Performance Evaluation of Kalman Filter Based Tracking for the New GPS L5 Signal

C. Mongrédien, M.E. Cannon and G. Lachapelle
Position, Location and Navigation (PLAN) Group
Department of Geomatics Engineering
Schulich School of Engineering
University of Calgary

BIOGRAPHY

Cécile Mongrédien is a PhD candidate in the Department of Geomatics Engineering at the University of Calgary, Canada, where she is a member of the Position, Location and Navigation research group. In 2004, she graduated from ENAC (French University for Civil Aviation), Toulouse, France, as an electrical engineer majoring in digital communications. Her research includes GPS modernization as well as GNSS receiver design.

Dr. Elizabeth Cannon is a professor in the Department of Geomatics Engineering. She has been involved with GPS research since 1984 and has published numerous papers on static and kinematic positioning. She is a Past President of the ION and the recipient of the 2001 Kepler Award. She is now Dean of the Schulich School of Engineering.

Dr. Gérard Lachapelle holds a CRC/iCORE Chair in Wireless Location in the Department of Geomatics Engineering. He has been involved with GPS developments and applications since 1980 and has authored/co-authored numerous related publications and software. More information is available on http://plan.geomatics.ucalgary.ca.

ABSTRACT

The performances of several GPS L5 tracking implementations are evaluated using IF samples obtained with a hardware simulator. The aim of this study is to determine the loop structure and parameters that are most suited to accommodate the various design innovations, such as the data/pilot implementation or spreading sequence definition, inherent to the GPS L5 signal. In particular, the Kalman filter based strategy is compared to the constant loop bandwidth approach for both code and carrier tracking. The analysis is conducted in the presence of various tracking error sources including noise, receiver clock jitter and dynamics. Tracking performances are assessed in the tracking, measurement and position domains with particular attention on carrier tracking and carrier phase measurement accuracy for potential high-accuracy applications.

Results show that, despite the improvements brought by the GPS L5 structure regarding the constant bandwidth approach, the Kalman filter based strategy remains very beneficial in terms of frequency tracking and carrier phase measurement accuracy.

INTRODUCTION

Over the years, the use of GPS during ionospheric storms or in adverse environments has shown the limitations of the GPS C/A signal in terms of tracking sensitivity, accuracy and reliability. To overcome these limitations, and enable GPS signal acquisition and tracking in environments where previously impossible, high sensitivity technologies have been developed. Amongst them, the use of Kalman filter based tracking (and acquisition) have been shown to result in significant sensitivity gain over various constant loop bandwidth implementations (Psiaki & Jung 2002, Humphreys et al. 2005, Yu et al. 2006). While originally introduced for its high sensitivity capabilities, later research demonstrated the ability of Kalman filter based tracking to produce high quality carrier phase measurements (Petovello & Lachapelle 2006), and therefore, its interest for high-accuracy applications.

In the high-accuracy context, several efforts have been made by the U.S. government to provide civilian users with improved position and location services. These efforts encompass the introduction of two new civil signals (namely GPS L2C and GPS L5) and the upgrade of the ground segment. The L5 signal, designed to support safety-of-life applications, is expected to provide the best performance of all GPS civil signals, and is the main focus of this research. In particular, GPS L5 code and carrier tracking performances are expected to be greatly enhanced by the use of a higher chipper rate and the presence of a pilot channel respectively (Hegarty 1999).
In light of the above, the advantages (or lack thereof) of the Kalman filter based implementation for the new GPS L5 signal need to be assessed in terms of accuracy and sensitivity. To this end, raw GPS L5 IF samples have been collected and post-processed using a modified version of GSNR\textsuperscript{TM} (Petovello & O’Driscoll 2007). This software receiver, developed at the University of Calgary, has been modified herein to process L5 samples and to accommodate the structural innovations inherent to this signal. After signal acquisition and FLL convergence, the user can seamlessly choose between constant bandwidth and Kalman filter based tracking.

This global approach enables performance analysis of the GPS L5 signal at various levels and provides a deeper understanding of the impact of code and carrier tracking accuracy at the measurement and position levels, which is the main contribution of this paper.

