Non-linear filtering using a DSP for estimating the optical carrier phase in a BPSK homodyne coherent communications system

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Abstract: In this work we describe a non-linear filter used for the estimation of the optical carrier phase in a homodyne coherent communications system with BPSK modulation. The non-linear filter is implemented using a digital signal processor and is characterized in a self-homodyne coherent optical communications system. Simulation and experimental results are reported.

Key-Words:- coherent optical communications, homodyne detection, maximum-likelihood estimation, non-linear filtering, phase noise, carrier synchronizers.

1 Introduction

The coherent optical communications systems have important advantages over the direct detection systems. They have greater performance sensitivity (up to 20 dB theoretical improvement) as a result of the operation close to the quantum noise limit [1], (making them very attractive for the implementation of both fiber optic long-distance links and free-space links [2]). They also have enhanced frequency selectivity allowing an optical frequency division multiplexing with narrower channel separations [3]. There exist, however, several important problems for the practical implementation of such systems, i.e.; a) the frequency stability of the optical sources, b) the phase noise inherent of the semiconductor lasers [4], among others.

As is well known [5], the phase-shift-keying (PSK) modulations are the less sensitive to the additive noise of the modulations used on the coherent optical communications systems. However, the PSK receivers are the more sensitive to the phase noise in the optical fields (in comparison with their ASK or FSK counterparts); therefore, the carrier synchronization process is crucial in the performance of these systems.

The carrier synchronization in the coherent optical communication systems is commonly made with synchronizing structures taken from the radioelectric communication systems [4,5,6,7,8]. These structures, however, are not, in general, optimum (in a statistical sense) for the synchronization of optical carriers [9].

In this work we report a non-linear filter (synchronization structure) synthesized specifically for BPSK coherent optical communication systems. The synthesis of this structure (reported in a previous work [10]) was made using the maximum-likelihood criteria and a variable state approach, taking into account the optical carrier phase noise and the additive post-photodetection noise [11].

The performance of the non-linear filter obtained is evaluated with computer simulations and implemented using a digital signal processor on a demonstrative experimental self-homodyne optical fiber communication system with controlled phase noise and BPSK modulation.

2 Filtering problem

Usually, for carrier synchronizing purposes it is necessary to made the phase carrier estimation process [12]. It can be shown [13] that if the parameter (the carrier phase) to be estimated is unknown but not random, the synchronizer structures like the PLL and the Costas loop are optimum carrier phase estimators (in a statistical sense). This estimation process is a particular case of a more general problem known as the filtering problem which is present in a great variety of engineering areas [14].

On the filtering problem a memoryless non-linear transformation is made over the stochastic signal $x(t)$, getting the signal $h[t:x(t)]$that is observed with an additive random perturbation $n(t)$. The observations are available over an interval $[t_0, t]$ that begins from an arbitrary time t_0 ending on the time t, that it is moving over the temporal axis on real time as more data arrive. The filtering problem consists on determining an optimum point realizable estimate of $x(t)$ based on all the available data $\{r(\tau): t_0 \leq \tau \leq t\}$ [14].

2.2 Non-linear filtering

In this work we have used the maximum-likelihood [15] as the optimality criteria for obtaining the optical carrier phase estimate $\hat{x}(t)$ (the estimate of x(t)).

In the figure 1 is shown the BPSK communication system for which the estimate is obtained.

The non-linear filter (synchronizer structure) was shintesized using, the so-called variance and estimator equations [14], with a Fokker-Planck description of the carrier phase noise process and taking into account the post-photodetection additive noise.On a previous work [10] we have reported the synthesis of the phase estimator used for this experiment, however, we rewrite below, for convenience, the variance and estimator equations and the solution obtained to them.

$$d\hat{x}(t) = \frac{2}{N_o} E\{(x-\hat{x})S(x,t,I_j)\}[dy(t) - ES(x,t,I_j)dt] \quad (1)$$

where $\hat{x}(t)$ is the MMSE estimate of the process x(t) given the observation process, and assuming that the data I_j was sent.

