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A Study of Land CSEM Reservoir Monitoring in a Complex 3D Model

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SUMMARY

We studied the effect on land CSEM measurements of resistivity changes after oil production by running numerical simulations for several configurations in a complex 3D model. We include estimates of noise levels that can be expected in a field experiment, for instance, magneto-telluric signals, repeatability errors, and the near-surface resistivity change caused by seasonal temperature variations. Borehole EM measurements are less sensitive to such influences. We conclude that land CSEM monitoring should be feasible for the example considered here, a thick reservoir at about a depth of one kilometer, although it will not be easy.

Introduction

During the last decade, several marine controlled-source electromagnetic (CSEM) surveys for hydrocarbon exploration have been conducted throughout the world. In some cases, CSEM was the only exploration tool, whereas in others, it complemented seismic surveys by providing an indication of the resistivity of targets identified by seismic imaging. This information can improve the probability of success in hydrocarbon exploration (Eidesmo *et al.* , 2002).

A potential application of controlled-source EM is monitoring a hydrocarbon reservoir during a recovery process. For instance, oil production with water flooding or steam injection creates resistivity changes in the subsurface, which occur primarily in the reservoir. Smaller effects may also be caused by geomechanical settling of the overburden. A central question in EM monitoring is whether or not resistivity changes in the reservoir are detectable. Orange *et al.* (2007) tried to assess the feasibility of this approach by studying a marine example using very simple models. Here, we do the same for a complex geological model and land measurements.

We present a modelling exercise to investigate the potential use of land electromagnetic measurements for reservoir monitoring. We selected a reasonably complex geological model and conducted numerical experiments to study the sensitivity of EM data to the changes in an oil-bearing reservoir due to water injection. We included noise and repeatability errors to asses the feasibility of land CSEM reservoir monitoring. Near surface effects due to seasonal and diurnal changes, or weather conditions such as rainfall and frost, are investigated as well.

Method

Maxwell's equation and Ohm's law describe the diffusion of electromagnetic wave into the earth. They were discretized and solved with a multigrid method (Mulder, 2006). We applied a primary-secondary formulation to slightly improve the numerical accuracy. The primary solution is the one for a half-space with the resistivity of the complex model at the source position.

We modified the SEG/EAGE Overthrust model (Aminzadeh *et al.* , 1997) to obtain a realistic and complex subsurface resistivity, replacing velocities by resistivities according to $\rho = (v/1700)^{3.88}$ (Meju *et al.* , 2003). Here, v is the velocity in m/s and ρ the resistivity in Ohm·m. The model has a size of 20 km by 20 km by 4.7 km. In the 3D model, we selected one part as an artificial reservoir sand that contains oil and water. We then defined two different states, the initial condition of the reservoir and a later state where part of the oil has been replaced by water. Figure 1 shows a vertical slice through the model at $y = 11375$ m for two different states, the initial condition of the reservoir and a later state where the oil-water contact has risen 100 m after water injection. The resistivity in the water-saturated part of the reservoir was 2 Ohm·m and in the oil-bearing part 100 Ohm·m.

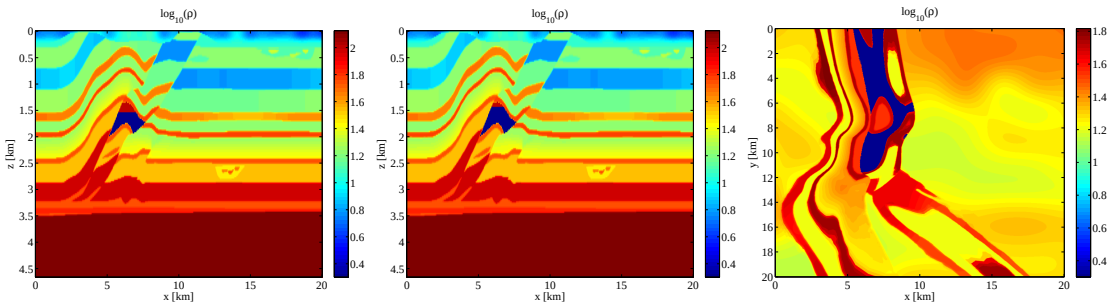

Figure 1: Resistivity based on the SEG/EAGE Overthrust model. The reservoir formation lies around $x = 6$ km and between 1.4 and 2.0 km depth. The dark blue part shows the injected water, the dark red above it is the oil-bearing sand. In the central panel, the oil-water contact has moved up 100 m relative to left panel. The right panel shows a horizontal cross-section of the central panel at 1450 m depth.

