Piezoelectric radiofrequency transducers as passive buried sensors

Thibault Retornaz, Jean-Michel Friedt, Sébastien Alzuaga, Thomas Baron, Éric Lebrasseur, Gilles Martin, Thierry Laroche, Sylvain Ballandras, Madeleine Griselin, Jean-Pierre Simonnet

To cite this version:

Thibault Retornaz, Jean-Michel Friedt, Sébastien Alzuaga, Thomas Baron, Éric Lebrasseur, et al.. Piezoelectric radiofrequency transducers as passive buried sensors. Nondestructive Testing and Evaluation, 2012, 27 (3), pp.209-218. 10.1080/10589759.2012.674524. hal-00776803

HAL Id: hal-00776803
https://hal.science/hal-00776803
Submitted on 11 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution 4.0 International License
Piezoelectric radiofrequency transducers as passive buried sensors

T. Réturnaz\textsuperscript{a}, J.-M. Friedt\textsuperscript{a,*}, S. Alzuaga\textsuperscript{b}, T. Baron\textsuperscript{b}, É. Lebrasseur\textsuperscript{b}, G. Martin\textsuperscript{b}, T. Laroche\textsuperscript{b}, S. Ballandras\textsuperscript{a,b}, M. Griselin\textsuperscript{c} and J.-P. Simonnet\textsuperscript{d}

\textsuperscript{a}SENSeOR SAS, Besançon, France; \textsuperscript{b}Time & Frequency Department, Institut FEMTO-ST, UMR CNRS 6174, Besançon, France; \textsuperscript{c}Laboratoire ThéMA, UMR CNRS 6049, Besançon, France; \textsuperscript{d}Laboratoire Chrono-Environnement, UMR CNRS 6249, Besançon, France

We demonstrate that single-piezoelectric substrate-based acoustic transducers act as ideal sensors for probing with various RADAR strategies. Because these sensors are intrinsically passive devices working in the radiofrequency range, they exhibit improved interrogation range and robustness with respect to silicon-based radio frequency identification tags. Both wideband (acoustic delay lines) and narrowband (acoustic resonators) \textit{transducers} are shown to be compatible with pulse-mode and frequency-modulated continuous-wave RADAR strategies, respectively. We particularly focus on the ground-penetrating RADAR (GPR) application in which the lack of local energy source makes these sensors suitable candidates for buried applications in roads, building or civil engineering monitoring. A novel acoustic sensor concept – high-overtone bulk acoustic resonator – is especially suited as sensor interrogated by a wide range of antenna set, as demonstrated with GPR units working in the 100 and 200 MHz range.

\textbf{Keywords:} ground-penetrating RADAR; acoustic wave sensor; piezoelectric substrate; wireless interrogation; passive sensor; HBAR

1. Introduction

Ground-penetrating RADAR (GPR) is a classical tool for nondestructive observation of buried structures and interfaces, both for geophysical purposes or civil engineering [1] and road-ageing assessment [2–4]. More generally, various RADAR strategies are used for monitoring liquid and granular media level [5,6] or target velocities. In such uses, the measurement is limited to electromagnetic wave reflection by dielectric permittivity or conductivity interfaces.

We aim here to demonstrate how acoustic wave sensors provide an ideal match to classical RADAR measurement techniques in order to provide passive sensors interrogated through a wireless link [7,8]. Surface acoustic wave (SAW) [9] sensors have been demonstrated as transducers for temperature [10–15], stress [16], torque [17], pressure [18–20] and chemisorption monitoring [21–23], as well as for tagging (identification only) applications [24–26]. However, since such devices will only work in a given restricted frequency range compatible with a given RADAR geometry, we extend the demonstration from SAW to a novel bulk acoustic wave resonator configuration operating in a wide frequency range and hence compatible with multiple RADAR antenna geometries. We specifically focus on the

\*Corresponding author. Email: jmfriedt@femto-st.fr
application of buried sensors interrogated by GPR – with an experimental demonstration using a pulse mode RADAR and discussion of the frequency-modulated continuous-wave (FMCW) and frequency-step continuous-wave (FSCW) configurations.