The variance equation is:

$$dv(t) = \frac{1}{t_c}dt + \frac{2}{N_o} E\{(x-\hat{x})^2 [S(x,t,I_j) - ES(x,t,I_j)]\}$$

$$\times [dy(t) - ES(x,t,I_j)dt] - \frac{2}{N_o} E^2 [(x-\hat{x})S(x,t,I_j)]dt \quad (2)$$

where v(t) is the variance in the estimation of x(t). The photodetected signal Vo(t), with amplitude $\sqrt{2P_H}$ (that depends mainly on the optical powers of the optical data signal and the local laser oscillator), has an additive amplitude noise $n(t)$, with white spectral density [11]:

$$S_n(f) = \frac{N_o}{2} \quad (3)$$

$$V_o(t) = \sqrt{2P_H}\sin(x + I_k) + n(t) \quad (4)$$

t_c is the coherence time related to the laser linewidth by [1]:

$$t_c = \frac{1}{2\pi f_L} \quad (5)$$

The solution of the coupled equations (1) and (2), considering that the error phase $(x-\hat{x})$ has a Gaussian distribution [9] are given by the following equations [10]:

$$x^*(t) = \int v^* \frac{\sqrt{8P_H}}{N_o}\cos(x^* + I_j)r(t)dt - \int v^* \frac{2P_H}{N_o}\sin(2(x^* + I_j))dt$$

(6)

$$v^*(t) = \int \frac{1}{t_c} - \frac{\sqrt{8P_H}}{N_o} v^{*2} \sin(x^* + I_j)r(t)dt$$

$$- \int \frac{4P_H}{N_o} v^{*2} \cos(2(x^* + I_j))]dt \qquad (7)$$

3 Carrier phase estimator

The mechanization of the equations (6) and (7) shown on figure 2 give us the phase estimator structure (non-linear) filter to be implemented with the digital signal processor.

4 Simulation results

In order to evaluate the performance of the phase estimator synthesized, we have made several simulations under different signal-to-noise conditions and with different levels of phase noise with and without data modulation.In the figure 3 are shown the waveforms of the carrier phase noise X (a Wiener process) [9], the binary data and the estimates obtained with the non-linear filter and with the conventional PLL. It can be observed that the non-linear filter has an improved performance compared with the conventional PLL as is shown on figure 4 where the phase error of both estimators is drawn.

5 Implementation

The non-linear filter described by the equations (6) and (7), was implemented using the digital signal processor ADSP-2181 from Analog Devices [16].

In order to calculate the sin(x) function we used the following approximation [17]:

$$\sin x = 3.140625x + 0.02026367x^2 - 5.325196x^3 + 0.5446778x^4 + 1.800293x^5 \quad (8)$$

where the angle x is scaled as shown:

$$x = \frac{value\_of\_the\_angle(rads)}{\pi} \quad (9)$$

The approximation (8) is valid only for values of the angle x scaled on the first quadrant [17], however, using $\sin(-x) = -\sin(x)$ and $\sin(x) = \sin(\pi - x)$ it is possible to obtain the sinus function of any angle from the values on the first quadrant.

In order to calculate the cos(x) function we have made use of the trigonometric identity:

$$\cos(x) = \sin\left(x + \frac{\pi}{2}\right) \quad (10)$$

The integrals needed for the non-linear filtering process, were calculated using an approximation of the trapezoidal method as indicated for the following difference equation [18]:

$$y(n) = y(n-1) + \frac{1}{2}\left[x(n) + x(n-1)\right] \quad (11)$$

where x(n) is the signal to be integrated and y(n) is the value of the integral calculated.

6 Experimental results

In order to characterize the carrier phase estimator, we have implemented an optical self-homodyne coherent communications systems with BPSK modulation as shown on figure 5. In the figure 6a is shown the phase noise process (x) and its estimate (x^*) using the non-linear filter implemented using the ADSP-2181, while in the figure 6b is shown the squared error on making the estimation. In the figure 7a is shown an oscilogram of the phase noise process, while in the figure 7b are shown the phase estimate using the ADSP-2181 for implementing the non-linear filter (the lighter signal) and the conventional PLL (the darker signal) respectively. In the case of the conventional PLL it can be observed an inverted noisy signal.

7 Conclusion

In this work we have described the implementation and characterization of a nonlinear filter for use on the estimation of the optical carrier phase on a BPSK homodyne coherent communications system. The nonlinear filter was synthesized taking into account the perturbations that exist on the optical channel, then as expected it has a better performance than the conventional synchronizer structures.

The implementation of the nonlinear filter based on the use of a DSP has the advantage of being very versatile and easy to modify but also has the disadvantage of the processing speed.