Water drive

In the first experiment, we consider oil production due to a water drive and assume that the oil-water contact has moved up 100 m as would happen as a result of water injection in the deeper parts of the reservoir sand. We start with the over-optimistic assumption of 100% sweep efficiency. A unit dipole source in the x-direction is positioned at (2000, 11375, 0) m. To find the frequency that is most sensitive to the change in the reservoir, we placed a receiver at (7000,

11375, 0) m and computed the in-line component of the electric field. Figure 2 shows the in-line electric field components as a function of frequency. We observe the largest relative difference in between 1 and 2 Hz, whereas the difference rapidly drops above 2 Hz.

Figure 3 displays the amplitude behaviour of time-lapse difference for the in-line electric field measured on the surface. We assume idealized conditions so that the difference is entirely due the resistivity change in the reservoir. The results in top panels of Fig. 3 show the effect of frequency on the absolute amplitude of the difference. The high frequency on the left provides a far better resolution than the lower frequencies to the right. The plots in bottom panels of Fig. 3 display the relative change $|\Delta E_1|/\sqrt{|E_1|^2+|E_2|^2}$ on a logarithmic scale. We have removed values below 1%, because we assume that the repeatability only allows for reliably measurements of relative differences above 1%. We observe that the resistivity change at 10 Hz can hardly be detected, but that we have a clear effect above the reservoir at 1 and 0.1 Hz. Figure 3 shows that at 10 Hz, a relatively high resolution is obtained by the changes of the recorded fields but that their amplitude is too small to be detectable because the attenuation is too strong at this high frequency.

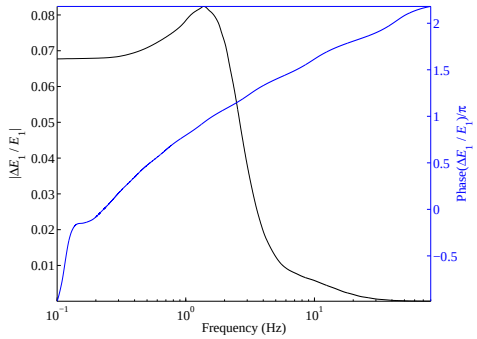

Figure 2: Relative difference of the in-line electric field components for a receiver at (7000, 11375, 0) m or 5 km distance from the source. Both the amplitude and the normalized unwrapped phase angle (the unit is π or 180°) are shown.

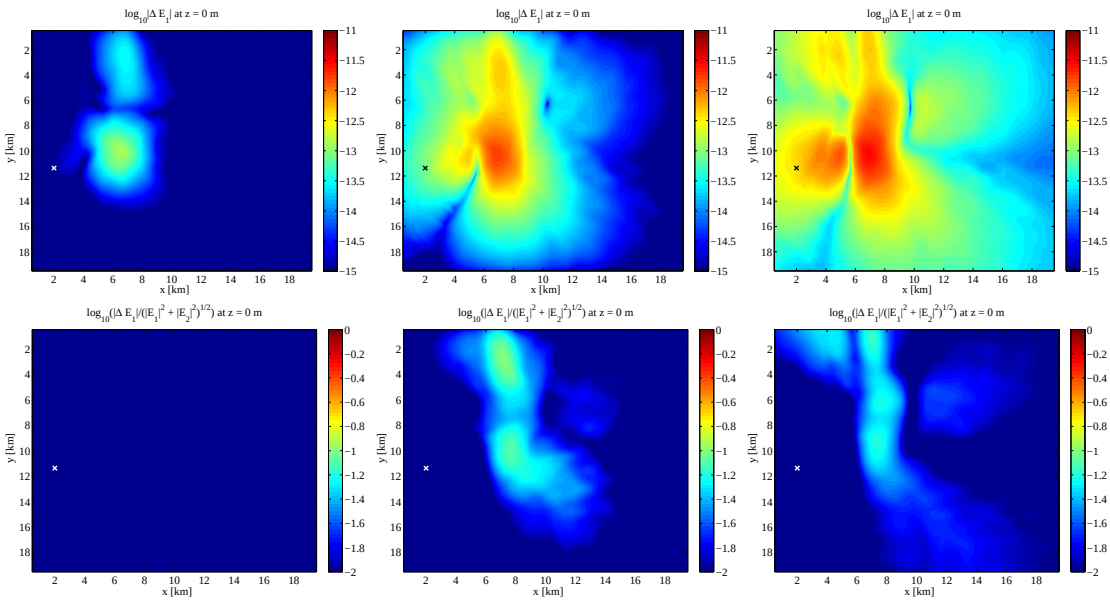

Figure 3: The top panels display the time-lapse differences of the in-line electric field observed on the surface (top view) at frequencies of 10, 1, and 0.1 Hz, from left to right. The bottom panels display the normalized fields with amplitudes below 1% suppressed.

