3D inversion of towed streamer EM data: a model study of the Harding field with comparison to CSEM

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The premise of the various marine controlled source electromagnetic (CSEM) methods is sensitivity to the lateral extents and thicknesses of resistive bodies embedded in conductive hosts. Over the past decade, CSEM surveys have been characterized by arrays of fixed ocean bottom receivers and towed transmitters, and applied to de-risking exploration and appraisal projects with direct hydrocarbon indication. The most successful applications of CSEM to date have been in complement to those seismic interpretations where lithological or fluid variations cannot be adequately discriminated by seismic methods alone (e.g., Hesthammer et al., 2010). However, relatively high acquisition costs have represented a significant obstacle to widespread adoption of conventional CSEM technology, particularly in frontier basins. To this end, a towed streamer system capable of simultaneous seismic and electromagnetic (EM) data acquisition has recently been developed and tested in the North Sea (Anderson and Mattsson, 2010; Mattsson et al., 2010; Linfoot et al., 2011; McKay et al., 2011) (Figure 1). This moving platform geometry enables EM data to be acquired over very large areas in both frontier and mature basins for higher production rates and lower costs compared to conventional CSEM methods.

In exploration, hydrocarbon reserves and resources are estimated with varying confidence from volumetrics that are predicted from different 3D earth models and scenarios. Quantitative interpretation of EM data is inherently reliant upon 3D earth models derived from inversion since EM data cannot simply be separated or transformed with linear operators as per seismic methods. However, methods for inverting CSEM data are complicated by the very small, non-unique and non-linear responses of hydrocarbon-bearing reservoir units when compared to the measured total fields. Moreover, 3D inversion of towed streamer EM data poses a significant challenge because of the increased scale of the surveys, the requirement for high resolution models, and the significantly increased number of transmitter-receiver pairs.

Inverting towed streamer EM data

Large-scale conventional CSEM surveys may have in the order of hundreds of fixed receivers, and in the order of thousands of transmitter positions. Reciprocity is routinely exploited in 3D conventional CSEM modelling and inversion to minimize the number of source terms that need to be solved (e.g., Zhdanov et al., 2011). Towed streamer EM surveys may have thousands of transmitter positions, and thousands of receiver positions. Reciprocity cannot be exploited for any computational efficiency. In this respect, towed streamer EM surveys are analogous to airborne EM (AEM) surveys, in that they consist of moving transmitter-receiver pairs. As per our recent developments culminating in the first practical, large-scale 3D AEM inversion methodology (e.g., Cox et al., 2010), we can exploit the fact that the volume of the towed streamer EM system's integrated sensitivity

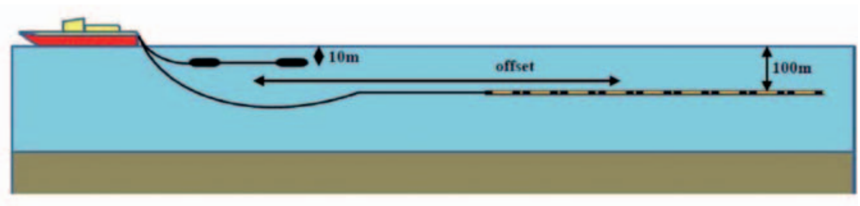

Figure 1 A schematic representation of a towed streamer EM system with a single transmitter in a streamer towed 10 m below the sea surface, and multi-offset receivers in a streamer nominally towed 100 m below the sea surface.

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is significantly less than the size of the survey area, and we introduce the concept of a moving sensitivity domain. That is, for a given transmitter-receiver pair, the responses and Fréchet derivatives are computed from a 3D earth model that encapsulates the towed streamer EM system's sensitivity. The sparse (rather than full) Fréchet matrix for the entire 3D earth model is then constructed as the superposition of Fréchet derivatives for all integrated sensitivity domains (Figure 2). It follows that memory and computational requirements can be reduced by several orders of magnitude. For example, the number of non-zero elements in each row of the Fréchet matrix is just the number of cells within each sensitivity domain (in the order of thousands to tens of thousands) rather than the total number of cells in the 3D earth model (in the order of millions). For example, this moving sensitivity domain concept has made it practical for us to invert AEM data from hundreds of thousands of transmitter positions to 3D earth models with over 15 million cells.