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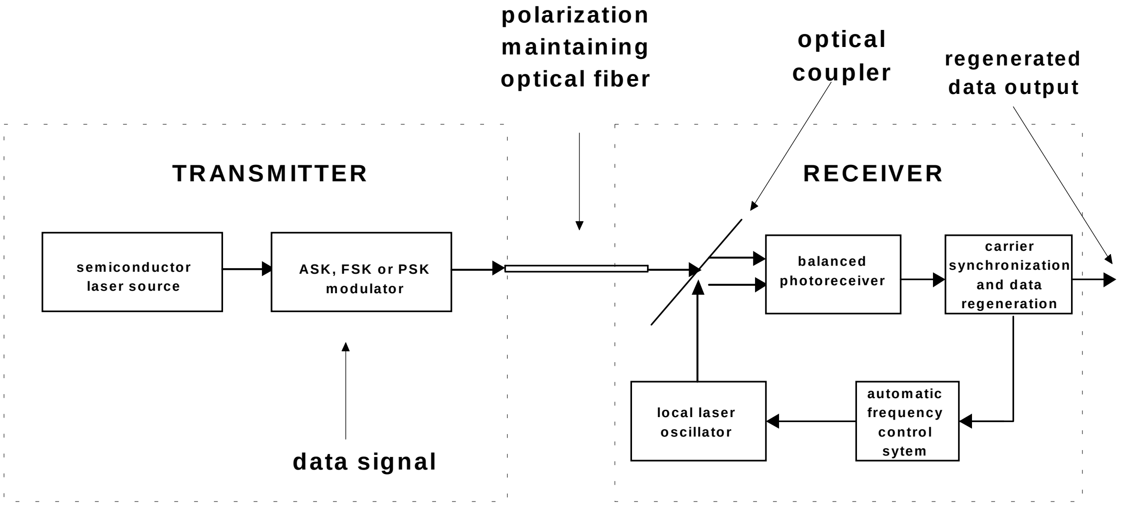


Figure 1 BPSK homodyne coherent communications system

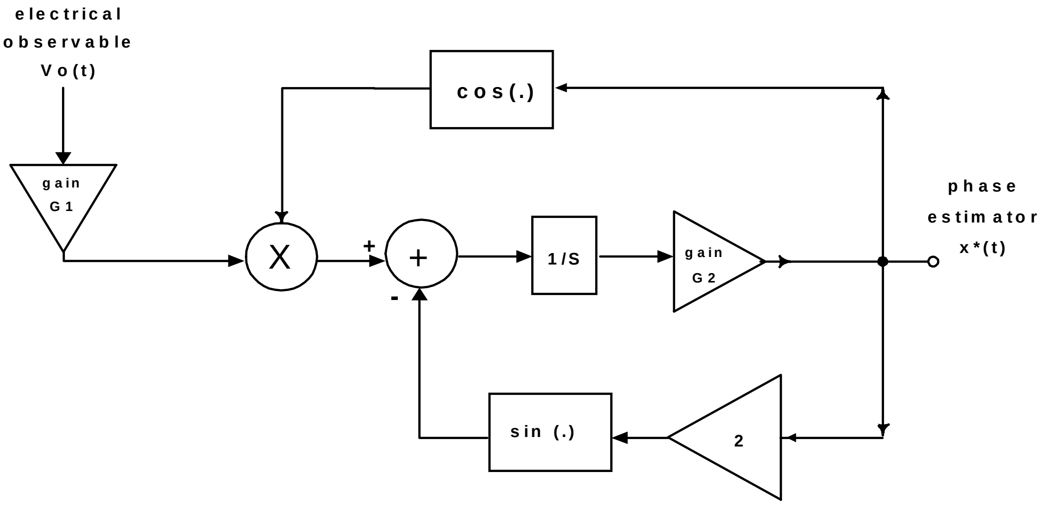


Figure2 Mechanization of the equations that describe the non-linear filter for the carrier phase estimation

