6th International Symposium on Three-Dimensional Electromagnetics
Berkeley, California, USA, March 28-30, 2017

Synthesizing 3D Time-Domain EM Data for Forward Modelling of Uranium Deposits

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SUMMARY

We present a method to compute time-domain EM forward responses for three-dimensional (3D) Earth models using many 3D frequency domain responses. Models are constructed using unstructured tetrahedral meshes providing a more precise means of replicating EM responses of targets with complicated, challenging geometries. Results for synthetic and real-world models demonstrate the accuracy of the approach as well as current developments in modeling geologically realistic conductors in 3D.

Keywords: forward modeling, time domain, frequency domain, finite element, case study, uranium.

INTRODUCTION

3D finite element forward modeling of EM data on unstructured meshes (e.g. Ansari and Farquharson 2014; Jahandari and Farquharson 2014; Puzyrev et al. 2013; Ren et al. 2014; Schwarzbach et al. 2011) has shown the ability to model the EM response of bodies with complicated geometries without the pixelation effect commonly seen in a rectilinear mesh. Methods also exist for incorporating structural geologic data, in a variety of forms, into these 3D meshes (e.g. Lelièvre et al., 2012). At least one method of forward modeling time-domain EM data on unstructured meshes has been recently developed (Fu et al. 2015) and has been successfully applied to petroleum exploration. However, an application with specific attention to mining exploration scenarios was still lacking.

It is possible by use of a Fourier transform to create a time-domain response using many individual frequency-domain responses computed for a single 3D model (e.g. Newman et al. 1986). The method presented here makes use of this approach as well as the 3D finite-element code of Ansari and Farquharson (2014), and has successfully reproduced known time-domain results for 1D half-spaces and a 3D conductor in a half-space model. Realistic models that incorporate actual drill log resistivity data have also been created and demonstrate the ability to detect small conductive bodies under a thick sediment package. Models have also been constructed to replicate geologic cross-sections provided by Areva Resources Canada (ARC), and the results were compared to time-domain EM data collected over known uranium deposits in the Athabasca Basin in Northern Saskatchewan, Canada.

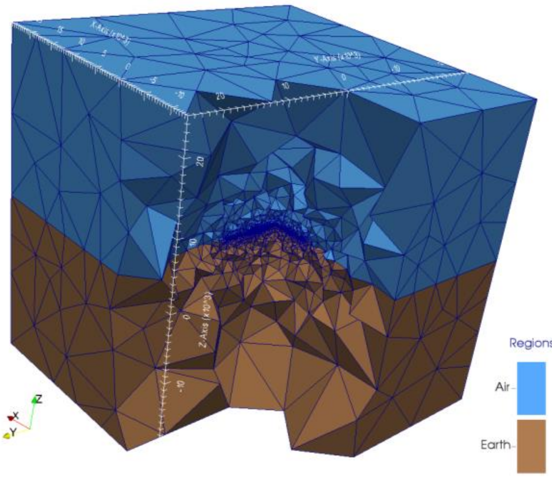

Figure 1. Cutaway of a 3D unstructured tetrahedral mesh. The air and earth are colored in light blue and tan respectively with edges of tetrahedra in dark blue. Mesh volume is 50 km^3.

MODEL DESIGN AND MESH REFINEMENT

The 3D model space is defined at its outer boundaries by a 50 km^3 cube (Figure 1). A large model volume is required to accommodate EM skin-depths over the broad frequency range needed to construct the time-domain response. The *x-y* plane at *z=0* represents the earth-air boundary. Two transmitter-receiver schemes have been tested for this study, fixed-loop and Slingram-style moving loop. The Slingram-style surveys are of the most interest to ARC, and consist of a 400m x 400m transmitter loop, paired with a receiver at an offset of 800m from the center of the transmitter. The transmitter and receiver pair step 100 m at a time along the length of the survey line. 3D models are discretized using unstructured tetrahedral meshes via the tetrahedral mesh generator TetGen (Si, 2007). Mesh refinement is critical at receiver locations but less important elsewhere in the model. As models become more complicated a lack of refinement is rarely the problem; instead, attention must be given to an intelligent mesh design that aims to reduce the overall number of cells required to represent geologic features. The number of cells in the model is directly related to the memory and time necessary to compute a solution: models with fewer cells require less computation time and memory.

FORWARD MODELING

Forward models are computed initially in the frequency domain using the 3D finite-element method of Ansari and Farquharson (2014). Models are computed for a single frequency at a time, with the results for many frequencies then combined at receiver locations. The use of sine and cosine transforms produce 3D time-domain d**B**/dt and **B**-field responses respectively (Newman et al. 1986). Time-domain models are constructed using 40 frequencies over a broad frequency range from 0.01 Hz to 100 MHz, with four representative frequencies per decade. A total of 80 frequency models are run to form a time domain response; 40 for the model itself and 40 for a background version of the model used for computation of the secondary magnetic field. This process can be both computationally intensive and time-consuming but these issues have been mitigated with the use of parallelization methods on a computing cluster.

