Advances in 3D interpretation of frequency domain electromagnetic measurements and its implication for CSEM survey design

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Introduction

Recent advances in forward and inverse modelling of frequency domain electromagnetic measurements have now made it possible to perform full 3D interpretation on personal computers in a reasonable time frame. Controlled source electromagnetic measurements (CSEM) are typically made by collecting data in the far-field of the transmitter, such that the interpretation of the measurements can be handled using methods developed for magnetotelluric (MT) fields. In this paper we explore some of the implications that 3D interpretation of CSEM data can have on survey design. Our research objective is to develop strategies to more effectively design practical surveys.

3D CSEM Modelling

We formulate a quasi-static 3-D frequency domain solution to Maxwell's equations. The mathematical details and details of numerical implementation have been previously published (Haber and Ascher, 2001, Haber *et al.* 2000) and an application of the 3D numerical codes to field data has been published (Oldenburg *et al.* 2004 and Oldenburg *et al.*, 2005*)*.

The forward modelling problem is one to generate the electric and magnetic vector fields arising from an exciting electric source at a discrete angular frequency ω for an arbitrary conductivity distribution. Maxwell's equations in the frequency domain can be written as

$$\nabla \times \mathbf{E} - i\omega\mu\mathbf{H} = 0$$

$$\nabla \times \mathbf{H} - (\sigma - i\omega\varepsilon)\mathbf{E} = \mathbf{J}^e$$

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where σ is the electrical conductivity, ε is the permittivity, and μ is the permeability. The term $\mathbf{J}^e$ represents the current density of the source. To develop a robust and stable numerical solution, we employ a Helmholtz decomposition

$$\mathbf{E} = \mathbf{A} + \nabla \phi$$
$$\nabla \cdot \mathbf{A} = 0$$

dividing the electric field into a scalar and vector potential. After substituting this decomposition into Maxwell's equations and some manipulation, we arrive at a system of equations for **A** and φ

$$\begin{pmatrix} \mathbf{L}_\mu - i\omega\hat{\sigma} & -i\omega\hat{\sigma}\nabla \\ \nabla \cdot \hat{\sigma} & \nabla \cdot \hat{\sigma}\nabla \end{pmatrix} \begin{pmatrix} \mathbf{A} \\ \phi \end{pmatrix} = \begin{pmatrix} -i\omega \mathbf{J}^e \\ -\nabla \cdot \mathbf{J}^e \end{pmatrix}$$

where the operator Lμ is defined as $\mathbf{L}_\mu = \nabla \times \frac{1}{\mu} \nabla \times \ \ - \nabla \frac{1}{\mu} \nabla \cdot$

The Earth is discretized into a domain of cells each characterized by a constant conductivity and permeability. The vector potential **A** is defined on the cell faces, while the scalar potential φ is defined at cell centers. The differential operators are discretized, and the boundary condition $n \times H = 0$ is applied. The result can be written as a large sparse linear system of equations, which can be written in a general form as

$$A(m)u = q$$

where the matrix A is an operator, dependent on the Earth model, the vector u contains the vector and scalar potentials, and the right hand side q contains the discretized source. This matrix system can be solved to obtain the electric and magnetic fields in a bounded domain for Earth models containing large contrasts in electrical conductivity and non-constant magnetic permeability.

CSEM Survey Design

Having the ability to model EM fields in 3D prompts a re-investigation of the design of CSEM surveys. Typically, a grounded dipole is deployed a great distance away from the area of interest to ensure that the incident waves from the source are planar. Having the ability to model the full 3D vector electric and magnetic fields removes the necessity of positioning the transmitter in the far-field. Additionally, measurements collected at a number of different transmitter locations and geometries and frequencies can be interpreted simultaneously. This prompts the investigation of survey design to get the most out of CSEM measurements.

We aim to optimize the measurement of field data such to maximize signal strength, sensitivity, resolution and logistical efficiency of the data acquisition. Survey design is very problem dependent, depending on the nature of the target, particularities of the location, and the geophysical method to be used. Survey design is particularly problem dependent in this case, as the operator matrix A is dependent on the Earth model. Thus synthetic model geometry must be chosen to investigate the design of CSEM surveys.

We choose a synthetic model representing the investigation of subsurface water for an underground mining environment. There exists the potential for a large body of water to infiltrate a thick layer of salt above an active underground salt mine, creating a large conductive body at depth.

