On the need for low phase noise oscillators for wireless passive sensor probing

N. Chrétien, J.-M Friedt, B. François, G. Martin, S. Ballandras

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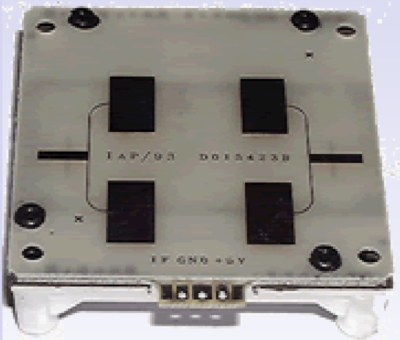
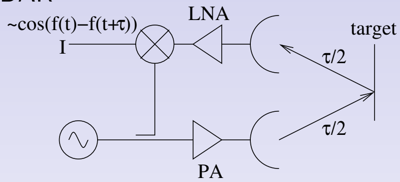
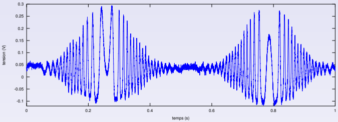
April 6, 2012

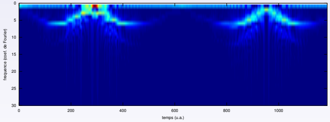
CW basics

It all started with ... 9 GHz CW RADAR [1]









[1] http://www.lextronic.fr/P1455-tete-hf-hyperfrequence-mdu1130.html & http://www.microwave-solutions.com/

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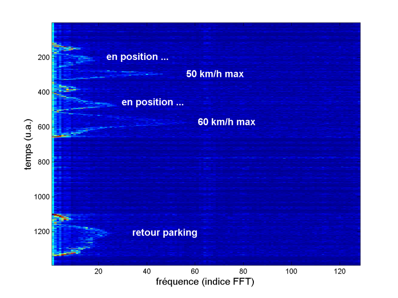

Target velocity induces frequency shift $f_D = 2 \times \frac{f_0 v}{c}$ when $v \ll c$

Contribution of the LO fluctuations during τ ?

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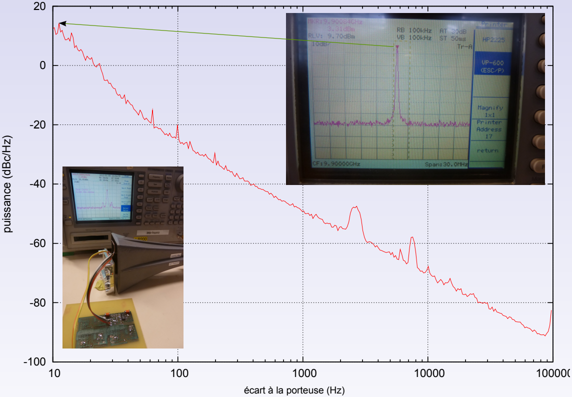
Phase noise limitation in CW

RADAR equation: $$\frac{P_{recv}}{P_{xmit}} = \frac{G_1 G_2 \lambda^2 \sigma}{(4\pi)^3 d^4}$$



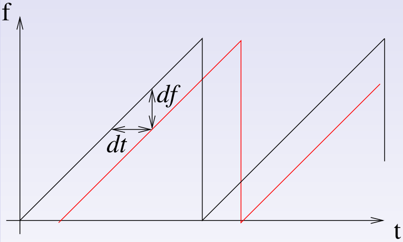
$\tau = 2d/c$ so $d \in [0.15 - 150]$ m $\Rightarrow \tau \in [1 - 1000]$ ns, *i.e.*
$f \in [1 - 1000]$ MHz where $L < -100$ dBc/Hz $\Rightarrow d = 560$ cm
($G_1 = G_2 = 8$ dBi, $\lambda = 3$ cm, $\sigma \simeq 1000$ cm^2 for 10×10 cm^2 metal plate, 16 Hz FFT)

