Decomposition of Marine Electromagnetic Fields Into TE and TM Modes for Enhanced Interpretation

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Summary

In marine electromagnetic (EM) surveying for hydrocarbon detection, the field's transverse magnetic (TM) mode is sensitive to hydrocarbon saturated reservoirs but also to geological features relating to local larger-scale resistive structures. The field's transverse electric (TE) mode is not sensitive to the hydrocarbon saturated reservoirs but sensitive to any local larger-scale resistive structures. Furthermore, the airwave predominantly is a TE mode. Therefore, decomposition of the marine EM field into TE and TM modes is of importance for reliable interpretation.

Introduction

It has long been known that the marine controlled source electromagnetic (mCSEM) method is preferentially sensitive to thin resistive layers (Constable et al. 1986 and Cheesman et al. 1987). Novel use of mCSEM, also called sea bed logging (SBL), for mapping hydrocarbons over shallow prospects in deep water was first described by Ellingsrud et al. (2002) and Eidesmo et al. (2002).

The electromagnetic (EM) field radiated by an electric or magnetic source can be considered to consist of two different modes: a TM mode component and a TE mode component. The relative contribution of each mode component depends on the type of source and its orientation. The subsurface response to the source signal is generally different for the TE and TM modes.

The TE mode is known to inductively couple well across the sea water/air interface and is therefore the dominating mode of the airwave component. The airwave propagates along the air and diffuses down to the receivers at the seafloor, thus disturbing the signal from the subsurface. The TM mode does not couple well at the interface sea water/air and has little contribution to the airwave component.

In contrast, the TM mode (which is dominated by vertical current flows) has a strong interaction with high resistive layers in the subsurface, in particular hydrocarbon saturated reservoirs. The TE mode (which is dominated by horizontal current flows) is very little affected by any hydrocarbons but on the other side sensitive to large-scale resistive bodies because of longer skin depths with increasing resistivity.

An analysis of both the TE and TM mode components thus holds the potential to determine if the increase in the measured EM field is caused by the presence of a hydrocarbon saturated reservoir or other resistive bodies in the subsurface. If there is an increase in a measured TM amplitude response and an unchanged, small TE amplitude response, it is probably caused by the presence of a resistive, hydrocarbon saturated reservoir. Variations in the amplitude enhancement as a function of offset provides information about the depth and extend of the hydrocarbon saturated reservoir. A measured increase in both the TE and TM amplitude response indicates a large-scale resistive body not necessarily saturated with hydrocarbons.

In addition, it is important to observe that the TM mode is not much influenced by the airwave. Therefore, in shallow water EM interpretation the TM mode is the preferred electromagnetic component for analysis with respect to sensitivity to the presence of subsurface hydrocarbon bodies.

Methodology

In the case that the EM field with any given polarization is described with respect to a plane of measurement, the field may be described as the superposition of two orthogonally polarized waves, one with its electric field parallel to the plane of measurement and another with its electric field perpendicular to the plane of measurement. Polarization with **E** parallel to the plane of measurement is called parallel polarization but also transverse magnetic (TM) polarization because the magnetic field is perpendicular to the plane of incidence (Born and Wolf, 2001). Polarization with **E** perpendicular to the plane of measurement is called perpendicular polarization but also transverse electric (TE) polarization because the electric field is perpendicular to the plane of measurement. Hence, with chosen coordinate direction $\mathbf{e}_3$, the transverse components of the marine electromagnetic field can be regarded as a superposition of two independent waves, one corresponding to $E_3 = 0$, $H_3 \neq 0$ (TE polarization), and the other to $E_3 \neq 0$, $H_3 = 0$ (TM polarization).

In some textbooks, on the other hand, TE polarization is called horizontal polarization or E polarization because the electric field is parallel to the horizontal (x_1, x_2)-plane, which can be a plane interface separating two homogeneous media or a plane of measurement. Likewise, TM polarization is called vertical or H polarization since a component of the electric field is perpendicular to the (x_1, x_2)-plane when the magnetic field is parallel to the same plane. This nomenclature is in agreement with that adopted in elastic shear wave geo-studies, where one often decomposes the shear wave into two waves: one with horizontal polarization (SH) and one with vertical polarization (SV). The electromagnetic TE mode corresponds to the elastic SH mode, and the electromagnetic TM mode corresponds to the elastic SV mode.

Several techniques have been proposed in papers and patent applications to decompose the spectrum of plane wave electric and magnetic fields into their respective TE and TM plane wave components (see e.g. MacGregor et al., 2005 and Nordskag et al., 2006). For this presentation, we compute the TM modes in the space domain by numerical differentiation of data recordings.

In a mCSEM/SBL survey in shallow waters the airwave dominates the measured EM field (cfr. Amundsen et al., 2006). As mentioned above the airwave is predominantly a TE mode and the TE response is insensitive to thin resistive structures. Therefore the TM response is the preferred EM component for analysis of hydrocarbons in the subsurface. As an example, we present numerical calculations of two models. The source chosen is unit horizontal electric dipole (HED) in the radial direction generating a 1 Hz signal and the receivers are situated on the seabed 100 m apart. The first model consists of an air halfspace, a water layer 100 m in depth with conductivity 3.33 S/m and a sediment halfspace with conductivity 1 S/m. Model two consists of an air halfspace, a water layer 100 m in depth with conductivity 3.33 S/m, a sediment layer 1500 m thick with conductivity 1 S/m, a hydrocarbon saturated reservoir 100 m thick with conductivity 0.02 S/m and a sediment halfspace with conductivity 1 S/m.