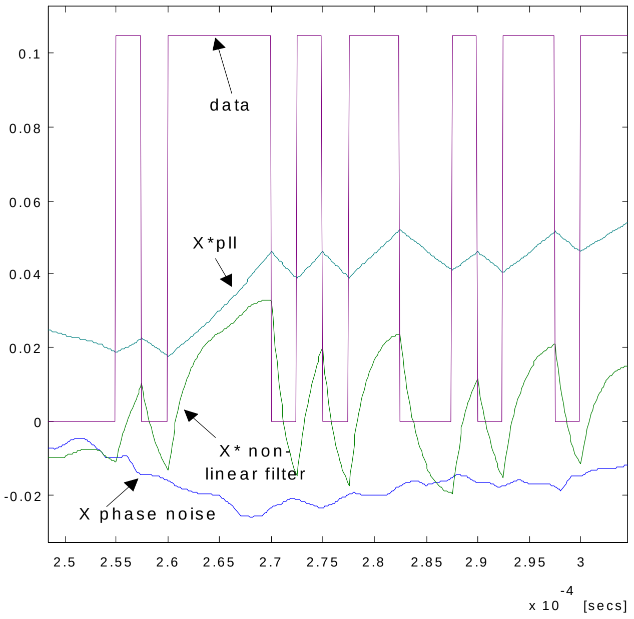


Figure 3 Typical waveforms obtained by simulation

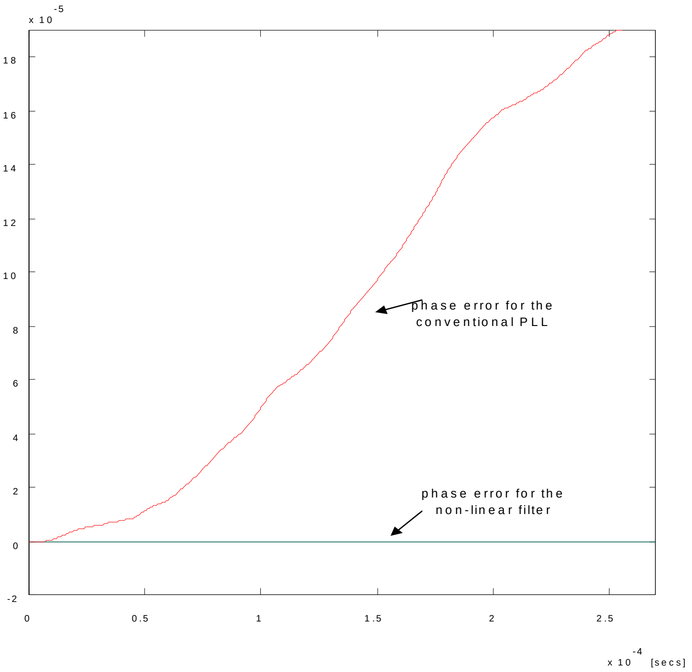


Figure 4 Phase error for the non-linear filter and for the conventional PLL

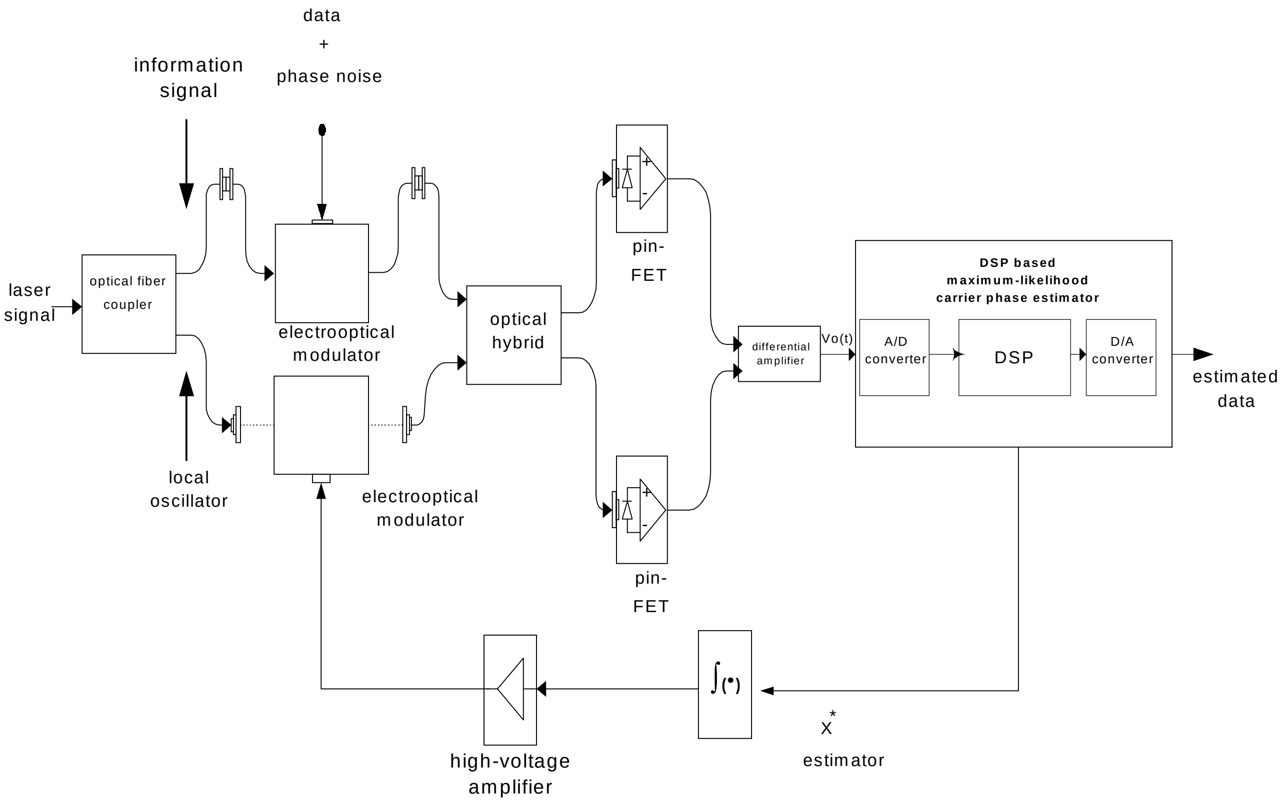


Figure 5 Self-homodyne coherent communications system with BPSK modulation and phase noise control

