# RADAR cooperative targets for wireless sensing: historical perspective on passive sensors – application to sub-surface sensing

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

November 8, 2020

# Outline

1. Why cooperative targets as passive wireless sensors ?
2. Historical background and design considerations
3. Acoustic transducers as RADAR cooperative targets: architectures
4. Buried sensor application examples
5. Probing sensors: short range RADAR system architecutres
6. Practical applications and conclusion
7. More information & quiz

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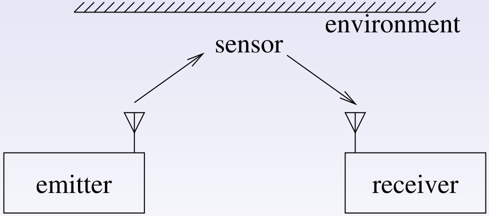
Acoustic transducers

Experimental demonstration

Dedicated hardware for sensor

# Introduction

- Passive transducers acting as RADAR cooperative targets for **wireless sensing** purposes
- **No energy source** at the sensor: measured backscattered signal property
- Separate sensor response from environmental reflections (clutter)



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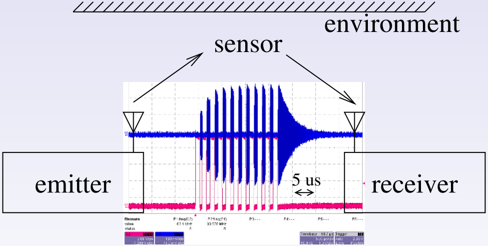


❶ How to introduce a dedicated signature from a cooperative target ?

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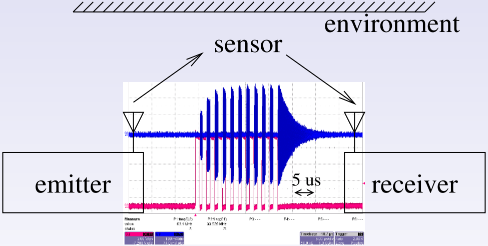


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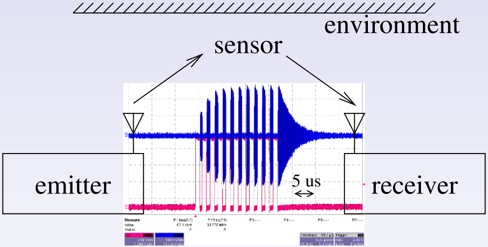


1. How to introduce a dedicated signature from a cooperative target ?
2. How to add a sensing capability ?
3. How to separate the emitted signal from the returned signal ?

# Historical background: RADAR cooperative targets

1. target whose backscattered signal is representative of its state (identification, measurement)
2. active targets: radar beacons (racon), IFF
3. passive targets: buried dielectric reflectors, Lüneberg spheres
4. this work: use of radiofrequency transducers based on surface acoustic wave propagation (RF filters)

H. Stockman, *Communication by means of reflected power* Proc. IRE **36** (Oct. 1948) pp.1196–1204

(picture from http://geogdata.csun.edu/~aether/pdf/volume_05a/rosol.pdf)

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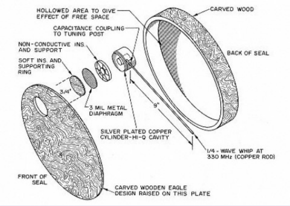


A. Glinsky, *Theremin: Ether Music And Espionage*, University of Illinois Press (2005)
P. Wright & P. Greengrass, *Spycatcher* (1987), pp.14–17 $\Rightarrow$ MI5 SATYR

http://madmikesamerica.com/2010/08/the-thing-and-the-curious-life-of-leon-theremin/thing2/

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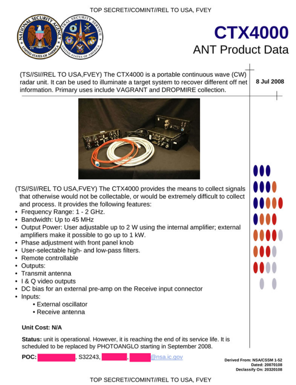
J. Appelbaum, J. Horchert & C. Stöcker, *Shopping for Spy Gear: Catalog Advertises NSA Toolbox*, Der Spiegel (12/29/2013) `http://leaksource.info/2013/12/30/nsas-ant-division-catalog-of-exploits-for-nearly`



TOP SECRET//COMINT//REL TO USA, FVEY

**CTX4000**
ANT Product Data

(TS//SI//REL TO USA,FVEY) The CTX4000 is a portable continuous wave (CW) radar unit. It can be used to illuminate a target system to recover different off net information. Primary uses include VAGRANT and DROPMIRE collection.

**8 Jul 2008**

(TS//SI//REL TO USA,FVEY) The CTX4000 provides the means to collect signals that otherwise would not be collectable, or would be extremely difficult to collect and process. It provides the following features:

- Frequency Range: 1 - 2 GHz.
- Bandwidth: Up to 45 MHz
- Output Power: User adjustable up to 2 W using the internal amplifier; external amplifiers make it possible to go up to 1 kW.
- Phase adjustment with front panel knob
- User-selectable high- and low-pass filters.
- Remote controllable
- Outputs:
- Transmit antenna
- I & Q video outputs
- DC bias for an external pre-amp on the Receive input connector
- Inputs:
  - External oscillator
  - Receive antenna

**Unit Cost: N/A**

**Status:** unit is operational. However, it is reaching the end of its service life. It is scheduled to be replaced by PHOTOANGLO starting in September 2008.

