Sensitivity of the near-surface vertical electric field in land Controlled-Source Electromagnetic monitoring

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Summary

We investigate potential benefits of measuring the vertical electric field component in addition to the routinely measured horizontal electric field components in onshore time-lapse controlled-source electromagnetics. Synthetic electromagnetic data based on a model of the Schoonebeek onshore oil field are used. We confirm that the vertical electric field component is more sensitive to small changes in the reservoir than the horizontal components, yet its amplitudes are small. Accordingly, optimal source-receiver geometry and precise knowledge of the verticality of the receiver dipole will be required for successful utilization of the vertical electric field.

Introduction

Marine controlled-source electromagnetic (CSEM) surveys are widely used as a tool for detecting and evaluating hydrocarbon reservoirs and as such are accepted by the industry (Constable, 2010). However, similar surveys on land are presently not routinely applied. There have been academic land CSEM surveys (Grayver *et al.*, 2014), and a small number of industry trials. One potential application of CSEM that has recently gained interest is measuring in time-lapse or continuous mode, e.g., reservoir monitoring during steam-assisted gravity drainage or during CO_2 injection. Steam injection for oil production creates resistivity changes that may be detectable by time-lapse EM measurements (Mansure *et al.*, 1993).

The seismic technique for time-lapse measurements has been developed significantly over the last decade. This method has recently been successfully applied for steam injection monitoring (Michou *et al.*, 2013). However, this requires substantial experimental effort; developing less expensive monitoring techniques is thus desirable. The resistivity difference between hydrocarbon-bearing and steam-saturated rocks can be significant, making the CSEM method potentially suitable for reservoir monitoring (Wright *et al.*, 2002), provided that the resistivity change can be detected in the presence of repeatability errors and noise (Wirianto *et al.*, 2010).

Synthetic feasibility studies suggest that CSEM monitoring should be feasible in marine environments using present-day standard survey configurations (Orange *et al.*, 2009; Constable and Weiss, 2006). On land, though, reservoir volumes affected by resistivity change need to be large before they become detectable using standard surface-based horizontal dipole-dipole configurations (Wirianto *et al.*, 2010). Therefore, we investigate the suitability of the vertical electric field for detecting resistivity changes related to steam injection in an onshore setting. We further aim to assess if combining time-lapse measurements of the vertical electric field with seismic exploration data may potentially be an economically viable alternative to high-resolution 4D seismic.

Measurement of E_z on land

In standard land CSEM surveys, five components of the electromagnetic field are routinely measured, namely, the two horizontal electric-field and three magnetic-field components (e.g., Streich *et al.*, 2013). These components can easily be measured by installing receivers at the Earth's surface. The vertical electric field E_z is very small at the air-ground interface, yet E_z amplitudes increase rapidly with depth. Consequently, E_z should be measurable by deploying vertical electrode dipoles in shallow boreholes. Previous feasibility studies on land CSEM monitoring clearly indicate that E_z should be the field component most sensitive to resistivity changes at depth. E_z measurements in a well at some distance from the reservoir should provide highest sensitivity to relatively small resistive reservoirs (Streich *et al.*, 2010; Wirianto *et al.*, 2010).

The drawback of lower amplitudes of E_z should be compensated by the fact that the 'air-wave', which masks much of the subsurface response, is polarized horizontally and thus has no strength in the vertical electric field (Hunziker *et al.*, 2011; Singer and Atramonova, 2013). Furthermore, noise levels should be lower in E_z than in the horizontal field components, because the receivers are planted in boreholes, slightly further from most electric infrastructure than horizontal dipole receivers. Moreover, major sources of cultural noise (e.g., power lines, pipelines) are oriented horizontally and therefore generate predominantly horizontal electric fields. Measuring E_z may thus be advantageous for noisy areas such as the production site in Schoonebeek.

For CSEM sources, similar considerations apply, as a consequence of source-receiver reciprocity. In both land and marine CSEM surveys, horizontal electric dipole sources are commonly being used, as these are best suited for imaging resistive reservoirs (Constable, 2010). Vertical electric sources would provide higher sensitivity to

DOI http://dx.doi.org/10.1190/segam2014-1460.1

resistive reservoirs than horizontal ones (Holten *et al.*, 2009), but again require boreholes, which makes them expensive and less accessible.

