USING ADAPTIVE FILTERS FOR GPS RECEIVERS

Elton Mendes de Souza[1] and Humberto Abdalla[2]
1: University of Brasilia (elton_souza@hotmail.com), 2: University of Brasilia (abdalla@ene.unb.br)

ABSTRACT

A satellite moving in relation to a GPS receiver generates a shift in the carrier frequency and the C/A code signal reception. This deviation is know as the Doppler effect and it varies in time depending on the relative acceleration of the GPS satellite/receiver and it can hinder or even preclude data reception. This paper presents an approach to mitigate this problem, with the insertion of adaptive filters in the tracking loops in order to use conventional GPS receivers in systems subjected to low and high accelerations. The results are compared with those obtained from the use of non-adaptive filters.

I. INTRODUCTION

Nowadays there are two navigation systems in full operation: the Global Positioning System, called GPS (Global Positioning System) developed by the United States; and the Russian system called GLONASS (Global Navigation Satellite System). This study is limited to the GPS system due to its greater use among the spatial navigation systems in the world [9].

Two situations are associated with user displacement while tracking the influence of browsing data: low and high dynamics.

Low dynamic situations occur when the GPS receiver is stationary with respect to Earth's surface or when the relative speed of the satellite/receiver GPS system is low. Examples of such situations: road traffic, shipping and commercial aviation. The relative speed between the user and the satellite causes a change in the frequency collected by the receiver. This effect is the same that occurs with frequency distortion of the sound of an ambulance that at first approaches and then moves away from an observer. When the ambulance approaches the observer feel the keenest sound indicating an increase in the frequency received. When the ambulance departs the observer feels the bass sound indicating a decrease in the frequency received. This behavior in the received frequency is also observed in all satellite transmission systems and should be minimized, as well as noise in the receiver, to enable correct reception of the data sent. This is called the Doppler effect and a variation of relative speed (acceleration) represents a variation of Doppler shift in time, that represents a variation of the received frequency. Low dynamic situations involving low accelerations, what means that the variation of the Doppler shift generated is also low, therefore, the concern with this effect is smaller than in situations of high dynamics.

High dynamic situations appear, for instance, in military aviation, launching rockets and missiles, in which the accelerations involved can be compared to the accelerations of the satellites. In those cases, the variation of the Doppler shift in the GPS signal is much larger than in low dynamic situations and if not corrected it may impair the reception, and it may become unviable.

In order to trace data and determine the user's position, commercial GPS receivers generally use PLLs (Phase-Locked Loop) for tuning the frequency received from the GPS signal, composed of carrier frequency added to the Doppler shift in frequency. For this case, PLL uses fixed filter coefficients which determine the order of the system and influence the bandwidth, which is related to the amount of additive noise present in the input signal reception step [2].

This work seeks to evaluate the signal tracking performance through PLLs that have adaptive forward filter coefficients compared to fixed filter coefficients. In the tracking program, these adaptive coefficients are updated according to its own natural frequency (directly proportional to bandwidth) in the PLL which in turn varies the action of the Doppler shift caused by relative acceleration of the receiver-satellite system.

The work entitled The Combined Adaptive Filter Tracking Receiver Design for High Dynamic Situations, published in Position, Location and Navigation Symposium, 2008 IEEE / ION is a reference in the area of adaptive tracking GPS signals. It uses Kalman filters to obtain the adjustment of the tracking. The adaptive filter developed here is different and is obtained from the update of the coefficients of a filter Butterwoth, which is characteristic of the PLL for commercial receivers, depending on the conditions and Doppler noise of the GPS signal at the input of the tracking process, making it more simpler and faster.

This paper is structured as follows:

- The Section II presents the characteristics of the GPS signal emphasizing the formatting of the transmitted signal and the diagram of the receiving system;
- In Section III, the tracking is discussed, as it is responsible for determining the navigation data, decrease the influence of the Doppler effect and noise on the GPS signal;
- The Section IV presents the use of PLL with constant coefficients in commercial GPS applications;
- In section V a constant coefficient filter is modified to adapt its coefficients to the Doppler and Noise conditions to which the receiver is subjected;

- In Section VI and VII the results are presented and discussed in order to find the best settings to use the adaptive filter;
- The Section VIII we propose a conclusion on the application of adaptive filter by comparing it with the use of non-adaptive filter in commercial GPS.

