A low cost approach to acoustic filters acting as GPR cooperative targets for passive sensing

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References and slides at http://jmfriedt.free.fr

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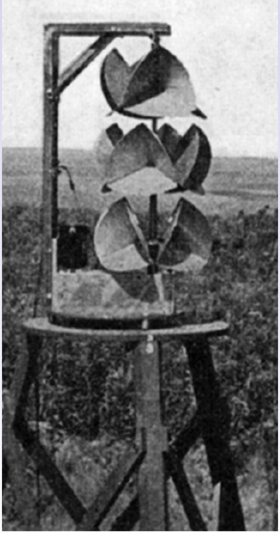
Outline

- What are RADAR cooperative targets ?
- Why GPR cooperative targets ?
- Radiofrequency acoustic transducers as cooperative targets
- Software optimization for dual sub-surface and sensor monitoring
- Low cost demonstration using off-the shelf radiofrequency filters

What are 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
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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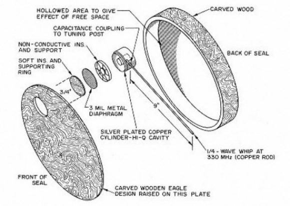

http://madmikesamerica.com/2010/08/the-thing-and-the-curious-life-of-leon-theremin/thing2/

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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

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LOUDAUTO

ANT Product Data

(TS//SI//REL TO USA,FVEY) Audio-based RF retro-reflector. Provides room audio from targeted space using radar and basic post-processing.

07 Apr 2009

(U) Capabilities

(TS//SI//REL TO USA,FVEY) LOUDAUTO's current design maximizes the gain of the microphone. This makes it extremely useful for picking up room audio. It can pick up speech at a standard, office volume from over 20' away. (NOTE: Concealments may reduce this distance.) It uses very little power (~15 uA at 3.0 VDC), so little, in fact, that battery self-discharge is more of an issue for serviceable lifetime than the power draw from this unit. The simplicity of the design allows the form factor to be tailored for specific operational requirements. All components at COTS and so are non-attributable to NSA.

(U) Concept of Operation

TS//SI//REL TO USA,FVEY) Room audio is picked up by the microphone and converted into an analog electrical signal. This signal is used to pulse position modulate (PPM) a square wave signal running at a pre-set frequency. This square wave is used to turn a FET (field effect transistor) on and off. When the unit is illuminated with a CW signal from a nearby radar unit, the illuminating signal is amplitude-modulated with the PPM square wave. This signal is re-radiated, where it is picked up by the radar, then processed to recover the room audio. Processing is currently performed by COTS equipment with FM demodulation capability (Rohde & Schwarz FSH-series portable spectrum analyzers, etc.) LOUDAUTO is part of the ANGRYNEIGHBOR family of radar retro-reflectors.

NSA/CSSM 1-52
Dated: 20070108
ify On: 20320108

Unit Cost: $30

Status: End processing still in development

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

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

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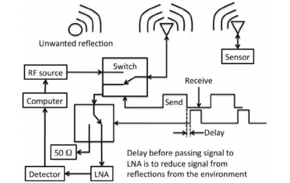
D. J. Thomson, D. Card, and G. E. Bridges, *RF Cavity Passive Wireless Sensors With Time-Domain Gating-Based Interrogation for SHM of Civil Structures*, IEEE Sensors Journal . **9** (11) (Nov. 2009), pp.1430-1438

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.



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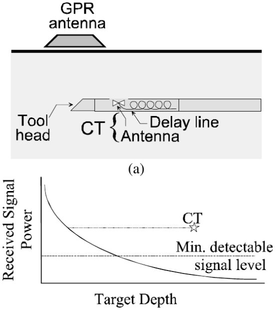
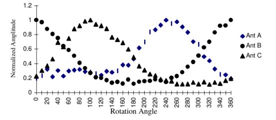
C.T. Allen, S. Kun, R.G Plumb, *The use of ground-penetrating radar with a cooperative target*, IEEE Transactions on Geoscience and Remote Sensing, **36** (5) (Sept. 1998) pp. 1821– 1825





(b)

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

Why GPR cooperative targets ?

