Adaptive Tracking Algorithm of Weak GNSS Signal

Faqin Gao*

School of Information Science, Zhejiang Sci-Tech University, Hangzhou, Zhejiang, China

Abstract: The receiver of a global navigation satellite system (GNSS) is likely to lose tracking for a GNSS signal in some degraded environments. To solve this problem, this paper analyzes both the bandwidth and the dynamic stress errors of the carrier tracking loop (CTL) of a GNSS receiver, and then designs a new adaptive tracking algorithm for GNSS signals. First, we design an error extraction module to extract phase errors so that a CTL can estimate phase errors without using a loop discriminator, which can reduce the requirements of the carrier-to-noise ratio (CNR) of GNSS signals. Second, we design a motion detection module to detect the real-time movement status of GNSS receivers. Then, using its detecting results as inputs, we design an algorithm to automatically make the CTL switch between a second-order loop and a third-order loop. Third, we design a bandwidth-adjusting module to adjust the bandwidth of CTL, according to the CNR and the movement status of a GNSS receiver. Finally, a simulation is performed to verify that our adaptive carrier tracking algorithm can effectively improve the precision of CTL, as well as enhance its dynamic range.

Keywords: GNSS receiver, Carrier Tracking Loop(CTL), Adaptive, Carrier to Noise Ratio(CNR), Bandwidth.

1. INTRODUCTION

A global navigation satellite system (GNSS) is a kind of satellite-based, radio ranging navigation system. Its applications have been widely used in economy and daily life. For example, it is commonly used for city traffic management, precision timing, geodesy, and in many other applications.

A GNSS signal becomes very weak when it reaches the GNSS receiver on the ground [1], especially in some complex degraded environments, such as an indoor environment or an urban environment. What's more, humans mostly live in indoor environments and in the city. As a result, it is important to conduct research on receiving technology about weak GNSS signals.

To directly address GNSS navigation problems in weak signal environments, experts have analyzed the acquisition algorithms of weak GNSS signals, as well as their tracking algorithms [1]. For example, many papers have investigated a high sensitivity tracking algorithm, but their environmental adaptability was limited. For example, Psiaki, *et al*. proposed a new kind of tracking algorithm to track a weak GPS signal, using extended kalman filter and Bayesian estimation technology [2, 3], but its loop order was fixed. Satyanarayana, *et al*. improved the loop structure to track weak signal based on a generalized likelihood ratio test (GLRT) and block processing method [4]. They removed navigation messages by a square method to allow long coherent integration. They said their method can acquire and track signals below 18 dB-Hz; however, this finding has been challenged by research that shows that they did not consider the effects of receiver movement status on the tracking performance of CTL.

As expected, research on adaptive tracking algorithms in a complex environment also received a great deal of attention at many international meetings. Many researchers have focused on adaptive tracking algorithms, but they can only automatically adjust bandwidth or loop order respectively, and further studies revealed an obvious defect that these research results cannot achieve-results in both a high sensitivity and a wide dynamic range. For example, although Liu, *et al*. tried to balance sensitivity and dynamic range [5], the improvement of dynamic performance was limited. Mariappan, *et al*. used adaptive least squares filter to improve the tracking loop [6]. Their CTL achieved the ability of adapting to environmental changes, but it could not accurately track a weak signal. Liu, *et al*. put forward a moving average method to replace a complex loop filter [7]. They claimed that their algorithm could improve dynamic performance in weak signal environments, but, in fact, the improved effect is extremely limited.

Based on existing research, this paper designs a GNSS adaptive tracking algorithm that can simultaneously adjust the tracking loop bandwidth and loop order in real time. An error extraction module is also designed as a substitute for a loop discriminator, which can significantly improve the sensitivity of a GNSS receiver. Using our algorithm, the GNSS receiver can achieve both a high sensitivity and a wide dynamic range.