II. Characteristics Of The GPS Sinal

The transmission of the GPS signal between the satellites and the receivers uses the CDMA (Code Division Multiple Access) multiplexing technique. Each satellite transmits a signal containing the precision code (P), for military use, the general code (C/A - Coarse / Acquisition) for civilian use and navigation data. The signals are transmitted on two carriers, L1 = 1575.42 MHz and L2 = 1227.6 MHz, both multiple clock frequency of 10.23 MHz [1].

In the transmission process, the L1 carrier frequency contains the C/A and P signals, while L2 carrier frequency contains only signal P. As the L2 carrier contains only the P code for military use, the analysis developed takes into account only the L1 carrier. Function of time, C/A and P signals in L1 are in phase quadrature and can be written as:

$$S_{L1}(t) = A_p P(t) D(t) \cos(2\pi f_1 t + \phi) + A_c C(t) D(t) \sin(2\pi f_1 t + \phi) \qquad (1)$$

where to code P, A_p is its amplitude, *P(t)* is the code itself, *D(t)* data, for the code C/A, A_c is its amplitude, C*(t)* is the code itself. As the work seeks applications involving only the C/A code, the first term of the sum (1) will be neglected [6].

The C/A code has the characteristics of a pseudo-random noise (Pseudorandom Noise - PRN) with a bit rate code (chip) 1023 kchips/s, repeated every 1s codes or 1023 chips[1].

As for the navigation data signal *D(t)*, each bit of information has a duration of 20 ms, which means that the frequency of the data signal is 50 Hz [1].

The Figure 1 shows the basic diagram of a GPS receiver. The signals are picked up by the antenna and separated into different channels. Each channel contains a signal of a specific satellite to be amplified, converted to an intermediate frequency and digitized. In the acquisition step, the input signal is correlated with the locally generated signal to confirm the presence of a GPS signal. In the acquisition, the beginning of the C/A code is also determined, and the Doppler shift that will be passed to the tracking is estimated [1].

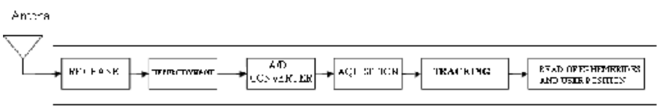


Figure 1. Basic structure of a GPS Receiver.

III. The Tracking

The tracking step lasts 500 ms and it is obtained by browsing data. To minimize the Doppler shift, taking into account the estimate submitted in the acquisition stage, it is necessary to remove the C/A Code, due to the phase shift that it causes to the carrier.

In order to track the GPS signal, it uses two PLL loops working chained, that will be shown separately, for explaining purposes. The first loop will track the C/A code (Code Loop), Figure 2. This loop works with digital signal correlations, by analogy to the PLL, it is called DLL (Digital Locked Loop). The second loop will track the carrier (Carrier Loop) and minimize the Doppler effect, obtaining the information signal, Figure 3.

In Figure 2 and Figure 3 the terms Early, Aligned and Late refer to C/A code signals generated internally by reference, with delays of +1/2, 0 and -1/2 chip, respectively. The code loop uses these signals in correlation with the input signal and subsequently the code discriminator determines a parameter to update the C/A signal internally generated in the next iteration of the system [8].

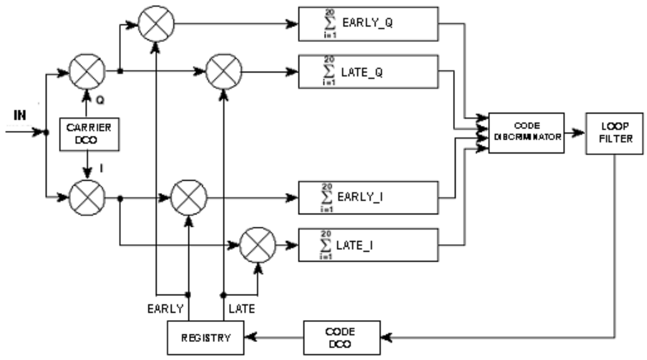


Figure 2. Code Loop.

