Focused-source electromagnetic survey versus standard CSEM: 3D modeling in complex geometries

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ABSTRACT

A novel focused-source electromagnetic (FSEM) method focuses the EM field in the vertical direction to provide deep-reading resistivity data. FSEM offers better spatial resolution and greater depth of investigation than the conventional controlled-source electromagnetic (CSEM) method for land and marine EM surveys. We have proven the high efficiency of FSEM by analyzing 3D models of various complex geologic formations in the presence of seafloor bathymetry, shallow resistive gas-hydrate overburdens, and secondary gas reservoirs formed above deeper oil reservoirs. Combining the power of our focusing technique with the power of our 3D numerical modeling method, we have developed exceptionally challenging test cases to conclude that FSEM automatically cancels unwanted shallow effects and allows simple visual interpretation of deep reservoir responses. In addition, FSEM is insensitive to imperfections in the setup geometry. We achieve these advantages using a proper combination of measurements acquired in the receiver excited by transmitters situated at different space points. The method is promising in anisotropic formations as well.

INTRODUCTION

Our focused-source electromagnetic (FSEM) technique extends a method presented by Davydycheva et al. (2006). They suggest a transient EM survey technique based on electric dipole-dipole and dipole-quadrupole measurement, showing that vertical focusing of the EM field results in a method to reveal and delineate hydrocarbon reservoirs as deep as 3 km below the earth’s surface. The method completely eliminates the axial horizontal current at the grounded electric quadrupole receiver situated between two horizontal grounded electric dipole transmitters (Figure 1a). Such a setup directs the exciting current under the receiver vertically downward, increasing the sensitivity to a relatively narrow column of rock directly below the receiver (for the current patterns, refer to Figure 1 of Davydycheva et al. [2006]).

The focusing reduces the distorting effect of unwanted shallow structures. Although separate responses of the receiver to each transmitter are noisy and spiky above a zone of shallow heterogeneities, a combination of these responses — with proper weights to cancel the shallow effects — becomes a smooth function, bearing information about deeper structures (see Davydycheva et al., 2006, their Figures 2 and 3). Thus, the focusing provides accurate, deep-reading resistivity data.

Vertical focusing of the EM field has been reported in Russian publications (Rykhlinski et al., 1986a; Rykhlinski et al., 1986b; Rykhlinski et al., 1987; Rykhlinski et al., 2003; Rykhlinski et al., 2004a, 2004b, 2004c). It originates from the resistivity well-logging principle used by the laterolog well-logging tool (Doll, 1951) and by logging through casing (Rykhlinski, 1970; Kashik et al., 2004). The laterolog eliminates the axial borehole current at the receiver, thereby reducing the effects of the conductive borehole and shoulder beds. However, the tool requires an automatic feedback loop to cancel the borehole axial current — hardly feasible on the earth’s surface. Our focusing takes a linear combination of measurements obtained with different grounded dipole transmitters, situated on both sides of the receiver. It is based on software rather than on a difficult hardware solution, yet it grants results practically equivalent to the laterolog’s physical feedback-loop focusing.

Davydycheva et al. (2006) have developed the theory behind the technique, assuming that the current on the x-axis between two grounded x-directed electric dipole transmitters (Figure 1a) is also x-directed. The technique eliminates the effect of this x-directed current, assuming that the y-directed current is negligible, which holds true for most geologic formations. However, strong local heterogeneities may occasionally cause perpendicular current leakage in very complex 3D formations. The latest version of FSEM (Rykhlinskaya and Davydycheva, 2010) develops the general theory of complete focusing and suggests an advanced setup, eliminating all horizontal currents at the receiver.
Davydycheva and Rykhlinski (2009a, 2009b) demonstrate several simple yet compelling examples that show the merits of complete focusing compared to the earlier version of our method (incomplete axial focusing neglecting y-directed currents) and the standard time-and frequency-domain controlled-source electromagnetic (CSEM) method (Dey et al., 1975; Chave and Cox, 1982; Strack, 1984; Chave et al., 1991; Everett and Edwards, 1993; Ellingsrud et al., 2002; Johansen et al., 2005). Here, we present the FSEM method’s reaction to more complex formations, including shallow resistive heterogeneities, seafloor bathymetry, and formation anisotropy.

The FSEM measurement setup cancels many unwanted effects and obtains smooth responses along the measurement profile even in the presence of various shallow heterogeneities, which may strongly affect traditional dipole-dipole measurement data. For example, Sasaki and Meju (2009) show that several small near-surface heterogeneities introduce a significant distortion to the standard CSEM response. In the case of a deep reservoir, the typically smooth response becomes spiky and noisy in the presence of near-surface inclusions. According to Sasaki and Meju (2009), this effect is more pronounced in deepwater surveys but is present in shallow-water cases as well.

The idea of directing the exciting current vertically downward for land and marine surveys has attracted scientists’ attention for years. The vertical electric dipole (VED) generally produces stronger vertical currents than the horizontal electric dipole (HED) and hence can be more sensitive to horizontal resistors than systems using an HED transmitter.

Holten et al. (2009) suggest using VED transmitters and receivers for a transient marine CSEM application. This method requires stationary transmitters and receivers because the slightest tilt resulting from the transmitter’s movement may distort the measurement. Indeed, at times after the current is shut off, the horizontal response from the HED is two to three orders of magnitude stronger than the vertical response from the VED (Chave and Cox, 1982). Besides, this method is hardly acceptable for land and shallow-water applications because of the difficulty in designing a VED that is long enough.

Another transmitter configuration, the circular electric dipole (CED), has been suggested for land applications (Mogilatov, 1996; Mogilatov and Balashov, 1996). It consists of a grounded positive pole surrounded by several grounded negative poles in a star configuration, with equal currents in each pole. In a 1D horizontally layered medium, the CED focuses the current vertically downward. Smka (2003) suggests two versions of a CED for marine and land applications. However, the vertical structure of the current excited by the CED is unavoidably destroyed in the presence of a shallow asymmetric heterogeneity or if the grounding impedances of the electrodes are not perfectly equal.

