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Capacitively coupled EM sensors integrated in non-corrosive casings for long-term CSEM monitoring

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Summary

We present a development of capacitively coupled EM sensors integrated in non-corrosive casings for permanent CSEM monitoring in boreholes. Capacitive sensors are required to detect low-frequency (diffusive-field) signals where voltage measurements fail and ammeters need to be used. The permanent installation in boreholes necessitates surface placement of the electronic components to ensure their longevity and accessibility. An issue is that small current signals need to be transferred over a large distance via cables whose capacitances are larger than the ones from the sensors, so a circuit of a Zero-Resistance Ammeter with Integrator (ZRA-I) was developed for annihilating the cable-capacitance effect. Via modelling, lab and small-scale field testing, we were able to show that capacitive sensors with ZRA-I electronics worked well: although the desired signal is slightly decreased compared to the one from galvanically coupled sensors, the signal-to-noise ratios are comparable, for the frequencies used. So we show that capacitive sensors can successfully be integrated in composite casings and, with the proper sensor electronics, can well be used for permanent CSEM monitoring in boreholes.

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Introduction

Geophysical monitoring is an important part of geothermal and hydrocarbon resource development. It provides means to optimize injection-production operations, to adapt development strategies during operations and to aid in predicting the economic performance of such operations. Here we focus on the use of the electromagnetic methodology (EM) for such applications, in particular with the aid of humanly controlled sources, known as CSEM. EM methods can detect fluid displacement in a reservoir, whenever a sufficient resistivity contrast exists between the displacing fluid and the fluid being displaced. Such a condition is typically met in hydrocarbon, geothermal and CO_2-storage reservoirs.

On land, many CSEM surveys are carried out with sources and receivers positioned at the surface. However, due to the noise near the surface (especially in urbanized areas), the variability of the near surface and the high attenuation of the (diffusive) electromagnetic fields, such surface surveys are of limited use in monitoring deep reservoirs. As also shown by (Wirianto *et al*., 2010), highest sensitivity can be obtained by placing sensors in a borehole around the reservoir.

Typically, EM sensors are coupled galvanically to the earth. But especially in deeper boreholes with brine as fluid, such coupling continually degrades the sensors so these are not suitable for permanent monitoring. However, capacitive coupling can also be used as a means to sense the EM field, avoiding direct contact with corrosive fluids (see, e.g., Kuras *et al*., 2006).

Next to the coupling issue, there is also the issue is that, commonly, the casing of a borehole is made of steel, heavily affecting the EM field and masking the response changes due to the production changes, in comparison to the large response of the steel casing. The recent development of composite casings has allowed to avoid the use of steel as casing. Composite materials have been developed for their resistance to chemical corrosion. The combination of capacitively coupled sensors and non-corrosive casings opens up the possibility for long-term downhole monitoring the EM field. This is the main topic of this abstract.

Laboratory testing and modelling

In order for a capacitive sensor to work as intended, the permittivity of typical composite casing should be determined, assuming the resistance is very high. To that end, we used impedance spectroscopy to determine the relative electric permittivity (ε_r) of a composite casing material manufactured by Huisman Equipment BV. The experiment setup consisted of two circular copper electrodes placed on the opposite sides of the composite material, the dielectric. Impedance measurements were made at room temperature using a capacitor tester. Each measurement cycle consisted of a measurement of the magnitude and phase angle of the impedance at 30 discrete frequencies over the frequency range of 20 Hz to 200 kHz. The values at the lower end of the spectrum contain some distortions, as was known on beforehand with respect to the measuring device; still at the higher frequencies ($>\approx$ 80 Hz), reliable values with standard deviations less than 0.02 were obtained. The relative electric permittivity of the investigated composite material sample ε_r was found to be 4.11 ± 0.16 at 20 Hz, nearly linearly decreasing to 3.90 ± 0.02 at 200 kHz.