The remaining of the paper is organized as follows. After a brief review of the L5 signal structure and software receiver implementations, the proposed tracking algorithms and their expected performance are presented in detail. The data collection system is then introduced. The performances of both implementations are then assessed at the tracking, measurements and position levels, with particular emphasis on the carrier phase measurements. Concluding remarks are then provided.

**GPS L5 SOFTWARE RECEIVER DESIGN**

**GPS L5 Signal Structure**

A full description of the GPS L5 signal structure can be found in the GPS L5 Interface Control Document (IS-GPS-705 2005); however its main characteristics are given here for convenience. The L5 signal is transmitted at 1176.45 MHz with a minimum specified received power of -154.9 dBW, equally shared between the two quadrature components. The structure of the signal is given by:

\[
s(t) = \sqrt{2P} \left( d(t)c_{L5}(t)NH_{10}(t)\cos(2\pi f_{L5}t + \phi) + c_{XQ}(t)NH_{XQ}(t)\sin(2\pi f_{L5}t + \phi) \right)
\]

where \(P\) is the total received power, \(d\) is the 100 Hz binary data modulation, \(c_{L5}\) and \(c_{XQ}\) are the 10.23 MHz binary PRN bit stream of data and pilot channel respectively, \(NH_{10}\) and \(NH_{XQ}\) are the 100 Hz and 50 Hz NH bit stream of data and pilot channel respectively \(f_{L5}\) is the L5 carrier frequency, and \(\phi\) is the time-varying carrier phase delay.

The presence of the pilot channel and the use of a faster chipping rate are the two features that are expected to improve GPS L5 tracking performance the most. The pilot channel allows significant phase tracking sensitivity gain since the absence of unknown data bit transition enables the use of both pure PLL tracking and longer coherent integration time. The 10.23 MHz PRN chipping rate helps improve the L5 signal inherent mitigation capacities against noise and multipath.

It is important to note that the introduction of secondary codes (also referred to as NH codes) plays a critical role in narrowband interference mitigation. This, in turn, can provide significant tracking improvement, especially in the L5 frequency band where aeronautical signals (such as DME/TACAN or JTIDS/MIDS) can heavily degrade the received GPS L5 carrier-to-noise ratio (Bastide 2005). Interference effects, however, are beyond the scope of this paper.

**Software Receiver Implementation**

With the exception of the tracking loops, the details of the GPS L5 software receiver implementation details will not be presented herein. As shown in Mongrédien et al. (2006), this software can successfully perform acquisition, tracking, data demodulation and subframe synchronization, and subsequently provide a navigation solution. It is important to note that the biases in the pseudorange measurements and positions mentioned therein have been removed after correction of an error in the satellite clock correction algorithm. Also note that the navigation solution has been extended to provide velocity and Doppler measurement error estimates.

**TRACKING ALGORITHMS**

The main objective of a GPS receiver during signal tracking is to generate a local replica that matches the incoming signal as closely as possible in order to perform, for each channel, effective code and carrier wipe-off and reliable navigation data bit decoding.

![Figure 1 – Schematic Single-Channel Tracking Loop Architecture](Image)

The basic architecture of a single-channel tracking loop is shown in Figure 1. The signal enters the tracking loop after down-conversion, filtering and sampling. The samples are first passed to a correlation and accumulation function where Doppler removal and code correlation are performed over a given period of time. After accumulation, the correlator outputs are passed to an error estimation function that tries to accurately determine the
errors in the code and carrier phase alignment. These estimates are then used, in a feedback loop, to update the code and carrier NCO and drive the local signal generation for the next epoch.

Assuming a known correlator offset $\Delta$ (e.g. for early or late correlators), known data bit transition and small carrier phase and code delay estimate errors, the in-phase (I) and quadra-phase (Q) correlations (on either data or pilot channel) can be approximated as (Holmes 2000):

\[
I = A \cdot I_{\text{nf}} f T D R A I (\delta \phi - \Delta) \frac{\sin(\pi \delta \phi T)}{\pi \delta \phi T} \cos(\delta \phi) + n_I,
\]

\[
Q = A \cdot I_{\text{nf}} f T D R A Q (\delta \phi - \Delta) \frac{\sin(\pi \delta \phi T)}{\pi \delta \phi T} \cos(\delta \phi) + n_Q
\]

where $I_{\text{nf}}$ is the correlation of the local spreading code with the filtered incoming spreading code, $\delta \tau$ is the code delay estimation error, $D$ is the varying navigation data bit sign on the data channel and one on the pilot channel, $\delta \phi$ is the frequency estimation error, $T$ is the coherent integration time, $\delta \phi$ is the average carrier phase estimation error over the integration interval and $n_I, n_Q$ are two independent Gaussian random variables with variance $N_o/4T$ where $N_o/2$ is the Power Spectrum Density (PSD) of the noise at the receiver antenna.

