X_\omega)_m \quad (t_s)_m \quad A_m]^T \quad (5)$$

X_m is the state vector which includes four state quantities. Where X_ϕ : the difference between input and local carrier phase; X_ω : the Doppler frequency difference; t_s : the difference between input and local code phase; A_m : the carrier amplitude; m : the reference index.

Then four state equations, reflecting the transformation relation between the reference index m & $m - 1$, are listed as follows:

$$\begin{aligned} \begin{bmatrix} X_\phi \\ X_\omega \end{bmatrix}_m &= \begin{bmatrix} 1 & \Delta T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_\phi \\ X_\omega \end{bmatrix}_{m-1} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} [G_\phi]_{m-1} \\ (t_s)_m &= (t_s)_{m-1} + \frac{\omega_{L2}\Delta T - [1 \quad 0][G_\phi]_{m-1}}{\omega_{L2} + (X_\omega)_{m-1}} + (G_{t_s})_{m-1} \\ A_m &= A_{m-1} + A_{G_{m-1}} \end{aligned} \quad (6)$$

Where ΔT is 20ms, which chooses the period of the CM code since it is shorter than the CL code; G_ϕ & G_{t_s} : the Gaussian white noise. ω_{L2} : the frequency of the L2C signal; A_m & A_{m-1} : carrier amplitude of index m & $m - 1$; $A_{G_{m-1}}$: the amplitude of index $m - 1$ white noise sequence.

These equations reflect the change of state quantities with time (or index number). As is shown in Step 2 in last section, the discriminator utilizes the difference between early and late energy to adjust initial signal until matching with each other. The measuring equation, a 4×1 matrix whose first two lines reflect the prompt carrier phase ($\delta = 0$) and last two lines reflect

the difference between early and late carrier phase, will be built next. Here $I_k(\delta)$ & $Q_k(\delta)$ can be expressed as follows:

$$\begin{aligned} I_k(\delta) &= \frac{1}{2} n_k \bar{A}_k D_k \cos(\Delta\phi_k) R(\Delta t_k + \delta) + v_{Ik} \\ Q_k(\delta) &= \frac{1}{2} n_k \bar{A}_k D_k \sin(\Delta\phi_k) R(\Delta t_k + \delta) + v_{Qk} \end{aligned} \quad (7)$$

Where n_k is the sampling number during 1ms; D_k : the navigation data; \bar{A}_k : the average carrier amplitude, $\Delta\phi_k$: the average carrier phase difference and Δt_k : the code phase difference during 1ms; $R(t)$: the correlation function; v_{Ik} & v_{Qk} : the uncorrelated white Gaussian noise sequences with $n\sigma_v^2/2$ variance as well as zero-mean. So the measuring equation is shown as Eqn (8).

$$Z_m = \begin{bmatrix} \sum_{k=k_m}^{k_m+19} I_k(0) \\ \sum_{k=k_m}^{k_m+19} Q_k(0) \\ \sum_{k=k_m}^{k_m+19} [I_k(\delta) - I_k(-\delta)] \\ \sum_{k=k_m}^{k_m+19} [Q_k(\delta) - Q_k(-\delta)] \end{bmatrix} = \frac{N\bar{A}_m D_m}{2} \begin{bmatrix} \cos(\Delta\phi_m) R(\Delta t_m) \\ \sin(\Delta\phi_m) R(\Delta t_m) \\ \cos(\Delta\phi_m) R_e(\Delta t_m) \\ \sin(\Delta\phi_m) R_e(\Delta t_m) \end{bmatrix} + v_m \quad (8)$$

$$(N = \sum_{k=k_m}^{k_m+19} n_k; D_m = [D_{k_m}, D_{k_m+1}, \dots, D_{k_m+19}]; R_e(\Delta t) = R(\Delta t + \delta) - R(\Delta t - \delta);)$$

Where k_m is the first index of 20ms integration time; $R_e(\Delta t)$: the correlated difference between early and late signal. v_m : the white Gaussian noise sequence. And where $\Delta\phi_m$: the average carrier phase difference. Δt_m : the average code phase difference and \bar{A}_m : the average carrier amplitude during 20ms, inferred by formula (5):

$$\begin{aligned} \Delta\phi_m &= \begin{bmatrix} 1 & \frac{\Delta T}{2} \end{bmatrix} \begin{bmatrix} X_\phi \\ X_\omega \end{bmatrix}_m + [0 \quad 1][G_\phi]_m; \\ \Delta t_m &= \frac{(t_s)_m + (t_s)_{m-1}}{2} - t_{midm}; \\ \bar{A}_m &= \frac{1}{2}(A_m + A_{m-1}) \end{aligned} \quad (9)$$

