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# Wireless interrogation of passive sensors in confined environment

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ABSTRACT: Monitoring is a key issue in the management of an underground radioactive waste disposal facility. The structures that will receive radioactive waste packages are confined, and space that could be used to lay a communication cable for the sensors is very limited. For instance, it is foreseen to place certain waste packages into horizontal disposal cells (pipe shape) in the rock medium. In this context, RADAR interrogation of passive scatterers is a promising solution for monitoring the structure. The RADAR interrogation technique has been developed for wireless instrumentation located in a confined environment. These sensors do not require a power source; they can be installed in a network configuration, and can potentially measure different physical parameters (e.g. temperature, pressure …). Technically, a scatterer is an antenna loaded by the variable passive impedance. The load changes with each physical parameter that needs to be measured. This method also requires a frequency modulated continuous wave (FMCW) RADAR. A FMCW RADAR could be used in such environment to interrogate multiple scatterers placed on the internal wall of the pipe.

## 1 INTRODUCTION

### *1.1 Context*

In most of the countries that use nuclear fuel as energy, underground repositories for radioactive waste are in the phase of preparation. Between 2020 and 2030, underground structures located as deep as -200 meters to -600 meters in salt rock, granitic rock or argillite rock will receive high-level radioactive waste.

ANDRA is the French National Radioactive Waste Management Agency in charge of driving the underground radioactive waste repository project called Cigeo (meaning "Industrial GEOlogical underground repository"). This structure will be composed of hundreds of kilometers of galleries at 500 meters underground. Due to the concerns associated with storage and disposal of radioactive waste, such repository structures are special. One way to address these concerns is to provide a comprehensive monitoring (Morice & Bertrand (2011)). The repository galleries will contain the waste packages and ensure the safety for the first decades. To mitigate the long-term danger of radioactive elements, the host rock as the final natural structure will assure the safety of the environment and the population for several thousands of years. Thus, to preserve its integrity, it is necessary to limit the modification to the host rock and the empty spaces within it, which in turn makes monitoring quite a challenging task regarding the confined environment and duration of measurements.

In this context, in 1991 Andra launched a major research program to study the possibilities of disposal of the radioactive waste in a Callovo-Oxfordian clay formation (approximately 155 million years old).

### *1.2 Objectives*

Wireless sensors are studied as a potential solution seeking to reduce the intrusiveness of the monitoring systems. With regard to the need to ensure the monitoring over several decades, with no possibility to access to the sensor, a battery-free system would be preferred: current state of the art long-lived batteries do not allow measurements for over more than 20 years.

Several locations in the Cigeo structure have been identified for the installation of such wireless transmission system. For instance, a wireless transmission system could be installed using reflected paths in ventilation system pipes, either in the intermediate level long-lived radioactive waste repository disposal cells which are in fact concrete-lined galleries, or in the high-level radioactive waste (HLW) repository disposal cells which are the 40 metre-long steel pipes of 70 cm in diameter.

This paper presents the development of a wireless transmission system achieved in the latter case: transmission in HLW repository disposal cells. It is a challenging development indeed, since little space will be available for electromagnetic wave transmission as is evident on Figure 1.