The next section will briefly describe RADAR basics and focus on GPR. Section 3 will summarise the main characteristics of acoustic transducers, while the following sections will aim at demonstrating the use of both kinds of RADARs targeted to probing the response of delay lines (Section 3), resonators (Section 4) and the novel high-overtone bulk acoustic resonator (HBAR) transducer (Section 6).

2. GPR basic principle

Classical GPR instrumentation is characterised by two main operation modes: the wideband pulse-mode GPR and narrowband FMCW and FSCW.

Pulse-mode GPR generates a short – wideband – energetic pulse and requires fast sampling of the returned signal: either using an equivalent time sampling [27] strategy for low-cost operation under the assumption of constant environmental conditions during the interrogation period (typically several tens of milliseconds), or baseband sampling thanks to recent fast A/D converters following the software-defined radio approach. The pulse width is defined by the antenna impedance, which is itself related to the antenna dimensions and dielectric properties of the surrounding medium. Hence, pulse-mode GPR will not generate a pulse centred on a known frequency but operates at a given wavelength defined by the dimensions of the emitting antenna. In such a configuration, for frequencies below 3 GHz, a capacitor is loaded with a high voltage and transfers radiated energy as a brief pulse thanks to an avalanche transistor whose current versus voltage characteristics is defined by a positive feedback loop. For a low enough intrinsic capacitance, the characteristic time needed to empty the high-voltage capacitor as radiated energy is defined by the resonance frequency of the antenna. Thus, the time constant can widely vary whether the antenna is surrounded by low-permittivity media (ice) or a high-permittivity environment (liquid water or water-saturated sand for example). This condition will become a significant hindrance when using a pulse-mode GPR to probe narrowband resonators which might become out of band when the GPR is used over unsuitable media.

In an FMCW – or the related FSCW – a continuous radiofrequency wave is emitted from one antenna. Either a low-frequency signal is recovered at a beat frequency proportional to the distance of the reflector (FMCW), or both phase and magnitude of the returned signals are recovered through I/Q demodulation in the case of an FSCW. Both strategies provide the needed information to either recover time-domain information representative of the stratigraphy of the environment through an inverse Fourier transform under the basic assumption of a constant permittivity of the media through which the electromagnetic waves propagate, or through more complex analysis of dispersive media if both permittivity and reflector depth are identified [28].

Considering that the dielectric properties of the homogeneous materials on both sides of an interface are known, the reflection coefficient of the electromagnetic wave is known from Fresnel equation under the far-field assumption (plane wave reaching the interface): this reflection coefficient will be compared with the reflection coefficient of the sensor we wish to probe using a GPR (Figure 1).

3. SAW delay line basic principle and interrogation strategies

SAW transducers are based on the conversion of an incoming electromagnetic wave to a mechanical wave (inverse piezoelectric effect) propagating at the air–substrate interface,
and then converted back as an electromagnetic wave (direct piezoelectric effect) returned to the reception antenna [29]. As such, the SAW transducer appears as a two-port electrical component, but understanding the underlying measurement principle is mandatory for proper design of the SAW in a sensing application. Since physical conditions of the environment of the transducer induce a change in the acoustic velocity of the mechanical wave propagating on the single-crystal piezoelectric substrate, the reflective radio-frequency properties of the electric dipole \( S_{11} \) measurement are indicators of these physical conditions. Under appropriate design conditions, one physical quantity will yield a dominant response with respect to other effects. In order to either perform multiple measurements or decorrelate the contribution of each physical quantity – including the distance of the RADAR antenna to the sensor – a differential approach is used.

