

## Introduction

During the last decade, an important innovation in the oil industry has been the development of a new generation of wells generally referred to as smart wells. These wells are equipped with down-hole sensors to monitor well and reservoir conditions and with valves to control the inflow of fluids from the reservoir to the well. The combination of monitoring and control has the potential to significantly improve oil and gas recovery. In fact, the adjustable settings of the inflow control valves (ICVs) can be varied to optimize the inflow profile along the well in response to monitoring data obtained from down-hole sensors. Addiego-Guevara et al. (2008) have demonstrated that control strategies always enhance production and mitigate reservoir uncertainty; a typical application is the management of undesired fluids to prevent early breakthrough within the production wells.

Currently the most frequently used permanent down-hole sensors measure pressure and temperature and cannot capture the fluid dynamics outside the well; monitoring techniques that could investigate at larger distances are strongly required. Chen et al. (2002) have considered borehole radar measurements as an imaging technique for oilfield application. They concluded that a penetration depth of several meters can be realized for relatively low conductive reservoirs with operating frequencies in the range of 100 to 500 MHz. We postulate that an array of down-hole electromagnetic (EM) sensors located in production wells can cover the imaging necessity required for thin oil reservoirs and for Steam Assisted Gravity Drainage (SAGD) process, where the distance between production and injection wells in general is relatively small (order of a few meters). It would be possible to detect the arrival of undesired fluids like water or steam, since their EM properties are strongly different with respect to all the other reservoir components, therefore reflections would occur at transitions from oil rich zones to water/steam rich zones.

In this paper we first have considered the EM wave propagation relevant to a borehole radar system in oil reservoirs. Then we have extended the unified approach defined by Noon et al. (1998) to evaluate the maximum penetration depth of a radar tool and we have proposed modeling results that highlight the determinant factors for the feasibility of such a system.

## Electromagnetic wave propagation

The ability of a borehole radar tool to image the near well region mainly depends on the applied frequency  $\omega$  and on the EM properties of the medium where the EM waves propagate: electrical conductivity  $\sigma$ , dielectric permittivity  $\varepsilon$  and magnetic permeability  $\mu$ .

In a homogeneous medium the complex propagation constant  $\gamma = \gamma_r + i\gamma_i$  has a real component  $\gamma_r$ , which represents the attenuation part, and an imaginary component  $\gamma_i$ , which represents the propagating part. Values of the attenuation ( $ATT$ ), in decibels, and of the phase distortion ( $PH_{err}$ ) are given by the following forms:

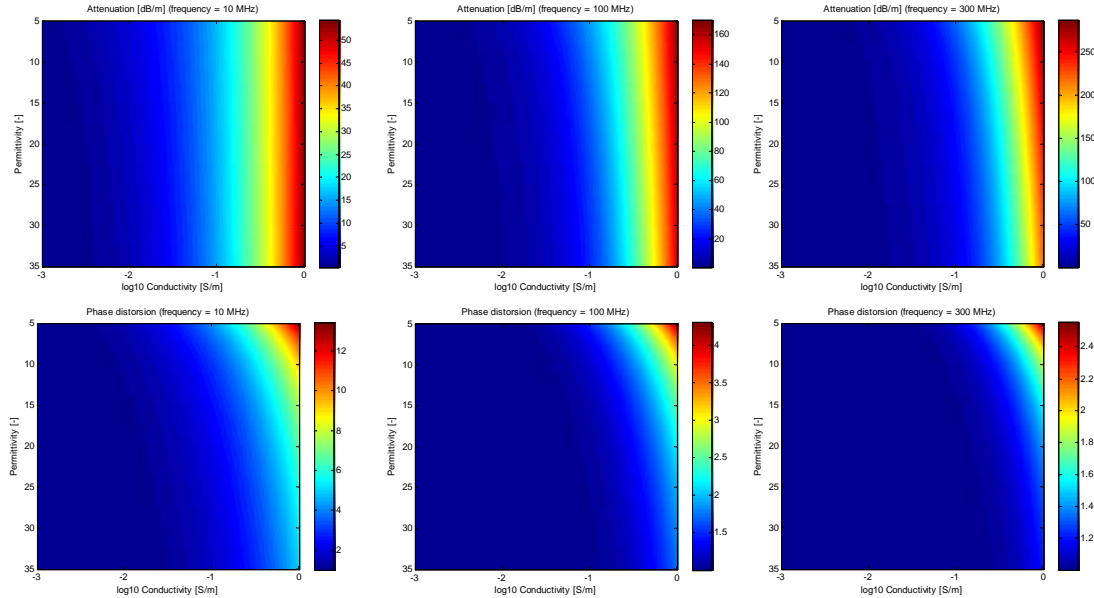
$$ATT = 20 \log_{10} \left( e^{\gamma_r} \right), \quad (1)$$

