On the Signal Propagation in Marine CSEM

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Summary
In marine CSEM (controlled source electromagnetics) and SBL (SeaBed Logging) one explores the subsurface by emitting low-frequency signals from an electric dipole source close to the seabed. The signals are recorded by receivers usually placed on the seafloor. The main goal is to determine and characterise possible thin resistive layers within the conductive surroundings beneath the seabed (Eidesmo et al., 2002). A typical geological model from an exploration case includes a sea-surface interface, a seabed interface, and a thin resistive layer within the conducting sediments below the seabed. The electromagnetic (EM) response from such a plane layered model can be easily calculated using standard modelling tools. However, to improve our understanding of the physics of marine CSEM, it can be of interest to analyze how the EM signals propagate in a stratified earth model. In order to do so, asymptotic evaluations of the integrals that describe the EM fields in planarly layered media can be performed. In this abstract, closed form space-domain expressions that can be derived from such an analysis of the field integrals are presented. For the model that has been evaluated, i.e. a shallow water case with a hydrocarbon layer in the subsurface, the dominating contributions to the field response are a TM-polarized waveguide response due to the thin resistive layer, and a TE-polarized sea-surface response. These responses account well for the entire field for the most interesting source and receiver offsets in conventional marine CSEM surveying for hydrocarbons.

Introduction
The modelling routines for stratified earth models are normally well suited to predict the full EM response from the subsurface since a layered structure often is a good approximation to geological scenarios in a typical CSEM-setting (Constable and Weiss, 2006). The mathematical formulation of the stratified CSEM problem is well known (e.g. Chave and Cox, 1982; Løseth, 2007). However, even if 1-D modelling predicts the response from any stratified earth model, it might not provide physical insight into how the EM fields have propagated. In many problems in physics, e.g. in wave theory, asymptotic analysis of a problem is performed in addition to numerical modelling in order to gain understanding of the physical problem. Even if the low-frequency marine CSEM problem is well described by a diffusion equation and thus can be interpreted as diffusion, the interpretation of EM field propagation in terms of highly attenuated waves is applicable.

In the asymptotic evaluation of the field integrals for stratified media by the method of steepest descents (cf. Felsen and Marcuvitz, 2003), one considers the integration variable, e.g. the horizontal wavenumber, as complex. By deforming the integration path, the main contribution to the integral can be pinned down to a short segment around the saddle point. The first term of the resulting asymptotic series can be interpreted as the geometrical optics contribution to the wave propagation. During the deformation of the integration path, poles and branch cuts might be encountered. The contribution from a branch point can be interpreted as a lateral wave. The residue contribution that results from encircling a pole in the complex wavenumber-domain can be interpreted as a guided wave-response. For a simple model with a conductive and a nonconductive halfspace, Baños (1966) and Bannister (1984) obtained simple expressions for the lateral wave at the sea-surface. Wait (1966) examined the possibility of a resistive layer in the earth’s crust to support guided waves.
Consider a model as sketched in Figure 1. Assume that a horizontal EM dipole source (HED) emits a signal of \( f = 0.5 \) Hz in seawater with conductivity \( \sigma = 3.2 \) S/m. The source height above the seabed is \( h_s = 30 \) m (depth \( d_s = 70 \) m) and the thickness of the water column is \( d_w = 100 \) m. A set of receivers on the seafloor are positioned in the inline direction of the dipole source. Thus the receiver height is \( h_r = 0 \) m (depth \( d_r = 100 \) m). In Figure 1, one of the receivers is sketched. Below the seabed, the overburden has thickness \( d_1 = 1000 \) m and conductivity \( \sigma_1 = 1 \) S/m. The thin resistive layer has thickness \( d_2 = 50 \) m and conductivity \( \sigma_2 = 0.01 \) S/m. The conductivity of the underburden is the same as in the overburden. The conductivity in air is zero, and the value of the magnetic permeability is taken to be that of free space in all the layers. The inline electric field component can be written as:

\[
E_{\rho} = -\frac{Il_x}{4\pi} (I_{TM} + I_{TE}),
\]  

where \( Il_x \) is the dipole current moment and \( \rho \) is the horizontal radial offset from the source. The integrals \( I_{TE} \) and \( I_{TM} \) that describe respectively horizontally polarized plane wave components (TE) and plane wave constituents with vertical polarization (TM), are evaluated separately. For the model in Figure 1 the field integrals can be approximated by the space-domain expressions (Løseth, 2007):

\[
I_{TE} \approx \frac{2e^{\kappa(d_s + h_s)}}{\sigma \rho^3} \left[ 1 + \epsilon e^{2ib_{dr}} \right] \left[ 1 + \epsilon e^{2ib_{dr}} \right] \left[ 1 + 2\epsilon^2 e^{2ib_{dr}} + 3\epsilon^3 e^{4ib_{dr}} + ... \right],
\]

\[
I_{TM} \approx nI_{TM} \left[ 1 + e^{2ib_{dr}} \right] \left[ 1 + e^{2ib_{dr}} \right] \left[ 1 + 2\epsilon^2 e^{2ib_{dr}} + 3\epsilon^3 e^{4ib_{dr}} + ... \right].
\]

