Synthesized-2D CSEM-interferometry using automatic source line determination

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summary

Interferometry by multidimensional deconvolution applied to Controlled-Source Electromagnetic data replaces the medium above the receivers by a homogeneous halfspace, suppresses the direct field and redatums the source positions to the receiver locations. In that sense, the airwave and any other interactions of the signal with the air-water interface and the water layer are suppressed and the source uncertainty is reduced. Interferometry requires grid data and cannot be applied to line data unless the source is infinitely long in the crossline direction. To create such a source, a set of source lines is required. We use an iterative algorithm to determine the optimal locations of these source lines and show that more source lines are required if the source is towed closer to the sea bottom and closer to the receivers.

Introduction

In marine Controlled Source Electromagnetics (CSEM), an electric source is towed in the water behind a boat. In the frequency-domain mode, the source emits a monochromatic low-frequency signal. The resulting electromagnetic field diffuses through the water and the subsurface to the multicomponent receiver stations at the ocean bottom. Since CSEM is sensitive to resistors in the subsurface, it can help to determine if a potential reservoir, which was localized by seismics, is hydrocarbon bearing or not. An overview over the method can be found in Constable (2010).

The signal does not only travel via the subsurface from the source to the receivers, but also directly through the water and along the air-water interface (Amundsen et al., 2006). The latter is known as the airwave. These travelpaths do not contain any information about the subsurface. To the contrary, they obscure the subsurface response. We aim to suppress the airwave, any other effects of the air-water interface and the direct field by interferometry (Wapenaar et al., 2008). Interferometry by multidimensional deconvolution (MDD) replaces the medium above the receivers with a homogeneous halfspace, redatums the sources to the receiver positions and suppresses the direct field. In this way also source uncertainty issues can be reduced. This approach has also been presented as Lorentz water-layer elimination (Nordskag et al., 2009). The resulting scattered Green's function of the subsurface, henceforth called reflection response, can be inverted for the subsurface conductivity distribution. We expect a better defined solution space than for an inversion scheme using standard CSEM data, because strong events like the airwave have been suppressed and the source uncertainty has been reduced.

Interferometry by MDD requires the fields to be properly sampled. That includes measurements on an areal grid to capture the 3D-structure of the electromagnetic field. To the authors knowledge, grid measurements are not common practice in CSEM up to now. Instead, one or a few receiver lines are recorded. Interferometry in a 2D-sense assumes the data to be truly 2D, i.e., the source is infinitely long in the crossline direction in which direction absence of heterogeneities in the subsurface is assumed. In order to apply this 2D-interferometry to line-data, we propose to create synthesized-2D data from the 3D data. This can be done by acquiring several source lines off the receiver line. Subsequent integration over these source lines simulates an infinitely long source in the crossline direction. Then, 2D-interferometry can be applied to the resulting data. This approach assumes the medium to be laterally invariant in the crossline direction. No assumptions are made about the medium in the inline direction.

Naturally, one wants to create this infinitely long source in the crossline direction by acquiring data along as few source lines as possible. In this paper, we discuss how to determine the position of the source lines avoiding unnecessary lines. Further, the synthesized-2D Interferometry scheme is presented using a numerical example.

Method

To determine the position of the source lines, an iterative scheme is used. As input, a selection of source lines as well as the electromagnetic field due to a dense source line spacing are needed. In the first iteration, the electromagnetic field for sources halfway between the given source lines is computed by linear interpolation. These interpolated source lines are compared with data due to a source at this position. If the relative error is larger than a predefined threshold, the source line is needed to properly sample the field. Otherwise, enough information is already provided by the current source-line distribution and that specific source line is therefore not needed. This scheme is repeated until the relative error for all interpolated source lines is below a prescribed threshold. The idea is to use this scheme prior to acquiring the data in the field on numerical data in order to determine the source lines which will be acquired in the field. In our example, presented in the next section, we use as input three source lines which are at -20, 0 and 20 km offset from the receiver line. The relative error is computed on the logarithmic amplitude of the electromagnetic field and the threshold is set to 5%.

