Wireless and Mobile Acoustic Sensor Interrogation for (Bio)Chemical Sensing and Industrial Control

J.-M Friedt [1], G. Martin[2], S. Ballandras[2]

[1] SENSeOR, Besançon, France (www.senseor.com)

[2] FEMTO-ST/CNRS, Besançon, France (www.femto-st.fr)

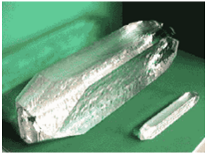
slides and references available at http://jmfriedt.free.fr/

May 18, 2008

Generating acoustic waves

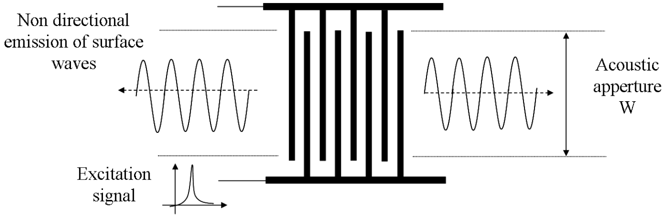
- Acoustic waves in solids: mechanical, thermal expansion, piezoelectric generation
- An RF voltage applied to an interdigitated transducer generates an acoustic wave
- Surface, bulk waves, shear/longitudinal/Rayleigh/guided (Love mode)
- Delay line (single path) or resonator (reflectors define a cavity)

material	wave	(m/s)	TCF	comment
$LiNbO_3$	shear	4700	-90 ppm/K	ferro. & pyroelectric, $T_C > 1200^oC$
$LiTaO_3$	shear	4100	-36 ppm/K	$525 < T_C < 700^o$C
$KNbO_3$	Rayleigh	2800	<1 ppm/K	huge coupling, $T_C \simeq 430^o$C
	shear	3500	?	
LiB_4O_7	Rayleigh	3500	-300 ppb/K^2	water soluble
langasite	Rayleigh	2900	-70 ppb/K^2	no Curie temperature, $> 1000^o$C
Quartz	Rayleigh	3150	-40 ppb/K^2	most used
	shear	5100	-60 ppb/K^2	less coupled



Acoustic wave sensors

- Interdigitated transducers (IDT) patterned (lithography) on piezo substrate define wavelength
- $\varepsilon_{piezo} \gg \varepsilon_{air} \Rightarrow$ efficient electric field confinement in piezo substrate
- Conversion from electric to acoustic wave
- Wavelength in the micrometer to tens of micrometers range, velocity $\in [3000 - 10000]$ m/s $\Rightarrow$ 2-3000 MHz depending on design

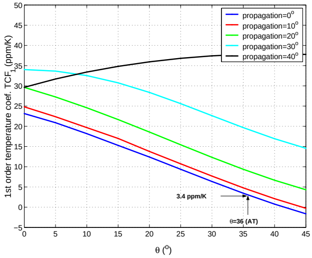


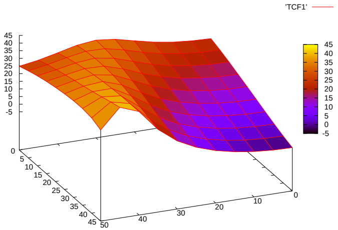
Sensing principle: variation of velocity induces variation of propagation delay

Acoustic wave sensors

- Boundary conditions define velocity and insertion losses.
- Thermal expansion/stress of the substrate change velocity $c = \sqrt{\frac{E}{\rho}}$ (E Young modulus, ρ density), complex in anisotropic materials
- Intrinsically radiofrequency devices $\Rightarrow$ no conversion from DC to RF
- $\Rightarrow$ sensitive to temperature, stress (pressure), gravimetric (mass), viscosity ...
- ... select the dominant effect by selecting the appropriate design.

For example: selection of a temperature compensated orientation for temperature-independent sensor.





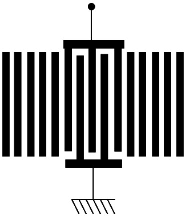
Temperature coefficient of frequency (TCF) computation by M. Bruniaux (SENSeOR)

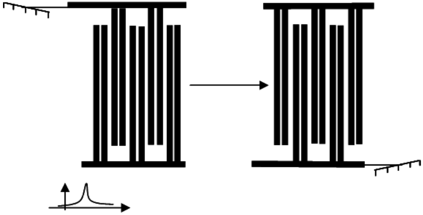
Interrogating acoustic wave sensors

- resonator = narrow band: look for resonant frequency (inverse Fourier transform of pulse, or frequency sweep) ; or oscillator and measure output frequency
- delay line = wide band: look for time delay of reflected signal or phase ; or set frequency and monitor phase and insertion losses

Radiofrequency emission ⇒ respect regulations.

- 433 MHz ISM band is only 2 MHz wide → resonator
- 2450 MHz ISM band is 80 MHz wide → resonator or delay line



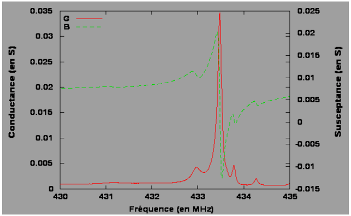


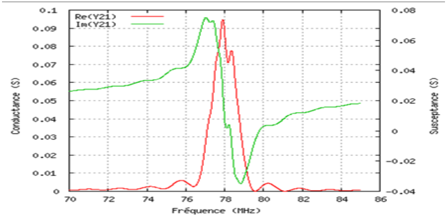
Interrogating acoustic wave sensors

- resonator = narrow band: look for resonant frequency (inverse Fourier transform of pulse, or frequency sweep) ; or oscillator and measure output frequency
- delay line = wide band: look for time delay of reflected signal or phase ; or set frequency and monitor phase and insertion losses

Radiofrequency emission ⇒ respect regulations.

