Resolution and Precision of Resistivity Models from inversion of Towed Streamer EM data

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Summary

Towed Streamer EM acquisition facilitates dense spatial sampling of Controlled Source Electromagnetic (CSEM) data. The spatial sampling density, i.e. the separation between each spatial measurement point along a survey line has a fundamental effect on the ability to recover a cross section of vertical and horizontal resistivity from 2.5D inversion. It is shown with a real data case from the North Sea that a 1000 m separation between the data points results in a poorly resolved overburden where the estimated resistivity structure is clearly not geologically consistent. This also affects the deeper structure where the resolution of the image of the reservoir is degraded. The inversion performance in terms of resolution and covariance is improved significantly when using all data in the Towed Streamer EM data set. A decrease of the spatial data point separation to 250 m makes the resulting overburden resistivity consistent and geologically sound when comparing with available geological information in the area of the survey. As a result, the resolution of the resistivity cross sections improve by a factor of 5 to 10. The covariance is on the other hand slightly increased by a factor of 2.

Introduction

The quality of resistivity images from CSEM data inversion can be quantified by calculating the corresponding resolution and covariance matrices. They reveal how well the inversion algorithm can recover the resistivity models and to what precision the resistivity values are estimated given the noise and uncertainties in the input data for the inversion. The spatial data density, i.e. how dense the frequency responses of the earth can be measured along a survey line will influence the inversion quality and hence the resolution and precision of the inversion results.

It is demonstrated in this abstract that an increase in the spatial data density from 1000 m to 250 m between the data points along a survey line improves the data resolution and precision in the inversion of Towed Streamer EM data significantly. The upper part of the overburden is in fact not correctly recovered with a spatial separation of 1000 m. The inversion result becomes geologically more realistic with higher resolution when the spatial data point separation is decreased to 250 m.

Resistivity resolution and covariance

First order expressions of the resistivity resolution and covariance are derived from the model update equation in the inversion algorithm, (Hansen, 1998). In this case the open source inversion code MARE2DEM, (Key, 2014), is used for inversion of Towed Streamer EM data. This code is based on a parallelized adaptive finite element method. Non-linear inversion is carried out using the Occam method, which is a regularized variant of Gauss-Newton minimization with smoothing. Kalscheuer (2010) showed that the first order linearized smoothness-constrained resolution and covariance expressions are representative and accurate estimates of the model variability.

The starting point in the derivation is the model update equation, which reads like:

$$\mathbf{m}_{k+1} = \mathbf{S}_k^{\otimes}\mathbf{W}\left(\mathbf{d} - \mathbf{F}(\mathbf{m}_k) + \mathbf{J}_k\mathbf{m}_k\right) \tag{1}$$

where

$$\mathbf{S}_k^{\otimes} = \left[\mu(\partial^T\partial) + \mathbf{S}_k^T\mathbf{S}_k\right]^{-1}\mathbf{S}_k^T = \text{ regularized inverse}$$

$$\mu(\partial^T\partial) = \text{ smoothing regularization}$$

$$\mathbf{S}_k = \mathbf{W}\mathbf{J}_k$$

$$\mathbf{J}_k = \text{Jacobian matrix} = J_{ij} = \frac{\partial F_i(\mathbf{m}_k)}{\partial \log_{10}\rho_j}$$

$$\mathbf{W} = \text{ Weight matrix} = \text{diag}\left(\frac{1}{\sigma_i}\right)$$

$$\mathbf{F}(\mathbf{m}_k) = \text{ Modelled frequency response}$$

$$\mathbf{d} = \text{ Frequency response from measured data}$$

$$\sigma_i = \text{ Standard deviation of } d_i$$

$$\rho_j = \text{ Resistivity}$$

$$\mathbf{m}_k = \text{ Model vector } k = (\log_{10}\rho_j)_k \tag{2}$$

The model after the final iteration of (1) is now assumed to be close to an exact model of the problem satisfying the data. The following relation can then be derived:

$$\mathbf{m}_{k+1} = \mathbf{R}_k\mathbf{m}_{exact} + \mathbf{S}_k^{\otimes}\mathbf{W}\mathbf{n} \tag{3}$$

