Piezoelectric radiofrequency transducers as passive buried sensors

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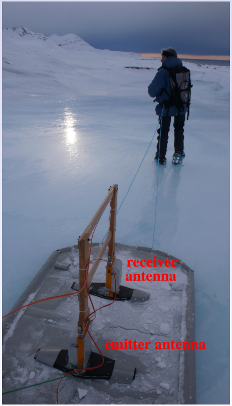
Basics of Ground Penetrating RADAR (GPR)

- bistatic configuration (physically separated emitter and receiver)
- electromagnetic pulse propagates in soil ($\varepsilon_{soil} \gg \varepsilon_{air}$)
- echos due to electromagnetic impedance variations (permittivity ε_r and conductivity σ)

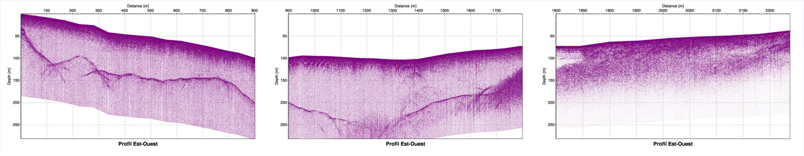
$$v = \frac{c}{\sqrt{\frac{\varepsilon_r}{2}\left(\sqrt{1+\frac{\sigma^2}{\varepsilon^2\omega^2}}+1\right)}}$$



- provides both magnitude *and phase* informations on the returned pulse
- typical frequency range: 50-1600 MHz, depending on antenna dimensions
- lighweight, cost-effective geophysical characterization instrument

Basics of GPR (2)

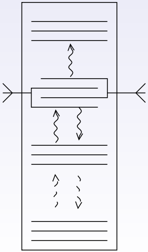
- Wideband device *but* no signal generator,
- pulse defined by the trigger of an avalanche transistor, and pulse width defined by antenna impedance,
- electromagnetic velocity in medium [1]: 50-300 m/μs (ice $\simeq$ 170 m/μs) $\Rightarrow$ typical sampling duration 0.5-5 μs
- stroboscopic (Equivalent-Time Sampling) acquisition with a pulse rate of 100 kHz $\Rightarrow$ maximum measurement duration <10 μs
- sampling rate $\simeq$ 6 to 10 times emitted pulse central frequency (600 to 10000 MHz)



[1] J.L. Davis & A.P. Annan, *Ground Penetrating RADAR for high resolution mapping of soil and rock stratigraphy*, Geophysical Prospecting **37**, pp.531-551 (1989)

Basics of Surface Acoustic Wave (SAW) delay lines

- acoustic = propagation of a mechanical wave on a substrate
- most efficient way of converting electromagnetic (EM) to mechanical: piezoelectric substrate + interdigitated transducers
- identification + sensor
- physical quantity measurement function of acoustic velocity
- incoming EM pulse generates mechanical pulse which returns as EM with a **time delay** function of physical quantity (temperature, stress, pressure ...)

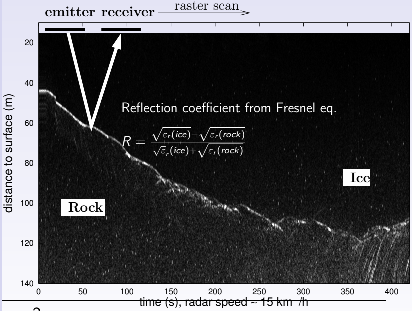


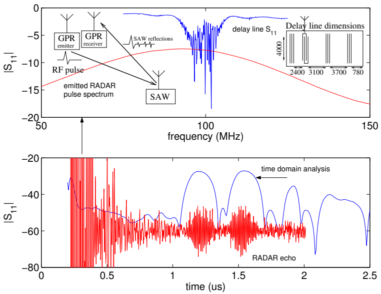
- high electromechanical coupling coefficient (LNO)
- mirror = patterned electrodes
- time delay between incoming pulse and reflection = measurement
- typical velocity: 1500-5000 m/s for most materials
- typical delays: 1-5 μs (3 μs at 3000 m/s $\Rightarrow$ 4.5 mm path)

SAW delay line as GPR cooperative target

Use GPR to probe SAW delay line [2]

