Carrier Tracking Loop using the Adaptive Two-Stage Kalman Filter for High Dynamic Situations

Kwang-Hoon Kim, Gyu-In Jee and Jong-Hwa Song

Abstract: In high dynamic situations, the GPS carrier tracking loop requires a wide bandwidth to track a carrier signal because the Doppler frequency changes more rapidly with time. However, a wide bandwidth allows noises within the bandwidth of the tracking loop to pass through the loop filter. As these noises are used in the numerical controlled oscillator (NCO), the carrier tracking loop of a GPS receiver shows a degraded performance in high dynamic situations. To solve this problem, an adaptive two-stage Kalman filter, which offers the NCO a less noisy phase error, can be used. This filter is based on a carrier phase dynamic model and can adapt to an incomplete dynamic model and a quickly changed Doppler frequency. The performance of the proposed tracking loop is verified by several simulations.

Keywords: Adaptive Kalman filter, carrier tracking loop, GPS receiver, high dynamic.

1. INTRODUCTION

In a GPS receiver, the input is the GPS signal and a phase lock loop (PLL) must track this signal. However, the GPS signal is a bi-phase coded signal. The carrier and code frequencies change due to the Doppler effect, which is caused by the motion of the GPS satellite as well as from the motion of the GPS receiver. In order to track the GPS signal, the C/A code information must be removed. As a result, it requires two PLLs to track a GPS signal. One is to track the C/A code and the other is to track the carrier frequency [1]. This paper only considers the latter.

The tracking performance of a PLL is affected by several factors, such as the signal-to-noise ratio (SNR), dynamic stress, thermal noise, and so forth. However specially, a PLL does not give a good performance under high dynamic situations. In high dynamic situations, the Doppler frequency changes more rapidly with time. Therefore in such cases, the carrier tracking loop of a GPS receiver requires a wide bandwidth to track a carrier signal. However, a wide bandwidth allows noises within the bandwidth of the tracking loop to pass through the loop filter. As these noises are used in the numerical controlled oscillator (NCO), the carrier tracking loop of a GPS receiver shows a degraded performance under high dynamic situations. To solve this problem, several researchers proposed the carrier tracking loop using the Kalman filter, which offers the NCO a less noisy phase error. The linear Kalman filter or the extended Kalman filter was used and these filters were based on a carrier phase dynamic model [2-6]. These Kalman filters estimated the carrier phase error between the incoming signal and the NCO by using an estimate of the Doppler frequency of a carrier phase dynamic model. However, under high dynamic situations, the Kalman filter may not track the Doppler frequency because the Doppler frequency changes more rapidly. As such, this paper proposes a new carrier tracking loop using an adaptive two-stage Kalman filter based on a carrier phase dynamic model. This adaptive filter was proposed by Kim and coauthors [7] and could adapt to an incomplete dynamic model and a quickly changed Doppler frequency. Section 2 shows the concept of the carrier tracking loop using an adaptive Kalman filter. Section 3 provides the adaptive two-stage Kalman filter. The derivation of a filter equation is omitted. Finally, the performance of the proposed tracking loop is verified by several simulations in Section 4.

2. CARRIER TRACKING LOOP DESIGN

2.1. Costas carrier tracking loop

A GPS receiver can track incoming GPS signals by using the PLL. The PLL replicates the incoming signal's frequency and phase. A Costas loop is one among these phase lock loops used for carrier phase recovery. Normally, a Costas carrier tracking loop is used in GPS receivers because the 50Hz navigation message data modulation signal remains after the carrier and code signals have been wiped off the incoming GPS signal [8]. Fig. 1 shows a block

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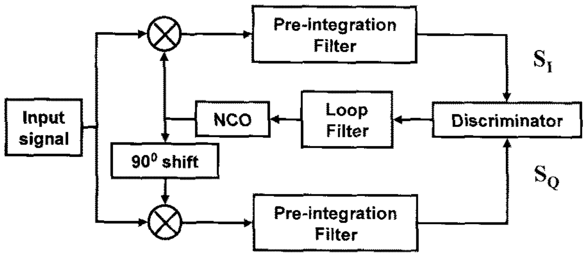

Fig. 1. The Costas loop.

diagram of a Costas loop.

