# Improving Seabed Logging Sensitivity in Shallow Water Through Up-Down Separation

F. Roth, F. A. Maaø

*Electromagnetic Geoservices (EMGS), Trondheim, Norway*

**Summary**

A shallow water Seabed Logging (SBL) model is presented to demonstrate that airwave removal by separation of up- and downward traveling wavefields is capable of increasing the detection depth of the SBL method by several hundreds of meters. To achieve such improvement, a proper choice for the seafloor resistivity in the up-down separation processing is essential. This is illustrated by examples of normalized magnitude vs. offset (MVO) curves obtained for various assumed seafloor resistivities, some of which produce processing artifacts in the form of very sharp, narrow anomalies. A good seafloor resistivity can be identified by an estimate of the upward traveling constituent of the reference field that is low in magnitude, has no localized magnitude minimum for any offset, and exhibits a relatively steep linear phase behavior. These criteria should be fulfilled for all source frequencies.

**Introduction**

In recent years, Seabed Logging has found wide application in marine hydrocarbon exploration and has established itself as a recognized prospect evaluation tool (Johansen et al., 2005). The measurement principle of Seabed Logging is to excite a guided electromagnetic (EM) field in a hydrocarbon reservoir, where, due to the resistive nature of hydrocarbon filled rocks, the guided field experiences little attenuation and leaks energy up to the seafloor. This leakage field is then recorded by ocean bottom electric and magnetic field receivers.

For very deep-water plays, the measured anomaly resulting from the leakage field is usually a good indicator for the presence of hydrocarbons. In shallow water, however, the ocean bottom receivers also measure a strong refraction and reflection off the sea surface, jointly referred to as the airwave, and possibly magnetotelluric fields. These downward traveling energy constituents mask the upward traveling leakage field from the reservoir such that the observed anomalies become very weak, in particular for deeper targets. Under such circumstances, interpretation of SBL data is facilitated by removal of the airwave and magnetotelluric fields. Not only are anomalies weak without this removal but – given bathymetry variations in the survey area – it can be impossible to choose a representative reference response for anomaly computation. This is especially critical for Scanning surveys in large frontier areas.

An effective method to remove the airwave and magnetotelluric fields has been introduced by Amundsen et al. (2006), which is based on wavefield decomposition into up- and downward traveling constituents. Assuming a primarily vertically traveling wavefield, the upward constituent of the *x*-component of the electric field just below the seafloor can be estimated at each receiver from the simple relation

$$E_x^{(U)} = 0.5\left(E_x - \sqrt{i\omega\mu_0\rho_{SF}}\,H_y\right), \qquad [1]$$

where the superscript *(U)* denotes "upward", $E_x$ and $H_y$ are the *x*-component and *y*-component of the measured electric and magnetic field, respectively, $\rho_{SF}$ is the resistivity of the seafloor, $\omega$ is angular frequency, $\mu_0$ denotes the free space magnetic permeability, and $i = \sqrt{-1}$. A similar expression exists

for the upward constituent of the $y$-component of the electric field. For large source-receiver offsets (i.e. > 3 km) the assumption of a vertically traveling wavefield is usually well satisfied.
In the following, we present synthetic examples of how Equation [1] improves SBL sensitivity to deep reservoirs in shallow water (250 m). As is most common in SBL data interpretation, we describe the reservoir response at a specified receiver by an anomaly curve obtained from normalizing the magnitude vs. offset (MVO) curve by a reference response:

$$|E_{x,\mathrm{norm}}(\mathrm{offset})| = \frac{|E_x(\mathrm{offset})|}{|E_x^P(\mathrm{offset})|} \qquad \left( = \left|1+\frac{E_x^S}{E_x^P}\right| = \left|1+\frac{|E_x^S|}{|E_x^P|}\exp\left(i(\phi_{E_x^S}-\phi_{E_x^P})\right)\right| \right). \tag{2}$$

Here $E_x^P$ stands for the reference response or primary field, which is the field that would be measured if no hydrocarbon reservoir was present. The reservoir gives rise to a so-called secondary field $E_x^S$, defined by the relation $E_x = E_x^P + E_x^S$. Using the notion of primary and secondary fields, the normalized magnitude $|E_{x\ \mathrm{norm}}|$ can be written as the term given in parentheses (where for brevity we have omitted the dependency on offset), which we will use later on in the text. Since the up-down separation given by Equation [1] requires knowledge or an "educated" guess of the seafloor resistivity $\rho_{SF}$, we also take a close look at the effect of assuming the wrong $\rho_{SF}$ and set up guidelines for choosing an appropriate resistivity value.

