G003

Data Preprocessing and Starting Model Preparation for 3D Inversion of Marine CSEM Surveys

J.J. Zach* (EMGS ASA), F. Roth (EMGS ASA) & H. Yuan (EMGS Americas)

SUMMARY

The marine controlled-source electromagnetic (MCSEM) method has been evolving into a geophysical imaging tool for increasingly complex geological settings. At the same time, 3D inversion algorithms for arbitrary survey layouts demand improved data quality compared to standard processing. Using a state-of-the-art survey acquired in the fall of 2007, we present a processing sequence starting from time-domain electromagnetic data acquired by seabed receivers to providing frequency domain data input and data weights for advanced processing. This includes determination and/or quality control of receiver orientation and time synchronization, and we show the quality of azimuthal receiver data to be adequate to be included in future inversions. Further, navigation data are adapted to a discretized grid upon determining the seafloor bathymetry. For missing or inadequate coverage from seismic surveys, the bathymetry can be extrapolated from navigation data with a spline-based algorithm, which is also described. It has proven beneficial, both in computational time and for recovering a meaningful model, to obtain a starting model for a full 3D inversion scheme by inverting reference receivers using a global, simulated annealing scheme, the result of which is imprinted onto the seafloor.

INTRODUCTION

The growth in the marine controlled source EM (MCSEM) industry during the past decade and continued evolution in operational accuracy and equipment enables the application of 3D inversion algorithms for complex survey layouts now introduced by the industry and research community (e.g., Bornatici et al., 2007; Gribenko, Zhdanov, 2007; Plessix, van der Sman, 2007). The demands on accuracy to procedures and supporting methods for data preprocessing and quality control have thus become more vital than was the case in traditional standard processing. We present a robust workflow for data processing and starting model preparation for frequency-domain CSEM data inversion. For demonstration thereof, we present a recent Seabed Logging (SBL) survey consisting of one line of 20 receivers dropped in a water depth of ~1000m. The present limitation to one line means no loss in the general applicability of the methods presented to any survey layout, whereas the quality of the datasets acquired in late 2007 represents the state of the art in data quality at this time.

METHODOLOGY 1: DATA PREPROCESSING

DATA CALIBRATION AND DEMODULATION

The seabed receiver data, which was recorded with time, is subjected to a short-time Fourier transform, typically over a period of $T \approx 25/f_0$, with a typical base frequency of f_0~0.25Hz. Figure 1 shows a receiver spectrogram resulting from the standard square pulse with 0.25Hz (without loss of generality; see also Mittet, Schaug-Pettersen 2007), along with a detailed view of the frequency range around the base mode.

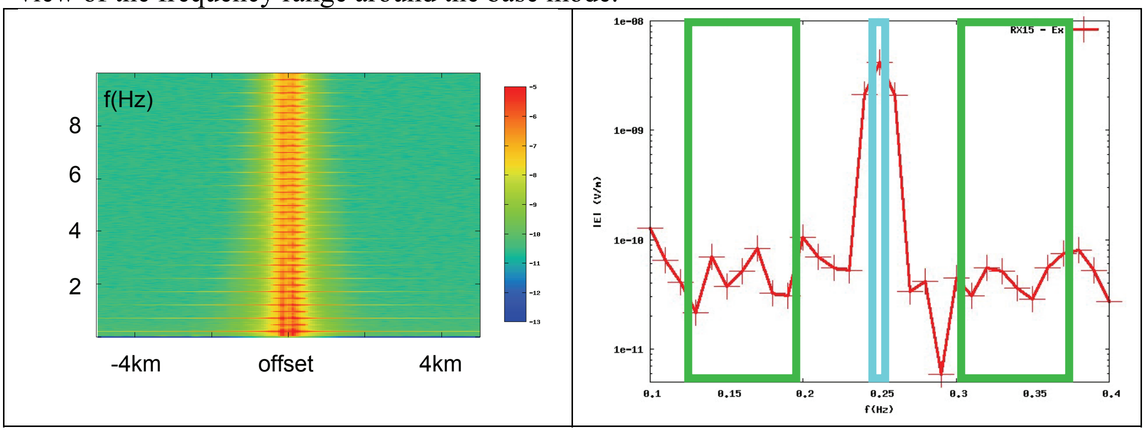

Figure 1: RX15: frequency spectrum versus offset upon source passage for a square-pulse SBL source (LHS); receiver spectrum around the base frequency at offset +4km; also shown are the windows for signal and noise magnitude extraction (blue and green boxes, respectively).