2.2. Carrier phase dynamic model

As mentioned in the introduction, several researchers proposed the carrier tracking loop using the Kalman filter based on a carrier phase dynamic model [2-6]. A carrier phase model is as follows [6].

$$\begin{bmatrix}\theta_{e,k}\\ f_{d,k}\\ f_{a,k}\end{bmatrix}=\begin{bmatrix}1 & \Delta t & \Delta t^2/2\\ 0 & 1 & \Delta t\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\theta_{e,k-1}\\ f_{d,k-1}\\ f_{a,k-1}\end{bmatrix}-\begin{bmatrix}\Delta t\\ 0\\ 0\end{bmatrix}f_{d,k-1}^{NCO}+W_n, \tag{1}$$

where $\theta_{e,k}$ is the carrier phase error between the incoming signal and the output of the NCO, $f_{d,k}$ is the Doppler frequency in the incoming signal, $f_{a,k}$ is the change rate of Doppler frequency caused by the acceleration along the line of sight (LOS) between the satellite and the receiver, $f_{d,k}^{NCO}$ is the Doppler frequency replicated by the NCO and $\Delta t = 0.001$ is the update period and pre-integration time. $W_n = \begin{bmatrix}W_\theta & W_d & W_a\end{bmatrix}^T$ is a noise vector which consists of discrete Gaussian white noise sequences. Assuming that these noise sequences are independent and the spectral intensity of the continuous time white noise process of these noise sequences are Q_θ, Q_d and Q_a, respectively. Q_θ is caused by the receiver clock phase bias. Q_d is caused by the receiver clock frequency drift. Q_a is caused by the acceleration along the LOS. The covariance Q which corresponds to the discrete noise process can be calculated as follows [6].

$$Q=\int_0^{\Delta t}\Phi_{k,k-1}Q_c\Phi_{k,k-1}^T dt$$

$$=Q_\theta\begin{bmatrix}\Delta t & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}+Q_d\begin{bmatrix}\frac{\Delta t^3}{3} & \frac{\Delta t^2}{2} & 0\\ \frac{\Delta t^2}{2} & \Delta t & 0\\ 0 & 0 & 0\end{bmatrix}$$

$$+Q_a\begin{bmatrix}\frac{\Delta t^5}{20} & \frac{\Delta t^4}{8} & \frac{\Delta t^3}{6}\\ \frac{\Delta t^4}{8} & \frac{\Delta t^3}{3} & \frac{\Delta t^2}{2}\\ \frac{\Delta t^3}{6} & \frac{\Delta t^2}{2} & \Delta t\end{bmatrix}, \tag{2}$$

where the system matrix and the spectral intensity in continuous time are

$$\Phi_{k,k-1}=\begin{bmatrix}1 & \Delta t & \Delta t^2/2\\ 0 & 1 & \Delta t\\ 0 & 0 & 1\end{bmatrix}, Q_c=\begin{bmatrix}Q_\theta & 0 & 0\\ 0 & Q_d & 0\\ 0 & 0 & Q_a\end{bmatrix}. \tag{3}$$

An Arctan discriminator is used in this paper. The measurement is obtained from this discriminator output $\theta_{e,k-1}^{mea}=\arctan\left(S_Q/S_I\right)$. S_Q and S_I are ouputs of the pre-integration filters.

The measurement can be modeled by θ_e^{ave} as

$$\theta_e^{ave}=\frac{1}{\Delta t}\int_0^{\Delta t}\Big[\theta_{e,k-1}+\left[f_{d,k-1}-f_{d,k-1}^{NCO}\right]\tau+\frac{1}{2}f_{a,k-1}\tau^2\Big]d\tau$$
$$=\theta_{e,k-1}+\frac{1}{2}\left[f_{d,k-1}-f_{d,k-1}^{NCO}\right]\Delta t+\frac{1}{6}f_{a,k-1}\Delta t^2 \tag{4}$$

As a result, the measurement equation is as follows.

$$\theta_{e,k-1}^{mea}=\begin{bmatrix}1 & \frac{\Delta t}{2} & \frac{\Delta t^2}{6}\end{bmatrix}\begin{bmatrix}\theta_{e,k-1}\\ f_{d,k-1}\\ f_{a,k-1}\end{bmatrix}-\frac{\Delta t}{2}f_{d,k-1}^{NCO}+V_{k-1} \tag{5}$$

where $V_k \sim \left(0, R_k\right)$ is a Gaussian white noise sequence.

