

# Time-lapse controlled-source electromagnetics using interferometry

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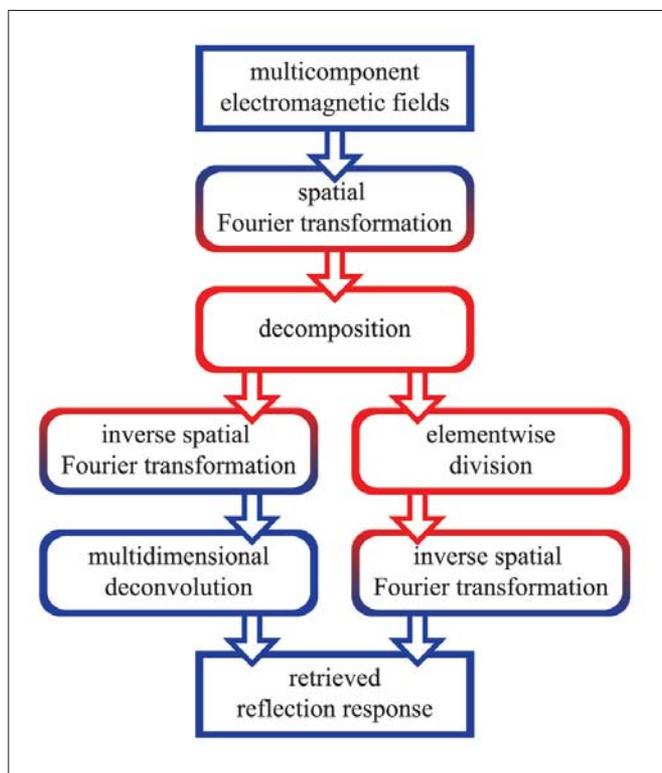
In time-lapse controlled-source electromagnetics, it is crucial that the source and the receivers are positioned at exactly the same location at all times of measurement. We use interferometry by multidimensional deconvolution (MDD) to overcome problems in repeatability of the source location. Interferometry by MDD redatums the source to a receiver location and replaces the medium above the receivers with a homogeneous half-space. In this way, changes in the source position and changes of the conductivity in the water-layer become irrelevant. The only remaining critical parameter to ensure a good repeatability of a controlled-source electromagnetic measurement is the receiver position.

## Introduction

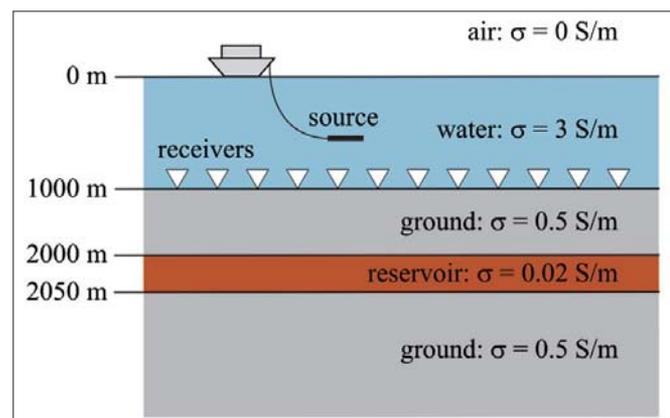
Marine controlled-source electromagnetics (CSEM) for exploration purposes aims to detect subsurface resistors such as hydrocarbon reservoirs. For this purpose, an electric source is towed by a boat over a set of multicomponent receivers at the ocean bottom. The source emits continuously a monochromatic low-frequency signal. A part of the resulting electric field diffuses through the subsurface, samples possible resistors, and is finally recorded at the receivers. For a more

detailed introduction to CSEM see Constable and Srnka (2007). A significant problem in CSEM is posed by the so-called airwave. It consists of an electromagnetic field, which diffuses vertically upward in the water layer and is refracted at the air-water interface. Due to the extremely low conductivity in air, the field propagates in the air as a wave with the speed of light; thereby the field is continuously diffusing from the air through the water-layer to the receivers. The airwave has a strong amplitude at all receivers if the water depth is small. Since the airwave does not carry information about the subsurface, one aims to remove it from the data. This can, for example, be achieved with interferometry by multidimensional deconvolution, which replaces the structure above the receivers (overburden) with a homogeneous half-space consisting of the same material parameters as the sediment below the receivers (Wapenaar et al., 2008). Consequently, all events related to the air and the water layer, which includes the airwave, are removed.

