Development of the Marine Circular Electric Dipole method to investigate resistive sub-seafloor groundwater targets in shallow marine environments

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Abstract

Recent Long Offset Transient Electromagnetic (LOTEM) measurements applying a horizontal electric dipole system performed between 2009 and 2011 by the IGM Cologne yielded the detection of a 3 km wide fresh groundwater body offshore the southern Mediterranean coastal plain of Israel. The results of the LOTEM measurement did not provide sufficient lateral resolution to solve the hydrogeological problem at hand. Therefore, two upcoming electromagnetic measurements (planned for 2015 and 2016) aim at answering the hydrogeological boundary conditions at the western edge of the fresh-water aquifer by employing a novel high-resolution method called Marine Circular Electric Dipole (MCED).

The primary aim of applying the novel MCED method is to theoretically and practically investigate its feasibility in shallow marine environments. Additionally, we intend to gain valuable information regarding the possible mechanism of the above described hydrogeological phenomenon. Future groundwater management projects will benefit from this study.

In this first phase of the project, developments in the hardware and the interpretation scheme are prioritised, where the latter will be presented and discussed. Inverse models, calculated by the developed 1D forward/inversion algorithm for MCED, are presented using synthetic data examples. Also, the effect of a two-dimensional resistive body on MCED data is discussed.

Electrical Resistivity Model

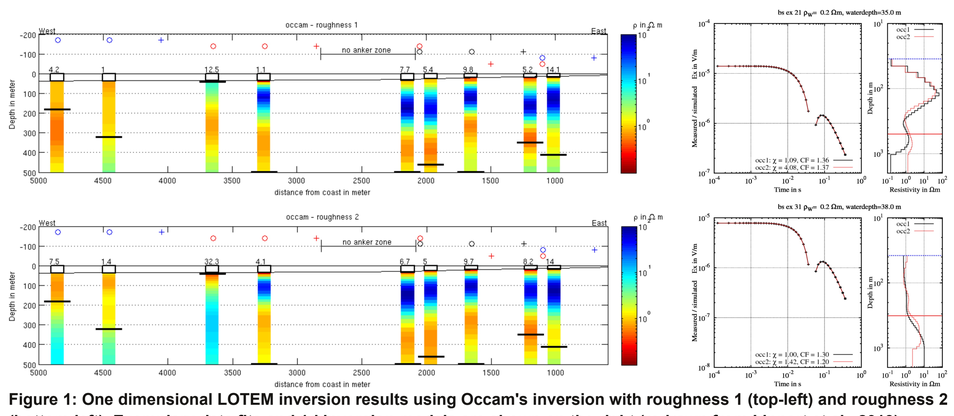

Figure 1: One dimensional LOTEM inversion results using Occam's inversion with roughness 1 (top-left) and roughness 2 (bottom-left). Exemplary data fits and 1d inversion models are shown on the right (redrawn from Lippert et al., 2013).

The electrical resistivity model that is used for subsequent modelling studies is derived from measured LOTEM data (see Fig. 1). The results show a high-resistive zone that extends away from the coastline to approximately 3.5 km. This resistive layer is interpreted as a fresh-water aquifer that continues beneath the Mediterranean Sea. However, the shape of the western aquifer-boundary remains unclear based on the interpretation of the LOTEM data.

Marine Circular Electric Dipole

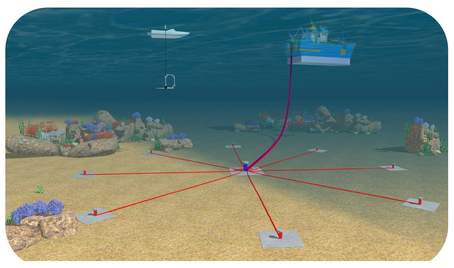

Figure 2: MCED setup in the marine environment

The Circular Electric Dipole (CED) (Fig. 2) is a purely galvanic source that generates a non-stationary transverse magnetic field in a horizontally stratified subsurface (Fig. 3). Theoretically, the transmitter antenna consists of an inner electrode and an outer continuum of electrodes arranged in a circle around the central electrode. For applicability reasons, the outer ring is approximated by a finite number of electrodes, exceeding the minimum number of eight.