- 433 MHz ISM band is only 2 MHz wide → resonator
- 2450 MHz ISM band is 80 MHz wide → resonator or delay line

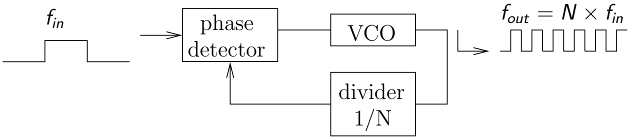




Phase locked loop (PLL)

Frequency *multiplication*:

- a high frequency steerable oscillator (Voltage Controlled Oscillator: VCO) is divided,
- the resulting low frequency is compared (phase measurement) with a stable low frequency oscillator (mixer or XOR + low pass filter),
- and the control signal is defined by the phase difference between the divided frequency and the reference.



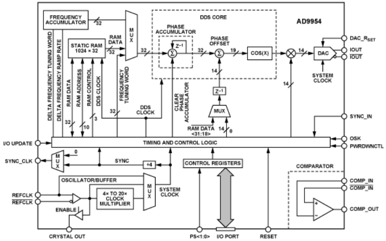
$\Rightarrow$ we will work in the 0-100 MHz range, and multiply to reach the wanted ISM band

$\Rightarrow$ source noise is multiplied by N: $\Delta f_{out} = N \times \Delta f_{in}$

Direct Digital Synthesizer (DDS)

1. A fixed quartz oscillator ...
2. is multiplied to a clock frequency (internal PLL) ...
3. which increases a counter ...
4. whose values is converted through a look-up table to a sine output ...
5. converted to an analog output by a fast D/A converter

Digital component, programmable output frequency
Reference oscillator defines the output stability
Complex output spectrum (f_{ck}, $f_{ck} \pm f\,wanted$ ...): low pass filter



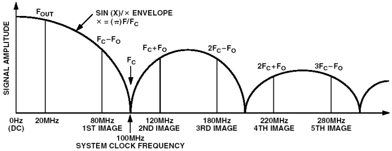
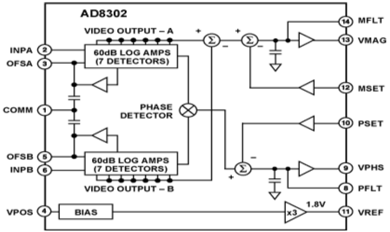


Figure 12. Output Spectrum of a Sampled Sin(x)/x Signal

From the Analog Devices AD9954 and AD9851 DDS datasheets

Mixer and I/Q demodulator

- Real and imaginary parts of the Fourier transform at the modulation frequency ⇒ phase and magnitude
- Analog Devices AD8302 includes auto-gain control from phase and magnitude measurements



60 dB dynamics, comparable with magnitude detector *but* provides demodulated output around reference signal

General strategy

- In order to comply with 433 MHz ISM regulations, use narrowband sensors
- In order to penetrate deep in dielectric substrates, avoid 2450 MHz (+technological constraints)
- Differential measurement (two resonances) to cancel correlated noises and *reference oscillator drift*
- Main issue: isolation between emission and reception stages (defines range)

$\Rightarrow$ generate a tunable frequency source, sweep ISM band and for each pulse, listen for response of resonator.

> If we are close to the resonance frequency, the energy loaded in the resonator empties to $1/e$ within Q/π periods.

Frequency source

- Fully software controlled strategy: program a frequency, send pulse, listen, goto next frequency
- Flexible approach allowing sub-band division of the ISM band
- avoids synchronization between a (continuous) saw-tooth sweep of VCO and listening period
- two strategies: sweep DDS and lock PLL (multiplication), or mix reference with variable frequency sources and band-pass wanted signal

Receiving

Two strategies: wide band (power measurement) or narrow band (demodulated) detection

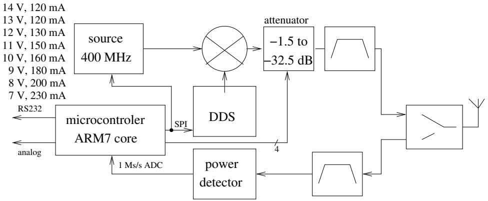
- wide bandpass filter (listen to the whole ISM band)
- amplify
- magnitude detector

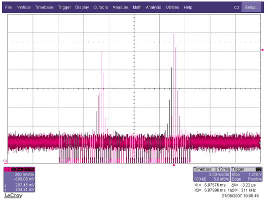
We will always work at baseband, no mixing to reach IF since detectors up to 3 GHz provide the required sensitivity

Radar mode, frequency sweep

- a programmable frequency source (DDS) generates the frequency f to be probed
- RF switches emit the frequency for a duration τ
- upon switching off the emission, listen for the magnitude of the response of the resonator (exponential energy decay in Q/π periods, i.e. $Q/(\pi \times f)$ s. $Q = 8000$ at $f \simeq 434$ MHz $\Rightarrow 5.9\ \mu$s
- repeat for all frequencies in the ISM band

$\Rightarrow$ 1 ISM band sweep requires $\simeq$ 10 ms



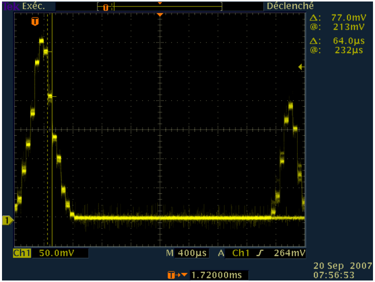


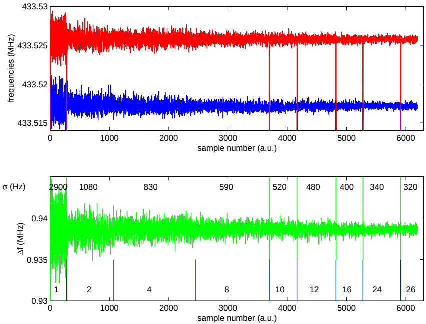
RF power measurement with 42 dB attenuator on antenna output

Radar mode, digitized signal

⇒ poor selectivity since we listen at the energy in the whole ISM band: sensitive to other RF sources

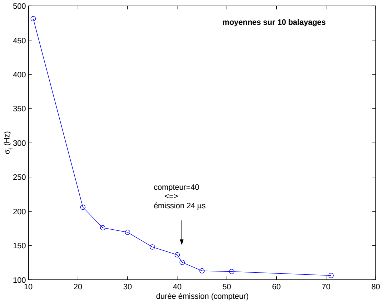
Improved resolution with averaging: sub-kHz resolution above 4 averages, usually 8 or 16 averages