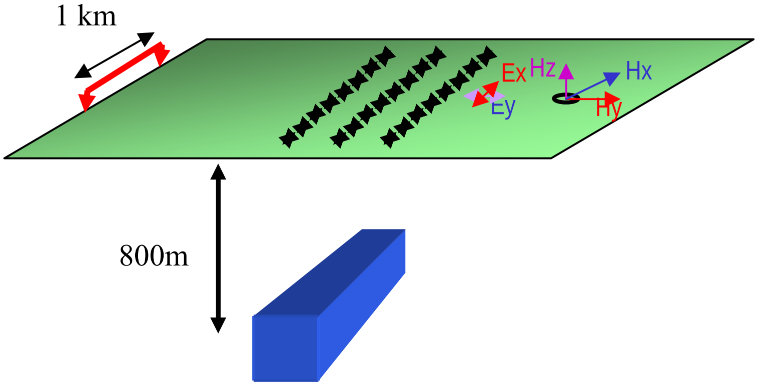
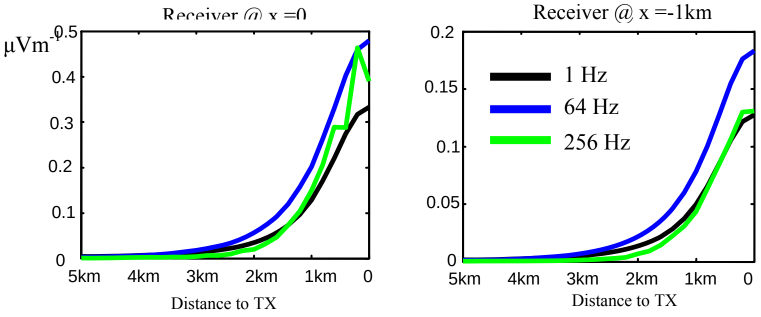


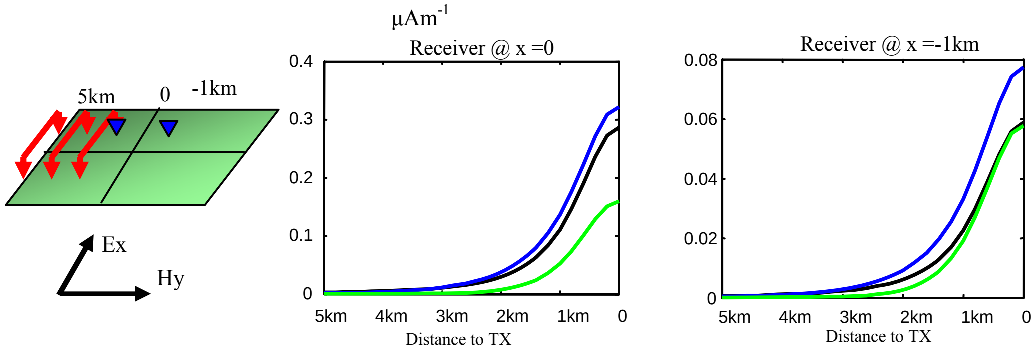
Figure 1. Synthetic model geometry of a deep conductive body. The conductor is 800m below the surface, 75m wide and 75m tall with a conductivity of 1 S/m. The background material is taken to be 200 Ohm-m.

The goal of the survey design is to identify location for transmitters and which frequencies to measure to optimize the signal strength from this deep body. The procedure is to model the secondary response arising solely from the conductive body, and identify which transmitter locations and frequencies couple well with this synthetic model geometry. The procedure used was to start with a grounded dipole source in the far-field and systematically move the dipole closer and look at the strength of the secondary fields arising solely from the anomalous conductive body.

The transmitter is a 1 kilometer long grounded dipole, transmitting at frequencies of 1, 64 and 256 Hz. A stationary receiver measures the electric field component parallel to the transmitter (Ex) and the perpendicular magnetic field component (Hy). Figures 2 and 3 show the results for this experiment. Each plot shows the amplitude of secondary field at a stationary receiver as the transmitter is brought from the far field to the near field. The results show a dramatic increase in the strength of the secondary field as the transmitter gets closer to the anomalous body.



Secondary Ex amplitude



Secondary Hy amplitude

Figure 2: Amplitude of the secondary electric and magnetic fields arising from the anomalous conductivity body shown in Figure 1.