RESULTS AND EXAMPLES

First, as a check to determine the accuracy of the forward modeling method, many conductor in half-space models were created, the model seen in figure 2 was created specifically to replicate a 3D integral equation result from Newman et al. (1986). The 1 Ohm-m conductor has a width of 20 m, strike length of 600 m, and depth extent of 60 m. The conductor sits at a depth of 40 m in a 100 Ohm-m half-space. The transmitter loop is 500 x 600 m in the *x* and *y* directions, and there is a 300m offset from the leading edge of the loop along the y-axis from the start of the receiver line. Ten receivers run along the y-axis at 20 m spacing from -90 m to 90 m, centered at the model's origin. Figure 2a and 2b show comparisons of the time-domain decay curves and the magnetic field response vs. distance along the receiver line respectively.

With the goal of creating models containing realistic geology, information was utilized from drill core data acquired by ARC as part of exploration operations at their Waterbury-Cigar Lake property. A simplified model was created (Figure 3) inspired by an ARC geologic cross-section for which moving-loop SQUIDTEM data had been previously collected. The model contains 19 individual regions with varied resistivity values including an air layer, a 400m thick sediment overburden, a multi-region graphitic conductor package, and a thick underlying basement layer. Rock types in the conductor package include graphite, calc-silicate, pelitic and granitic gneiss, as well as two unknown regions, all having variable thickness and dipping to the south under the N-S survey line. Many different simulations have been carried out using variations of this model and Figure 4a shows a

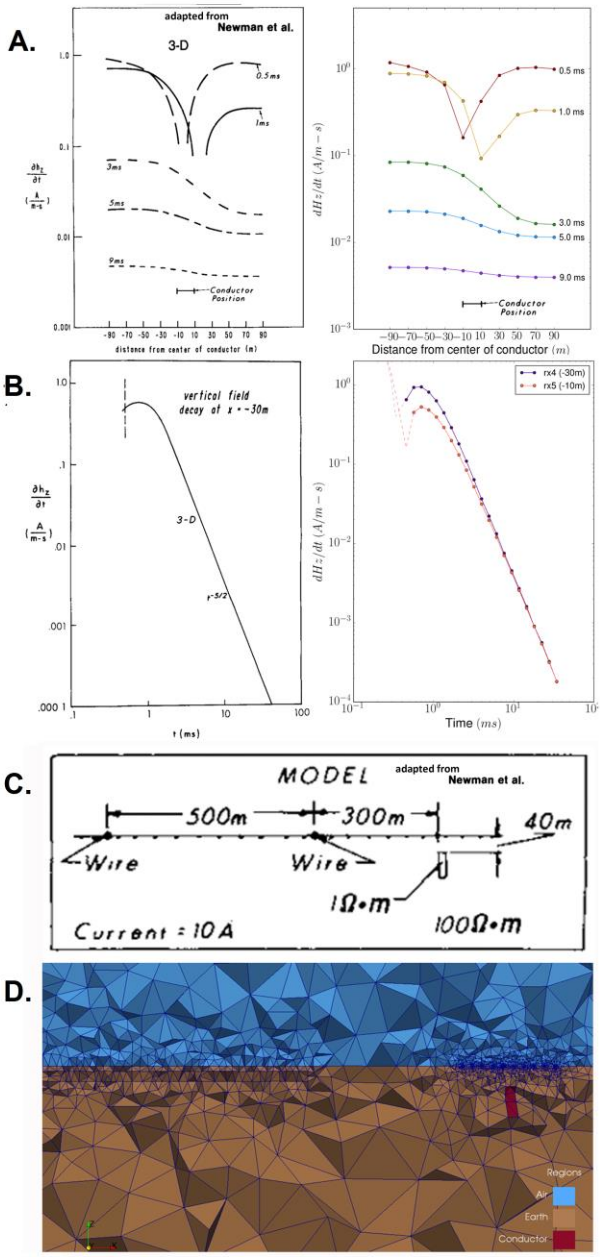

Figure 2. A) Time-domain decay curves for simple conductor in half-space model; results at left are from Newman et al. (1986), and at right from this study. B) Magnetic-field response along the receiver line at five time channels, results from Newman et al. (1986) at left, and from this study at right. C) Diagram of the model specifications from Newman et al. (1986). D) 2D cross-section of 3D model mesh used in this method.

