CONTROLLED-SOURCE ELECTROMAGNETIC SOUNDING IN SHALLOW WATER: PRINCIPLES AND APPLICATIONS

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ABSTRACT

The marine controlled-source electromagnetic (CSEM) method is being applied to the problem of detecting and characterizing hydrocarbons in a variety of settings. Until recently, its use was confined to deepwater (water depths greater than approximately 300 m) because of the interaction of signals with the atmosphere in shallower water depths. The purpose of this study was to investigate, using a simple 1D analytical analysis, the physics of CSEM in shallow water. This approach demonstrates that it is difficult to simply decouple signals that have interacted with the earth from those that have interacted with the air using either frequency-domain or time-domain methods. Stepping away from wavelike approaches, which if applied without care can be misleading for the diffusive fields of CSEM, we demonstrate an effective way to mitigate the effect of the air in shallow water surveys by decomposing the EM signal into modes and using only the mode least affected by interaction with the atmosphere. Such decomposition is straightforward in a 1D earth, and we demonstrate that the approach remains valid in higher dimensional structures. We also show that the coupling between signals diffusing through the earth and those that have interacted with air can be used to our advantage in the interpretation of marine CSEM data.

INTRODUCTION

The controlled-source electromagnetic (CSEM) method was originally developed in the late 1970s (Young and Cox, 1981) and has been applied to the study of volcanic and hydrothermal systems (Evans et al., 1994; MacGregor et al., 1998, 2001) and hydrocarbons trapped in relatively shallow sedimentary structures in the form of marine gas hydrates (Edwards, 1997; Yuan and Edwards, 2000). More recently, it has been used successfully to determine the presence and extent of hydrocarbon-bearing reservoirs at greater depths in the earth. The method uses a high-powered horizontal electric dipole (HED) to transmit a low-frequency EM signal through the seafloor to an array of multicomponent EM receivers (shown schematically in Figure 1). By studying the received signal as the source is towed through the array, the bulk electrical resistivity of the seafloor can be determined at scales of a few tens of meters to depths of several kilometers.

Transmission frequencies are typically between 0.01 and 10 Hz. At such low frequencies, the behavior of EM fields in the earth is governed by the diffusion equation rather than the wave equation. Although it would be convenient to apply the well-known battery of seismic data processing techniques as they stand to the CSEM method, this is difficult without first considering the differences between the physics underlying the two methods.

Early applications of the CSEM method in hydrocarbon exploration concentrated on targets lying in deep water (300 m and greater) (Ellingsrud et al., 2002; Johansen et al., 2005). This is because, in shallow water, signals that have interacted with the air dominate the response. These signals have been dubbed the airwave because they were initially identified, using the seismic parallel, as a refracted wave through the highly resistive atmosphere. However, many exploration targets lie in water depths much shallower than 300 m. Several approaches to mitigate the effect of the airwave have been proposed, based on the wavelike description of the airwave feature. These range from frequency-domain approaches in which up- and downgoing signals are separated (Amundsen et al., 2006) to time-domain approaches (Constable and Weiss, 2006; Ziolkowski et al., 2006).

In this paper, we return to fundamentals. First, we use a simple 1D approach to understand the physics of CSEM applied in shallow water. This will show that the concept of an air interaction, rather than the airwave, is more appropriate because of complex coupling between signals interacting with the seafloor below and air above. To explain this, we use a mode decomposition approach for CSEM similar to that developed by Chave and Cox (1982). The CSEM signal can be decomposed into a transverse electric (TE) and transverse...
magnetic (TM mode), which are affected in different ways by the air interaction. We then apply this approach to frequency-domain CSEM sounding, investigate how the air interaction may be used, and examine both frequency- and time-domain CSEM methods in shallow water.

**AIRWAVE SIGNATURE**

The airwave phenomenon has been described by a number of authors, including Chave and Cox (1982), Constable and Weiss (2006), and Um and Alumbaugh (2007). For completeness, we provide a summary of the effect using the simple 1D scenario shown in Figure 1. The corresponding horizontal electric field in an inline geometry (in which the receiver and source dipole are aligned along the dipole axis) for various water depths is shown in Figure 2a for its amplitude and Figure 2b for its phase. The corresponding vertical electric-field component is shown in Figure 3. When the water depth is infinite, we can see the amplitude (with a logarithmic scale) and phase (with a linear scale) have a close-to-linear behavior especially at large offsets. This is characteristic of the electric-field propagation in the simple uniform earth considered here.

As we decrease the water depth, the amplitude of the measured electric field increases. This increase is seen at all offsets, although it is most marked at the longest ranges shown. When the water depth is finite, there is an abrupt change of the slope amplitude curve (for example, this occurs at around 9500 m for the 1500-m water depth case, occurring at shorter and shorter offset as the water depth is reduced). Similarly in the phase response, the effect of reducing the water depth is to flatten the phase at progressively shorter offsets.

Taken together, these amplitude and phase effects are the classic indicators of airwave contamination. At face value, these signatures can be explained by a simple coupling with the atmosphere via a refracted wave at the sea surface propagating in the air (Constable and Weiss, 2006; Um and Alumbaugh, 2007). Because air is infinitively resistive, waves propagate with no attenuation; so the decay of electric-field strength is controlled primarily by the spherical divergence term. Similarly, waves travel with an infinite phase velocity, giving a corresponding flattening of the phase curve. Such an airwave signal has been thought to contain little earth information, making the CSEM method useless in shallow water.