2.3. Costas loop using an adaptive filter

The carrier tracking loop of a GPS receiver requires a wide bandwidth to track a carrier signal under high dynamic situations. However, a wide bandwidth allows noises within the bandwidth of the tracking loop to pass through the loop filter. As a result, the carrier tracking loop shows a degraded performance under high dynamic situations. To solve this problem, the Kalman filter can be used as indicated in Fig. 2. This Kalman filter estimates the output of discriminator and a Doppler frequency. That is, the Kalman filter gives the loop filter the less noisy carrier phase error. Of course, this filter is based on a carrier phase dynamic model. However, a Doppler frequency of a carrier phase dynamic model is rapidly changed under

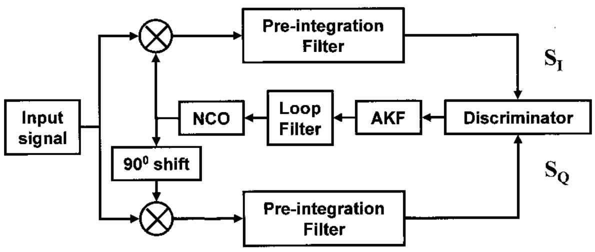

Fig. 2. Costas loop using an adaptive Kalman filter.

high dynamic situations. Thus, to estimate a Doppler frequency, an adaptive Kalman filter noted in Section 3. Equations (6-8) are given for this adaptive Kalman filter.

$$\begin{bmatrix} \theta_{e,k} \\ f_{d,k}^{NCO} \end{bmatrix} = \begin{bmatrix} 1 & -\Delta t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \theta_{e,k-1} \\ f_{d,k-1}^{NCO} \end{bmatrix} + \begin{bmatrix} \Delta t & \frac{\Delta t^2}{2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} f_{d,k-1} \\ f_{a,k-1} \end{bmatrix} + \begin{bmatrix} W_\theta & 0 \\ 0 & 0 \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} f_{d,k} \\ f_{a,k} \end{bmatrix} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} f_{d,k-1} \\ f_{a,k-1} \end{bmatrix} + \begin{bmatrix} W_d & 0 \\ 0 & W_a \end{bmatrix}, \tag{7}$$

$$\theta_{e,k-1}^{mea} = \begin{bmatrix} 1 & -\frac{\Delta t}{2} \end{bmatrix} \begin{bmatrix} \theta_{e,k-1} \\ f_{d,k-1}^{NCO} \end{bmatrix} + \begin{bmatrix} \frac{\Delta t}{2} & \frac{\Delta t^2}{6} \end{bmatrix} \begin{bmatrix} f_{d,k-1} \\ f_{a,k-1} \end{bmatrix} + V_{k-1}. \tag{8}$$

3. ADAPTIVE TWO-STAGE KALMAN FILTER

The well-known Kalman filtering has been widely used in many industrial areas. This Kalman filtering technique requires complete specifications of both dynamical and statistical model parameters of the system. However, in a number of practical situations, these models contain parameters that may deviate from their nominal values by unknown constant or unknown random bias. To solve this problem, a new procedure for estimating the dynamic states of a linear system in the presence of unknown constant bias was suggested by Friedland [9]. This filter is called the two-stage Kalman filter (TKF). Many researchers have contributed to this problem. Ignagni and Keller suggested the alternate derivation of Friedland's bias filtering technique in the case of unknown constant bias [10,11]. Recently, the TKF to consider not only a constant bias but also a random bias has been proposed through several papers [12-16] with the representative optimal TKF being proposed by Hsieh [15]. This optimal TKF assumes that the dynamic model and the noise covariance of a random bias are known. Nevertheless, in most cases, they are unknown. If this information is incomplete, the performance of the TKF may be degraded or diverged. To solve this problem, the TKF has to be adapted to an environment of incomplete random bias information. This problem was solved by the adaptive two-stage Kalman filter (ATKF), which was proposed by Kim and coauthors [7]. Furthermore, the adaptive two-stage nonlinear filter expanded from the ATKF was applied to the INS-GPS loosely coupled navigation system with unknown fault bias and showed a good performance [17]. The concept and the derivation of the ATKF are explained in another paper [7]. As such, this section only briefly introduces the ATKF. Consider the following linear discrete-time stochastic system represented by