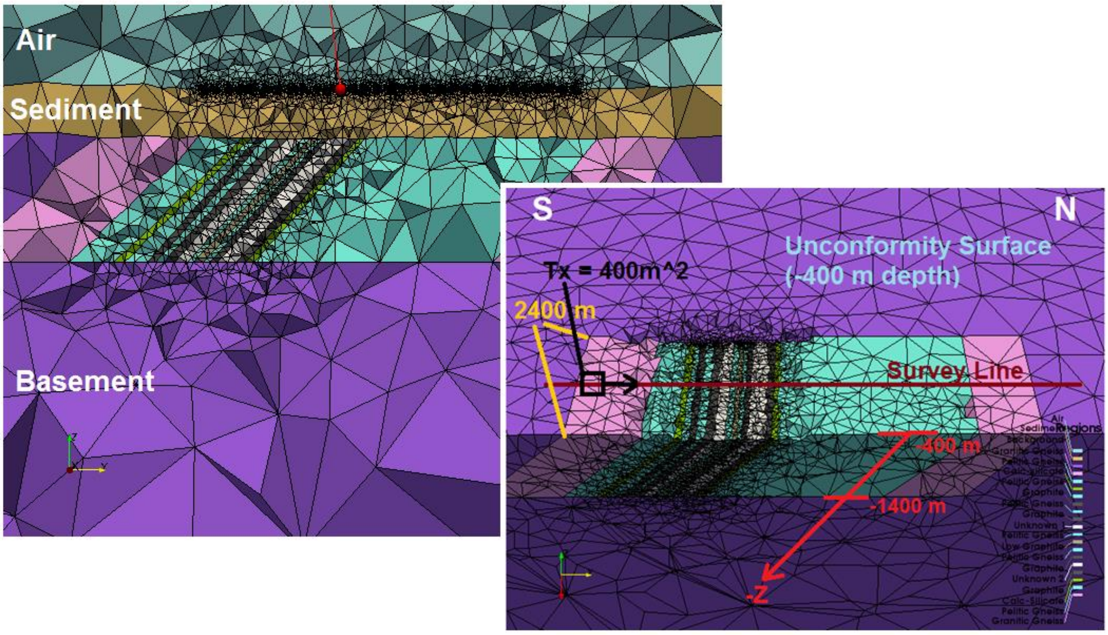

Figure 3. At left is a slice along the x-axis of a version of the cross-section model where the graphitic conductor package has a 1 km depth extent, at right is a 2D cutaway of a 3D view of the mesh showing both the strike length and depth extent of the package.

selection of mid-time results for a single Slingram style survey with an 800 m Tx-Rx offset, and a 400 m^2 Tx loop. The secondary B-field response in pT/A was calculated by removing the effects of a background model run on the same mesh. The results are similar in appearance to the ARC SQUIDTEM data seen in Figure 4b. However, more work is currently being done to better match the amplitude of the ARC data as well as to replicate the ARC response more accurately over the entire time-window of interest (.01 – 42.0 ms).

CONCLUSION

A method for synthesizing time-domain EM data using a 3D frequency-domain EM forward modeling code is presented. The method has been developed specifically to model the 3D magnetic-field response of deeply buried, thin, near vertical conductors associated with uranium deposits of primary interest in the Athabasca Basin, Canada. The results presented demonstrate the accuracy of the developed method as well as the ability to model realistic geology. This method has also been used successfully in other work to model airborne EM surveys over similar model meshes. Currently work is underway in better understanding how small changes to the model such as in the geometry of the graphitic conductor package, Tx-Rx geometry, region resistivities, and methods of obtaining the secondary field can lead to the best possible matching of data collected in the field.

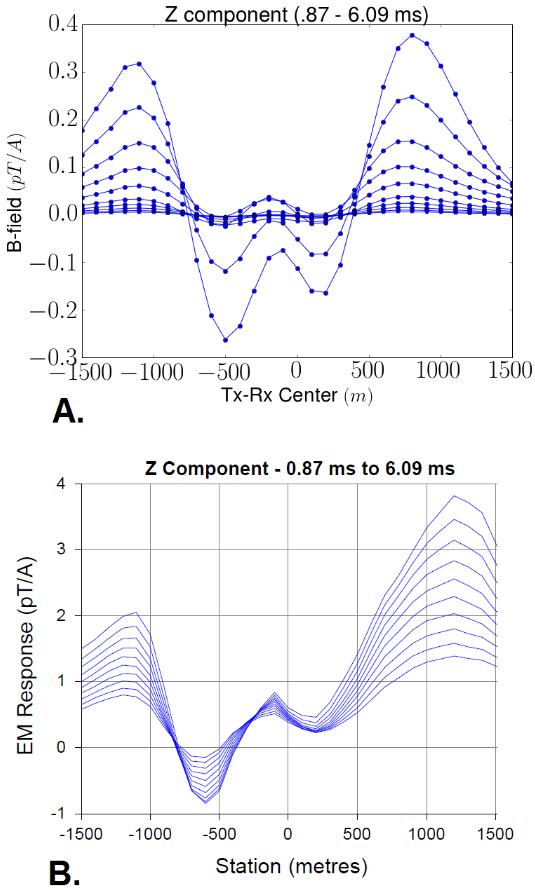

Figure 4. Secondary B-field vs distance response at mid-times for one version of the cross-section model (A) and the corresponding ARC SQUIDTEM data (B).

ACKNOWLEDGMENTS

We would like to thank ARC for their support of this project and permission to publish this work, and specifically Patrick Ledru for his support.

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