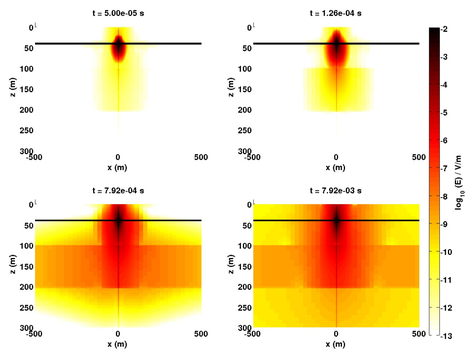

Figure 3: MCED switch-on signal for a three-layer model at selected times

1D Forward Algorithm

A 1D inversion algorithm for MCED is being developed and is currently in the rigorous testing phase. Exemplary inversion tests are shown in Figure 5. The newly developed forward algorithm was implemented into an existing 1D inversion software for transient marine EM methods (Scholl & Edwards, 2007).

The forward operator is based on the standard upward and downward recursion formula for a stratified halfspace above and below the transmitter (Fig. 4). The electric/magnetic fields at any boundary are then obtained by a simple superposition of eight horizontal electric dipoles arranged in a star-shaped pattern with a common midpoint. The results of the forward operator were tested and validated through comparisons to a 1D forward code (Mogilatov & Balashov, 1995) and SLDMEM3t (Druskin and Knizhnerman, 1994).

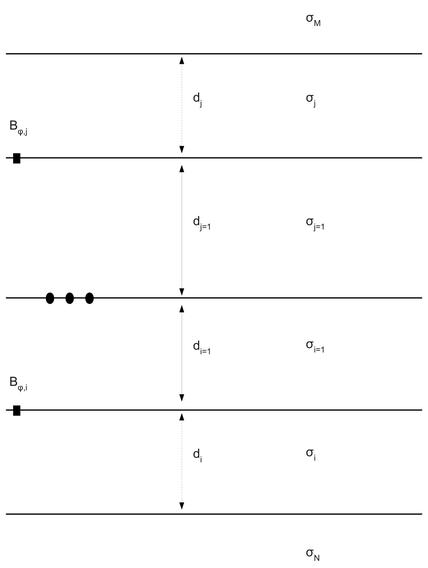

Figure 4: Sketch of the geometry for derivation of the fields of a circular electric dipole (redrawn after Scholl & Edward, 2007).

1D Inversion Trials

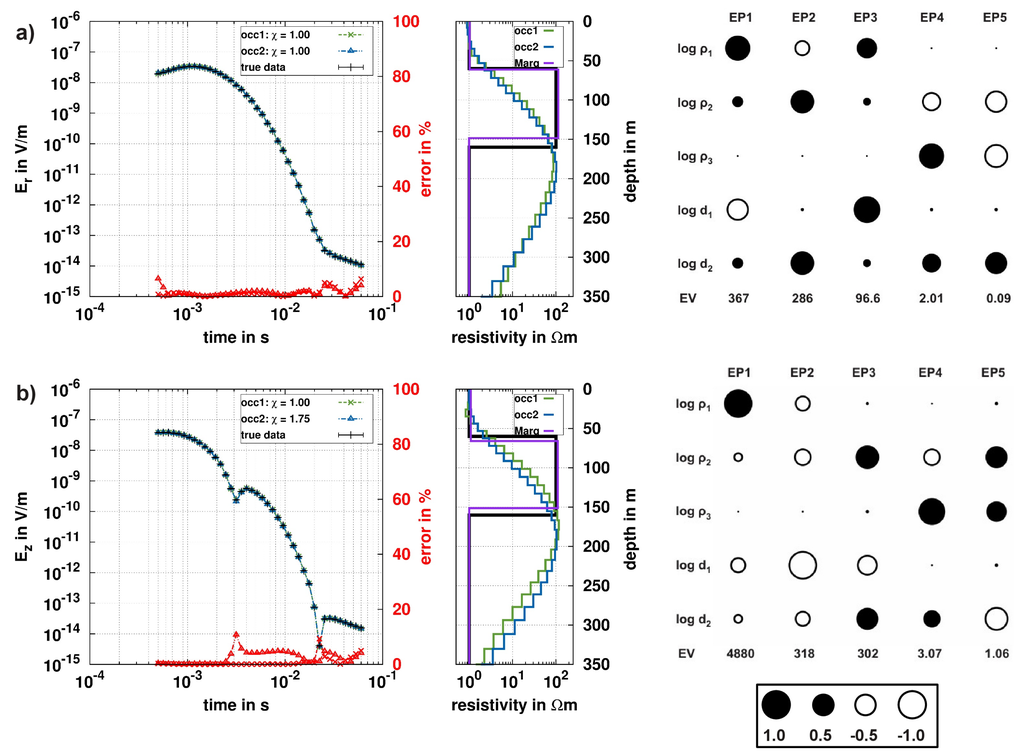

Figure 5: 1D MCED inversion results for Er (a) and Ez (b) receivers. The "true model" displayed in black was derived from the results of the LOTEM measurements in Israel. On the right, Eigenparameters and Eigenvalues of the Jacobian for the investigated three-layer model are shown. Large circles represent large entries of the eigenparameter matrix V.