However, two points are worth noting. First, in the shallowest water depths, the effect of interaction with the air on the signal recorded at the seafloor can be seen at all ranges and is not simply confined to ranges greater than a critical offset. Second, at all offsets (including those beyond the onset of the airwave signature), the measured signals depend on seafloor structure. For example, although the phase curve flattens, the gradient is not reduced to zero; the phase velocity is still finite and dependent on seafloor resistivity. Although the sensitivity is reduced, the signal still contains usable information on earth structure. This is discussed further in subsequent sections.

The simple airwave explanation seems to describe the propagation of CSEM signals in shallow water in a qualitative manner. However, to develop methods that will allow the CSEM method to be applied in all water depths, we must first develop a fully quantitative understanding of the airwave phenomenon.

The vertical electric field does not display the classic airwave signature (Figure 3). For this component, there is no abrupt change in the slope of the amplitude curve and no flattening of the phase. Whereas the effect of varying the water depth is much smaller in the vertical component, it is nevertheless still present at all source-receiver separations. The difference in behavior of the horizontal and vertical electric field components is discussed in more detail next.

**1D INTEGRAL EQUATION ANALYSIS IN THE FREQUENCY DOMAIN**

An instructive first step is to consider the diffusion of the fields of a point horizontal electric dipole in a 1D layered structure. Maxwell’s equations (equations 1) describe the electric field $E$ and magnetic flux density $B$ in a medium of elec-

![Figure 1. The CSEM method uses a high-powered HED source to transmit signals to an array of seafloor receivers that detect and record the electric and/or magnetic field at the seafloor. The source in this case is $z^* = 50$ m above seafloor, and the receivers are close to the seafloor at $z = 0.5$ m. The source and receiver dipole axes are aligned to give an inline geometry. Both source and receivers are embedded in an $H_0$-m-thick layer of $0.313\ \Omega m$ resistivity: seawater, which overlies a uniform 1-$\Omega m$ earth structure.](image)

![Figure 2. (a) Amplitude and (b) phase of the horizontal electric field versus offset calculated from the model shown in Figure 1 for a range of water depths $H_0$. The transmission frequency is 0.25 Hz.](image)

![Figure 3. (a) Amplitude and (b) phase of the vertical electric field versus offset calculated from the model shown in Figure 1 for a range of water depths $H_0$. The transmission frequency is 0.25 Hz.](image)
electric permittivity $\epsilon$ and magnetic permeability $\mu$ (where we assume $\mu = \mu_0$), in which the current density is $J$ and the charge density $Q$. They are

$$\nabla \cdot E = \frac{Q}{\epsilon_0},$$

$$\nabla \times E = -\frac{\partial B}{\partial t},$$

$$\nabla \times B = \mu_0 \left( j + \epsilon_0 \frac{\partial E}{\partial t} \right). \quad (1)$$

Assuming no charge buildup, Maxwell’s equations (equations 1) can be combined with Ohm’s law: $j = \sigma E$, in which $\sigma$ is the conductivity of the medium. This gives a partial differential equation:

$$\nabla^2 E + i \omega \mu_0 (\sigma - i \omega \epsilon) E = -i \omega \mu_0 j.$$ \quad (2)

If we further assume a low-frequency signal with harmonic time dependence and angular frequency $\omega$, propagating in a medium of high conductivity for which $\omega \epsilon \ll \sigma$, equation 2 simplifies to this parabolic partial derivative equation:

$$\nabla^2 E + i \omega \mu_0 \sigma E = -i \omega \mu_0 j,$$ \quad (3)

where $j$, is the current density caused by the source dipole.

This can be solved using a Green’s function technique. These results have been presented in, for example, Chave and Cox (1982), who give expressions for the electric and magnetic fields of an HED in deep water. However, for finite water depths, only the potentials are derived. Here, we extend this work to include analytic expressions for the electric and magnetic fields of an HED in deep water. However, for finite water depths, only the potentials are derived. Here, we extend this work to include analytic expression of the electric field in the general case of finite water depth caused by an HED in the seawater layer. Only a summary of main results used in the subsequent analysis is given here.

For the 1D case (in which the earth is represented by a stack of layers), the electric field can be decomposed into two mutually independent modes (Chave and Cox, 1982). As an example, equation 4 shows the radial field of an HED source:

$$E_r = E_r^{TM} + E_r^{TE}. \quad (4)$$

The transverse electric (TE) mode is characterized by horizontal current loops, so that coupling between adjacent layers in a 1D structure is purely inductive; there is no current flow across boundaries. The transverse magnetic (TM) mode is characterized by current loops in a vertical plane so that adjacent layers in a 1D earth are coupled both inductively and galvanically. The mode definitions used here apply to the fields of finite dipole sources and should not be confused with the mode definitions commonly applied in, for example, magnetotelluric methods.