**POC:** [redacted], S32243, [redacted], [redacted]@nsa.ic.gov

**Derived From: NSA/CSSM 1-52**
**Dated: 20070108**
**Declassify On: 20320108**

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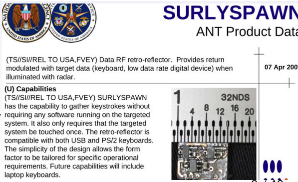

**SURLYSPAWN**
ANT Product Data

(TS//SI//REL TO USA,FVEY) Data RF retro-reflector. Provides return modulated with target data (keyboard, low data rate digital device) when illuminated with radar.

**07 Apr 200**

**(U) Capabilities**
(TS//SI//REL TO USA,FVEY) SURLYSPAWN has the capability to gather keystrokes without requiring any software running on the targeted system. It also only requires that the targeted system be touched once. The retro-reflector is compatible with both USB and PS/2 keyboards. The simplicity of the design allows the form factor to be tailored for specific operational requirements. Future capabilities will include laptop keyboards.

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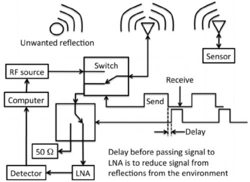
Fig. 1. Passive RFCSs are mounted on or embedded within structures. A sensor with antenna is pictured in the upper left-hand corner. The sensor is approximately 90 mm in length. The sensor is interrogated using a pulse/echo technique. The sensor is passive and does not require any local power, such as a battery.




D. J. Thomson, D. Card, and G. E. Bridges, *RF Cavity Passive Wireless Sensors With Time-Domain Gating-Based Interrogation for SHM of Civil Structures*, IEEE Sensors Journal . **9** (11) (Nov. 2009), pp.1430-1438

G. Poteat, *Stealth, countermeasures and ELINT, 1960–1975 (U)* (2014)

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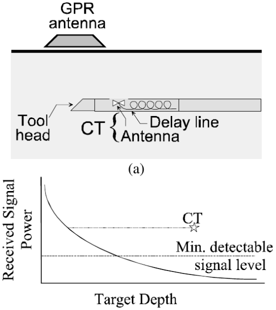
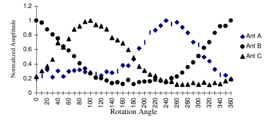
C.T. Allen, S. Kun, R.G Plumb, *The use of ground-penetrating radar with a cooperative target*, IEEE Transactions on Geoscience and Remote Sensing, **36** (5) (Sept. 1998) pp. 1821– 1825



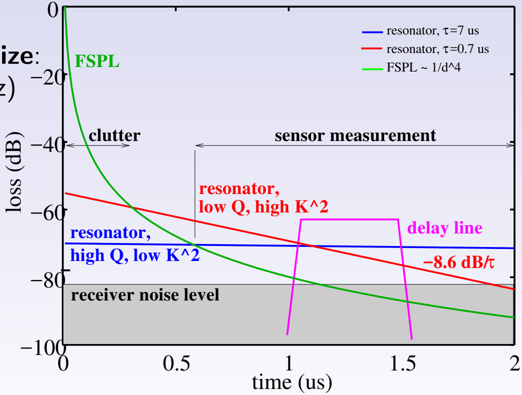




(b)

Figure 3. Normalized response at different rotation angles for (a) the two-CT configuration and (b) the three-CT configuration.

# Development strategy

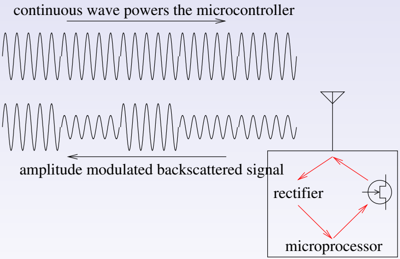
- **Delay line** for delayed echo (1 $\mu$s=100 m coaxial cable !)
- **Resonators** for energy storage and slow release [1]
- $20\log_{10}(e) = 8.6$ and exponential decay of an unloading resonator is $\exp(-t/\tau)$ with $\tau = Q/(\pi \cdot f_0)$
- Rising frequency for **shrinking antenna size**: $\lambda$ (m) $= 300/f$ (MHz)

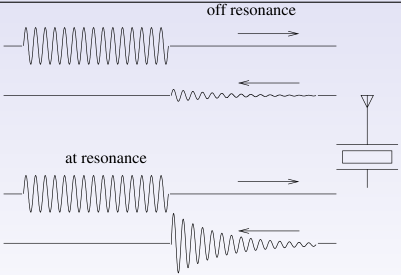



[1] https://www.isa.org/participate-in-a-technical-division/communications-division/dielectric-resonators

# RFID v.s linear transducers

| RFID | linear transducers |
|---|---|
| rectifier for powering the microcontroller = diodes | linear transduction process (piezoelectric, dielectric resonator loading) |
| near field coupling | far field interrogation |
| backscattered signal modulation | delayed echo |
| periodic bit sampling | frequency sweep or Fourier transform of returned signal |




S. Preradovic & N.C. Karmakar, *Multiresonator-Based Chipless RFID Barcode of the Future*, Springer (2012) ou A. Vena, É. Perret & S. Tedijini, *La RFID sans puce*, ISTE Ed. (2016)

"Chipless RFID" !