- complement passive interface monitoring with sensor interrogation
- intuitive: both techniques provide informations in the time domain
- small dimension (<1 cm×1 cm), passive, wireless, rugged
- linear conversion process from EM to mechanical: no threshold voltage (cf diodes in Si based RFID)





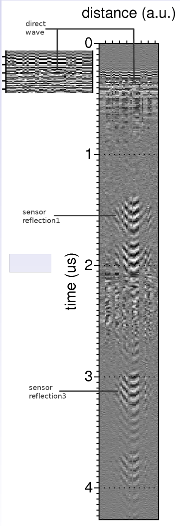
[2] previous cooperative target research:
C.T. Allen, K. Shi, R.G. Plumb, *The use of ground penetrating radar with a cooperative target*, IEEE Geoscience and Remote Sensing **36** (5), 1821-1825 (1998)
G.S. Stump & C.T. Allen, *Apparatus and method for detecting an underground structure*, US Patent 5,819,859

SAW delay line measurement strategy

- time multiplexing of the sensor information
- typical time delay on acoustic sensor (1-3 μs) easily separated from dielectric interfaces, yet still accessible to GPR sampling duration
- identify the sensor signal, search for the envelope (rough delay) followed by accurate velocity (phase) identification $\Rightarrow$ physical measurement [a]
- in case of uncertain identification, data migration will *not* converge for sensors whose delays are not due to EM travel time (hyperbola curvature)

$$4 \times c^2 t^2 - x^2 = d^2$$

(sensor depth d)

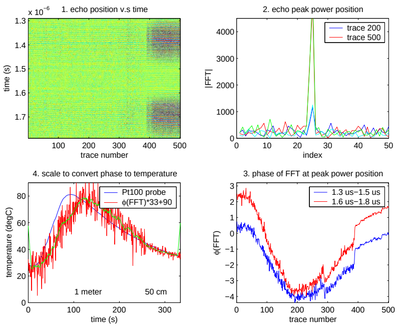


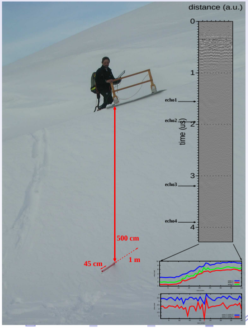
[a] Friedt & *al.*, *Surface acoustic wave devices as passive buried sensors*, J. Appl. Phys **109** (3), 034905 (2011)

Measurement strategy

Digital signal post-processing, *no modification* of GPR hardware

1. record the echos for as long as the delay line answers to incoming RF pulse
2. Fourier transform to identify returned frequency
3. for each returned pulse (known time delay range), phase of Fourier transform
4. *difference* of Fourier phases (referenced measurement) function of the physical quantity measured (design of sensor)





Link budget for delay lines

- RADAR illumination of point-like target: decay as $1/d^4$
- Free Space Propagation Loss (FSPL)

$$10 \times \log_{10}\left(\frac{\lambda^2}{4\pi} \times \frac{1}{(4\pi d^2)^2}\right) = 10\log_{10}\left(\frac{\lambda^2}{(4\pi)^3 d^4}\right)$$

- Considering we know the range at ice-rock interface and reflection coeffient

$$\left(\frac{\varepsilon_{ice} - \varepsilon_{rock}}{\varepsilon_{ice} + \varepsilon_{rock}}\right)^2 \simeq 19 \text{ dB}$$

- $FSPL_{ice-rock} + IL_{ice-rock} = FSPL_{SAW} + IL_{SAW}$

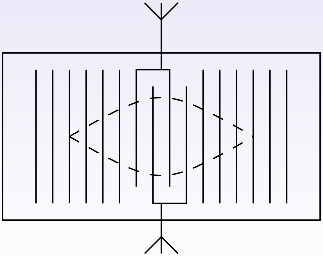
$$\Rightarrow d_{SAW} = d_{ice-rock} \times 10^{(IL_{ice-rock} - IL_{SAW})/40} \simeq 40 \text{ m}$$