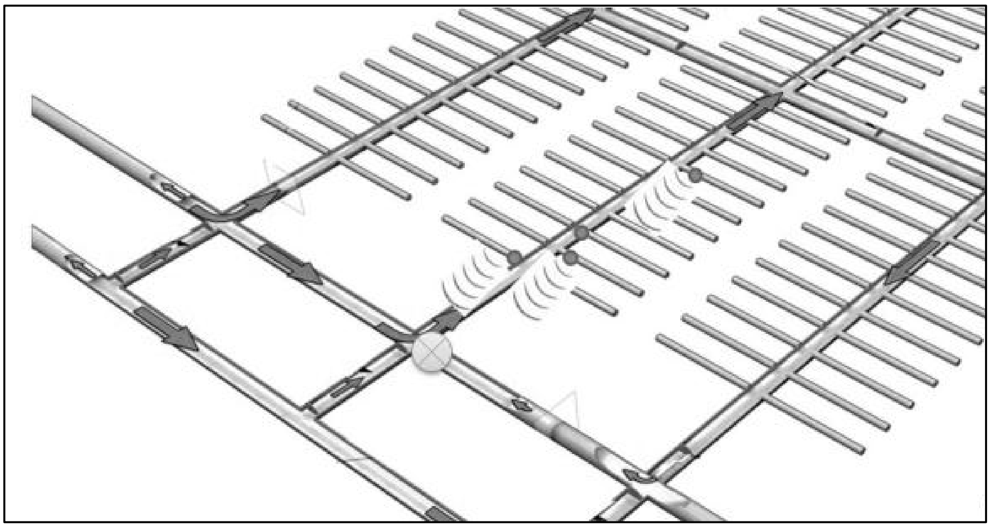

Figure 1. Wireless transmission system in Cigeo galleries

Typical parameters to read: temperature, pressure, relative humidity and gas concentration.

### *1.3 Ways and means*

#### 1.3.1 Principle description

The systems developed in the present work rely on a RADAR method and passive impedance load sensitive to a physical parameter such as temperature (Thai (2010)), pressure (Jatlaoui (2008)), gas concentration (Hallil (2009)), and strain (Thai (2011)). The systems fulfill the previously mentioned objectives: no cables between the acquisition system and the sensor, no need to power the sensing elements (sensors are powered by the electromagnetic field emanating from the Radar), long transmission range (appr. tens of meters in practice). The reflections of the electromagnetic waves are limited to pipe surface reflections. Several studies the results of which are not presented in detail in this paper, deal with waves in "channel" reflections.

Compared to RFID (Radio Frequency IDentification) and SAW (Surface Acoustic Waves) as presented by Olariu & al. (2011), the advantages of the proposed system are based on the transmission range and adaptability to various sensors.

### 1.3.2 RADAR description

A device to be used in the present work is a Frequency Modulated Continuous-Wave (FWMC) millimeter-wave RADAR. It is made of a transmitting antenna, a receiving antenna and electronic components; their functions are presented in Figure 2.

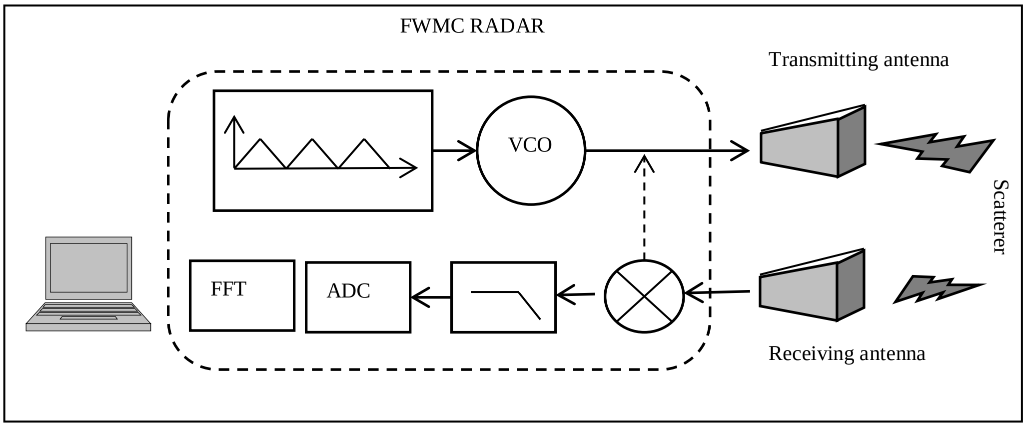


Figure 2. RADAR setup description

A triangle frequency modulated signal (chirp) is generated in the RADAR device. For such modulation the frequency of the transmitted signal is tuned linearly as a function of time. The resulting chirp signal is characterized by the carrier frequency $f_0$ of 30GHz, a bandwidth of $F=650MHz$ and $T_R=1ms$ period for the triangle modulation (VCO stands for Voltage Control Oscillator). The chirp is mixed with the backscattered signal (dotted arrow) to produce a low-frequency (LF) signal named the *beat signal*. Processing is then applied to this beat signal by filtering, Analog-to-Digital Conversion (ADC) and Fast Fourier Transformation (FFT). The RADAR interrogator transmits electromagnetic power of 10dBm.