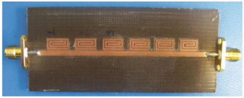


Fig. 3.27 Photograph of 6-bit multiresonator on Taconic TLX-0

# How to use a transducer for measurement ?

Intrinsic material property

- a dielectric resonator resonance frequency is $f_{TE01} \simeq \frac{34}{a\sqrt{\varepsilon_r}}\left(\frac{a}{L}+3.45\right)$ GHz ($a$ radius, $L$ length in mm) [2]
  $\Rightarrow$ dilatation ($df_{TE01} \simeq \frac{34}{\sqrt{\varepsilon_r}}\frac{dL}{L^2}$) and permettivity effect

**Extrinsic** transducer property

- varying load on a 2-port device (coupling between port connected to antenna and port connected to sensor): resistor (strain gauge), capacitor (moisture)
- disturbing the fringing electrical field

IEEE SENSORS JOURNAL, VOL. 9, NO. 11, NOVEMBER 2009

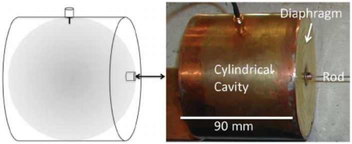



Fig. 13. Displacement sensor employing a corrugated diaphragm on one end with a rod attached. As the rod is displaced, the diaphragm is displaced causing the cavity to change dimension and hence shift the resonant frequency. The cavity is 100 mm in diameter. An SMA connector-wire probe is used to couple signals in and out of the cavity.

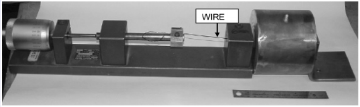
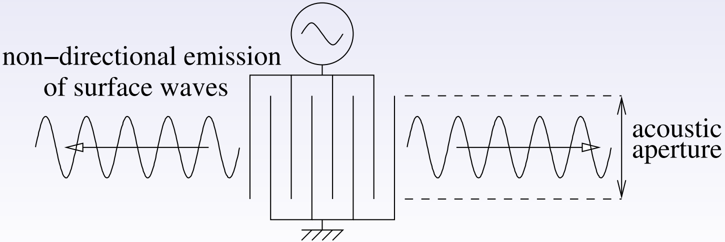



Fig. 14. Displacement sensor was mounted on a displacement test fixture, and a wire rod was attached to the front of the displacement sensor. Using the micrometer, the diaphragm of the displacement sensor was translated in 0.1 mm increments. At each increment the resonant frequency of the cavity was determined using the servo method described.

[2] D. Kafjez & P. Guillon, *Dielectric resonators, 2nd Ed*, Noble (1998), p.3

# Acoustic transducers

- Interdigitated transducers (electrodes – IDT) patterned on a piezoelectric substrate convert an incoming electromagnetic wave to an aocustic wave.
- Linear process: the frequency must remain constant at varying velocity. The wavelength shrinks by $10^5$: velocity $\in [3000 - 10000]$ m/s $\Rightarrow$ 2-3000 MHz depending on design.
- $\varepsilon_{piezo} \gg \varepsilon_{air} \Rightarrow$ efficient electric field confinement in piezo substrate
- tune acoustic aperture as a function of number of electrodes in IDT to reach 50 Ω at resonance



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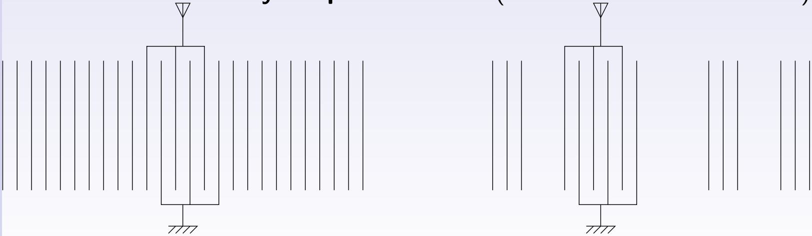
# Acoustic transducers

- **Delay line** architecture: the wave is generated by the IDT, meets the mirrors patterned on the subtrate after propagating over free space, and is reflected back to the IDT for direct piezoelectric acoustic to electromagnetic conversion (right)
- **Resonator**: the wave travels back and forth $Q$ times between the Bragg mirror (left)
- impulse response of the acoustic wave = **Fourier transform of the IDT pattern** ⇒ copy-pasting $Q$ times the IDT in the resonator configuration shrinks the required bandwidth
- Delay lines: **strongly coupled** materials ($IL \simeq K^2$ at low frequency)
- Resonators: **weakly coupled** materials (lowers ohmic losses in IDT)



Resonator Delay line

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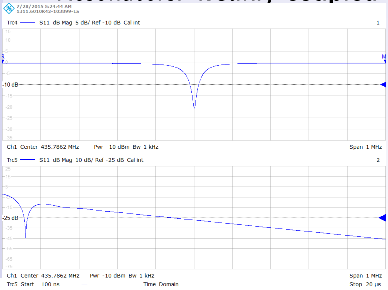


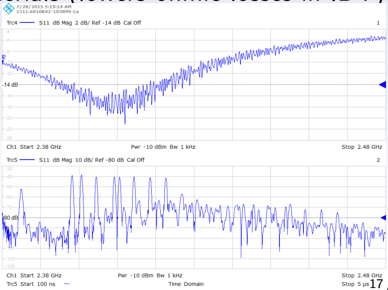

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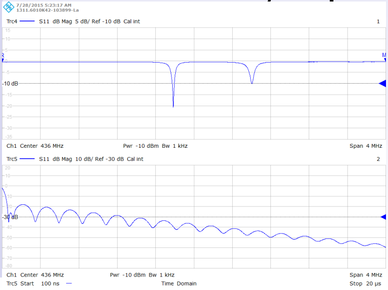