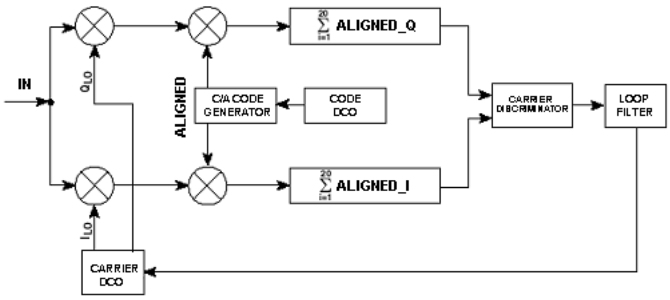


Figure 3. Carrier Loop.

In Figure 3 it can be seen that both loops use the in-phase (I) and quadrature (Q) demodulation of the input signal (IN). The intention is that the tracking of the navigation data and the provision of an error parameter for frequency and phase between the input and reference signals and. In Figure 4 the application of the I/Q demodulation is shown for these cases:

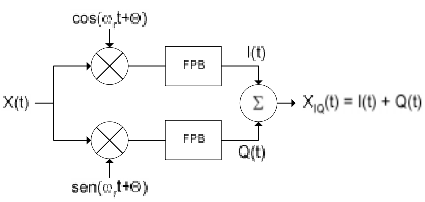


Figure 4. I/Q demodulation.

The signal *X(t)* is defined by equation (2), where D(t) is the data signal modulated by a carrier ω_p and $n_i(t)$ and $n_q(t)$ are the in-phase and quadrature components of the noise band pass [3]:

$$X(t) = D(t)\cdot\cos(\omega_p t) + [n_i(t)\cdot\cos(\omega_p t) + n_q(t)\cdot\sin(\omega_p t)] \tag{2}$$

It is considered that the error frequency ω_e is relatively small and is given by the difference [3]:

$$\omega_e = \omega_r - \omega_p \tag{3}$$

The signal in phase I(t) is obtained by multiplying the input signal *X(t)* by the reference signal $\cos(\omega_r t + \theta)$ after passing through a filter to obtain [3]:

$$I(t) = \frac{1}{2}[D(t) + n_i(t)]\cos(\omega_e t + \theta) + \frac{1}{2}n_q(t)\sin(\omega_e t + \theta) \tag{4}$$

where θ is the phase difference between *X(t)* and the reference.

Similarly, the quadrature signal is obtained by multiplying the reference signal $\sin(\omega_r t + \theta)$ resulting [3]:

$$Q(t) = \frac{1}{2}[D(t) + n_i(t)]\sin(\omega_e t + \theta) + \frac{1}{2}n_q(t)\cos(\omega_e t + \theta) \tag{5}$$

The signal $X_{IQ}(t) = I(t) + Q(t)$ whose phase angle is indicative of the error between the input signal and the reference signal is obtained from (4) and (5). The error indicator is obtained [3]:

$$\theta_e(t) = k_p \arctan\left(\frac{Q(t)}{I(t)}\right) \tag{6}$$

where k_p is the gain of the discriminator. Once done closing the loop with the minimization of ω_e and θ the channel in phase contains the data plus noise while channel quadrature contains only noise, as (7) and (8) [3].

$$I(t) = \frac{1}{2}[D(t) + n_i(t)] \tag{7}$$

$$Q(t) = \frac{1}{2}n_q(t) \tag{8}$$

IV. PLL WITH NON ADAPTATIVE FILTERS

In GPS, PLL operates in the recovery of the carrier and C/A code from a reference signal with BPSK (Binary Phase Shift Keying) modulation. The basic structure of a PLL is shown in Figure 5. The voltage controlled oscillator (VCO) produces a signal *v(t)* that follows the phase of the input signal *y(t)*. The phase detector generates the signal *e(t)* that is the phase error between the input *y(t)* and the output of the VCO, *v(t)*. The resulting error signal may be filtered to become a control signal, *c(t)* for the VCO. Then, the control signal acts to compensate for the difference between the phases of the VCO and the phase of the input.