*Address correspondence to this author at the School of Information Science, Zhejiang Sci-Tech University, Hangzhou, Zhejiang, China;
E-mail: gfqzjlg@gmail.com; gfaqin@pitt.edu

E-ISSN: 2409-9694/15

2. QUESTIONS

Although the tracking process of GNSS signals has been thoroughly analyzed, little is known about the mechanisms that govern parameters of changing CTLs in different environments. It was well accepted that GNSS signal tracking faces these two main problems:

(1) The bandwidth of the tracking loop. The doppler frequency in high dynamic GNSS signals shifts over a large range. As a result, the tracking loop of a GNSS receiver should have wide bandwidth in order to reduce dynamic stress errors. However, this will reduce the ability of a GNSS receiver to remove noise, which may cause a loss of captured signals. The question of how to automatically adjust the optimal bandwidth of CTLs is still open.

(2) The order of the tracking loop. The tracking range of the second-order loop is wide, but its tracking accuracy is relatively low. The tracking accuracy of the third-order loop is high, but its tracking range is narrow. In a highly dynamic environment, a second-order loop should be adopted to prevent the loss of lock in high dynamic application; but, on the other hand, in order to improve tracking accuracy, we should use the third-order loop.

From these analyses, we must make sure that the bandwidth and the order of CTL is determined by the specific application environment; i.e., it is necessary for the ability to adapt to environmental changes.

3. ANALYSES

Previously, it has been reported that the measurement error of CTL is affected by many factors, such as thermal noise, dynamic stress, mechanical vibration, Allan deviation, and so on. A three-fold CTL measurement error means that the variance can be written as in Equation 1 [3]:

$$3\sigma_{CTL} = 3\sqrt{\sigma_{noise}^2 + \sigma_{vibra}^2 + \sigma_{Allan}^2} + \theta_{dynamic} \quad (1)$$

σ_{CTL} is a one-fold CTL measurement error (mean variance); σ_{noise} is the measurement error caused by thermal noise; σ_{vibra} is the measurement error caused by mechanical vibration; σ_{Allan} is the measurement error caused by the Allan deviation; and $\theta_{dynamic}$ is dynamic stress error. The conservative maximum acceptable error of CTL is that the three-fold CTL measurement error variance should not exceed one-quarter of the phase tracking range. The accepted phase tracking range of the CTL discriminator is 180 degrees when the data are modulated. So:

$$3\sigma_{CTL} \le \frac{180^\circ}{4} = 45^\circ \ then\ \sqrt{\sigma_{noise}^2 + \sigma_{vibra}^2 + \sigma_{Allan}^2} + \frac{\theta_{dynamic}}{3} \le 15^\circ \quad (2)$$

The measurement error caused by thermal noise can be expressed as

$$\sigma_{noise} = \frac{180}{\pi}\sqrt{\frac{B}{C/N_0}\left(1 + \frac{1}{2T_{coh}C/N_0}\right)} \quad (3)$$

where B is the bandwidth of CTL; C/N_0 is the value of CNR; and T_{coh} is the coherent integration time. We can see that σ_{noise} is determined by CNR(C/N_0) and noise bandwidth B. This is similar to the finding that, with a continuous decrease in CNR, thermal noise effects will gradually increase-and the more narrow the bandwidth, the better the ability to remove thermal noise. Formula (3) also shows that, in a low C/N_0 environment, there are two ways to reduce the noise error σ_{noise}. One is to prolong the coherent integration time T_{coh}, while the other is to reduce the noise bandwidth B. To further determine whether this conclusion is right or not, the relationship among bandwith B, CNR, and tracking errors caused by thermal noise is simulated and analyzed. The results shed light on the central concept of our adaptive tracking algorithm.

When the GNSS receiver is moving quickly, dynamic stress errors and their effects on tracking performance cannot be ignored. The dynamic stress errors of n-th order CTL and the second-order CTL are shown in Equation (4).

$$\theta_{dynamic}^n = P_n \frac{dR^n/dt^n}{B_n} \quad \theta_{dynamic}^2 = 0.2809\frac{dR^2/dt^2}{B_2} \quad (4)$$

where R is the straight-line distance between receiver and satellite; dR^n/dt^n is the n-th derivatives of R; and B_n is the bandwidth of the n-th order CTL. We can see that the dynamic stress error rate of the CTL is closely related to the order of CTL, the bandwidth, and the movement state of the GNSS receiver. To circumvent their relationship, we have simulated the dynamic stress error rate of the CTL.