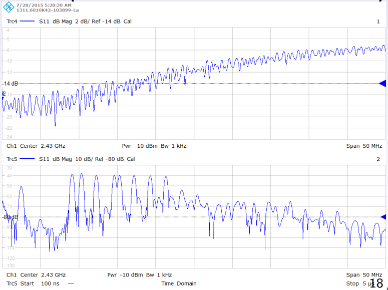

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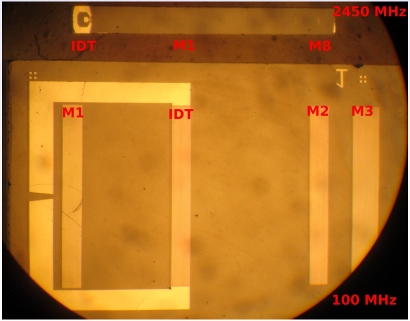
# Acoustic transducers

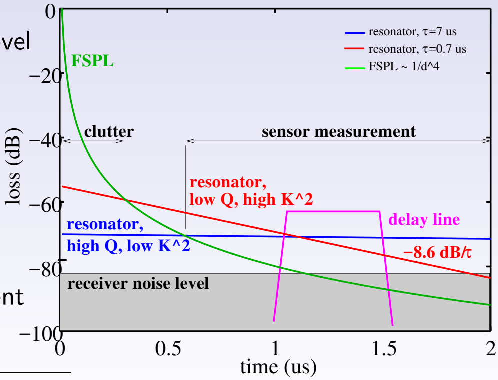
- Acoustic = **mechanical wave** propagating in **solid** media
- Surface acoustic wave transducer: use a **piezoelectric substrate** to convert an electromagnetic wave to acoustic wave
- Classical analog radiofrequency processing circuit (seen as an electrical dipole by the user)
- the acoustic wave is $10^5$ **slower** than the electromagnetic wave
- $\lambda = c/f$: shrink $c \Rightarrow$ shrink $\lambda \Rightarrow$ compact sensors
- **Cleanroom** processing since 1 m wavelength at 300 MHz $\rightarrow$ 10 $\mu$m wavelength.
- At 2.45 GHz, $\lambda = 1.2$ $\mu$m or 300 nm wide electrodes !
- Piezoelectric substrate is anisotropic: select crystal orientation to **maximize** sensor sensitivity (stress, temperature, pressure, chemical sensing)



# Acoustic transducers as RADAR cooperative targets

Two ways of delaying sensor signal beyond clutter:

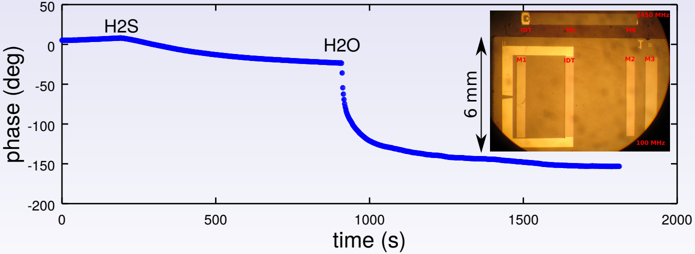
- **delay path** long enough (1 $\mu$s=100 m-long coaxial cable but 2 mm long acoustic path) [3]
- **resonator** stores energy and slowly releases it with a time constant $Q/(\pi f)$
- initial returned signal level given by the **electro-mechanical coupling** coefficient of the piezo substrate
- accurate time delay as **phase** measurement using cross-correlation
- **differential** measurement to get rid of reader-sensor distance




[3] L. Reindl *& al.*, *Theory and application of passive SAW radio transponders as sensors.*, IEEE Trans. UFFC, **45** (5), 1281–1292 (1998)

# Experimental demonstration: chemical sensing

- Propagation path coated with a layer absorbing the compound to be detected
- boundary condition (gravimetric sensor): sensitivity $\simeq$ (attached mass)/(moving mass) $\Rightarrow$ for a given layer thickness, dependent on $\lambda$ & wave confinement
- $c = \sqrt{E/\rho}$ with $E$ the elastic constant and $\rho$ the density:
  - load mass $\Rightarrow \rho \uparrow \Rightarrow c \downarrow$
  - stiffen the layer $\Rightarrow E \uparrow \Rightarrow c \uparrow$
- basic principle of the so called Quartz Crystal Microbalance

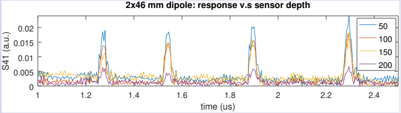


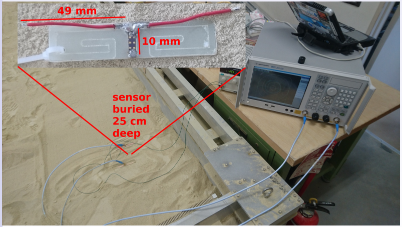

Sub-surface hydrogen sulfide ($H_2S$) detection using 100 MHz GPR [4]

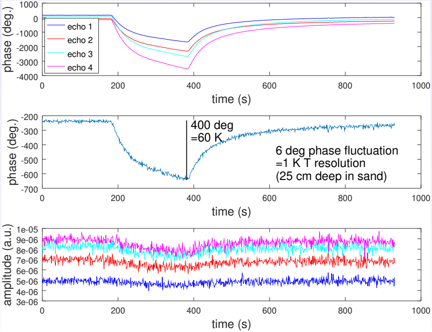
[4] D. Rabus, J.-M. Friedt, & *al.*, *Sub-surface $H_2S$ detection by a Surface Acoustic Wave passive wireless sensor interrogated with a ground penetrating radar*, ACS Sensors **5** (4), 1075–1081 (2020)

# Experimental demonstration: temperature sensing

- 870 MHz, 10 mm×3 mm sensor, for small antenna size
- 70 ppm/K temperature sensitivity: heating resistor next to sensor
- 4 echoes ("bits") between 1.2 and 2.3 $\mu$s
- $S_{21}$ FSCW measurement and inverse Fourier transform for time-domain analysis