- Complement buried structure information with physical quantity measurement
- Accessible quantities: temperature, stress (pressure), identifier (ID)
- Measurement range: depends on RADAR cross section – typical losses in the 30-40 dB range

Passive cooperative target (no local battery source) for extended life expectancy (limited by packaging)

Envisioned applications:

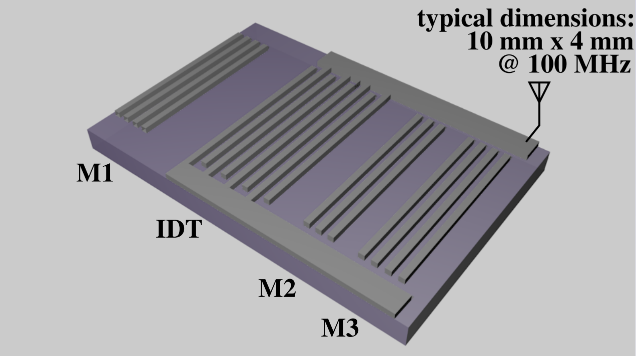
- pipe tagging/stress/temperature
- soil moisture [1]
- concrete temperature [2]

[1] L. Reindl *& al.*, *Radio-requestable passive SAW water-content sensor*, IEEE Trans. Microwave Theory & Techniques, **49** (4), (Apr. 2001), pp. 803–808

[2] J. Kim, R. Luis, M.S. Smith, J.A. Figueroa, D.C. Malocha, B.H. Nam, *Concrete temperature monitoring using passive wireless surface acoustic wave sensor system* Sensors and Actuators A **224** (Febr. 2015), pp.131–139

SAW basics

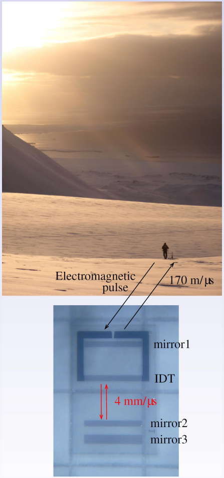
Demonstrated with dedicated readers for Surface Acoustic Wave (SAW) transducers (Transense, CTR, Sengenuity, RSSI, SenSanna, Frec|n|sys, SENSeOR).



- Sensor: $\phi = 2\pi \cdot D/\lambda = 2\pi D \cdot f/c$ with $dc/c(T,\sigma)$ known
- GPR is wideband pulse generator $\Rightarrow$ delay line architecture.
- This work aims at providing GPR-compatible SAW sensors ...
- ... or divert existing SAW filters for sensing purpose.

Radiofrequency acoustic (SAW) transducers as cooperative targets

- from a user perspective, an electrical dipole
- physics: conversion of incoming RADAR pulse to an acoustic (mechanical) wave through inverse piezoelectric effect
- acoustic wave propagates on the surface of the piezoelectric substrate at a speed of 3000-5000 m/s
- the acoustic wave is reflected by patterned mirrors, reaches the transducer and is converted back to an electromagnetic pulse (RADAR echo) $\Rightarrow$ **tag** or **sensor**



Piezoelectricity is **linear process**: returned power is a fraction of incoming power, no threshold

Unlike RFID which requires power *while* being operated, SAW transducers are ideally suited for GPR interrogation

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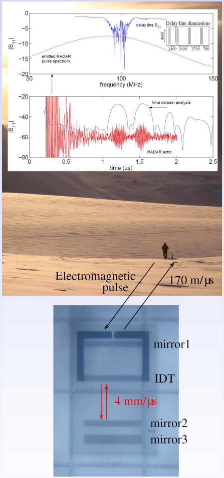

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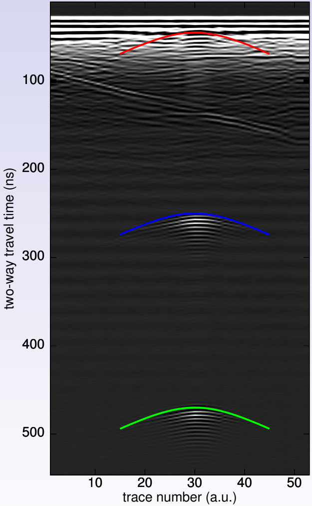
Software optimization for dual sub-surface and sensor monitoring