The next step is taking into account the shape of the capacitive sensor for applications in boreholes, so cylindrical ones. Its characteristics need to be determined, such as its (frequency-domain) response and its capacitance. Analytical expression for the capacitance of cylindrically shaped sensors are well known. Also for subsequent modelling, a COMSOL® model was set up and calibrated against the analytical model. Then, the laboratory experiments were carried out with prototype sensors (see Figure 1), first compared to the equivalent galvanically coupled cylindrical sensor, and second compared to the analytical and numerical models. The capacitively coupled sensors show some reduced amplitudes compared to the galvanically coupled ones, in our case some factor of 8 dB, while the phase starts to deviate more than 2 degrees below about 0.3 Hz, and further increasing with decreasing frequency. The capacitances obtained from the analytical and numerical models are very similar to the ones obtained from the experiments, showing that we understand the behaviour well.

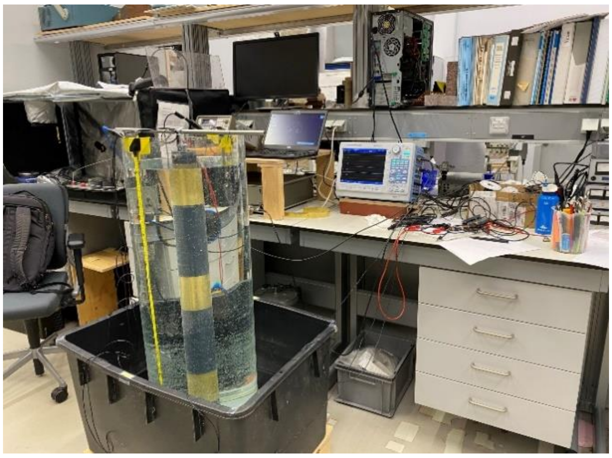

Figure 1 *Prototype capacitive sensor in a water tank in the laboratory of the TU Delft.*

Reducing effect of long cables: electronics of Zero-Resistance Ammeter with Integrator

When designing sensors to be used in a borehole, especially deep ones, the cable will have an effect on the response via its capacitance. Over 1 kilometre or so, the capacitance of the cable can exceed the one from the sensor, so this needs to be somehow removed. It is assumed that placing electronics downhole is to be avoided since that is not very attractive for longer-term monitoring. To this end, a so-called Zero-Resistance Ammeter with Integrator (ZRA-I) was developed

Using this design, the responses of water-tank experiments were simulated using a combination of COMSOL® and the open-source software KiCad. Also physical experiments were carried out in the lab using short and long cables. It was found that the ZRA-I performs well, thereby minimizing the effect of a long cable, but the signal level also decreased substantially, namely some 16 dB compared to a measurement when the ZRA-I is excluded. Still, the ZRA-I electronics have some unknown scaling factor and direct comparisons under exactly the same noise conditions could not be done since only one water tank was available and due to the laboratory environment with multiple EM noise sources active throughout the day making accurate signal-to-noise ratio (SNR) estimation difficult. Possibly, the noise levels are also lower; later, via field tests, where such comparisons could be done, it was found out that this was indeed the case.

First field test

Based on the encouraging results in the lab, a first field test was planned and carried out. It took place near Delft, near a village called De Zweth, in The Netherlands (see Figure 2). Its main objectives were:

1. Obtain data in a setting that better approximates the environment for which the sensors are intended: sensors placed in a borehole, more realistic receiver – transmitter offsets, EM field not confined by water-tank walls.
2. Provide a better estimate of the sensors' sensitivity and signal-to-noise ratio (SNR) than could be made in a noisy laboratory environment.

The same sensors as used in the lab were placed in very shallow boreholes, next to each other: two sets of galvanically coupled and capacitively coupled ones. As source, a Zonge GGT-3 Transmitter was used: it was used to send out discrete-frequency square-wave signals. Measurements were taken at a single source-receiver separation (20 m) for a 0.25 – 520 Hz range of source frequencies (see Figure 3). Sensor voltages were recorded both in differential and single-ended mode.

