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Improving the performance of the carrier tracking loop for GPS receivers in presence of transient errors due to PVT variations

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Abstract—The increase in integration density and the requirement of low power supplies to reduce energy consumption can make circuits more and more sensitive to upsets errors. The loss of robustness increases with process/voltage and temperature (PVT) variations. This paper ¹ shows that the impact of errors that appear when computing the estimation of the Doppler offsets in a GPS application can be greatly reduced by tuning appropriately the carrier filter bandwidth. The effectiveness of the proposed was proven by comparing the performance a faulty GPS receiver to a non-faulty (noisy-free) GPS receiver at two levels: the standard deviation of the tracking error variance (by theory and by simulation) as well as the standard deviation between positions given by the faulty (noisy) and non-faulty (the noiseless) GPS receivers. Modifying properly the optimal filter bandwidth values gives astonishing results in terms of robustness against errors. The modification of the bandwidth filter values introduces almost no position degradation in a noise-free GPS receiver (only 11 cm in average). With 40 % of error, the standard deviation of the error in the position does not exceed 2 m by increasing the PLL bandwidth while the tracking loop does not support more than 6% of errors.

I. INTRODUCTION

During the last decades, increased advancement of CMOS technology coupled with process/voltage/temperature (PVT) variations, have made internal upsets on devices more frequent [1]. These upsets manifest as momentary fault in the device's behavior and their occurrence can significantly affect the circuit performance and output states. Until today, this problem has mostly been addressed at the lower design level by proposing resilience techniques to protect particular components. Examples are Razor flip-flops [2] to detect signal delay errors, double sampling [3] for combinational circuits, error correcting codes used first to protect memories [4] and then applied for interconnect networks [5], and TIMBER (Time Borrowing technique) [6] that masks timing error by borrowing time from successive pipeline stages without requiring hardware support. Predictions techniques, such as Algorithmic Noise Tolerance (ANT) technique [7], propose to increase the reliability of circuit by adding a reduced precision replica to the original function. This reduced precision replica consumes much less

power than the original function. The final output is chosen between the original function output and the output of the replica. Only in extremely critical applications, such as space, avionics and healthy applications, where the system cost is less important than its reliability, Triple modular redundancy (TMR) [8] is proposed. Fault tolerance has been studied for mobile systems to build mobile devices more robust to transient errors due to PVT variations. For example, the authors of [9] propose some resilience techniques for double-iterative Multiple-Input Multiple-Output Bit-Interleaved Coded Modulation (MIMO BICM) receivers. These techniques have been realized on different layers of abstraction in order to have a mutual trade-off of system performance, hardware reliability and implementation complexity.

Global Positioning System (GPS) is a well known-technology that allows determining both the physical position and the absolute time of a receiver. GPS signals are made of three components: spreading code, navigation message and carrier. The analytical expression of the transmitted signal of a satellite a is

$$e_a(t) = c_a(t) d_a(t) e^{2\pi j f_{L1} t} \quad (1)$$

, where

- $d_a(t)$: navigation message of the a^{th} satellite,
- $c_a(t)$: a^{th} Coarse/Acquisition (C/A) satellite spreading code with a Binary Phase Shift Keying (BPSK) modulation (i.e. $c_a \in \{-1, 1\}$),
- f_{L1} : the carrier frequency in the L1 GPS Band (Open Service).

In the receiver side, the GPS incoming signal is first demodulated by a frequency $F_{L1} - F_I$ (F_I represent the intermediate frequency), and, after a pass band filter, sampled at a frequency of 4 MHz. The n^{th} received sample $s(n)$ is given by:

$$s(n) = \sum_{k \in \{1..K\}} A_k(nT) d_k(nT - \tau_k(nT)) c_k(nT - \tau_k(nT)) e^{j\theta_k n + \varphi_k} + w(n) \quad (2)$$

where

- $\{1..K\}$: Set of satellites visible at time n ,
- $\theta_k = 2\pi T (f_{d(k)}(nT) + F_I)$,