Borehole measurements of E_z are likely too expensive and thus impractical for most exploration surveys. However, for monitoring purposes a more permanent setup is often desired to facilitate repeat measurements over time. Also, in monitoring applications, the changes in the subsurface that need to be detected are commonly subtler than the accuracy needed in an exploration survey. In many cases, the target region is reasonably well known, such that survey geometries can be optimized for resolving the target without using redundant instruments.

In this contribution, we attempt to evaluate the sensitivity of the vertical electric field to resistivity changes and compare it to horizontal electric field sensitivities. Furthermore, we study the influence of not precisely vertical sensor installation on the measured responses.

Modeling

We attempt to assess EM monitoring feasibility for the Schoonebeek heavy oil field in the Northern Netherlands. This field is currently being redeveloped by injecting low-pressure steam into horizontal wells for enhanced oil recovery. The reservoir is fairly resistive, such that the injected steam, despite originating from purified water, is expected to reduce the resistivity in the reservoir. Reservoir resistivity after steam injection is still expected to be elevated compared to the surrounding rocks.

Figure 1 shows a simplified 1D model of the Schoonebeek region derived from averaging regional logging data (TNO, 2014). The model consists of multiple layers with different conductivity, and a reservoir at a depth of 685 – 700 m. We simulate an x-directed horizontal electric dipole (HED) source. E_z receivers are modeled as vertical electric dipoles located 100 m below the surface. Synthetic data are calculated using a reflectivity code (Hunziker *et al.*, 2014).

Results

The electric field amplitudes for the model defined in Figure 1, an HED point source and a 20 x 20-km grid of receivers oriented in the *x, y* and *z* directions are shown in Figure 2. A frequency of 0.5 Hz is used, and the source current is 1 A.

Figure 2a, d and g show the electric field amplitudes for a model into which a steam layer has been included at depth 685 – 690 m. For the steam a conductivity value of 0.05 S/m is assumed. Electric field amplitudes for the background model without any injected steam are displayed in Figure 2b, e and h. Field ratios between pre- and post-injection data are plotted in Figure 2c, f and i. The white area at large source-receiver offsets represents regions in which field amplitudes are smaller than 10^{-14} V/m and thus not expected to be measurable. Our noise floor assumption is more conservative than commonly used for marine surveys, because we expect higher levels of cultural noise (Streich *et al*., 2013).

As expected, the field amplitudes for vertical receivers are much smaller than for horizontal receivers and decay more rapidly with distance from the source (Figure 2g, h). The amplitudes for the horizontal field components due to horizontal sources are above the assumed noise floor for offsets exceeding 10 km (Figure 2a, b, d, e). However, the vertical component is much more sensitive to changes in the reservoir. Figure 2i shows that the amplitude response of the model including a steam layer differs from the background model response by up to 25 % (obviously, changes due to a laterally limited steam volume would be significantly smaller). For the horizontal components the changes due to steam injection are minor, except for small areas near the local minima of E_x (Fig. 2c), in which reliable measurements would not be possible.

Because of the low amplitudes of E_z and the subtle changes expected, optimizing the source-receiver layout is of vital importance for monitoring applications. Receivers placed too close to the source are unsuitable for depth imaging, because strong direct fields mask subsurface responses, and because of their high sensitivity to near-surface

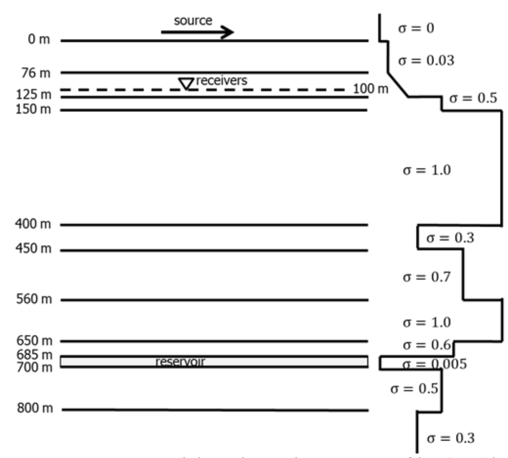

Figure 1*: Layer model and conductivity profile (in S/m) derived from logging data. The source represented by the black arrow is placed at the surface, and receivers are placed at a depth of 100 m.*