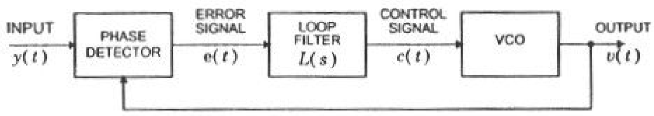


Figure 5. Laço de Portadora.

The transfer function H(s) is given by, where *s* is Laplace variable:

$$H(s) = \frac{k_0 k_1 L(s)}{s + k_0 k_1 L(s)} \tag{9}$$

where *L(s)* is the filter adopted in the loop and k_1 and k_0 are the gains of the VCO and Phase Detector, respectively [2].

The filters L(s) are active proportional integral types, where τ_1 and τ_2 are the filter coefficients [1].

$$L(s) = \frac{s\tau_2 + 1}{s\tau_1} \tag{10}$$

The system is allowed to be of second order and underdamped, where the transfer function is [1]:

$$H(s) = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{11}$$

where ζ is the damping factor and ω_n the natural frequency.

From (9) and (10) and comparing to (11) we obtain:

$$\zeta = \frac{\omega_n \tau_2}{2} \tag{12}$$

$$\omega_n = \sqrt{\frac{k_0 k_1}{\tau_1}} \tag{13}$$

It can be demonstrated that the noise equivalent bandwidth is given by [3]:

$$B_n = \frac{\omega_n}{2}\left(\xi + \frac{1}{4\xi}\right) \tag{14}$$

where B_n and ω_n are directly proportional.

As already said, a receiver subjected to different accelerations causes variations of Doppler shift. If the variation of the Doppler shift in a time interval is moderate and less than B_n the system will track the signal. The tracking will remain possible for offset values just above the value of B_n. But if the deviation continues to increase, the system may lose tracking [1]. Thus, for purposes of tracking data, the non-adaptive filters have a B_n not adjustable due to τ_1 and τ_2 fixed values.

V. PLL WITH ADAPTIVE FILTERS

The width of B_n regulates the amount of noise present in the tracking, but the greater the amplitude of tracking, the more robust is the tracking against the Doppler shift. Therefore, the bandwidth should be appropriate to the level of noise and Doppler shift so as not to compromise the reception of the navigation data.

The PLL systems are systems of 2nd order to 1st order filter where the coefficients can be written as a function of the natural frequency ω_n and damping ζ. Observing (12) and (13) we obtain:

$$\tau_1 = \frac{k_0 k_1}{\omega_n^2} \quad (15)$$

$$\tau_2 = \frac{2\zeta}{\omega_n} \quad (16)$$

Keeping the value of the damping fixed at 0.707 [3], the coefficients are dependent on the natural frequency which is calculated at each iteration of the tracking program [10] in function of the variation of the Doppler shift caused by the relative acceleration of the satellite/receiver system and the influence of additive noise. Then for each value of ω_n, by (14), we can calculate a value for B_n accompanying the Doppler shift of the signal at the time, or rather, in each integration period of the system a filter is obtained, in which coefficients are adapted to the condition of speed variation on the system satellite/receiver [7].

VI. RESULTS

To analyze the influence of adaptive filters in the process of tracking of navigational data received, three scenarios were constructed.

Scenario 1: Using adaptive filters in both loops.

Scenario 2: Using adaptive filter only in the carrier loop.

Scenario 3: Using adaptive filter only in the code loop.

The results obtained in the three cases are compared qualitatively (graphical analysis) with the tracking process of non-adaptive filters loops.