The most common SAW sensor configuration is the SAW tag, a wideband device excited by a short electromagnetic pulse and whose returned information is a series of pulses: the number of returned pulses is defined by the number of mirrors patterned through cleanroom lithography techniques on the piezoelectric substrate. For sensing application, only a few mirrors are needed (at least two, one for the reference pulse and the other for the measurement). Coding has been demonstrated with a large number of bits, with over 20 mirrors patterned on the substrate [26]. Since the reflected pulse time interval only provides a rough estimate of the physical quantity due to the minute velocity changes associated with the transducer environment property change, a phase subtraction between successive pulses is classically used to provide a precise measurement of the acoustic velocity and hence physical quantity (Figure 2) [30]. Such a measurement requires either both the returned magnitude and phase information or, as provided by GPR, a baseband measurement of the returned power. Since baseband sampling at several times the central frequency – sampling at 500–40000 MHz for central frequencies typically in the 50–1500 MHz range – is technically challenging and hardly compatible with embedded, low power designs [31], an equivalent time sampling assuming a slowly varying
environment of the reflectors is often used. In such a strategy, $N$ successive measurements are carried out at times $N \times \Delta \tau$ after the excitation pulse is emitted, yielding a series of $N$ samples separated by a time interval $\Delta \tau$ or an equivalent sampling rate of $1/\Delta \tau$. Hence, the challenge of sampling at 40 G samples/s is replaced with a slow analogue-to-digital converter measuring the voltage recorded by a fast sample-and-hold with 25 ps accuracy (7.5 mm-long transmission line in vacuum). Typical time-domain reflections are in the range of 1–5 ms since the acoustic velocity is typically in the range of 3000–5000 m/s depending on the piezoelectric substrate and the kind of acoustic wave propagating, yielding sensors with dimensions in the centimetre range (a 5 ms delay at 5000 m/s requires a 1.25 mm long acoustic path). Five microseconds are a typical measurement interval for GPR associated with a 425 m deep interface in ice for example (the electromagnetic velocity in ice is assumed to be 170 m/μs in this example [32]), beyond the typical attenuation range of the electromagnetic pulse.

In an alternative configuration, the acoustic wave is confined between two Bragg mirrors, providing energy confinement conditions consistent with a narrowband transfer function, or in terms of time-domain analysis a long energy dissipation time. In such a configuration, the usable returned signal is no longer a time delay but a frequency, since such a resonator acts as a narrowband transducer. Resonators are poorly suited to pulse-mode GPR interrogation since the short sampling duration (typically 5 μs at most) is hardly compatible with an accurate returned signal frequency identification. Indeed, piezoelectric single-crystal substrates exhibit for temperature sensing a maximum sensitivity of 100 ppm, so that the frequency of a 100 MHz transducer must be identified with 10 kHz accuracy.

Figure 2. Top: experimental frequency domain characterisation of the 100-MHz Malå RAMAC GPR pulse (red) and transfer function of a SAW delay line (blue) – schematic of the delay line with all dimensions in μm. Bottom: time-domain signal returned by the SAW when probed using a GPR (red) and network analyser characterisation by inverse Fourier transform of the frequency-domain characterisation (blue).
for 1 K accurate temperature measurements. Such an accuracy would require at least a 100-μs long record based on basic Fourier transform, or a 20-fold in the frequency identification improvement of the 5-μs long record if some assumption (single returned frequency) is made [33]. Furthermore, we have observed that the time reference of pulse-mode GPR hardly provides the needed accuracy for such a precise frequency measurement, and a differential (two resonance frequency identification) approach is mandatory to get rid of delay line ageing and drift, as well as sensor ageing and electromagnetic environmental variations (impedance pulling of the frequency). On the other hand, dedicated interrogation hardware has been developed for probing such narrowband sensors with excellent resolution [34], which happens to work following principles similar to FMCW GPR [35,36]. Actually, FMCW has been demonstrated as an excellent strategy for probing resonators acting as temperature sensors [34].