Solving equation 3 gives an integral equation for each of the components of the resulting electric field and magnetic flux density. As an example, equation 5 shows the TM mode and equation 6 the TE mode for the radial electric field of an HED source at height $z'$ above the seafloor calculated at a receiver lying at height $z$ above the seafloor, the source being above the receiver, as in Figure 1 (the general expressions for the remaining components of the field in the seawater layer caused by an HED source are given in Appendix A for the electric field and in Appendix B for the magnetic flux density):

$$E_r^{TM} = \frac{P \cos \theta}{4 \pi \sigma_0} \int_0^\infty \frac{J_0(kr)}{r} \left( \frac{1}{1 - R_l^{TM} R_l^{TM}} \right) \times \left( -e^{-\beta_l (z' - z)} + R_l^{TM} e^{-\beta_l (z' + z')} + R_l^{TM} e^{\beta_l (z' - z)} \right) dk,$$ \quad (5)

$$E_r^{TE} = \frac{P \cos \theta}{4 \pi \sigma_0} \int_0^\infty \frac{i \omega \mu_0 \sigma J_1(kr)}{r \beta_0} \times \left( \frac{1}{1 - R_{air}^{TE} R_l^{TE}} \right) \times \left( e^{-\beta_{lH} (z' - z)} + R_l^{TE} e^{-\beta_{lH} (z' + z')} + R_{air}^{TE} e^{\beta_{lH} (z' - z)} \right) dk,$$ \quad (6)

in which $r$ is the distance between the source and receiver, $\theta$ is azimuth defined as the angle between the dipole axis and the line joining source and receiver, $P$ is the source dipole moment, $\sigma_0$ is the conductivity of the seawater layer, $k$ is the horizontal wavenumber and $\beta_0$ is the complex wavenumber in the sea defined as $\beta_0 = \sqrt{k^2 - i \omega \mu_0 \sigma_0}$. $J_0$ and $J_1$ are first- and second-order Bessel functions respectively, defined in equations 7 and 8 as

$$J_0(kr) = \sum_{n=0}^\infty \frac{(-1)^n}{2^{2n+1} (n!)^2} (kr)^{2n}, \quad (7)$$

$$J_1(kr) = \sum_{n=0}^\infty \frac{(-1)^n}{2^{2n+1} n! (1 + n)!} (kr)^{2n+1}. \quad (8)$$

Information about the resistivity structure in which the field difuses is contained in reflection coefficients $R_l$ and $R_{air}$. More precisely, information about the earth is contained in coefficients $R_l$, which are calculated by applying the boundary conditions for the field components recursively at each material boundary in the structure starting from the deepest layer (Figure 4). $R_l^{TM}$ is given by equation 9 and $R_l^{TE}$ by equation 10, both with $l = 1, 1$ being the layer number, as in

$$R_{l-1 \rightarrow l}^{TM} = \frac{\beta_l - \beta_{lH} e^{-2\beta_l H_l}}{\beta_l + \beta_{lH} e^{-2\beta_l H_l}}, \quad (9)$$

$$R_{l-1 \rightarrow l}^{TE} = \frac{\beta_l - \beta_{lH} e^{-2\beta_l H_l}}{\beta_l + \beta_{lH} e^{-2\beta_l H_l}}. \quad (10)$$
Interaction of the TM and TE mode signals with the air-sea interface is described by the expressions given in equations 11 and 12, which depend on the water depth $H_w$, the conductivities of the air and seawater, and the frequency of the signal, as follows:

$$R_{\text{air}}^{\text{TM}} = \frac{\beta_0 \sigma_{\text{air}} - \sigma_{\text{air}} \beta_0}{\beta_0 \sigma_{\text{air}} + \sigma_{\text{air}} \beta_0} e^{-2\beta_0 H_0},$$  

(11)

$$R_{\text{air}}^{\text{TE}} = \frac{\beta_0 - \beta_{\text{air}}}{\beta_0 + \beta_{\text{air}}} e^{-2\beta_{\text{air}} H_0}.$$  

(12)

Reflection coefficients are expressed in the horizontal wavenumber domain and in the vertical spatial domain. If we assume that the air is infinitely resistive then the TM-mode reflection coefficient at the sea surface is $-1$, as expressed by

$$R_{\text{air}}^{\text{TM}} |_{\text{air} \to \infty} = -1,$$  

where $\sigma_{\text{air}} \to 0$.  

Assuming the same for the TE-mode reflection coefficient at the sea surface gives us

$$R_{\text{air}}^{\text{TE}} |_{\text{air} \to \infty} = \frac{\beta_0 - \beta_{\text{air}}}{\beta_0 + \beta_{\text{air}}} e^{-2\beta_{\text{air}} H_0},$$  

where $\sigma_{\text{air}} \to 0$.  

In contrast to the TM mode, the amplitude of the TE-mode reflection coefficient is not equal to one (except at zero wavenumber), allowing transmission of signals into the air. This indicates that TE- and TM-mode signals interact differently with the air-sea interface, with the TE mode contributing primarily to the classic airwave signature.

To illustrate this, we now concentrate on the vertical electric field. In contrast to the horizontal electric field, the vertical electric field, for a 1D earth, depends only on this TM mode, as in

$$E_z = \frac{P \cos \theta}{4\pi \sigma_0} \sum_{k=0}^{\infty} k^2 J_1(kr) \left( 1 - \frac{R_{\text{air}}^{\text{TM}} R_{\text{L}}^{\text{TM}}}{\text{coupling}} \right) \times \left( e^{-\beta_{\text{air}} z' - z} - \frac{R_{\text{L}}^{\text{TM}}}{2} e^{-\beta_{\text{air}} z' + z'} \right) + \frac{R_{\text{air}}^{\text{TM}} R_{\text{L}}^{\text{TM}}}{4} e^{-\beta_{\text{air}} z' - z} dk.$$  

(15)

As a result, the vertical electric field response shown in Figure 3 varies with water depth to a much lesser degree than the horizontal components, which depend on both the TE and TM modes. However, if we mathematically reduce the air resistivity significantly (to 1000 $\Omega$m), we can see in Figure 5 an airwave signature developing in the vertical electric field. Decreasing the air resistivity means that the TM-mode reflection coefficient is not equal to $-1$ and depends on the horizontal wavenumber, as for the TE mode.