Where t_{midm} is the code phase of the middle integration time. In Eqn (8), if we define

$$\text{“Transfer function” } h(\Delta\phi_m, \Delta t_m, \bar{A}_m) = \frac{N\bar{A}_m}{2} \begin{bmatrix} \cos(\Delta\phi_m) R(\Delta t_m) \\ \sin(\Delta\phi_m) R(\Delta t_m) \\ \cos(\Delta\phi_m) R_e(\Delta t_m) \\ \sin(\Delta\phi_m) R_e(\Delta t_m) \end{bmatrix}, \text{ the measuring equation is}$$

also expressed as:

$$Z_m = D_m h(\Delta\phi_m, \Delta t_m, \bar{A}_m) + v_m \quad (10)$$

According to the state equations as well as the measuring equation, the $\Delta\phi$, Δt and \bar{A} above can be obtained from UKF block diagram to offset the input in-phase and quadrature phase signal in each iteration during last combination algorithm to decrease tracking errors, as shown in Figure 1. Fortunately, experiments will prove the accuracy superiority of UKF application next section.

4. SIMULATION AND DISCUSSION

4.1 CM/CL Code Combination Discussion

Both energy utilization and accuracy play important roles in tracking of GPS receiver. Considering the single CL code acquisition need much more time and higher computational complexity, we employ the time-frequency dual folding algorithm, our previous study achievement, in signal acquisition. Necessary parameters during both acquisition and tracking are list as follows: 1) Sampling frequency f_s ; 2) Center frequency f_c ; 3) Pseudo

code rate r_{IF} ; 4) Down-conversion multiple k_f of CL code signal; 5) The amount groups k_g of CL code signal.

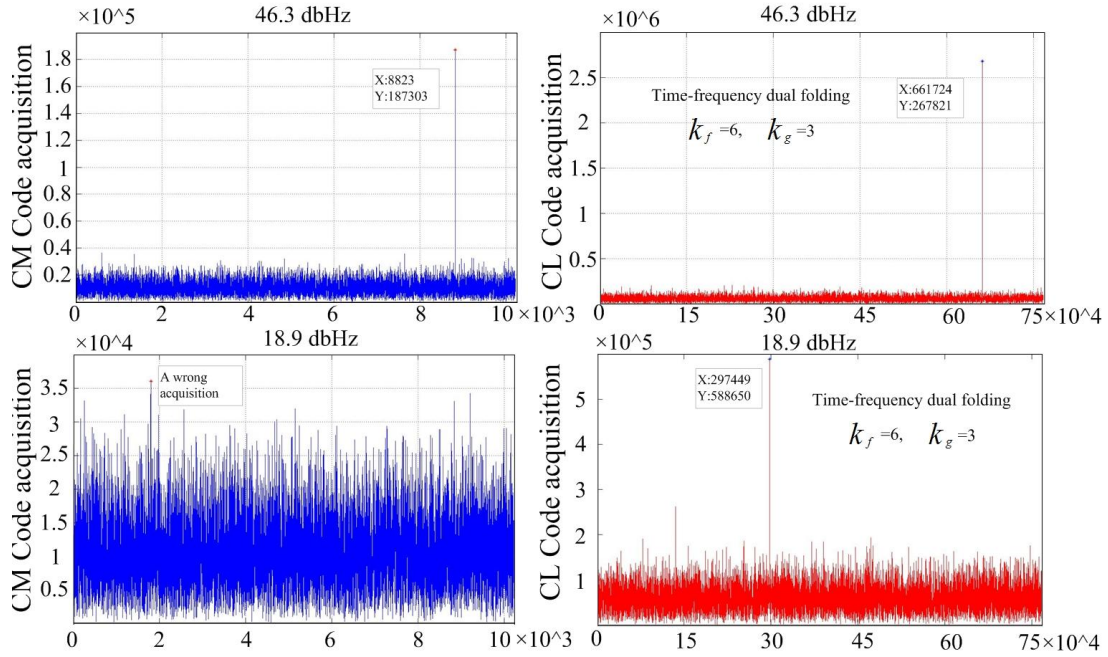


Figure 3. Results of: Correlation function of CM/CL code of No. 5 satellite

Figure 3 shows the acquisition results of single CM code and CL code of No. 5 satellite in open space and jammed environment. Where $k_f=6$, $k_g=3$ means “down-conversion multiple is 6” and “the amount groups is 3” in time-frequency dual folding algorithm, thus the effective code length of CL code becomes 1/18. From Figure 3, we notice that both CM code and CL code can provide an effective coarse estimation of the code delay and the Doppler frequency shift in open space. However, when in low signal-to-noise ratio environment, the former produces a wrong acquisition result, which proves the necessity of CL code involved in jammed environment.