RECEIVER ROTATION

One of the major challenges in interpreting SBL data is the receiver orientation. In deep water, this presently necessitates towing the source over each receiver, upon which the rotation angle is found following the optimization procedure after Mittet et al. (2007). While picking the optimum angle is automated by using a median filter, visual inspection of the rotation angle versus offset and QC of the inline-rotated field after rotation is still necessary (see figure 2 for receivers from the presented data example).

EXTRACTION OF NOISE

As first proposed simultaneously by Peter van der Sman from Shell and EMGS staff, the signal-to-noise ratio of a given frequency mode f_i is approximated by the magnitude ratio between f_i and a given frequency range $\Delta f_{int} < f_{i+1}-f_i$ in the spectral neighborhood of the mode (see the blue versus the green boxes in the right panel of figure 1). The resulting signal and average noise amplitudes for three modes are plotted in the left panel of figure 3 for an example receiver of the present survey. The dominant noise source is the electronics with a relatively flat frequency dependence in the range from ~0.1-10Hz, and the apparent increase of noise with frequency is due to the lower source energy content in the higher modes for the square pulse used. The SNR is plotted in the right panel of figure 3, together with the 26dB-level which is a frequently used acceptance threshold for inversion. The SNR-curves cross levels between 10 and 50dB within a very short offset range of ~100m, so that a binary weighting scheme can be used, in which data are either fully allowed or dismissed.

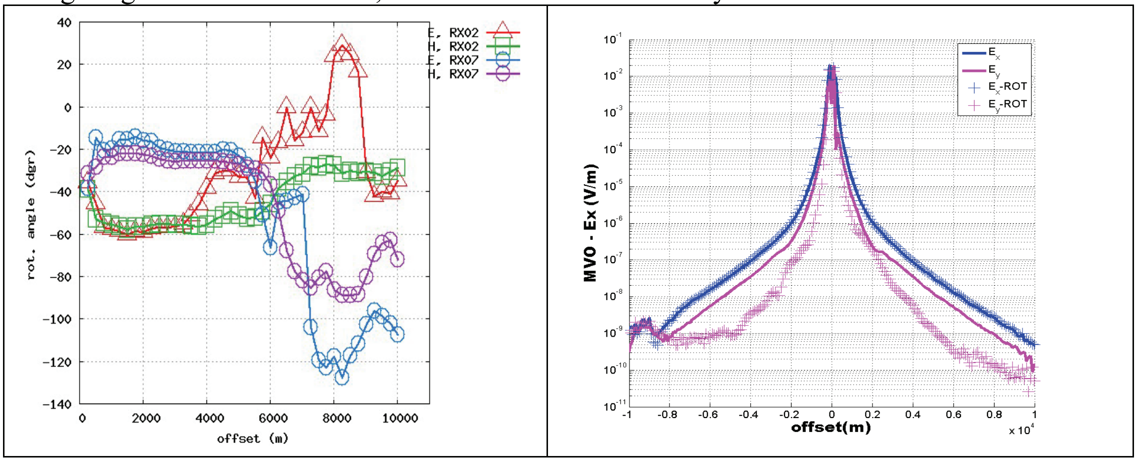

Figure 2: LHS: Inline rotation of receivers: orientation versus offset from electric and magnetic field for example receivers (RX2 and RX7). RHS: (Ex, Ey) (pre-rotation, receiver coordinate system) versus (Ex, Ey) (post-rotation, towline coordinate system).