Outline

1. pulsed CW RADAR as SAW delay line reader
2. FMCW RADAR as SAW resonator reader
3. ADC jitter effect on delay line measurement

From CW to FMCW

- Static target = no returned signal
- Linear passive sensors ⇒ returned freq. = emitted freq.
- How to recover delay information ? frequency sweep
- Spatial resolution is defined by *bandwidth* Δf only



1. Δf is swept during Δt so after a time delay dt: $df = \Delta f \times \frac{\tau}{\Delta t}$
2. Application: 100 MHz during 1 ms ⇒ 1 μs target (150 m) = 100 kHz beat
3. FFT(output)=distance (delay)
4. range cell $r = c/(2\Delta f)$ (since $df > 1/\Delta T$ & $df = \frac{\Delta f}{\Delta t} \times \frac{2d}{c}$)

Bistatic configuration only requires a VCO and a mixer (+amplifiers)[2]

[2] Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging, at http://ocw.mit.edu/resources/res-ll-003-build-a-small-radar-system-capable-of-sensing-range-doppler-and-synthetic-aperture-radar-imaging-january-i

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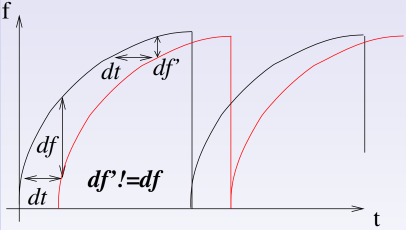

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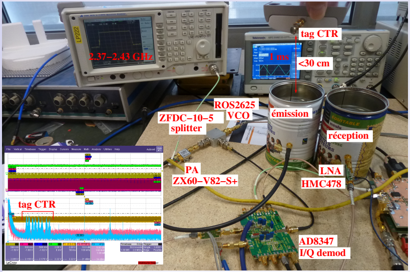

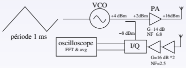

1. Δf is swept during Δt so after a time delay dt: $df = \Delta f \times \frac{T}{\Delta t}$
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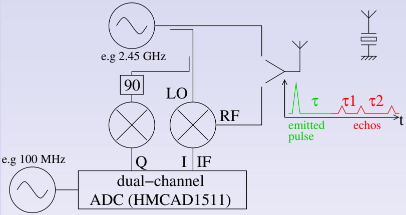
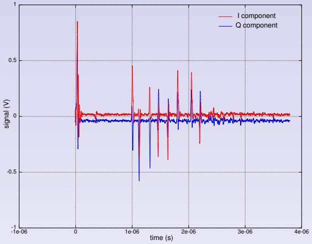
Pulse mode SAW delay line reader





- $\Delta\varphi = 2\pi d_{SAW}/\lambda = 2\pi d_{SAW} f/v = 2\pi f\tau$ (τ propagation duration of the pulse, *i.e.*) $\Rightarrow$ $\boxed{\partial\Delta\varphi = 2\pi f \partial\tau}$ $\Leftrightarrow \partial\tau = 1/(2\pi f)\partial\Delta\varphi$
- Information of interest: $|I + jQ|$ for coarse measurement, $arg(I + jQ)$ for accurate delay measurement
- $\tau \in [1-5]$ μs, pulse width ~30-40 ns

Phase noise definition

Mixer output m:

$$m = \cos\left(2\pi\left(f(t)+\delta f\right)\right) \times \cos\left(2\pi\left(f(t+\tau)\right)\right)$$
$$\propto \cos\left(2\pi\left(f(t)+\delta f \pm f(t+\tau)\right)\right) \quad (1)$$

If δf negligible: $m \simeq \cos\left(2\pi\left(f(t)-f(t+\tau)\right)\right)$.
should vanish when the target is not moving, but $f(t+\tau)$ and $f(t)$ differ