Figure 2 *Field survey at De Zweth.*

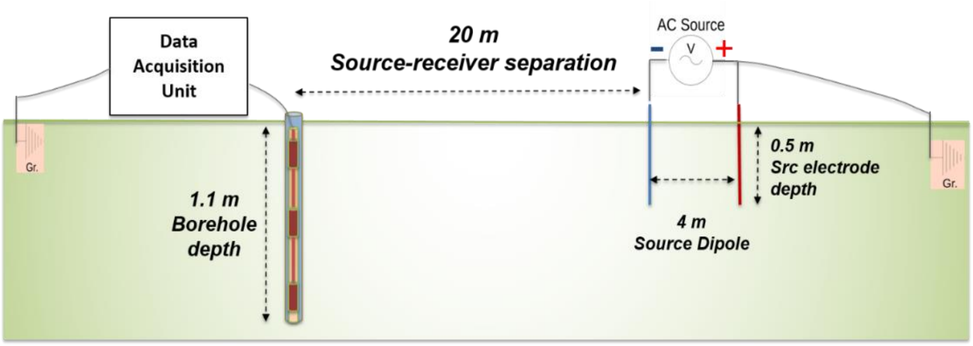

Figure 3 *Schematic cross-section of the field setup*

We evaluated the capacitive sensors by comparing them their recordings to the galvanic sensors. First we compared the SNR of both sensors connected to the basic benchmark acquisition circuit (buffer amplifier + ADC) via short-length cables (10 m); this shows the differences in sensitivity that are solely due to different coupling mechanism to the electric field (capacitive and resistive). Difference in SNR of the capacitive relative to the galvanic sensors is shown in Figure 3, together with their error bars. We can see that SNR of the capacitive sensors 8 dB lower than that of the galvanic ones for source frequencies ≤ 4 Hz, and increasing for higher source frequencies, surpassing the galvanic sensors by ~2 dB at 128 Hz. This frequency-dependency is expected since the impedance of a capacitive electrode will decrease with the increasing frequency resulting in a higher signal amplitude.

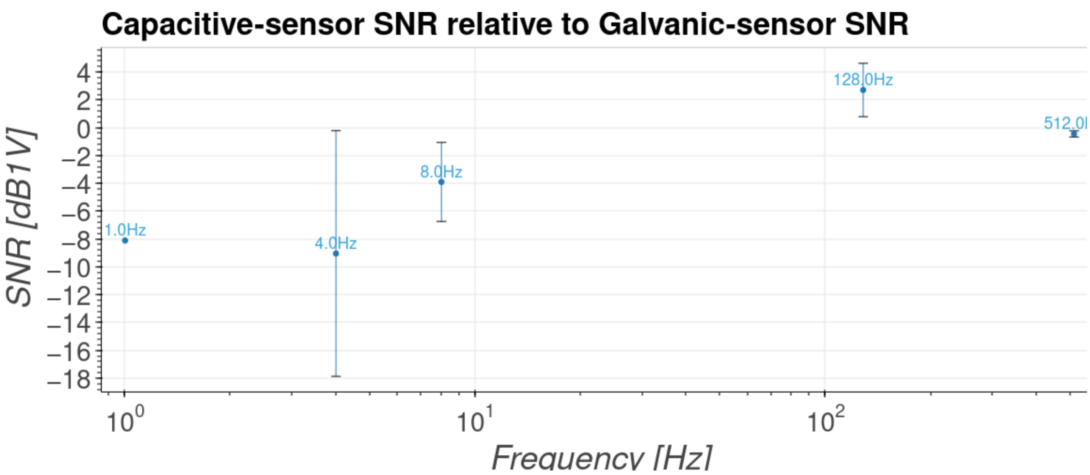

Figure 3 *Difference in SNR of the capacitive and galvanic electrodes (in dB scale). Both electrode types connected to same signal acquisition circuit (Buffer+ADC) via short cables (10 m). Error bars indicate one standard deviation.*

Next, we compare the sensitivity of the capacitive sensors with the ZRA-I electronics and the basic benchmark acquisition circuit and evaluate ZRA-I for its efficiency in removing the parasitic capacitance of the cable (see Figure 4). Due to limited aims of this field test, the measurements with the

ZRA-I electronics were made only at a single frequency of 8 Hz. We observed that the ZRA-I circuit effectively removes the parasitic capacitance of the cable and increases the SNR of the capacitive sensors when compared to the capacitive sensor without ZRA-I (buffer amplifier + ADC) for different cable lengths.