$$x_{k+1} = \Phi_k x_k + B_k b_k + w_k^x, \tag{9a}$$

$$b_{k+1} = A_k b_k + w_k^b, \tag{9b}$$

$$z_k = H_k x_k + D_k b_k + v_k, \tag{9c}$$

where x_k is the $n \times 1$ state vector and z_k is the $m \times 1$ measurement vector. Φ_k and H_k are state transition matrix and observation matrix respectively. b_k is the $p \times 1$ bias vector with unknown magnitude. All matrices have the appropriate dimensions. The noise sequence w_k^x, w_k^b, and v_k are zero mean uncorrelated Gaussian random sequences with

$$E\left[\begin{bmatrix} w_k^x \\ w_k^b \\ v_k \end{bmatrix} \begin{bmatrix} w_j^x \\ w_j^b \\ v_j \end{bmatrix}^T\right] = \begin{bmatrix} Q_k^x & 0 & 0 \\ 0 & Q_k^b & 0 \\ 0 & 0 & R_k \end{bmatrix} \delta_{kj}, \tag{9d}$$

where $Q_k^x > 0, Q_k^b > 0, R_k > 0$ and δ_{kj} is the Kronecker delta. The initial states x_0 and b_0 are assumed to be uncorrelated with the white noise processes w_k^x, w_k^b and v_k. Assume that x_0 and b_0 are Gaussian random variables with

$$E[x_0] = x_0^*, \quad E\left[\left(x_0 - x_0^*\right)\left(x_0 - x_0^*\right)^T\right] = P_0^x > 0, \tag{9e}$$

$$E[b_0] = b_0^*, \quad E\left[\left(b_0 - b_0^*\right)\left(b_0 - b_0^*\right)^T\right] = P_0^b > 0, \tag{9f}$$

$$E\left[\left(x_0 - x_0^*\right)\left(b_0 - b_0^*\right)^T\right] = P_0^{xb}. \tag{9g}$$

Definition 1: A discrete-time adaptive two-stage Kalman filter is given by the following coupled difference equations when the information of the linear stochastic system given by (9) is incomplete [7].

$$\tilde{x}_k(-) = \bar{x}_k(-) + U_k \bar{b}_k(-), \tag{10a}$$

$$\tilde{x}_k(+) = \bar{x}_k(+) + V_k \bar{b}_k(+), \quad (10b)$$

$$P_k^{x*}(-) = \bar{P}_k^{x*}(-) + U_k \bar{P}_k^{b*}(-) U_k^T, \quad (10c)$$

$$P_k^{x*}(+) = \bar{P}_k^{x*}(+) + V_k \bar{P}_k^{b*}(+) V_k^T, \quad (10d)$$

where A_k and Q_k^b are partially known. The modified bias free filter is

$$\bar{x}_k(-) = \Phi_{k-1}\bar{x}_{k-1}(+) + u_{k-1}, \quad (11a)$$

$$\bar{P}_k^{x*}(-) = \lambda_k^x \left[\Phi_{k-1}\bar{P}_{k-1}^{x*}(+)\Phi_{k-1}^T + \bar{Q}_{k-1}^x \right], \quad (11b)$$

$$\bar{K}_k^{x*} = \bar{P}_k^{x*}(-) H_k^T \left[H_k \bar{P}_k^{x*}(-) H_k^T + R_k \right]^{-1}, \quad (11c)$$

$$\bar{P}_k^{x*}(+) = \left(I - \bar{K}_k^{x*} H_k \right) \bar{P}_k^{x*}(-), \quad (11d)$$

$$\bar{\eta}_k^x = z_k - H_k \bar{x}_k(-),\ \bar{x}_k(+) = \bar{x}_k(-) + \bar{K}_k^{x*} \bar{\eta}_k^x, \quad (11e)$$