$$PH_{err} = \gamma_i / \left( \omega \sqrt{\mu \varepsilon} \right). \quad (2)$$

An analysis of these values can constrain the operating frequency and the EM properties that a medium should have to make wave propagation (radar tools) prevail over diffusion phenomena (induction tools). Therefore, we need to consider realistic values of EM properties and evaluate, through equations (1) and (2), attenuation and phase distortion for a broad band of radar frequencies. We have used the CRIM law (Seleznov et al. 2004) to get effective values of permittivity and the classic Archie's law for the conductivity values.

As an example, we present attenuation and phase distortion for three frequencies (10, 100 and 300 MHz) in figure 1. Analysis shows, that for the given range of medium parameters, wave propagation starts to dominate around 100 MHz; at lower frequencies, as can be seen in fig. 1d, the phase distortion is not tolerable, and, on the other side, higher frequencies make the

attenuation increase (fig. 1c). Another observation that can be deduced from figure 1 is the strong effect of conductivity on both attenuation and phase distortion: increase of  $\sigma$  makes  $ATT$  and  $PH_{err}$  raise, hampering the wave propagation domain. Therefore, we think that a borehole radar system should operate above 100 MHz and that the natural regime for EM propagation would be favorable in reservoirs with  $\sigma < 0.03$  S/m.



**Figure 1:** Attenuation and phase distortion as a function of  $\epsilon$  and  $\sigma$  for frequency of 10 MHz (fig. 1a-1d), 100 MHz (fig. 1b-1e) and 300 MHz (fig. 1c-1f).

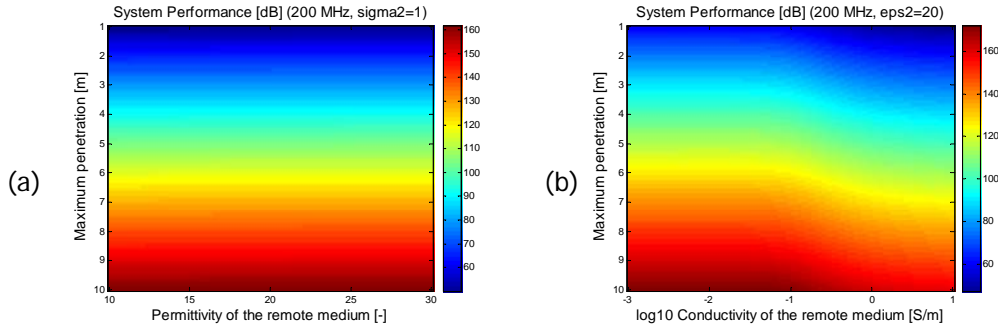
### Feasibility study

The operating performance of a radar tool can be expressed in terms of the Radar Range Equation (RRE). Following the approach for evaluating the penetration depth of a radar system described by Noon et al. (1998), we can derive the RRE for smooth planar interfaces:

$$G_{Tx} G_{Rx} \zeta_{Tx} \zeta_{Rx} SP = \left[ \frac{|\Gamma|^2 e^{(-4\alpha R_{max})} \lambda^2}{64\pi^2 R_{max}^2} \right]^{-1} \quad (3)$$

On the left hand side of equation (3) there are the system dependent parameters which express the minimum detectable signal and can be lumped in a unique value of System Performance (SP); on the right hand side, instead, there are the medium and target dependent parameters: attenuation ( $\alpha$ ), wavelength ( $\lambda$ ), reflectivity ( $\Gamma$ ) and maximum penetration depth ( $R_{max}$ ).