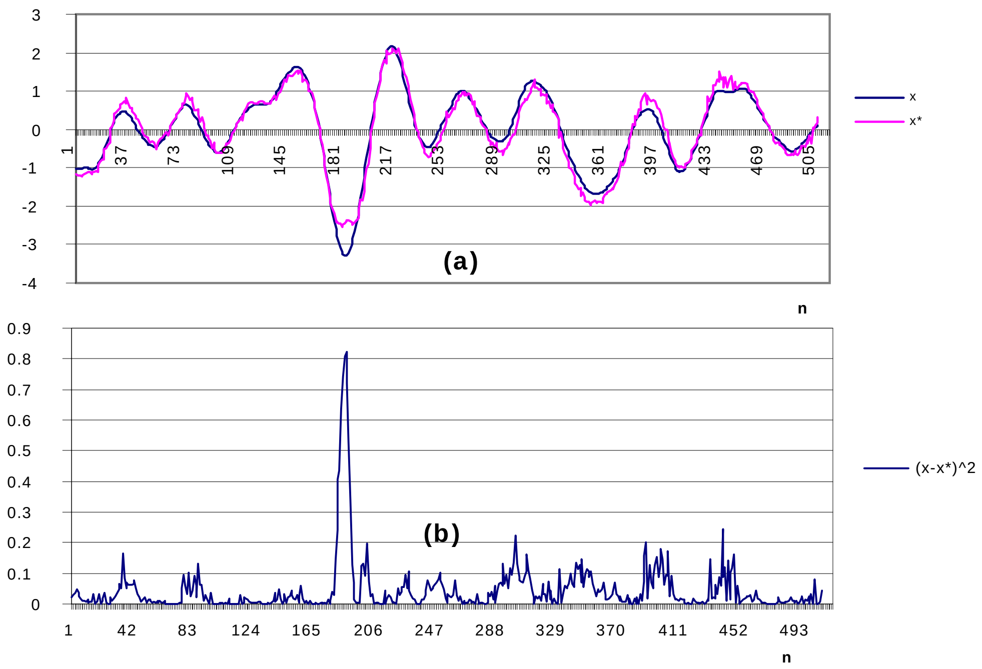
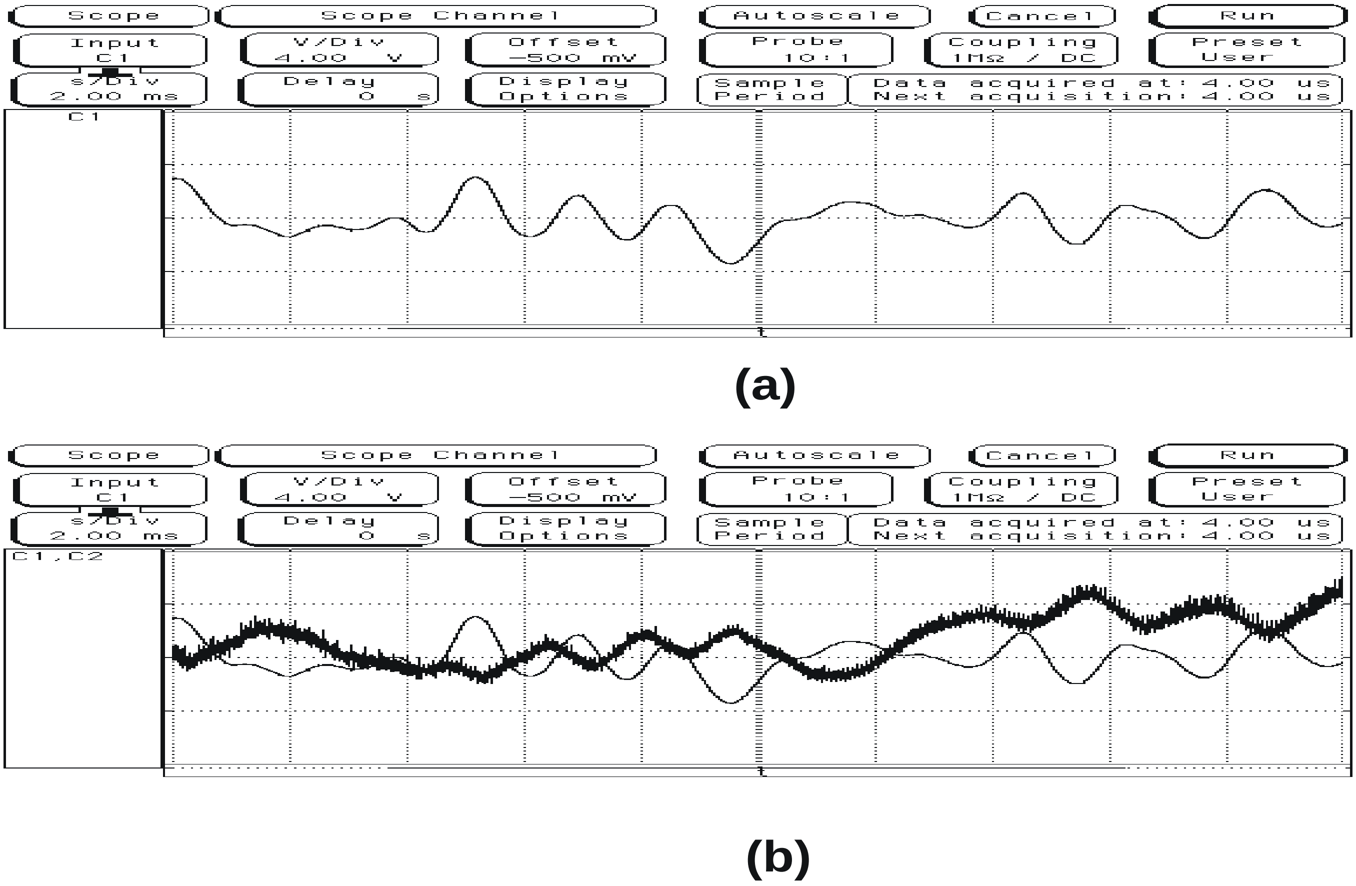


Figure 6 a)phase noise (x) and its estimate (x^*) using the ADSP-2181; b) squared error in making the estimation process



Input C1
V/Div 4.00 V
Offset -500 mV
Probe 10:1
Coupling 1MΩ / DC
Preset User
s/Div 2.00 ms
Delay 0 s
Data acquired at: 4.00 us
Next acquisition: 4.00 us

Input C1
V/Div 4.00 V
Offset -500 mV
Probe 10:1
Coupling 1MΩ / DC
Preset User
s/Div 2.00 ms
Delay 0 s
Data acquired at: 4.00 us
Next acquisition: 4.00 us

Figure 7 a) oscillogram of the phase noise process; b) oscillogram of the phase noise estimate with the non-linear filter (lighter trace) and the conventional PLL (darker trace).