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where

$$\mathbf{R}_k = \mathbf{S}_k^{\otimes}\mathbf{S}_k \quad (4)$$

The matrix $\mathbf{R}_k$ is the resolution matrix of the inversion, (Hansen 1998). It reveals how well the inversion algorithm can recover a resistivity model. In fact the resolution matrix quantifies the smoothing regularization effect in this case. This means that $\mathbf{R}_k$ maps the spreading of resistivity elements in $\mathbf{m}_{exact}$ to the model vector $\mathbf{m}_{k+1}$. The resolution is perfect if the resolution matrix equals the unit matrix. The inversion has then recovered the resistivity model perfectly. Hence, the diagonal elements of $\mathbf{R}_k$ quantify how well each cell in the inversion grid is resolved. A number less than one in a cell means that the resistivity value of the exact model is spread out over a number of adjacent cells in the inversion result. Each column in the resolution matrix shows how the values in the exact model are spread to several cells in the model from inversion.

The model covariance is a measure of the stability of the model from inversion. It describes how the data errors given by σ_i, i.e. the standard deviations, propagate into errors of the model $\mathbf{m}_{k+1}$. The covariance matrix is directly derived from eq. (2) and becomes:

$$\text{cov}\left[\mathbf{m}_{k+1}\right] = \mathbf{S}_k^{\otimes}\mathbf{S}_k^{\otimes T} \quad (5)$$

where the covariance of $\mathbf{Wn}$ is equal to one.

The Alvheim Boa field in the North Sea

The resolution and covariance are calculated for resistivity cross sections along a survey line shown as line 202 in figure 1. Towed Streamer EM data were acquired along this survey line close to the Alvheim Boa reservoir on the Norwegian sector in the North Sea. The reservoir is of sandstone type with a burial depth of 2,100 m below the mud-line. The reservoir reaches its maximum thickness (red) immediately to the west of the survey line. The water depth underneath the survey line varies between 110 and 125 m. The overburden consists of shale and sandstone layers. See (Mattsson, 2013) for a more thorough description of this survey particular survey.

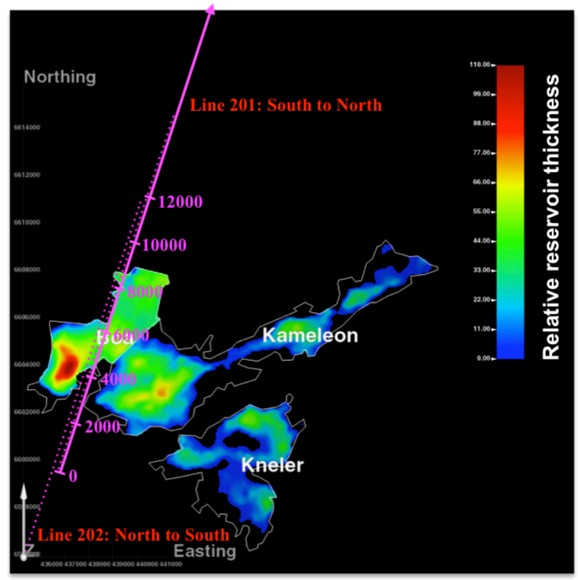

Figure 1: A thickness map of the Alvheim Boa reservoir including two towed streamer EM survey lines.

The Towed Streamer EM system consisted of an 800 m long electric bi-pole source towed at a depth of 10 m. A 100 s long Optimized Repeated Sequence (ORS) (Mattsson et al., 2012) followed by 20 s silent time was used as source sequence, a shot, to inject 1500 A electric current into the seawater. In this case the useful frequencies were five and ranged from 0.15 to 0.75 Hz. The ORS sequence was repeated in 60 shots along the survey line separated by 250 m. The resulting electric field was measured in an EM streamer towed at a depth of 50 m at offsets from 1000 to 7500 m. The source and the streamer were towed from the same vessel at a speed of 4 kn. Finally, the electric field was then deconvolved with the source sequences to obtain the frequency responses of the earth.

2.5D inversion of Towed Streamer EM data

The frequency responses for all the 60 shot points are inverted with the 2.5D MARE2DEM code. Nine offsets between 1450 m and 7500 m and five frequencies from 0.15 Hz to 0.75 Hz are used for each of the shots. The resulting vertical and horizontal resistivity cross-section of the sub-surface as a result of the inversion is shown in figure 2. The inversion reached a Root Mean Square misfit of 0.85 after 10 iterations.