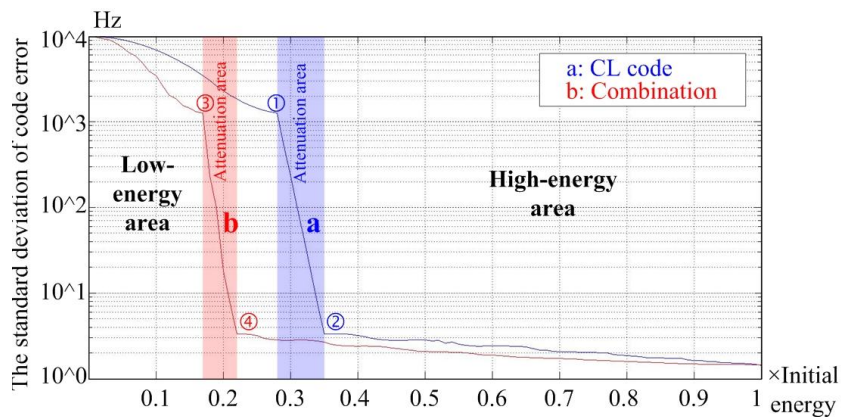


Figure 4. Results of: The relation between code error and energy attenuation

Unfortunately, if we change the signal energy in the test above (18.9dbHz) through cutting down amplitude of input signal, the acquisition performance will change and lead to the instability of receiver effects. The statistical results of each 100 tests in different attenuation multiples are shown in Figure 4, with single CL code and combination algorithm. It shows that property of CL code acquisition begin to decline when the energy attenuation multiple

drops to 0.34 (the point ②). However, the degenerative point is 0.22 (the point ④) in combination algorithm. Meanwhile, the error of the latter is smaller in the whole curve as well, especially between the attenuation areas of two, which proves the superiority of combination of CL and CM code in low signal-to-noise ratio, low-energy area, such as an indoor environment.

During combination, the weighting parameters α & β are obtained according to the variance of the CM code phase and CL code phase when make a combination tracking, which is expressed as follows:

$$\frac{\alpha}{\beta} = \frac{\sigma_{\tau_2}^2}{\sigma_{\tau_1}^2} = \frac{1 + 1/[b(C/N_0)T_2]}{1 + 1/[a(C/N_0)T_1]} \quad (11)$$

Where $a = b = 0.5$; $T_1 = 0.02s$; $T_2 = 1.5s$; and $C/N_0 = 18.9\text{dbHz}$. So, $\alpha = 0.146$ and $\beta = 0.854$ in each tracking iteration. Figure 5 gives the tracking results of single CL code and the UKF combination algorithm, which includes 400ms frequency tracking and 800ms phase tracking. It shows that the subtle signal jitter of combination algorithm is smaller than CL code tracking, proving the better stability. And that a simply estimation of computational complexity of single CL code and combination is $c_{CL}:c_{Com} = 1:1.06$, indicating the approximate computational burdens. This test result means the higher accuracy and twice energy utilization get in return at the cost of a few computational loads.

