A high-stability dual-chip GPR for cooperative target probing

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***Abstract*—A complete Ground Penetrating RADAR (GPR) system, including emitter, receiver and processing circuit, has been assembled with minimum part numbers for a compact, low power solution aimed at probing passive cooperative targets acting as subsurface sensors. The high timing stability of the recorded signal needed for phase analysis is met by clocking all circuits, including the stroboscopic timer, with a quartz disciplined reference signal. We demonstrate 21 ps timing stability when measuring the long term evolution of two echoes separated by 300 ns, consistent with the ability to measure with 1 K resolution surface acoustic transducers designed as GPR cooperative sensors, dedicated to temperature sensing in the current demonstration. The solution takes advantage of some of the latest microcontroller peripherals including a timer with 217 ps resolution, for an equivalent time sampling up to 4.6 GS/s. Wireless measurement at a range of 70 cm is demonstrated through air, with a signal to noise ratio allowing for far range measurement in dielectric subsurface media.**

I. Introduction: sub-surface passive sensors

Ground Penetrating RADAR (GPR) is classically used for probing sub-surface interfaces inducing electromagnetic wave reflection due to permittivity or conductivity variations of the medium properties. Sub-surface utilities – water and sewage pipes, electrical cables, optical fiber communication networks – are mapped using GPR as well to avoid damage during road work or additional subsurface utility installation. Beyond passive target detection, cooperative targets are designed either to tag these sub-surface environments, allowing the identification of the owner of each subsurface feature, or for sub-surface sensing properties such as temperature (representative of gas or water leak inducing cooling of the surround soil, or heating of electric cable flowing excessive current), stress (indicating movement of the soil surrounding a pipe, or pressure of the fluid inside the pipe), or chemical compound concentration. The design consideration for the cooperative target acting as tag or sensor when probed from the surface by GPR is on the one hand to delay the returned information beyond passive interface echoes – here considered as clutter – and on the other hand to introduce some delay representative of the information being transmitted to the surface. Considering that a GPR signal generated in the Very High Frequency (100-300 MHz since the 30-100 MHz frequency range yields uncomfortable antenna size when operating in urban environments) or Ultra High Frequency (300-3000 MHz) bands will not penetrate more than 150 m deep even in low loss media such as ice, delaying the sensor response by 1 μs allows for identifying with certainty that any signal beyond this delay is attributed to the sensor, with an excellent signal to noise ratio since clutter has faded out. Delaying a signal by 1 μs requires a 150 m long electromagnetic delay line, which is shrunk to 1.5 mm if the wave is slowed down by a factor of 10^5, as is achieved by converting the electromagnetic wave to an acoustic wave. This approach is the classical Surface Acoustic Wave (SAW [1], [2]) analog radiofrequency component design consideration, in which electrodes connected to the input port (antenna in the case of wireless communication) are patterned on a piezoelectric substrate converting the electromagnetic wave to an acoustic wave and back: from a user perspective, the SAW device is an electrical dipole with geometrical dimensions unreachable using purely electrical means for delaying the incoming signal. Typical sensor dimensions are in the square centimeter range, while the antenna remains the limiting size factor with typical dimensions in the electromagnetic half-wavelength length.

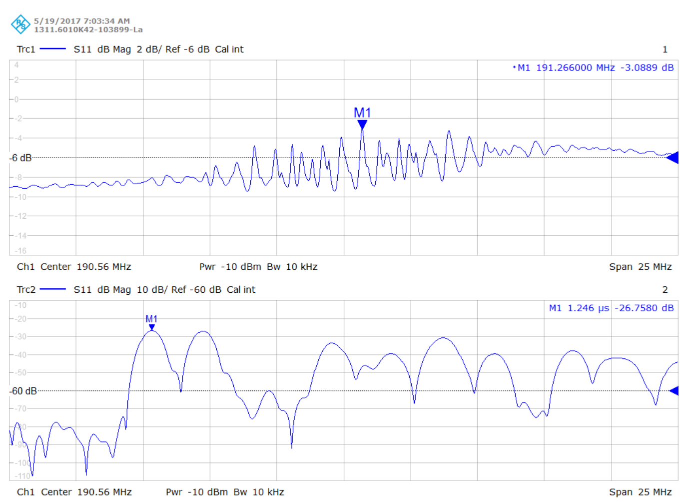

Fig. 1. Top: frequency domain response of the sensor designed as a GPR cooperative target, operating close to the 200 MHz range classically used for shallow sub-surface measurements. Bottom: time-domain response, with echoes delayed by 1 to 2 μs, well beyond clutter yet still visible by GPR. The time delay between the two echoes around 1.2 and 1.5 μs will be the focus of the investigation.