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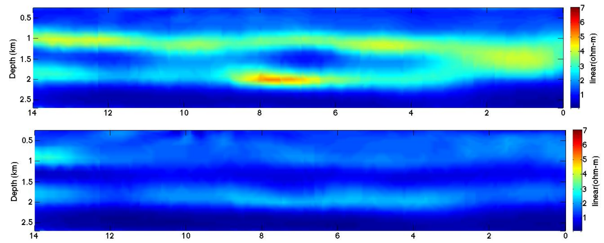

Figure 2: The vertical (top) and horizontal (bottom) resistivity cross-sections resulting from inversion of Towed Streamer EM data with a shot separation of 250 m.

The horizontal axes in figure 2 show the distance in km from north (right) to south (left). The vertical resistivity shows a resistive anomaly of 5-6 Ohm m at a depth of 2 km below the mud-line coinciding laterally with the Boa reservoir location. There is also a layer of slightly higher resistivity at a depth of 1000 m corresponding to a sand layer in the overburden. The horizontal resistivity is somewhat lower through out the cross section. It is shown below that the towed streamer EM data has equal resolution and precision in the horizontal resistivity as for the vertical resistivity.

The data is now decimated to every fourth shot, which means that the shot separation is increased from 250 m to 1000 m. The same offsets and frequencies are still used for each shot. The corresponding inversion results are shown in figure 3. It is now seen that the overburden is irregular and patchy and does not look geologically consistent. The anomaly coinciding with the Boa reservoir is still there but less pronounced. This shows the importance of dense spatial sampling. In particular, 1000 m shot separation is too sparse.

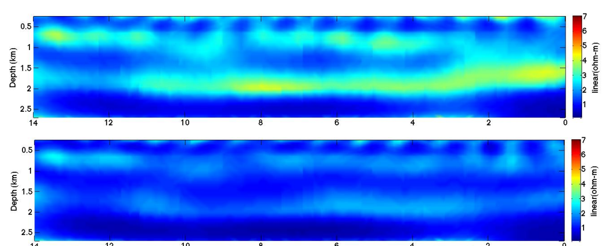

Figure 3: The vertical (top) and horizontal (bottom) resistivity cross-sections resulting from inversion of Towed Streamer EM data with a shot separation of 1000 m.

Resolution of the inversion result

The quality of the inversion results in figures 2 and 3 is now quantified by calculating the corresponding resolution and covariance matrices according to equation (4). The resolution of the resistivity values in each cell in figures 2 and 3, i.e. the diagonal of the corresponding resolution matrices is plotted in logarithmic scale in figures 4 and 5, respectively.

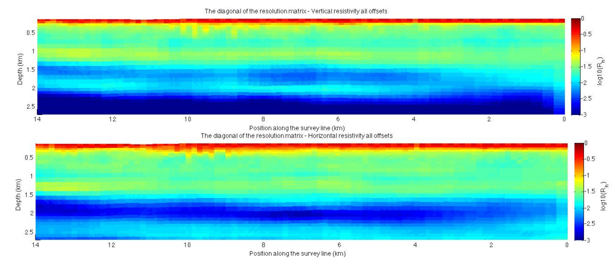

Figure 4: The vertical resistivity resolution (top) and horizontal resistivity resolution (bottom) with a shot separation of 250 m.

It can be seen that the resolution is only close to one in the first 200-300 m of the overburden. It then rapidly decreases towards 0.001 below 2200 m for the vertical resistivity with 250 m shot spacing. This means that a vertical resistivity value in a cell below 2200 m in an exact model is spread out over a number of cells. This spread implies that only large-scale structures of constant vertical resistivity can be resolved below this depth. Hence, the precision is degraded below 2200 m in this case for the vertical resistivity. The resolution for the horizontal resistivity is better at this depth and is similar to the vertical resistivity resolution in the overburden. This also tells us that the sensitivity for the horizontal resistivity is on the same level as for the vertical resistivity except at the resistive sand layer at 1000 m depth and at the resistive anomaly corresponding to the Boa reservoir.

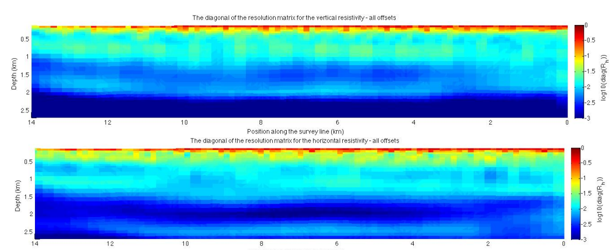

Figure 5: The vertical resistivity resolution (top) and horizontal resistivity resolution (bottom) with a shot separation of 1000 m.

