# 3D Focusing Inversion of Multi-transient EM Data in the Frequency Domain

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## Summary

We have produced an inversion code for frequency-domain controlled source EM data based on the 3D MT focussed inversion method developed by the Consortium for Electromagnetic Modelling and Inversion (CEMI). Broad-band frequency-domain data are easily determined from a knowledge of the earth's impulse response obtainable using the transient EM approach. A rigorous integral equation (IE) based forward modeller and regularized focussing inversion are employed. The method is efficient since Green's tensors need to be precomputed only once and saved for multiple use on every iteration of inversion and the same precomputed Green's tensors can be used for the Fréchet derivative calculation. In addition, forward modeling is required only once for each iterative step, resulting in a relatively fast but rigorous inversion method. To obtain a stable solution for blocky geological structures, we apply a regularization method based on a focussing stabilizing functional (Zhdanov 2002, Zhdanov et al. 2008). This stabilizer helps generate a sharp and focussed image of the anomalous resistivity distribution. The methodology is tested on a synthetic marine EM data set which presents a typical offshore petroleum scenario.

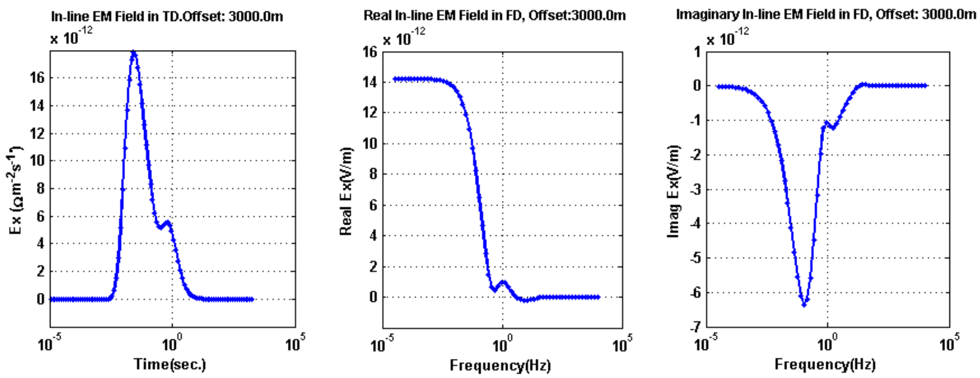
## Introduction

In order to interpret electromagnetic (EM) data some formal inversion or migration process must be applied to generate a resistivity model. Full 3D inversion using all of the data simultaneously to derive a single model is the goal and that is achieved here. CEMI developed a 3D inversion program for inverting passive magnetotelluric data. We have adapted that code by replacing the passive source by a galvanic source and inserting the appropriate IE modeler. Other components of the rigorous fast inversion process remain the same. In place of apparent resistivity and phase for magnetotelluric inversion, the code now makes use of real and imaginary parts of the earth's impulse response as a function of frequency. Responses at any number of frequencies may be used and these are available through Fourier transformation of the earth's impulse response determined fully by the multi-transient EM method.

## The Multi-Transient Electromagnetic method

In the MTEM method (Wright et al. 2002) current is injected into the earth through two source electrodes and this creates a potential distribution. A transient change is introduced at the source and the resulting changes in the potential distribution are monitored by measuring the changing potential difference between two receiver electrodes placed at some offset from the source. The source transient may be a step change in current, a pseudo-random binary sequence (PRBS) or any other waveform of a transient nature. One source-receiver pair constitutes one recording channel and many channels are recorded for each source position. The whole array, source plus receiver spread, is moved over the region of interest much as in roll-along seismics.

Deconvolution of the potential difference at a receiver by the source measurement yields the earth's impulse response for that source-receiver pair. The transient response contains a wide spectrum of frequencies and a wealth of information. The response may be analysed in the time domain (Figure 1a) and inverted directly or may be analysed in the frequency domain, where both the real and imaginary parts of the EM field over a broadband range of frequencies can be used for EM inversion (Figures 1b and c).