Thus, any passive vertical focusing can be successful only in relatively simple geologic formations that have homogeneous or simple 1D overburden and that have perfectly accurate positioning of the transmitter and receivers.

Veeken et al. (2009a) and Veeken et al. (2009b) use dipole and quadrupole receivers that acquire the first and second differences of the electric potential, which also ensures passive vertical focusing. They emphasize exploiting the shallow induced polarization (IP) effect, which is often present in shallow rocks above deeper oil or gas reservoirs as a result of halo diffusion or hydrocarbon seepage. Thus, they concentrate their efforts on revealing the presence of near-surface polarizable rocks, which can indirectly indicate the presence of deeper hydrocarbons.

In this paper, we explain differences and similarities between the approach of Veeken et al. (2009a, 2009b) and our active focusing system. Both techniques originate from a method suggested by Rykhlinski et al. (1986a) and discussed by Davydycheva et al. (2006). Our proposed methodology eliminates the horizontal current at the receiver, no matter how complex the surrounding medium. In addition, our method is insensitive to imperfections in positioning the exciting transmitters and receivers.

**METHODOLOGY: SETUP SCHEME**

Figure 1b shows the proposed setup scheme, consisting of four grounded HED transmitters and a five-electrode quadrupole receiver. If \( V \) is the potential of the electric field, then the depicted voltmeter (in the receiver) measures the voltage

\[
V = \frac{d^2U}{4} = \frac{U_1 - 2U_5 + U_3 + U_2 - 2U_5 + U_4}{4},
\]  

(1)

which is the sum of two second differences of the electric potential between electrodes 1, 5, 3 and 2, 5, 4, respectively, divided by four (in other words, the circular second difference of the electric potential). Thus, the depicted receiver is in effect a combination of two quadrupoles having negative (internal) colocated poles. We also measure the horizontal components of the electric field, i.e., the first differences of the electric potential \( U_1 - U_5 \) and of \( U_3 - U_4 \), using the standard dipole measurement. (Receiving HEDs are embedded in our receiver; they are not shown in Figure 1.)

Each transmitter excites the geologic formation by repeating low-frequency square pulses of the EM field. When the current is on, the geometric DC sounding is performed across a wide range of the setup offsets, providing preliminary data on the formation resistivity. It may reflect the presence of hydrocarbon-bearing rocks, which are often more resistive than surrounding rocks. The transient response

\[
V = \frac{(U_1 + U_2 + U_3 + U_4 - 4U_5)}{4}
\]
of the formation is measured during the off-time. We use the square pulses of alternating polarity to remove static, industrial, and magnetotelluric noise.

When using the simplified axial setup (Figure 1a), we analyze two ratios of dipole and quadrupole measurements from each transmitter at work, i.e., ratios of the first and second differences of the electric potential. Such a measurement is sometimes referred to as the difference-normalized method (DNM; Davydycheva et al., 2006) or the differentially normalized electromagnetic method (DNME; Veeken et al. [2009a] and Veeken et al. [2009b]), discussed in earlier Russian publications (Bubnov et al., 1984; Mandelbaum et al., 1988; Legeido et al., 1990, 1997). Taking a particular linear combination of these two measurements at the receiver provides vertical focusing of the electric current and eliminates the influence of the x-directed axial current at the receiver. We calculate the following function:

$$R_x = \left[ \sum_{i=1}^{2} w_i \frac{U_i^1 - 2U_i^2 + U_i^3}{U_i^1 - U_i^3} \right]^{-1},$$

where $U_i^j$ is the electric potential in the $i^{th}$ electrode of the receiver excited by the $i^{th}$ transmitter, the weight $w_1 = 1$, and the weight $w_2$ is adjusted from the condition of equal potentials in electrodes 1 and 3 when both transmitters are excited:

$$U_1^1 - U_1^3 + w_2(U_2^1 - U_2^3) = 0. \tag{3}$$

This technique is fully equivalent to the element-by-element recording method derived by Davydycheva et al. (2006, their Appendix A). There, neglecting $y$-directed current on the setup axis, the authors prove that the effect of the horizontal $x$-directed current is fully cancelled and that the effect of the vertical current is duplicated. Thus, the method reduces the sensitivity to the lateral variations of the resistivity in the near-surface layer and increases the sensitivity to deeper structures situated below the receiver.

When using the advanced setup (Figure 1b), we account for the $y$-directed current. Thus, we now analyze four ratios of dipole and quadrupole measurements from each transmitter at work. Taking a particular linear combination of these four measurements at the receiver provides a complete vertical focusing of the electric current and eliminates the influence of $x$- and $y$-directed axial currents at the receiver. We calculate the function

$$R_{xy} = \left[ \sum_{i=1}^{4} w_i \frac{U_i^1 + U_i^2 + U_i^3 + U_i^4 - 4U_i^5}{U_i^1 - U_i^3} \right]^{-1}, \tag{4}$$

where $w_1 = 1$ and the weights $w_2$, $w_3$, and $w_4$ are obtained from the condition of equal potentials in electrodes 1, 2, 3, and 4 when all transmitters are excited.

Thus, to obtain the proper weights for each measurement, we solve the following linear system with respect to the weights $w_2$, $w_3$, and $w_4$:

$$U_1^1 - U_1^3 + w_2(U_2^1 - U_2^3) + w_3(U_3^1 - U_3^3) + w_4(U_4^1 - U_4^3) = 0,$$

$$U_1^4 - U_1^2 + w_2(U_2^4 - U_2^2) + w_3(U_3^4 - U_3^2) + w_4(U_4^4 - U_4^2) = 0,$$

$$U_1^1 - U_1^3 + w_2(U_2^1 - U_2^3) + w_3(U_3^1 - U_3^3) + w_4(U_4^1 - U_4^3) = 0.$$

$$U_1^4 - U_1^2 + w_2(U_2^4 - U_2^2) + w_3(U_3^4 - U_3^2) + w_4(U_4^4 - U_4^2) = 0. \tag{5}$$

This solution is equivalent to creating an equipotential surface around electrodes 1, 2, 3, and 4 by means of the automatic feedback loop. It is easy to prove that it does not matter what to put in the denominator of equation 4, $U_1^i - U_3^i$ or $U_1^i - U_2^i$: The results are identical.