DOI http://dx.doi.org/10.1190/segam2014-1460.1

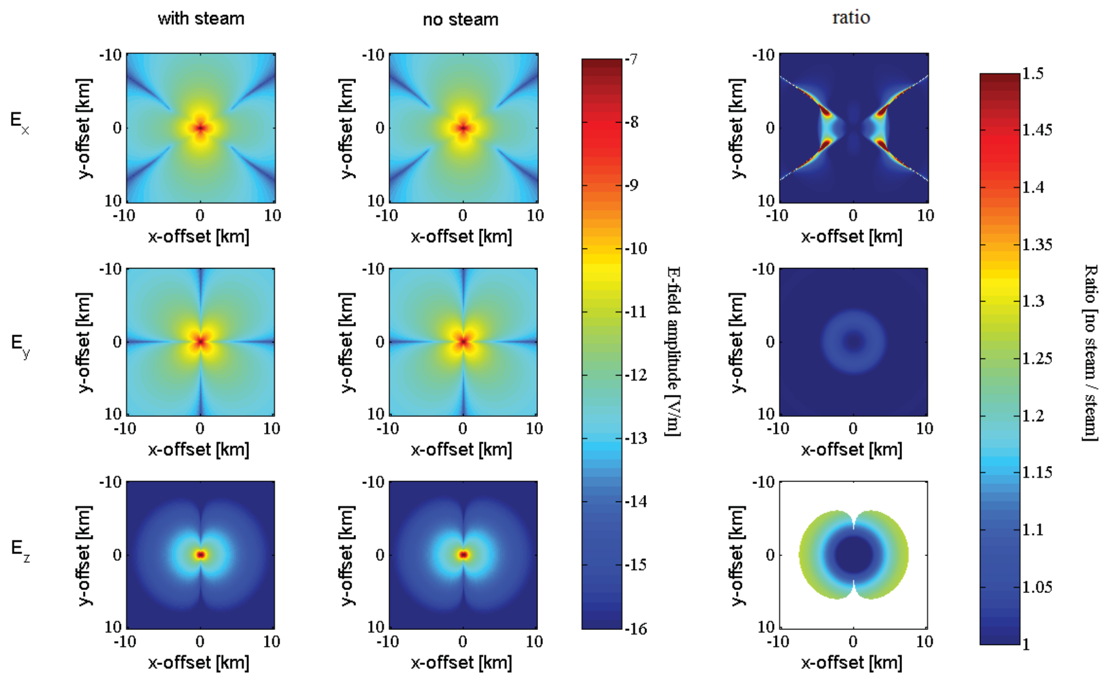

Figure 2: *Electric field amplitudes for the model from Figure 1 with a 5 m thick steam layer inside the reservoir (left column) and without steam layer (central column), and corresponding field ratios (right column), for a frequency of 0.5 Hz. Field ratios are not shown where amplitudes are below 10^{-14} V/m. E_x (a – c), E_y (d – f) and E_z (g – i) receivers are located at a depth of 100 m, and an x-directed point source is assumed.*

heterogeneity (Grayver *et al.*, 2014). Receivers placed too far from the source suffer from low signal-to-noise ratios especially when measuring the vertical electric field component.

While injecting steam, the size of the steam body increases laterally over time. To roughly assess the effect of growing steam volume in 1D, we let the thickness of the steam layer increase from 0 to 15 m from the top of the reservoir, assuming a steam conductivity of 0.05 S/m (Figure 3). Correspondingly, the thickness of the reservoir is reduced from 15 to 0 m. Both, the E_z and E_x amplitudes depend on the thickness of the steam layer. Whereas changes in E_x are minor, changes in E_z are clearly recognizable.

Another crucial aspect is the effect of installing electrode dipoles in slightly tilted boreholes. Hunziker *et al.* (2011) showed for a marine environment that for a slightly dipping vertical source, the air-wave contribution to the full electric field is significant. Because E_z commonly is more than an order of magnitude smaller than the horizontal electric field, not knowing the borehole tilt and thus not accounting for it, would result in wrong interpretation.