### 1.3.3 Scatterer

The signal generated by the RADAR is transmitted to a scatterer. This scatterer is composed of a Ka-band antenna connected to a coaxial cable (delay line) and at its end - to an impedance load (element sensitive to the physical quantity of interest).

A coaxial cable is needed to connect the sensitive element to its antenna. But it has also another role: it acts as a delay line that allows separating the signal of the antenna's structure from the signal of the impedance load. As shown on Figure 3, the coaxial cable length accurately settles the shift of frequency between the reflected signal due to the antenna and the reflected signal due the sensor load. It is important to note the following: as the highest reflected signal comes from the antenna, it tells us where to look for the measurement in the spectrum of the beat signal (that can be polluted by other signal peaks).

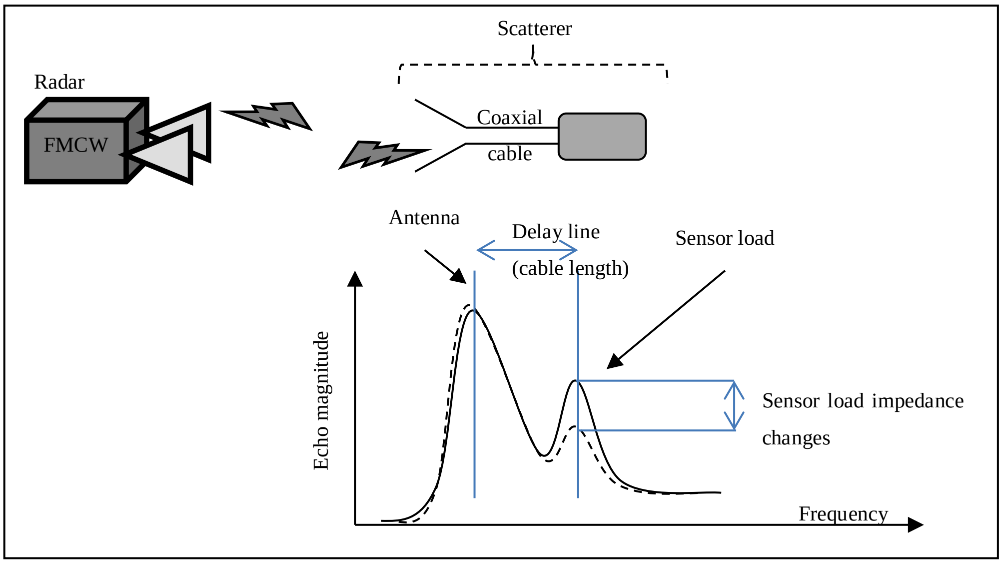


Figure 3. Spectrum of the beat signal synthesized by the FMCW RADAR when the impedance load is 50 Ohms (dashed line) and 0 Ohm (solid line)

As the physical quantity fluctuates, the impedance of the sensing element changes, and, consequently, the Radar Cross Section of the loaded antenna varies. This variation can be remotely derived from the analysis of the beat signal spectrum synthesized by the FMCW RADAR. The fluctuation of the physical quantity is finally deduced from this variation. This summarizes the principle of RADAR interrogation of passive sensors. Any sensitive element for which the electrical impedance is greatly dependent on the physical quantity of interest in the frequency range of the RADAR can be used by this method.

## 2 EXPERIMENTS

The aim of the test is to demonstrate the feasibility of carrying out the temperature measurement with wireless sensors in HLW disposal structures.

### *2.1 Laboratory tests*

Preliminary tests have been performed in the LAAS electronics laboratory. The setup of the preliminary tests is presented in Figure 4.

In order to simulate the real case conditions we will encounter in HLW repositories, we used a metallic vent pipe with the same diameter as the one used in the disposal facility: 700 mm. Two scatterers with impedance loads and coaxial cables have been installed inside the pipe.