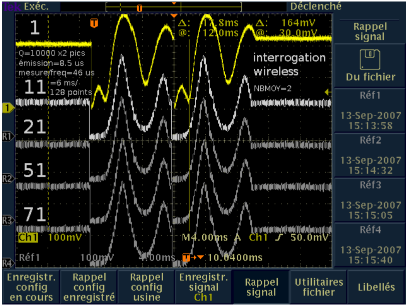




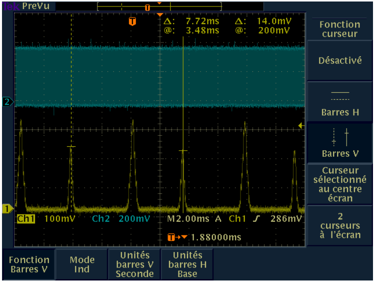
Radar mode, pulse duration

Tradeoff between resolution (the longer the pulse, the narrower the bandwidth) and sweep time





Radar mode : results



With these parameters: 7.7 ms/sweep $\times$ number of averages

- flexible frequency emission does not necessarily require equally spaced frequencies (zoom ...)
- accumulate sweeps until the pre-defined number of averages is reached ($\Rightarrow$ known noise level on the measurement)

Radar mode, wideband interrogation

- Generate a short radiofrequency burst: in the 433 MHz ISM band, the burst must be tuned to comply with regulations while spreading energy on a wide enough frequency range (here ≃40 kHz)
- Sample returned signal
- Inverse Fourier Transform (DFT) ⇒ identify resonance frequency
- iterative process converges quickly towards the resonance frequency

⇒ heavy requirements on signal processing hardware (fast sampling rate and Fourier transform)

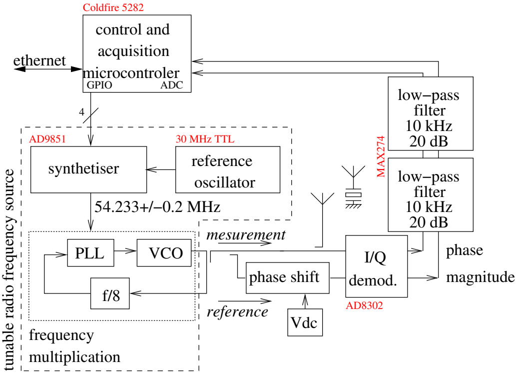
This solution is used by Transense

`http://www.transense.co.uk/technologies/technical_publications/`

CW mode

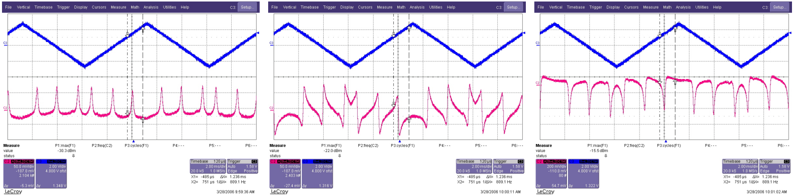
- Continuous radiofrequency emission: avoids wideband signal associated with chopping
- Impedance variation measurement as transmitted power through coupler, or I/Q demodulator

⇒ close to the principle of RFID (magnetic coupling of antennas) but lower dynamics and sensitivity



Radar mode v.s. CW mode

- No demodulation $\Rightarrow$ poor signal to noise ratio associated with the wide band reception filter
- *but* cancelling direct signal in a CW configuration is difficult (30 dB at best)



Blue: VCO polarization, i.e. frequency ; red: phase measurement
From left to right: $\Delta\varphi = 0, 90, 180^o$ on the reference arm

$\Rightarrow$ signal shape change with distance can be compensated for by $\Delta\varphi$ in reference arm

IQ Mobil: modulated 2.4 GHz carrier

- A 2.4 GHz carrier (compatible with ISM regulations) is modulated at the interrogation frequency ($\simeq$ 10 MHz)
- A non-linear element on the passive receiver removes the carrier and probes the resonator
- The decay of the resonator is monitored as an antenna impedance variation which modulates the continuously emitted 2.4 GHz carrier.

$\Rightarrow$ lower range due to high carrier frequency and need of a nonlinear element on the receiver

`http://www.iqmobil.com/index.php?m=IQLECTURES&language=en`

Local reference stability issue

Differential measurement: the uncertainty on the local oscillator is seen on the frequency *difference*
If a differential (two resonator setup) is not feasible

- Assume we want a sensor working in -20 to 120^{o}C range.
- Assume we wish to comply with 433-ISM regulation (1.5 MHz bandwidth)
- Assume we have a referenced (2 resonance) temperature sensor

$\Rightarrow$ 750 kHz/140 K=5.4 kHz/K *i.e.* 12 ppm/K.

Due to fabrication dispersion, we actually use 6 ppm/K

For 0.1 K accuracy, we must provide a long term local oscillator stability better than 0.5 ppm over the whole temperature range.

One conceivable solution (if applicable): lock local oscillator on GPS.

GPS reference

UT ONCORE™
(Precision Timing)

R1121A111x		<50ns		X		RA/OSX	Binary
R1121A115x		<50ns		X		ST/OSX	Binary
R1221A111x		<50ns		X	X	RA/OSX	Binary

VP ONCORE™
(All Apps)

B3121B111x	BIN/RTCM			X		RA/OSX	BIN/NMEA
B3221B111x	BIN/RTCM			X	X	RA/OSX	BIN/NMEA
B3121P111x	BIN/RTCM	<50ns		X		RA/OSX	BIN/NMEA
B4121P115x	BIN/RTCM	<50ns		X		ST/OSX	BIN/NMEA
B3121Z111x	BIN/RTCM	<50ns	X	X		RA/OSX	BIN/NMEA
B3221Z111x	BIN/RTCM	<50ns	X	X	X	RA/OSX	BIN/NMEA