Apparently, in homogeneous space or in a horizontally layered 1D medium, this technique results in equal weights of all four measurements. The response from a single transmitter in a 1D medium is identical to the response from the combination of the transmitters shown in Figure 1.

In arbitrary 3D media, all four resulting coefficients or weights $w_i$ may be different to compensate for the distorting effects of various shallow lateral heterogeneities. This makes the method insensitive to unwanted lateral effects and sensitive to a relatively narrow column of rock situated directly below the receiver.

The method also allows us to ignore the effect of grounding impedances in the electrodes. Because we analyze ratios of dipole and quadrupole measurements, such an effect, being present in both numerator and denominator, mostly cancels out. Thus, we can afford simple steel electrodes rather than complex lead/lead-chlorine (Pb/PbCl) (Holten et al., 2009) or silver/silver-chlorine (Ag/AgCl) electrodes often used in CSEM (Chave et al., 1991).

Theoretically, it is possible to obtain the second difference of the electric potential using two standard HED $x$- and $y$-directed receivers situated close to each other, subtracting their measurements to obtain the difference. However, subtracting two relatively close and often noisy signals could result in error accumulation. Using the quadrupole receiver allows direct measurement of $d^2U$ (equation 1), avoiding the subtraction. A similar method that directly measures $d^2U$ has been applied successfully to a logging-through-casing resistivity tool (Kashik et al., 2004). The tool allows nanovolt-scale measurements and records the smallest radial current leakage into the relatively resistive formation, even with a large axial current in the conductive steel casing.

In addition, we implement a method that accumulates signals coming from subsequent pulses until the noise is suppressed below 5% (on noise suppression for different CSEM configurations, including the FSEM/DNM method; see Pankratov and Geraskin [2010]).

On land, our method requires three parallel measurement profiles, as depicted in Figure 1b. In marine applications, the receivers are typically stationary and situated on the seafloor, and the transmitters are towed above the receivers. A large array of data is typically gathered; all sea-bottom receivers register signals from the transmitter in all positions of the sea vessel moving along a few parallel profiles above the receiver line under global-positioning-system (GPS) control. Because the vessel moves, the effective length of the exciting dipole may be longer than the physical transmitter length and depends on the vessel’s speed. Thus, varying the speed also improves the signal-to-noise ratio (S/N).

Smrka and Carazzone (2010) use the sum of measurements taken at the receiver for different positions of the excited transmitter to construct a virtual concentric ring (a version of the CED). However, they suggest giving all measurements equal weight. Such a passive focusing ensures the vertical structure of the current only in a simple 1D medium and does not allow for removing unwanted shallow and lateral effects as our active focusing system does. Unlike our quadrupole receivers, the standard dipole sea-bottom receivers used in methods of Smrka (2003) and Smrka and Carazzone (2010) do not allow accurate measurement of the vertical component of the electric field when the strong horizontal components are not compensated.

Standard CSEM acquires a large array of data as well; data are typically acquired in all sea-bottom receivers for all available trans-
mitter positions. Later, they are used in 2D or 3D inversion, which is usually necessary to interpret the data. However, FSEM does not require a cumbersome 2D or 3D inversion; because of vertical focusing and removal of lateral effects, a simple 1D inversion for 1D layered model parameters or even visual data interpretation permits interpreting data taken at a single receiver. Thus, a qualified geophysicist or engineer need only select the proper measurements from the data array and postprocess them to apply the focusing technique. Data from each receiver are processed independently of other receivers, increasing efficiency of the method. This allows fast post-processing of large data arrays using only the points of interest, e.g., above the middle of a seismic structure and around its edges. Below, we show that FSEM's higher spatial resolution enables accurate detection of 2-km-deep resistive structures whereas the standard CSEM method does not.

The cornerstone of our method is the active focusing system, combining the measurements obtained from four separate transmitters. A modification of the method developed by Veeken et al. (2009a) and Veeken et al. (2009b) does not use the active focusing system because the authors apply a towed transmitter-receiver setup that prohibits using more than one transmitter. Nevertheless, they do use passive vertical focusing by means of a three-electrode quadrupole receiver (see the current pattern for such a receiver in Figure 1c by Davydycheva et al. [2006]). Thus, their results in a layered 1D medium would be equivalent to our axial focusing version of the method (Figure 1a; equations 1 and 2) because the 1D medium responses to transmitters 1 and 2 are identical.

3D MODELING METHOD

For the modeling, we use a 3D finite-difference (FD) method developed by Davydycheva and Druskin (1999). The problem with respect to the EM field excited by a grounded electric dipole is discretized on an FD grid and solved iteratively. We use the Lebedev staggered FD grid approach, which enables efficient treatment of the arbitrarily dipping anisotropy of the electric conductivity. Such a grid gives the ability to determine different components of the electric field \((E_x, E_y, E_z)\) and the electric current density \((J_x, J_y, J_z)\) at the same spatial nodes. This allows application of the general anisotropic Ohm's law (connecting all components of \(E\) and \(J\) at the same point) and enables efficient handling of dipping-anisotropy and dipping-medium interfaces.

We use a fast multifrequency or multitime solver: the spectral Lanczos decomposition method (Druskin and Knizhnerman, 1994). It allows simultaneous computation of wide-band results at practically no cost. The CPU time required for a wide band of frequencies or times for typical marine/land CSEM applications varies from 2 minutes to 1 hour per point (one transmitter position) on a modern laptop computer, depending on the medium model.

As a result of the material averaging technique within the FD grid boxes and the optimal (spectrally matching) model-independent gridding technique, the method requires the FD grid to be neither fine nor conformal to interfaces. This allows accurate modeling of dipping interfaces; Zaslavsky et al. (2006) prove this statement, demonstrating a complex bathymetry test. (They apply a different iterative solver to the same FD scheme.) Thus, the grid construction is nearly independent of the conductivity model.