To summarize, whereas the interaction of both modes with the air-sea interface affects the observed response in shallow water, it is the TE mode that contributes primarily to the classic airwave effect because of the high resistivity contrast at the sea surface interface.

Turning again to equations 5 and 6, the contribution from each mode is expressed by four terms, labeled 1 to 4. Term 1 does not depend on either $R_{\text{air}}$ or $R_{\text{L}}$ and so can be thought of as the direct signal through the water column between the source and receiver. Term 2 depends only on $R_{\text{air}}$ and so corresponds to the signal that has interacted with the seafloor. Similarly, term 3 depends only on $R_{\text{L}}$ and so can be thought of as the signal interacting with the air. Finally, term 4 depends on both $R_{\text{air}}$ and $R_{\text{L}}$ and corresponds to an interference term between earth and air signals.

Although there is a clear airwave term (term 3 for both the TE- and TM-mode components), it is an oversimplification to suggest that this is the only contribution to the airwave interaction. Clearly, in equations 5 and 6, all the terms are coupled both to the earth and the air through the denominator term in the equations. This denominator can be expressed as an infinite series, depending on both the earth and air properties:

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Figure 4. Schematic of the referential used for the recursive reflection coefficient calculation. Here, $l = 0$ is the seawater layer with water depth $H_w$, $l = 1$ is the first earth layer with thickness $H_1$, and $l$ increases with depth in the earth.

Figure 5. (a) Amplitude and (b) phase of the vertical inline electric field versus offset, calculated for the model shown in Figure 1 for 100-m water depth. The transmission frequency is 0.25 Hz. The solid curve represents the real case in which the resistivity of the air is infinite. To illustrate the effect on the TM mode of the reflections at the sea surface, the dashed curve represents a virtual case in which the air resistivity is reduced to 1000 $\Omega$m.
Using this formulation, we can express the coupling between the earth and air as an infinite series of multiple reflections between the sea surface and seafloor. Note that higher-order terms in this expansion cannot be neglected. Failure to include higher-order terms results in a poor approximation to the full solution, as shown in Figure 6.

For the model shown in Figure 1 and a transmission frequency of 0.25 Hz, the series for each mode must be expanded to at least the fifth-order term to obtain a result that is within 1% in amplitude and less than 0.6° in phase from the exact solution. Note, however, that the number of terms that must be included to ensure an accurate solution depends both on the structure under study and the transmission frequency. Although a multiple removal technique could be envisaged to suppress the multiples in these signals, because these depend both on earth and air resistivity, valuable information about earth structure could be lost.

For signals in the earth and seawater, the low-frequency approximation used to arrive at equation 3 is valid. In the air, this approximation may break down, and displacement currents must be included in the formulation. Figure 7a shows the cross section of the percentage difference in the in-plane horizontal electric field between the calculated fields, with and without inclusion of displacement currents. The model used is shown in the same picture (water depth is 100 m and reservoir thickness 20 m), and the transmission frequency is 0.25 Hz. Figure 7b is the equivalent for the in-plane vertical electric field. Although inclusion of displacement currents affects the response in the air and close to the air-sea interface by up to 2%, the calculated fields at the seafloor and in the earth are unaltered. The sea is filtering out effects of the displacement current. Even when displacement currents are included, giving a corresponding modification in the reflection coefficients $R_{n}^{\text{TE}}$ and $R_{n}^{\text{TM}}$, the results at the seafloor, including the coupling between earth and air, are unaltered.

From this simple 1D analytic analysis, it becomes clear that signals interacting with the air and earth are highly coupled in a complex way. If the airwave were simply a signal that propagated through the air, it would be possible to calculate its effect for a known earth structure and subtract it from the data (Lu et al., 2005). Figure 8a and b illustrates this. For simplicity, the airwave response is calculated from a geoelectric model in which the earth is replaced by an infinite seawater layer, keeping the air-sea surface interface as it is.

\[
\frac{1}{1 - R_{n}^{\text{air}} R_{L}} = \sum_{n=0}^{\infty} (R_{n}^{\text{air}} R_{L})^{n}. \quad (16)
\]

Figure 6. (a) Amplitude and (b) phase of the horizontal electric field versus offset, calculated for the model shown in Figure 1 for 100-m water depth. The transmission frequency is 0.25 Hz. Black continuous curve represents the full solution given in equations 5 and 6. The other curves show the results when only terms up to the n\text{th} order in the expansion of the denominator coupling term are included. Next, we plot error on the amplitude (c) and phase (d) of the horizontal electric field versus offset. These are calculated for the model shown in Figure 1 for 100-m water depth as a result of expansion of the coupling term in equations 5 and 6 compared with the full solution. For this particular model, the series must be expanded until the fifth term to give accurate results.

