Surface Acoustic Wave Resonators as Passive Buried Sensors

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Intoduction
Surface acoustic wave (SAW) devices meet ground penetrating RADAR (GPR):

- **SAW devices** provide transducers able to store and release energy provided as an electromagnetic wave ⇒ wireless
- Two major classes of transducers: narrowband resonators (frequency domain) and wideband delay lines (time domain)
- The velocity of the acoustic wave might be a function of a physical quantity (temperature, stress ...) depending on design ⇒ signature characteristic of the measured quantity
- **GPR** is a classical time-domain technique for probing dielectric interfaces in ground
- bistatic antenna configuration: a short (single) RF pulse is emitted and echos are monitored ⇒ scan to gather a map of the interfaces
Buried SAW resonators

- Narrowband SAW resonator designed as temperature sensors are buried at various depths ranging from 30 to 80 cm.
- Frequency sweep using a narrowband RADAR to identify the resonance frequency and hence the temperature

The emitted power is 10 dBm, receiver detection limit -70 dBm \( \Rightarrow \) in this experiment, no direct signal was gathered when burying the SAW

An electromagnetic waveguide is provided through a metallic wire thrown in the hole (no electrical connection on either side of the wire)
These SAW devices were not individually calibrated ⇒ relative temperature observation
Measurement during ≃ 1.25 year: SAW devices are robust to the environment
No loss in RF signal quality over time
The underground signal closely matches a running average over several weeks of surface temperatures.

Air temperatures from http://www.meteo-franche-comte.fr/
- Measurement in agreement with the expected temperature trend but poor interrogation range because we wished to respect ISM band regulations (50% duty cycle ⇒ mean power = 0.5 peak power).
- GPR is classically used in geophysics to probe dielectric interfaces several meters deep

⇒ switch from resonator to delay line as GPR cooperative target
SAW delay line

- Point-like reflectors appear as hyperbola
- The interface echo from the buried antenna will be followed by reflections within the delay line $\Rightarrow$ the hyperbola associated with dielectric interface reflections will be followed by acoustic sensor echos.
- Challenge: GPR hardware must be adapted because a single RF pulse is insufficient to load energy in SAW delay line
We experimentally demonstrate that the best response of the delay line is achieved when the number of periods of the signal is equal to the number of interdigitated transducers.

- Tradeoff between loading a delay line (multiple periods) and spatial resolution (single pulse) ⇒ development of a dedicated solution, using a 860 MHz SAW delay line (sensor from the Kongsberg Sentry temperature monitoring system).
- No ISM band regulations (wideband, here 30 MHz at 860 MHz), peak power ≫ mean power.
SAW delay line interrogation prototype

Experimental results using the Universal Software Radio Peripheral (USRP, http://www.ettus.com/) and GNURadio opensource software: prototyping tools for developing RF interrogation units (opensource, modular)
- Magnitude and phase of the reflections of the delay line: the phase is defined but does not vary, probably because the received signal is too weak (insufficient receiver amplification)
- Signal processing: polynomial fit of the reflection magnitude and identification of the position of the maximum referenced to the emission pulse.
• Evolution of the duration between excitation pulse and reflections (4 reflections) as a function of temperature.
• These data are extracted from the magnitude only ($\approx \pm 3^\circ C$), since the receiver gain was insufficient to define the phase.
Interrogation range estimate

How to estimate the interrogation range of SAW devices considering the detection range of GPR used on ice-rock interface?

Two approaches: planar wave approach (Fresnel equation, reflection coefficient from permittivity change) or FDTD modelling.

1. \( \varepsilon_{\text{ice}} \approx 3.1, \; \varepsilon_{\text{rock}} \approx 5 \Rightarrow \text{reflected power} \; R = \left( \frac{\sqrt{\varepsilon_{\text{ice}}} - \sqrt{\varepsilon_{\text{rock}}}}{\sqrt{\varepsilon_{\text{ice}}} + \sqrt{\varepsilon_{\text{rock}}}} \right)^2 \), here -19 dB

2. Free Space Propagation Loss=\(20 \log_{10} d + 20 \log_{10} f + 32.44\) (\(f\) in MHz and \(d\) in km): at 100 MHz, FSPL\((2 \times 100\; \text{m})\)\(\approx 58\; \text{dB}\) and FSPL\((2 \times 15\; \text{m})\)\(\approx 42\; \text{dB}\).

3. 2D-FDTD simulation considering a hole (air, \(\varepsilon = 1 \Rightarrow R \approx -8\; \text{dB}\)) in rock.

Since typical SAW insertion losses are in the -35 dB range, the interrogation range will be reduced from 100 m to 15 m due to lower reflection coefficient of SAW delay line.
Sensor signature/2D-FDTD simulations

(a) infinite radius, 5 m deep, source in ground
(b) infinite radius, 5 m deep, source in air
(c) 30 cm radius, 5 m deep, source in ground
(d) 30 cm radius, 5 m deep, source in air
(e) 30 cm radius, 10 m deep, source in ground

Expected signal measurement technique: the sensor appears as multiple hyperbola, the summit of the 1st one being the sensor position and the delay to the next ones being related to the physical quantity.
Conclusion and perspectives

1. We have demonstrated that SAW devices provide rugged sensors compatible with underground measurements.
2. We have illustrated the detection range of GPR on ice/rock interface and verified that distances up to 100 m can be reached.
3. We have demonstrated the use of a prototyping tool – USRP – for testing RADAR interrogation strategies of delay lines.
4. We have estimated the interrogation range of delay lines using GPR.

We still have to

1. demonstrate the wireless signal detection of buried 860 MHz delay lines using USRP.
2. develop a SAW delay line working efficiently at 100 MHz, a frequency providing good compromise between antenna size and interrogation range.
3. finalize 3D-FDTD simulation to assess the interrogation range.

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