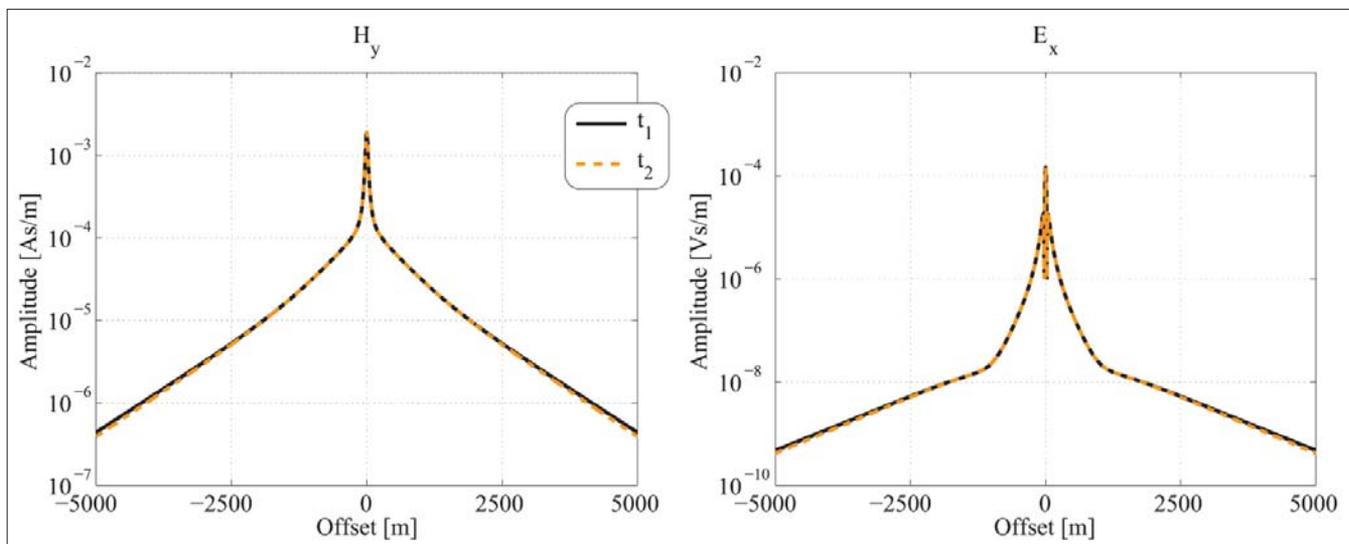
In this study, we use a different property of interferometry in connection with a time-lapse CSEM measurement. Constable and Weiss (2006) have shown that CSEM is sensitive to changes in thickness of a subsurface resistor, which hints at the feasibility of time-lapse CSEM. Orange et al. (2009) numerically tested the detectability of different reservoir depletion models. They concluded that depleting a reservoir produces small but measurable changes in the CSEM response. To measure these changes, they suggest a maximum repeatability error of less than 1% to 2% of the CSEM measurement. Wirianto et al. (2010) tested the feasibility of land CSEM reservoir monitoring on a complex geological model by numerically simulating surface-to-surface and surface-to-borehole acquisition geometries. They conclude similarly that



**Figure 1.** Graphical representation of the processing flow. Blue boxes are in the space domain, red boxes in the spatial Fourier domain. The right path is possible only in case of a laterally invariant medium.



**Figure 2.** The modeling setup (not to scale). The source (black horizontal bar) is 25 m above the receivers (white triangles). The electric conductivity  $\sigma$  is given in every layer.



**Figure 3.** The crossline magnetic field  $H_y$  (left panel) and the inline electric field  $E_x$  (right panel) recorded at the first time of measurement  $t_1$  (solid black curve) and at the second time of measurement  $t_2$  (dashed orange curve) as a function of offset with respect to the source position. Note that the amplitude scale is different for the electric field than for the magnetic field.

a repeatability error smaller than 1% is required to successfully detect changes in the reservoir. To achieve this, we propose to use interferometry by MDD. Interferometry does not only replace the overburden with a homogeneous half-space, it also redatums arbitrarily distributed sources with random source strengths to a well-defined receiver array. In other words, it does not matter where the sources are located in the ocean and therefore source-mispositioning issues become irrelevant. Because the water layer is removed, possible changes in seawater conductivity are removed as well and, generally, the detectability of changes in the subsurface is increased, because the airwave is removed as described in the previous paragraph. The only possibly problematic issue that remains in time-lapse CSEM is the repeatability of the receiver positions, but that should be easier to achieve than the repeatability of the source, because the receivers are stationary.

In the next section, we briefly describe how interferometry by MDD works. Then we apply interferometry to numerically simulated time-lapse CSEM data consisting of two times of measurement.

### Theory

Interferometry by MDD can roughly be divided into two parts:

- First, the recorded electromagnetic fields need to be decomposed into upward- and downward-decaying components, which was first done by Amundsen et al. (2006). We use an algorithm of Slob (2009). To perform the decomposition, the material parameters just below the ocean bottom, but not those of the ocean, are necessary. This algorithm requires in 3D that all four horizontal components of the electromagnetic field are recorded. Furthermore, the data need to be sampled properly (dense enough) and completely (also at zero offset) in order to transform the data to the spatial Fourier domain (Hunziker et al., 2010).