Motorola Oncore VP

Standard Features

- 12-channel GPS receiver with up to 2 channels for SBAS
- L1 frequency, C/A code (SPS)
- DGPS ready (Remote)
- 1-Hz update rate
- 1 PPS (TTL)
  Precision: 250 ns (Stand-alone)

Thales A12

- Operating temperature range of -30°C to +75°C
- 1PPS output aligned on GPS Time ± 200 ns
- 1Hz measurement output aligned on GPS Time
- Support for 62 predefined datums
- Field-upgradeable firmware (stored in Flash memory) through the TTL serial port
- Code and Carrier Phase tracking of L1 GPS frequency for increased accuracy

Novatel Superstar2

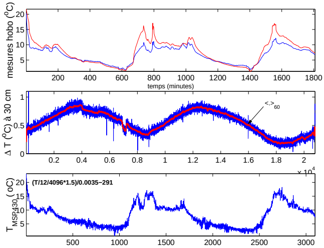
The SUPERSTAR II also takes advantage of the corrections offered by SBAS systems such as WAAS and EGNOS for improved accuracy. For precise timing applications, the SUPERSTAR II features a 1PPS accuracy of 50 nanoseconds (typical).

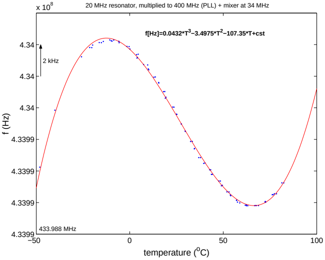
200 ns on a 1 s 1PPS signal ⇒ 0.2 ppm relative stability (< 0.5 ppm) *on the long term* since the GPS signal will not be affected by thermal drift, stress etc ...

(aging and drift monitored and compensated for by the ground segment of GPS)

Local reference stability issue (2)

- A reference oscillator might display a relative short term (<100 s) stability in the $10^{-9} - 10^{-10}$ range *under stable environmental condition*
- Embedded sensor monitoring $\Rightarrow$ the reference oscillator is subject to large temperature variations (TTL oscillator)

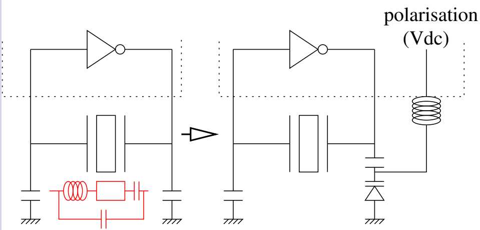


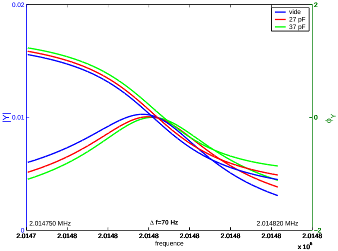


Left: 2.5-day measurement (1 measurement/min), interrogation unit outdoor
Middle: 4 month measurement (1 measurement/day), interrogation unit indoor
Right: reference output (20 MHz) multiplied to 433 MHz output, function of T

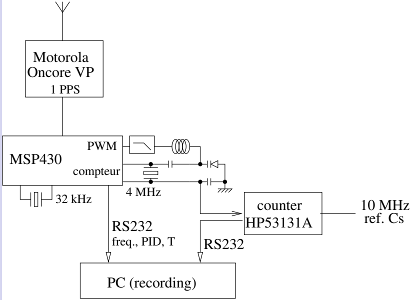
Local reference stability issue (3)

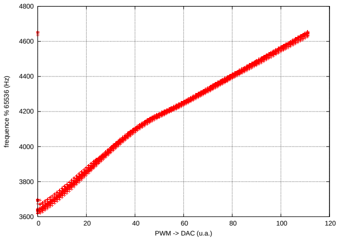
- Tuning a reference signal is performed by varying the capacitor on one of the arms of the quartz resonator
- A frequency counter monitors the oscillator frequency (here the gate time is accurate) and compensates for any drift from the setpoint frequency
- Direct counter ⇒ extremely simple to add to any microcontroller: use input capture and internal timer to monitor the oscillator

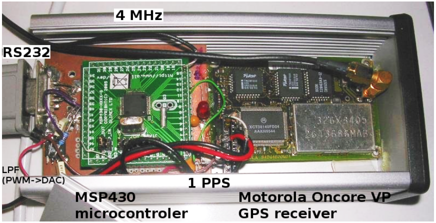




Local reference stability issue (4)

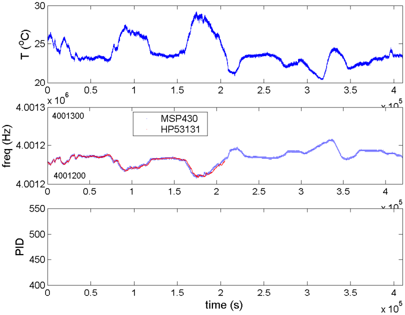




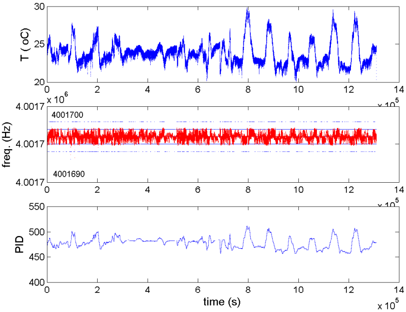


- Evolution of the frequency as a function of DC tuning voltage (open loop).
- 1 kHz tuning around 4 MHz (250 ppm)

Local reference stability: time analysis

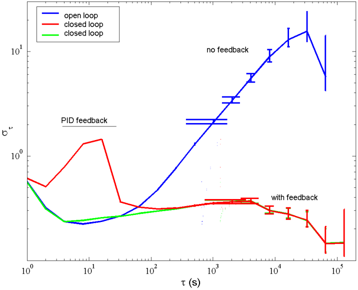


Open loop: -1 ppm/K around 25°C, temperature fluctuations are visible on the frequency