$$C_k^x = H_k \bar{P}_k^{x*}(-) H_k^T + R_k, \quad (11f)$$

$$\bar{C}_k^x = \lambda_k^x C_k^x = \frac{1}{M-1} \sum_{i=k-M+1}^{k} \bar{\eta}_i^x \bar{\eta}_i^{xT}, \quad (11g)$$

$$\lambda_k^x = \max\left\{1,\ trace\left(\bar{C}_k^x\right) / trace\left(C_k^x\right)\right\} \geq 1, \quad (11h)$$

and the bias filter is

$$\bar{b}_k(-) = A_{k-1}\bar{b}_{k-1}(+), \quad (12a)$$

$$\bar{P}_k^{b*}(-) = \lambda_k^b \left[A_{k-1}\bar{P}_{k-1}^{b*}(+) A_{k-1}^T + Q_{k-1}^b \right], \quad (12b)$$

$$\bar{K}_k^{b*} = \bar{P}_k^{b*}(-) N_k^T \Big[H_k \bar{P}_k^{x*}(-) H_k^T + R_k + N_k \bar{P}_k^{b*}(-) N_k^T \Big]^{-1}, \quad (12c)$$

$$\bar{P}_k^{b*}(+) = \left[I - \bar{K}_k^{b*} N_k \right] \bar{P}_k^{b*}(-), \quad (12d)$$

$$\bar{\eta}_k^b = z_k - H_k \bar{x}_k(-) - N_k \bar{b}_k(-) = \bar{\eta}_k^x - N_k \bar{b}_k(-), \quad (12e)$$

$$\bar{b}_k(+) = \bar{b}_k(-) + \bar{K}_k^{b*} \bar{\eta}_k^b, \quad (12f)$$

$$C_k^b = H_k \bar{P}_k^{x*}(-) H_k^T + R_k + N_k \bar{P}_k^{b*}(-) N_k^T, \quad (12g)$$

$$\bar{C}_k^b = \lambda_k^b C_k^b = \frac{1}{M-1} \sum_{i=k-M+1}^{k} \bar{\eta}_i^b \bar{\eta}_i^{bT}, \quad (12h)$$

$$\lambda_k^b = \max\left\{1,\ trace\left(\bar{C}_k^b\right) / trace\left(C_k^b\right)\right\} \geq 1 \quad (12i)$$

with the coupling equations

$$N_k = H_k U_k + D_k,\ V_k = U_k - \bar{K}_k^{x*} N_k, \quad (13a)$$

$$U_k = \bar{U}_k \left[I - \lambda_k^b Q_{k-1}^b \left[\bar{P}_k^{b*}(-) \right]^{-1} \right], \quad (13b)$$

$$\bar{U}_k = \left(\Phi_{k-1} V_{k-1} + B_{k-1} \right) A_{k-1}^{-1}, \quad (13c)$$

$$u_k = \left(\bar{U}_{k+1} - U_{k+1} \right) A_k \bar{b}_k(+), \quad (13d)$$

$$\bar{Q}_k^x = Q_k^x + U_{k+1} Q_k^b \bar{U}_{k+1}. \quad (13e)$$

Also, the initial conditions are

$$V_0 = P_0^{xb} \left(P_0^b \right)^{-1},\ \bar{x}_0(+) = x_0^* - V_0 b_0^*,\ \bar{b}_0(+) = b_0^*, \quad (14a)$$

$$\bar{P}_0^{b*}(+) = P_0^b,\ \bar{P}_0^{x*}(+) = P_0^x - V_0 P_0^b V_0^T. \quad (14b)$$

The ATKF of Definition 1 is based on the two-stage Kalman filter of Heish [15] and the adaptive fading Kalman filter [7]. This ATKF gives a solution for the system with the unknown random bias on the assumption that the stochastic information of the random bias is incomplete. The carrier tracking loop under high dynamic situation must track unknown Doppler frequency. Thus, this paper treats unknown Doppler frequency as the unknown random bias of (9b). The ATKF can track unknown Doppler frequency, which changes more rapidly with time.