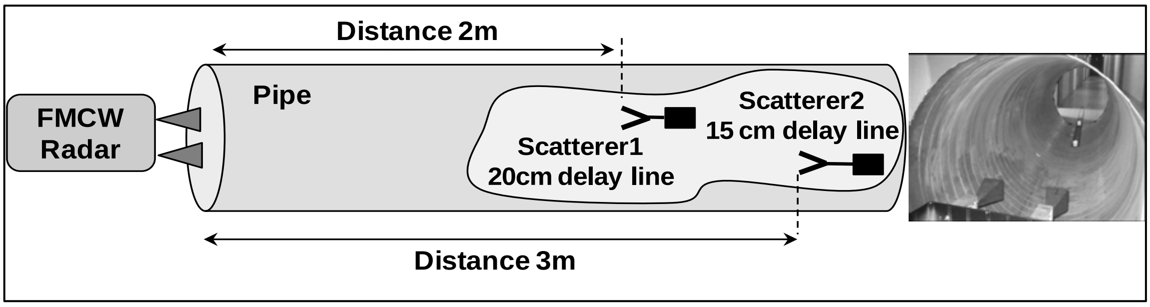


Figure 4. Experimental setup with a vent pipe

The distance between the scatterer 1 (resp. scatterer 2) and the RADAR reader is 2 m (resp. 3 m) and the length of the coaxial cable is 15cm (resp. 20cm). The load impedance of the two scatterers is either 0 Ω or 50 Ω.

The spectrum of the beat signal synthetized by the RADAR system is presented in Figure 5. We observe echos from both antennas and also echos from the 0 Ω load of each scaterer. The echos from the loads disappear as their impedance is set to 50 Ω (match load).

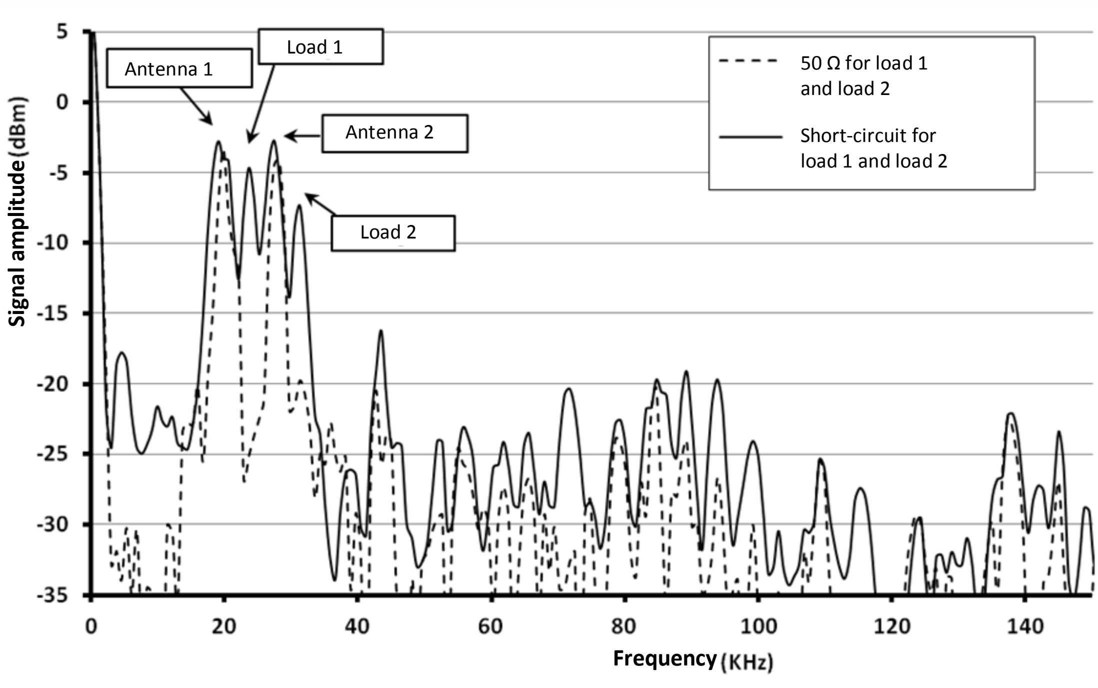


Figure 5. Spectrum of the beat signal synthesized by the millimeter-wave FMCW RADAR when two scatterers are located in the vent pipe

These measurements demonstrate the efficiency of the methods presented previously in Section 1.3. This method allows to distinguish easily and to identify several wireless sensors. The position of each antenna and each sensitive element are predicted. As expected, the amplitude of the sensor's echo changes with the impedance load.