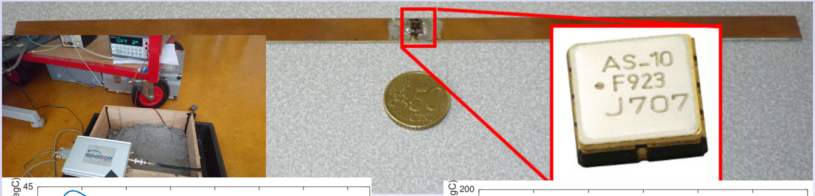


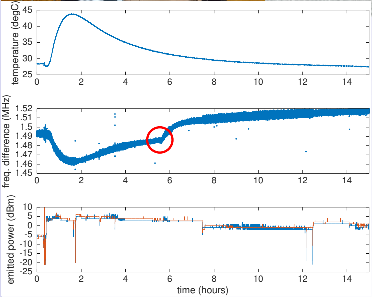



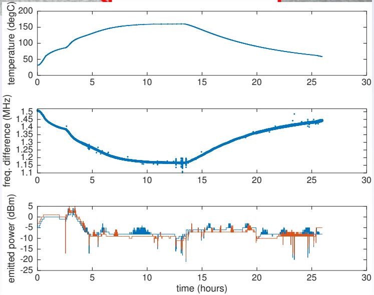



# 434 MHz resonator measurement in concrete

Dedicated frequency stepped resonator measurement electronics for a dedicated temperature sensor.




Curing

Heating at 160°C

# Short range RADAR architecture

RADAR cross section measurement of cooperative target: time-domain (broadband) or frequency domain (narrow-band) characterization to meet regulations (434±2 MHz ISM[5] band vs 2400-2480 MHz band)

- broadband (2400–2480 MHz)
  - pulsed RADAR (powerful pulse emitted and fast sampling/stroboscopy)
  - Frequency Stepped Continuous Wave (FSCW) and inverse Fourier transform
  - Frequency Modulated Continuous Wave (FMCW) beat signal
- narrowband (433.05–434.79 MHz)
  - broadband emission and Fourier transform on the received signal
  - known narrowband emission signal and power/phase measurement

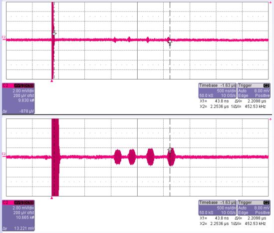
$$\boxed{\text{Delay} \leftrightarrow \text{phase: } \Delta\varphi = 2\pi f \Delta\tau}$$

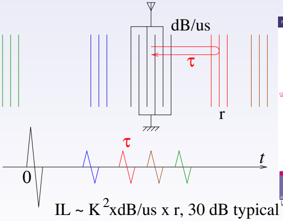
[5] Industrial, Scientific and Medical

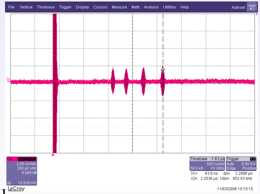
# Broadband: pulsed RADAR

- Optimum echo duration is $1/K^2$ periods [6] : at 2.4 GHz on YXl/128° LNO ($K^2 \simeq 5\%$): 8 ns wide pulses or 125 MHz bandwidth (close to the available 80 MHz)
- Challenge: high energy, short pulse (=high voltage)
- Challenge: broadband data acquisition (range resolution $dR$ is $c/(2B)$: 1-m resolution = 150 MHz bandwidth)

https://www.radartutorial.eu/19.kartei/03.atc/karte013.en.html





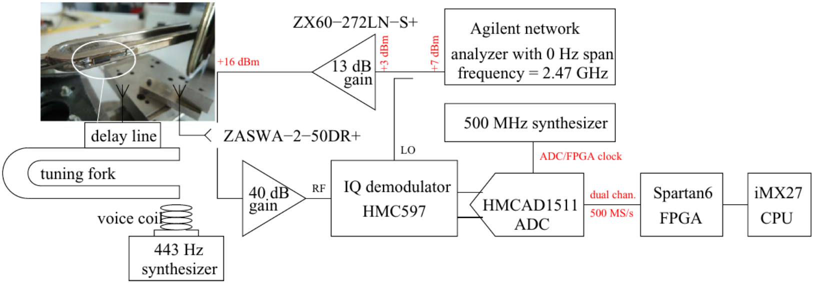



[6] D. Morgan, *Surface Acoustic Wave Filters, 2nd Ed.* (2007)

# Fast measurement strategy

- $LiNbO_3$ delay line glued to a tuning fork acting as a **strain** sensor
- longest delay defines refresh rate [7]: here 4 $\mu$s $\Rightarrow$ 250 kS/s
- pulse length defined by switch speed
- use of **fast ADC** (>100 MS/s) **but** low resolution

Goavec-Mérou *et al.* Rev. Sci. Instrum. **85**, 015109 (2014)

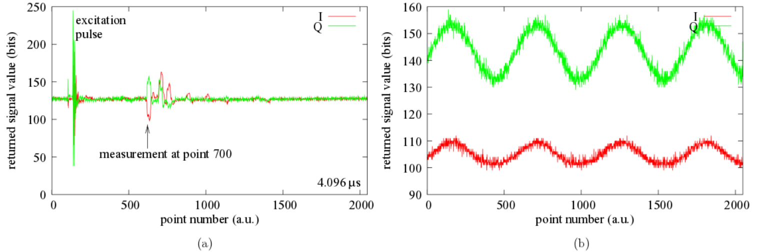



[7] G. Goavec-Mérou & al., *Fast contactless vibrating structure characterization using real time FPGA-based digital signal processing: demonstrations with a passive wireless acoustic delay line probe and vision*, Rev. Sci. Instrum **85** (1) 2014, pp.015109