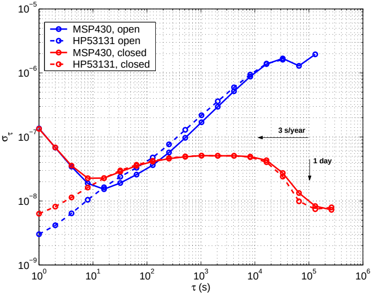


Closed loop: temperature fluctuations are visible on the feedback control

Local reference stability issue (5)



frequency deviation Δf

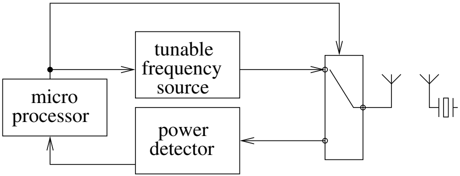


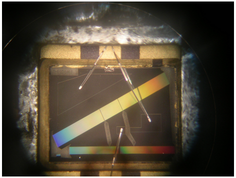
relative frequency deviation $\Delta f / f$

- $5 \times 10^{-8} = 0.05$ ppm is consistent with 50 ns relative stability
- Such a stability is enough for our sensing applications
- Global reference for *all* interrogation units, even widely spaced apart

Temperature sensor design

- Dual resonator SAW sensor to subtract correlated noise sources (stress, environmental effect of antenna)
- Two resonators on a same substrate, different orientations for different temperature drift coefficients



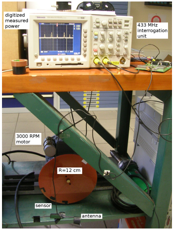


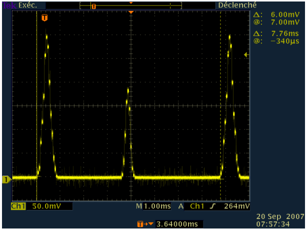
Interrogation unit: principle of radar:

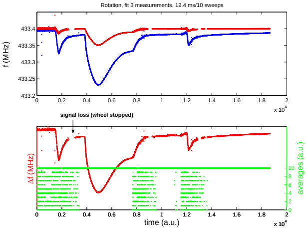
1. switch on radiofrequency source at f
2. wait τ seconds until resonator is loaded ($\tau \geq Q/f$)
3. switch off emission and listen for resonator discharge
4. repeat for $f \rightarrow f + f_{step}$
5. after sweeping ISM band, search max=resonance frequency

Temperature sensor on a wheel

Example of a temperature measurement on a wheel rotating at 3000 RPM
$\Rightarrow$ 0.2 to 1^{o}C relative temperature measurement



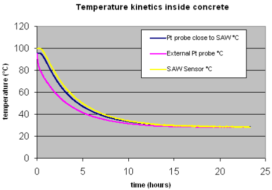




- Absolute temperature requires preliminary calibration
- Interrogation time <10 ms
- Range $\simeq$2 m in free space, 30 cm in soil, a few cm in living body

Buried sensors

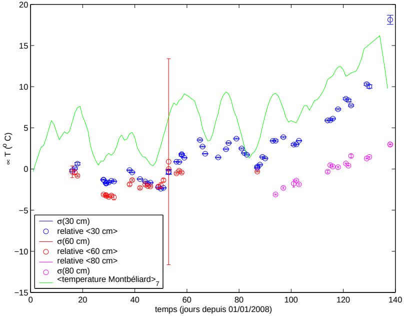
- no battery and wireless monitoring ⇒ compatible with long-term monitoring of building
- complement to current Ground Penetrating Radar (GPR) methods ("cooperative target")
- range of 30 cm demonstrated in wet soil, should be possible beyond considering the range of GPR

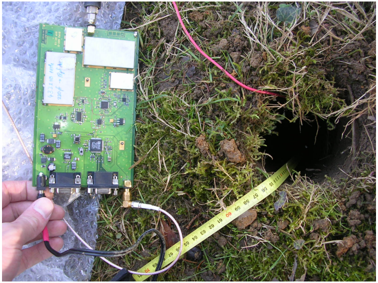


Data provided by L. Chommeloux (SENSeOR)

Buried sensors (2)

Evolution of the temperature 30, 50 cm & 80 cm (wired) deep, in wet soil [1]



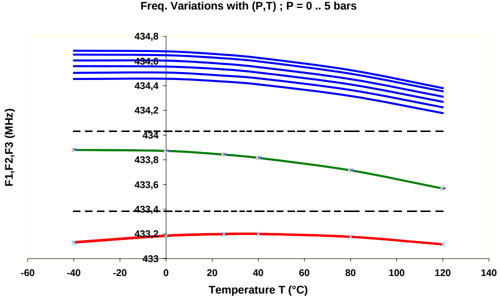


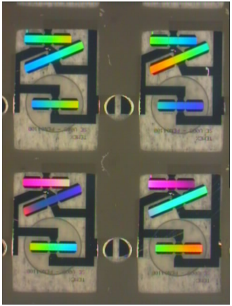
$\varepsilon_{soil} \simeq 9 - 20 \Rightarrow \lambda_{soil}/2 \simeq 8 - 11$ cm

[1] Temperature: `http://english.wunderground.com`, IVERMOND1 station

Temperature and pressure sensor

- Packaging challenge: include a reference cavity at known pressure
- Temperature is needed to compensate reference pressure change
- Three resonators: one reference, one temperature, one pressure

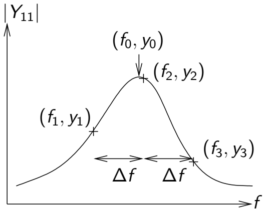




Data provided by L. Chommeloux (SENSeOR)

Polynomial fit

How to improve the measurement resolution and reduce sweep time



$$f_0 = f_2 + \frac{\Delta f}{2} \times \frac{y_1 - y_3}{y_1 + y_3 - 2y_2} \Rightarrow d(f_0 - f_2) = \frac{\Delta f}{(u+v)^2} \times (|v|du + |u|dv)$$

where $u = y_1 - y_2$ et $v = y_3 - y_2$, du et dv being the associated uncertainties.