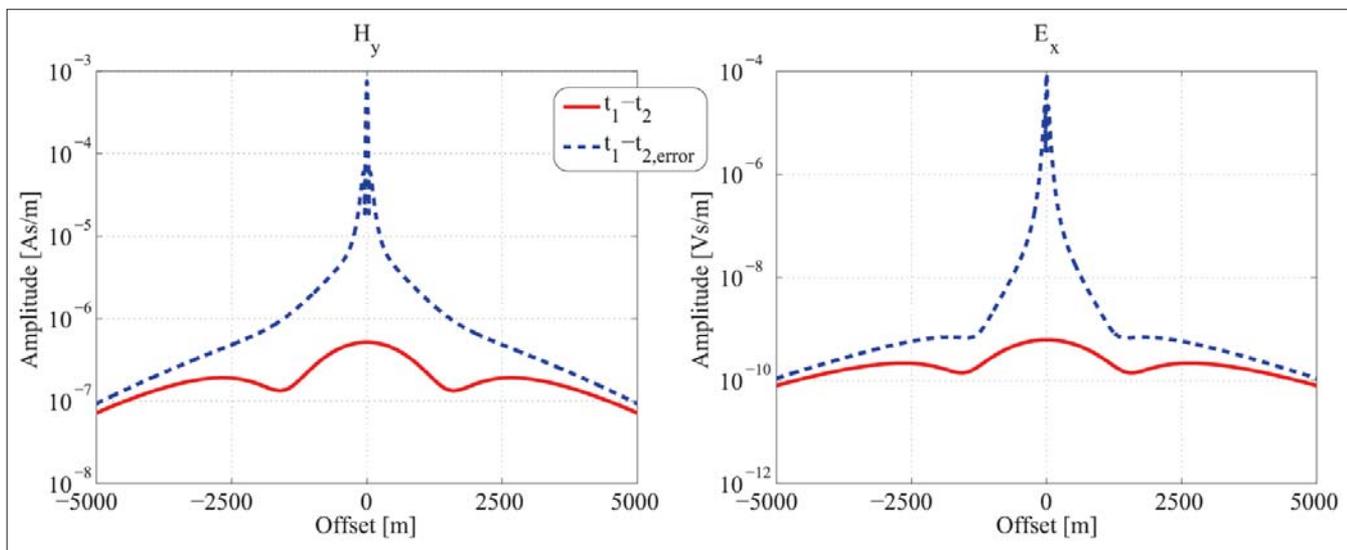
- In the second part, the reflection response (i.e., the scattered Green's function of the subsurface) is retrieved by multidimensional deconvolution of the upward-decaying field with the downward-decaying field (Wapenaar et al., 2008). This can, for example, be achieved with a least-squares inversion. In case of a laterally invariant medium, the deconvolution can be carried out in the spatial Fourier domain. In this case, the deconvolution becomes an elementwise division.

The different steps of the processing flow are represented in Figure 1. Since here we use a 1D Earth model, we solve for the reflection response in the spatial Fourier domain. Hunziker et al. (2009) have shown that the complete interferometry by MDD processing can also be applied if the data are contaminated with realistic levels of noise.

### Results

The modeling setup at the first time of measurement  $t_1$  is shown in Figure 2. The source is towed 25 m above the receivers. The depths as well as the electric conductivities  $\sigma$  of all layers are given in the figure. At the second time of measurement  $t_2$ , 20% of the reservoir has been produced by bottom flooding. This is modeled by moving the bottom of the reservoir 10 m upward. Thus the reservoir thickness at  $t_2$  is 40 m. A third data set is recorded at the same time ( $t_2$ ), but with a different acquisition condition. This means that the source is towed 15 m higher than at  $t_1$  and the salinity of the sea is changed, resulting in an electric conductivity  $\sigma$  of 3.2 S/m compared to 3 S/m at  $t_1$  in the water layer. We refer to this data set as  $t_{2,error}$ .

The data are modeled in 2D, which means that the source is infinitely long in the crossline direction. In that case, the requirement to record all four horizontal components of the electromagnetic field in order to use the decomposition algorithm by Slob reduces to two components (i.e., the inline



**Figure 4.** Difference of the magnetic field (left panel) and the electric field (right panel) at the two times of measurement. Solid red curve: at the time of measurement  $t_2$  the source is at the same position and the conductivity of the water is the same as in  $t_1$ . Dashed blue curve: at the time of measurement  $t_2$  the source is misplaced vertically by 15 m and the conductivity of the water layer is increased from 3 S/m to 3.2 S/m.