When considering GPS L5 correlator outputs, two particular aspects need to be mentioned. First, due to the width of the main lobe of the L5 signal PSD, it is impossible (as it is often done for GPS C/A) to neglect the effect of front-end filtering. As illustrated in Figure 2 and discussed in Betz & Kolodziecki (2000), the front-end filtering tends to round off the correlation function and limit the benefits of narrow correlator implementation. It therefore partially offsets the advantages of higher chipping rate in terms of noise mitigation.

Second, due to the data/pilot implementation, the GPS L5 power is equally split between the data and pilot in-phase correlators (assuming small carrier tracking errors). To maximize available power and enhance tracking performance, coherent combining of the data and pilot channels is performed at the correlator level (Mongrééden et al. 2006):

\[
X_{\text{comb}} = X_{\text{pilot}} + \text{sign}(D)X_{\text{data}}
\]

where $X$ is the correlation (in-phase or quadra-phase) of the subscripted quantity.

Note that, even though this recombining needs to be performed for each data bit interval (i.e. every 10 ms), it can be extended over longer integration periods. The advantages of this strategy in terms of accuracy, reliability and sensitivity were previously demonstrated (ibid). It is however important to mention that, since this scheme essentially relies on hard data bit sign decision, bit sign error will degrade the correlations and may trigger loss of lock at low signal power. In the frame of high-accuracy application, however, this problem should remain marginal.

**CONSTANT BANDWIDTH TRACKING**

Constant bandwidth tracking refers, in this paper, to code and carrier loops derived originally from control theory. This theory has been developed in the analogue domain, and can only be adapted to the case of a discreet GPS signal within the frame of the continuous update approximation (Kaplan 1996). The discussion that follows is placed within this framework, which limits the range of workable pairs for the values “coherent integration time – loop filter bandwidth”.

While it is understood that both code and carrier tracking loops need to be in lock for the receiver to successfully track the received signal, it is common to study their behaviour individually, assuming perfect tracking from the other loop. First the carrier tracking loop will be described, and a brief sensitivity analysis presented. Then the code tracking loop will be reviewed.

**Carrier tracking**

A typical Phase Locked Loop (PLL) architecture is shown in Figure 3. After code and carrier wipe-off, the in-phase and quadra-phase correlations are passed to a discriminator that estimates the average phase error over the previous integration interval. This phase error estimate is then fed to a low-pass filter that is meant to reduce the noise without removing any useful signal information (such as phase shifts due to dynamic and/or clock jitter). This latter estimate is finally used to update the local carrier NCO and drive the local carrier replica over the next integration period.
Both discriminator and loop filter play a critical role in the overall performance of the PLL. The data/pilot combined correlator used herein can be considered free of unknown transition and therefore a pure PLL discriminator can be implemented. The main advantage of such a discriminator resides in its extended linear tracking region (twice that of a Costas discriminator), and therefore improved sensitivity. Common such discriminators are the coherent and the four-quadrant arctangent. The former is implemented herein, and a 10-Hz third-order loop filter is used to mitigate the noise.

Figure 3 – Schematic PLL Representation

PLL Error Sources

The main error sources in a PLL are thermal noise, oscillator phase noise, oscillator vibration and dynamics.

Thermal noise

The theoretical PLL tracking error variance due to Gaussian noise when using a coherent discriminator (assuming perfect normalization and perfect code tracking) can be expressed as (Julien 2005):

\[
\sigma_{PLL,noise}^2 = \frac{B_T(1-0.5B_eT)}{C/N_0} \int G(f) df \tag{5}
\]

where \( B_T \) is the loop bandwidth, \( C/N_0 \) the carrier-to-noise ratio of the received signal, \( G(f) \) the PSD of the incoming signal, and \( B_e \) the one-sided front-end filter bandwidth.