On one hand, narrowing bandwidth B can help to achieve accurate tracking, and the coherent integration time T_{coh} should be as long as possible to reduce the thermal noise measurement error σ_{noise}. On the other hand, bandwidth B should be as wide as possible and the coherent integration time T_{coh} should be as short as possible. So that the dynamic stress measurement error $\theta_{dynamic}$ and measurement error of time crystal σ_{Allan} can be reduced. These two aspects contradict one another and they are mutually restricted, which limitates the performance improvement of the traditional CTL.

Therefore, it is necessary to create an adaptive tracking algorithm that can adjust the bandwidth and order automatically, according to the movement state of the GNSS receiver and the ability of the CNR to adapt to a changing environment. Tackling such a daunting challenge will help to improve the precision of the CTL and enhance its dynamic range.

4. METHODS

Although some recent research has proposed the adaptive adjustment technology of CTL, the existing research results are not suitable for a low-CNR environment. To tackle this problem, we analyze the CTL and find that the loop discriminator plays an important role in determine tracking sensitivity. Based on this analysis, we designed a symbol decision method, which makes the adaptive tracking algorithm suitable for low CNR environment. What is more, our adaptive tracking algorithm can adaptively adjust bandwidth and the order of the CTL, according to a changing environment.

Figure **1** shows the structure of the adaptive tracking loop.

4.1. Symbol Decision Method

In our algorithm, the phase tracking error of CTL is directly estimated from the output of an accumulation submodule (including the upper one and the lower one, as seen in Figure **1**, described as output I and output Q, respectively) by searching a look-up table and then computing. Our method is described as follows. First, navigation message bit d_k is estimated by symbol decisions method according to output I. Then, the estimated value $\hat{d}_k$ is multiplied by output I and output Q; for example:

$$
\begin{aligned}
I_k &= A d_k \hat{d}_k R_c(\tau) \frac{\sin(\pi f T)}{\pi f T} \cos\theta + \eta_I \\
Q_k &= A d_k \hat{d}_k R_c(\tau) \frac{\sin(\pi f T)}{\pi f T} \sin\theta + \eta_Q
\end{aligned}
\tag{5}
$$

A is a constant coefficient and $R_c(\tau)$ is the correlation function of pseudo random code between the input GNSS signal and the local signals. θ is the carrier phase difference between the input signal and the local signal. T is the integration time (or the pre-detection integration time). $\eta_I ! \eta_Q$ are white Gauss noise with zero mean.

When CNR is big than 20dB-Hz, the mean value of $d_k \hat{d}_k$ is greater than 0.8. For purposes of brevity, $d_k \hat{d}_k$ is set as 1. From formula (5) we can get: $\tan\theta \approx (Q_k / I_k)$. Since the curve of the tangent function is a smooth monotone curve between $(-\pi/2 \sim \pi/2)$, it can be approximated by using a piecewise polynomial fitting method. We put the coefficient of the fitted