Figure 7. Cross section of the percentage difference in response with and without inclusion of displacement currents in the formulation for (a) the amplitude of the in-plane horizontal electric field and (b) the amplitude of the in-plane vertical electric field. The model used is shown in the figure as well (water depth is 100 m, reservoir thickness 20 m). The source is a horizontal electric dipole at the origin for a frequency of 0.25 Hz. The boundary at $z = 0$ represents the seafloor.

Figure 8. (a) Amplitude and (b) phase of the inline horizontal electric field versus offset for the model shown in Figure 1 with a water depth $H_0 = 100$ m. The frequency is 0.25 Hz. The solid curve is the total electric field. The dashed curve is the response when the airwave signature (calculated from a structure in which the earth is replaced by an infinite seawater layer) is subtracted. This simple approximation clearly does not account for the nature of the air interaction.
This is then subtracted from the response of the earth structure shown in Figure 1.

There is little change in the observed airwave signature because the calculated airwave in this instance includes only the third term of equations 5 and 6. As shown earlier, this includes only a small part of the coupling between the air and earth, so its subtraction causes little change to the response. Subtracting a response calculated from a more complex earth structure can yield a response that appears less airwave contaminated. However, this is akin to a standard data normalization process, giving an anomalous response relative to the chosen geoelectric background: Both air and earth interactions are more complex earth structure can yield a response that appears less change to the response. Subtracting a response calculated from a model shown in Figure 1 for 100 m of water depth and varying resistivity. The frequency is 0.25 Hz. The larger the resistivity, the longer the range at which the airwave signature occurs. However, note that even at long range, there is a significant difference in the responses; even in the airwave-dominated regime, we remain sensitive to earth structure.

This interaction between earth and air is highly dependent on signal frequency (Figure 11). The lower the signal frequency, the longer the range at which the airwave signature occurs. However, at very low frequencies, resolution of fine-scale structure can be compromised, so the acquisition frequencies must be optimized for a given target reservoir. This is illustrated in Figure 12b, which shows how the sensitivity at the seafloor to the reservoir structure shown in Figure 12a varies with range and frequency. For this case, optimum sensitivity to the reservoir is achieved for signal frequencies between 0.07 and 0.3 Hz. The sensitivity is defined as a dimensionless quantity as follows:

$$\text{sensitivity} = \frac{\partial \ln E}{\partial \ln \rho_{\text{target}}}. \quad (17)$$

To summarize, a simplified view of the airwave as a refracted wave coming from the sea-surface interface can be used to describe aspects of the airwave phenomenon in only a qualitative manner. Failing to account for the coupling of air and earth terms will result in incorrect quantitative results. As a consequence, air interaction is a more appropriate description of the effect than airwave. Having investigated the true nature of the airwave phenomenon, we now look at its influence on data sensitivity for both time-domain and frequency-domain acquisition scenarios.

**TACKLING THE AIRWAVE PROBLEM IN THE FREQUENCY DOMAIN**

Frequency-domain CSEM sounding is the most commonly applied method in hydrocarbon exploration (Ellingsrud et al., 2002; Johansen et
shows the sensitivity to changes in the resistivity of a target layer. In contrast to the horizontal electric field (Figure 14b), the sensitivity to the target layer using the vertical component is almost unaffected by the shallow-water environment.

A similar result could be achieved using the radial field of a vertical electric dipole. Although in theory either approach can provide a measurement almost independent of the water depth, in practice the

Figure 12. (a) Geoelectric model representing a hydrocarbon exploration target. The source, a horizontal electric dipole, is 50 m above the sea bed. Source and receivers are aligned to give an inline geometry. (b) Variation in the sensitivity of the amplitude response to the target hydrocarbon layer shown in Figure 12a with varying transmission frequency and source-receiver offset. See text for discussion.

Figure 13. Dimensionless sensitivity of the horizontal electric field at the seabed to 1D changes in a 1 Ω-m uniform earth structure for an (a) infinite water depth and (b) 100 m of water depth. Dimensionless sensitivity, defined as sensitivity = (δ ln E)/(δ ln ρ_{res}), is contoured versus depth and source-receiver separation. The source and receiver are aligned to give an inline geometry, and the transmission frequency is 0.25 Hz.

Figure 14. Dimensionless sensitivity of the horizontal electric field at the seabed to the properties of a 20-m-thick 100 Ωm target reservoir layer embedded at a depth z below the seabed for (a) an infinite water depth and (b) 100 m of water depth. Dimensionless sensitivity, defined as sensitivity = (δ ln E)/(δ ln ρ_{res}), is plotted as a function of source-receiver separation and target depth z. Transmission frequency is 0.25 Hz.
measurement can be hard to achieve. Because the vertical component is often several orders of magnitude smaller than the horizontal one, even small inclinations (1°–2°) in the measurement away from vertical result in a significant horizontal component and the corresponding coupling with the resistive atmosphere.

To avoid this problem, the mode decomposition can be performed using only horizontal electric fields and/or magnetic flux density (Andréis et al., 2005; Andréis, 2006). Using the divergence of the electric field in the Maxwell’s equations 1, assuming no charge buildup we can see that the linear combination of two orthogonal gradients of the horizontal electric field gives a quantity that depends only on the vertical component of the field and hence the TM mode

$$\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} = -\frac{\partial E_z}{\partial z}. \quad (18)$$

Because this decomposition requires calculation of an electric-field gradient, a good signal-to-noise ratio is needed. A similar decomposition is possible should a TE-mode-only quantity, sensitive to background structure, be required. The sensitivity of a TM-mode decomposed field is shown in Figure 15b and is comparable, both quantitatively and qualitatively with the equivalent sensitivity for the vertical electric field.