Furthermore, since the piezoelectric substrate acoustic properties (velocity) are dependent on the surrounding environmental properties such as temperature and stress, the returned echo is naturally delayed by a duration dependent on these properties. Enhancing the sensitivity of one quantity and rejecting interfering effect of other quantities is the topic of sensor design, using the anisotropic nature of piezoelectric substrates to select the best substrate orientation meeting the demands of strong electromechanical coupling, high sensitivity to one physical quantity, and appropriate wave polarization. In this paper, we shall assume that the cooperative target has been designed, matching a GPR operating frequency band and delaying echoes by durations compatible with GPR sampling times (Fig. 1), and we focus on the ability to accurately measure the returned echo delays in order to recover the sub-surface properties as detected by the sensor.

II. Timing generator and drift issue

Past investigations on using GPR for probing cooperative targets acting as passive sub-surface sensors for temperature, strain or pressure monitoring aimed at using commercially available GPR instruments, with a focus of reaching users already equipped with hardware needed for sub-surface investigations. In this context, the transducers we develop (Fig. 1), aimed at delaying the measurement beyond clutter in a compact geometry, were to be used by the GPR community to complement subsurface interface investigations. Such an approach has met a challenge with the discovery that the commercial GPR unit we are using, Malå ProEx GPR control unit, is plagued by excessive sampling rate drift due to the design of its stroboscopic timing generator [3] (Fig 2).

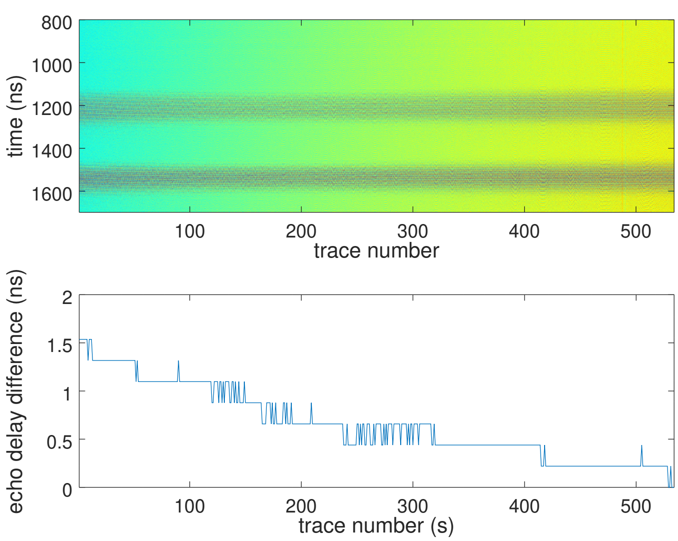

Fig. 2. The most stable of the five Malå ProEx control units tested with 100 and 200 MHz transducers acting as reference echo delays. This particular unit drifts by over 1.5 ns when measuring the echo delay difference of 300 ns, or a 0.5% drift over 534 seconds, acceptable for GPR interface depth analysis but unacceptable for passive sensor measurement. Top is a B-scan radargram with the fast time along the Y-axis and the slow time along the X-axis, and bottom is the extracted time difference between echoes measured as the position of the cross-correlation maximum.

By using a commercial instrument well beyond its design conditions, limitations are met that prevent the reliable interrogation of sensors. Indeed, assuming a temperature sensitivity of the sensor of -70 ppm/K, and an echo delay difference of 300 ns, measuring with 1 K temperature resolution requires a timing stability of $70 \cdot 10^{-6} \times 300 \cdot 10^{-9} = 21$ ps. For a 100 MHz central pulse frequency, such a stability is equal to $0.021/10 \times 360 = 0.8°$ phase stability. Achieving such a stability relies on two issues:

- assessing the local oscillator stability is better than the expected variation induced by the sensor characteristics variation,
- assessing that the sampling frequency is more stable than the targeted sensor variation: indeed, for discrete time signal processing, sampling frequency stability is a core assumption that has been addressed in [4].