For the analysis (Figure 6), a random sequence is generated simulating navigation data transmitted by the satellite to the receiver without noise. The navigation data collected at the receiver to perform the tracking contains navigation data and additive noise with power of -130 dBm (minimum power to work with GPS) and -111 dBm, respectively. The receiver is subjected to a constant acceleration seven times the acceleration of gravity, where the Doppler shift of the carrier and the C/A code is shown in Figure 6. For the tracking period of 500 ms this is exactly equivalent to what is graphically represented in the graphs of Doppler-Code and Doppler-Carrier, Figure 6, which showed variations of 180 Hz and 0.12 Hz, respectively [1].

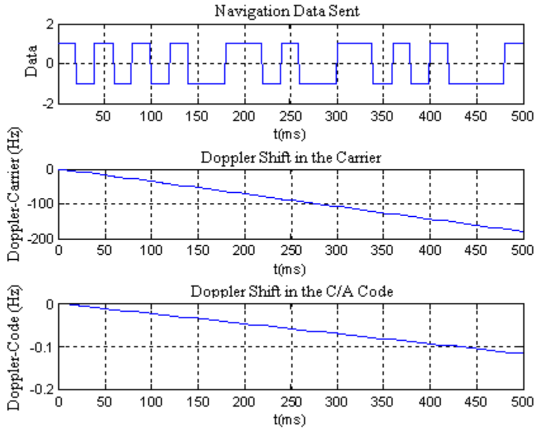


Figure 6. Navigation Data Sent and Doppler Shift in the Carrier and in the C/A Code

For the output signal of the tracking, a graphical analysis is performed, where the navigation data tracked, the frequencies generated from VCOs and their respective errors for carrier and code loops are shown. The frequency and the error of the PLL and DLL links refer, respectively, to the frequency generated by the internal oscillators (VCOs) and the error parameter obtained in the discriminator in each loop.

Initially, Figure 7 shows the case (graphical reference) where the non-adaptive filters are used. Later in Figure 8 we show the results obtained for Scenario 1 where adaptive filters are used in the code and carrier loops. The following Figure 9 represents the Scenario 2 where the adaptive filter is present only in the loop carrier. Finally in Figure 10, the results obtained for Scenario 3 which uses adaptive filters only in the code loop.

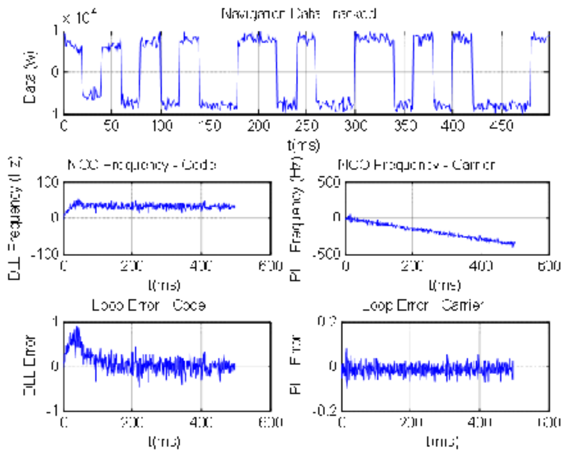


Figure 7. Reference – Tracked Data –Loop of Not Adaptive Filters

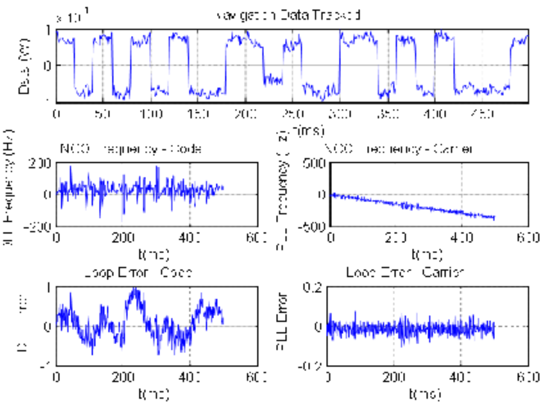


Figure 8. Scenario 1 – Adaptive Filter in the Carrier and Code Loops.