The TE-mode contribution is due to the presence of the sea-surface interface. The term in front of the parenthesis on the right hand side of Equation [2] describes the response in a model with just a seawater and air halfspace (cf. Bannister, 1984). The parameter \( k \) is the wavenumber in seawater. From a branch point analysis of the field integrals, one finds that this is a TE-mode and that the TM-response is negligible in a conductive/nonconductive halfspace-model. In a model with just a thin resistive layer within a conductive background medium, the TE-response is accounted for by the
saddle point contribution. When a seabed is introduced into the thin layer/background-model, the TE-mode only sees the seabed. Thus, in the full model in Figure 1, the sea-surface response is amplified due to the seabed. The amplification as described by the terms in the parenthesis in Equation [2], where the variable \( r_1 \) denotes the seabed reflection coefficient for normal incidence, can be interpreted as amplification of the received signal, larger effective source strength, and generation of reverberations. The TM-mode contribution \( I_{TM} \) in Equation [3] is due to the presence of the thin resistive layer. A model with a thin resistive layer contained within a conductive wholespace, the residue contribution in the complex wavenumber domain, due to the pole in the TM-reflection coefficient, is:

\[
I_{TM}^R \approx \frac{\pi}{2 \sigma_1} \frac{1}{1+n_1^2} \left( k_{p,5} \left( 1-n_1^2 \right) - n_1^2 k_{p,1} \left( 1-n_1^2 \right) \right) d_1 \left[ H_0(k_p \rho) - \frac{1}{k_p \rho} H_1(k_p \rho) \right] e^{i k_{p,2} \rho},
\]

where \( k_p \) is the overburden wavenumber, and \( n_1 = \sqrt{\sigma_2 / \sigma_1} \). The pole is located at:

\[
k_p = k_1 \sin \theta_p^{TM}, \quad \text{with} \quad \cos \theta_p^{TM} = \sqrt{\frac{1-n_1^2}{1+n_1^2}} + \frac{\frac{1}{k_1 d_1}}{1+n_1^2 + \frac{1}{k_1 d_1}},
\]

and \( H_0 \) and \( H_1 \) are the Hankel functions of first kind with order 0 and 1 respectively. The introduction of the seabed interface into the simple thin layer model, introduces the refraction index \( n = k_1 / k \) in Equation [3]. Thus, the thin layer TM-response is slightly more damped due to the transmission through the seabed. A consideration of the multiples in the seawater column introduces the terms in the parenthesis in Equation [3]. Hence, in shallow water, the TM-response from the thin layer increases due to the reverberations in the seawater layer and the amplifications of the signal at the source and receiver.

Accuracy of the Explicit Expressions

We now show that that Equation [1-5] are in excellent agreement with exact numerical results. Figure 2 shows the magnitude and phase response versus source and receiver offset for the TM-polarization component. The red curve represents the simple case of a thin resistive layer in a conductive background medium. The green curve shows the response when a seabed is introduced into this model. The TM-response in the full model (described in Figure 1) is presented by the blue curve. The explicit expressions derived from the asymptotic analysis are plotted as dotted lines with the same colour as the corresponding exact modeling results.

![Figure 2. TM-responses for the inline electric field component.](image-url)
In Figure 3, the total field response is plotted in black. The TE- and TM-components are plotted in magenta and blue respectively. The expressions from Equation [2] and [3] are plotted with dotted lines. At distances less than 3 km, the agreement would improve by adding the saddle point contributions.

Figure 3. Electric field in the inline direction with its TE- and TM-polarization contributions.

Conclusions
We have shown that asymptotic analysis can be applied to the marine CSEM/SBL problem to provide physical insight into how the EM signals propagate. With reference to Figure 1, the dominating contributions are the sea-surface response (I) and the guided response from the thin resistive layer (V). The direct wave in seawater (II), lateral wave along the seabed (III), and geometrical reflection from the thin resistive layer (IV) are negligible contributions. If the thin resistive layer were absent, the dominating contribution for the TM-polarization would be from the lateral wave along the seabed (III). The expressions derived by asymptotic analysis have been verified by exact numerical modeling.

References