As shown in equation 5, a smaller loop bandwidth and longer coherent integration time will help reduce the PLL tracking error variance. It is however important to bear in mind that the loop filter bandwidth should be selected so as not to remove any signal dynamic information. Similarly, the coherent integration should be chosen to ensure good loop response to sudden signal change.

Designing the PLL as a frequency locked loop, it is possible to estimate its frequency estimation error as (ibid):

\[
\sigma_{PLL,f}^2 = \frac{\kappa B_T^2 B_e^2}{3} \sigma_{PLL,noise}^2 \tag{6}
\]

where \( \kappa \) is a constant that depends on the loop filter bandwidth.

The frequency estimation error in white noise of a PLL using a coherent discriminator, a 10 Hz loop filter and a 10 ms coherent integration time is shown in Figure 4.

![Figure 4 - PLL Frequency Tracking Error in White Noise](image)

These results are important since they illustrate the typical frequency estimation error of the Doppler measurements derived from the PLL. Additionally, as will be seen in the next section, the PLL is used as an aid to code tracking. Consequently, having an idea of the accuracy of this aiding is important when designing the Delay Lock Loop (DLL). Finally, as shown in Equations 2 and 3, the correlations used in the code and carrier phase tracking loops are affected by the frequency accuracy of the carrier wipe-off. It is then of major importance to know the estimated frequency error in order to have an idea of the degradation that the correlator output will undergo.

The model for other error sources can be found in Irsigler & Eissfeller (2002). It is worth noting that, contrary to thermal noise, signal variations induced by oscillator effects and/or dynamics are better mitigated when using a wider loop filter bandwidth.

On a final note, it is worth pointing that the extended GPS L5 wavelength will help improve resistance to cycle slipping.

Code Tracking

A typical DLL architecture is shown in Figure 5. The principle of a DLL is very similar to that of a PLL. After code and carrier wipe-off, the early, prompt and late correlations are passed to a discriminator that estimates the code phase error over the previous integration interval. This estimate is then low-pass filtered and used in a feedback process to drive the code NCO and local
code generation. As previously mentioned, the code tracking loop implemented herein is aided by the carrier tracking loop; in other words, the carrier NCO rate is scaled to effectively down-convert the Doppler effects at the chipping rate frequency. In this way, the dynamics (and oscillator) effects no longer need to be tracked by the DLL which is therefore only affected by noise and code-carrier divergence effects. Accordingly, the DLL loop filter order and bandwidth can be reduced to maximize noise mitigation.

Again, discriminator and loop filter implementation play a critical role in the overall DLL tracking performance. When considering DLL discriminator design, one of the most important parameter is the early-late spacing. Indeed, as shown in Van Dierendonck et al. (1992), a narrow spacing improves the discriminator inherent noise and multipath mitigation capacities. However, due to the front-end filtering limitations discussed earlier, a 1-chip early late spacing is chosen for the dot-product discriminator implemented herein, and a first-order 1 Hz loop filter is used to mitigate the noise.

![Figure 5 – Schematic DLL Representation](image)

**DLL Main Error Sources**

These consist of thermal noise and dynamics.

**Thermal Noise**

The theoretical DLL tracking error variance due to Gaussian noise when using a Dot-Product discriminator (assuming perfect normalization and perfect carrier tracking) can be expressed as (Julien 2005):

\[
\sigma_{\delta}^2 = \frac{B_i^2}{C} \left(1 - \frac{1}{2} B_i \right) \left[ \frac{\int g(f) \sin^2(\pi f \delta) df}{\int g(f) \sin(\pi f \delta) df} \right]^2 (7)
\]

where \( \delta \) is the early-late spacing.

The standard deviation of the code delay estimation due to white noise when using a dot-product discriminator, a 1 Hz loop filter and a 10 ms coherent integration time is shown in Figure 6.

![Figure 6 – DLL Tracking Error in White Noise](image)

Note that when carrier aiding is used, the effects of dynamics on the code tracking loop can be neglected.

**KALMAN FILTER BASED TRACKING**

The Kalman filter implementation presented herein closely follows that proposed in Petovello & Lachapelle (2006).