While a digital ramp generation solution solving the commercial GPR drift issue has been developed, it requires heavy modifications on the commercial hardware, yielding loss of warranty with hardware upgrades few geophysicists might wish to attempt themselves. The alternative is the development of dedicated hardware for sub-surface cooperative target interrogation: having demonstrated that a single-microcontroller solution meets the stability requirements for sensor probing, assembling a complete GPR unit still requires providing an emitter solution. Past demonstrations [4] had focused on a fixed frequency, radiofrequency pulse synthesis approach with a linear amplification. However, such a solution is limited by the compression point of the linear amplifier, or the large average power consumption of linear amplifiers. Here, we will investigate the compatibility of the classical avalanche transistor circuit, remind the reader of the design considerations of this circuit, and demonstrate how well suited it is to the receiver presented previously [4].

The rationale for developing dedicated embedded hardware is for long term, continuous monitoring of sub-surface soil or concrete properties. Battery operation requires efficient handling of power, while shrinking dimensions helps packaging the setup in an enclosure protecting the circuit from environmental conditions. These target application conditions do not preclude meeting the timing stability requirements of wireless sensor measurement by probing the cooperative backscattered radar cross-section, and measuring the fine phase shifts introduced by the effect of temperature on the piezoelectric substrate the transducer is made of.

III. Stable receiver design

Despite the trend for real time acquisition with high speed analog to digital converters, allowing for fast acquisition and hence stacking capability for reducing the noise level and thus improving receiver detection limit, we here aim at an embedded reader with low power characteristics. We implement a single-sample per emitted pulse stroboscopic strategy. The core issue of the receiver stability has been addressed by clocking all timing signals of circuit from a single, quartz stabilized source. While the current design exploits a temperature compensated oscillator (TCXO), high stability applications not requiring low power consumption might rely on a high quality Oven Controlled Crystal Oscillator (OCXO) for better stability.

The core element of the proposed designed is the STMicroelectronics STM32F334 microcontroller and most significantly its high resolution timer (HRTIM) providing 217 ps, self-compensated versus power supply and temperature drift timing capability. All operations, namely triggering the emission pulse, triggering the analog to digital track and hold, and repeating the measurement process for the number of samples to be acquired, are interrupt driven, freeing the main program loop for interacting with the user and sending the collected traces back to the user. The main limitation of this microcontroller is its lack of memory, with 16 KB RAM only allowing for storing a maximum of 8000 samples encoded as 2-byte words. Thus, despite the support for this microcontroller in higher abstraction programming frameworks such as the NuttX executive environment (nuttx.org), the sparse memory requires efficient use and programming at a low level to avoid wasting resources.

Implementing the stroboscopic measurement on this platform has been described previously [4], with the core characteristics being the equivalent sampling rate of 4.16 GS/s, sufficient to characterize cooperative targets whose response are centered on 100, 250, 500 or 800 MHz, the currently targeted frequency ranges matching the shielded antenna set provided by most commercial GPR manufacturers including Malå Geoscience, whose product are considered as the reference in this investigation. Selecting the antenna operating frequency is driven by penetration depth and sensor antenna dimensions, with shallow concrete monitoring best addressed with the higher operating frequency range and deeper soil subsurface properties down to a few meters requiring the lower frequency range. The added value of the present investigation focuses on the high power emitter and demonstration of a wireless sensor measurement using the complete setup.

IV. Pulse generator

Two strategies have been considered for demonstrating the complete measurement setup. Past investigations have considered generating a pulse by gating a frequency source, namely a Direct Digital Synthesizer (DDS), programmed to emit continuously on the center operating frequency of the cooperative target. Doing so, we avoid the issue of working at a fixed wavelength defined by the dipole antenna dimensions, as is done in pulsed RADAR systems, and define the operating frequency which is also the core characteristics of the sensor. This frequency is in this case forced by the DDS and independent of soil permittivity, while the transfer function (filtering capability) of the antenna will attenuate the emitted pulse upon poor impedance matching conditions. However, amplifying the gated continuous wave to levels comparable to those achieved with a high power pulse generator has not been achieved, and we now describe the classical avalanche transistor pulse generator [5], [6] and the design constraints extracted from the literature.

