Abstract—Tracking dynamics on the GPS signal is still a big challenge to the receiver designer as the operating conditions are becoming more volatile. Usually, the Phase-locked loop (PLL) is used in GPS receivers to track an incoming signal and to provide accurate carrier phase measurements. However, in high dynamic situations, the conflict between improving PLL tracking performance and the ability to track the signal necessitates some compromises in PLL design. Optimizing the stand-alone system for dynamics, generally, degrades the accuracy of measurements. The advanced signal processing techniques as maximum likelihood (ML) and extended Kalman filter (EKF) can be used to track a common trajectory exhibiting high dynamics. However, the estimated values of these algorithms can not be used directly to demodulate the signals. A combination of both inertial measurement unit (IMU) and GPS is an attractive method to deal with the problem of high dynamic tracking. Unfortunately, these units of IMU are often very expensive. In this paper, a new Kalman filter aided phase-lock loop is proposed to address this issue. Doppler derived from EKF is used to aid the carrier tracking loop for improving the performance under dynamic conditions. While the cost is significantly reduced compare with the IMU method. Simulations show that the method is feasible.

Keywords-high dynamic; Kalman filter; Phase-lock loop; signal processing

I. INTRODUCTION

Tracking dynamics on the GPS signal is still a big challenge to the receiver designer as the operating conditions are becoming more volatile. In GPS receivers, the Phase-locked loop (PLL) is used to track an incoming signal and to provide accurate carrier phase measurements [1][2][3]. However, High noise and high platform dynamics scenarios present a difficult problem for most GPS receivers. In a high noise environment, a simple solution is to decrease the closed-loop bandwidth of the tracking loops since the amount of noise present in the system is directly proportional to the bandwidth. However, as the receiver platform experiences high dynamics, a Doppler shift is induced on the received RF signal. In order to track this shift without error, the bandwidth of the tracking loops must increase. Given these two constraints, there are certain scenarios that will prohibit signal lock from being maintained [3]. In some applications, a loss-of-lock condition is unacceptable, and a backup system must be implemented. Typically, this backup system is a high grade inertial measurement unit (IMU)[4][5]. Unfortunately, these units are often very expensive. Less expensive IMU’s generally have large output errors which degrade the estimate of the platform’s position and velocity. A desirable approach would be a combination of both IMU and GPS that is robust to the stresses posed by high dynamics and high noise while accounting for errors in the inertial measurements. Contrary to use IMU, some advanced signal processing techniques were proposed to directly estimate the carrier frequency for high dynamic trajectories. Hurd etc. [6] compare four different estimation techniques applied to the problem of continuously estimating the rapidly varying parameters of sinusoidal signal. These techniques include an approximate maximum likelihood (ML) estimator, an extended Kalman filter (EKF), a cross-product automatic frequency control loop and a phase-locked loop. Numerical simulations show that the ML and EKF can achieve good tracking at low SNR and high dynamic situations. However, it is not show how to use the estimation to demodulate the received signal. In this paper, a Kalman filter aided phase-lock loop is proposed to address this issue. Doppler derived from EKF is used to aid the carrier tracking loop for improving the performance under dynamic conditions. While the cost is significantly reduced compare with the IMU method. Simulations show that the method is feasible.

The paper is organized as follows. In Section II, the common trajectory and the appropriate signal model used in the simulations is described. Section III presents the description of the proposed Kalman filter aided phase-lock loop algorithm. The performance of the proposed algorithm is investigated by computer simulation in Section IV. Finally, some conclusions are drawn in Section V.

II. COMMON TRAJECTORY AND SIGNAL MODEL

The trajectory used in this paper is the same as in [6], which consists of positive and negative going jerk pulse of 0.5s duration and magnitude of 100g/s, separated by 2s of constant acceleration, as shown in Fig.1(a). The corresponding acceleration and velocity trajectories are shown in Fig.1(b) and 1(c). The initial conditions for acceleration were chosen for symmetric 25g excursions. The velocity trajectory is converted to an equivalent Doppler frequency trajectory as
\[ f_d(t) = \left( \frac{f_c}{c} \right) v_d(t) \quad \text{(Hz)} \]  

Here \( v_d(t) \) is the Doppler velocity, \( f_c \) denotes the carrier frequency (set to 1.5GHz in this paper), and \( c \) is the speed of light.

Consider the input signal of a single channel after sampled in IF with the absence of modulated data, the received signal after A/D may be represented as

\[ r(n) = A P[(1 + \xi)nT_s - \xi T_d] \times \cos[(\omega_0 + \omega_d)nT_s + \phi_0] + N(n) \]  

Where \( A \) is the received signal envelope, which is assumed unite; \( P(\ldots) \) is a \( \pm 1 \) value PN sequences with the rate \( R \), delayed by \( \xi T_s \). For simplicity, we assume the PN sequences have been removed. \( \omega_0 = 2\pi f_0 T_s \) and \( \omega_d = 2\pi f_d T_s \) are the digital radian frequencies corresponding to the Intermediate carrier Frequency(IF) and Doppler shift \( (T_s \text{ is the sampling period}) \), \( \phi_0 \) is the initial carrier phase at \( n = 0 \), and \( N(n) \) is the equivalent input Gaussian noise at IF.

The digital radian frequency corresponding to the Doppler shift has the form of

\[ \theta(t) = \theta_0 + 2\pi(f_0 t + \frac{f_1 t^2}{2} + \frac{f_2 t^3}{6} + o(f)) \]  

Where \( f_0 \) is the Doppler frequency, \( f_1 \) and \( f_2 \) are the second and third derivatives of \( \theta(t) \), corresponding to Fig.1(c), Fig.1(b) and Fig.1(a) respectively.