We use equidistant gridding inside the transmitter-receiver domain and optimize the grid refinement outside. Instead of minimizing the global truncation error — typically done in many other numerical approaches — we minimize the error at the receiver and optimize the approximation of the boundary conditions at infinity. Outside the transmitter-receiver domain, the grid steps aggressively increase, following the optimal gridding algorithm (Davydycheva et al., 2003) until reaching the grid-domain boundary determined by the minimal frequency or longest time. Compared to the heavily used Yee FD grid (see, e.g., Druskin and Knizhnerman, 1994; Weiss and Newman, 2002; Mulder, 2008), the Lebedev grid allows reduced grid size because it features an error-cancellation property at the medium interfaces and at the grid-domain boundary (Davydycheva, 2010).

The focusing technique favors use of the Lebedev FD grid rather than the standard Yee grid. The Lebedev grid allows defining \(x\) and \(y\)-components of the electric field at the same spatial points, resulting in an accurate focusing procedure on the grid. The standard Yee grid determines the components at different space points, therefore requiring an interpolation procedure to get them at the same point. Computing acceptable interpolated values and differences of the electric field (i.e., the second differences of the electric potential; equation 1) may require unrealistically dense and large Yee grids.

Frenkel and Davydycheva (2009) carefully validate the FD modeling software against a quasi-analytic 1D code for the standard CSEM method in deep- and shallow-water conditions.

MODELING EXAMPLES

In an earlier work (Davydycheva and Ryklinski, 2009b), we compare the performance of the marine version of FSEM versus the standard time- and frequency-domain CSEM on examples of two resistive structures situated 1 km below the seafloor, with a constant water depth of 200 m and in the absence of other unwanted shallow effects (flat homogeneous seafloor). Let us study the FSEM method in more practical and challenging cases of deeper reservoirs and complex geometries.

Consider the following models:

• **Model 1.** — Two 2-km-deep, 50-\(\Omega\)m resistive reservoirs in a formation of isotropic resistivity of 1 \(\Omega\)m. The larger prism has vertices at \(x_1 = -5\), \(z_1 = 2.25\); \(x_2 = -4\), \(z_2 = 2.05\); \(x_3 = 0\), \(z_3 = 2.05\); \(x_4 = 1\), \(z_4 = 2.25\); \(-3 < y < 3\). The smaller prism has vertices at \(x_1 = 2\), \(z_1 = 2.25\); \(x_2 = 3.5\), \(z_2 = 2.05\); \(x_3 = 5\), \(z_3 = 2.25\); \(-1.5 < y < 1.5\). Vertices are measured in kilometers. Water depth is 0.2 km (Figure 2).

• **Model 2.** — Two 2-km-deep reservoirs with properties of model 1, and two shallow 50-\(\Omega\)m resistive prisms. Vertices are at \(x_1 = 0.5\), \(z_1 = 0.3\); \(x_2 = 0.75\), \(z_2 = 0.4\); \(x_3 = 1\), \(z_3 = 0.3\); \(-0.25 < y < 0.25\) and \(x_1 = 4.1\), \(z_1 = 0.3\); \(x_2 = 4.35\), \(z_2 = 0.4\); \(x_3 = 4.6\), \(z_3 = 0.3\); \(-0.25 < y < 0.25\). Water depth is 0.2 km (Figure 3).

• **Model 3.** — An anisotropic analog of model 1. Two 2-km-deep reservoirs have the properties of model 1 in a formation with horizontal and vertical resistivities of 1 and 1.5 \(\Omega\)m, respectively. Water depth is 0.2 km.

• **Model 4.** — Two 2-km-deep, 50-\(\Omega\)m resistive reservoirs with properties of model 1 and a shallow, semi-infinite, 0.1-km-thick resistive (5-\(\Omega\)m) layer in a 1-\(\Omega\)m isotropic formation with vertices at \(x_1 = -1\), \(z_1 = 0\); \(x_2 = 0\), \(z_2 = 0.1\) (Figure 4).

• **Model 5.** — Two 2-km-deep, 50-\(\Omega\)m resistive reservoirs with properties of model 1 and a shallow, semi-infinite, 0.1-km-thick conductive (0.5-\(\Omega\)m) layer in a 1-\(\Omega\)m isotropic formation.

• **Model 6.** — Bathymetry case. Two 2-km-deep, 50-\(\Omega\)m resistive
reservoirs in a 1-Ωm isotropic formation. Water depth varies from 200 to 90 m between $x = -0.9$ and $-0.6$ km (Figure 5).

- **Model 7.** — The same as model 6, but the water depth is a constant 90 m (no bathymetry).

Two deep structures present in all of the models approximate typical shapes and sizes of actual oil reservoirs. The shallow resistive structures in models 2 and 4 represent shallow gas reservoirs formed as a result of seepage from deeper reservoirs or gas-hydrate areas commonly observed right below the seafloor. The shallow conductive structure in model 5 represents water-saturated sand.

For our study, we selected relatively shallow-water tests, considered to be especially challenging for the standard CSEM method because of the strong airwave effect, which may significantly mask the deep reservoir response (Dell’Aversana, 2007; Andreis and MacGregor, 2008).

Figures 6–9 (views a and b) model the standard dipole-dipole CSEM measurements in a wide range of frequencies and times. We model responses of sea-bottom receivers to a moving $x$-directed HED transmitter situated 0.03 km above the receiver line. For simplicity of representation, we vary the $x$-coordinate of the receiver, keeping the offset (transmitter-receiver distance) a constant 5.2 km. Our offset choice was based on previous studies; we found that shorter offsets typically do not have enough sensitivity to structures at depths up to 2 km, whereas longer offsets do not resolve the smaller deep resistive prism well enough (see also Frenkel and Davydycheva, 2009a for a study of optimal frequency-offset configurations for revealing relatively small resistive targets). We show relative or normalized responses for the sake of simpler representation and analysis, i.e., the electric field $E(x)$ divided by the response measured at a reference point situated far enough from the reservoir (the first or last point on the receiver line). This normalized-response approach is suitable for model studies but should be used with extreme caution in the field because the choice of reference point may be ambiguous. The absolute responses (in V/m) are shown as well, on the bottom (transmitter dipole moment was 1 A-m).