4. SIMULATION

As mentioned in the introduction, the performance of a GPS tracking loop with a low PLL bandwidth is better than that with a high PLL bandwidth, because a high bandwidth allows noises within the bandwidth of the tracking loop to pass through the loop filter and these noises degrade the tracking performance. Therefore, the general method is to use a low bandwidth. However, a GPS tracking loop with a low PLL bandwidth may not track a fast Doppler frequency. As a result, a GPS tracking loop uses a high PLL bandwidth in the case of high dynamic situations. But, if the PLL loop using the ATKF is considered in a GPS tracking loop, we can expect that a GPS tracking loop will show a good performance even though a low bandwidth is used. Of course, in the case of a high bandwidth, the general PLL loop and the PLL loop with the ATKF demonstrate a similar performance because two PLL loops can track a Doppler frequency. To verify the performance of a carrier tracking loop using an ATKF, the 3rd order PLL with and without the ATKF are simulated under high dynamic situation as follows. Simulation conditions and PLL

Table 1. Simulation conditions.

L1 Carrier Frequency	1575.42 MHz
Code Frequency	1.023 MHz
Signal-to-Noise Ratio	-20dB
Intermediate Frequency	1.4054 MHz
Sampling Frequency	17.5 MHz
Simulation Time	1572 msec

Table 2. PLL configuration.

Order of the PLL	Three
Discriminator	Arctan
PLL Bandwidth	7Hz, 15Hz
Pre-integration Time	1 msec

configuration are shown in Table 1 and 2. For example, the GPS L1 signal (1575.42 MHz), -20dB SNR, the 3rd order PLL, an Arctan discriminator, and 1ms pre-integration time are used in simulations. Simulations are performed by MATLAB software. User trajectory is a half-circle with initial velocity and centripetal acceleration, which are 50m/s and 100m/s^2, respectively.

4.1. High bandwidth

To easily track a signal, firstly the bandwidth of the PLL is selected as 15Hz. Fig. 3(a) shows that the 3rd order PLL without the ATKF tracks all channels but gives a large Doppler frequency error during the initial interval. Fig. 3(a) also presents that the Doppler frequency error is about 40 degrees as more time passes. Here the Doppler frequency error means a difference between a true Doppler frequency and an estimated Doppler frequency replicated by the NCO. Fig. 3(b) indicates that a discriminator gives more noisy output during initial interval. On the other hand, Fig. 4(a) shows that the 3rd order PLL with the ATKF gives a small Doppler frequency error as compared with Fig. 3(a). But as time goes by, the Doppler frequency error of Fig. 4(a) becomes similar to that of Fig. 3(a). Fig. 4(b) shows that a discriminator gives less noisy output than Fig. 3(b).

4.2. Low bandwidth

Secondly, the bandwidth of the PLL is selected as 7Hz. Fig. 5(a) shows that the 3rd order PLL without the ATKF gives a large Doppler frequency error during initial interval and also cannot track one channel. A discriminator of Fig. 5(b) gives more noisy output. On the other hand, Fig. 6. shows the result of the 3rd order PLL with the ATKF. Fig. 6(a) indicates that the 3rd order PLL with the ATKF gives a small Doppler frequency error as compared with Fig. 5(a) and also tracks all channels without fail. Fig. 6(a) shows that the Doppler frequency error is about 25 degrees as time goes by. Fig. 6(b) presents that a discriminator gives less noisy output than Fig. 5(b).

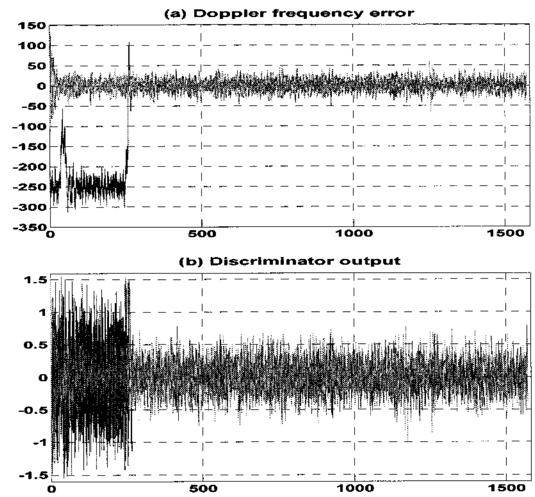

Fig. 3. The 3rd PLL without the ATKF (BW:15Hz).