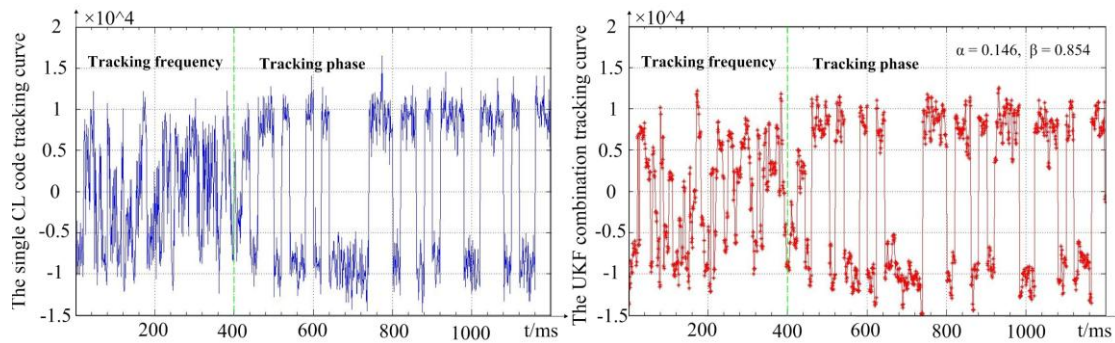


Figure 5. Results of: The tracking results of single CL code and combination

During the 400ms frequency tracking scheme, the ratio A_{ca}/P_{ca} between amplitude of the carrier phase error and carrier period is used for evaluating the carrier tracking performance of tracking models above. The carrier phase error curves, tested in different signal-to-noise ratio environments (choosing six places) are shown in Table 1. It clearly indicates that the choice of code has a great influence in carrier frequency tracking effects, even all models based on UKF algorithm. It is easy to find that carrier errors of three are similar when in high signal-to-noise ratio environment. But the speed of CM code tracking degradation is much faster than other two models if the signal-to-noise ratio begins to decline. According to the average degradation speed, the combination strategy improves the performance of frequency tracking about 32.6% by single CM code and about 2.4% by single CL code as a whole.

Table 1. The carrier phase error statistics of models

	C/N_0 (Hz)	18.9	25.6	30.4	44.5	46.3	53.1
A_{ca}/P_{ca} based on	CM code	0.235	0.198	0.126	0.064	0.056	0.050
	CL code	0.133	0.129	0.082	0.054	0.055	0.050
	UKF Combination	0.132	0.124	0.078	0.055	0.054	0.048

In addition, Figure 6 shows the carrier error curves of single CM code and combination of both in 18.9dbHz, which shows that the error is -5~5 chips and -2.5~2.5 chips, proves the superiority of combination algorithm.

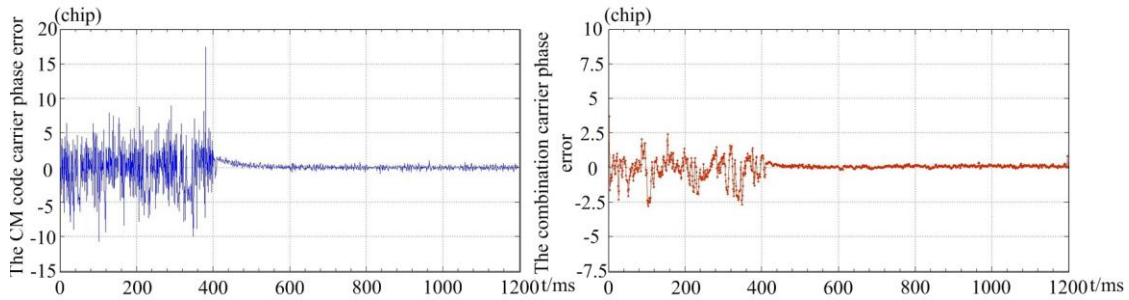


Figure 6. Results of: The carrier phase error curves (18.9dbHz)

4.2 Performance Analysis of UKF Algorithm

During the 800ms code phase tracking scheme, to prove the effectiveness of UKF algorithm, Figure 7 gives the code errors of tracking loop with and without UKF in 18.9dbHz as well as 46.3dbHz environments. These curves clearly show that UKF design improves the tracking performance tremendously. The maximal code phase error of traditional tracking loop is more than 0.6 chips; nevertheless, it is limited in $-0.1\sim 0.2$ chips with UKF algorithm in jammed environment. And in 46.3dbHz signal-to-noise ratio area the code error of UKF is much smaller as well, which is limited in $-0.01\sim 0.035$ chips.