(a) (b) (c)

Figure 1 (a) Time-domain impulse response (b) real part of frequency-domain impulse response (c) imaginary part of frequency-domain impulse response for the in-line E-field at an offset of 3000 m over a 3D marine model with 100 m of water and with a resistive block (200 Ωm) embedded in a halfspace (1Ωm).

## 3D focussing EM inversion

In general, the EM inversion problem can be expressed by an operational equation:

$$d = A(\sigma) \ , \tag{1}$$

where $d$ stands for a data vector, $\sigma$ is model vector, and $A$ is a forward modeling operator. Equation (1) is ill posed, i.e., the solution can be non-unique and unstable. The conventional way to solve this ill-posed inverse problem is based on minimizing the Tikhonov objective function:

$$P(\Delta\sigma) = \varphi(\Delta\sigma) + \alpha s(\Delta\sigma) \, , \tag{2}$$

where $\Delta\sigma$ is a model perturbation vector taking the model $\sigma$ to a better fitting model $\sigma + \Delta\sigma$, $\varphi(\Delta\sigma)$ is a misfit functional between the predicted and observed data, $s(\Delta\sigma)$ is a stabilizing functional and $\alpha$ is a regularization parameter. The traditional smooth inversion algorithms are based on the minimum-norm or maximum-smoothness stabilizing functionals (e.g., Occam inversion, Hobbs et al. 2006). These stabilizers produce smooth geological models , which in many practical situations do not describe properly the blocky geological structures.

In order to produce focussed images of targets with sharp boundaries , we use two type of stabilizing functionals (Zhdanov, 2002): minimum-support ($s_{MS}(\Delta\sigma)$) and minimum vertical-support ($s_{MVS}(\Delta\sigma)$) (Zhadnov et al. 2007 and 2008).

$$s_{MS}(\Delta\sigma) = \iiint_V \frac{(\Delta\sigma - \Delta\sigma_{apr})^2}{(\Delta\sigma - \Delta\sigma_{apr})^2 + e^2} dv \tag{3}$$

$$s_{MVS}(\Delta\sigma) = \iiint_V \frac{(\Delta\sigma)^2}{\iint_S (\Delta\sigma)^2 dxdy + e^2} dv \tag{4}$$

where $\Delta\sigma_{apr}$ is an a-priori model and $e$ is the focussing parameter. The minimum-support stabilizer selects a model with the smallest domain of anomalous resistivity. The minimum vertical-support stabilizer provides a solution having the smallest vertical dimensions of the anomalous resistivity.

We employ the re-weighted conjugate gradient algorithm to solve the minimization problem (2) (Zhdanov et al., 2008). As EM resolution decreases rapidly with depth, we include the model-weighting matrix in the inversion in order to provide equal sensitivity to both deep and shallow regions.

The critical factor in the inversion is computation of the Fréchet derivatives. Conventional direct computation is very time consuming. In this paper, we employ the QA approximation (Zhadnov, 2007 and 2008) for models with a variable background resistivity to calculate Fréchet derivatives more efficiently. Each iteration step requires just one forward modeling calculation.

## Synthetic marine data inversion

We consider a 2-D survey conducted in shallow water with a sea depth of 100 m. The survey consists of 35 transmitter positions each with 37 receivers on the sea floor. Each source-receiver pair constitutes one recording channel. The transmitter generates a transient EM in-line field with broadband frequency range. The whole array and data coverage over the region of interest are shown in Figure 2. We investigate the use of 7 frequencies 0.01, 0.05, 0.1, 0.25, 0.5, 0.75 and 1.0 Hz for inversion. Real and imaginary parts at these 7 frequencies extracted from 856 impulse responses yield 11,984 values for inversion.