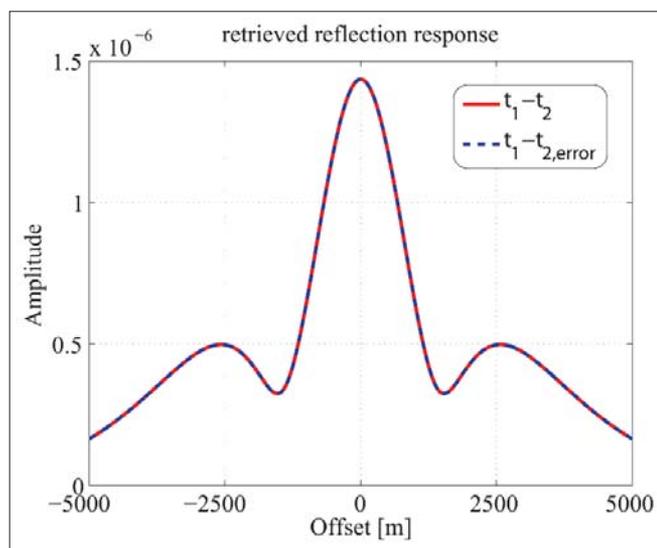
electric component  $E_x$  and the crossline magnetic component  $H_y$ ). These two components are shown for the two times of measurement  $t_1$  and  $t_2$  in Figure 3.

The electromagnetic fields at the two times of measurement are very similar to each other. Small differences are visible only at larger offsets. In order to visualize the differences more clearly, the fields are subtracted. The solid red curve in Figure 4 is the difference between the responses at the two times of measurement with exactly the same acquisition parameters for  $t_1$  and  $t_2$ . The dashed blue curve is the difference between the response at  $t_1$  and  $t_{2,error}$  (i.e., with the altered acquisition parameters at  $t_2$ ). The dashed blue curve is at small and intermediate offsets much higher than the solid red curve. This means that the misplacement of the source and the change in the electric conductivity of the ocean have a larger impact on the recorded electromagnetic fields than the change of the reservoir thickness.

We apply interferometry by MDD to these data sets to remove the effects of the misplacement of the sources and the increase in conductivity of the ocean. The differences of the retrieved reflection responses are depicted in Figure 5. Because interferometry redatumms the sources to receiver positions and since the overburden is replaced by a homogeneous half-space, the effects of the mispositioning of the sources and the change in ocean conductivity are removed. Therefore, the solid red curve ( $t_1 - t_2$ ) is identical with the dashed blue curve ( $t_1 - t_{2,error}$ ). This is achieved without knowing the actual source locations in both time-lapse measurements and without knowing the conductivity values in the sea. Only the conductivity just below the ocean bottom is required for the decomposition. This value can be easily obtained from local measurements.

## Conclusions

Three CSEM data sets are modeled. The first one at  $t_1$  before production of an oil reservoir, the second one at  $t_2$  after



**Figure 5.** The difference of the retrieved reflection response at the two times of measurement. Solid red curve =  $t_1 - t_2$ . Dashed blue curve =  $t_1 - t_{2,error}$ . Note that the vertical axis is linear in this figure.

depletion of the reservoir by 20%, and a third one in the same situation as the second one, but with simultaneously an error in the source position and an increased conductivity of the ocean. The last data set is referred to as recorded at  $t_{2,error}$ . The difference of the data sets recorded at  $t_1$  and  $t_2$  with the same acquisition condition reveals that the change in the reservoir thickness can be detected very well. The difference between the data set at  $t_1$  and the data set at  $t_{2,error}$  with the changed acquisition condition has much larger values than the difference between  $t_1$  and  $t_2$ . In other words, the change in reservoir thickness has a much smaller impact on the time-lapse data than the change in the source position and the change of the ocean conductivity.

We apply interferometry by MDD to these data sets in order to retrieve the reflection response. By applying inter-

ferometry, the medium above the receivers is replaced by a homogeneous half-space and the sources are redatumed to receiver positions. In other words, the changes in the acquisition condition are completely removed in the retrieved reflection response. Consequently, by applying interferometry by MDD to time-lapse CSEM data, the source positions do not need to be at the same locations, because they are redatumed to receiver positions. Furthermore, changes in the salinity of the ocean can also be removed successfully.

What remains as a critical acquisition parameter in time-lapse CSEM is the position of the receivers. Orange et al. (2009) concluded that receiver positions should be known and repeatable to less than 5–10 m accuracy. They propose to use permanent monuments at the ocean bottom to which the receivers can be attached by remotely operated vehicles. Andreis and MacGregor (2010) simply assume the usage of a permanent receiver system to overcome this issue. **TLE**

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