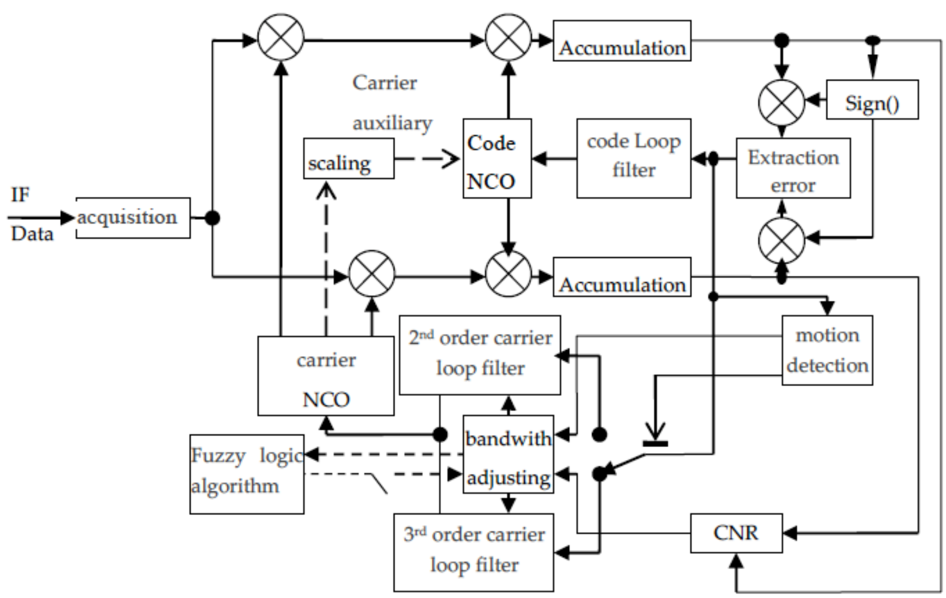


Figure 1: Improved schematic structure of the tracking loop.

polynomial in a look-up table; then, we can compute the value of phase error θ by using the table looking-up method.

4.2. Adaptive Carrier Tracking Loop (ACTL)

We can deduce the optimal bandwidth of CTL:

$$(B)_{PLL-opt} = \sqrt[2m+1]{\frac{\left(\frac{4\pi m P_m^m}{3}\frac{f_L}{c}\frac{d^m R}{dt^m}\right)^2}{\frac{1}{C/\mathrm{N}_0}\left(1+\frac{1}{2T_{coh}C/\mathrm{N}_0}\right)}} \tag{6}$$

where P_m^m is m-th power of the proportional coefficient of m-th order filter; f_L is the frequency of the input GNSS signal; and c is the speed of light. We can see from the above equation that the upper limit of bandwidth mainly depends on the thermal noise, and the lower limit of bandwidth mainly depends on the dynamic stress error. The bandwidth of the CTL should be adjusted to optimal when detecting the CNR and the dynamics of the GNSS receiver. It is reasonable that a high-order loop should be used in highly dynamic environments, and vice versa. The basic idea and specific strategies are described as follows.

(1) Motion detection module detect movement state D_a (acceleration or jerk) of the GNSS receiver, according to I_k, Q_k, based on the detection results of D_a and CNR. Bandwidth adjustment module adjusts the order of CTL according to the regulations shown in Table **1**. For example, if the values of D_a and CNR are lower than their respective thresholds, then the CTL should change to the second order.

(2) The bandwidth adjustment module adjusts the bandwidth of the CTL, according to CNR and movement state D_a. These specific strategies are shown in Table **1**.

In Table **1**, for acceleration, all data with values smaller than 3m/s^2 belongs to the subset called "close to zero." All data with values larger than 18m/s^2 belongs to the subset called "higher." For jerk, all data with values smaller than 3m/s^3 belongs to the subset called "close to zero," while all data with values larger than 70m/s^3 belongs to the subset called "higher." For CNR, all data with values smaller than 32dB-Hz belongs to the subset called "small," while all data with values that lie in [32dB-Hz~38dB-Hz] belongs to the subset called "medium," and all data with values larger than 38dB-Hz belongs to the subset called "large."

In Table **1**, bandwidth can be reduced only if it is larger than the minimum allowable bandwidth. Otherwise, the bandwidth remains unchanged. Bandwidth can be increased only if it is smaller than the maximum allowable value of bandwidth. Otherwise, the bandwidth remains unchanged. In this paper, the minimum allowable bandwidth value is set to 2Hz[1]; when the CNR is large, the maximum allowable value of bandwidth is set according to its different environments.