View c of Figures 6–9 shows time-domain FSEM modeling for the same offset of 5.2 km. The curves depict the functions $R_{xy}$ (equation 4) (top row) and $R_x$ (equation 2) (bottom row) measured by the receiver, which is excited by four (top row) or two (bottom row) transmitters situated 0.03 km above the seafloor (Figure 1a and b), normalized to equal one far enough from the reservoirs for simplicity of analysis.

Figure 2. Model 1. The $xz$ cross section show two 2-km-deep reservoirs (white). Water depth is 200 m (black = 0.3 Ωm water). White dots signify sea-bottom receivers.

Figure 3. Model 2. The (a, b) $xz$ (in different scales) and (c) $xy$ plane views show two 2-km-deep reservoirs and two shallow resistive inclusions (white). Water depth is 200 m (black = 0.3 Ωm water). White dots in (a) and (b) signify sea-bottom receivers.

Figure 4. Model 4. Two 2-km-deep reservoirs and a shallow resistive semi-infinite layer: (a, b) $xz$-plane view and (c) $xy$-plane view. Water depth is 200 m (black = 0.3 ohm-m water).
It is easy to see that the FSEM method provides clear responses of both structures in all cases. Figure 6c shows that the FSEM response of the larger deep reservoir (model 1) varies from 70% to 200% (from the background level) at different times, whereas frequency- and time-domain CSEM (Figure 6a and b) provide only a 30% anomaly above the larger reservoir. The smaller reservoir anomaly exceeds 35% using the FSEM method, and there is a clear separation between the responses of the two structures; the standard CSEM method gives a 30%–40% anomaly above the larger reservoir but hardly detects the smaller reservoir in the frequency and time domains (Figure 6a and b).

**Effect of shallow resistive inclusions**

Figure 6d and e shows the CSEM response to model 2, the same reservoirs in the presence of two shallow inclusions. Each shallow structure gives two rather sharp spikes, significantly distorting the deep-reservoir responses at all frequencies and times. The first spike is present when the receiver is above the inclusion, and the second is present when the transmitter is above it. Thus, the effect of shallow heterogeneities on standard CSEM responses is not local; rather, it is present when the receiver or the transmitter is in the vicinity of the heterogeneity. Ignoring or low-pass filtering these four spikes inevitably would lead to misinterpretation of the deep-reservoir response and to loss of information, especially on the smaller reservoir. This problem requires a full 3D inversion of wide-frequency/time-band CSEM data to account for the nonlocal shallow effects properly.

On the contrary, the effect of the unwanted shallow structures on the FSEM method (Figure 6f) is local; it is observed only if the receiver is right above the shallow structure. The focusing automatically takes care of the shallow effects and allows a simple visual interpretation. At early times, the shallow effects are strong and the reservoirs’ signatures are relatively weak. Later, the signal from the reservoir arrives, providing the clear anomalies above the both reservoirs, but the shallow anomalies stay the same. This is why we can afford a simple 1D inversion at each point of the profile.

Below, we discuss the time-differentiation method that offers an extra benefit to our focusing method and cancels the unwanted shallow effects almost completely by subtracting the responses arrived at different time moments after the current-off.

**Effect of formation anisotropy**

Figure 7a and b shows that the formation anisotropy (model 3) reduces the CSEM anomaly above the larger reservoir to 25%–30%, whereas the FSEM method (Figure 7c) provides a clear anomaly of more than 100% of the background level. The smaller reservoir response is about 25% for FSEM and is far below the detection level for frequency- and time-domain CSEM. In the case of formation anisotropy, the standard CSEM method typically requires longer offsets than in the respective isotropic formation to get the stronger responses from resistive targets (Hobbs et al., 2009). However, in this case, the offset increase can hardly help detect the reservoirs because their diameters are comparable to or less than the offset. A study of optimal offset ranges for particular reservoir sizes, depths, and formation resistivity and anisotropy values is the topic for a separate paper.

**Effect of shallow, semi-infinite resistive/conductive layers**

Figure 8a-c shows the model 4 simulation. Responses of the two deep reservoirs are distorted by the effect of the shallow semi-infinite resistive layer. The time- and frequency-domain CSEM methods show an elevation of the responses above the shallow resistive structure (Figure 8a and b). When moving along the profile, the elevation occurs twice: first at $x = -3.5$, when the receiver enters the shallow resistive zone, and later at $x = 1.5$, when the transmitter enters it ($x$ characterizes the transmitter-receiver midpoint). The 1-Hz curve in Figure 8a shows this double elevation exceptionally. As a result of the strong skin effect, deep reservoirs do not affect this high-frequency curve, and it only represents the effect of the shallow structure. Thus, a full multifequency or multitime 3D inversion would be required to properly account for this double-elevated effect of the shallow resistive zone.

On the other hand, the FSEM response demonstrates just one elevated area exactly above the resistive structure, proving that the shallow effect on FSEM is local, unlike the double-elevation shallow effect on standard CSEM. The observed elevation above the shallow structure allows application of a simple 1D inversion scheme for FSEM. A point-by-point inversion for the horizontally layered 1D model parameters will automatically take care of this elevation.

Figure 8d-f shows the model 5 simulation. The responses of two deep reservoirs are distorted by the effect of a shallow, semi-infinite conductive layer. The behavior of time- and frequency-domain CSEM curves is similar to Figure 8a and b (resistive case). But instead of the double elevation of the responses above the shallow structure, we observe two negative stairsteps (especially in the 1-Hz curve, Figure 8d). On the contrary, the FSEM response is practically insensitive to the shallow conductor (compare with Figure 6c, two reservoirs only). Again, this allows a simple 1D inversion scheme.
Seafloor bathymetry effect

Figure 9a-c shows the responses to model 6 (bathymetry case) when the water depth varies from 200 to 90 m. Figure 9d-f shows the case for a constant water depth of 90 m. The standard CSEM response with the bathymetry (Figure 9a and b) is completely different from the CSEM response without the bathymetry (Figure 9d and e). The frequency- and time-domain curves (Figure 9a and b) show a strong double elevation: first when the receiver arrives at the shallow zone and second when the transmitter passes over this zone. The bathymetry distorts the CSEM response of the reservoir beyond recognition. This case requires a full 3D inversion to extract reservoir parameters; it is questionable if this information can be extracted reliably in principle.