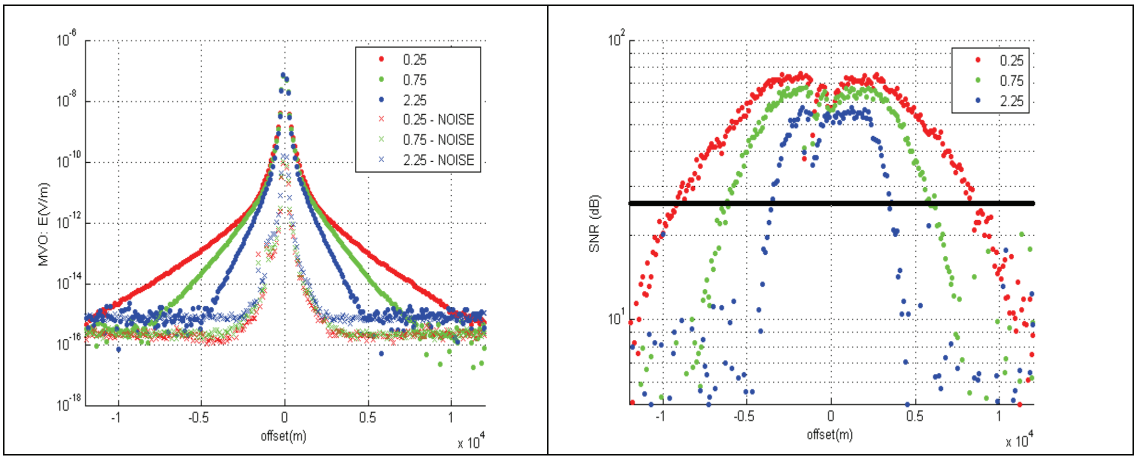

Figure 3: LHS: Signal and noise levels for the modes 0.25, 0.75 and 2.25Hz versus offset for a representative example receiver (RX19), normalized to a unit dipole source for each mode. RHS: SNR for the same receiver.

TIMING ACCURACY AND PHASE

Many earlier marine CSEM surveys were challenged by inaccurate clock synchronization between source and receivers, which were partly caused by temperature shifts. While Mittet et al. (2007) reported a method to use the source-signature on receiver passage to correct the phase, this is not effectively possible for azimuthal lines. However, the quality of the time synchronization in the present survey is proving to be accurate to much better than 1 degree without applying such corrections. The left panel of figure 4 shows the inline electric phase versus offset for half (for visual clarity) of the receivers, which matches the required 0→180→0 degree phase shift at passage of the source. Hence, the presently achieved data quality would permit a full 3D inversion of a survey including azimuthal data, as illustrated in the right panel of figure 4.

METHODOLOGY 2: INITIAL MODEL PREPARATION

SEAFLOOR CONSTRUCTION FROM BATHYMETRY DATA

The seafloor will define the minimal boundary in a gridded inversion model below which the conductivity is permitted to change. In cases where independent bathymetry information (e.g. from 3D seismic) is unavailable or limited in its coverage, we construct a seafloor based on water depth measured along the source towlines. For grid acquisition surveys with multiple towlines, we employ a continuous curvature spline algorithm (Smith and Wessel, 1990), whereas for single-line surveys, a gridding technique based on position projections onto the towline is used, as illustrated in figure 5, which show the seafloor to the present example survey. Both gridding techniques have the desirable feature of matching the water depth along the towlines very precisely. This is especially important to accurately model the strong airwave in shallow water, which is highly dependent on water depth. Not being able to do so would result in resistive or conductive inversion artifacts.

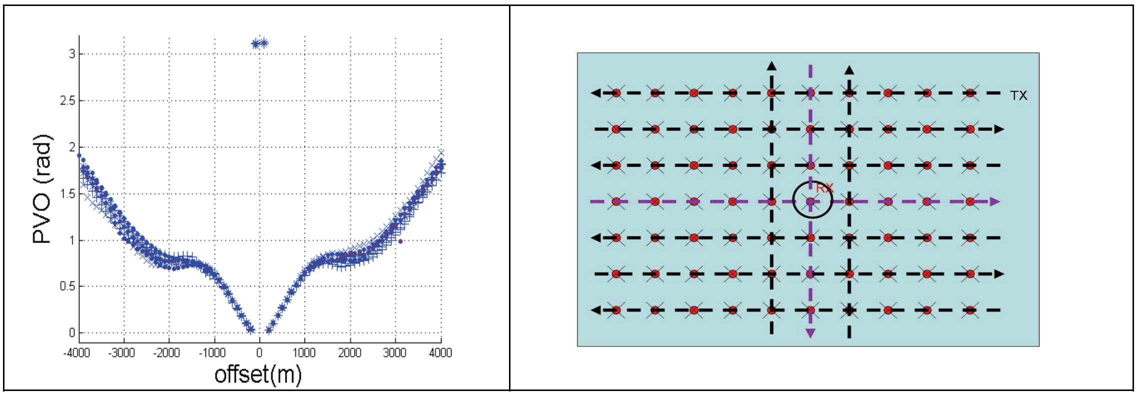

Figure 4: The consistent inline electric phase (shown on the LHS for one half of the receivers) in the present survey versus offset on source passage without any timing corrections indicates the full usability of azimuthal data in the future inversion of 3D acquisition grids (RHS).