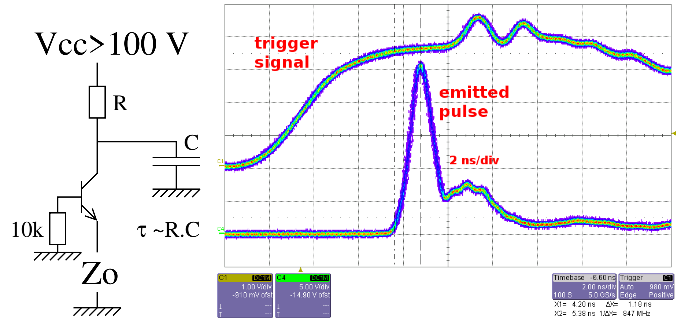

Fig. 3. Before triggering the avalanche regime by biasing the transistor base, an oscillator configuration is assembled (left) by loading the base to ground through a resistor. In this configuration, the collector capacitor C slowly charges through the resistor R with a time constant RC, before reaching the avalanche voltage. Breakdown then occurs in the transistor junction, allowing charges accumulated in the capacitor to flow in a fraction of a nanosecond. Once emptied, the capacitor starts charging again. While the stability of the resulting oscillator is poor, the RC network is tuned to match the targeted pulse repetition rate to be induced by triggering the pulse by polarizing the base: the collector voltage should then be close but not above the avalanche threshold voltage to prevent self-discharge prior to the base pulse trigger. Right: comparison of the trigger signal generated by the microcontroller (top) and the pulse at the emitter of the avalanche transistor (bottom). X-axis scale is 2 ns/division: the emitted pulse is less than 1 ns wide at half height.

The classical avalanche transistor pulse generator uses a junction in its avalanche regime, in which the current *rises* in a positive feedback loop involving excitation of valence electrons to the conduction band when subject to a high enough electric field [7]. In this regime, triggering a breakdown regime by rising the base voltage initiates a catastrophic increase of current that would destroy the junction unless the current source empties in an interval short enough to prevent excessive heating of the transistor. This condition is met by feeding the transistor collector with a high voltage capacitor connected to the high voltage power supply by a resistor whose value is high enough for the charge and discharge duty cycle to be low enough to leave time for the transistor to cool down before the avalanche voltage is reached again (Fig. 3). This RC circuit happens to be the core design issue in the avalanche transistor pulse generator design:

- the capacitor empties quickly in the transistor and loads slowly through the resistor with a time constant $\tau = RC$.
- the energy running from the capacitor through the transistor as a pulse is emitted is $E = \frac{1}{2}C \cdot V_{avalanche}^2$
- the capacitor must have the ability to unload its charges in a fraction of a nanosecond, so must be radiofrequency compliant while supporting high voltages. Assembling multiple capacitors in series helps meets the latter requirement. As the current from the capacitor runs through the transistor, the load Z_{load} energy is $\frac{V_{load}^2}{Z_{load}} \cdot dt$. Balancing the energy equation budget,

$$\frac{1}{2}C \cdot V_{avalanche}^2 = \frac{V_{load}^2}{Z_{load}} \cdot dt$$

so that the output pulse voltage is

$$V_{load} = V_{avalanche}\sqrt{\frac{Z_{load}}{2 \cdot dt}C}$$

This equation predicts a square root dependence of the output pulse voltage with the high voltage capacitance,

- the avalanche regime saturates once the avalanche voltage remains on the collector and spreads the pulse, reducing the output bandwidth. during the time dt the pulse lasts.

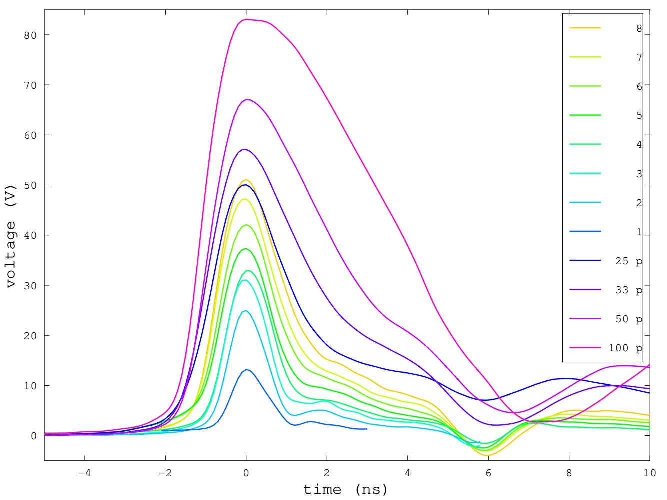

Fig. 4. Evolution of the emitter pulse voltage as a function of collector charge capacitance. The legend indicates the number of 3 pF capacitors connected in parallel to the transistor collector.