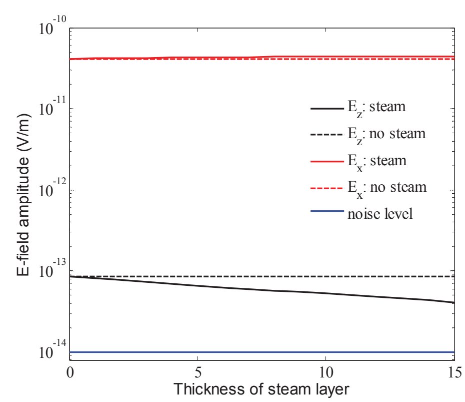

Figure 3*: Thickness of steam layer and the corresponding vertical and horizontal electric field amplitudes for the Schoonebeek model with increasing steam thickness at a source-receiver offset of 4 km.*

DOI http://dx.doi.org/10.1190/segam2014-1460.1

Field measurements have shown that shallow boreholes drilled using conventional flushing techniques can deviate from the vertical by more than 3 m at a depth of 100 m. Figure 4 shows, for the example of a 1-km long source and point dipole receivers, that this tilt strongly influences the data. The top row in Figure 4 shows vertical electric field amplitudes for a model with and without steam and their relative difference for a perfectly vertical borehole. Figure 4 d, e and f show data for a borehole tilted by 3 m per 100 m depth. The shape of the electric field has completely changed and looks much more similar to the E_x component rather than the E_z component. Further, the electric field loses its symmetric shape. Nevertheless, relative differences between pre- and post-injection responses should remain recognizable within an area laterally offset by ~3 – 5 km from the source. This shows that even a relatively small deviation influences the reservoir response significantly.

Conclusions

We have demonstrated that the vertical component of the electric field is significantly more sensitive to changes of reservoir resistivity than the horizontal electric field components. For monitoring purposes, measurements of E_z in shallow boreholes can be used for detecting changes in the vertical electric field. Tilt of the receiver borehole will strongly influence the measurements, whereas some sensitivity to the reservoir is maintained. Thus, borehole deviation has to be measured precisely and included in modeling and interpretation.

Acknowledgments

We thank Joeri Brackenhoff for his contribution to this work.

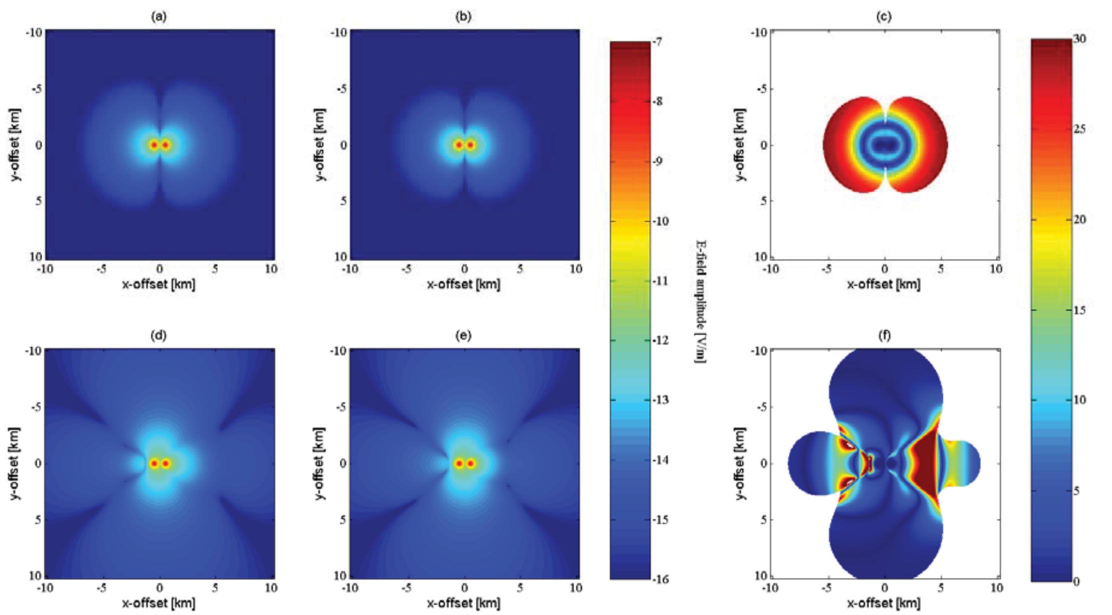

Figure 4: *Comparison of electric fields that would be measured in a perfectly vertical borehole (a -- c) and a borehole tilted by 3 m at a depth of 100 m (d – f), for a frequency of 0.5 Hz and a 1-km long source. Amplitudes normalized by source length are shown for a model with (a and d) and without steam (b and e). Relative differences of responses with and without steam are shown in (c) and (f). where white areas mask regions in which amplitudes are below noise floor 10^{-14} V/m. Note that the amplitudes in (c) and (f) are clipped at 4%.*

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