Acoustic wave transducers as Ground Penetrating RADAR cooperative targets for sensing applications

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October 5, 2017

RADAR cooperative target

- a **passive** target is illuminated by an electromagnetic wave,
- this target is designed so that the backscattered signal is representative of a **measurement**,
- the sensor is separated from clutter using **Time Division Multiple Access** (delay the sensor response beyond clutter)
- the sensor response is preferably included in a **time/phase** information rather than an amplitude, sensitive to too many effects.

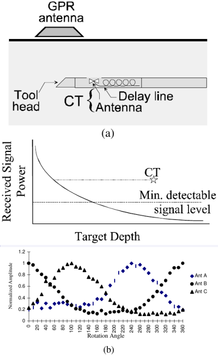


Figure 3. Normalized response at different rotation angles for (a) the two-CT configuration and (b) the three-CT configuration.

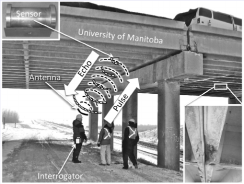
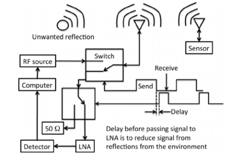


Fig. 1. Passive RFCSs are mounted on or embedded within structures. A sensor with antenna is pictured in the upper left-hand corner. The sensor is approximately 90 mm in length. The sensor is interrogated using a pulse/echo technique. The sensor is passive and does not require any local power, such as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

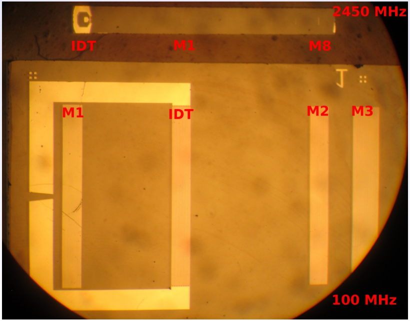


[1] C.T. Allen, S. Kun, R.G Plumb, *The use of ground-penetrating radar with a cooperative target*, IEEE Transactions on Geoscience and Remote Sensing, **36** (5) (Sept. 1998) pp. 1821– 1825

[2] 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

Acoustic transducers

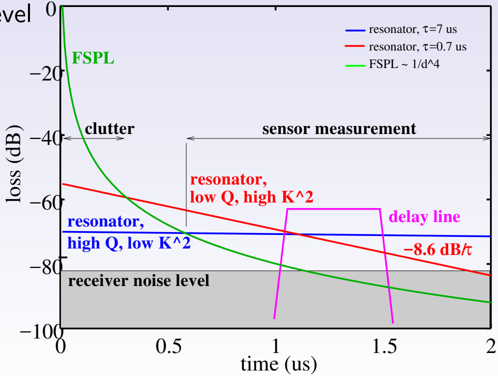
- Acoustic = **mechanical wave** propagating in **solid** media (no relation to sound/seismics)
- Surface acoustic wave transducer: use a **piezoelectric substrate** to convert an electromagnetic wave to acoustic wave
- Classical analog radiofrequency processing circuit (seen as an electrical dipole 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 μm wavelength.
- At 2.45 GHz, $\lambda = 1.2$ μm 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

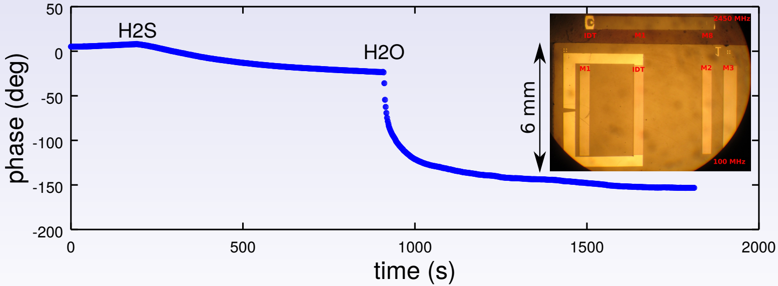
Two ways of delaying sensor signal beyond clutter:

- **delay path** long enough (1 μs=100 m-long coaxial cable but 1 mm long acoustic path)
- **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



Experimental demonstration: chemical sensing

- Coat the propagation path with a layer absorbing the compound to be detected
- $c = \sqrt{E/\rho}$ with E the elastic constant and ρ 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