5. EXPERIMENTS

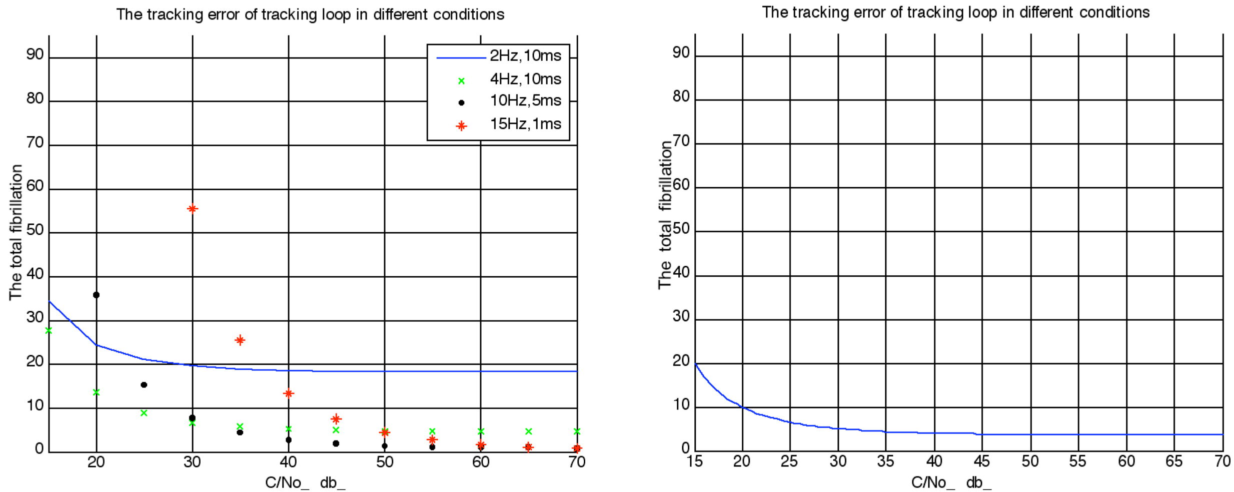
Simulations are performed in the MatLab programming environment. Parameters are set according to GPS settings, and the code correlation gap of tracking loop is 0.5 chip.

First, satellite signals in different situation are simulated. Then the performance of the tracking algorithm is tested. Figure **2** shows the results of the tracking algorithm tests.

We simulate the tracking error rate of non-adaptive CTLs under different movement states and CNR values. Some of these results are shown in Figure **2**(**a**). We can see that the 1σ phase tracking error increases gradually with the decreasing of CNR. What's more, the wider the bandwidth, the greater the increase in the

Table 1: Adjustment Strategies of Loop Order and Bandwidth

CNR	Movement State (Acceleration or Jerk)			
	All Close to Zero	**Others**	**Higher Acceleration**	**Higher Jerk**
Small	To reduce (if 3rd order, it turns to 2nd order)	The same	To increase (if error is over threshold, then turns to 3rd order)	To increase (if error is over threshold, then return to 3rd order)
Medium	To reduce	The same	To increase (if error is over threshold, then change the order of CTL)	To increase (if error is over threshold, then return to 3rd order)
Large	To reduce	To reduce	If error is over threshold, then change the order of CTL	If error is over threshold, then return to 3rd order



(a) non-adaptive (b) adaptive

Figure 2: The tracking error of the CTL under different conditions.

rate of error. However, when CNR is high enough, the wider the bandwidth, the smaller the phase tracking error. When the initial bandwidth is set to 4Hz, the tracking error of adaptive CTLs under different CNRs is simulated, and the results are shown in Figure **2**(**b**). We can see that, while the CNR values and movement state vary over a wide range for different bandwith and integration time, the total tracking error value changes linearly. In particular, these experiments are generally in agreement with previous theoretically analyses. When the value of CNR lies in the range of [15dB, 70dB], regardless of the movement state of GNSS receiver and CNR, the 1σ phase tracking error is less than 20°. These experiment results indicate that the adaptive carrier tracking algorithm can greatly improve tracking accuracy in various environments.