After the synthesized-2D data have been created, the interferometry workflow consists roughly of three steps. Firstly, a synthetic aperture source is created by weighting and summing source positions in the inline direction (Fan et al., 2010) in order to damp high wavenumbers to avoid aliasing of sparsely sampled data, as it is common in CSEM. We use a Gaussian distribution function to determine the weights of the different source positions:

$$f(x) = \exp\left(-\frac{(x - x_{\text{syn}})^2}{2(l/\nu)^2}\right), \tag{1}$$

where x represents the inline position of the source and, accordingly, x_{syn} gives the centre of the synthetic aperture source. The length of the synthetic aperture source l is 5 km and the factor ν is set empirically to 5. Secondly, the multicomponent fields are decomposed into upward and downward decaying fields, $\hat{\mathbf{P}}^-$ and $\hat{\mathbf{P}}^+$, respectively. The quantities $\hat{\mathbf{P}}$ are matrices with the receivers for one source on the columns and the sources for one receiver on the rows (Berkhout, 1982). The circumflex indicates the frequency-space domain. The decomposed fields can be related to each other by the reflection response of the subsurface $\hat{\mathbf{R}}_0$: $\hat{\mathbf{P}}^- = \hat{\mathbf{R}}_0\hat{\mathbf{P}}^+$. Thirdly, we solve for $\hat{\mathbf{R}}_0$ using the least-squares solution $\hat{\mathbf{R}}_\mathbf{0} = \hat{\mathbf{P}}^-(\hat{\mathbf{P}}^+)^\dagger[\hat{\mathbf{P}}^+(\hat{\mathbf{P}}^+)^\dagger + \varepsilon^2\mathbf{I}]^{-1}$, where the dagger means complex conjugation and transposition. The stabilization parameter ε prevents the inversion from getting unstable. The matrix $\mathbf{I}$ is the identity matrix. In a medium that is also laterally invariant in the inline direction, it is possible to solve for $\hat{\mathbf{R}}_0$ in the frequency-wavenumber domain. Then the deconvolution becomes a much more efficient elementwise division.

Results

We model the inline electric field component E_x and the crossline magnetic field component H_y for one line of receivers and a dense set of source lines for the setup shown in Figure 1. The source height h is 50 m. The electromagnetic field for a receiver spacing of 10 m and a source line spacing of 10 m is shown in Figures 2a and 2b. Note that the dense receiver line spacing is only for illustration purposes. For the rest of the numerical experiment we use a receiver spacing of 640 m. In contrast, the dense source line spacing is used in the iterative scheme to find the best distribution of source lines. The source line distribution found is indicated by black dashed lines for the crossline magnetic field and white dashed lines for the inline electric field. The different colours are only for illustration purposes. The source-line distribution is the same for the magnetic as for the electric field because the algorithm simultaneously optimizes it for both components. Note, that there are two more source lines at -20 and 20 km crossline offset, which are not visible on the plot due to the limited offset range shown. In total a set of 21 source lines are required.

In Figures 2c and 2d, the amplitude and the phase of the synthesized-2D electromagnetic field are shown (dashed red curve). In the same figures, also a modelled-2D field is plotted (solid blue curve). The synthesized-2D data agrees with the modelled-2D data up to an offset of 5 km, but deviate for larger offsets. If the source lines are infinitesimally close together for an infinite offset range, the construction of the synthesized-2D field would be perfect. In our case we have a sparse source-line distribution for a limited offset range. The automated scheme to determine the locations of the source lines has done a good job, because also a denser distribution does not improve the correctly constructed offset-range. Consequently, only source lines at larger offsets would increase the well constructed offset range. We do not include those source lines, because in reality a signal from sources that are so far off the receiver line would drop below the noise floor.