We base our frequency-domain modelling on the 3D contraction integral equation (IE) method (Hursán and Zhdanov, 2002). In practice, there are several distinct advantages to using an IE method in a moving sensitivity domain inversion, rather than any of the finite-difference, finite-volume, or finite-element methods. First, the Green's tensors and background electric fields beyond the towed streamer EM system's sensitivity domain needn't be calculated, and all boundary conditions on the sensitivity domain are perfectly matched. Second, the body-to-body Green's tensors can be pre-computed for a single sensitivity domain and translated across the entire 3D earth model. Third, the integral equation can be written to directly solve for the total electric field in the 3D earth model while preserving the distributed source term. Fourth, the integral equation can be expressed as a convolution, enabling FFT matrix-vector multiplications to reduce computational complexity in Krylov subspace methods from $O(n^2)$ to $O(n \log n)$. Fifth, the Fréchet derivatives can be accurately calculated for negligible expense using the quasi-analytical method. Sixth, the transmitter-receiver pairs and their sensitivity domains need not correspond with grid positions, edges or centers. Finally, in practice, sensitivity domain-related indexing can be generalized to include frequency-dependent model discretization and footprint size. For time-domain EM, the system responses and Fréchet derivatives can be obtained by Fourier transform of the frequency-domain responses and Fréchet derivatives.

We use a reweighted regularized conjugate gradient method for minimizing our Tikhonov parametric functional that incorporates focusing regularization (Zhdanov, 2002). As demonstrated by Zhdanov et al. (2011), focusing regularization is required for recovering 3D resistivity models with sharp contrasts, for example, between a hydrocarbon-charged reservoir and its surrounding host. Traditional methods of smooth regularization tend to underestimate the 3D resistivity model with overly smooth models. Moreover, Zhdanov et al. (2011) demonstrated that focusing regularization can improve inversion convergence over smooth regularization.

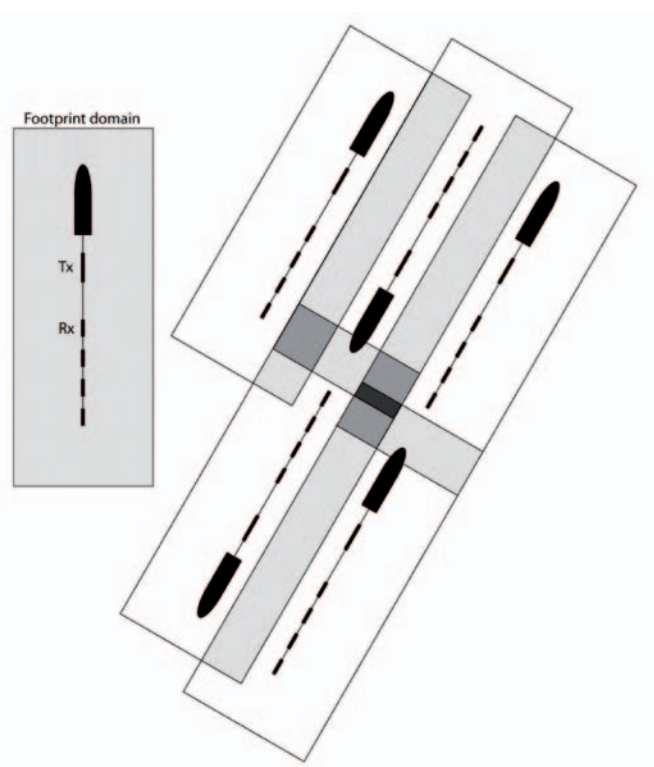

***Figure 2** Plan view of multiple towed streamer EM sensitivity domains superimposed over the same 3D earth model. Darker shading indicates a higher fold of different sensitivity domains.*