If $|du| = |dv|$, then

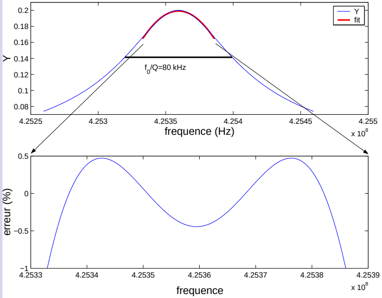
$$d(f_0 - f_2) \simeq \frac{du}{2|u|} \Delta f$$

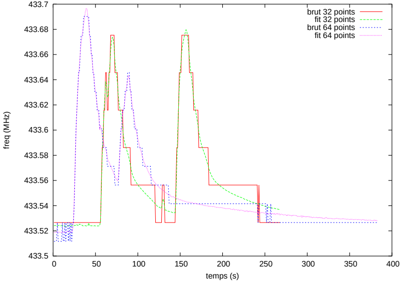
$\rightarrow$ select Δf large enough for y_1 and y_3 to be far from y_2 while keeping the parabolic approximation correct.

Polynomial fit (2)

The approximation is true to within 5% if $f \in [f_0 \pm f_0/Q/3]$

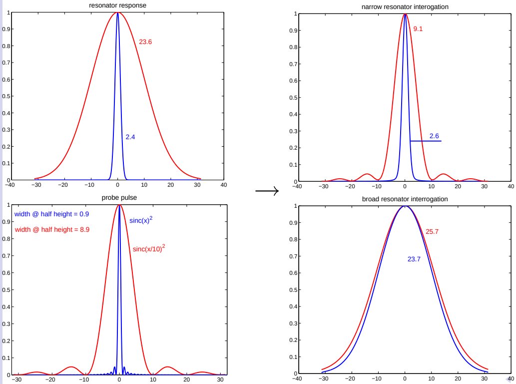
$\Rightarrow$ select $\Delta f = f_O/(3 \times Q)$





Resolution of radar strategy

- Broadband (narrow pulse and inverse DFT) is limited by the duration of the listening step, i.e. by the response time of the resonator ($\sim$ Heisenberg).
- Narrowband frequency sweep: linear response of the resonator to the probe pulse $\Rightarrow$ we read a power output, *not* a frequency measurement from the sampled data.



The duration of the pulse (frequency occupation) determines the observed Q for narrowband resonators, and hence the accuracy of the frequency measurement ($f_2 - f_0 \propto 1/Q$) $\Rightarrow$ if pulse is narrower than Q, resonator determines accuracy, other pulse defines equivalent Q

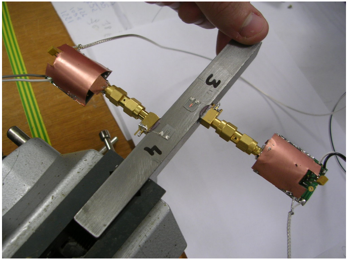
Listen before talk (LBT)

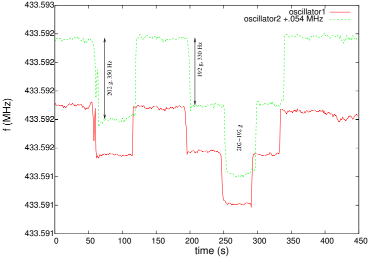
- Strategy to avoid performing a measurement when another signal occupies the RF channel
- since we integrate the energy in the ISM band, we must avoid measuring during another RF emission

$\Rightarrow$ read output of power detector before sending a probe pulse

Wired v.s wireless

- Wireless sensing opens new applications for passive sensors, but measurement precision=250 Hz (sweep time+signal processing),
- Closed loop (oscillator) still most sensitive solution: 1.4×1.4 cm^2 iron beam loaded with 200 g weights, 2 oscillators



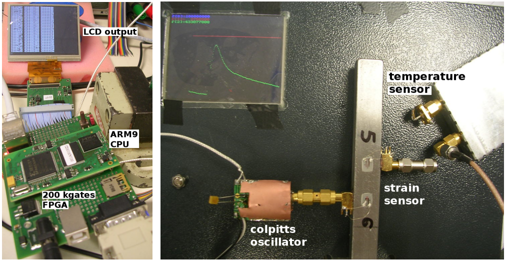


Instrumentation issue is now moved to the *frequency counter*

Design and realization of the oscillators: G. Martin

Wired v.s wireless

- Issue with oscillators: sensors will see varying environments ⇒ Barkhausen conditions are more difficult to meet
- Two strategies for frequency counting: direct and reciprocal counters [2]
- Direct counter requires accurate gate signal: cf earlier discussion on GPS
- Reciprocal counter was implemented in an FPGA (3 channels: 1 reference, 2 measurements) `http://www.armadeus.org`



[2] `http://cp.literature.agilent.com/litweb/pdf/5965-7660E.pdf`

Wireless delay line measurement

- $Q \times f$=cst: increasing f reduces Q, and response time $= Q/\pi$ oscillation periods $\Rightarrow$ radar only applicable < 1 GHz
- Delay line needs long enough pulse to generate acoustic wave, but short enough to define each reflection
- Classically used for identification (SAW-tags): here we want to add measurement
- Time domain analysis, but information can also be extracted from inverse Fourier transform of wideband frequency sweep (network analyzer)
- very fast interrogation: a single pulse + 10 μs delay provides all data

4 reflections, temperature sensor delay line

General strategy

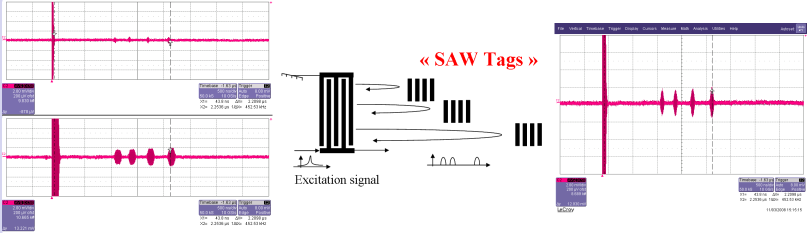
- Delay line requires accurate determination of a *time delay* [3]
- Accurate time $\leftrightarrow$ wideband (technical issue for frequency sweep + regulations)
- Time is phase: $\Delta f/f = \Delta c/c = \Delta\varphi/\varphi$ or 250 Hz at 433 MHz is 0.6 ppm $\Rightarrow$ measure $\Delta c \simeq$mm/s or $\Delta\varphi \simeq$0.2 m^o
- time-analysis requires fast sampling (even at IF$\simeq$70 MHz)