The reflection response which has been retrieved by applying the interferometry workflow described in the previous section to synthesized-2D data is shown in Figure 2e with a dashed red line. It agrees at all offsets very well with the reflection response retrieved from the modelled-2D data (dashed blue line). The question arises, what has happened with the artefacts caused by the incomplete construction of the synthesized-2D fields at large offsets? When creating the synthesized-2D data, the TE-mode and, therefore, also the airwave is suppressed. Since the construction is not perfect, the airwave is still present in the synthesized-2D data. By applying the interferometry workflow, the airwave and, therefore, the artefacts from the incomplete construction are suppressed.

The solid grey curve of Figure 2e is a directly modelled reflection response computed on a very dense receiver spacing. In other words, the correct solution. The two retrieved reflection responses agree with the directly modelled reflection responses for small and intermediate offsets, but deviate at large offsets. The reason can be found in the choice of the parameter ν in the synthetic aperture source and, indirectly, in the receiver spacing. A large receiver spacing requires a smaller value for the parameter ν in order to filter out more high wavenumbers. Consequently, denser receiver spacings allow choosing a larger value for ν and lead to the disappearance of these artefacts in the retrieved reflection responses.

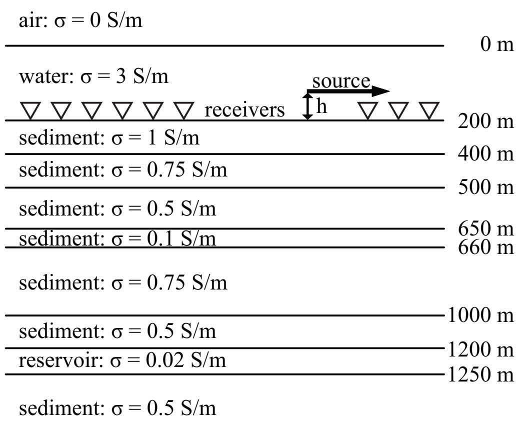

Figure 1 *Model used for synthetic data (not to scale). The parameter h indicates the height of the source (black arrow) above the sea bottom. The receivers are located at the sea bottom (white triangles). The parameter σ specifies the conductivity of each layer.*

This numerical experiment has also been computed on the same setup for a source height h of 25 m and 10 m. If the source is towed closer to the sea bottom, the amplitude of the direct field is much stronger for small source-receiver offsets. In other words, the decay of the amplitude from the direct field is increased. To capture that decay more and more source lines are required. For the case of the source being towed 25 m above the sea bottom, 25 source lines are necessary, and for the case of the source being towed only 10 m above the sea bottom, 35 source lines are necessary, in order to properly construct the synthesized-2D data. The locations of the source lines used are given in Figure 2f as a matrix plot for the positive offsets. Water conductivity and frequency may also influence the amount of source lines necessary.

Conclusions

2D CSEM interferometry can be applied to line data if the data are converted to synthesized-2D data by integrating over a set of source lines in the crossline direction. We have used a numerical optimization algorithm to show that for a dataset with the source 50 m above the sea bottom 21 source lines are required to properly construct synthesized-2D data. More source lines are necessary if the source is closer to the sea bottom.