The mode decomposition described here is valid only in a 1D layered earth structure. It is clear that for a highly 3D earth structure, the decomposition into TE and TM-modes becomes an approximation. To see the effect of 2D earth on the TM-mode decomposition, we use the model shown in Figure 16. The background consists of a layer overlaying a more resistive basement, with a dipping interface between the two. Embedded in this is a 100-Ωm resistivity, 100-m-thick reservoir that is 1 km below the seafloor. The water depth is 100 m.

We consider the response of two sources: one to the left of the reservoir and one to the right. Figure 17a shows the amplitude of the inline, horizontal electric field (dashed line) and TM decomposition (solid line) versus range for source 1. The TM decomposition, with units of $V/(Am^3)$, is multiplied by the source-receiver separation to give a quantity that can be compared directly to the electric-field amplitude, with units $V/(Am^3)$. Vertical dot-dashed lines show the positions of each reservoir edge.

Figure 17b is the equivalent of Figure 17a but for source 2. The equivalent phase plots are shown in Figure 17c and d. Looking at overall variation in the signal, the classic airwave signature observed in the horizontal electric field, characterized by a decrease in the rate of attenuation of the field and a rolling over in the phase, has been removed in the TM decomposition despite the lateral variation in the model. This does not mean that the TM-mode decomposition is unchanged in shallow water compared with deepwater. As observed in the vertical electric field
(Figure 3a and b), the observed signal changes as water depth varies; however, sensitivity to seafloor is maintained.

Edge effects from the 100-μm body are limited in the horizontal electric field. However, in the TM decomposition, we see a pronounced and localized effect at the boundary of the resistive body. At this point, the TM-mode decomposition shows a high sensitivity to the higher dimensionality of the model. This effect greatly improves the sensitivity of the TM decomposed field to lateral variations, compared with the standard horizontal electric field.

TACKLING THE AIRWAVE PROBLEM IN THE TIME DOMAIN

In EM surveys on land, the direct wave propagates without attenuation between the source and receiver. In this situation, the direct wave is decoupled completely from signals interacting with the earth, and the signal can be relatively straightforwardly separated from signals that have propagated through the earth. Plus, because of the rapid propagation of the direct signal, the airwave occurs for a short time before the arrival of the signal which interacts with the earth. Researchers have suggested that a similar separation will be possible in the shallow marine environment (Constable and Weiss, 2006; Ziolkowski et al., 2006). Edwards (2005) shows the effect of a finite water layer on the time-domain response and interprets aspects of this response as an airwave signature.

The governing equations for EM propagation are the same in the time and frequency domains. To calculate the time-domain response, the frequency-domain equations must be integrated over an appropriate frequency spectrum, namely,

\[ f(t) = \int_{-\infty}^{\infty} F(f)e^{i2\pi ft}df, \]  \hspace{1cm} (19)

where \( F \) is the frequency-domain expression of the response given by equation 4.

The physics of the time-domain problem is therefore identical. As discussed earlier, because of the coupling term in equations 5 and 6, it is clear that even in the time domain the earth and air signals are not simply decoupled. To illustrate this, Figure 18a and b shows the impulse response for the horizontal, inline electric field calculated for the model shown in Figure 1. The source-receiver offset is 5 km, and results are shown for varying water depths.

The first maximum in the curve corresponds to the air interaction. However, in the marine case, this is no sharp instantaneous direct arrival as observed on land. As we increase the water depth, the maximum occurs at a later time and has a smaller amplitude. The second, smaller maximum corresponds to signals that have diffused through the earth. For an infinite water depth, this is the only peak present in the response. However, the two maxima are not clearly separated, and the magnitude of the second peak, as well as the arrival time of its maximum, vary with water depth.

Indeed, for a 1000-m water depth, there is no maximum corresponding to an airwave signal, rather, a variation in the magnitude of the earth signal. This figure demonstrates the difficulty in separating the earth and air signals which, from the formulations presented, are tightly coupled. Even in deepwater, the signals still are affected by the interaction with the air at all times.

The same sensitivity exercise performed in the frequency domain is now done in the time domain. A source-receiver separation of 5 km is chosen as typical of the offsets required to detect reservoir targets. Figure 19a shows the sensitivity of the horizontal electric field at the seafloor to the uniform earth structure shown in Figure 1 for an infinite water depth. There is little sensitivity to earth structure before 0.3 s. This represents the time needed for the first signals to propagate from the source to the receiver. As in the frequency domain, sensitivity decreases with depth in the earth. We can compensate for this by increasing the source-receiver separation.

Figure 19b is the equivalent in 100 m of water. The main difference between Figure 19a and b is the overall decrease in sensitivity (as observed in the frequency domain). It is also notable that in shallow water the sensitivity to earth structure occurs earlier than in the deepwater case. This is a consequence of the coupling between earth and air. The interaction with the atmosphere, carrying information on seafloor structure, propagates faster.