# Fast measurement strategy

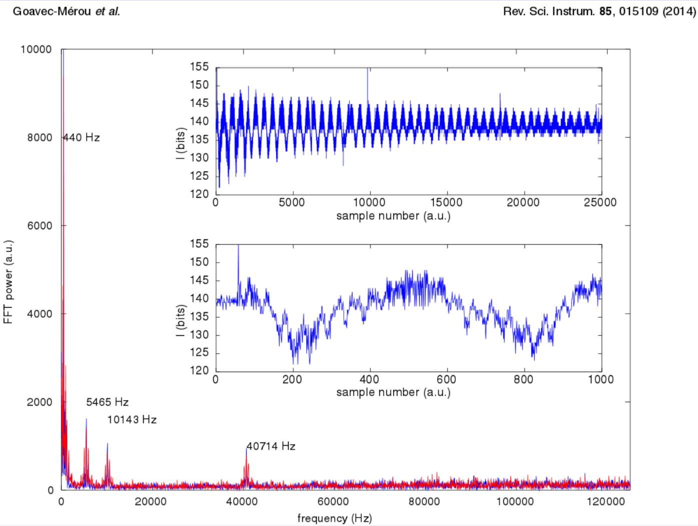
- focus on **one echo** and display time-evolution of I and Q coefficients
- DAC outputs for high bandwidth, oscilloscope display or storage for post-processing

015109-7 Goavec-Mérou *et al.* Rev. Sci. Instrum. **85**, 015109 (2014)




Here, a 440-Hz tuning fork is continuously excited by a microphone

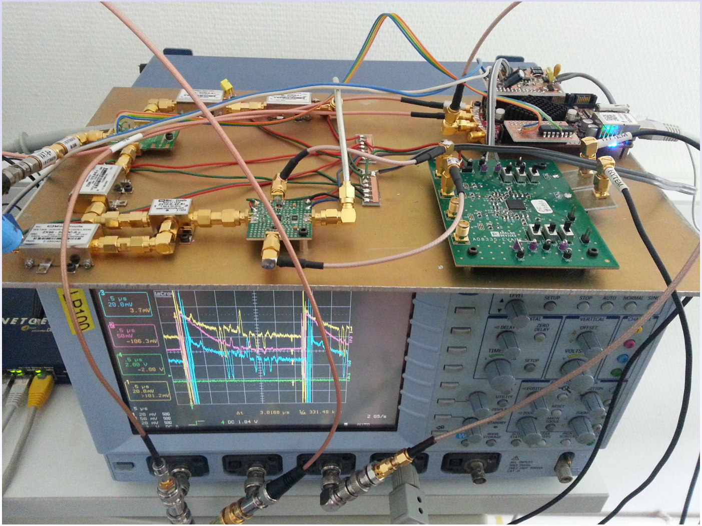
# Fast measurement strategy




Impulse reponse: mode distribution **consistent** with acoustic (audio card) and optical measurements

# Fast measurement strategy

"Compact" implementation using the Redpitaya hardware (Zynq CPU including a fast FPGA and 125 MS/s ADC)



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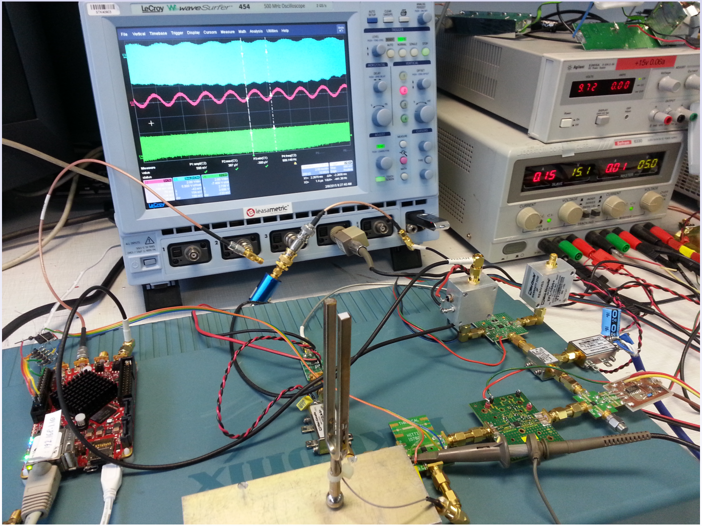
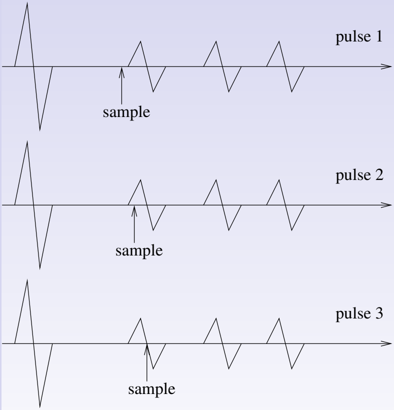


# Broadband: pulsed radar stroboscopic measurement

Assuming a constant and repeatable environment




Sampling synchronized on pulse emission

- Send a short pulse, sample one signal after $t$
- Send a new pulse, sample one signal after $t + dt$
- Repeat for $N$ samples
- Equivalent sampling rate is $1/dt$
- Delay lines (eg DS1023) with programmable delay $\propto$ 0.25 ns $\leftrightarrow$ 4 GHz
- Requires a fast Track and Hold but compatible with high resolution ADC
- Measurement duration is $N \times$longest echo delay