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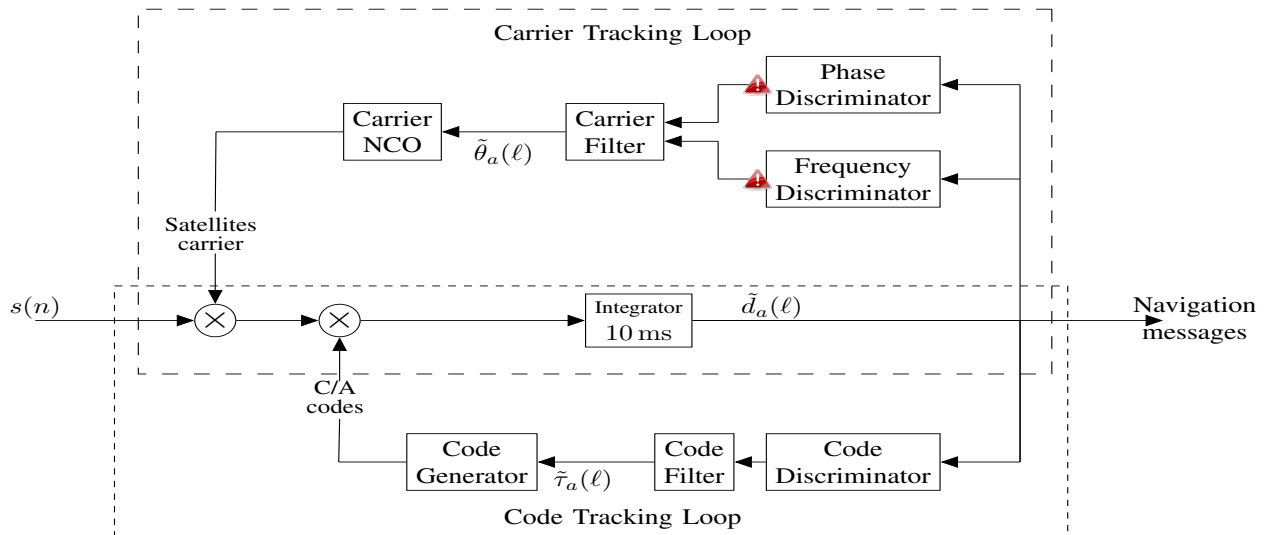


Fig. 1. Generic digital receiver channel block diagram. $\tilde{d}_a(\ell) \triangleq \sum_{10\text{ms}} s(n) c_a(nT - \tilde{\tau}_a(nT)) e^{-j(\tilde{\theta}_a n + \tilde{\varphi}_a)}$. A perfect time alignment ($\tilde{\tau}_a = \tau_a$) and a perfect frequency and phase alignment ($\tilde{\theta}_a = \theta_a$ and $\tilde{\varphi}_a = \varphi_a$) implies that $\tilde{d}_a(\ell) = d_a(\ell)$. Thus a navigation message is extracted. Components with warning marks at the output are assumed to be faulty in this paper.

- $A_k(nT)$: Attenuation parameter of k^{th} satellite signal at time nT ,
- $\tau_k(nT)$: Propagation delay between satellite k and receiver at time nT ,
- $f_{d(k)}(nT)$: Doppler frequency of satellite k at time nT ,
- T : Sampling period ($T = 0.25 \mu\text{s}$),
- $w(n)$: additive white gaussian noise.

To determine the exact position of a GPS receiver, distances separating the GPS receiver from at least four GPS satellites should be computed. To make the distance measurement, GPS receivers try first to extract the navigation message transmitted by each GPS satellite from the digital incoming signal. To do, the GPS receiver architecture formed of K tracking channel modules; the role of each channel module is to track a unique acquired GPS satellite and to extract the corresponding navigation message. A simplified representation of the channel tracking module is given in Fig. 1. Extraction of a navigation message is a recursive process and is accomplished by cancelling, first, the carrier offset and the C/A code thanks to a locally estimated replica of the C/A codes and the carrier and, then, by computing the correlation function. This correlation function is computed each $T_{\text{int}} = 10 \text{ ms}$ (two multiplication and the integration process in Fig. 1). A maximum correlation output between local and incoming signals is achieved when the two signal are aligned. Two feedback loops are used to update local generated signals to track over time Doppler effects: the carrier tracking loop and the code tracking loop. The carrier tracking loop performs the task of aligning the local generated carrier with the incoming signal while the code tracking loop ensures the time alignment of the local generated codes. Since the carrier tracking loop is less noisy than the code tracking loop, the carrier loop output may provide Doppler assistance to the code loop. Each loop is made of discriminators, filters and generators.