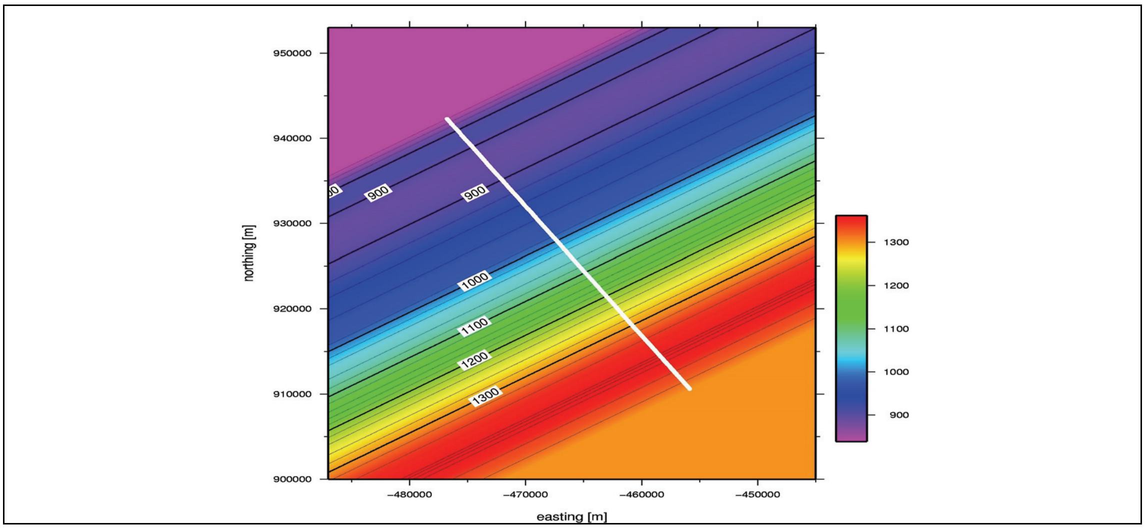

Figure 5: Seafloor for the presented SBL survey line constructed from navigation data.

ADAPTATION OF NAVIGATION AND BATHYMETRY ON FINITE GRID

The source navigation data recorded during towing is comprised by a suite of continuously operating accoustic, echosounder and pressure measurements, which are recorded every 10 seconds. The most accurately known navigation datum is from the source altimeter, an accoustic Doppler gauge measuring the distance of the towing electrode to the seafloor to within ~0.1m. The midpoint of the source is extrapolated using the source velocity vector. In the model representation used by discrete grid inversion schemes, the source is therefore placed at a consistent altitude relative to the seafloor. Other important parameters extracted for consistent forward modeling include the source tilt and feathering.

DETERMINING A STARTING MODEL WITH GLOBAL PLANE LAYER INVERSION

For reasons of numerical complexity, it is desirable to reduce the number of iterations in a full 3D inversion scheme by using a starting model which is, in turn, the result from a numerically less challenging scheme. We have standardized a global simulated-annealing scheme as described in Roth and Zach (2007) to invert selected reference receivers with low anomaly signature. To prevent artifacts at discontinuities of the initial resistivity model inherent to local, particularly gradient-based, inversion approaches, the initial model needs to be sufficiently smooth. The more stringent the smoothness constraint $\Delta\rho$/bin, however, the less perfectly receiver data are explained. Figure 6 shows the relative magnitude versus offset E_{model}/E_{meas} for different constraints after 1000 iterations in the plane layer inversion of a reference receiver. The offset range used in the inversion was limited from 3km to 9km, in which the magnitude fit improves from ~5% to ~1% when varying $\Delta\rho$/bin from 0.5 to 0.1Ωm. The left panel of figure 7 shows the resulting resistivity-vs-depth profile, whereas the right panel shows the plane layer result imprinted on the bathymetry in a 3D model.