For completeness, Figure 20a and b shows the sensitivity to the properties of a 20-m-thick layer of resistivity 100 Ωm at varying depths \( z \) in the earth. When the water depth is infinite (Figure 20a)

![Figure 18. (a) Normalized horizontal electric field impulse response for the model shown in Figure 1. The source-receiver separation is 5 km, and the water depth \( H_0 \) is varied. There is no clear separation of air and earth signals in time. (b) Zoom of panel (a) highlighting the effect of earth structure on the time-domain response.](image)

![Figure 19. Dimensionless sensitivity (as defined in Figure 15b), in the time domain of the horizontal inline electric field at the seabed to the uniform earth structure shown in Figure 1, for (a) an infinite water depth and (b) 100 m of water depth. The source-receiver separation is 5 km.](image)
comparing the results to Figure 19a, we see that the main peak in sensitivity occurs earlier, as a result of the high-resistivity layer in the structure. The deeper the reservoir layer, the later its effect is observed in the response. Figure 20b shows the equivalent sensitivity for 100 m of water. As before, the overall sensitivity is decreased compared with the deepwater case. Signals arriving at all times are affected by interaction with the air, and a simple separation of earth and air signals is not possible without first isolating a TM-mode component as in the frequency-domain case.

CONCLUSION

It is seductive to think of the airwave as a simple signal following a propagation path through the air. With this analogy, it would be relatively straightforward to remove this signal. However, here we have demonstrated that the airwave is a much more complex phenomenon. In shallow water, an electric dipole source as used commonly in marine CSEM surveying generates a pattern of diffusive TM- and TE-mode signals that couple the earth and air interactions.

Separating these signals is not simple. In some situations, through careful survey design and interpretation, the information content of the air interaction itself can be utilized. The effect of the air interaction also can be mitigated by employing acquisition and interpretation strategies that generate and extract only the TM-mode component of the field, which we have demonstrated is less affected by a finite-water depth than the TE-mode component. This can be achieved, for example, by concentrating on the vertical component of the electric field or performing a decomposition to extract only TM-mode-dependent signals. In this paper, for clarity, we have used simple 1D structures. In most cases, however, the earth is three-dimensional. In this case, the decomposition of the received signals into TE and TM modes becomes an approximation; however, the TM-mode decomposition in itself is a useful indicator of lateral resistivity variations in the earth.

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APPENDIX A

ELECTRIC-FIELD EQUATIONS

All parameters in the following equations are defined in the text.

The radial component of the electric field \( E_r \) in the seawater layer from an HED source in the seawater layer is

\[
E_{r}^{TM} = \frac{P \cos \theta}{4 \pi \sigma_0} \int_0^\infty \beta_0 \left( J_0(kr) - \frac{J_1(kr)}{r} \right) \left( 1 - R_{\text{air}}^{TM} R_{\text{L}}^{TM} \right) \left( 1 + R_{\text{air}}^{TM} R_{\text{L}}^{TM} \right) \frac{e^{-\beta_0 z + z'}}{1 + \frac{R_{\text{air}}^{TM} R_{\text{L}}^{TM} e^{-\beta_0 z - z'}}{2} + \frac{R_{\text{air}}^{TM} e^{-\beta_0 z + z'}}{3} + \frac{R_{\text{air}}^{TM} R_{\text{L}}^{TM} e^{-\beta_0 z - z'}}{4} \right) dk,
\]

where

\[
E_{r}^{TE} = \frac{P \cos \theta}{4 \pi \sigma_0} \int_0^\infty \frac{1}{r} \beta_0 \left( \frac{\beta_0 \beta_0}{r} \right) \left( 1 - R_{\text{air}}^{TE} R_{\text{L}}^{TE} \right) \left( 1 + R_{\text{air}}^{TE} R_{\text{L}}^{TE} \right) \frac{e^{-\beta_0 z + z'}}{1 + \frac{R_{\text{air}}^{TE} R_{\text{L}}^{TE} e^{-\beta_0 z - z'}}{2} + \frac{R_{\text{air}}^{TE} e^{-\beta_0 z + z'}}{3} + \frac{R_{\text{air}}^{TE} R_{\text{L}}^{TE} e^{-\beta_0 z - z'}}{4} \right) dk.
\]

The azimuthal component of the electric field \( E_\theta \) in the seawater layer from an HED source in the seawater layer is

\[
E_{\theta} = E_{\theta}^{TM} + E_{\theta}^{TE},
\]

where

\[
E_{\theta}^{TM} = \frac{P \sin \theta}{4 \pi \sigma_0} \int_0^\infty \beta_0 \left( \frac{1}{r} \right) \left( 1 - R_{\text{air}}^{TM} R_{\text{L}}^{TM} \right) \left( 1 + R_{\text{air}}^{TM} R_{\text{L}}^{TM} \right) \frac{e^{-\beta_0 z - z'}}{1 + \frac{R_{\text{air}}^{TM} R_{\text{L}}^{TM} e^{-\beta_0 z + z'}}{2} + \frac{R_{\text{air}}^{TM} e^{-\beta_0 z - z'}}{3} + \frac{R_{\text{air}}^{TM} R_{\text{L}}^{TM} e^{-\beta_0 z + z'}}{4} \right) \left( 1 - \frac{R_{\text{air}}^{TM} R_{\text{L}}^{TM} e^{-\beta_0 z - z'}}{2} + \frac{R_{\text{air}}^{TM} e^{-\beta_0 z - z'}}{3} + \frac{R_{\text{air}}^{TM} R_{\text{L}}^{TM} e^{-\beta_0 z - z'}}{4} \right) dk.
\]
The vertical component of the electric field $E$ in the seawater layer from an HED source in the seawater layer (upper signs correspond to $z^\prime > z$: source above receiver, lower signs correspond to $z^\prime < z$: source below receiver) is