**3d Simulation And Processing Results**
Figure 1 illustrates a vertical cross-section of the 3D model that has been considered. The SBL response to this model has been simulated for varying reservoir depths between 750-2950 m below the seafloor using the FDTD program described by Maaø (2006). Responses have been computed for a source frequency of 0.25 Hz, a source elevation of 30 m above the seafloor, and a receiver positioned at the edge of the reservoir (see Figure 1). The reference response for anomaly computation was obtained from a simulation without the reservoir.

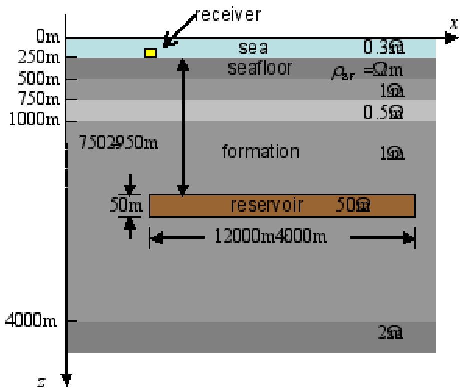


**Figure 1.** Illustration of the reservoir model.

The resulting anomaly curves without and with up-down separation are shown in Figure 2a and 2b, respectively, where the true seafloor resistivity of 2Ωm has been assumed. Since the receiver is located at the left edge of the reservoir, we show only data for source positions to the right of the receiver. The dashed horizontal line marks a fictitious detection threshold, i.e. if this particular reservoir produces an anomaly greater than 1.3 we will consider it detectable by the SBL method (NOTE: There is no universally valid threshold for the SBL method!). To account for the receiver noise floor (1e-10 V/m), no normalized magnitudes are plotted at offsets where the magnitude of the secondary field falls below the noise floor. Two important observations can be made. First of all, for this particular model, the up-down separation increases the detection depth from about 1.05 km to 1.95 km, thereby increasing the applicability of the SBL method immensely. And second, without up-down separation

(Figure 2a), “negative” anomalies (< 1.0) occur at large offset. The “negative” anomalies are a direct result of the strong airwave in shallow water SBL data. This follows from the equality term included in parentheses in Equation [2], which indicates that the normalized magnitude | $E_{x\ norm}$ |, despite its name, mixes magnitude and phase effects. When the airwave dominates the primary field $E_x^P$, the ratio | $E_x^S$ | / | $E_x^P$ | easily becomes smaller than one in conjunction with phase differences ($\Phi_{FS} - \Phi_{FP}$) greater than 90 degrees, thus yielding | $E_{x\ norm}$ | < 1.0. In such cases, it may be desirable to plot the ratio | $E_x^S$| / | $E_x^P$| instead of | $E_{x\ norm}$ |, as this produces an anomaly curve with no “negative” anomalies.