# Broadband: FSCW

- (switched) FSCW: network analyzer principle [8]
- Slow frequency sweep of the souce
- record I/Q coefficients for fixed frequency (circulator, reflectometric bridge to cancel direct wave)
- time domain response as iFFT of spectral responses
- select *"wisely"* the frequency span to match sensor transfer function

⇒ slow but efficient (excellent SNR from narrowband measurement)
⇒ no requirement on the source other than programmable frequency steps (DDS)

[8] F. Lurz, T. Ostertag, B. Scheiner, R. Weigel and A. Koelpin, *Reader Architectures for Wireless Surface Acoustic Wave Sensors*, MDPI Sensors **18** (6), DOI 10.3390/s18061734 (2018)

Introduction

Background

Passive sensor strategy

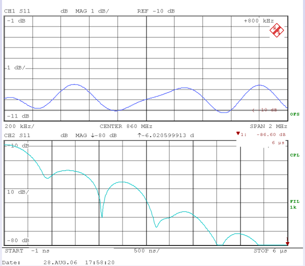
Acoustic transducers

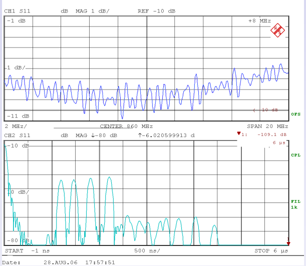
Experimental demonstration

Dedicated hardware for sensor

# Broadband: FSCW

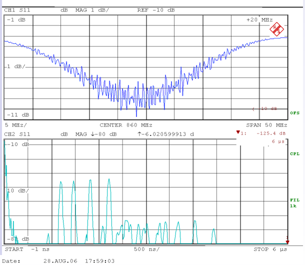
Frequency measurement (top) and inverse Fourier transform (bottom) to measure the time-domain response: broader span → better time resolution, within sensor bandwidth



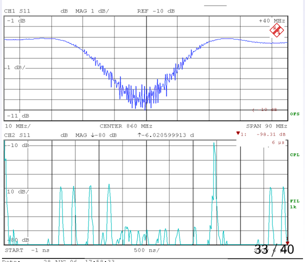




↓50 MHz

90 $MHz$ ↓

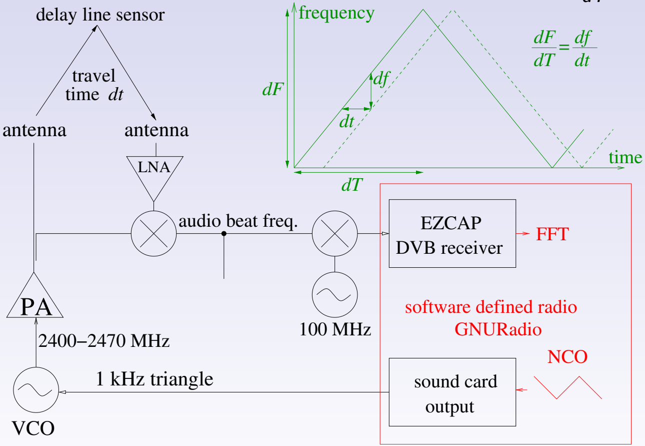



Inverse Fourier transform of frequency sweep: narrow frequency sweep (2 MHz, top left) does not provide enough time resolution. This delay line requires at least 20 MHz bandwidth.



# Broadband: FMCW [9]

- A VCO is swept over range $dF \simeq 100$ MHz at a rate $dT \simeq 10$ ms.
- The returned signal is delayed by $dt \simeq 3$ $\mu$s
- Mixing VCO and returned signal yields beat $df = dt \cdot \frac{dF}{dT} \simeq 30$ kHz




[9] N. Chrétien, J.-M. Friedt, G. Martin, S. Ballandras, *Acoustic transducers as passive sensors probed through a wireless radiofrequency link*, Instrumentation, Mesure, Métrologie (I2m), **13** (3-4) 1590-178 (2013)

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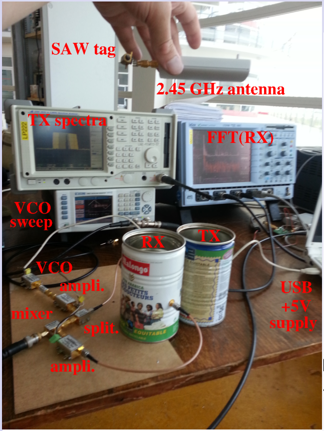
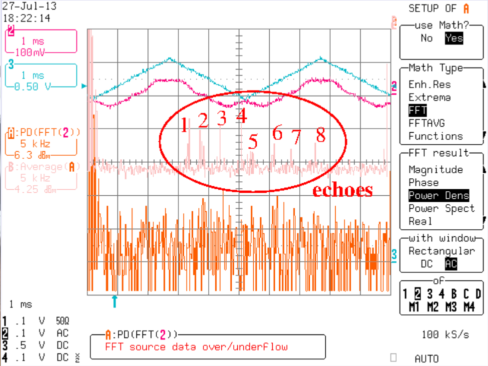
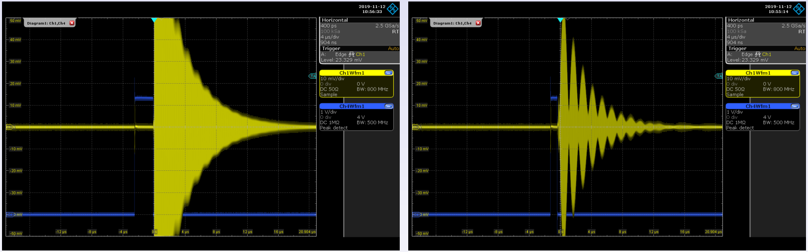