Using equation (3) it is possible to estimate the SP that a radar system would demand to detect interfaces between two medium with diverse EM properties and for different penetration depths. A broad range of EM contrasts that can occurs at oil-water and oil-steam interfaces in oilfield conditions have been considered and the calculated SP values are shown in figure 2. Medium 1 has been modeled with proper  $\epsilon$  and  $\sigma$  of high oil saturation rock, while we have allowed the EM properties of medium 2 to assume a broad range of values characteristic of rock saturated by undesired fluids like water or steam. It seems that permittivity variations of the remote medium do not affect the SP (fig. 2a); instead, conductivity variations of the remote medium affect the SP and a conductivity increase causes a reduction of the SP needed to detect the same interface (fig. 2b). Therefore, in case of favorable EM properties of the first medium, higher investigation depths can be reached if the discontinuity has a strong conductivity contrast. Moreover, it seems that investigation depths in the order of ten meters can be achieved with typical SP of current radar systems being around 160 dB and an operating frequency of 200 MHz.



**Figure 2:** System performance of a borehole radar tool operating at 200 MHz. EM properties of medium 1 are fixed ( $\sigma = 0.01$  S/m and  $\varepsilon = 10$ ); medium 2, instead, has fixed conductivity  $\sigma = 1$  S/m and variable  $\varepsilon$  in fig. 2a and fixed  $\varepsilon = 20$  and variable  $\sigma$  in fig. 2b.

### Modeling results

In order to evaluate the most determinant parameters for the feasibility of a borehole radar tool, we have modeled the electric field reflected by transitions between oil rich zones to water/steam rich zones. We have followed the reflection operator approach given in Nguyen et al. (1998). This technique requires a layered configuration; every layer has relative permittivity  $\varepsilon_{ri}$ , conductivity  $\sigma_i$ , relative magnetic permeability  $\mu_{ri} = 1$  and propagation constant  $\gamma_i = (i\omega/c)\sqrt{\varepsilon_{ri} - (i\sigma/\varepsilon_0\omega)}$  with  $i = 1, \dots, N$ . Based on the wave equation and the boundary conditions at each of the N layers, the reflection generator can be expressed by the following recursion formula:

$$\hat{R} = \frac{r_n + R_{n+1} \exp(-2\gamma_{n+1}h_{n+1})}{1 + r_n R_{n+1} \exp(-2\gamma_{n+1}h_{n+1})} \quad n = 0, \dots, N \quad (4)$$

where  $h_{n+1} = z_{n+1} - z_n$  is the thickness of each layer and  $r_n = (\gamma_n - \gamma_{n+1})/(\gamma_n + \gamma_{n+1})$  is the local reflection coefficient. Once the reflector operator is known, it is possible to calculate the electric field for every layer.