GPS receivers are widely used in mobile context, and there is motivation to minimise power consumption and maximise battery life in these devices. In [10] and [11], strategies have been proposed and evaluated for upset protection in the Gold sequence generators and the Numerically Controlled Oscillator (NCO) respectively. The authors of [12] presents two approaches to deal with internal logic upsets inside correlation process used in the tracking process of GPS receivers.

When the Carrier discriminator output is corrupted, distance measurements in the GPS receiver are disturbed and this leads to a faulty localization of the receiver. This paper will present a system level solution to limit the impact of internal upset when they are produced in the carrier discriminator. The remainder of this paper is organised as follow. Sec. II gives detailed information in a compact form about the GPS receiver architecture and its carrier tracking loop. Sec. III introduces the the linear representation of the carrier tracking loop. Metrics used to evaluate the proposed method are defined in Sec. IV. Sec. V and VI provide performance results offers conclusions.

II. GPS TRACKING LOOPS

GPS receivers use two feedback loops to update local generated signals to be synchronised with incoming signals: the carrier tracking loop and the code tracking loop. Two parameters are characterising the carrier: the frequency and the phase. Thus, the carrier tracking loop is formed of two nested loops: a phase loop or Phase Locked Loop (PLL) and a frequency loop also called Frequency Locked Loop (FLL). The FLL and PLL are each one made of a discriminator and use a common loop filter: the carrier filter. The FLL produce an estimate of the frequency error between the incoming signal and the local generated carriers (the role of the frequency discriminator in Fig. 1). A well designed frequency locked loop will generally yield a frequency estimate that converges

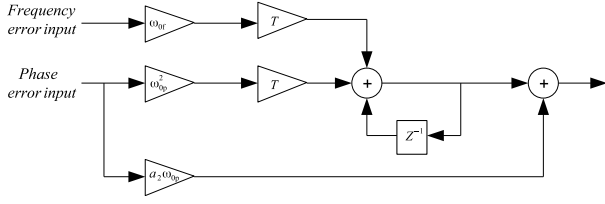


Fig. 2. First order FLL assisted second order PLL where $\omega_{0f} = \frac{B_{FLL}}{0.25}$ and $\omega_{0p} = \frac{B_{PLL}}{0.53}$. B_{PLL} and B_{FLL} are the phase and the frequency filters bandwidths. $a_2=1.414$

toward the true carrier frequency of the incoming signal. With this frequency uncertainty, a receiver try to estimate the second carrier parameter: its phase. Homologous to the FLL, the PLL is a recursive estimator of the carrier phase offset. Frequency and phase offsets are then applied to the carrier Filter. The filtered carrier error estimate is applied to the receiver NCO, to adjust the local carrier for the generation of the next local carrier signal. There are several discriminators for each PLL and FLL. The choice depends on the application and the implementation's complexity. The reader is invited to read [13] for more details. Arc Tangent (ATAN) based discriminators are the most used because of their performances [13]. They are defined as

$$\text{Err}_{FLL}(n) = \frac{\tan^{-1}\left(\frac{\text{cross}(n)}{\text{dot}(n)}\right)}{2\pi T_{int}}; |\text{Err}_{FLL}(n)| < 25 \text{ Hz} \quad (3)$$

$$\text{Err}_{PLL}(n) = \frac{\tan^{-1}\left(\frac{Q(n)}{I(n)}\right)}{2\pi}; |\text{Err}_{PLL}(n)| < 0.25 \text{ rad} \quad (4)$$

where

- $\text{cross}(n) = I(n-1) \times Q(n) - I(n) \times Q(n-1)$,
- $\text{dot}(n) = I(n-1) \times I(n) + Q(n) \times Q(n-1)$,
- $I(n)$: n^{th} In-phase copy of the correlation function result during 10 ms,
- $Q(n)$: n^{th} Quadrature copy of the correlation function result during 10 ms,
- \tan^{-1} : the inverse tangent function.