However, the FSEM response with the bathymetry is distorted only above the steep part of the seafloor and in its close vicinity. Beyond this zone, the FSEM curves (Figure 9c) look nearly identical to the respective curves without the bathymetry [compare with Figure 9f (constant water depth of 90 m) and Figure 6c (constant water depth of 200 m)]. These apparently identical curves create the possibility of a simple visual interpretation even in this exceptionally challenging case because we can observe a clear elevation of the FSEM response directly above two reservoirs with a clear separation between them, independent of the seafloor shape. A simple 1D inversion could also provide a reasonable solution in all receivers, except perhaps for the case of a receiver situated right on the edge of the

Figure 6. Synthetic responses to model 1 (see Figure 2): (a) frequency-domain CSEM, (b) time-domain CSEM, and (c) FSEM responses for (top) complete and (bottom) axial focusing. Across the bottom are the responses to model 2 with two shallow inclusions (see Figure 3): (d) frequency-domain CSEM, (e) time-domain CSEM, and (f) FSEM responses. Offset is 5.2 km. Thin vertical lines signify the reservoir edges; small triangles show positions of the shallow inclusions.
shallow zone. (It would be difficult to acquire or model data reliably in this receiver, which prevents us from showing the modeled result.)

Figure 10 illustrates the performance of the frequency-domain phase-shift measurement for the bathymetry model. The phase shift is often believed to be more sensitive to deep resistive structures (Mittet, 2008). Indeed, in the absence of bathymetry, the 0.1-Hz curve (Figure 10a, constant water depth of 200 m) shows two clear anomalies: one about 20° above the larger reservoir and one about 5° above the smaller one. However, Figure 10b reveals that the bathymetry has a stronger effect on the phase measurement and masks the deep reservoir responses (also compare to Figure 10c, constant water depth of 90 m). The phase shift mostly “sees” the bathymetry, showing a double staircase of several dozen degrees. The responses of both reservoirs are lost in the staircase response of the seafloor. Obviously, separating all of these anomalies using the phase-shift measurement becomes extremely challenging. In addition, the phase shift is very difficult to measure and handle accurately because it requires synchronizing clocks in the transmitter and receiver and storing huge data arrays.

**Effect of imperfections in the setup geometry**

Our method implies a more complex scheme of data acquisition than the traditional dipole-dipole measurement scheme used in standard CSEM. Ideally, the four transmitters are positioned symmetrically at equal distances from the receiver (Figure 1b). But this may be difficult to achieve in practice. In this section, we analyze the effects of imperfections in positioning the existing transmitters.

Figure 11 depicts a setup scheme for a situation where one of the transmitters is misplaced, and Figure 12a shows the respective response to model 1. Compared to the FSEM response depicted in Figure 6c where all transmitters are placed symmetrically, one can see that the misplaced transmitter has no noticeable effect on the FSEM response to model 1. Compared to the FSEM response depicted in Figure 1b, constant water depth of 200 m, the effect is not significant either. This example proves that the method retains capability even if for some reason only two of three required profiles are available.

Thus, the method is relatively insensitive to positioning errors of the transmitters with respect to the receiver. Keeping the symmetry of the setup and the constant offsets for all four transmitters is recommended to achieve the same depth of investigation for all transmitter-receiver measurements, but perfect symmetry is unnecessary.

Our focusing technique handles varying measurement conditions for different transmitters in a similar way: it gives a different weight to a “corrupted” measurement, if any. However, the final result stays almost the same because the focusing ensures no horizontal current below the receiver.

**Extra benefit from frequency/time differentiation**

Our suggested method offers an additional opportunity to cancel the shallow effects: using the difference of the responses measured at two different frequencies (in the frequency domain) or at two different time moments (in the time domain). The responses of shallow structures cancel out after the subtraction, whereas the deep-reservoir responses remain.

Ryhklinski et al. (1986a) suggest the frequency differentiation for land/marine EM surveys. Dmitriev and Davydycheva (1989) have shown that the frequency differentiation effectively cancels out shallow effects in the DNM method but is not very efficient for a standard EM survey. (They develop and apply a 2.5D integral equation modeling method to prove this concept.) More recently, Chen and Alumbaugh (2009) and Maaø and Nguyen (2010) have studied the frequency differentiation effect for standard CSEM on relatively simple 2D and 3D examples.

![Figure 7. Synthetic responses to anisotropic model 3: (a) standard CSEM, frequency domain; (b) standard CSEM, time domain; (c) FSEM responses, complete (top) and axial (bottom) focusing. Thin vertical lines signify the reservoir edges.](image-url)
It is worth mentioning that a similar principle has been applied commercially in new-generation triaxial induction well logging. Shallow effects caused by the borehole and invasion zones around it are suppressed by subtracting data acquired at different frequencies (Rabinovich et al., 2006).

Davydycheva et al. (2006, their Figure 6) prove that time differentiation gives a similar effect for land/marine time-domain EM. Models 1, 2, 4, 5, and 6 demonstrate how frequency/time differentiation modifies the standard CSEM and FSEM responses and enables removal of shallow effects.