Model study: Harding, North Sea

Harding is a medium-sized oil and gas field covering approximately 20 km^2 located in block 9/23B in the UK sector of the North Sea, about 320 km northeast of Aberdeen. The field has a high net-to-gross, high quality, Eocene Balder sandstone reservoir about 1700 m below the seafloor in a 110 m water column. Production commenced in 1996 from the Harding Central and South reservoirs with 300 mboe initially in place. Since then, two further reservoirs have been developed: Harding South East, and by extended reach drilling, Harding North. The reservoirs contain gas, and this has been injected back into a gas cap for later production. Oil production is now in decline, with current production of approximately 10,000 b/d with increasing water cut. The remaining hydrocarbon column consists of a gas cap about 100 m thick, and a thin oil rim about 20 m thick (Ziolkowski et al., 2010).

The Harding Central porosity and fluid saturation models were obtained from history matched reservoir simulations constructed from production data, well logs, and 3D seismic interpretations. Core analyses show Harding's

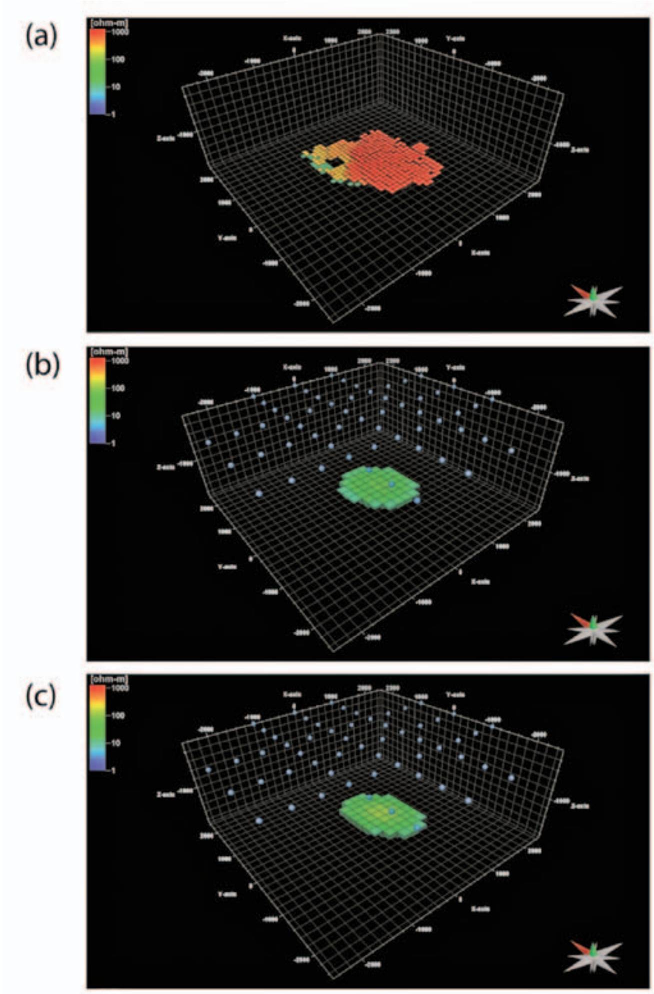

Figure 3 *(a) 3D perspective view of the Harding Central reservoir model, with resistivity values greater than 10 ohm-m shown. (b) 3D perspective view of the Harding Central reservoir model recovered from 3D inversion of towed streamer EM data, with resistivity values greater than 10 ohm-m shown. The blue dots indicate the different transmitter positions. (c) 3D perspective view of the Harding Central reservoir model recovered from 3D inversion of conventional CSEM data, with resistivity values greater than 10 ohm-m shown. The blue dots indicate the different seafloor-based receiver positions.*