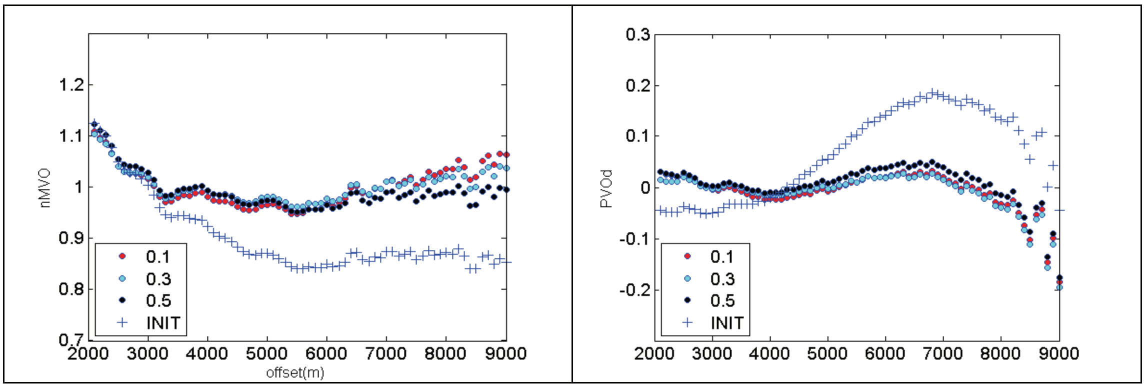

Figure 6: Global simulated-annealing inversion of the out-towing, inline electrical field in RX19 after 1000 iterations. Relative magnitude (LHS) and phase (RHS) versus offset E_{model}/E_{meas} for different smoothness constrains $\Delta\rho$/bin. The initial model response (2Ohm.m halfspace) is shown for comparison.

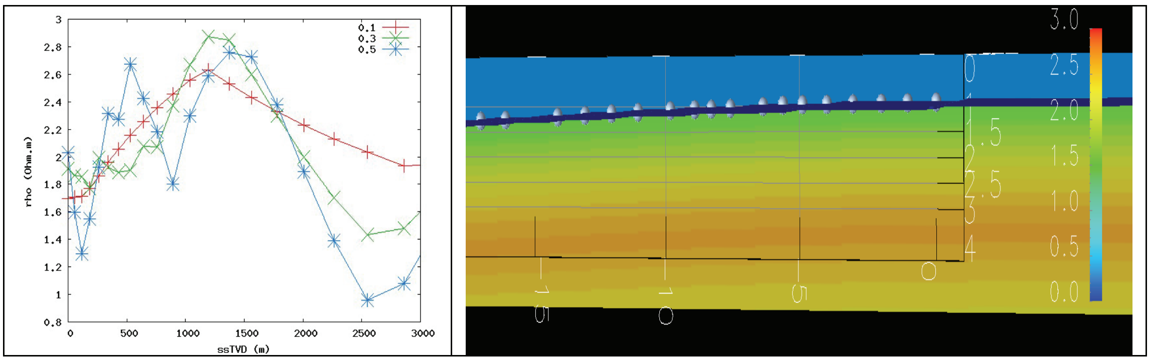

Figure 7: LHS: resistivity-vs-depth profile for different smoothness constraints (see also caption of figure 6). RHS: plane-layer result for $\Delta\rho$/bin =0.1Ωm imprinted onto a 3D discrete grid based on the seafloor shown in figure 5.

CONCLUSIONS

We have standardized and tested pre-processing and model preparation workflows for advanced processing of MCSEM data such as 3D inversion. Sufficient quality of all, including azimuthal, data to invert for both magnitude and phase is demonstrated. Spanning the seafloor from navigation data together with the global simulated annealing inversion of reference receivers comprise reliable and robust methods to prepare a starting model for a gradient-based inversion scheme. Paticularly, the global inversion stage has been shown to reduce the number of iterations in a full 3D scheme by up to a factor of three and has, in some cases, helped to recover resistive anomalies not found with a smooth starting model.

ACKNOWLEDGEMENTS
We acknowledge EMGS, particularly Multiclient Services in Houston, for permission to publish the data, as well as the R&D and G&G departments of EMGS for collaboration and support. We further would like to credit Peter van der Sman and Rene-Edouard Plessix from Shell for valuable discussions.

BIBLIOGRAPHY

- Bornatici, L., Mackie, R., Watts, M.D. [2007] 3D inversion of marine CSEM data and its application to survey design. EGM 2007 conference proceedings, Capri, Italy.
- Gribenko, A., Zhdanov, M. [2007] Rigorous 3D inversion of marine CSEM data based on the integral equation method. Geophysics 72, WA73-WA84.
- Mittet, R., Aakervik, O.M., Jensen, H.R., Ellingsrud, S., Stovas, A. [2007] On the orientation and absolute phase of marine CSEM receivers. Geophysics 72, F145-F155.
- Mittet, R., Schaug-Pettersen, T. [2007] Shaping optimal transmitter waveforms for marine CSEM surveys. San SEG 2007 conference proceedings, San Antonio.
- Plessix, R.-E., van der Sman, P. [2007] 3D CSEM modeling and inversion in complex geological settings. Expanded abstracts, SEG 2007 Annual meeting, San Antonio.
- Roth, F., Zach, J.J. [2007] Inversion of marine CSEM data using up-down wavefield separation and simulated annealing. SEG 2007 conference proceedings, San Antonio.
- Smith, W.H.F., and Wessel, P. [1990] Gridding with continuous curvature splines in tension, Geophysics, 55(3), 293-305.