6. CONCLUSIONS

We have focused our investigations on tracking algorithm of GNSS signals, and have designed an adaptive tracking algorithm that can adaptively adjust the bandwidth and the order of CTL, according to the movement state of the receiver and CNR. It can switch between a second-order loop and a third-order loop, and the bandwidth of CTL can always tend toward an optimal value, which allows the CTL to have both a large dynamic range and a high degree of precision. Moreover, the CTL designed in this paper does not use a loop discriminator, and its phase error is estimated directly from the output of submodule accumulation, which reduces the CNR requirement. As a result, the tracking performance of the GNSS signal in a low CNR environment has been improved. Our findings provide evidence that it is necessary to develop adaptive GNSS signal tracking algorithms, and that these algorithms can effectively improve the performance of GNSS receivers.

In our research, we have brought together a great deal of work on GNSS signal tracking, which has so far only scratched the surface of this fertile field of investigation. Further study is needed to determine the extent to which the bandwith and the coherent integration time can be optimized, according to the overall movement state and CNR.

ACKNOWLEDGEMENTS

This material is based upon work funded by the Zhejiang Provincial Natural Science Foundation of China under Grant No. LY14F030025, and it is also financially supported by the National Natural Science Foundation of China under Grant No. 61402417.

REFERENCES

[1] Xie G. The principle of GPS and GPS receiver design. Beijing: Publishing House of electronics industry 2009. *(In Chinese)*

[2] Lin WX. Performance research on high dynamic GNSS receiver carrier tracking. Master thesis, Xiamen University 2014. *(In Chinese)*

[3] Yan K, Ziedan N I and Zhang H. Weak GPS signal tracking using FFT discriminator in open loop receiver. GPS Solutions 2014: 1-13. http://dx.doi.org/10.1007/s10291-014-0431-3

[4] WANG J H and ZHANG X. Carrier tracking of weak GNSS signals based on FFT and navigation data estimation. Journal of National University of Defense Technology 2012; 34(5): 78-82. *(In Chinese)*

[5] Stienne G, Reboul S and Azmani M. GNSS dataless signal tracking with a delay semi-open loop and a phase open loop. Signal Processing 2013; 93(5): 1192-1209. http://dx.doi.org/10.1016/j.sigpro.2012.12.011

[6] Liu Y, Yao ZC and Cheng JR. Weak GNSS signal tracking algorithm based on Adaptive Extended Kalman Filter. Computer measurement and control 2014; 22(006): 1842-1845. *(In Chinese)*

[7] Zhao X and Wang SC. An Ultra-tightly Coupled Tracking Method Based on Robust Adaptive Cubature Kalman Filter. Acta Automatica Sinica 2014; 40(11): 2530-2540. (In Chinese)

[8] Satyanarayana S, Borio D and Lachapelle G. A non-coherent block processing architecture for standalone GNSS weak signal tracking. Proc ION/GNSS Portland OR 2011: 1777-1785.

[9] Tian Y. High sensitivity GPS signal tracking using a Bayes approach. Master thesis, Shanghai: Shanghai Institute of Microsystem and information technology of Chinese Academy 2009. *(In Chinese)*

[10] Liu Y and Zhu YB. A FLL-PLL Cooperative GNSS Weak Signal Tracking Framework. Applied Mechanics and Materials 2014; 551: 470-477. http://dx.doi.org/10.4028/www.scientific.net/AMM.551.470

[11] Mariappan S, Rao GS and Babu SR. Enhancing GPS Receiver Tracking Loop Performance in Multipath Environment Using an Adaptive Filter Algorithm. Indian Journal of Science and Technology 2014; 7(S7): 156-164.

[12] Liu JL, Wu HB and He ZM. An Improved Tracking Architecture for Weak GNSS Signal Based on Moving Average Method. Applied Mechanics and Materials 2014; 602: 1571-1575. http://dx.doi.org/10.4028/www.scientific.net/AMM.602-605.1571

Received on 09-06-2015 Accepted on 09-07-2015 Published on 31-12-2015

DOI: http://dx.doi.org/10.15377/2409-9694.2015.02.02.1