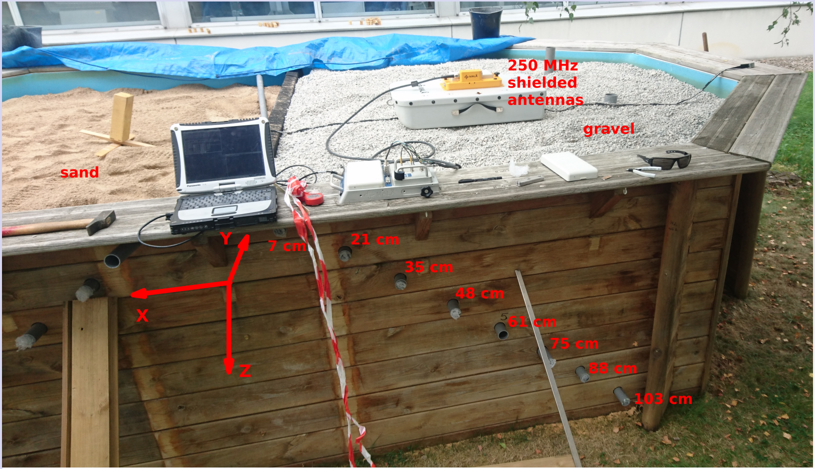


Sub-surface hydrogen sulfide detection using custom GPR [1]

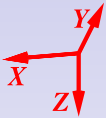
[1] F. Minary, D. Rabus, G. Martin, J.-M. Friedt, *Note: a dual-chip stroboscopic pulsed RADAR for probing passive sensors* Rev. Sci. Instrum. **87**, p.096104 (2016)

Sandbox experiment

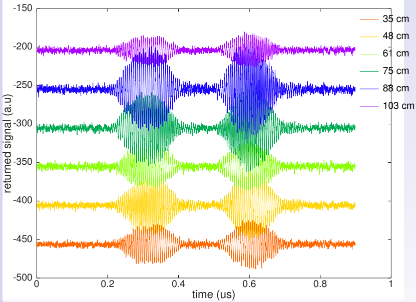
Antenna radiation pattern characterization and interrogation range

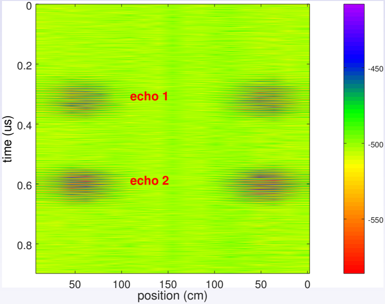


Returned signal with depth/position



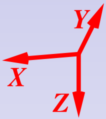
Left: returned signal as a function of depth $Z \Rightarrow \gg 1$ m range



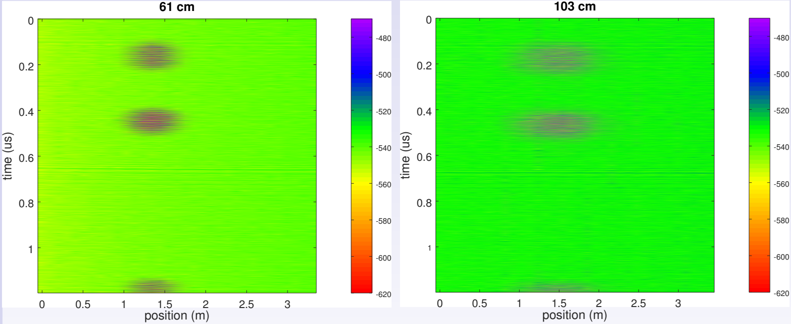


Right: returned signal as a function of position $\perp$ to dipole axis (X)

Sandbox experiment



Returned echoes as a function of the position of the sensor along the pipe (Y), moving in a direction parallel to the length of the dipole.

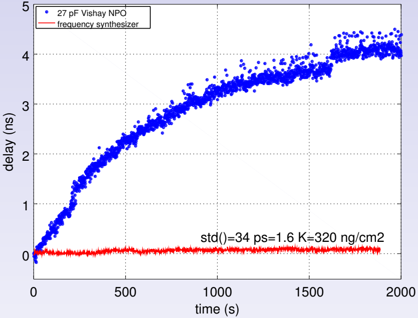


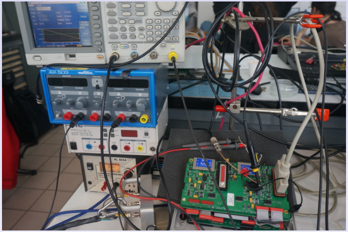
61 cm in gravel 103 cm in gravel

⇒ 50° angular aperture along the dipole direction and 70° ⊥ to dipole axis.

Timebase stability issues

Malå ProEx v.s homemade impulse GPR v.s iFFT(network analyzer) ?