Errors in CSEM data

So far, we have assumed that the time-lapse difference of the in-line electric field is only due to oil being displaced by water. Errors, caused by the equipment, by resistivity changes in the near-surface, or by external EM sources, should also be taken into account. In this section, we describe how various types of "noise" can be incorporated in the numerical experiments. The numerical computations will not be free of errors either.

CSEM measurements will be affected by several noise sources. For example, a recording instrument has a certain noise floor and a limited dynamic range. The magneto-telluric (MT) background comprises EM signals caused by natural sources as thunderstorms and interactions of the solar wind with the ionosphere and magnetosphere. Man-made EM sources, such as power lines and communication signals, are a third source of noise.

In practice, the noise is reduced by performing measurements over many cycles and conducting pre-processing of the data, possibly including reference measurements of the MT background at some distance from the reservoir area.

Repeating measurements even after a short period may alter the EM response of the area, due to variations in instrument properties, positioning differences, temperature changes, rainfall, and so on. We refer to these differences as repeatability errors. With careful and extensive pre-processing, these errors can be reduced to the order of a percent. In the numerical experiments, we mimicked the repeatability errors by adding random numbers to the measured electric fields with a maximum amplitude of 1% relative to the signal strength at each receiver.

We added the effect of various sources of noise to the numerical modelling results in the following way. First, we calculated the electric field for the configuration that represents the resistivity model before production. We used a 20 A current source, typical for land EM experiments. Secondly, we generated random numbers with a maximum amplitude of 10^{-11} V/m and added these to the recorded field. We included repeatability errors by adding a random number with a maximum amplitude of 1% relative to the signal strength at each receiver. We repeated the above steps for the configuration that represents the resistivity model after production. Finally, we included a 6-decade dynamic range of the recording by suppressing data outside the range of 10^{-13} V/m to 10^{-7} V/m. Figure 4 displays the difference in absolute amplitudes of the electric field component E_1 for various source positions.

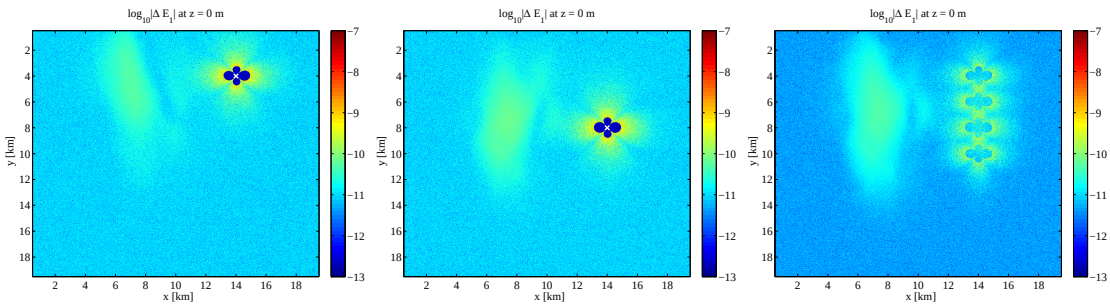

Figure 4: The time-lapse difference of the electric-field component E_1 with added noise at 1 Hz, recorded on the surface for a surface source with an x-position of 14 km and with $y = 4$, or 8 km, from left to center panel. The right panel displays the average after stacking data for four different surface sources with an x-position of 14 km and with $y = 4$, 6, 8, and 10 km.