We demonstrate [8] that assuming the interrogation range of a GPR under given conditions is known – based on radargrams recorded at interfaces with reflection coefficient

![Figure 3](image-url)

Figure 3. Processing steps for identifying the sensor signal: bottom left, the raw radargram acquired using a 100-MHz antenna set, two-way trip over a 100-MHz delay line acting as a sensor. An 11th-order polynomial fit was removed from each trace to reduce low-frequency background fluctuations from one trace to another. Top right: magnitude of the Fourier transform of the recorded signal, excluding the emitted pulse, exhibiting the returned signal at 100 MHz when the sensor is visible (blue, trace 40) and invisible (red, trace 1). While the magnitude of the Fourier transform is the most visual indicator of the sensor detection, the phase of the Fourier transform at the maximum returned power frequency is the most accurate signature for quantitative information retrieval. Bottom right: comparison of the time domain reflected signal when the sensor is visible (blue, trace 40) and absent (red, trace 1). Top left: the integral of the magnitude of the Fourier transform of the returned power in the 95–105 MHz band is an indicator of the presence of the sensor (the RADAR is located over the sensor at traces 30 and 55).
ICE–ROCK (e.g. ice–rock interface in our case) – and considering the insertion loss $\text{IL}_{\text{SAW}}$ of a SAW sensor is known, then the distance $d_{\text{SAW}}$ at which a sensor can be interrogated is given by

$$d_{\text{SAW}} = d_{\text{ice–rock}} \times 10^{(\text{IL}_{\text{ice–rock}} - \text{IL}_{\text{SAW}})/40}.$$ 

Using typical constants of a reflection coefficient at the ice–rock interface of $-19\,\text{dB}$ (assuming a relative permittivity of ice of 3.1 and 5 for rock) and insertion losses of $-35\,\text{dB}$ for an SAW delay line, then the interrogation range of a sensor is 0.4 times that found for the ice–rock interface. Considering we are able to gather a usable signal for ice–rock interfaces deeper than 100 m, the SAW sensor should be readable at a depth of at least 40 m. Experimental data were gathered with a sensor buried 5 m deep in snow, exhibiting a signal-to-noise ratio consistent with a 40 m maximum depth interrogation range [8]. Acoustic sensor data analysis when probed by GPR only requires software signal processing, and no hardware modification:

1. a Fourier transform on the returned signal radargram (Figure 3, bottom left) identifies whether a sensor is located within the RADAR interrogation range (Figure 3, top right),
2. for each trace (Figure 3, bottom right) in which a frequency signature of the sensor is identified (Figure 3, top left), the phase of the Fourier component including most of the power is indicative of the acoustic delay, and hence of the physical quantity under investigation.

4. Probing resonators with GPR

Pulse-mode GPR is intrinsically wideband devices hardly compliant with most radiofrequency regulations, but acceptable for geophysical applications. The antenna size – and hence central frequency of the emitted pulse – is usually selected as a trade-off between depth resolution (the higher the frequency, the better the resolution) and penetration distance of the electromagnetic wave (the lower the frequency, the deeper the reflected signal which can be detected). Hence, an associated sensor must adapt to the available frequency range of common GPR – typically in the range of 50–1500 MHz. Although acoustic delay lines are wideband devices, a given sensor will nevertheless only be compatible with a single antenna (100, 200, 400 MHz or above range).

SAW delay lines are 500 μm thick, 1 cm$^2$ large sensors: the associated antenna must be much larger to be efficient at the incoming electromagnetic wavelength. Although the dipole length is reduced thanks to the high relative permittivity of the medium in which the sensor is buried, the antenna dimension nevertheless remains in the tens of centimetres length. A linear polarisation of the antenna connected to the sensor – as provided by the most simple geometry of the dipole antenna – also means that the ground-based interrogation GPR must be oriented accordingly so that the buried and surface dipoles are parallel. We have experimentally observed that in a crossed-polarisation configuration, the returned power is too low to allow for a useful measurement, meaning that multiple sensors can be located in common view of the GPR and selected through surface antenna orientation during the measurement.