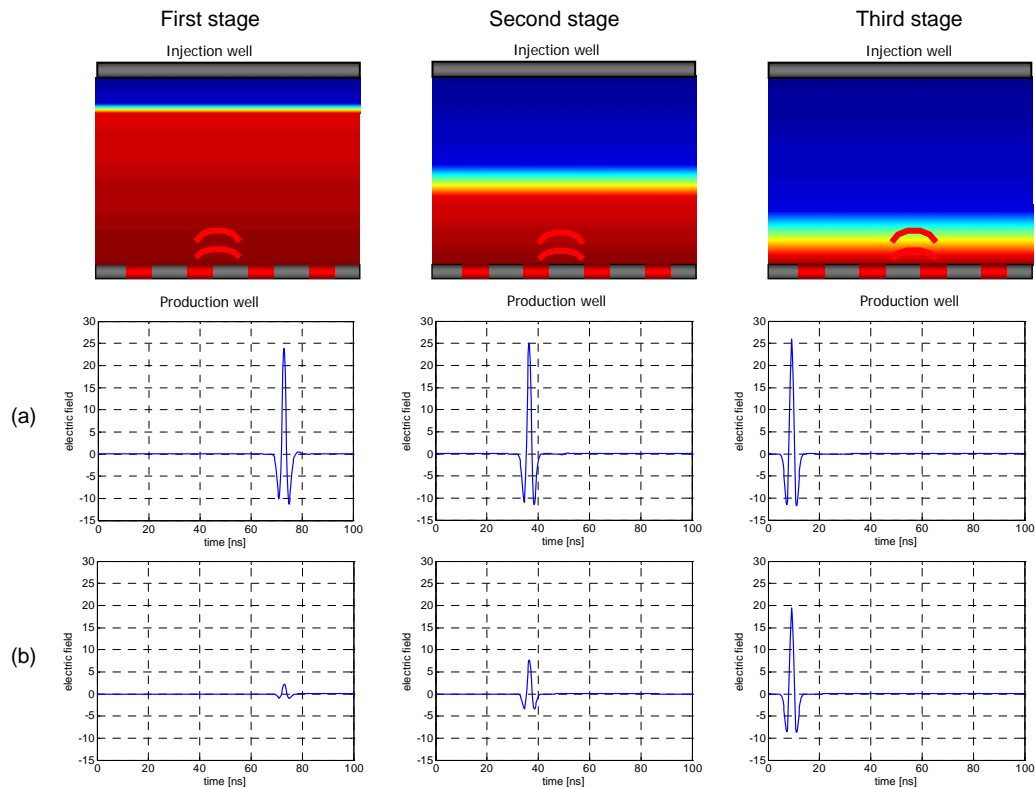
To adapt this numerical procedure to a SAGD process we model the portion of reservoir embedded between the production and the injection wells as a layered system. Using CRIM law for permittivity and Archie's law for conductivity we have defined the EM properties for an oil rich zone, adjacent to the production well, and for a steam rich zone, surrounding the injection well. Both these zones are modeled as two single layers; the transition zone, however, is modeled as a multi-layer system where the EM properties of the layers gradually change from oil rich zone to steam rich zone.

As it can be seen in figure 3, the residual water conductivity in the oil rich zone affects the reflected electric field. High conductivity causes a reduction of the reflected amplitude because the attenuation increases. Therefore the detection of a steam front will strongly depend on its position (fig. 3b). When conductivity is lower, the reflection is almost constant for all the considered stages of the SAGD process (fig. 3a).

### Conclusions

This study has suggested that a borehole radar system could be used as an imaging tool in the order of several meters in the near well region. This makes it especially suitable for application in thin oil rims or SAGD processes. Reflections generated by water/steam fronts are strong enough to be detected. The main constraint so far seems to be the conductivity of the formation: if at the location of the radar system the conductivity is too high, the reflection from oil/water or oil/steam interface could not be detected. Furthermore an operating

frequency higher than 100 MHz has been recommended to work in the natural regime of radar measurements.



**Figure 3:** Modeled reflected electric field as a function of time for three sequent positions of a steam front in a SAGD process. Two different conductivity of formation water are considered: 0.01 S/m (a) and 1 S/m (b).

### Acknowledgements

This research was carried out within the context of the ISAPP Knowledge Centre. ISAPP – Integrated System Approach Petroleum Production – is a co-operation project of Shell International Exploration and Production BV, TU Delft, and Netherlands Organization for Applied Research TNO.

### References

- Addiego-Guevara, E. A., and M. D. Jackson, 2008. Insurance value of intelligent well technology against reservoir uncertainty, SPE, 1-16.
- Chen, Y. H., and M. L. Oristaglio, 2002. A modeling study of borehole radar for oil-field applications, *Geophysics* 67, 1486-1494.
- Nguyen, B. L., J. Bruining, and E. C. Slob, 1998. Delineation of air/water capillary transition zone from GPR data, *SPE Reservoir Evaluation & Engineering*, 319-327.
- Noon, D. A., G. F. Stickley, and D. Longstaff, 1998. A frequency-independent characterization of GPR penetration and resolution performance, *Journal of Applied Geophysics* 40, 127-137.
- Seleznev, N. V., A. Body, T. Habashy, and S. Luthi, 2004. Dielectric mixing laws for partially saturated carbonate rocks, 45<sup>th</sup> Annual Logging SPWLA Symposium.