Despite the filtering capability of the dipole antenna fitted to the balun transformer output, its input acting as a 50 Ω load between the avalanche transistor emitter and ground (Fig. 5), the spectrum is broadband enough (Fig. 6) to address the narrowband sensor we consider, since acoustic transducers will typically exhibit bandwidths of 1/10th of the operating frequency (the bandwidth being given by the electromechanical coupling coefficient of the piezoelectric substrate, about 5 % in the case of lithium niobate YXl/128°).

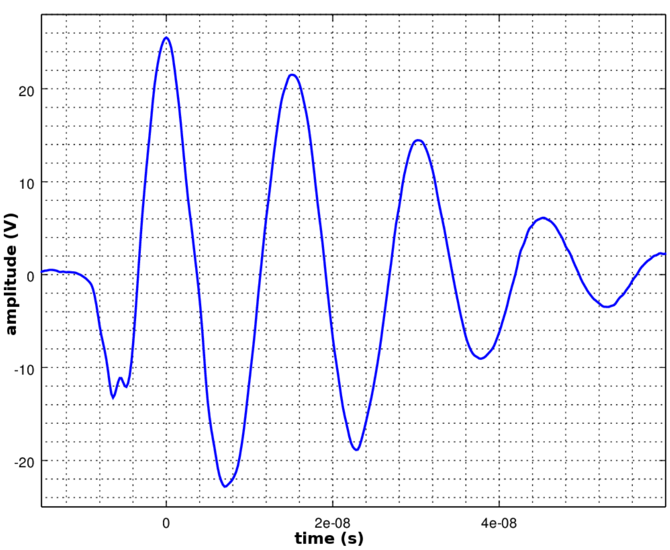

Fig. 5. Emitted pulse: while the ringing is not suitable for GPR applications, narrowing the emitted pulse bandwidth by allowing ringing better matches the SAW sensor spectral response whose bandwidth is given by the product of the operating frequency by the electromechanical coupling coefficient.

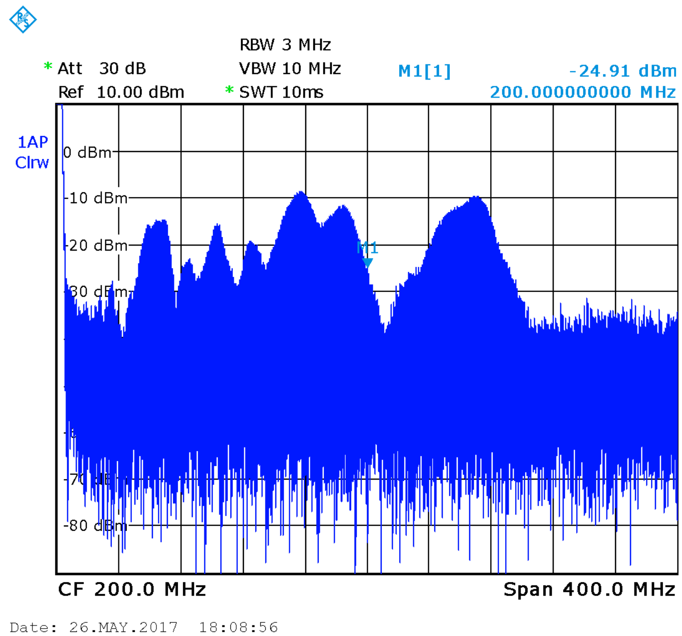

Fig. 6. Wireless measurement of the spectrum of the pulses emitted at the dipole antenna output.

The receiver antenna feeds a monolithic amplifier which directly feeds the analog to digital converter. Even with such a basic setup a measurement range in air – without benefiting from the beam directivity brought by positioning the antennas on the high-premittivy ground – of 70 cm will be demonstrated in the next section.

V. Result and discussion

The complete circuit includes the stroboscopic receiver, the avalanche transistor based pulse emitter, and high voltage supply. The latter, providing the avalanche transistor collector voltage above the avalanche threshold voltage, is in the 120 to 160 V range: embedded solutions such as Traco's THV 12-180P 2 W (180 V, 12 mA) DC-DC converter are well suited to the task. The receiver supply is 380±10 mA at 5 V or a power consumption of 1.9 W.