Delay lines are used by Kongsberg's SENTRY (Norway), CTR (Austria) and RFSAW (US)

[3] L. Reindl, *Wireless Passive SAW Identification Marks and Sensors*, 2nd Int. Symp. Acoustic Wave Devices for Future Mobile Communication Systems, Chiba Univ. 3rd-5th March (2004), available at `www.usl.chiba-u.ac.jp/~ken/Symp2004/PDF/1B3.PDF`

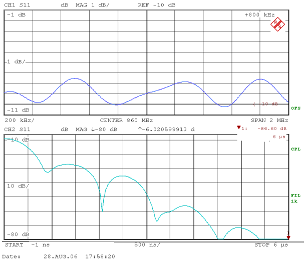
Optimal energy injection: time aspect

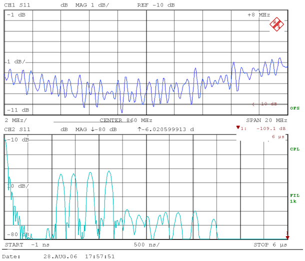
- A delay line is made of N transducers (IDT), N small enough to keep a narrow pulse but long enough to couple energy.
- Optimum interrogation time : N periods at central frequency.



- Here the signal is recorded at baseband frequency (850 MHz) at 10 GS/s.
- Mixing shifts the signal to a lower intermediate frequency but wideband still requires at least 100 MS/s

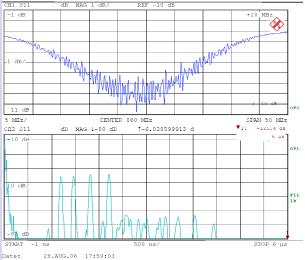
Optimal energy injection: frequency aspect



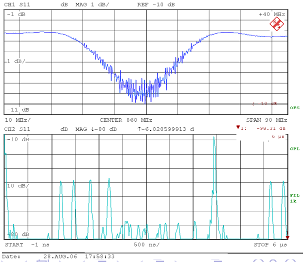


↓50 MHz

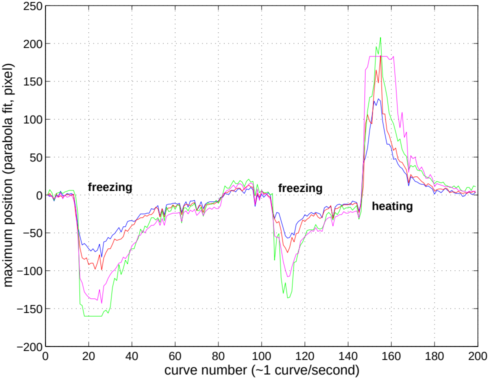
90 *MHz* ↓



Inverse Fourier transform of frequency sweep: narrow frequency sweep (2 MHz, top left) does not provide enough time resolution. This delay line requires at least 20 MHz bandwidth.



Measurement example: 860 MHz temperature sensor

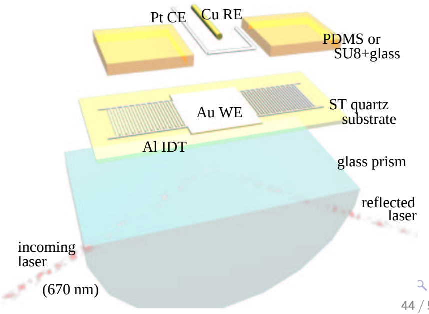


- 4 reflectors at varying distance from transducer ⇒ 4 different delays, varying with temperature
- rough delay estimate with envelope maximum identification, followed by fine tuning with phase identification (cross correlation)

SAW delay line for thin film characterization

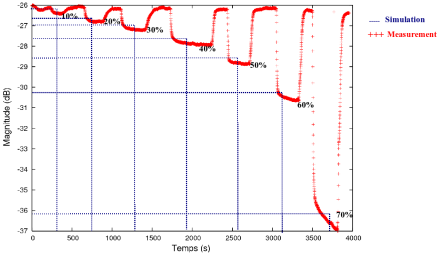
- *Direct detection* (bio)sensor
- evanescent wave interacts with the first ≃100 nm of the adsorbed layer
- sensitive to mass and viscosity (+ permittivity/conductivity)
- compatible with other *simultaneous* measurements (optics, electrochemistry, SPM)
- sub-second time resolution ⇒ kinetics
- sensitivity: 200 to 400 cm^2/g (Love mode), detection limit ≃100 ng/cm^2

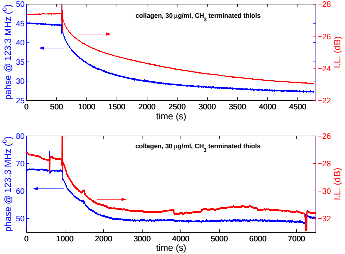
⇒ transmission measurement of a wave propagating over a pattern-free sensing area



Acoustic device characterization

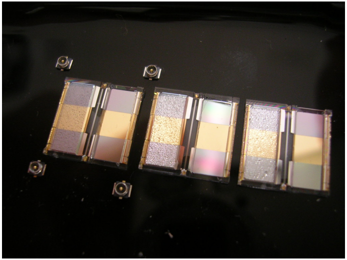
- Wireless takes full advantage of the performances of piezoelectric RF sensors
- Wired provides best performances
- Under unknown and variable environments, what is the most robust solution to always get a signal ?
- Measurement of viscous solutions (bio/polymer layers) ⇒ large viscosity variations