Figure 13a-c shows the differential responses to model 2 (two deep reservoirs and two shallow resistive inclusions). Here, we plot the differences between the responses depicted in Figure 6d-f. For the frequency-domain CSEM method (Figure 13a), we show the differences between the 0.1- and 0.25-Hz normalized amplitude responses (solid lines) and between the 0.25- and 1-Hz responses (dashed lines). For the time-domain CSEM response (Figure 13b), we plot the differences between the normalized responses obtained at \( t = 2 \) s after the current is turned off, and at \( t = 0 \) (solid line), at \( t = 4 \) s and 1 s (solid line with dots), and at \( t = 8 \) s and 1 s (dashed line). For the FSEM response, we plot the differences (between the curves depicted in Figure 6c) at \( t = 2 \) s and \( t = 0 \), at \( t = 4 \) s and 1 s, and at \( t = 8 \) s and 1 s as well. The subtraction almost completely cancels the effect of the shallow inclusions in the FSEM response; shallow inclusions do not corrupt model 1 readings (two reservoirs only, Figure 13f). On the contrary, the standard frequency- and time-

**Figure 8.** Synthetic responses to model 4, with two reservoirs situated 2 km below the seafloor in the presence of a semi-infinite resistive 5-\( \Omega \)m layer (see Figure 4): (a) frequency-domain CSEM, (b) time-domain CSEM, and (c) FSEM responses for (top) complete and (bottom) axial focusing. Across the bottom is the corresponding case with a conductive (0.5-\( \Omega \)m) semi-infinite layer: (d) frequency-domain CSEM, (e) time-domain CSEM, and (f) FSEM responses for (top) complete and (bottom) axial focusing. Thin vertical lines signify the reservoir edges.
domain CSEM responses do not demonstrate this remarkable property: Subtracting the normalized responses does not cancel the effect of the shallow structures (compare to Figure 13d and e). It is easy to check that subtracting the absolute electric field values does not work any better.

Figure 13g-o shows the frequency- or time-differentiation effect on all three methods discussed for model 4 (shallow resistive semi-infinite layer), model 5 (shallow conductive layer), and model 6 (bathymetry layer), respectively. The ability of FSEM and the inability of standard CSEM methods to remove shallow effects by means of differentiation in time (frequency) become obvious. FSEM allows visual interpretation for the deep reservoirs in all cases, whereas the bathymetry and shallow semi-infinite layers cripple the standard CSEM responses, masking the deep reservoirs’ signatures.

Concluding remarks on modeling

Thus, all of the examples we consider show that standard CSEM is less sensitive to deep reservoirs and has lower spatial resolution than the FSEM technique. Varying the excitation frequency or measurement time does not improve the spatial resolution of conventional CSEM in the shallow-water cases compared to DC excitation (black curves, Figures 6–9). Indeed, the response of the smaller structure can hardly be distinguished from the response of the larger one at all

Figure 9. Synthetic responses to model 6, bathymetry case. Water depth varies from 200 to 90 m. Reservoirs are situated 2 km below the 90-m-deep seafloor line (see Figure 5): (a) frequency-domain CSEM, (b) time-domain CSEM, and (c) FSEM responses for (top) complete and (bottom) axial focusing. Across the bottom is the corresponding case without the bathymetry (constant water depth of 90 m everywhere): (d) frequency-domain CSEM, (e) time-domain CSEM, and (f) FSEM responses for (top) complete and (bottom) axial focusing. Thin vertical lines signify the reservoir edges.
frequencies and times. In our shallow-water cases, nonzero frequency/time does not seem to provide additional information and only reduces the CSEM reservoir anomalies compared to the DC response because of the airwave and skin effects.

Moreover, the smaller reservoir response at the highest frequency of 1 Hz is practically absent because of the dominating airwave. At zero frequency (DC), even though the airwave is absent and does not mask the responses of both reservoirs, there is almost no separation of the responses for the two structures because the spatial resolution of standard CSEM is restricted by the minimum of offset and wavelength. For example, in the DC case (infinite wavelength), the resolution is determined by the offset only. At the standard 0.25-Hz frequency, the wavelength in the seafloor is 6.3 km, which is longer than the offset of 5.2 km. So the resolution is again restricted by the offset. At 1 Hz, the wavelength is 3.2 km, but the reservoir responses are weak (almost absent) because they are dominated by the airwave. On the contrary, as a result of the focusing, the spatial resolution of FSEM is not restricted by the offset; we can successfully resolve the smaller target, whose diameter is about twice as small as the offset (5.2 km). This makes our focusing technique especially attractive for shallow-water and land applications. (All field tests reported earlier were completed on land or in shallow water.) Deepwater application is a topic for future study.

Our examples do not allow a visual interpretation of the standard CSEM responses. The shape of the response varies dramatically, depending on frequency or time even in the absence of shallow effects that mask the deep reservoir responses beyond the recognition. Thus, a time-consuming 3D inversion of multifrequency or multi-time data becomes quite necessary. In contrast, the FSEM method allows a simple visual interpretation based on the shape of responses even in the presence of multiple unwanted effects. Shallow effects on FSEM are local (i.e., related only to the receiver situated right above the shallow structure), whereas they are nonlocal in the case of standard CSEM. In such a way, they prevent visual interpretation and simple inversion schemes.

Remarkably, in all of the cases discussed, the relative FSEM reservoir responses (Figures 6–9) strengthen as the measurement time

![Figure 11. Setup scheme with one of four transmitters, T3, incorrectly positioned or misplaced. The x-, y-, and z-coordinates of the quadrapole receiver are (0, 0, 0.2); the coordinates of the transmitters (in km) are (5.2, 0, 0.17), (5.2, 0.8, 0.17), (5.2, 0.8, 0.17), and (−5.2, 0.8, 0.17).](image)

![Figure 10. Standard CSEM phase response in the frequency domain to (a) model 1 (constant water depth of 200 m), (b) model 6 with bathymetry (water depth varies from 200 to 90 m; see Figure 4), and (c) model 7 (constant water depth of 90 m).](image)

![Figure 12. FSEM synthetic response (complete focusing) to model 1 (a) with incorrectly positioned transmitters T3 as depicted in Figure 11 and (b) with two transmitters, T3 and T4, incorrectly placed on the receiver profile. Thin vertical lines signify the reservoir edges.](image)
Figure 13. Effect of frequency or time differentiation. (a, d, g, j, m) Frequency-domain CSEM; (b, e, h, k, n) time-domain CSEM; and (c, f, i, l, o) FSEM responses for complete focusing. (Row 1) For model 2; triangles signify locations of two shallow inclusions. (Row 2) For model 1. (Row 3) For model 4, a shallow resistive semi-infinite layer. (Row 4) For model 5, a shallow conductive semi-infinite layer. (Row 5) For model 6, the bathymetry case.
increases — at least until the absolute signal is strong enough. (At our 5.2-km offset, it decays not more than four or five times within 8 s after the current shuts off. See the lower plots in view b of Figures 6–9.) This allows us to analyze the later responses from deeper structures. On the other hand, the standard time-domain CSEM reservoir anomalies fade away earlier.