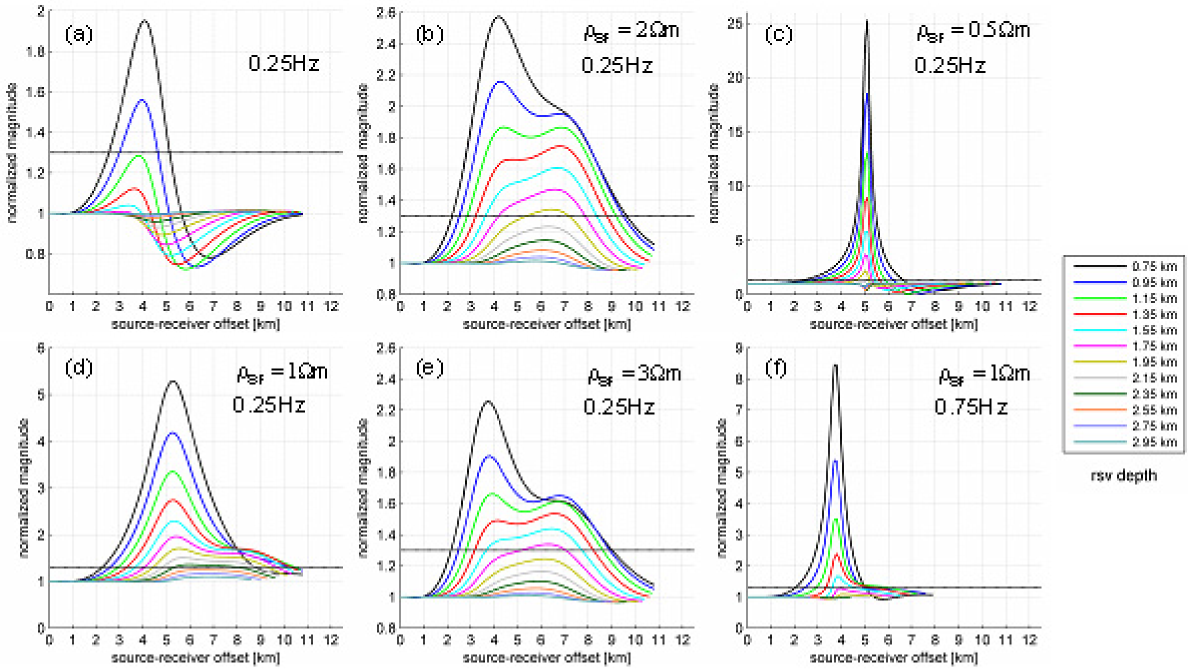


**Figure 2.** Normalized magnitude vs. offset (MVO) curves computed according to Equation [2] (a) without up-down separation, (b)-(f) with up-down separation.

It is important to note that up-down separation cannot eliminate the effect of the airwave entirely since the upward traveling wavefield also contains reflections of the airwave from shallow seafloor layering. These airwave reflections manifest themselves in Figure 2b by the decrease in normalized magnitude at offsets greater than 4.5 km. In deep water or in the case of a more homogenous seafloor, the anomaly would continue to grow beyond 4.5km.

Figures 2c-e show anomaly curves that are obtained when a wrong seafloor resistivity is assumed in the up-down separation, i.e. $\rho_{SF}$ = 0.5, and 3Ωm. Comparing with Figure 2a, we observe that for all three assumed seafloor resistivities, although being wrong, the anomalies are stronger than without up-down separation. However, for $\rho_{SF}$ = 0.5 and 1Ωm the anomalies are even stronger than when the correct seafloor resistivity is assumed (Figure 2b), with particularly large and spiky anomalies for $\rho_{SF}$ = 0.5Ωm. This raises the question of which is the most appropriate seafloor resistivity to choose?

To better understand the dependency of the normalized magnitude | $E_{x\ norm}$ | on the assumed seafloor resistivity, let us analyze the field ratio $E_x^S$/ $E_x^P$ in Equation [2] after up-down separation, i.e. $E_x^{S(U)}$/ $E_x^{P(U)}$. If the true seafloor resistivity is assumed, the denominator $E_x^{P(U)}$ approaches the true upward traveling constituent of the primary field (assuming small measurement errors), which is usually relatively weak compared to the true upward traveling constituent of the secondary field $E_x^{S,(U)}$ produced by the reservoir. Thus, we may conclude that the correct seafloor resistivity will always give a strong anomaly. Larger anomalies can only be observed in the presence of an airwave residual that cancels $E_x^{P(U)}$ out, in which case the denominator of the ratio $E_x^{S(U)}$/ $E_x^{P(U)}$ approaches zero. Since the phase of the airwave is practically constant, this cancellation occurs only for a narrow range of source-receiver offsets such that the anomaly becomes very spiky. The strong anomalies in Figure 2c are an example of such cancellation and are really more of a processing artifact than a meaningful anomaly. It is important to understand that such amplification of anomalies must be avoided, since slight resistivity variations in the formation that produce a weak secondary field might produce anomalies of the size that are representative for hydrocarbon reservoirs.