Using unshielded dipole antennas both on the emitter, receiver and sensor sides, the returned echoes are well detected at a range of 70 cm (Fig. 7), with 100 MHz sensor responses polluted by local FM broadcast station signals (Fig. 8) but the 200 MHz sensor exhibiting excellent signal to noise ratio (Fig. 9). This setup focuses on the electronics and the demonstration of the proper operation of the stroboscopic receiver coupled to the avalanche transistor pulse emitter: no care has been brought on antenna design or beam focusing through high permittivity ground.

Since the time of flight measurement by analyzing the position of the maximum of the cross-correlation between two echoes is based on analyzing the analog signature of the sensor signal, the measurement resolution is directly related to the measurement signal to noise ratio: Fig. 10 exhibits one such

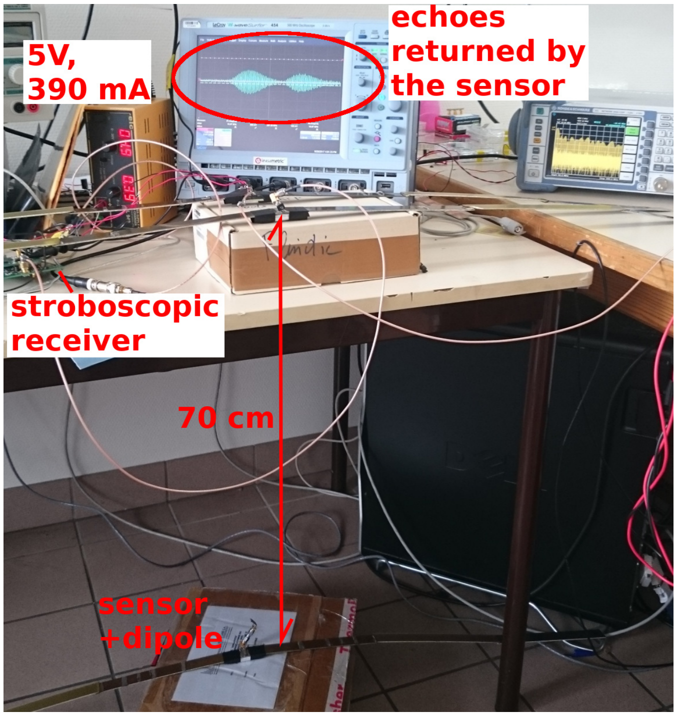

Fig. 7. Experimental setup for assessing the wireless measurement. The oscilloscope scale is 100 mV/division, demonstrating that the signal is readily sampled after 15 dB gain by a monolithic amplifier on the embedded stroboscopic board fitted with a 2.5 V-full-range Linear Technology LTC1407 analog to digital converter.

measurement, with an initial baseline for assessing the time difference resolution and stability, followed by three freezing spray cooling steps to demonstrate the transducer temperature sensing capability.

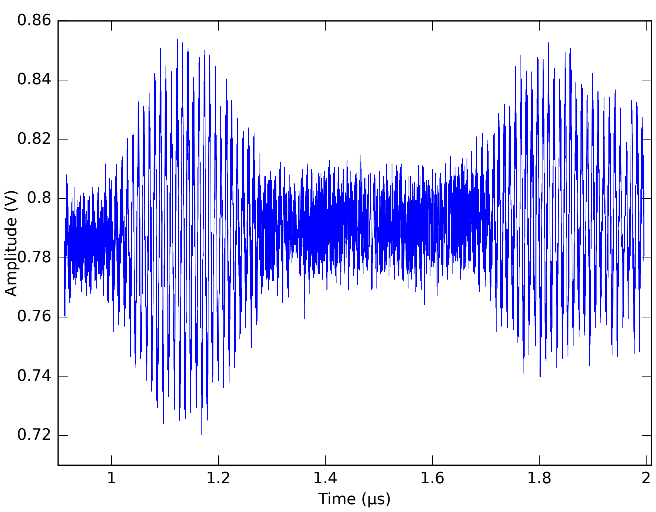

Fig. 8. Signal received from a 100 MHz sensor when excited by the custom pulse emitter, and sampled by the stroboscopic receiver: a nearby FM broadcast station degrades the signal to noise ratio since unshielded antennas are used, but the sensor two echoes for a differential measurement remain well visible.