[9] N. Chrétien, J.-M. Friedt, G. Martin, S. Ballandras, *Acoustic transducers as passive sensors probed through a wireless radiofrequency link*, Instrumentation, Mesure, Métrologie (I2m), **13** (3-4) 1590-178 (2013)

# Narrowband: Fourier transform [10]

1. A “broadband” emission pulse covers the 2 MHz-wide 434-MHz ISM band
2. Returned signal is sampled fast enough and stored
3. Fourier transform (DSP/FPGA) to convert time-domain measurements to frequency-domain

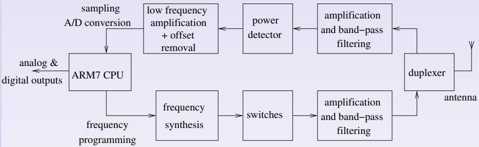


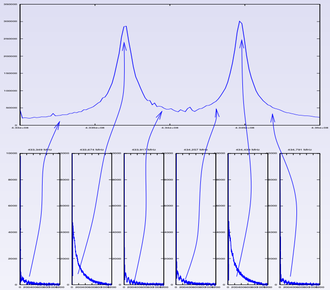
Time-domain characterization of a dual-resonator SAW sensor: left narrowband excitation, right broadband excitation ($\Rightarrow$ beatnote)

[10] M. Hamsch, R. Hoffmann, W. Buff, M. Binhack, M. & S. Klett, *An interrogation unit for passive wireless SAW sensors based on Fourier transform*, IEEE Trans. UFFC **51** (11), 1449–1456 (2004)

# Narrowband: swept emission

1. A narrowband source is swept over the 2 MHz-wide 434-MHz ISM band [11]
2. Returned signal power is measured (single scalar measurement)
3. Flexibility to implement agile strategies with DDS emission [12]

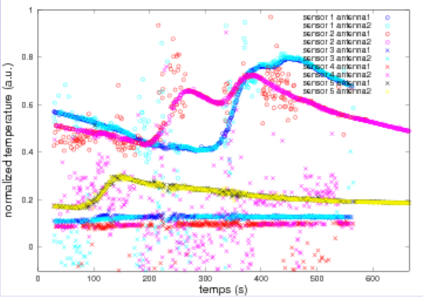


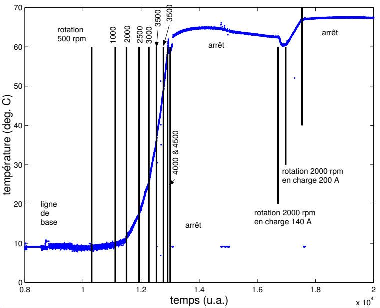



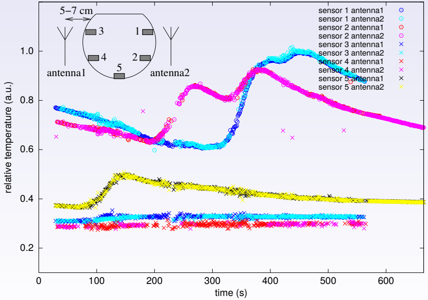
[11] J.-M Friedt, C. Droit, G. Martin, and S. Ballandras, *A wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement*, Rev. Sci. Instrum. **81**, 014701 (2010)

[12] C. Droit, G. Martin, S. Ballandras, J.-M Friedt, *A frequency modulated wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement*, Rev. Sci Instrum. **81** 056103 (2010)

# Measurement examples



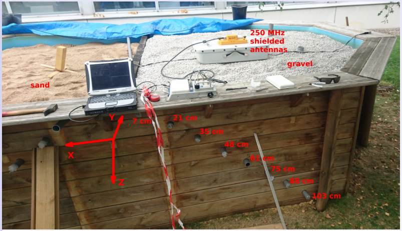



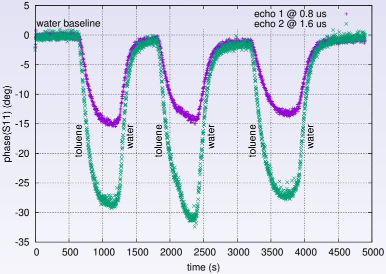



# Conclusion

- Development of **passive** cooperative target for **wireless** sensing in industrial equipment, civil engineering structures and buried environments (e.g. pipes).
- Acoustic (≤2.4 GHz) and dielectric (10-24 GHz) resonator or delay line demonstrated as **cooperative targets for sensing** applications
- **Systems** approach: link budget from emitter, to sub-surface antenna, to transducer and back to receiver [13] [14]

Ongoing work: subsurface pollution detection (chemical sensing) using GPR




[13] J.-M Friedt, *Passive cooperative targets for subsurface physical and chemical measurements: a systems perspective*, IEEE Geoscience and Remote Sensing Letters **14** (6), pp.821-825 (2017)

[14] F. Minary, D. Rabus, G. Martin, J.-M. Friedt, *Note: a dual-chip stroboscopic pulsed RADAR for probing passive sensors*, Rev. Sci. Instrum. **87**, p.096104 (2016)

# For more information ...

J.-M Friedt, S. Ballandras,
*Capteurs acousto-électriques radiofréquences – modes d'interrogation*,
Techniques de l'Ingénieur E3212 v2 (2020) [in French [15]], available at

`http://jmfriedt.free.fr/tech_inge.pdf`

Please answer the questions at

`http://jmfriedt.free.fr/tech_inge_questions.pdf`

[15] https://www.techniques-ingenieur.fr/base-documentaire/electronique-photonique-th13/materiaux-pour-l-electronique-et-dispositifs-associes-42271210/capteurs-acousto-electriques-radiofrequences-modes-d-interrogation-e3212/