The secondary fields also show that the secondary fields computed at 64 Hz generate the strongest secondary field strength, while the 1 Hz and 256 Hz signals are lower. This indicates that the conductive geometry shown in Figure 1 couples well with intermediate frequencies between 1 Hz and 256 Hz.

An important consideration is the ratio of the secondary signal to the primary signal. The transmitter is continually exciting the ground in frequency domain measurements and CSEM measurements collect signal from both the transmitter and the ground simultaneously. As the primary signal arising from the transmitter is much stronger than the secondary field from the anomalous conductive body, it is possible to effectively wash out the secondary signal in the presence of a strong primary.

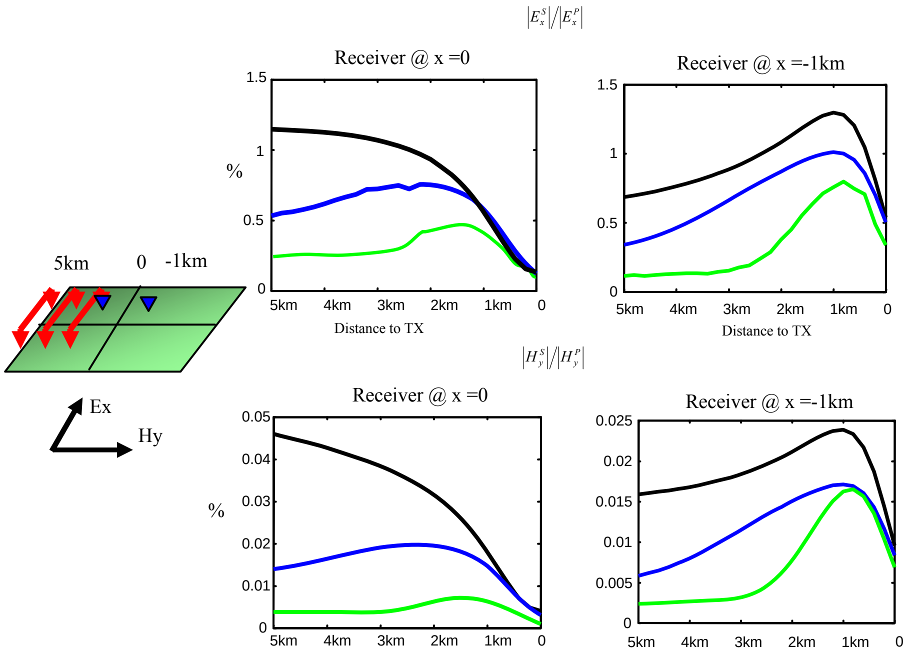


Figure 3: Ratio of secondary-to-primary field ratio

For a receiver located at x=0, directly above the conductive prism, the secondary field signal strength decreases monotonically for the 1 Hz transmitter, yet shows an increase for transmitter offsets between 1 and 3 kilometers for the 64 and 256 Hz signals. For the receiver positioned at -1km, further away from the transmitter, the ratio of secondary-to-primary increases for all three frequencies as the transmitter is brought in from the far-field, but drop off quickly in the last kilometer.

The information present in Figures 2 and 3 can be combined into a single metric quantifying the merit of the survey design. We define this metric by first normalizing the secondary field strength and the secondary-to-primary ratio both to 1, then taking the product. The result of this for both the electric and magnetic field is shown in Figure 4.