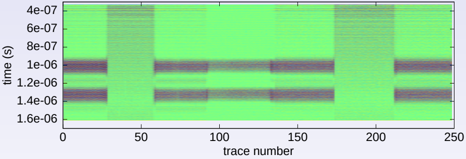
Result consistent with the signal to noise ratio of the 5 m deep-measurement

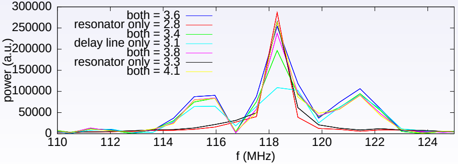
Alternate strategy: resonators

- Interrogation range of delay lines limited by high insertion losses
- Resonators: energy confinement of the acoustic energy in a cavity formed by two Bragg mirrors around IDT
- Narrowband devices unsuitable in GPR interrogation ... or are they ?

Experimental demonstration using samples from Xeco mesa-shaped (100 MHz) AT-cut fundamental mode resonators (`www.xeco.net`).



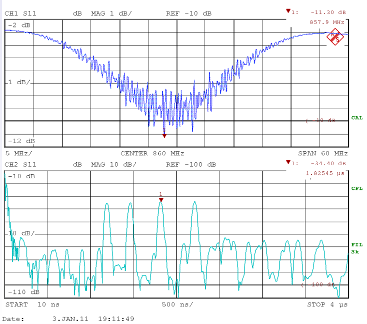


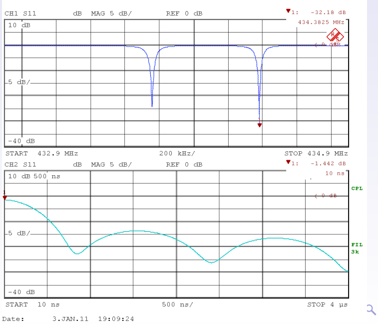


Link budget for resonators

Low loss but only a **fraction of the incoming energy** lies within the bandpass of the narrowband resonator

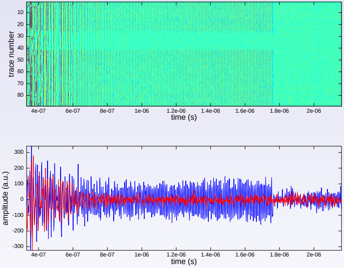
- ratio of the bandwidths: $Q = 12500$ resonator at 100 MHz $\Rightarrow \Delta f = 8000$ Hz.
- A 25 MHz wide pulse hence only transfers about 3×10^{-4} of its energy to the resonator, or -35 dB.
- Adding intrinsic loss of resonator (-1 dB), the global resonator losses are of the same order of magnitude of typical delay line insertion loss (-30 to -40 dB)



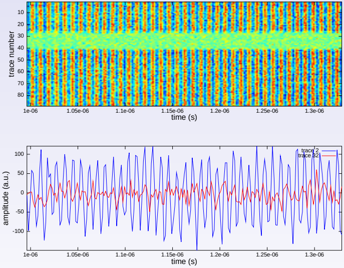


Resonator interrogation

- Time-domain response: Q/π periods $\simeq 40\ \mu$s
- A GPR will usually record up to 5 μs at a sampling rate of $10\times$ emitted pulse frequency (1500 samples max with Malå RAMAC)
- pulse central frequency defined by antenna dimensions + environment $\Rightarrow$ emitted pulse might not be centered on resonance



Returned signal (resonance freq.$\times\exp(-t/\tau)$)



Zoom on returned signal

Ability to identify resonance frequency dependent on signal to noise ratio

Resonance frequency identification

Considering the signal has been recorded, how to extract a frequency information from such a short ($< 5\ \mu$s) measurement ?

Fourier: N time domain $\rightarrow$ N frequency domain = 200 kHz steps, typical sensor: up to 60 ppm/K=6 kHz/K at 100 MHz

Time domain analysis for frequency identification (QSense, NMR):

- Levenberg-Marquart non-linear least square (requires strong decay [3])
- Pisarenko/MUSIC (`rootmusic()` under Matlab)
- Harmonic inversion (`ab-initio.mit.edu`, `harminv` under Debian GNU/Linux) [4]
- Prony/Cadzow

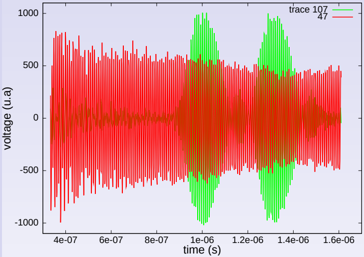
In all cases, add the **assumption of a single, isolated** frequency.