> the phase noise spectrum of an oscillator is defined as the Fourier transform of the autocorrelation function of the oscillator output frequency [3]

or [4] phase fluctuation density in a 1 Hz-wide bandwidth

$$S_{\Delta\varphi} = \frac{\Delta\varphi^2_{RMS}}{\text{measurement bandwidth}}\ \text{rad}^2/\text{Hz}$$

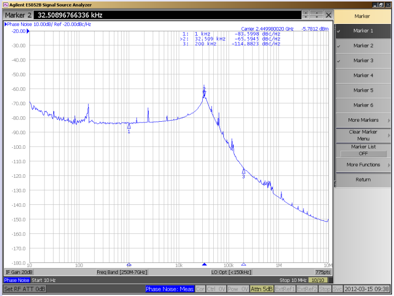
and the classical representation of the noise spectrum is given by
$L(f) = \frac{1}{2}S_{\Delta\varphi}(f) = 10 \times \log_{10}\left(\frac{P_{SSB}}{P_S}\right)$ dBc/Hz.

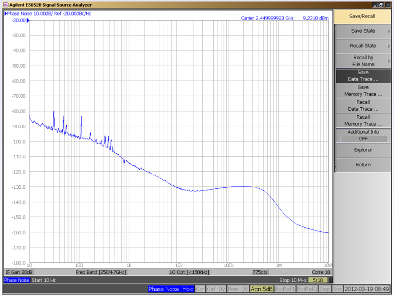
[3] E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge Univ. Press (2010)

[4] *Phase noise characterization of microwave oscillators – phase detector method*, Agilent Product Note, vol. 11729B-1.

Influence on RADAR detection limit

- So we have local oscillator noise spectra $L(f)$, how to analyze these results for delay line measurement resolution ?
- Assumptions: -130 dBc/Hz and -170 dBc/Hz at $f_{carrier} = 1/\tau$.
- Phase measurement within a 30 ns long pulse (bw=30 MHz): $\Delta\varphi_{RMS} = \sqrt{2 \times 10^{-(130..170)/10} \times 30 \times 10^6}$ rad i.e. 0.14° to 0.0014° (and 14.0° for -90 dBc/Hz)





2.45 GHz source generated by an Analog Devices ADF4360-0 Phase Locked Loop (poorly controlled), & Rohde & Schwartz SMA 100 A tabletop frequency synthesizer.

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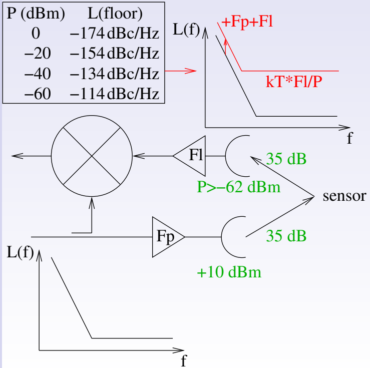


Returned power P induced noise floor elevation: $P \in [-70..0]$ dBm range, and noise floor is the highest of either initial noise floor$+F_p + F_l$ *or* LNA noise floor $kT/P = -198.6 + 10\log_{10}(P)$

Influence on delay line resolution

$$\Delta\varphi = 2\pi \times d_{SAW}/\lambda = 2\pi \times d_{SAW} \times f/v$$

The variation with temperature T of this phase difference is associated with the velocity variation, so that

$$\left.\frac{\partial\Delta\varphi}{\Delta\varphi}\right|_T = \left.\frac{\partial v}{v}\right|_T \Leftrightarrow \partial\Delta\varphi(T) = 2\pi\frac{d_{SAW} \times f}{v} \times \left.\frac{\partial v}{v}\right|_T$$

For a $LiNbO_3$ substrate, $v \simeq 3000$ m/s, $\partial v/v \simeq 60$ ppm/K. If $d_{SAW} = 10$ mm and $f = 100$ MHz, then $2\pi \times 60 \times 10^{-6} \times 10^{-2} \times 10^8/3000 = 0.13$ rad/K$= 7.2\ ^o$/K.