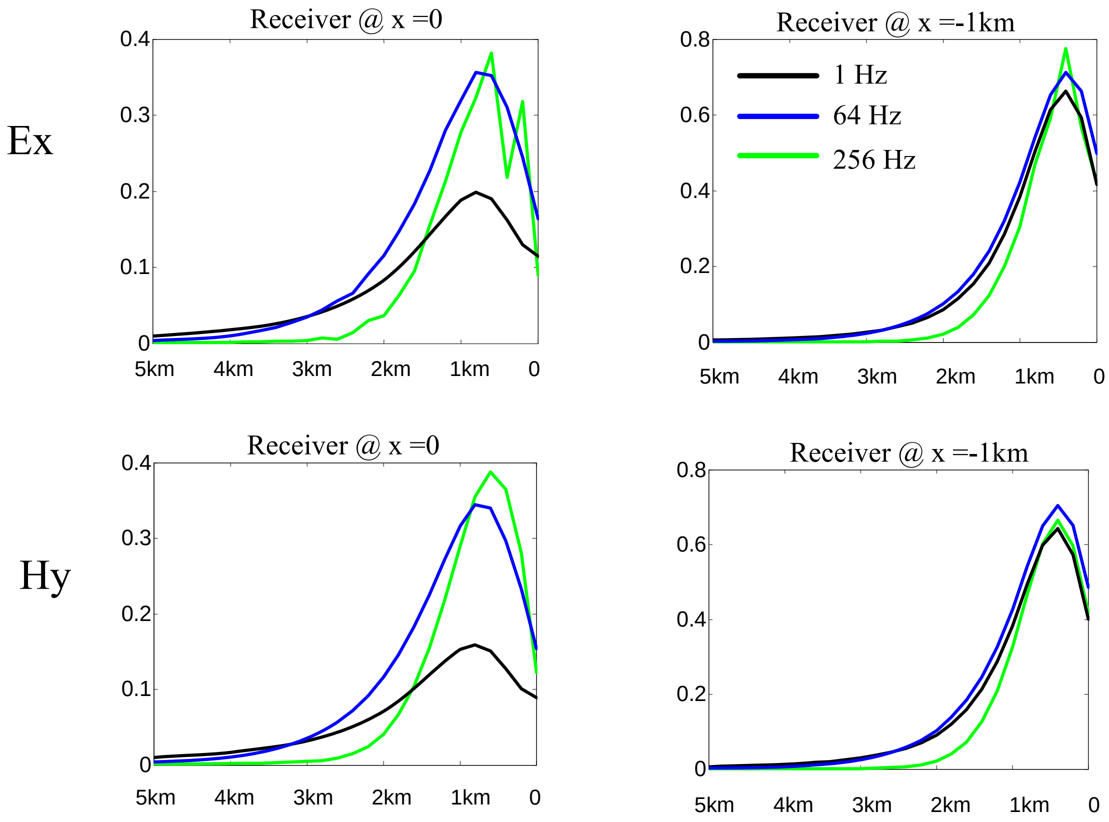


Figure 4: survey design metric, as the product of the normalized secondary field strength and secondary-to-primary ratio.

This simple metric indicates that a transmitter located 1 kilometer from the body results in an optimal survey when looking at receivers both directly above the body, and 1 kilometer away (this receiver is 2 kilometers from the body).

Practical Field Procedure

3-D CSEM allows for a very general layout of transmitters and receivers. To make field data collection practical and cost effective it is necessary to have a field procedure that takes advantage of the ability for 3-D CSEM to interpret several transmitter geometries simultaneously, yet minimizes the number of times a receiver station must be populated.

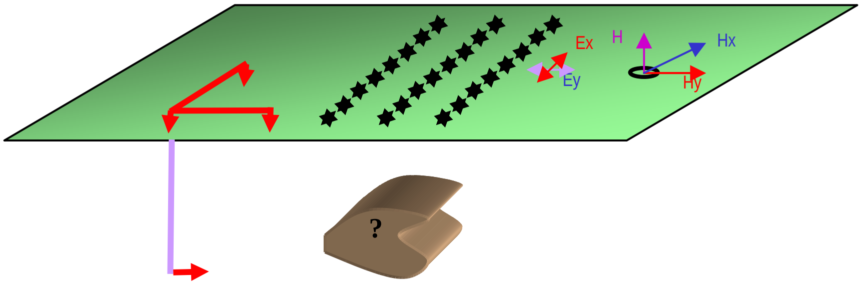


Figure 5: Possible field procedure for CSEM measurements using two orthogonal surface transmitters and a borehole transmitter.

One possible field survey campaign is shown in Figure 5. A single transmitter is deployed, and connected to two orthogonal surface sources and a borehole source. For each receiver location, the transmitter is switched between the three orientations. This has the advantage of not having to re-visit the same receiver location for each of the three transmitters.

Conclusion

Interpretation of frequency domain electromagnetic measurements is advancing beyond the realm of synthetic problems and is now being applied to complicated real world problems faced by geophysicists. We now have the capability to invert all types of EM data: any field components due to any configuration of transmitter without restrictions about their relative geometry. This prompts the investigation of CSEM survey design so that we are fully taking advantage of the flexibility of this interpretation method. We find that by moving the transmitter much closer to the region of interest that it is possible to increase the strength of signals arising from conductive bodies in the ground and increase the relative strength of this signal to the primary field. This opens the possibility of designing surveys that yield more information about a given exploration target in a cost effective and logistically expedient manner.

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