**Dynamic Model**

The filter implemented herein directly uses the early, prompt and late correlators’ output to estimate the amplitude, code phase error, initial carrier phase error, initial carrier frequency error and initial carrier acceleration error. This translates into the following state model:

\[
\frac{d}{dt} \begin{pmatrix} A \\ \delta \tau \\ \delta \varphi_0 \\ \delta \alpha_0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \beta & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} A \\ \delta \tau \\ \delta \varphi_0 \\ \delta \alpha_0 \end{pmatrix} + \begin{pmatrix} w_A \\ w_\tau \\ w_\varphi \\ w_\alpha \end{pmatrix} (8)
\]

where \( \beta \) converts units of radians into units of chips and \( w \) is the process noise of the subscripted quantity. In essence, this model uses the carrier frequency and acceleration error to propagate the code and carrier phase. The amplitude and code phase process noise are expected to account for signal level variations and code-carrier ionospheric divergence, respectively. The carrier phase and carrier frequency process noise are expected to

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account for the oscillator jitter effects. Similar to Brown & Hwang (1992), the oscillator frequency noise is modelled through two components, namely white noise and random walk. Finally, the carrier acceleration process noise is expected to account for the receiver-satellite line-of-sight dynamics.

Measurement Model
The Kalman filter measurement model is derived from the correlators’ output expression given in Equations 2, 3 and 4, where the frequency error and amplitude terms are merged, and the average phase error is expanded as:

$$\delta\phi = \delta\phi_0 + \frac{\delta\phi_0}{2} T + \frac{\delta\phi_0}{6} \frac{T^2}{2}$$

where the zero subscript indicates a value at the beginning of the integration period and $$\delta\alpha$$ is the phase acceleration.

When considering this measurement model, three particular aspects need to be further discussed. First, the filtered correlation function is modelled herein using a fifth order polynomial. In addition to accurately model the front-end filtering effects, this approach alleviates slope discontinuity issues (present in the triangular correlation function) and ensures numerical stability of the filter. Second, a hard data bit sign decision is implied through the use of the data/pilot combined correlator. Finally, the noise correlation between the early, prompt and late correlator outputs is accounted for in the measurement covariance matrix.

Expected Advantages of Kalman Filter Based Implementation
The expected benefits of the Kalman filter implementation are two fold. First, by weighting the quality of the prediction against that of the measurements, the Kalman gain (which is recomputed prior to each tracking loop update) effectively provides adaptive bandwidth filtering. This should therefore minimize the need for longer coherent integration time. Second, the dynamic and measurement models offer a unique opportunity to utilize any prior information about the operating environment of the receiver (e.g. oscillator used, expected level of receiver dynamics, front-end filtering).

TEST DESCRIPTION
To evaluate both tracking implementations several data sets have been used. All were obtained using the Spirent GSS 7700 Hardware Simulator. Although this simulator is capable of producing RF samples at the L1, L2 and L5 frequencies, only the latter was simulated. All data set were collected using the same 10-satellite base scenario with variations in the satellite signal power profiles, and receiver dynamics. Each scenario lasted typically less than two minutes.

Data Collection System
The data collection setup is shown in Figure 7. The signal from the simulator is passed to a NovAtel Euro-L5 card that acts as the front-end to the software receiver (the NovAtel card is also a four channels GPS L5 receiver). L5 samples (using 2-bits quantization) are tapped at a rate of 56 MHz. These samples are then repackaged into a more compact format using an FPGA card before being passed to the data acquisition card. This card then stores the samples into files for later processing. In addition, an external oscillator is used to drive the NovAtel card.

Figure 7 – Data Collection Set-up
The use of a hardware simulator provides a highly controllable and repeatable test environment. The errors simulated herein are those relevant to the tracking context. The satellite induced and atmospheric errors that mostly translate into ranging biases are not simulated herein. It is noted that although ionospheric scintillations could affect tracking performance, they are not studied herein as the Spirent 7700 does not have this capability. Errors under consideration are therefore noise, oscillator phase noise and dynamics.

Performance Evaluation
To determine the code and carrier tracking accuracy, the following approach is taken. Using the known position and velocity of the receiver, true pseudoranges and Doppler measurements are computed for each satellite. These values are then compared to the ones obtained from the tracking loops and the differences used to form an estimated measurement error. In the absence of ranging
errors, the measurement error variance is a direct measure
of the tracking variance.