2D Modelling Study

The measured LOTEM data indicates a 2D, potentially 3D, resistivity distribution in the subsurface. To investigate the effect of such resistivity distribution on MCED data, several modelling studies were performed using the finite-difference algorithm SLDMEM3t (Druskin & Knizhnerman, 1994). The transmitter geometry using a finite-difference grid is displayed in Figure 6.

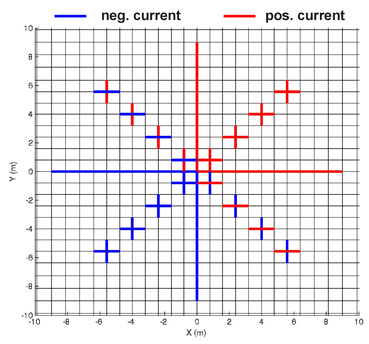

Figure 6: Finite-difference representation of a CED

A simplified 2D model was derived from the results of the LOTEM measurements neglecting the coastline and bathymetry. For this model, MCED-Er data was calculated at selected stations located along a profile running perpendicular to the 2D structure. The offset between the transmitter and receiver is 50 m and we assume a 2% error on the data. Subsequently, we attempted to interpret the 2D data using 1D inversion. The inversion results at eight selected stations are shown in Figure 7. The results indicate the strong distortion caused by the resistive body. Noticeably, a 1D inversion is not feasible between x = 600 m and x = 4000 m due to the appearance of one or more sign reversals in the calculated transients. For stations located at x < 500 m, a 1D inversion is indeed feasible, although misleading within the direct vicinity of the 2D structure.

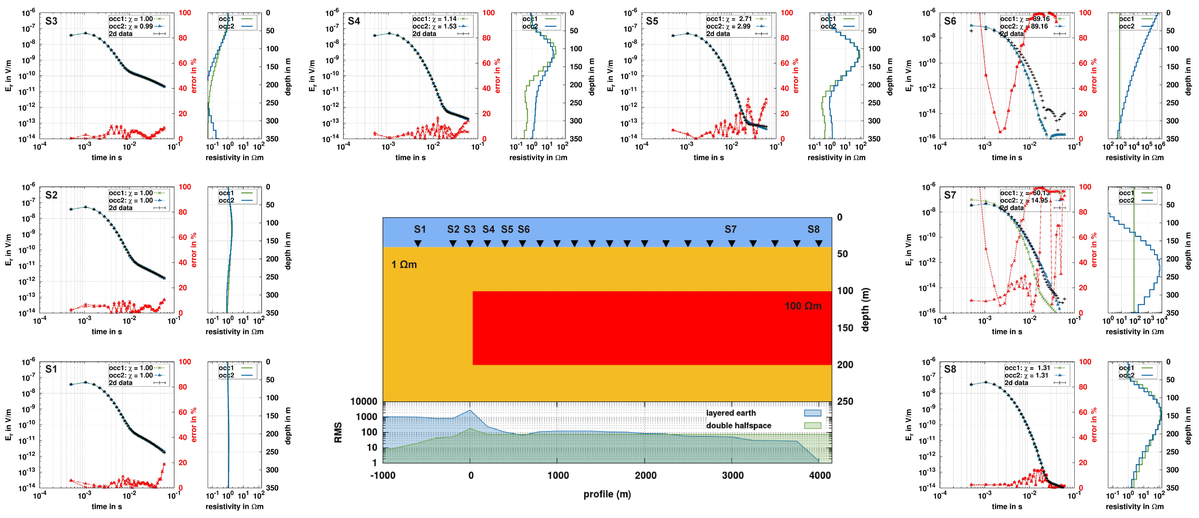

Figure 7: Two-dimensional modelling/inversion study to investigate interpretation errors caused by a resistive multi-dimensional body using 1D inversion. The estimated 2D effect in form of RMS-error is plotted beneath the model for a 1D layered earth (blue) and a double half-space without resistive target (green).

Conclusion & Outlook

We propose to apply the novel Marine Circular Electric Dipole method in the marine environment to investigate a sub-seafloor aquifer-system off the Mediterranean coastline of Israel. Recent software developments allow a preliminary interpretation of MCED data using the 1D inversion schemes of Occam and Marquardt. However, multi-dimensional modelling results indicate that a 1D interpretation is not sufficient when investigating complex resistive structures.

Hardware developments are also underway. First preliminary test measurements on a lake near Cologne and in the North Sea are planned for Fall 2014. The first measurements in Israel are planned for August/September of 2015.

Acknowledgements:

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