We have seen that the targeted stability on the time domain

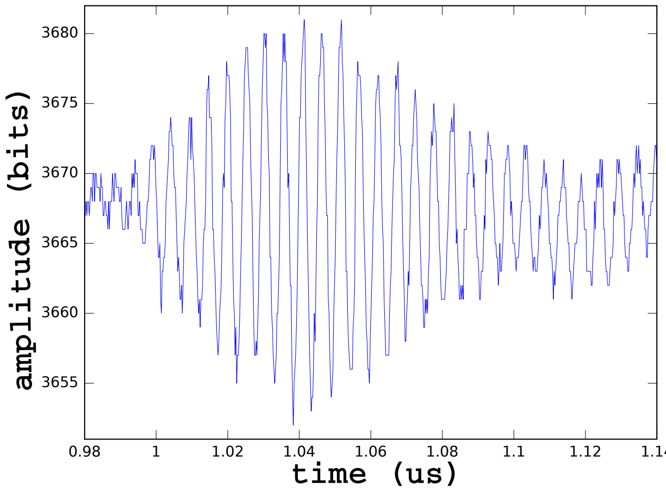

Fig. 9. Signal received from a 200 MHz sensor when excited by the custom pulse emitter, and sampled by the stroboscopic receiver: the response is well resolved by the 4.6 GS/s equivalent sampling rate.

echo measurement, with two echoes separated by $\tau = 300$ ns, is 0.8° phase stability or 21 ps for 1 K resolution and a sensor operating around 100 MHz. Such stability levels are demonstrated experimentally in Fig. 10, in which a long term baseline is acquired before inducing a sensor temperature variation by spraying a freezing gas over the sensing element to demonstrate the temperature sensing capability.

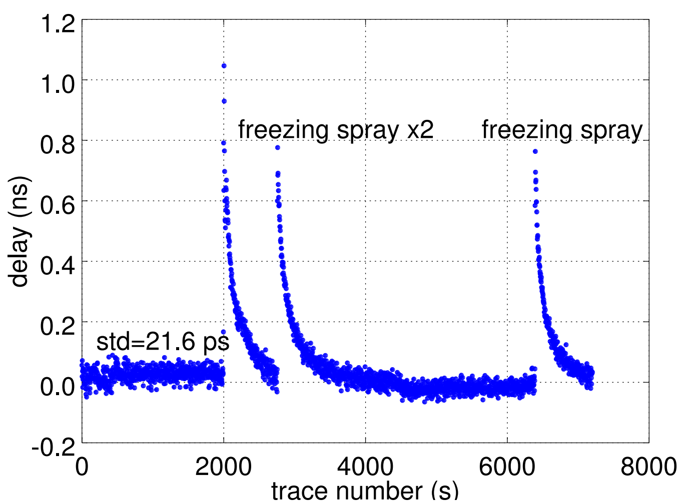

Fig. 10. 2-hour long measurement, with an initial baseline stability assessment by leaving the sensor run in a constant environment, followed by three cooling steps to demonstrate the sensing capability and short response time, limited by thermal diffusion through the ceramic package and the insulating piezoelectric substrate.

The time delay rises due to the negative temperature coefficient $S = -70$ ppm/K of the piezoelectric substrate: cooling the substrate slows down the wave and hence increases the time-delay between echoes. The observed $\Delta\tau = 1$ ns delay matches the expected temperature drop ΔT since $\Delta T = \frac{1}{S} \cdot \frac{\Delta\tau}{\tau} = -47$ K. The freezing spray is claimed to cool the exposed part down to -50 ° with respect to room temperature

[8], consistent with our measurement and the short term exposure of the sensing element to the spray.

VI. Conclusion

Based on past investigations which identified local oscillator drift as being the main hindrance for the use of commercial Ground Penetrating RADAR for probing passive transducers acting as sub-surface cooperative targets, we have assembled a custom pulse emitter coupled to a stroboscopic receiver meeting the sub-tens of ps stability requirement for sensor monitoring. The avalanche transistor based pulse emitter allows for probing 100 and 200 MHz sensors at a range of over 70 cm in air, without profiting from the focusing properties of high permittivity soil. The basic dipole antenna exhibiting some ringing and hence reduced bandwidth is well suited for acoustic sensor interrogation since the piezoelectric transducer bandwidth is defined by the electromechanical coupling coefficient and is a few percents: the optimum number of carrier periods for probing the sensor, equal to the inverse of the electromechanical coupling coefficient, is met by the wide-dipole architecture. Power consumption is compatible with an embedded application or long term monitoring using a battery powered system.

Acknowledgment

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