The loop filter order and bandwidth are the parameters characterising a carrier filter. There are many design approaches to construct digital loop filters. Details about loop filters characteristics can be found in [13]. Ground GPS receivers use the first order FLL assisted second order PLL as shown in Fig. 2. If the phase error input is zeroed in this filter, the filter becomes a pure FLL. Similarly, if the frequency error input is zeroed, the filter becomes a pure PLL. Next section will present the linearised representation of the carrier tracking loop.

III. LINEAR MODEL OF THE CARRIER TRACKING LOOP

The carrier tracking loop, shown in Fig 1, is linear and can be represented by a system of z-domain transfer functions where the system is updated each 10 ms. A linearised representation of the loop is quite useful as it facilitates the estimation tracking performance. The linearised model of the

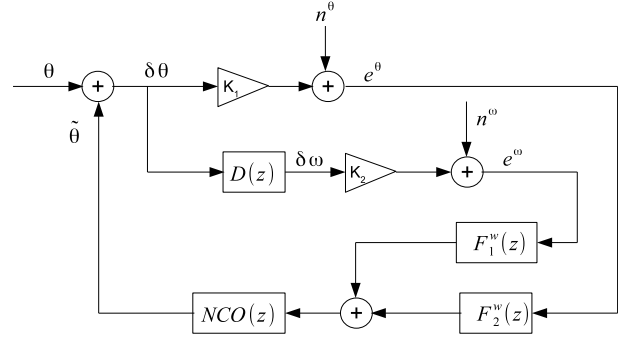


Fig. 3. Structure of the GPS carrier tracking loop

carrier tracking module is represented in Fig. 3. The carrier phase and frequency are represented by respectively θ and ω . The functions $NCO(z)$ and $D(z)$ represent the z-transform of the numerically controlled oscillator and the frequency discriminator respectively. In fact, the numerically controlled oscillator is a digital integrator and its transfer function is represented by

$$NCO(z) = \frac{T_{int}}{z-1} \quad (5)$$

The frequency estimate in the presence of transient errors can be approximated by a gain plus an independent corrupting noise

$$e^\omega = K_2 \delta\omega + n^\omega \quad (6)$$

The phase estimate can also be defined as

$$e^\theta = K_1 \delta\theta + n^\theta \quad (7)$$

The z transform of the frequency discriminator function is defined by

$$D(z) = \frac{z-1}{z T_{int}} \quad (8)$$

Scalars K_1 and K_2 represent the gain of the phase and the frequency discriminators. The authors of [14] demonstrate that values of these parameters depend on the discriminator function and the signal noise ratio (SNR) of incoming signals. In this work, ATAN discriminators are considered where $K_1 = K_2 = 1$ for $SNR > 20dB$.

The carrier filter can be linearised and defined as follow

$$F(z) = \frac{A_0 z}{z-1} E^\omega(z) + \left(B_0 + \frac{B_1 z}{z-1}\right) E^\theta(z) \quad (9)$$

where $E^\omega(z)$ and $E^\theta(z)$ represents the z transform of the frequency error, e^ω , and the phase error and e^θ respectively, $A_0 = \omega_{0f} T_{int}$, $B_0 = a_2 \omega_{0p}$ and $B_1 = \omega_{0p}^2 T_{int}$.

The transfer function between the frequency noise and the tracking phase error, $H_n^\omega(z)$ and the transfer function between the phase noise and the tracking phase error, $H_n^\theta(z)$, are defined by

$$H_n^\omega(z) = \frac{\Delta\Omega}{N^\omega} = \frac{NCO(z) F_1^\omega(z)}{1 + NCO(z) F_1^\omega(z) D(z) + NCO(z) F_2^\theta(z)} \quad (10)$$

$$H_n^\theta(z) = \frac{\Delta\Theta}{N^\theta} = \frac{NCO(z) F_2^\omega(z)}{1 + NCO(z) F_1^\omega(z) D(z) + NCO(z) F_2^\theta(z)} \quad (11)$$

where upper case symbols represents the z-transform of the corresponding lower case time series, $F_1^\omega(z) = \frac{A_0 z}{z-1}$ and $F_2^\theta(z) = B_0 + \frac{B_1 z}{z-1}$.