In all of our modeling examples, we ignore the IP effect. Earlier publications show that the IP effect sometimes helps distinguish hydrocarbons from other resistive rocks: dry carbonates, rock salt, volcanic rocks, and permafrost zones (see Davydycheva et al., 2006; Khaliulin and Nezhdanov, 2006; Veeken et al., 2009a; Veeken et al., 2009b; He et al., 2010; Pankratov and Geraskin, 2010). The IP affects spectral properties of the formation resistivity, which becomes a complex function of the excitation frequency in the low-frequency range with many rocks. It is usually absent in resistive rocks such as basalt, carbonates, and rock salt, but it is always present in clays, some sandstones, and hydrocarbon-saturated rocks, where the electric resistivity has a noticeable frequency-dependent imaginary part. Thus, it may provide additional information that helps distinguish between hydrocarbons and other types of resistive rocks. Davydycheva et al. (2006) give a detailed review of the IP effect on EM measurements.

However, the IP effect plays only a complementary role in our method. We offer proof that the FSEM method has advantages over the standard CSEM method even in the absence of the IP — at least for on-land and shallow-water marine applications. Our objective is to show that the success of FSEM comes not only and not mainly from exploiting the IP effect. However, because we analyze transient data during the off time, it may be useful to take the IP into account because it typically slows time decay of the EM field and may affect late responses. This is why we prefer taking advantage of the IP effect when inverting field data rather than ignoring it.

Davydycheva et al. (2006) show three successful field tests obtained at the Ob estuary (western Siberia), on the Verkhnechonskoye oil deposit and on the Bratsk gas-condensate deposit (both in eastern Siberia). Recent field results obtained on the Tympuchikan gas-condensate deposit in Yakutia, eastern Siberia, with the latest modifications of the method are reported by Davydycheva and Rykhlimski (2009b). In all cases, the method was applied to a complex geologic environment, including permafrost zones, shallow basalt intrusions, resistive carbonates, and/or rock-salt overburden.

In all field tests, a simple visual interpretation or 1D inversion at each point of the profile was applied. The 3D or 2D images of the formation resistivity and the IP parameters were obtained by stitching together simple point-by-point 1D images. The focusing technique enabled a reasonable estimation of the conductivity of a 2–3-km-deep rock column, confirmed by drilling. A high resolution of the method allowed workers to distinguish hydrocarbon-saturated zones of moderate size in challenging cases when the reservoir diameter was comparable to its depth.

Our active focusing system enables investigation of the whole column of rock situated below the receiver. Analyzing the focused responses at different times after the current shuts off and at various offsets, we can extract data more or less sensitive to deeper or shallower rocks and can directly observe the deep-reservoir response in such detail that allows analyzing the spectral properties of the reservoir resistivity.

Skepticism related to exploiting the IP effect for oil and gas exploration exists (see, e.g., Veeken et al., 2010). We believe the reason for this skepticism is the rather low sensitivity to deep resistors and low spatial resolution of the standard dipole-dipole measurement, which does not allow analyzing the deep-reservoir resistivity in detail. Early (within a few seconds) transient dipole-dipole measurement is mostly dominated by the constant-resistivity EM response, whereas the IP effect typically reveals itself later, when the relative reservoir response of the standard CSEM mostly fades away. (Figures 6–9 prove that in the cases studied above, this occurs within the first few seconds.) That is why the IP may affect the FSEM late-time response much more than the CSEM response.

Even though the standard time-domain dipole-dipole measurement is part of our workflow, we have no reliable data nor modeling examples indicating whether this measurement alone, or other modifications of the standard CSEM method, can take advantage of the IP effect.

**CONCLUSIONS**

We have developed a theoretical background for a new FSEM method and have shown that it has the potential for revealing and delineating deep hydrocarbon reservoirs in challenging cases where the standard marine or land CSEM method fails to provide reliable results. Our method enables directing the EM energy deep into the geologic formation, similar to the acoustic beam used in seismic exploration. We have suggested a simple implementation of the focusing principle and demonstrate its successful application on complex 3D modeling examples. The new method provides great depth of investigation and automatic removal of unwanted shallow effects. The high spatial resolution allows a simple visual interpretation in a vast variety of complex 3D formations. Thus, the applicability of 1D inversion schemes may become possible. Another attractive feature of the method is a relatively high S/N.

The method may be more time consuming in terms of operational efficiency than standard CSEM, but this is counterbalanced by easier postprocessing. When a relatively simple 1D inversion is applicable, the data can be postprocessed quickly on a single laptop.

The focusing technique is based on a similar principle used in resistivity well-logging tools such as the laterolog. The first primitive logging devices gave only an approximate estimate of formation resistivity in a shallow zone around the borehole. After introducing the focusing principle, resistivity well logging progressed significantly. However, the laterolog logging method requires an automatic feedback loop to remove the strong borehole axial current. This makes its on-land or marine application difficult. We have developed a simple but successful implementation of the focusing idea for land and marine applications.

Compared to resistivity logging, the marine and land EM survey is in the beginning stages of full adoption by the industry. Since the middle of the 20th century, EM logging methods have undergone massive development, making them routine and reliable techniques for formation evaluation. Modern logging devices use various combinations of measurements acquired with different transmitter-receiver pairs to enhance/remove various wanted/unwanted effects. This provides their high spatial resolution, great depth of investigation, and separation of various shallow and deep effects.

Full 3D inversion for EM measurements is rarely applied in commercial resistivity logging. Even though it may be very promising for complex EM logging tools in certain complicated 3D formations, 3D inversion for EM logging application is still slow and impractical. Whenever an advanced logging technique exists that avoids 3D inversion, it is predominantly used.
Marine and land EM methods have much room for improvement. Their further development is inevitable until they become a routine and reliable addition to the seismic survey. We suggest a significant improvement: techniques to enhance/remove various wanted/unwanted effects that open opportunities to investigate complex 3D formations without a full 3D inversion. The latter may be promising and useful but not completely necessary, a topic for future study.

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