It is difficult to see that the anomalies for $\rho_{SF}$ = 1Ωm are influenced by an airwave residual as well. One way to deal with this ambiguity is to compute anomalies for the various harmonics of the source signal (e.g. 0.25, 0.75 and 1.25Hz). If $\rho_{SF}$ is a good choice, the anomaly of a reservoir should be smooth and wide for any frequency. That this is not the case for $\rho_{SF}$ = 1Ωm, is demonstrated by Figure 2f, showing the anomaly curves for a source frequency of 0.75 Hz.

To choose an appropriate seafloor resistivity $\rho_{SF}$, it also helps to analyze the magnitude and phase of the estimated upward traveling constituent of the primary field, $E_x^{S(U)}$, for various seafloor resistivities, as shown in Figure 3. A good choice of $\rho_{SF}$ is characterized by low magnitudes, no localized magnitude minimum, and a steep linear phase behavior out to large source-receiver offsets. These criteria are fulfilled for $\rho_{SF}$ = 1 and 2Ωm. Localized magnitude minima, as observed for $\rho_{SF}$ = 0.5Ωm at approximately 5km offset, will result in very spiky anomalies as explained above.

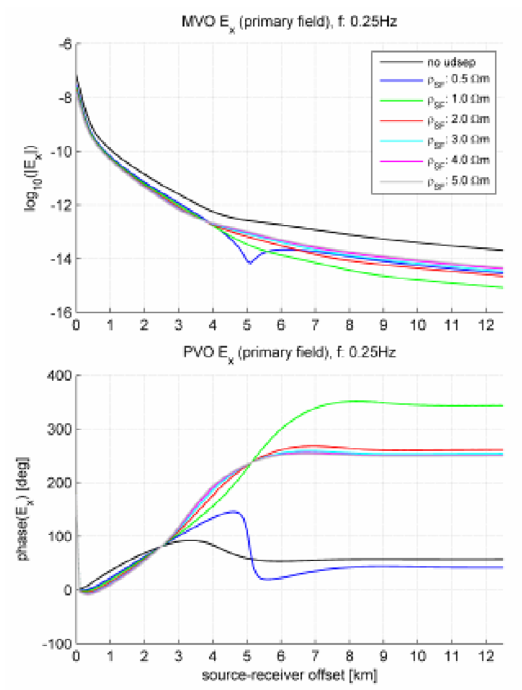


**Figure 3.** Analysis of the magnitude (MVO) and phase (PVO) of the reference response (primary field) without and without the reference response (primary field) without and with up-down separation for various seafloor resistivities. The magnitude has been scaled by the source dipole moment (1000A x 270 m).

## Conclusions

In shallow water, up-down separation significantly improves the sensitivity of the SBL method to deep hydrocarbon reservoirs. For the model analyzed here, detection depth increased as much as from 1.05 km to 1.95 km.

For the up-down separation to produce meaningful results, it is important to choose a seafloor resistivity close to the true one. The following guidelines help to make a good choice:

- Magnitude anomalies from hydrocarbon reservoirs tend to be smooth and wide for all source frequencies. No spiky anomalies should be observed.

- Negative magnitude anomalies (< 1.0) are likely indicators of airwave residuals.
- The estimated upward traveling constituent of the primary field should be low in magnitude, have no localized magnitude minimum for any offset, and exhibit a relatively steep linear phase behavior out to large offsets.

In addition to these guidelines, it is possible to invert the primary field (reference response) to obtain a resistivity-depth profile from which a seafloor resistivity estimate can be extracted (Mittet et al., 2004).

**References**


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