Displayed in Figure 1 are the amplitude and phase spectra versus offset in the radial direction for the electric field response of model one (blue curve) and model two (red curve). The blue curve is hidden behind the red curve. Since both models consist of shallow water layer the airwave dominates the received signal and the two models are hardly distinguishable for all offsets. At offsets larger than 3 km the phase is constant, which is a clear indication of the airwave dominating the measured field. The normalized electric amplitude is displayed in Figure 2 and is close to unity for all offsets. An interpreter will thus have difficulties determining if there exist a hydrocarbon saturated reservoir or not in the subsurface.

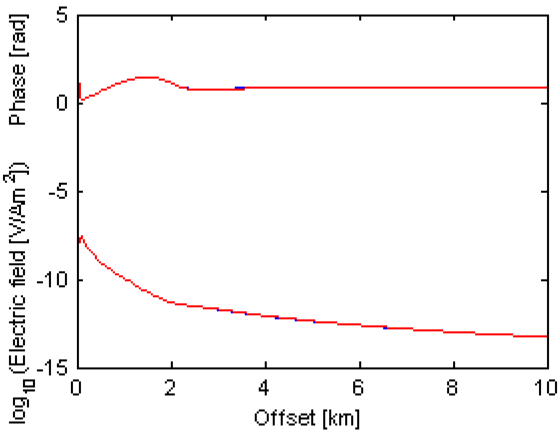

Figure 1. The radial EM response of model one (blue curve) and model two (red curve).

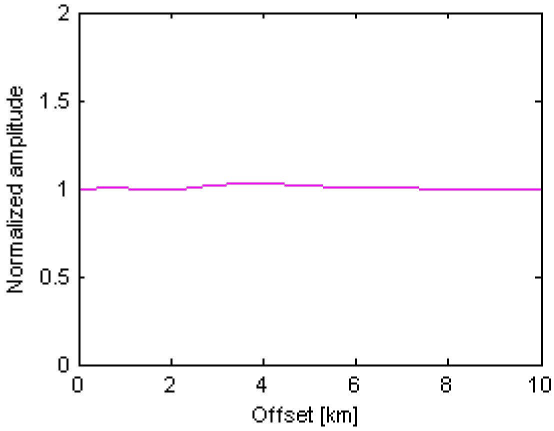

Figure 2. The normalized EM response of the two models.

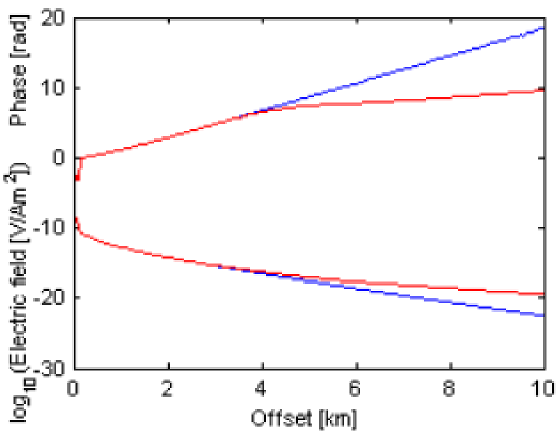

Figure 3. The TM response of model one (blue curve) and model two (red curve).

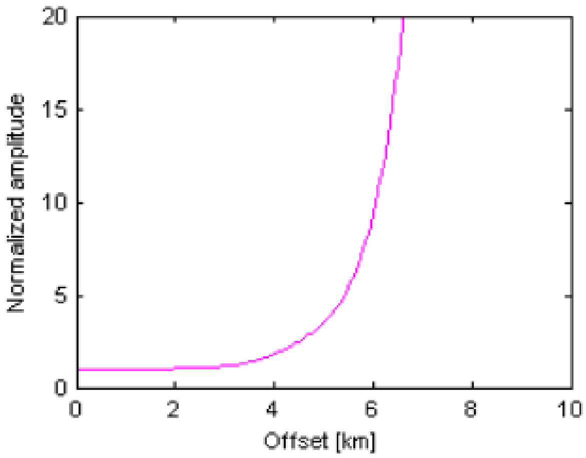

Figure 4. The normalized TM response of the two models.

The TM amplitude and phase responses of model one (blue curve) and model two (red curve) are displayed in Figure 3. Since the TM mode is sensitive to changes in resistivity and not to the airwave we get a separation of the two curves at offsets greater than 3 km. At smaller offsets the direct field from the source and the lateral wave along the seabed will dominate the measured field. To better see the difference in the TM response between the two models we display the normalized TM response in Figure 4. As illustrated in Figure 4, the TM response in amplitude of the model with a hydrocarbon saturated reservoir is dramatically stronger than the TM response in amplitude without a hydrocarbon saturated reservoir.

Conclusions

We have presented and tested a method for the TM and TE decomposition of the mCSEM fields. The mode decomposition may in the future impact both the state-of-the-art acquisition, processing and interpretation strategies for marine controlled source electromagnetic surveying.

Acknowledgement

JIN thanks the Norwegian Research Council, Norsk Hydro, Statoil ASA, and ElectroMagnetic Geoservices for funding this work.

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