IV. METHOD PROPOSED AND EVALUATION

When designing the carrier filter there is a trade-off between noise resistance and response to dynamics. Narrow bandwidth filters are more resistant to noise, that makes them suitable for moderate jamming (low SNRs) environments [15]. Wide bandwidth tracking loops are more responsive to dynamics. Thus, carrier filter bandwidth requirements for GPS receivers are conflicting. For a ground GPS receiver, values of the phase and frequency filters bandwidths are both equal to 4 Hz [16]. When the Carrier discriminator output is corrupted due to PVT variations, distance measurements in the GPS receiver are disturbed and this leads to a faulty localization of the receiver. To deal with the effects of transient errors produced in the carrier discriminator, we propose in this paper to modify the optimal filter bandwidth values. The proposed method will be evaluated using two metrics: the Mean Squared Error (MSE) and the transient error induced Tracking Error Variance.

A. Mean Squared Error (MSE):

The methodology used to compute the MSE metric is threefold:

- Use the front end of a GPS receiver to store incoming GPS signal $s(n)$ over a significant period of time (few minutes).
- Process the stored input GPS signal with a reference noiseless GPS receiver [16] to generate the set of successive estimated positions $X(j)_{j=1\dots Q}$.
- Replace the noiseless GPS receiver with a noisy GPS receiver, and, process the stored incoming GPS signal, by Monte-Carlo simulations, N times to generate sets of noisy position $\tilde{X}^i(p)_{j=1\dots Q}$, $i = 1..N$.

The model of noise (n^ω and/or n^θ) used in this case is very simple. For each active tracking module, every output of the frequency and/or the phase discriminators is assumed to be exact with a probability $(1-p)$ or to be faulty with a probability p . In case of faulty result, a random value in $[-b, b]$ is uniformly added to the output of a discriminator ($b = 25$ Hz and $b = 0.25$ rad when the frequency and/or the phase discriminators are faulty). The value of b is chosen based on (3) and (4). Then we can study

$$\sigma_X(p) = \sqrt{E(|X - \tilde{X}|^2)}, \quad (12)$$

where p is the probability of the upsets' injection model (noise) at the output of discriminators. This parameter gives us an idea about how many meters, on average, the position given by the noisy GPS is far from the position given by the noiseless GPS.

B. Transient error induced Tracking Error Variance

To evaluate the transient error induced carrier tracking error, the Power Spectral Density (PSD) of the noise N^ω and N^θ

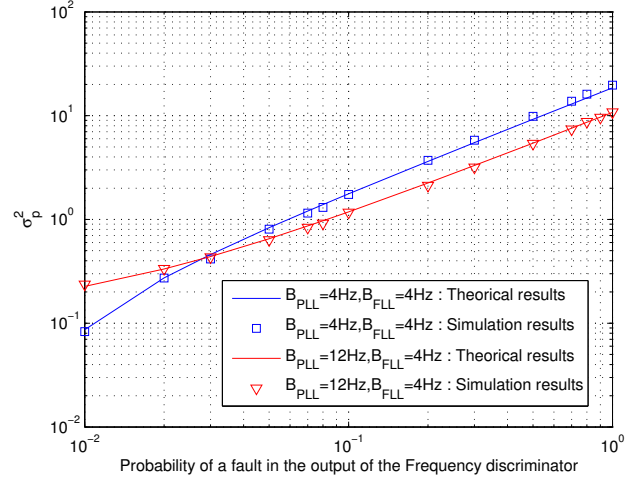


Fig. 4. Theoretical and simulated tracking error variance for a range of the probability of a fault

must be found. N^ω is assume to be a uniform random variable in $[-b, b]$, thus, its PSD is defined as:

$$S_n^\omega = (2b+1)(b+1)\frac{p}{6}. \quad (13)$$

This power spectral density is used in conjunction with (10) to find the tracking error variance when the frequency discriminator is faulty. The variance of $\delta\omega$, denoted $\delta_{\delta\omega}^2$, is given by

$$\sigma_{\delta\omega}^2(p) = \frac{1}{2\pi T} \int_{-\pi}^{\pi} S_n^\omega(\omega) |H_n^\omega(\omega)|^2 d\omega. \quad (14)$$