It is important to note that this statement only holds true
insofar as the satellite velocity and position are correctly
estimated. To verify this, the values computed by the
software receiver are time-matched and compared to the
simulated ones (given by the hardware simulator). The
agreement was found to be at the millimetre and sub
millimetre per second for position and velocity
respectively.

Another limitation inherent to this test set-up is the
accuracy of the hardware simulator itself. This accuracy is
mostly limited by the quality of the clock used. The
quoted accuracies are 1 cm and 1 mm/s RMS for the
pseudorange and pseudorange rate errors (i.e. Doppler)
respectively. It is important to bear in mind that these
accuracies account for errors in simulated satellite
induced and atmospheric biases; in the scenarios
considered herein, the accuracy can be expected to be
higher. Complete anticipated accuracies can be found in

KALMAN FILTER BASED IMPLEMENTATION
VALIDATION

The first step in assessing the Kalman filter based
tracking performance is to ensure that the filter can
accurately track signals, at high $C/N_0$. In the base scenario
used, the estimated $C/N_0$ for all satellites varies between
45 and 48 dB-Hz.

As illustrated in Figure 8, the Kalman filter based tracking
can track the PRN Doppler frequency more precisely than
the constant bandwidth PLL. The results shown for PRN
15 are representative of all the simulated satellites.

Figure 8 – Estimated Doppler for PRN 15 Using the
Constant Bandwidth and Kalman Filter Based
Tracking Implementation

In addition, the phase error estimation is computed for
every satellite. It is defined as the difference between the
average phase error estimated by the Kalman filter (i.e.
the initial carrier phase, frequency and acceleration errors
propagated through the integration interval) and the true
average phase error contained in the correlator output.

Figure 9 – L5 Carrier Phase Estimation Error for All
Satellites

Figure 9 shows the carrier phase estimation error, scaled
to units of length. As can be seen, after convergence, the
results are at the sub-millimetre level (1σ), and the RMS
across all satellites is 0.3 mm. This confirms that the
Kalman filter based tracking implementation is able to
accurately track both the phase and frequency of the
incoming signal carrier.

PERFORMANCE IN NOISE

To evaluate the performance of the Kalman filter based
tracking implementation in the presence of noise, more
sophisticated scenarios are used. Namely, two different
signal power profiles are implemented. They are
illustrated in Figure 10 and Figure 11 respectively.

In the first power profile, the signal power is dropped
progressively (1 dB/s) for three different satellites and
subsequently held constant. In the second power profile,
the signal power is dropped for a single satellite in three
5-dB steps. In both cases, the power of the remaining
satellites is held constant in order to maintain high quality
clock bias and clock drift estimates.

Figure 10 – Signal Power Profile 1 for All Simulated
Satellites Relative to -154.9 dBW
The estimated Doppler and pseudorange (PR) error standard deviation (STD) obtained using Power Profile 1 are shown in Figure 12 and Figure 13 respectively.

It appears in the Figure 12 that, in terms of frequency tracking, the Kalman Filter based implementation outperforms its constant bandwidth counterpart by approximately one order of magnitude across the various C/N₀ and coherent integration times tested. It also shows that the frequency tracking errors derived from the Kalman filter based implementation have little susceptibility to C/N₀ and/or coherent integration time variations. On the contrary, the frequency tracking errors derived from the constant bandwidth implementation increase with decreasing coherent integration times and/or C/N₀, which is in accordance with the theoretical derivations shown earlier.

It is worth noting, however, that the deficiency of Kalman filter based code tracking accuracy could easily be circumvented using its superior carrier tracking accuracy. This could be done, at the measurement level, using carrier smoothing; or, at the position level, using a Kalman filter based navigation algorithm that would make use of the Doppler and velocity estimates to propagate the position. The former would be particularly beneficial since, as illustrated in Figure 14, the Kalman filter based carrier phase measurements are much more accurate than their constant bandwidth counterpart. This result is consistent with the improvements observed earlier on the carrier tracking.

The static results presented herein demonstrate the advantages of the Kalman filter based implementation for tracking errors increase with decreasing coherent integration times and/or C/N₀. This behaviour is expected for the constant bandwidth implementation but not for the Kalman filter based implementation.
carrier phase and frequency tracking and thus for high accuracy applications.