## *2.2 In situ tests*

The Cigeo monitoring strategy requires performing on-field tests after the laboratory tests. One of the objectives of ANDRA's Bure underground laboratory (URL) is to realize the on-field testing. Several demonstrators of HLW repository have been implemented in Bure URL at 500m underground. Two prototype cells have been used for Radar transmission testing: ALC3001 and HAT1602 (shown in Figure 6).

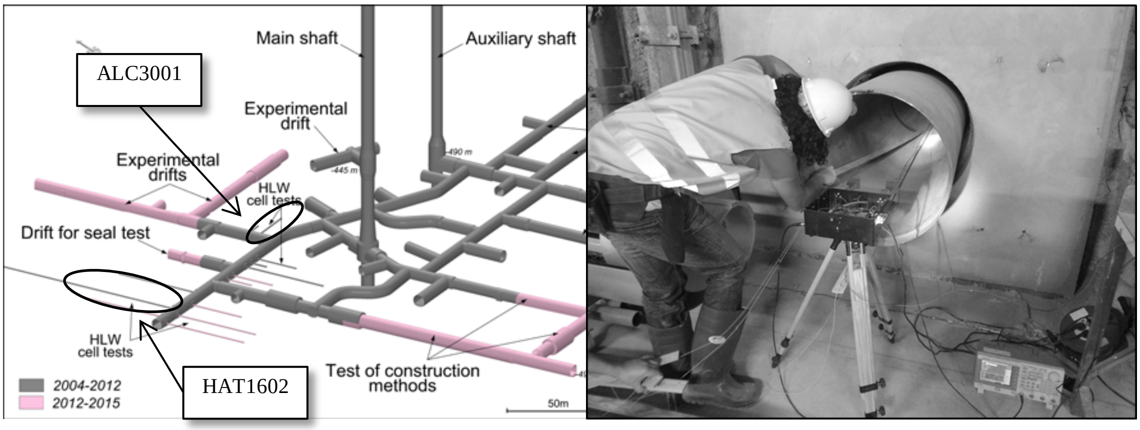


Figure 6. Experiment setup in High Level radioactive waste cell demonstrator in Bure Underground Research Laboratory (URL)

The specifications of these HLW demonstrators are given in Table 1. They differ on two points: their length and the junctions of their pipe segments.

| | First HLW cell demonstrator (ALC3001) | Second HLW cell demonstrator (HAT1602) |
|---|---|---|
| External diameter (mm) | 700 | 700 |
| Thickness (mm) | 20 | 20 |
| Pipe segment length (m) | 2 | 2 |
| Overall length (m) | 10 | 100 |
| Junction between two pipe segments | Welded | Clipped |

Table 1. HLW test cell specifications

The RADAR interrogator system was placed at the entrance of the repository cells as shown on the right of Figure 6. In the first HLW cell demonstrator (ALC3001) many undesired reflections appeared on the RADAR measurements. This can be explained by the protuberance of rough welding between the pipe segments. The effect of the junction issues is also observed on the measurements in the second HLW cell (HAT1602) as shown in Figure 7.

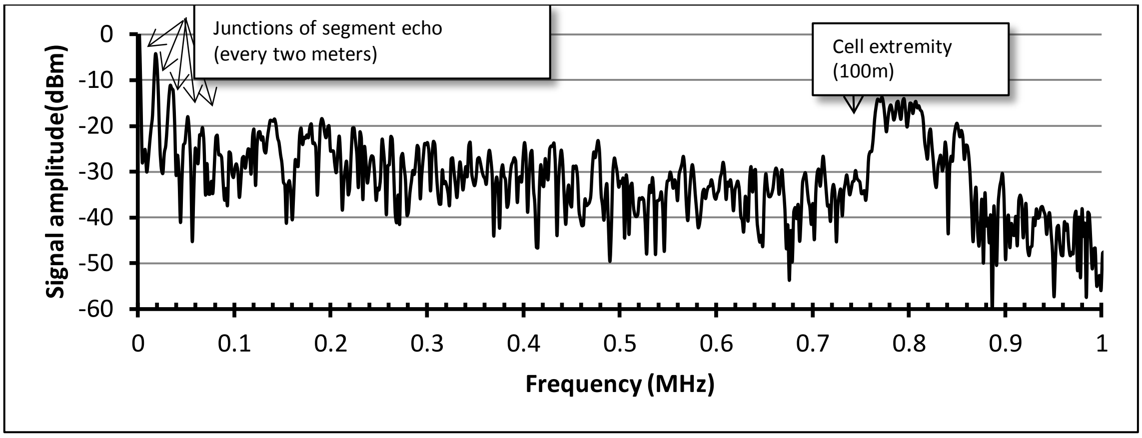


Figure 7. Spectrum of the beat signal synthesized by the millimeter-wave FMCW RADAR when no scatterer is placed inside the HAT1602

