Adaptive Tracking Algorithm of Weak GNSS Signal

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

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 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.

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. 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. 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. however,some researches show that they did not consider the effects of receiver movement status on the tracking performance of CTL.

As expected, 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.

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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.

Symbol decision method

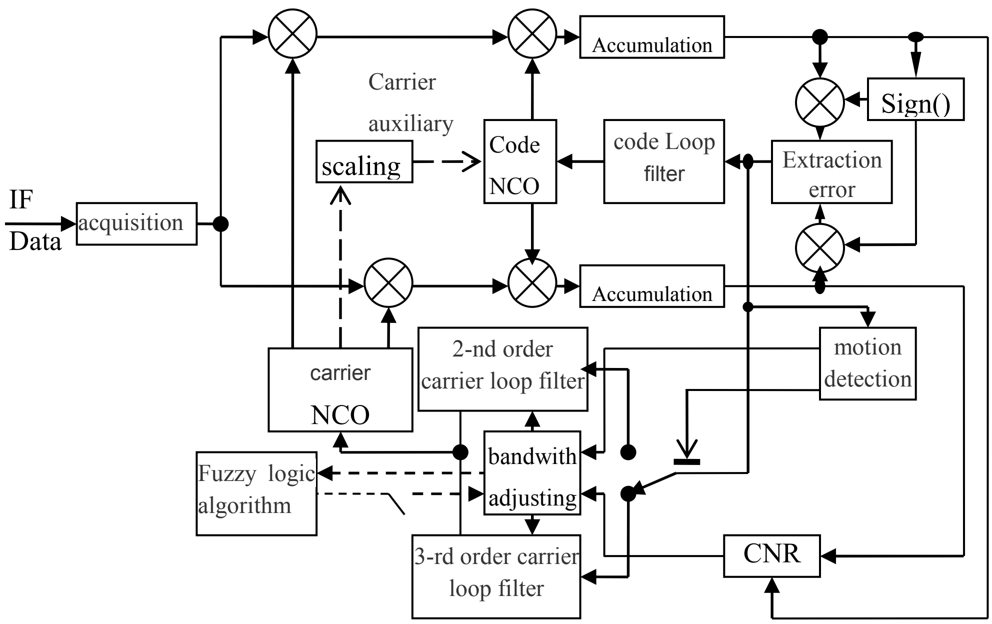


Fig.1 Improved schematic structure of the tracking loop

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:

$$I_k = Ad_k\hat{d}_kR_c(\tau)\frac{\sin(\pi fT)}{\pi fT}\cos\theta+\eta_I \qquad Q_k = Ad_k\hat{d}_kR_c(\tau)\frac{\sin(\pi fT)}{\pi fT}\sin\theta+\eta_Q \qquad (5)$$

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

Adaptive carrier tracking loop(ACTL)

We can deduce the optimal bandwidth of CTL:

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

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 shown in Table 1.

Table 1: Adjustment strategies of loop order and bandwidth

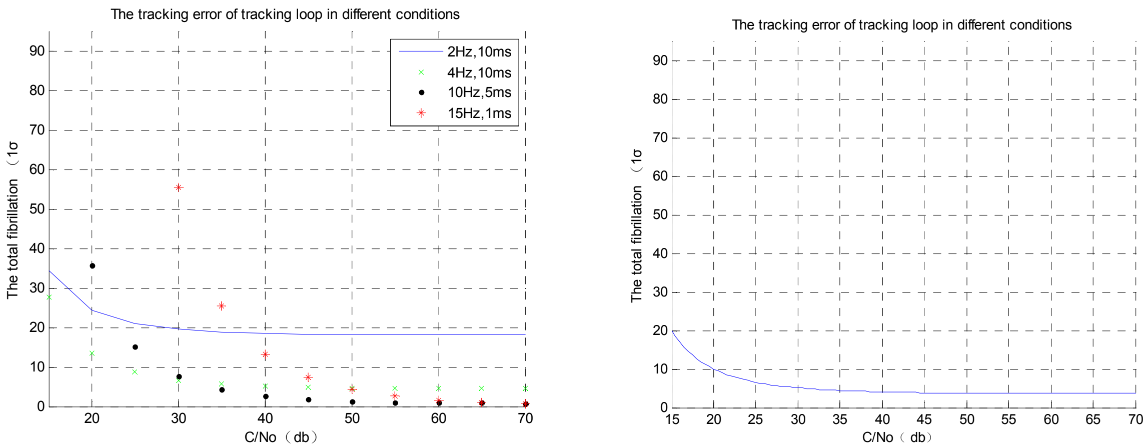
CNR	movement state（Acceleration or Jerk）			
	All close to zero	**others**	**Higher acceleration**	**Higher Jerk**
Small	To reduce (if the 3rd order, it turns to the 2nd order)	the same	To increase (if the error is over threshold, then returned back to the 3rd order)	To increase (if the error is over threshold, then returned to the 3rd order)
medium	To reduce	the same	To increase (if the error is over threshold, then change the order of CTL)	To increase (if the error is over threshold, then returned to the 3rd order)
large	To reduce	To reduce	if the error is over threshold, then change the order of CTL	if the error is over threshold, then returned to the 3rd order

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.”

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.



(a) *non-adaptive* (b) *adaptive*

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

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 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.

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.

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.

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