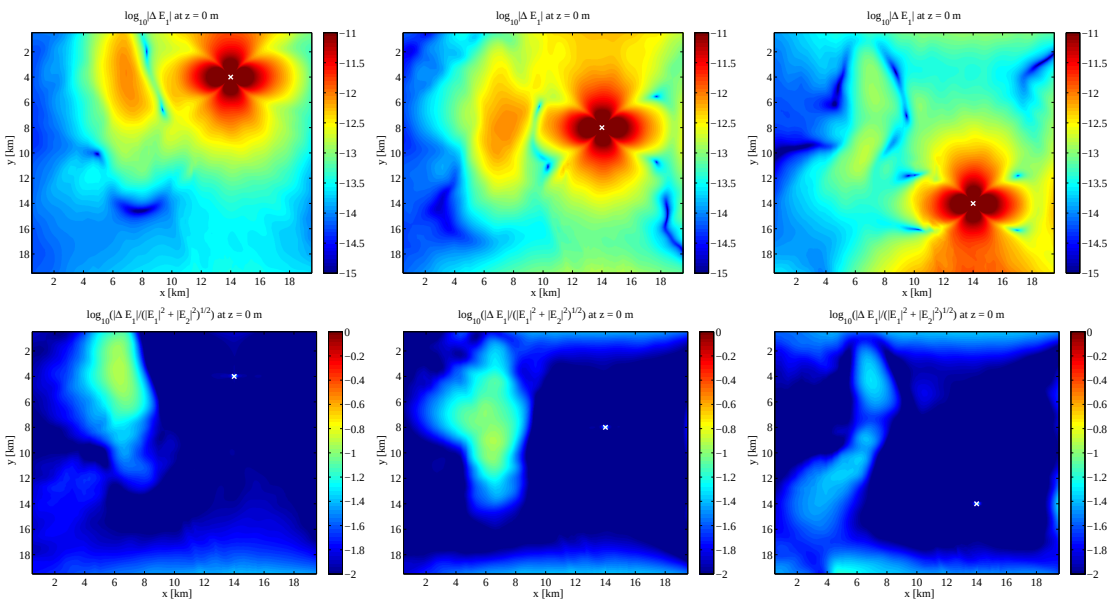

Figure 5: The top panels show the time-lapse differences of the in-line electric field observed on the surface (top view) with surface source positions at x =14 km and y = 4, 8, and 14 km, from left to right. The bottom panels display the normalized fields with amplitudes below 1% suppressed. Here, we applied a 5% near-surface resistivity increase.

Near-surface effects, caused by seasonal and diurnal changes, may also play a role. Frost, for instance, will increase the resistivity of the top soil and affect the time-lapse EM measurements. In the context of agriculture and flood forecasting, the soil penetration of frost has been extensively studied and typically reaches a depth of the order of a meter. In dry areas, precipitation may have a strong effect.

Without being specific about the cause, we increased the resistivity by 5% in the grid cells just below and adjacent to the surface. These cells had a cell height of 25 m. Figure 5 displays the amplitude behaviour in the horizontal electric field components at 1 Hz for the same case as in Fig. 3 but with the near-surface resistivity increase included. The top panels of Fig. 5 show the effect of near-surface on the absolute amplitude change, whereas the bottom panels display the relative change. Although the presence of the near-surface effect produces a strong source imprint in the plots of the absolute difference, the relative changes does not change too much compared to the case where the near-surface effect was absent.

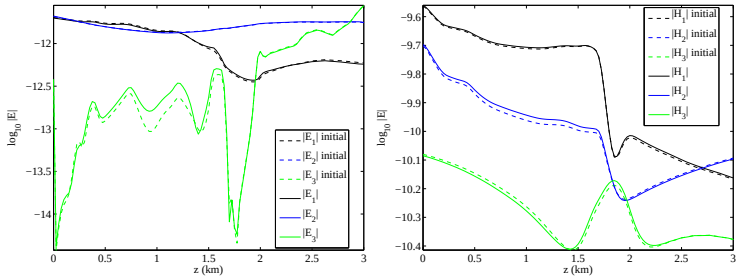

Figure 6: The panel shows the electric (left) and the magnetic (right) field components in an observation well for a dipole source in the x-direction at a frequency of 1 Hz. The dashed lines represent the initial fields, the drawn lines after production.

Vertical monitoring well

Measurements in a well should be less sensitive to near-surface resistivity variations. Figure 6 displays field components measured in a vertical well positioned at $x = 8$ km and $y = 3$ km. The dashed lines represent the initial fields, the drawn lines the fields after production, using the same parameters as in Fig. 3. The effect of oil displacement is captured best by E_3, the vertical electric field component, which is relatively easily measured in a vertical well.

Conclusion

We have studied the effect of resistivity changes due to oil production on land CSEM measurements for a complex geological model. The results show that the change should be detectable if interfering coherent signals can be removed by distant reference measurements and preprocessing of the recorded data, if the random background and instrument noise level can be controlled by stacking over a sufficiently long time, and if the repeatability is of the order of a percent.

If time-lapse differences are measured in a vertical monitoring well, the vertical electric component appears to be the most sensitive to resistivity changes.

Acknowledgment

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