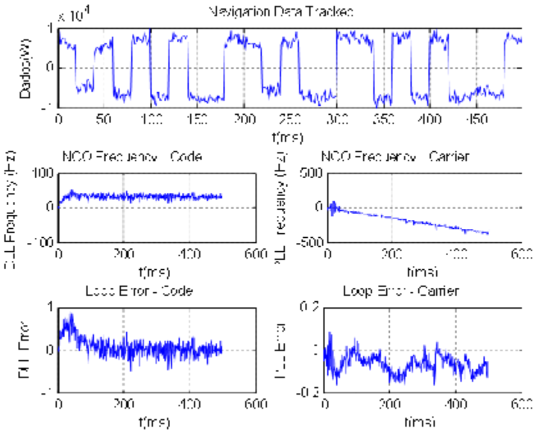


Figure 9. Scenario 2 – Adaptive Filter in the Carrier Loop.

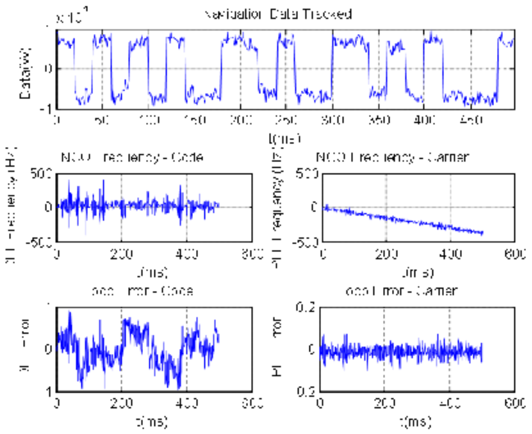


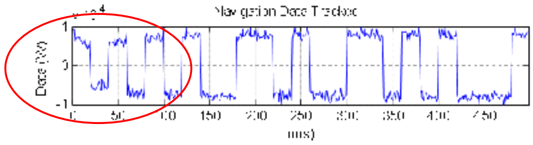
Figure 10. Scenario 3 – Adaptive Filter in the Code Loop.

VII. ANALYSIS OF RESULTS

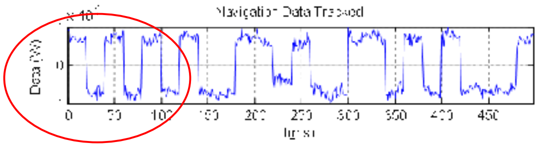
Compared to the reference, the first result observed is that in all three scenarios which used the adaptive filter, the data were screened, although there were some distortions in the appearance of the error signal of PLL and DLL.

For the results presented, several comparisons can be made with reference and various scenarios pointed out, but for high dynamic systems, two comparisons were outstanding, because they deal with the speed that performs tracking and combats noise effect.

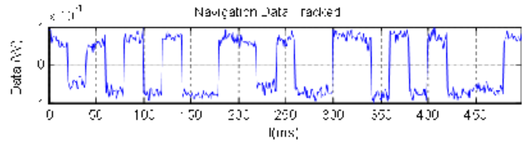
The first comparison is made between the reference in Figure 7 with Scenarios 1 and 3, where it is observed that the graphic tracked data for (Figure 8 and 10) in the first 100 ms reached the maximum amplitude in less time without oscillation.



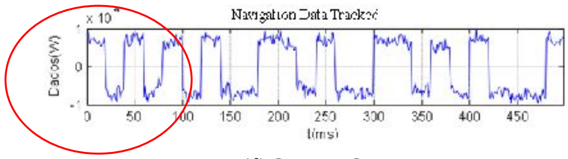
(a) Reference.



(b) Scenario 1.



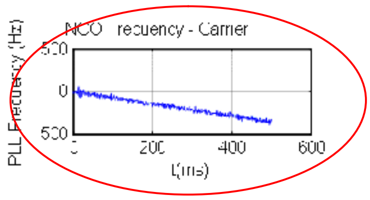
(c) Scenario 2.