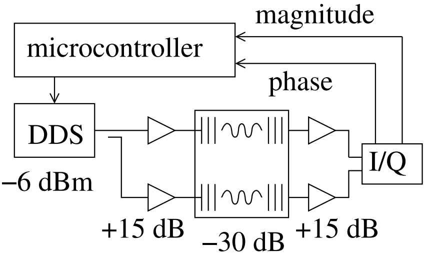




Acoustic device characterization

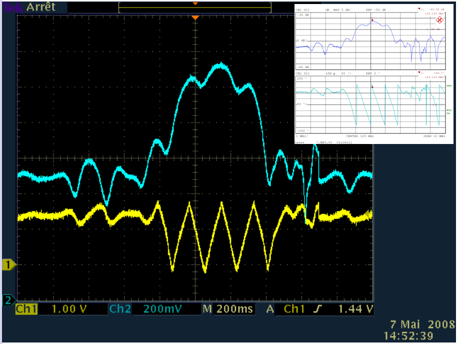
- Wireless takes full advantage of the performances of piezoelectric RF sensors
- Wired provides best performances
- Under unknown and variable environments, what is the most robust solution to always get a signal ?
- Measurement of viscous solutions (bio/polymer layers) $\Rightarrow$ large viscosity variations

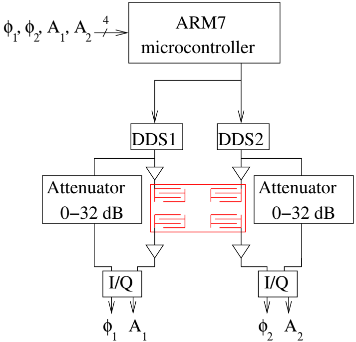




Acoustic device characterization (2)

Comparison of our measurement and the result from a commercial network analyzer (Rohde & Schwartz)

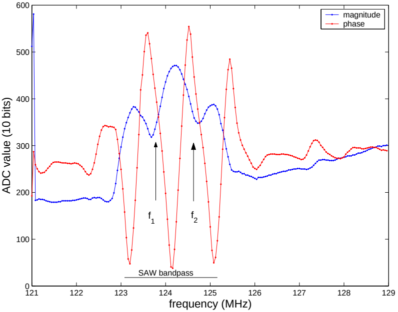


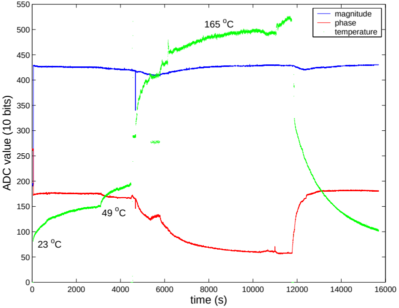


Works with high insertion losses (here peak at -42 dB, min around -75 dB), reduces impact of manufacturing variability.

Open loop delay line interrogation

Measurement example: setpoint selection and temperature dependent behavior of a Love mode acoustic delay line





- 125 MHz Love mode sensors, sensitivity: $\frac{\Delta f}{f} \times \frac{A}{\Delta m}$=200-400 cm^2/g
- phase to frequency slope: $\frac{d\varphi}{df} = 360 \times \frac{L}{v} = 0.5 \times 10^{-3}$ ^{o}/Hz
- phase measurement noise (AD8302 or network analyzer): 0.3^o

$\Rightarrow$ detection limit: 600 Hz or 12 ng/cm^2

Software controlled oscillator

- The detection limit is reduced due to poor *baseline stability*: replace delay line with resonator (high Q)
- Monitor phase at a given frequency
- Feedback phase variation on the frequency of the frequency synthesizer $\Rightarrow$ two strategies, either wideband delay lines monitored at fixed frequency (phase + magnitude), or (narrowband) resonator tracked.
- Sensitivity: phase rotation π in a bandwidth $\Delta f = f/Q$ i.e. phase to frequency slope $\frac{d\varphi}{df} = \frac{\pi \times Q}{f}$
- At $f = 434$ MHz, $Q = 8000 \Rightarrow d\varphi = 5.8 \times 10^{-5}$ rad/Hz
- A noise level of $0.3^o = 5 \times 10^{-3}$ rad is equivalent to 90 Hz (good oscillators provide relative short term stability around 10^{-9}, or 0.5 Hz)

Phase tracking

Two option when monitoring the evolution of a SAW sensor:

- probe at fixed frequency: valid as long as the frequency is within the bandpass $\leftarrow$ fixed frequency oscillator and variable acoustic conditions
  $\Rightarrow$ the parameters of the interrogation signal are kept constant and varying conditions on the SAW
- track a given quantity (magnitude or phase) $\leftarrow$ variable frequency source and fixed acoustic conditions
  $\Rightarrow$ requires tunable frequency source but fixed working conditions of the acoustic device

For example, the AD8302 I/Q demodulator displays largest noise and error at 0 & 180^o, minimum at $\pm 90^o$ $\Rightarrow$ track the phase at which measurement is optimum

Never stabilize an oscillator on a delay line

Conclusion

- Presentation of various means of interrogation for wireless acoustic wave sensors: resonators (narrow band) and delay lines (wideband)
- Demonstration of results acquired on buried or moving targets: fast and accurate differential measurement of resonance frequencies
- Presentation of wired solution for sensors submitted to widely varying conditions (viscosity/mass) and characterization

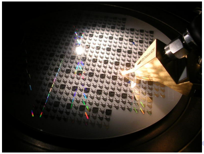
Our ability to implement these principles on embedded devices is strongly dependent on technology: fast moving field with the expansion of wireless (active) sensor networks and wireless communications.

femto-st sciences & technologies

http://www.femto-st.fr

SENSeOR

http://www.senseor.com



Further readings

- D. Royer, E. Dieulesaint & D.P. Morgan, *Elastic waves in solids, vol. 1 & 2*, Springer (2000)
- K.Finkenzeller, *RFID Handbook – Fundamentals and Applications in Contactless Smart Cards and Identification, 2nd Ed.*, John Wiley & Sons (2003)
- L. Reindl, *Wireless Passive SAW Identification Marks and Sensors*, Tutorial presented at the 2002 IEEE Intl Frequency Control Symposium (2002), available at `http://www.ieee-uffc.org/freqcontrol/tutorials/Reindl_2002_files/frame.htm`
- antennas: C. A. Balanis, *Antenna theory – Analysis and design, 2nd Ed.*, John Wiley & Sons (1997)