5. Sensor signal identification

Using the same instrument to probe both the buried dielectric and conductivity interfaces and sensor signal yields the issue of classifying which reflection is associated with which
phenomenon. In case of the pulse-mode GPR, two criteria allow for the identification of a sensor signal (Figure 4):

(1) the design of SAW delay line typically locates the first reflection at least 1 µs after the incoming electromagnetic pulse reaches the sensor. Such a delay (500 ns two-way trip) would be associated with an interface located 42 m deep in ice or 7.5 m deep in water. The signal-to-noise ratio of the reflected signal, associated with a sensor shallower than expected from an electromagnetic propagation, will obviously allow the association of the returned signal with the sensor rather than with a buried interface. Such a classification step is similar to the time-domain multiplexing familiar to radiofrequency communications,

(2) during the migration post-processing step, the hyperbola curvature on which all points associated with a single point-like reflector lie is dependent on the reflector depth. Since the time delay due to a SAW delay line is associated with an acoustic velocity rather than with the electromagnetic velocity, the curvature of the hyperbola on which the sensor-related echoes lie will be that of a shallow reflector and the automated migration algorithm will not be able to focus all the data on a single point-like reflector.

In the case of narrowband reflectors, the quality factor of acoustic sensors – typically in the 10,000 range below 400 MHz – is much larger than any natural reflector, even dielectric media located between parallel conducting plates acting as reflectors. Hence, the long (several microseconds) time-domain echo, or in the frequency domain the narrowband frequency definition of the returned signal, is hardly missed for a dielectric reflector.

![Figure 4. Left to right: two examples of 100-MHz delay line probed with a Malà RAMAC bistatic GPR connected to a 100-MHz dipole antenna (1261 MHz sampling frequency, 4487 and 5060 samples, respectively); two examples of probing a 200-MHz delay line using a Malà RAMAC bistatic GPR connected two 200 MHz dipole antenna (1261 MHz sampling frequency, 5060 samples). The reflections from the sensor are located at delays 1.3, 1.6, 2.8 and 3.5 µs. The first, second and fourth images depict two-way trips over the sensor, while the third image was acquired with only a one-way trip over the sensor. All data processed with the Seismic Unix software.](image)
6. Novel resonator design for use with GPR

In order to provide a sensor configuration compatible with multiple antenna geometries, e.g. compatible with the frequency range of 100–400 MHz, a frequency comb must be generated over this frequency range. One geometry which appears promising for such a purpose is the HBAR [37] configuration in which a bulk acoustic wave is confined inside a low-acoustic loss thick (300–500 μm) substrate, while the high-operating frequency condition is defined by a thin (<100 μm) piezoelectric layer coated on the dielectric substrate. The broadband envelope of the transfer function (Figure 5, left) – here with a maximum returned power around 200 MHz – is defined by the piezoelectric layer thickness, and the comb period (whether in time or frequency domain) by the thickness of the thick substrate. We have demonstrated high-quality factor and wide frequency operation range with such a configuration (Figure 5, right): the 1 × 1 mm HBAR is connected to 2 × 40 cm enamelled wire dipole antenna.

7. Conclusion

Beyond the use of RADARs in general and GPR in particular for probing passive reflectors, we demonstrate that acoustic wave devices are perfectly suited as cooperative targets for monitoring physical quantities thanks to existing RADAR systems. Both wideband sensors – acoustic delay lines – and narrowband sensors – resonators – are suited for the various classical RADAR measurement strategies, namely pulse-mode and FMCW measurements. The recorded signals require no modification of the hardware, and identifying the physical quantity under investigation only requires post-processing of the data to extract either an accurate time delay (as a phase between successive echoes in the wideband strategy) or frequency (in the FMCW narrowband strategy), both of which are representative of the acoustic velocity in the sensor and hence the physical quantity affecting most significantly the sensor behaviour thanks to a design reducing the influence of unwanted velocity variation.
sources. Furthermore, a differential approach in which sensors with different behaviours to external disturbances are interrogated reduces the influence of correlated noise, ageing and local time reference drift.

Acknowledgements
Part of the funding for this project was provided by the French National Research Agency (ANR) under the Cryo-Sensors grant.