reservoir Balder sands to be clean, so Archie's law is appropriate to relate the petrophysical properties to resistivity. Resistivity logs from well 9/23B-7 showed resistivities greater than 1200 ohm-m through the dry gas intervals. In actuality, some intervals may exceed resistivities of 1200 ohm-m, but resistive limits of CSEM responses mean that their actual values are indiscernible from CSEM data. As per Ziolkowski et al. (2010), our 3D resistivity model consisted of a 110 m 0.3 ohm-m water column overlying an otherwise homogeneous half-space of 1.0 ohm-m in which the Harding reservoir model was embedded (Figure 3a).

The towed EM survey consisted of six survey lines; three oriented north-south, and three-oriented east-west. The line spacing was 1 km. Each line contained 44 transmitter-receiver pairs spaced 500 m apart (264 total). The towed EM system consisted of a 300 m long electric bipole transmitter towed 10 m below the sea surface, and inline electric field receivers towed 50 m below the sea surface at offsets of 1325 m, 1850 m, 2025 m, and 2545 m. Data were simulated for 010 Hz, 0.25 Hz, and 1.00 Hz. For inversion, data were threshold above their respective noise floor.

For comparison, the conventional CSEM survey consisted of six survey lines; three oriented north-south, and three oriented east-west. The conventional CSEM survey was actually collocated with the towed EM survey. The line spacing was 1 km. Each line contained 11 receivers spaced 500 m apart, giving a total of 66 receivers. Data were simulated to offsets of 5500 m for inline and vertical electric fields and transverse magnetic fields at frequencies of 0.10, 0.25, 0.50, and 0.75 Hz. For inversion, data were threshold above their respective noise floors. The conventional CSEM data were inverted using the iterative migration method described by Zhdanov et al. (2011).

To compare the 3D inversions of both towed EM and conventional CSEM data, a common 3D earth model was used. That model consisted of a 110 m thick 0.3 ohm-m water column overlying an otherwise homogeneous half-space of 1.0 ohm-m. The 3D inversion domain was discretized to cells of 200 m x 200 m x 20 m dimension. No a priori model was used, and the inversion itself was unconstrained. Results of the 3D towed streamer EM inversion are shown in Figure 3b (with transmitter positions superimposed). Results of the 3D conventional CSEM inversion are shown in Figure 3c (with receiver positions superimposed). As one can see, there is much similarity between the results from the towed EM and conventional CSEM inversions. For all intents and purposes, the results may be considered equivalent.

Conclusions

Obviating the need for ocean bottom receivers, the towed EM system enables CSEM data to be acquired simultaneously with seismic over very large areas in frontier and mature basins for higher production rates and relatively lower cost than conventional CSEM methods. The increased volume of CSEM data represents a challenge to existing 3D CSEM inversion methods. To that end, we have introduced a practical methodology for the large-scale 3D inversion of towed streamer EM data that is based on a moving sensitivity domain. We have demonstrated this with model studies for the Harding field in the UK sector of the North Sea. We have compared our 3D inversion of synthetic towed streamer EM data with 3D inversion of synthetic conventional CSEM data, and observed similarity between the 3D resistivity models. This demonstrates that towed streamer EM data can adequately recover medium-sized hydrocarbon targets to depths of about 2 km.

Acknowledgements

The authors acknowledge TechnoImaging and Petroleum GeoServices (PGS) for support of this research and permission to publish. Zhdanov and Čuma acknowledge support from the University of Utah's Consortium for Electromagnetic Modeling and Inversion (CEMI) and Center for High Performance Computing. The Harding 3D resistivity models were developed as part of a research project H0531E between PGS, BP, and the UK Department of Trade and Industry (now Business, Innovation and Skills). BP and Maersk, as operators of the Harding field, are acknowledged for release of the Harding reservoir model. Drs Bruce Hobbs and Ed Morris are acknowledged for their assistance with the Harding reservoir models.

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