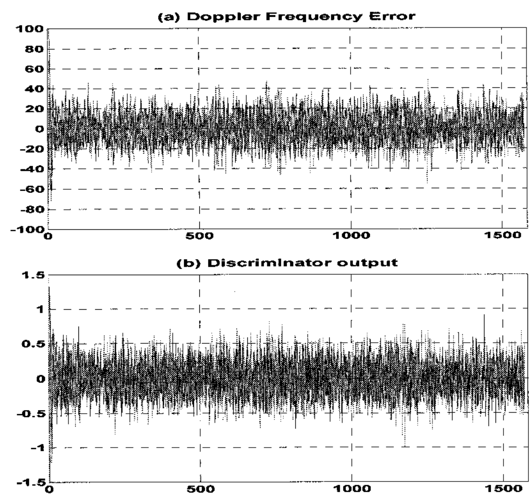

Fig. 4. The 3rd PLL with the ATKF (BW: 15Hz).

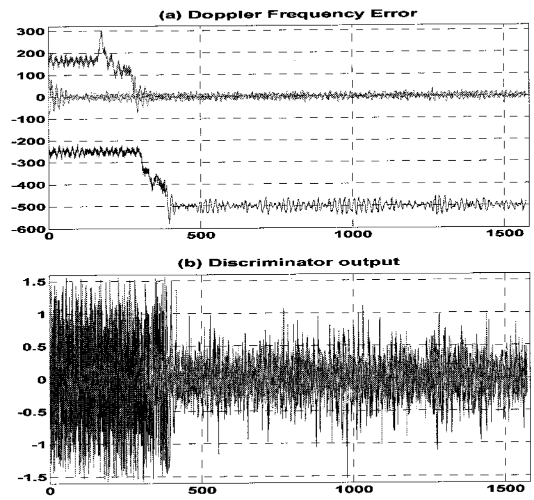

Fig. 5. The 3rd PLL without the ATKF (BW: 7Hz).

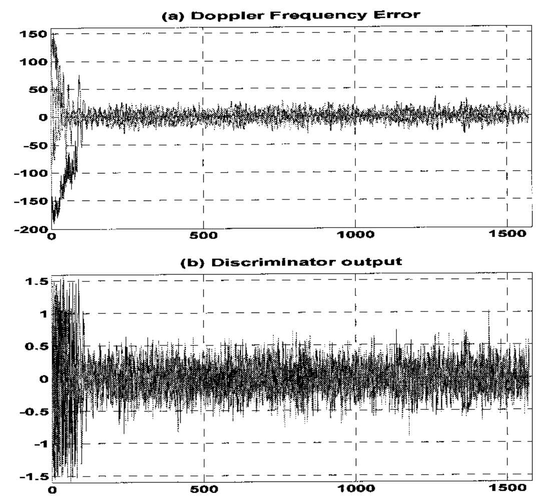

Fig. 6. The 3rd PLL with the ATKF (BW: 7Hz).

As a result, the 3rd order PLL with the ATKF gives a small Doppler frequency error and a good tracking performance as compared with the 3rd order PLL without the ATKF.

6. CONCLUSIONS

The carrier tracking loop of a GPS receiver demonstrates a degraded performance under high dynamic situations. The reason is that a carrier phase error generated from a discriminator is a noisier signal than that generated from low dynamic situations and this signal is used as an input of the loop filter. To solve this problem, this paper proposes a new carrier tracking loop using an adaptive two-stage Kalman filter, which can track a quickly changed Doppler frequency. A new carrier tracking loop gives a smaller Doppler frequency error than the conventional PLL. Also, this new carrier tracking loop shows a good performance under a low bandwidth as compared with the conventional PLL.

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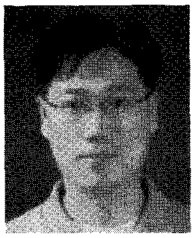

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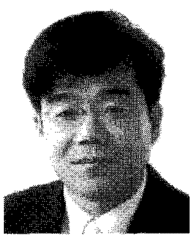

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