### III. AIDED TRACKING LOOP STRUCTURE

In [7], Doppler derived from IMU is used to aid the carrier tracking loop for improving the performance under dynamic conditions. Similarly, we use the EKF instead of the IMU to extract the Doppler signal to aid the PLL (Fig. 2). Therefore, the NCO gets its correction signal not only from within the channel, but also from the EKF. This additional signal from the EKF removes the dynamics from the GPS signal. This feature allows the tracking loop bandwidth to be decreased and subsequently keeps the loop in lock. The estimate of the Doppler frequency is injected into the tracking loop after the loop filter but before the NCO as shown in Fig.2.

The whole system work as follows, the received signal from RF Front-end is sampled at 70MHz, and converted to digital signal by AD. A FFT based acquisition unit is used to acquire the approximate code offset and carrier Doppler. Then the digitized signal is send to the tracking loop, using the acquired approximate code offset and carrier Doppler as the initial state. A fourth order Extended Kalman Filter (EKF) (detailed in [6]) has been use to extract the values of various derivatives of \( \theta(t) \), denoted by \( f_0(k), f_1(k) \) and \( f_2(k) \) respectively.

### IV. Performance analysis by computer simulations

If not mentioned, the simulations are use the trajectory defined in section II, the AD samples in 70MHz, and the integrate & dump period is 1ms.

#### A. EKF tracking performance

The tracking performance of the EKF is simulated in an equivalent low pass signal, the EKF used is a fourth order, and the CNR is 40dB-Hz. The total simulate time is 8s.

Fig.3. is an illustration of the EKF tracking performance. It shows that the EKF has good tracking performance in high dynamic situation. The RMS error of the Doppler estimation is 1.31Hz. It has been show in [6] that, the EKF has a threshold about 24dB-Hz, and at CNR 26 dB-Hz, the RMS error of the Doppler estimation is 2.2Hz, which is smaller than the 5Hz error of the IMU used in [7]. So we can say that, this accuracy can be used to aid the tracking loop. Fig.4 is the RMS error of the Doppler estimation in our simulation, which is a bit higher than that in [6]. As we can see, an RMS error
smaller than 5Hz can still be achieved when CNR higher than 30dB-Hz with a suitable $\alpha$ chooses.

B. Tracking Loop’s Performance

The tracking performance of the aided loop is compared with a conventional loop in this section. The conventional loops have a limitation on the dynamics to be handled, and when the dynamics exceed the bandwidth, they switch back to wideband PLL or narrowband FLL (frequency lock loop) temporarily relinquishing the measurements for the navigation algorithm. However, the aided tracking loops remain in the narrowband PLL mode even during high dynamics. Fig.5 shows the plot comparing the two loops with the velocity trajectory defined in section II. While the conventional loops increase in frequency with the input, the aided loops with a bandwidth of only 10Hz maintain almost a constant Doppler. This property of maintaining a stable Doppler irrespective of the input dynamics makes the aided systems attractive in dynamic applications.

Fig.6 shows the plot comparing the two loops in the whole simulate time 8s. The conventional loop uses a 3-order PLL, with the loop band wide enough to track the dynamics (Fig.6(b)). However, this tracking is too rough to be used as the local carrier to perform demodulation, as can be seen in Fig.5 for the detail. The aided loop use an EKF aided 2-order PLL, with the loop band as small as 10Hz. As can be seen from Fig.6(a), the loop filter’s output maintaining a stable Doppler with a little fluctuation. We can also see that, the output of the aided loop is much noisy, and may greatly influence the demodulation process. This undesired result is probably caused by the biased aiding Doppler signal estimated from EKF and must be avoided.

C. Compared with the INS aided system

Compared with the INS aided system, the Kalman aided system can has the following advantages: (1) The EKF can be realized by software in a FPGA+DSP platform, thus greatly reduced the cost compared with the INS; (2) unlike the INS aided system, which need the velocity information about satellite and the receiver platform when calculating the
Doppler, the EKF aided system estimates a synthetic Doppler between the satellite and the receiver, which can be directly used to aided the PLL. However, some disadvantages can also be pointed out: (1) The EKF aided system is sensitive to the noise and the quantificational errors. Jamming signals can influence the EKF, and so to the whole system. (2) Like the inertial aiding of the tracking loops, if the aiding signal does not properly represent the true Doppler, it results in a tracking loop bias, which degrades the phase output of the Costas discriminator. This phenomenon, which is unseen in stand-alone systems, is prevalent in receivers with Doppler aiding. Ultimately, the challenge lies in removing any of the undesired effects created by the aiding signal.

V. CONCLUSION AND FURTHER WORK

An EKF aided carrier tracking loop has been proposed. It can extract the Doppler frequency by EKF, and use this Doppler to aid the NCO in high dynamic situations. The feedback Doppler signal removes most of the dynamics from GPS signals rendering the GPS signal to be ‘almost’ dynamic-free. So, any residual dynamics on GPS signals to be tracked is only due to the local oscillator. As the Doppler due to oscillator is much less, carrier bandwidth can be reduced significantly to improve the accuracy of raw measurements. However, the quality of the aiding Doppler signal is very important in such an aided mechanism, as any bias on this signal degrades the I and Q measurements.

To further increase the performance of this aided loop, some work may be tried: (1) Smoothing the output of EKF to further reduce the influence of the noise in the aiding signal; (2) Some advanced signal processing technique like maximum likelihood estimator (MLE) can be used instead of EKF to increase the estimation accuracy.

REFERENCES