Acknowledgements

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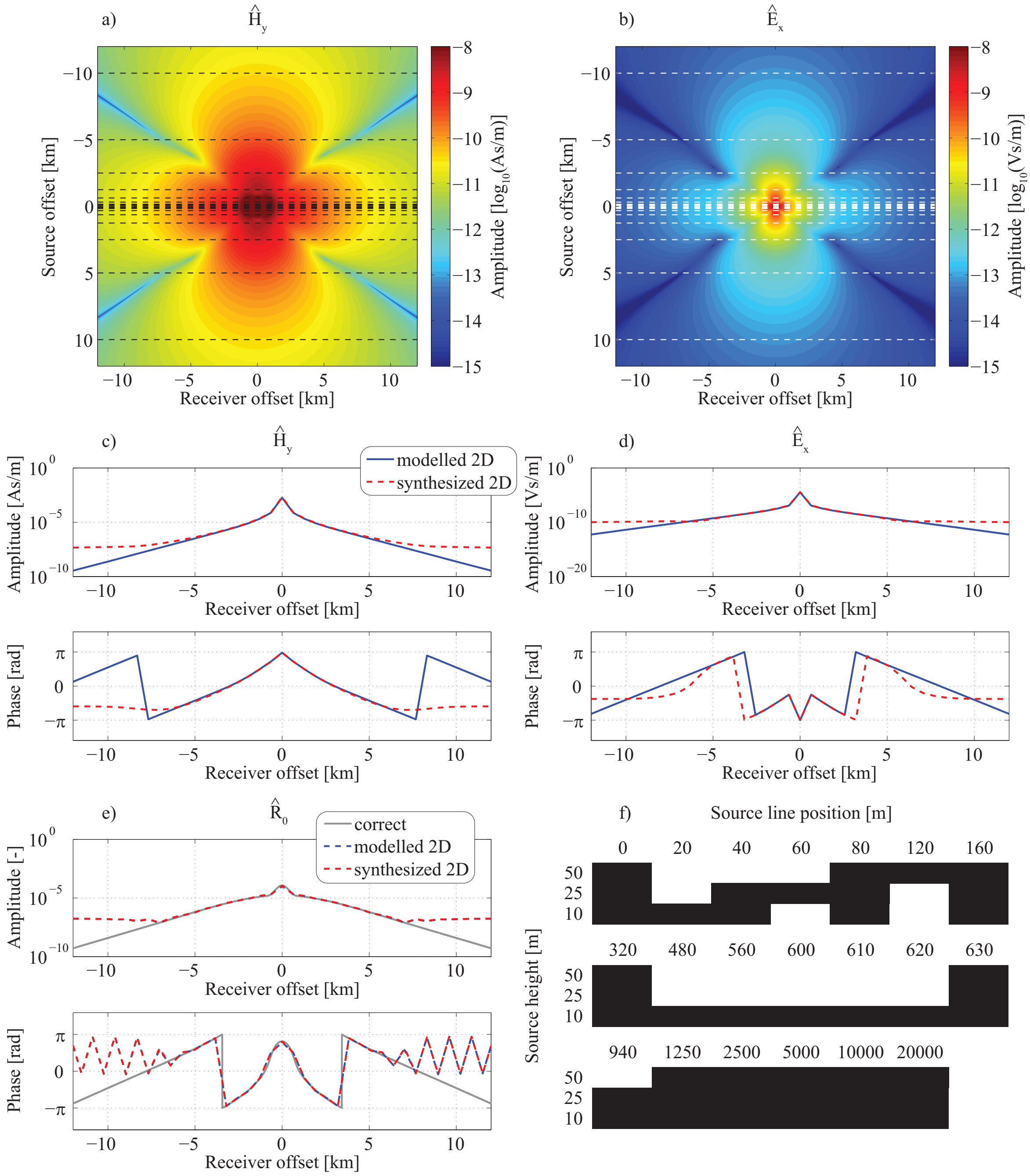

Figure 2 *a) Crossline magnetic field and b) inline electric field for a densely sampled line of receivers and a dense set of source lines. The source lines selected in order to create the synthesized-2D data are indicated by dashed lines. c) 2D crossline magnetic field and d) 2D inline electric field. The synthesized-2D fields are plotted with a dashed red line, the modelled-2D fields with a solid blue line. e) Reflection responses: retrieved from the synthesized-2D data (dashed red line), retrieved from the modelled-2D data (dashed blue line) and directly modelled reflection response (solid grey line). f) Source lines used to construct the synthesized-2D field for source heights of 50 m, 25 m and 10 m for positive crossline offsets are indicated by black boxes.*