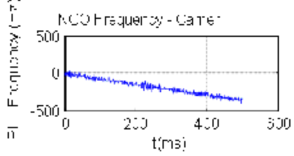
(d) Scenario 3.

Figure 11. Data Tracked

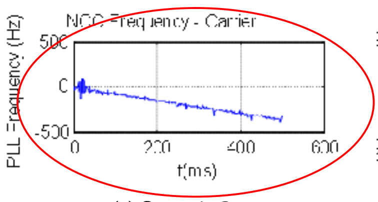
The second comparison is made between Scenario 2 in Figure 12(c), where it is possible to observe a decrease in the presence of noise in the curve of the VCO frequency compared to the reference Figure 12(a).



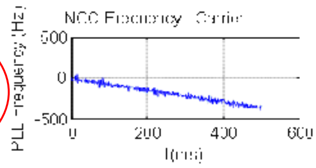
(a) Referency



(b) Scenario 1



(c) Scenario 2



(d) Scenario 3

Figure 12. Freqüência do NCO de Portadora

VIII. CONCLUSIONS

This work demonstrates the use of adaptive filters in the tracking of navigation data under the influence of Doppler shift and noise, because they are the major factors that can disrupt the tracking data in the GPS system. Several configurations were analyzed using three different scenarios. The coefficients of these filters have been updated in function of their own bandwidth required for tracking data influenced by the Doppler shift. The choice of whether or not use the adaptive filter will depend on the application for which the receiver is used. For applications high dynamic where it is desired rapid tracking data (for example, in aircraft attitude determination), the settings of Scenarios 1 and 3 are the most suitable, because the tracking data with the maximum amplitude in less time decreases the probability of a false interpretation of noise with real data tracked. As for applications low dynamics where you want a more precise position of the user (for example, georeferencing applications and determination of geographic areas), the most appropriate would be Scenario 2 due to the decreased presence of noise. Thus, to obtain the navigation data in a shorter time and combating noise, the use of the adaptive filter was efficient. Finally it can be also asserted that the inclusion of adaptive filter in tracking loop can allow the use of the C/A code for applications that were restricted to code P. The results demonstrate the potential of integrating adaptive filtering techniques for mitigating the frequency offsets arising from high dynamic systems. Although the results are encouraging further studies are needed to quantify objectively the actual improvement achieved with the embracement of adaptive filters, for example, the study of the behavior of the use of adaptive filters in a receiver subjected to acceleration variable in time.

REFERÊNCIAS

[1] TSUI, J. B., Fundamentals of global positioning system receivers: a software approach, Wiley Interscience Publications, NY, 2000.

[2] EGAN, W., Phase-Lock Basics, Wiley Interscience Publications, New York, 1998.

[3] VILLALBA C., L. F., Receptor GPS por software, Tese de Mestrado, 104f, Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, 2004.

[4] VILLALBA, L.; WALTER, F., Receptor GPS por Software, Anais do IX Encontro de Iniciação Científica e Pós-Graduação do ITA, 2003, São José dos Campos.

[5] PERONI, R., Fundamentos de GPS, Faculdade do Noroeste de Minas, maio 2004, http://minx.com.br/manual_GPS.pdf

[6] WALTER, F., "Equações Básicas do GPS", Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brasil, 2002

[7] HAYKIN, S., Adaptive Filter Theory Terceira edição, Prentice Hall, Upper Saddle River, NJ, 1996.

[8] PARKINSON, B., Spilker, J., "Global Positioning System: Theory and Applications", Volume 1, American Institute of Aeronautics and Astronautics, Inc., Washington, DC, 1996, chapter 4, pp 125-160.

[9] KAPLAN, E., "Understanding GPS: principles and applications", Artech House Publishers, Norwood MA, 1996, chapter 2, pp 50-85

[10] PLAUSINAITIS D. , AKOS D. M., SoftGNSS, 3th version, 1999

[11] BARRY J. R., LEE E. A., MESSERSCHIMITT D. G., Digital Communication, 3th edition, 2004.