- Separate sensor response from subsurface reflectors by delaying echo beyond any possible interface reflection (2 μs = 4 mm long sensor at 4000 m/s)
- Short term response = buried structures ("clutter")
- Long term response = buried sensor

Available GPR only allows for a small number of samples (<5000) ⇒ long duration measurement must be at slow sampling rate ⇒ lost resolution in the shallow region [3]



[3] J.-M Friedt *& al.*, *Surface Acoustic Wave Devices as Passive Buried Sensors*, J. Appl. Phys. **109** (3), (02/2011) p.034905

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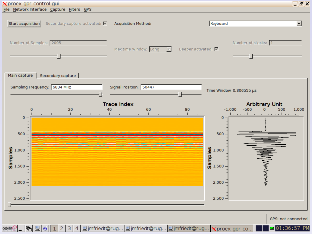
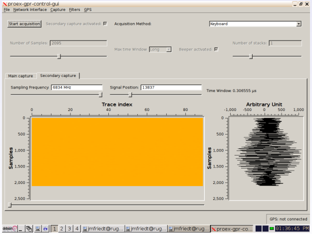
Solution: define two time windows, one focusing on the subsurface structures (e.g. 0-200 ns) and another on the sensor (e.g. 1000-1200 ns)





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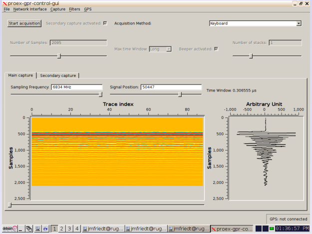
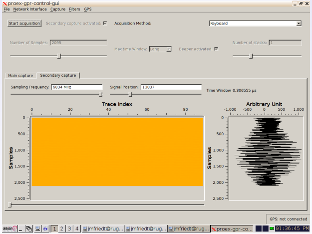
Only **software re-design, hardware remains the same** (reconfigure start delay of the stroboscopic measurement)





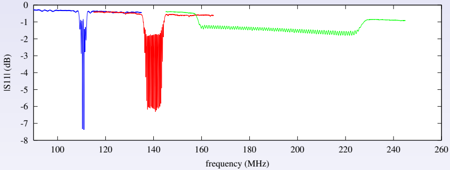
⇒ demonstrated on Malå ProEx GPR

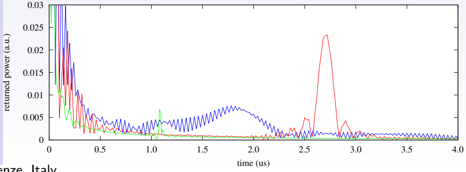
`https://sourceforge.net/projects/proexgprcontrol/`

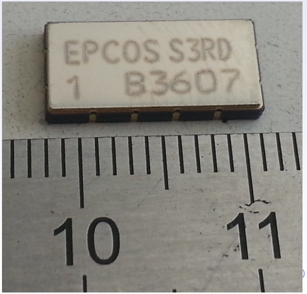
Low cost demonstration using off-the shelf radiofrequency filters

- Dedicated transducers require cleanroom fabrication capability able to handle piezoelectric substrates
- Design considerations:
  - transducer transfer function must match GPR pulse spectrum
  - delay must be within measurement range of GPR
  - reflective transducer operation (most filters operate in transmission)

Measurement example, using an TDK/Epcos B3607 filter:







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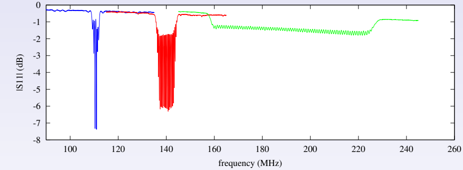