- Challenge of homemade GPR: avalanche transistor pulse generator design
- Challenge of network analyzer: time-gating for isolation

Targeted **stability**: 70 ppm/K for a delay difference of 0.3 μs requires 21 ps stability for 1 K resolution

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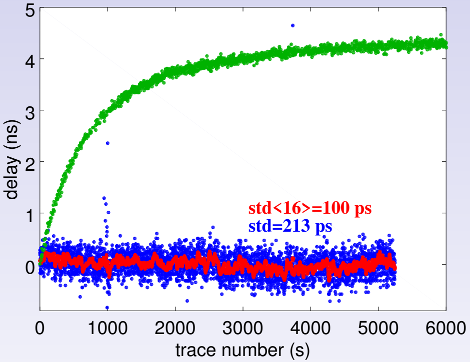

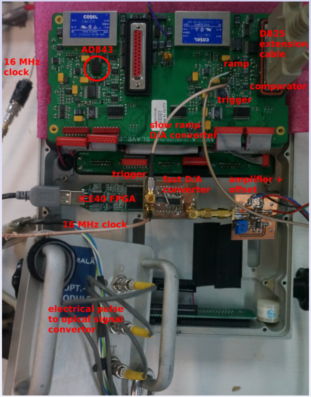

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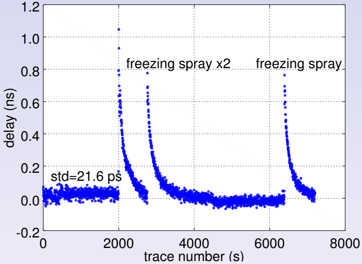
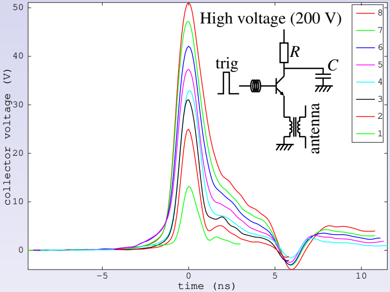


Temperature measurement



Avalanche transistor pulse

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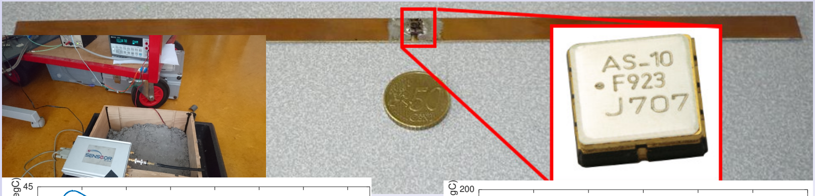
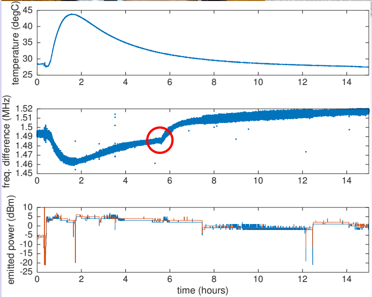
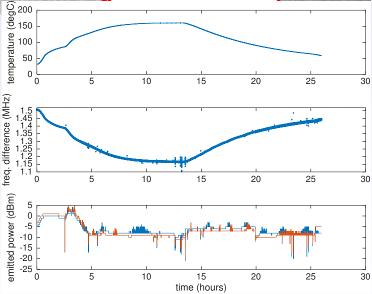
434 MHz resonator measurement in concrete

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







Curing

Heating at 160°C

Assess penetration depth of a 400 MHz antenna Malå probing sensors ?

Conclusion

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

But practical implementation remains to be demonstrated:

- Practical implementation in a useful scenario ? impact of rebars ?
- Use of commercial GPR, dedicated GPR or dedicated cooperative target reader ?
- Impact of strong radiofrequency emission regulations in Japan ?

A strong team of possible partners exists on both sides to achieve this goal (Pr. Hashimoto in Chiba [2], Pr. Yamanaka [3][4] and Pr. Esashi [5] in Sendai, Pr. Kondoh in Shizuoka University).

[2] www.te.chiba-u.jp/~ken/

[3] www.material.tohoku.ac.jp/~hyoka/BallSAW-H2sensor2003IEEEus.pdf

[4] www.tohoku.ac.jp/en/news/university_news/falling_walls_venture_sendai_2017_1.html

[5] J.H. Kuypers, L.M. Reindl, S. Tanaka S, M. Esashi, *Maximum accuracy evaluation scheme for wireless saw delay-line sensors*, IEEE Trans. Ultrason. Ferroelectr. Freq. Control. **55**(7):1640-52 (2008)

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