Phase noise	half distance between reflectors	resolution
-170 dBc/Hz	10 mm	2×10^{-4} K
-170 dBc/Hz	1 mm	2×10^{-3} K
-130 dBc/Hz	10 mm	0.02 K
-130 dBc/Hz	1 mm	0.2 K
-90 dBc/Hz	10 mm	2 K
-90 dBc/Hz	1 mm	20 K

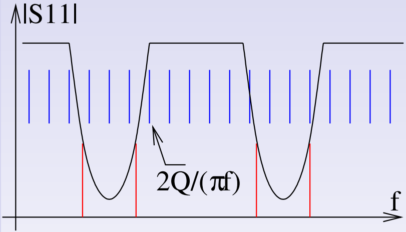
Temperature measurement resolution, assuming a 60 ppm/K temperature drift of the delay-line sensor, as a function of various local oscillator parameters.

Resulting design rules

Design rules for SAW delay lines:

- minimize phase noise of LO ! poor phase noise might become limiting factor in resolution
- keep maximum delay below inverse of Leeson frequency $f_L = f_{LO}/(2Q_{LO})$ (above f_L, noise floor is only defined by F and P of feedback amplifier)
- resolution increases with $\tau \Rightarrow \boxed{\tau \leq 1/f_L}$
- $Q = 2000$, $f_{LO} = 2.45$ GHz $\Rightarrow f_L = 600$ kHz $\Rightarrow \tau \leq 1.6\mu$s
- $Q = 20000$ (HBAR), $f_{LO} = 2.45$ GHz $\Rightarrow f_L = 60$ kHz $\Rightarrow \tau \leq 16$ μs (24 mm-long propagation path)
- electromagnetic clutter fades within 700 ns (100 m range) and typical pulse length 40 ns spaced by at least 100 ns, 1.5 μs $\Rightarrow$ 5 reflections for **multi-parameter-sensing**

Application to SAW resonator sensors



- resonator load and unload time constant: $\tau = Q/(\pi f_0)$
- typical measurement duration: 256τ
- minimum measurement duration: 8τ (2 resonators, 2 measurements/resonance) [a]

[a] J.-M Friedt, C. Droit, S. Ballandras, S. Alzuaga, G. Martin, P. Sandoz, *Remote vibration measurement: a wireless passive surface acoustic wave resonator fast probing strategy*, accepted Rev. Sci. Instrum. (accepted March 2012)

$Q = 10000,\ f_0 = 434$ MHz $\Rightarrow \tau = 7\ \mu$s

$\Rightarrow$ measurement duration $\in [60 - 1900]\ \mu$s $\Rightarrow f \in [500 - 17000]$ Hz

Phase noise to frequency noise conversion

Phase noise $S_{\Delta\varphi}$ and frequency fluctuations $S_{\Delta f}$ at f from the carrier are related ($f = d\varphi/dt$) through

$$S_{\Delta f} = f^2 \times S_{\Delta\varphi} = \frac{\Delta f_{RMS}^2}{BW}$$

$\Rightarrow$ for a measurement bandwidth BW of $2f$, frequency fluctuations are given by

$$\Delta f_{RMS}^2 = BW \times f^2 \times S_{\Delta\varphi}$$

and

$$\boxed{\Delta f_{RMS} = \sqrt{BW \times f^2 \times 2L(f)}}$$

Resonator measurement limitations

- 2.5 kHz/K temperature sensitivity (170 K measurement range within the 1.7 MHz wide 434 MHz ISM band)
- 25 Hz frequency resolution (10 mK resolution) requires -105 dBc/Hz.
- consistent with the phase noise spectra provided in [5] ($L(f) = -105$ dBc/Hz at $f \in [500 - 5000]$ Hz at 434 MHz, DDS).