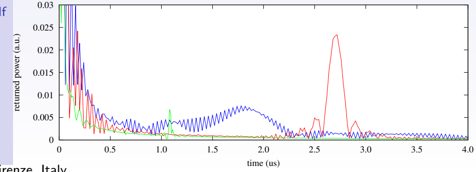

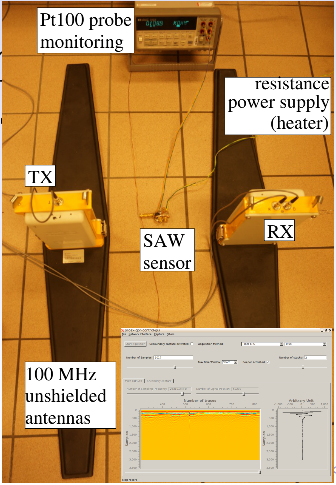

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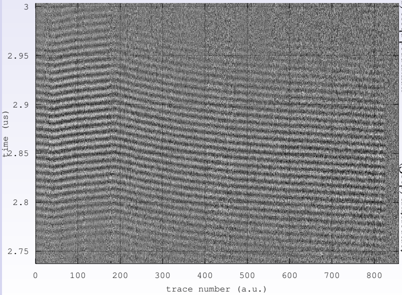
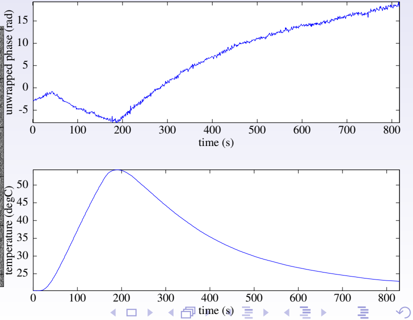
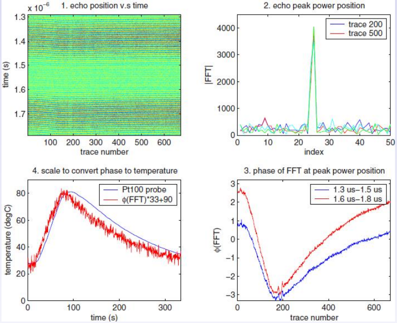




Signal processing steps

Converting the echo delays to a meaningful measurement:

1. multiple echoes from the sensor to get rid of RADAR-target distance dependence
2. phase measurement of each returned echo: **cross-correlation**
3. for single echo (eg SAW filter): phase of the Fourier transform of the main spectrum component (assuming constant RADAR-target distance)
4. SAW delay lines will usually be more narrowband than RADAR pulse ⇒ long echo ⇒ improved SNR
5. sub-sampling period resolution: **polynomial fit** of the cross-correlation maximum
6. danger: multiple nearby cross-correlation peaks ⇒ risk of 2π rotation: $\varphi = 2\pi D/\lambda = 2\pi D \cdot f/c \Rightarrow d\varphi_T = -2\pi Df/c \cdot dc_T/c$ where $dc_T/c(LiNbO_3) = 60$ ppm/K. If $D = 1$ cm, 2π phase rotation on $LiNbO_3/128$ for **35 K** at 100 MHz ($c_{LNO128} \simeq 4000$ m/s).



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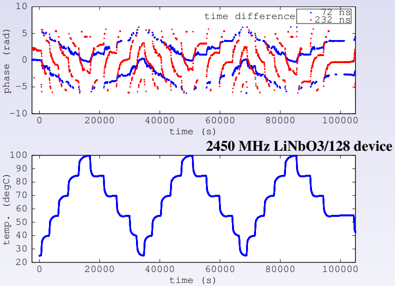

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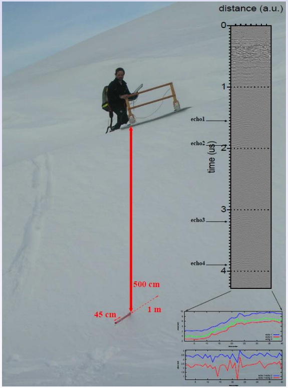
Conclusion and perspectives

- Extend the range of applications of (Ground Penetrating) RADAR by monitoring physical quantities
- Use existing instruments for probing cooperative targets [3]
- Acoustic transducers provide a compact solution ...
- ... ideally suited to GPR interrogation.
- Software enhancement dedicated to sensor monitoring



Perspectives:

- software improvement for **real time display** of the sensor visibility and physical quantity value (calibration)
- beyond physical quantity: **chemical** compound detection (dedicated sensor design)

Acknowledgement: TDK/Epcos kindly provided samples of the B39111B5232H310 and B39191B5087H810 filters, with support of S. Ballandras (Frec|n|sys).

[3] J.-M Friedt, A. Saintenoy *& al*, *High-overtone Bulk Acoustic Resonators as passive Ground Penetrating Radar cooperative targets*, J. Appl. Phys **113** (13), 2013