References
[1] G. Clemena, Handbook on Nondestructive Testing of Concrete, 2nd ed., CRC Press, West Conshohocken, PA, USA, 2003.
[2] T. Saarenketo and T. Scullion, Road evaluation with ground penetrating radar, J. Appl. Geophys. 43 (2000), pp. 119–138.
[3] National Research Council Rxford M. Morey, Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities, American Association of State Highway and Transportation Officials, National Cooperative Highway Research Program, National Academy Press, Washington, DC, 1998.
[4] K. Maser, Condition assessment of transportation infrastructure using ground-penetrating radar, J. Infrastruct. Syst. 2 (1996), pp. 94–110.
[5] G. Brooker, Sensors and Signals, Australian Centre for Field Robotics, University of Sydney, Australia, 2007.
[6] B. Lipták, Level Measurement, Vol. 1, Chapter 3, CRC Press, Boca Raton, FL, USA, 2003.
[7] C. Allen, K. Shi, and R. Plumb, The use of ground-penetrating radar with a cooperative target, IEEE Trans. Geosci. Remote Sensing 5(2) (1998), pp. 1521–1525.
[8] J.M. Friedt, T. Rétoiraz, S. Alzuaga, T. Baron, G. Martin, T. Laroche, S. Ballandras, M. Griselin, and J.P. Simonnet, Surface acoustic wave devices as passive buried sensors, J. Appl. Phys. 109 (2011), p. 034905.
[9] R. White and F. Voltmer, Direct piezoelectric coupling to surface acoustic waves, Appl. Phys. Lett. 7 (1965), pp. 314–316.
[10] X.Q. Bao, W. Burkhard, V.V. Varadan, and V. Varadan, SAW temperature sensor and remote reading system, IEEE Ultrasonics Symposium, Denver, CO, USA, 1987, pp. 583–585.
[11] W. Buff, S. Klett, M. Rusko, J. Ehrenforst, and M. Goroli, Passive remote sensing for temperature and pressure using SAW resonator devices, IEEE Trans. Ultrason. Ferroelectrics Freq. Contr. 45 (1998), pp. 1388–1392.
[12] G. Scholl, F. Schmidt, T. Ostertag, L. Reindl, H. Scherr, and U. Wolff, Wireless passive SAW sensor systems for industrial and domestic applications, IEEE International Frequency Control Symposium, Pasadena, CA, 1998, pp. 595–601.
[13] W. Bulst, G. Fischerauer, and L. Reindl, State of the art in wireless sensing with surface acoustic waves, IEEE Trans. Indus. Electronics 48 (2001), pp. 265–271.
[14] L. Reindl and L. Shrenau, Wireless measurement of temperature using surface acoustic waves sensors, IEEE Trans. Ultrason. Ferroelectrics Freq. Contr. 51 (2004), pp. 1457–1463.
[15] S. Schuster, S. Scheibhofer, L. Reindl, and A. Stelzer, Performance evaluation of algorithms for SAW-based temperature measurement, IEEE Trans. Ultrason. Ferroelectrics Freq. Contr. 53 (2006), pp. 1177–1185.
[16] A. Pohl, R. Steinl, and L. Reindl, The ‘intelligent tire’ utilizing passive SAW sensors – measurement of tire friction, IEEE Trans. Instrum. Meas. 48 (1999), pp. 1041–1046.
[17] J. Beckley, V. Kalinin, M. Lee, and K. Voliansky, Non-contact torque sensor based on SAW resonators, IEEE International Frequency Control Symposium and PDA Exhibition, New Orleans, LA, USA, 2002, pp. 202–213.
[18] H. Scherr, G. Scholl, F. Seifert, and R. Weigel, Quartz pressure sensor based on SAW reflective delay line, IEEE Ultrasonics Symposium, San Antonio, TX, USA, 1996, pp. 347–350.
[19] G. Bruckner, A. Stelzer, L. Maurer, J. Biniasch, L. Reindl, R. Teichmann, and R. Hauser, A high-temperature stable SAW identification tag for a pressure sensor and a low-cost interrogation unit, IEEE Sensor, 11th International Sensor Congress (SENSOR), Nuremberg, Germany, 2003, pp. 467–472.
[20] H. Oh, W. Wang, K. Lee, I. Park, and S. Yang, Sensitivity improvement of wireless pressure sensor by incorporating a SAW reflective delay line, Int. J. Smart Sens. Intell. Syst. 1 (2008), pp. 940–954.