Phase noise	frequency	Q	$\Delta f_{RMS}(Hz)$	resolution
-170 dBc/Hz	434 MHz	10000	0.01	4.10^{-7} K
-130 dBc/Hz	434 MHz	10000	1	4.10^{-5} K
-90 dBc/Hz	434 MHz	10000	140	5 mK
-170 dBc/Hz	2.450 GHz	1500	2	10^{-5} K
-130 dBc/Hz	2.450 GHz	1500	230	1 mK
-90 dBc/Hz	2.450 GHz	1500	23000	0.1 K

assuming a 60 ppm/K sensitivity. For 5.7 ppm/K sensitivity, the values in the last column are multiplied by 10.

[5] J.-M Friedt, C. Droit, G. Martin, and S. Ballandras A wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement Rev. Sci. Instrum. vol. 81, 014701 (2010)

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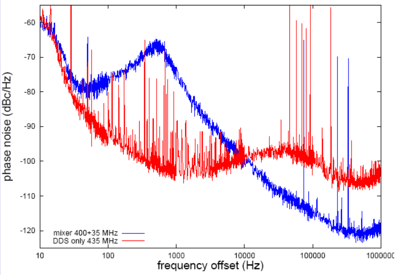

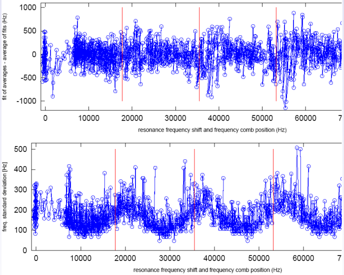

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ADC jitter influence on SAW delay line measurements

Delay line seems favorable since oscillator has less time to drift, *but* fast sampling of the returned signal is needed.

Phase noise to jitter conversion [6]: $\sigma_t = \frac{\int_{f_1}^{f_2} 2L(f)df}{2\pi f_c} \simeq \frac{\sqrt{2\times 10^{-S_\varphi/10}\times BW}}{(2\pi\times BW)}$

Jitter σ_t yields [7] resolution loss of $SNR = (2\pi f_s \sigma_t)$

- 0.13 rad/K $\Rightarrow$ 0.13 rad over 2π rad range requires 6 bit resolution
- 40 ns pulse $\Rightarrow BW \simeq 100$ MHz, and duration of A/D < 5 μs
- if $L(f) = -130$ dBc/Hz in $f \in [0.2 - 200$ MHz range $\Rightarrow \sigma_t = 7$ ps,
- 1 K resolution: σ_t must not exceed 42 ps (6 bit at 100 MS/s),
- 0.1 K resolution requires a 9 bit ADC and a maximum jitter of 5 ps.

Digital PLL of an iMX27 CPU is specified at a maximum jitter of 200 ps

[6] W. Kester, *Converting oscillator phase noise to time jitter*, Analog Devices MT-008 Tutorial, 2008

[7] D. Redmayne, E. Trelewicz, and A. Smith, *Understanding the effect of clock jitter on high speed ADCs*, Linear Technology Design Note 1013, 2006

Conclusion (& perspectives)

- delay line provide short delay response (floor since far from carrier) $\Rightarrow$ low phase noise *but* high losses (IL) and fast sampling rate at receiver $\Rightarrow$ moves requirements on LO from emission to ADC clocking circuit
- pulse-mode (UWB) delay line reader does *not* require tunable LO $\Rightarrow$ improved stability ?
- resonator seems to be LO limited (25 Hz for -105 dBc/Hz *tunable* (DDS) LO)
- design rule for delay lines: keep $1/\tau > f_L$

$\rightarrow$ need to experimentally demonstrate all these concepts !
$\rightarrow$ low phase noise LO by avoiding PLL and using high Q/high frequency resonators ?
$\rightarrow$ $\partial\Delta\varphi \propto \partial\tau \times f \Rightarrow$ does increased phase slope with frequency compensate for increased phase noise of oscillator ?