This paper will focus on the difference in the tracking error variance between the noiseless and the noisy GPS receivers, σ_p^2 .

$$\sigma_p^2 = \sigma_{\delta\omega}^2(p=0) - \sigma_{\delta\omega}^2(p). \quad (15)$$

V. PERFORMANCE RESULTS

Using expressions (10) and (14), the tracking error variance of the carrier loop, when transient errors appear in the frequency discriminator (i.e $N^\theta = 0$), can be estimated for different values of carrier filter bandwidths. Both simulated results (markers) and theoretical estimates (solid lines) are shown in Fig. 4. The relationship between the tracking error variance and the probability of a fault is linear ($\alpha p + \beta$). For a high upset probability, the tracking error variance is decreasing for high value of PLL bandwidth filters ($B_{PLL} = 12\text{Hz}$). Fig. 5 presents estimated $\sigma_X(p)$ from Monte-Carlo simulations when only the frequency discriminator is faulty. For instance, for a probability of upsets up to $p = 0.6$, the error in position does not exceed 1 meter by using 12 Hz as the bandwidth in the PLL filter. On the other hand, when $N^\omega = 0$ (only the phase discriminator is faulty), $\sigma_X(p)$ does not exceed 0.1 meters for high probability of upsets as shown in Fig. 6. This result is explained by the fact that the FLL is more sensitive to dynamic stress than the PLL.

Finally, we propose to evaluate the proposed technique when the frequency and the phase discriminators are both faulty

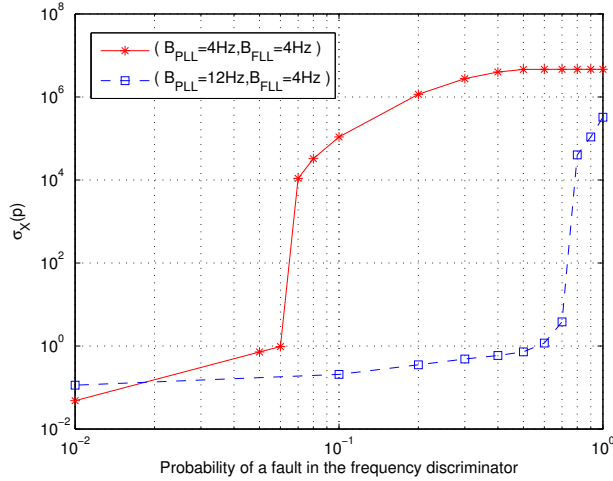


Fig. 5. $\sigma_X(p)$ when only the frequency discriminator is faulty for different values of filters bandwidth. $\sigma_X(p) = 4.65 \times 10^6$ m (which represents the reference position) is equivalent to a loss of the GPS signal tracking.

($N^\omega \neq 0$ and $N^\theta \neq 0$). As shown in Fig. 7, for the curve with red color where $B_{PLL} = 4Hz, B_{FLL} = 4Hz$, once the probability of upset errors exceed 0.06, tracking loops diverges and the GPS become not able to track GPS satellites' signals and compute its position ($\sigma_X(p > 0.06) = 4.65 \times 10^6$ m which represents the noiseless position). However, by increasing the PLL bandwidth from 4 to 12 Hz, $\sigma_X(p)$ decreases and remains lower than 2 meters for a probability of upset errors inferior than 0.4 (40 %). To illustrate more the effectiveness of the proposed method, three version of a GPS receiver are used inside a car to reproduce its trajectory when it was moving in the city of Toulouse in France. The three versions are the noiseless GPS receiver, the faulty GPS receiver when $B_{PLL} = 4Hz, B_{FLL} = 4Hz, p = 0.1$, and the faulty GPS receiver when $B_{PLL} = 12Hz, B_{FLL} = 4Hz, p = 0.3$. Positions given in each case are shown Fig. 8 with respectively the color orange, red and blue. By increasing the PLL filter bandwidth the trajectory of the approximately equivalent to the noiseless position with 2 m on average as error.