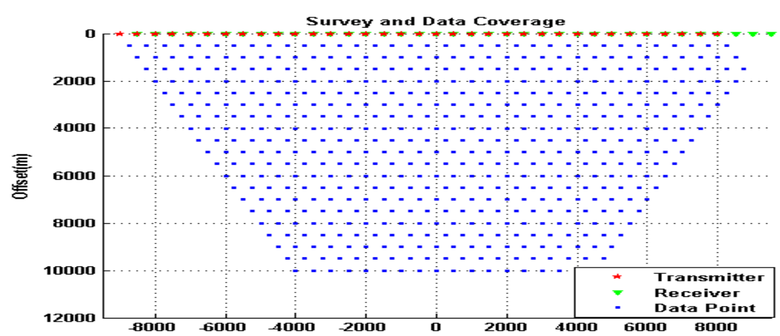
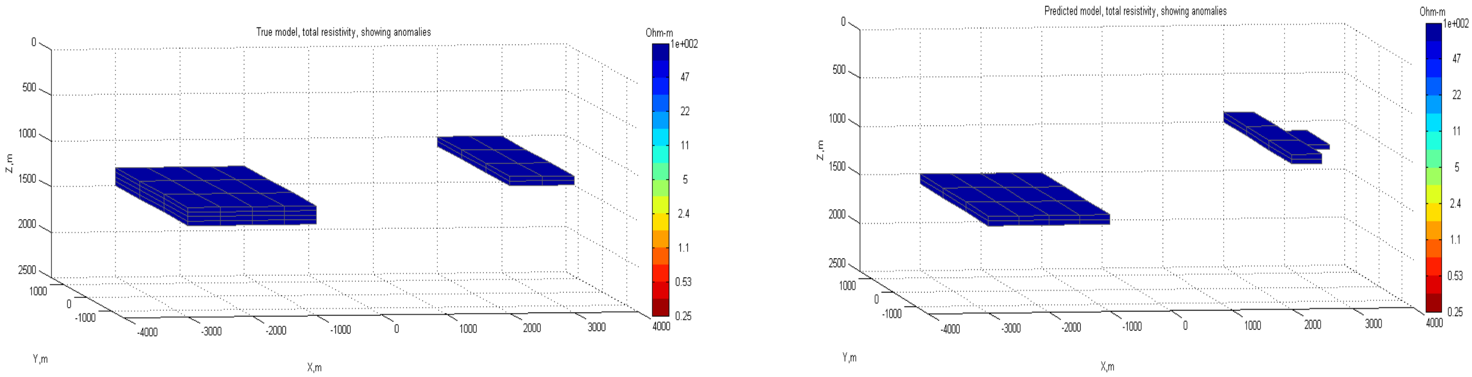



Figure 2. Sub-surface coverage (856 source-receiver pairs) for the synthetic EM marine survey

To test the developed inversion code, we choose a reservoir model typical of marine surveys. The model is formed by two thin resistive reservoirs located at different depths (Figure 3a). The resistivity of sea water is

0.313 ohm-m and homogenous sea-floor sediments have a resistivity of 1 ohm m. Both thin petroleum reservoirs have the same resistivity of 100 ohm m. Figure 3b presents the inverse model obtained from focussed inversion. The depth and resistivity of both thin reservoirs are recovered well in the inverse image.




(a) (b)

Figure 3. (a) The model formed by two resistive reservoirs located at depths of 1.5 and 1 km. Reservoir dimensions are 2 km x 3 km x 200 m and 1 km x 3 km x 100 m respectively (b) inversion result showing recovery of the two thin resistors.

## Conclusions

The focussed inversion method developed by CEMI for inverting magnetotelluric data may be applied to controlled source electromagnetic data after suitable adaptation. The current configuration uses earth responses for a broad frequency range as input to the inversion. Real and imaginary parts of the earth's response may be obtained over such a broad frequency range by Fourier transformation of the earth's impulse response. Tests on a synthetic marine survey demonstrate that the inversion can deliver a stable image and recover both the depth and resistivity of resistive targets if broad band EM data are used.


## Acknowledgements

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