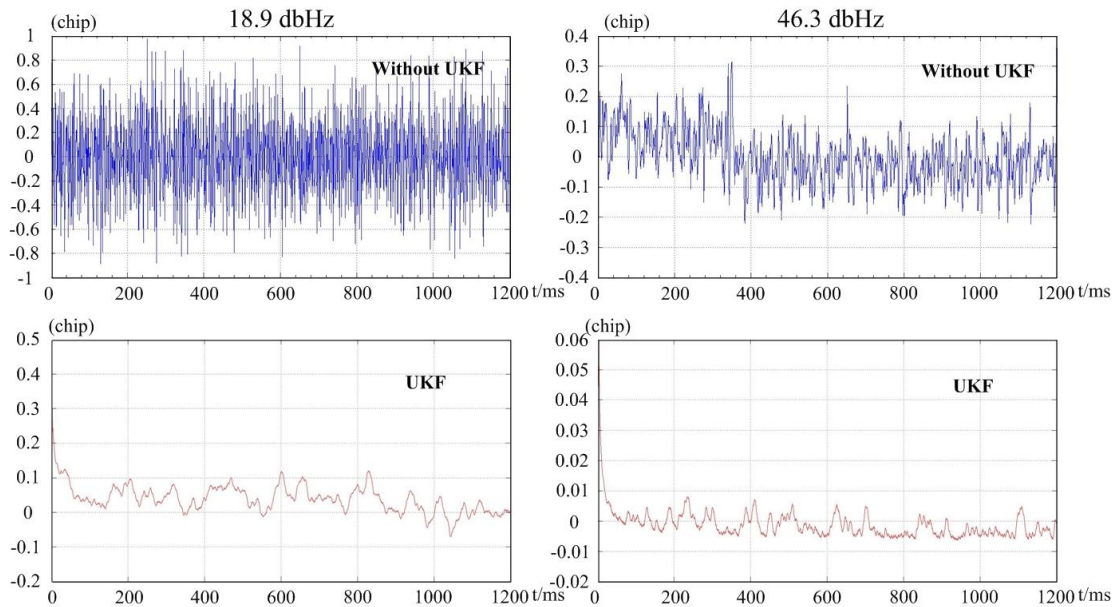


Figure 7. Results of: The code error curves of different and models

Table 2. The standard deviations of code phase error

	C/N_0	Traditional algorithm	UKF algorithm
Standard deviation	18.9 dbHz	0.34	6.2×10^{-2}
$\sigma(\text{chip})$	46.3 dbHz	6.8×10^{-2}	5.1×10^{-3}

Meanwhile, the standard deviations of algorithms are analyzed and compared in Table 2, in terms of the experiment results of Figure 7. The table highlights the advantages of UKF method compared to the conventional pure tracking loop since the error standard deviation of the latter is 13.3 & 5.5 times of the former in open & jammed environment.

In particular, we compared the EKF and UKF design strategy of L2C signal receiver. The difference of both is that UKF uses the statistical property while EKF is inclined to utilize the Jacobian matrix and partial differential algorithm for signal estimation¹¹. So, viewed from the algorithm theory, the UKF tends to be more accurate in high-complexity and nonlinearity signal application.

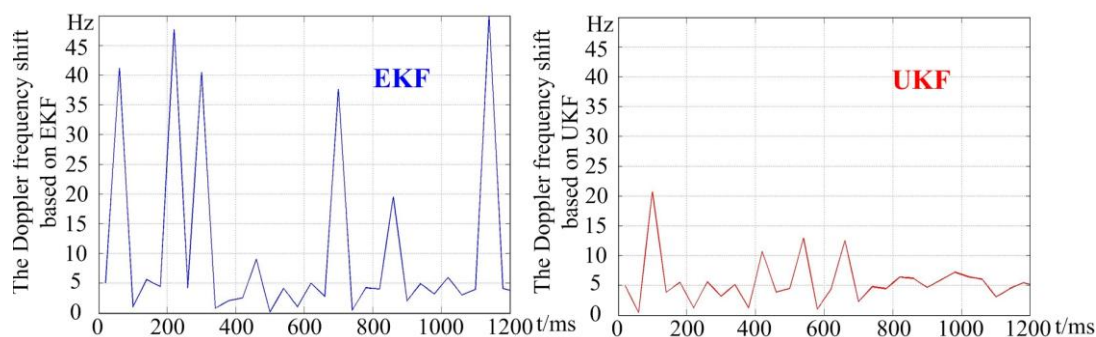


Figure 8. Results of: The Doppler frequency shift curves (18.9dbHz)

Figure 8 shows the Doppler frequency shift curves of EKF and UKF in 18.9dbHz environment. It can be seen that the fluctuation of EKF is large than UKF, indicating that the UKF tracking loop is more stable. Meanwhile, proposed UKF strategy needs lesser time to convergence than EKF tracking loop. Moreover, UKF and EKF algorithms are both three orders, but the computational complexity of EKF is larger than UKF because of its complicated Jacobian matrix estimation. So, UKF tracking loop is more suitable in GPS L2C signal tracking.

To sum up, experiments above prove that the tracking based on UKF for GPS L2C CM/CL combined signal is effective, with relatively high accuracy, energy utilization and relatively relaxed computational load, which is particularly appealing for a GPS software receiver implementation.

5. CONCLUSION

The strategy of CM and CL code combination based on UKF, proposed in this paper, provides an efficient means of GPS L2C signal application in low signal-to-noise ratio environment. Combination of codes improves the energy utilization by 50%, which plays an important role in weak signal area. During the combination algorithm, the operation of weighting assignment between CM code and CL code is to obtain minimal code and carrier errors. Meanwhile, the UKF tracking loop dramatically decreases the code and carrier phase error as well as increases signal tracking accuracy. Experiments in both open space and jammed area demonstrate the stability of described approach, by comparing single code and combined code tracking, UKF and EKF tracking loop.

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