PERFORMANCE IN PRESENCE OF OSCILLATOR CLOCK ERROR

To illustrate the influence of oscillator modelling in Kalman filter based tracking, the three different clock models, shown in Table 1, are used to process a unique data set.

Table 1 – Oscillators Parameters (Winkel 2003)

<table>
<thead>
<tr>
<th>Oscillator Parameters</th>
<th>Quartz</th>
<th>OCXO</th>
<th>Rubidium</th>
</tr>
</thead>
<tbody>
<tr>
<td>h₀ [s]</td>
<td>2e-19</td>
<td>8e-20</td>
<td>2e-20</td>
</tr>
<tr>
<td>h₋₁ [Hz]</td>
<td>7e-21</td>
<td>2e-21</td>
<td>7e-24</td>
</tr>
<tr>
<td>h₋₂ [Hz]</td>
<td>2e-20</td>
<td>4e-23</td>
<td>2e-23</td>
</tr>
</tbody>
</table>

As mentioned earlier, the white frequency noise (or equivalently phase noise random walk) h₀, and frequency noise random walk h₋₂ are the two noise processes effectively used to model the clock behaviour. It is important to note that, for the typical tracking time intervals (i.e. less than 1 s), the behaviour of the oscillator is mostly influenced by the white frequency noise component (Julien 2005).

The results for various CN₀ and coherent integration times are shown in Figure 15.

As shown in Figure 15, the Kalman filter based implementation performs best when an OCXO model is used. This was expected as the oscillator used is an OCXO. It is interesting to note that, despite significant parameter differences, the quartz and rubidium models provide similar results. This underlines the importance of proper clock modelling when using a Kalman filter based tracking implementation.

PERFORMANCE IN PRESENCE OF RECEIVER DYNAMICS

To analyse the influence of dynamics on both tracking implementations, the receiver is set to travel eastward with a constant velocity of 5 m/s (after a static period and a short acceleration). Additionally, the first signal power profile is used.

Figure 16 illustrates both the impact of vehicle dynamics and thermal noise on the Doppler for PRN 24. It can be seen that both implementations are able to accurately follow the vehicle dynamics, but that the constant bandwidth implementation suffers significant degradation due to the decrease in signal power.

As shown in Table 2, the resulting velocity estimates are much more accurate when using Kalman filter based tracking.

Table 2 – Velocity Estimation Errors in the Presence of Receiver Dynamics

<table>
<thead>
<tr>
<th>Velocity Estimation Error</th>
<th>Kalman Filter Based Tracking</th>
<th>Constant Bandwidth Tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>East [cm/s]</td>
<td>0.5</td>
<td>4.4</td>
</tr>
<tr>
<td>North [cm/s]</td>
<td>0.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Up [cm/s]</td>
<td>0.4</td>
<td>14.3</td>
</tr>
</tbody>
</table>

The results obtained in the presence of receiver dynamics are consistent with the one obtained in the static case, and confirm the superiority of Kalman filter based tracking for Doppler and velocity estimation.
CONCLUSION

Several tracking algorithms were implemented and tested using a GPS L5 hardware simulator and a GPS L5 software receiver.

The constant bandwidth algorithm was implemented in order to capitalize on the L5 signal structure innovations (i.e. use of a faster chipping rate and the presence of a pilot channel) as much as possible. The achieved accuracy is in line with the theoretical tracking bounds derived from control theory (within the limits of the continuous update assumption).

The Kalman filter based implementation was selected to minimize non-linear operation and allows the best versatility possible. The Kalman filter’s ability to accurately track the phase and frequency of the incoming signal carrier was demonstrated. It was shown that, in the presence of white Gaussian noise and oscillator phase noise, the Kalman filter based implementation outperforms its constant bandwidth counterpart for carrier tracking, but that it was the opposite for code tracking. The latter however is believed to stem from an implementation issue rather than from inherent characteristics of the aforementioned tracking implementation. It was furthermore demonstrated that the code accuracy limitations of the Kalman filter based implementation could easily be circumvented.

Finally, it is important to recall that the overall performance of the Kalman filter based tracking implementation is greatly conditioned by the accuracy with which the various process noise models can reproduce the actual receiver operating environment.

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