VI. CONCLUSION

There is continual motivation to reduce power consumption and extend battery life of mobile devices. Power consumption and device lifetime can be improved by operating at minimal supply voltage, which increases the likelihood of upsets errors. This problem increases with the advancement of CMOS technology in combination with process/temperature and voltage (PVT) variations. This paper proposes a system level method to deal with upset errors inside the carrier discriminator used in the tracking process of GPS receivers. This method is based on modifying properly filters bandwidth. Thus, we are able to mask transient errors when they are produced in the carrier discriminator without requiring hardware support. The Mean Squared Error ($\sigma_X(p)$) is used as a metric to evaluate the proposed approach. The tracking error variance of the carrier

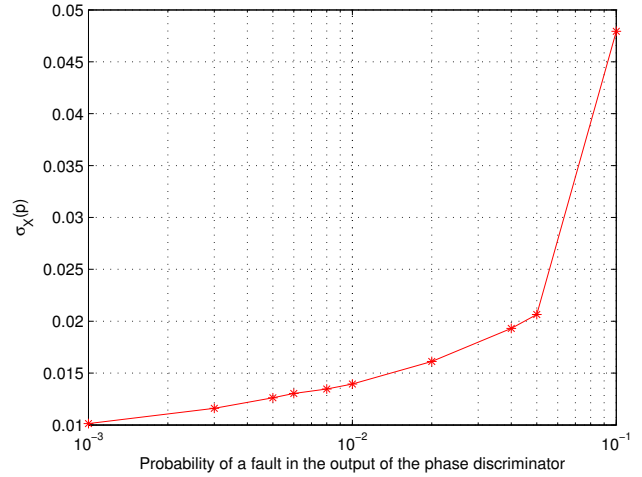


Fig. 6. $\sigma_X(p)$ when only the phase discriminator is faulty

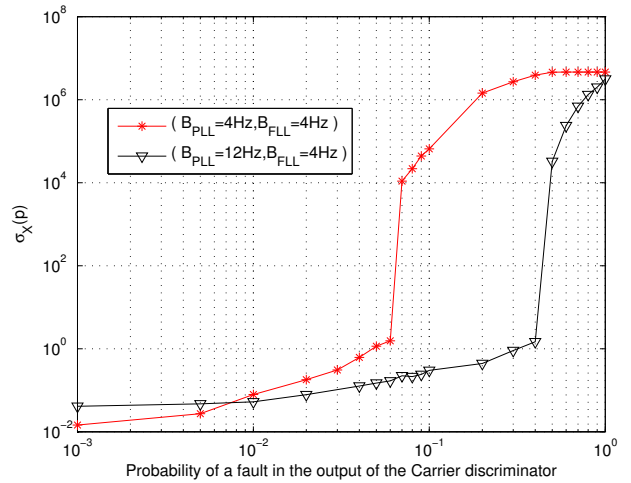


Fig. 7. $\sigma_X(p)$ when the carrier discriminator is faulty

tracking loop is also examined by both the theoretical and simulated method. It is shown that tuning PLL filter bandwidth yields to an important improvement in the robustness of GPS tracking loops against transient errors. With 40 % of upset errors, $\sigma_X(p)$ does not exceed 2m while the reference GPS receiver does not support more than 6 % of errors.

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Fig. 8. Position given by a noiseless GPS receiver (color orange), by a faulty GPS receiver when $B_{PLL} = 4\text{Hz}$, $B_{FLL} = 4\text{Hz}$, $p = 0.1$ (color red), a faulty GPS receiver when $B_{PLL} = 12\text{Hz}$, $B_{FLL} = 4\text{Hz}$, $p = 0.3$ (color blue) displayed using Google earth

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