$$E_z = \frac{P \cos \theta}{4 \pi \sigma_0} \int_0^\infty k^2 J_1(kr)$$

 $$\times \left( \frac{1}{1 - R_{TM} R_{TE}^{TM}} \right) \left( e^{-\beta_0|z^\prime|} + \frac{R_{TM} e^{-\beta_0(z + z^\prime)}}{2} \right)$$

 $$+ \frac{R_{TM} e^{\beta_0(z + z^\prime)}}{3} + \frac{R_{TM} e^{\beta_0(z - z^\prime)}}{4} \right) dk.$$  

(A-6)

\[E_z = \frac{P \sin \theta}{4 \pi \sigma_0} \int_0^\infty k J_0(kr)\left( e^{-\beta_0|z^\prime|} + \frac{R_{TM} e^{-\beta_0(z + z^\prime)}}{2} \right)\]

$$\times \left( \frac{1}{1 - R_{TM} R_{TE}^{TM}} \right)$$

$$+ \frac{R_{TM} e^{\beta_0(z + z^\prime)}}{3} + \frac{R_{TM} e^{\beta_0(z - z^\prime)}}{4} \right) dk.$$  

(A-7)

**APPENDIX B**

**MAGNETIC FLUX DENSITY EQUATION**

All parameters in the following equations are defined in the text.

The radial component of the magnetic flux density $B$ in the seawater layer from an HED source in the seawater layer is

$$B_r = B_r^{TM} + B_r^{TE},$$  

(B-1)

where (upper signs correspond to $z^\prime > z$: source above receiver, lower signs correspond to $z^\prime < z$: source below receiver)

$$B_r^{TM} = \frac{\mu_0 P \cos \theta}{4 \pi} \int_0^\infty \frac{J_1(kr)}{r} \left( 1 - \frac{1}{R_{TM} R_{TE}^{TM}} \right)$$

$$\times \left( e^{-\beta_0|z^\prime|} + \frac{R_{TM} e^{-\beta_0(z + z^\prime)}}{2} \right)$$

$$- \frac{R_{TM} e^{\beta_0(z + z^\prime)}}{3} + \frac{R_{TM} e^{\beta_0(z - z^\prime)}}{4} \right) dk.$$  

(B-2)

$$B_r^{TE} = \frac{\mu_0 P \sin \theta}{4 \pi} \int_0^\infty \frac{J_1(kr)}{r} \left( 1 - \frac{1}{R_{TM} R_{TE}^{TM}} \right)$$

$$\times \left( e^{-\beta_0|z^\prime|} + \frac{R_{TM} e^{-\beta_0(z + z^\prime)}}{2} \right)$$

$$+ \frac{R_{TM} e^{\beta_0(z + z^\prime)}}{3} + \frac{R_{TM} e^{\beta_0(z - z^\prime)}}{4} \right) dk.$$  

(B-3)

The azimuthal component of the magnetic flux density $B$ in the seawater layer from an HED source in the seawater layer is

$$B_\theta = B_\theta^{TM} + B_\theta^{TE},$$  

(B-4)

where (upper signs correspond to $z^\prime > z$: source above receiver, lower signs correspond to $z^\prime < z$: source below receiver)

$$B_\theta^{TM} = \frac{\mu_0 P \cos \theta}{4 \pi} \int_0^\infty \frac{J_1(kr)}{r} \left( 1 - \frac{1}{R_{TM} R_{TE}^{TM}} \right)$$

$$\times \left( e^{-\beta_0|z^\prime|} + \frac{R_{TM} e^{-\beta_0(z + z^\prime)}}{2} \right)$$

$$- \frac{R_{TM} e^{\beta_0(z + z^\prime)}}{3} + \frac{R_{TM} e^{\beta_0(z - z^\prime)}}{4} \right) dk.$$  

(B-5)

$$B_\theta^{TE} = \frac{\mu_0 P \cos \theta}{4 \pi} \int_0^\infty \frac{J_1(kr)}{r} \left( 1 - \frac{1}{R_{TM} R_{TE}^{TM}} \right)$$

$$\times \left( e^{-\beta_0|z^\prime|} + \frac{R_{TM} e^{-\beta_0(z + z^\prime)}}{2} \right)$$

$$+ \frac{R_{TM} e^{\beta_0(z + z^\prime)}}{3} + \frac{R_{TM} e^{\beta_0(z - z^\prime)}}{4} \right) dk.$$  

(B-6)

The vertical component of the magnetic flux density $B$ in the seawater layer from an HED source in the seawater layer is

$$B_z = \frac{\mu_0 P \cos \theta}{4 \pi} \int_0^\infty \frac{J_1(kr)}{r} \left( 1 - \frac{1}{R_{TM} R_{TE}^{TM}} \right)$$

$$\times \left( e^{-\beta_0|z^\prime|} + \frac{R_{TM} e^{-\beta_0(z + z^\prime)}}{2} \right)$$

$$- \frac{R_{TM} e^{\beta_0(z + z^\prime)}}{3} + \frac{R_{TM} e^{\beta_0(z - z^\prime)}}{4} \right) dk.$$  

(B-7)
REFERENCES