Then we chose to use a thermistor for the impedance load - as it is a sensor easy to calibrate and to set up. The sensor's antenna and sensing element have been mounted on a long wooden stick that allows placing the sensor at different distances in the repository cells.
In order to measure various temperatures, a heating device was placed under the thermistor.

The resulting beat signal spectrum in this configuration is shown in Figure 8.

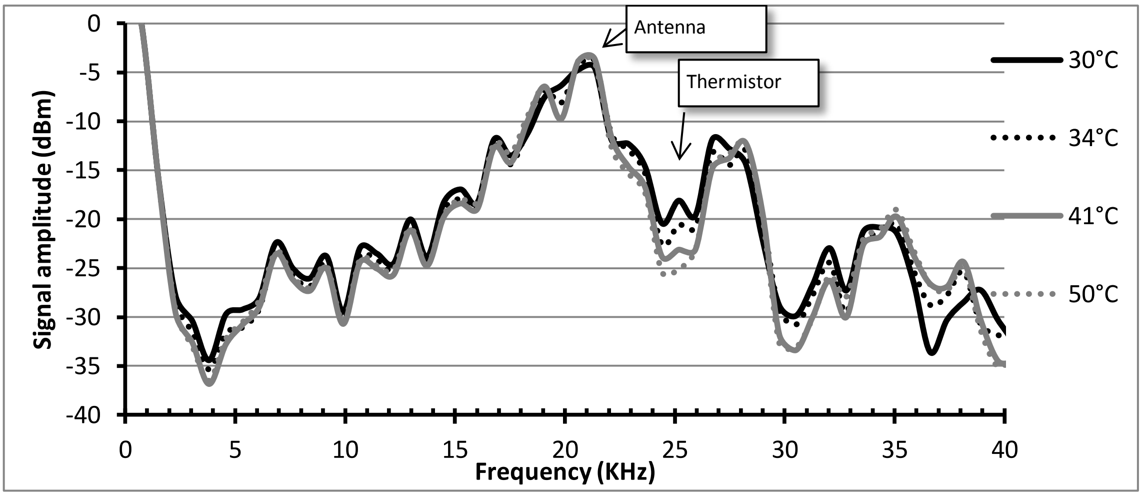


Figure 8. Spectrum of the beat signal synthesized by the millimeter-wave FMCW RADAR when a thermistor connected to the Ka-band antenna in located inside HAT1602

Thanks to the knowledge of the distance between the RADAR’s antennas and the sensor’s antenna we determine the scatterer echo position from the other echo (from multipath reflections) perturbing the measurement. As expected, when we increased the temperature close to the thermistor, we observed the decrease of the sensor’s echo.

## 3 CONCLUSIONS

RADAR interrogation of passive scatterers distributed along the internal wall of air-filled circular pipes is experimentally explored. From the measured backscattered signal in such multipath environment, the location of the scatterers inside the pipe was identified successfully.

Nevertheless, in a real scenario a strong signal of the junctions can cover the sensor's echo if the position is not well chosen. This can limit possible positions for installing the sensor's antennas.

Further work will be carried out to improve this method. In particular, the RADAR and its antenna will have to evolve. The research work on micro-fluidic sensors in order to improve the sensitivity of the measurements is ongoing (Bouaziz & al., 2013). Repeaters and networking solutions are also currently being developed.

Variation of the scatterers' load impedance may be remotely and wirelessly derived. Consequently, the remote measurement of physical/chemical quantities from the RADAR interrogation of passive wireless sensors (such as, e.g., those recently proposed by Jatlaoui & al. (2008) and Thai & al. (2011) that are located in the environment such as pipes is possible.

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