[21] Y. Dong, W. Cheng, S. Wang, Y. Li, and G. Feng, A multi-resolution passive SAW chemical sensor, Sensors Actuators B 76 (2001), pp. 130–133.

[22] W. Seidel and T. Hesjedal, Multi-frequency and multi-mode GHz surface acoustic wave sensor, IEEE Ultrasonics symposium, Honolulu, HI, USA, 2003, pp. 1408–1411.

[23] M. Dierkes and U. Hilleringmann, Telemetric surface acoustic wave sensor for humidity, Adv. Radio Sci. 1 (2003), pp. 131–133.

[24] A. Pohl, F. Seifert, L. Reindl, G. Scholl, T. Ostertag, and W. Pietsch, Radio signals for SAW ID tags and sensors in strong electromagnetic interference, IEEE Ultrasonics Symposium, Cannes, France, 1994, pp. 195–198.

[25] L. Reindl, G. Scholl, T. Ostertag, W. Ruile, H. Scherr, C. Ruppel, and F. Schmidt, Wireless remote identification and sensing with saw devices, Sensor, International Congress Sensor ‘97, May 13–15, Nuremberg, Germany, 1997, pp. 161–166.

[26] C. Hartmann, A global SAW ID tag with large data capacity, Proceedings of 2002 IEEE Ultrasonics Symposium, Munich, Germany, 2002, pp. 65–69.

[27] J. Han, R. Xu, and C. Nguyen, On the development of a low-cost, compact planar integrated-circuit sampling receiver for UWB systems, Ultra-Wideband, Short-Pulse Electromagnetics, Vol. 8, Springer, New York, NY, USA, 2007, pp. 161–170.

[28] H.P. Marshall and G. Koh, FMCW radars for snow research, Cold Reg. Sci. Technol. 52 (2008), pp. 118–131.

[29] V. Plessky and L. Reindl, Review on SAW RFID tags, IEEE Trans. Ultrason. Ferroelectrics Freq. Contr. 57 (2010), pp. 654–668.

[30] J. Kuypers, L. Reindl, S. Tanaka, and M. Esashi, Maximum accuracy evaluation scheme for wireless saw delay-line sensors, IEEE Trans. Ultrason. Ferroelectrics Freq. Contr. 55 (2008), pp. 1640–1652.

[31] S. Kim, S. Carnes, A. Haldemann, E. Ng, and S. Arcone, Miniature ground penetrating radar, CRUX GPR, IEEE Aerospace Conference, Big Sky, MT, USA, 2006.

[32] J. Davis and A. Annan, Ground penetrating radar for high resolution mapping of soil and rock stratigraphy, Geophys. Prospect. 37 (1989), pp. 531–551.

[33] D. Rife and R. Boorstyn, Single-tone parameter estimation from discrete-time observations, IEEE Trans. Inform. Theory IT-20 (1974), pp. 591–598.

[34] G. Hofbauer, FMCW based readout system accuracy enhancement techniques for surface acoustic wave RFID sensors, IEEE/MTT-S International Microwave Symposium, Honolulu, HI, USA, 2007, pp. 575–578.

[35] S. Scheiblihoefer, S. Schuster, M. Jahn, R. Feger, and A. Stelzer, Performance analysis of cooperative FMCW radar distance measurement systems, IEEE MTT-S International Microwave Symposium Digest, Atlanta, GA, USA, 2008, pp. 121–124.

[36] 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 (2010), p. 014701.

[37] D. Gachon, E. Courjon, G. Martin, L. Gauthier-Manuel, J.C. Jeannot, W. Daniau, and S. Ballandras, Fabrication of high frequency bulk acoustic wave resonator using thinned single-crystal lithium niobate layers, Ferroelectrics 362 (2010), pp. 30–40.