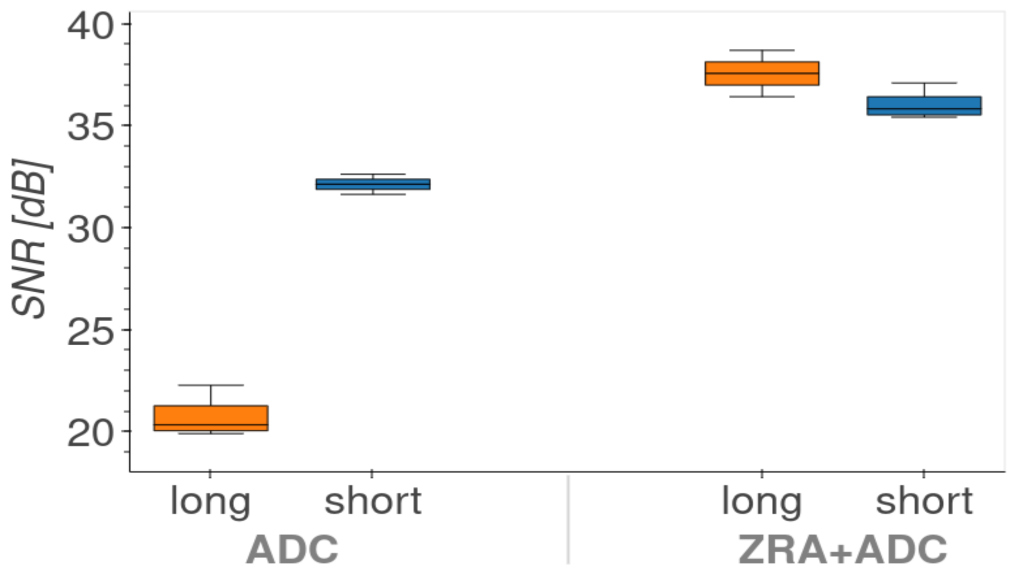

Figure 4 *Capacitive sensors with two acquisition circuits (ZRA-I+ADC and Buffer+ADC), two cable lengths: long (130 m,* **orange boxes)***, short (10 m,* **blue boxes***). Error bars show 1 std. deviation.*

Discussion

Based on the first results in the field, the next step of designing a sensor to be moulded into a composite casing was done. A specific item was that the sensor could not be one big cylindrical sensor since then it could not be properly integrated in the casing-fabrication process: it needed to be a strip that can be helically wound around the cylindrical casing. Therefore, some further modelling was done, and it was shown that such a helically wound strip (see Figure 5) as sensor little affected the capacitance. Based on the modelling results a decision was made to proceed with the fabrication of full-sized prototypes.

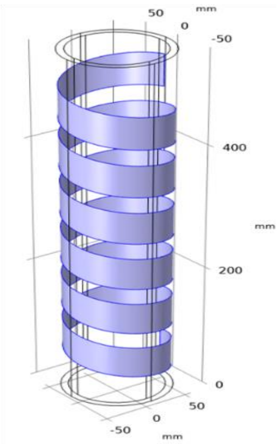

Figure 5 *Design of helically wound capacitive sensor for a borehole.*

Conclusions

Based on modelling, laboratory and field testing, we have shown that capacitive sensors integrated within a non-corrosive (e.g., composite) casing can be successfully carried out. Some prototype sensors were built and modelled, and tested in the lab and once in the field. It showed that the electronics, via a Zero-Resistance Ammeter with Integrator, to remove the (mainly capacitive) effect of long cables, worked well. The capacitive sensors with ZRA-I electronics did decrease the amplitude of the signal compared to galvanically coupled ones, as was expected, but the noise also decreased, so the signal-to-noise ratios were only little decreased as shown via a small field test.

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