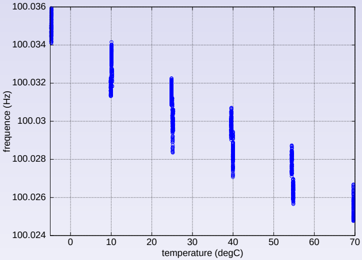
[3] M. Rodahl, F. Höök, A. Krozer, P. Brzezinski, B. Kasemo, *Quartz crystal microbalance setup for frequency and Q-factor measurements in gaseous and liquid environments*, Rev. Sci. Instrum. **66**, 3924 (1995)

[4] V.A. Mandelshtam & H.S. Taylor, *Harmonic inversion of time signals and its applications*, J. of Chemical Physics **107** (17), pp. 6756-6769 (1997)

Experimental result

Traces including a resonator response (red) and delay line response (green)



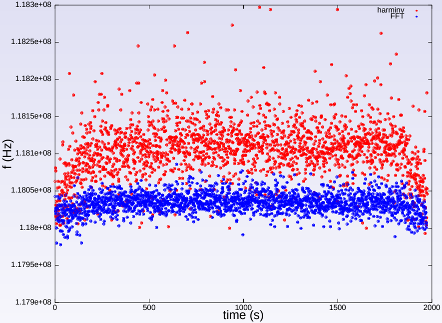


- Very low temperature drift with temperature of the Xeco resonator
- Issue: GPR pulse central frequency is defined my permittivity of medium. What if a notch occurs at the resonance frequency ?

Experimental result

- finite duration measurement ⇒ *sinc*() in frequency domain
- fit resonance with parabola

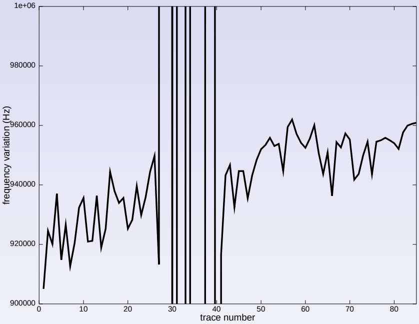
→ Comparison of a polynomial fit of the Fourier transform peak (blue) and harmonic inversion strategy (`harminv`, red)



Fixed number of points ⇒ reduce sampling rate in order to maximize sampling duration

Experimental result

Polynomial fit of FFT peak ⇒ 30-fold frequency resolution improvement (dependent on Q, sampling rate and sampling duration)



- $\sigma_f \simeq$6500 Hz so might be useful if $CTF_1 \simeq$65 ppm/K: huge temperature drift ! (or insufficient frequency resolution).
- Quartz max. temperature drift: $\simeq$80 ppm/K.

Differential strategy using resonators

GPR provides a very poor time/frequency reference (2 Malå RAMAC units tested, one -3% off and the other one +18% off !)

- Use of dual mode-resonators, with two different dependecies of velocity with temperature,
- one well known cut: SC-cut (3700 m/s and 4040 m/s) bulk acoustic resonators
- or dedicated surface acoustic wave resonators with two different propagation directions (SENSeOR's TSE AS10)

Notice that we provide here a **calibration strategy** for GPR sampling rate

Conclusion

- use of a widely available geophysics characterization tool for probing sensors ("cooperative targets")
- piezoelectric-based (linear) transducers for improved interrogation range (demonstrated: 5 m, estimated: 40 m in ice)
- signal processing for (time-based) delay line: temperature
- $\Rightarrow$ acoustic delay lines for tagging or sensor applications
- assesment of this interrogation strategy to resonators
- comparable interrogation range but challenging for frequency identification

Perspectives: High-overtone Bulk Acoustic Resonator (**HBAR**) as an intermediate transducer beween delay line and resonator ?
Optimized antenna geometry for practical applications (polarization, size) ?

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