The resolution decreases with a factor of 5-10 in the whole subsurface for both the vertical and horizontal resistivities when the shot separation is increased to 1000 m, figure 5. This means that the sensitivity decreases and as a consequence the inversion results are degraded as seen in figure 3. Hence, the spatial data density available with the towed streamer EM acquisition system increased the resolution and accuracy of the inversion results by a factor of 5-10 in this case.

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Covariance of the inversion result

The covariance of the 2.5D inversion results is calculated from expression (5). The model vector is the logarithm of the actual resistivity values according to (2) which implies that equation (5) expresses the relative covariance of the resistivity values. The square root of the diagonal of the covariance matrix, i.e. the relative standard deviation is plotted for the 250 m shot separation case in figure 6.

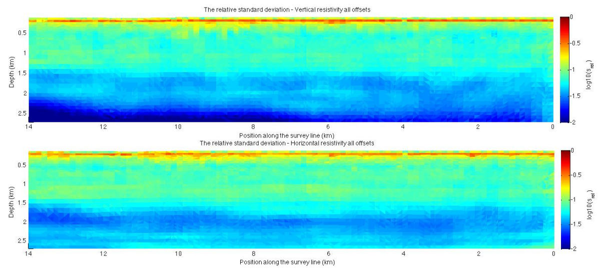

Figure 6: The vertical resistivity relative standard deviation (top) and horizontal resistivity standard deviation (bottom) with a shot separation of 250 m.

The relative standard deviation is varies between 0.1 – 0.3 in the upper part of the overburden and decreases gradually with depth. It can be seen that it is roughly the same for both the vertical and horizontal resistivity cross-sections. The fact that the standard deviation decreases with depth is due to the influence of the smoothing regularization. The data sensitivity is decreased with depth, which increases the regularization and makes the data errors less pronounced in the resistivity values.

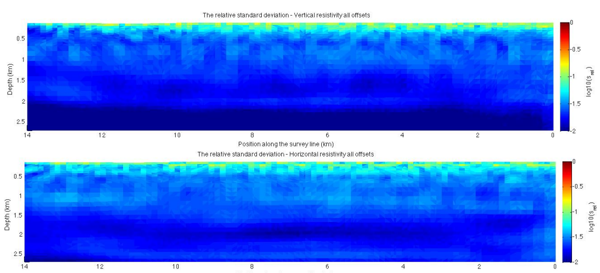

Figure 7: The vertical resistivity relative standard deviation (top) and horizontal resistivity standard deviation (bottom) with a shot separation of 1000 m.

The relative standard deviation is slightly decreased when the Towed Streamer EM data is decimated to a shot separation of 1000, figure 7. In fact, the values are generally decreased by a factor of 2 through out the cross-sections. The reason for this is the less amount of data compared to the 250 m separation case with four times as much data in the inversion. Again, the standard deviation is roughly the same for both the vertical and the horizontal resistivities.

Conclusions

It has been shown that the resolution and covariance of resistivity cross-sections from 2.5D inversion of Towed Streamer EM data are degraded by as much as a factor of 10 when the data is decimated from 250 m spatial separation to 1000 m spatial separation. The effect of that is manifested in the inversion results. In particular, the overburden vertical and horizontal resistivities become geologically inconsistent with a 1000 m separation where as a 250 m separation results in a plausible resistivity structure. The oscillating behavior of the overburden resistivity structure disappears when the spatial separation is 250 m, i.e. when all the data is used in the inversion. These results also apply in 3D inversion of towed streamer EM data from a set of parallel survey lines over an area.

It is also concluded that the resolution covariance measures of the final model after inversion are useful tools to quantify the quality of the model estimation. A striking feature is that the relative standard deviation is decreased with depth. The decrease appears contradictory but can be explained by the fact that the inversion is driven more by the smoothing regularization deeper down than in the shallow part of the sub-surface. This is due to less data sensitivity deeper down and hence less influence of the data errors in the deep structure. In the shallow part, the inversion is to a greater extent driven by the data. The regularization is less inflential which increases the uncertainty but at the same time also increases the resolution. Notable is also that the relative standard deviation is decreased by a factor of 2 when going from a 250 m shot separation to a 1000 m shot separation. This indicates that even though the resolution has been increased with a geologically improved inversion result, the uncertainty of the frequency response data has higher impact on the inversion result with a shorter shot separation, i.e. more data. However, in total the inversion result is improved by a shorter shot separation when both the resolution and the standard deviation are taken into account.

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EDITED REFERENCES

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