3-D Modeling of Airborne and Land-based Controlled-Source Electromagnetic Data: Comparison on CPU and GPU Platform

İsmail Demirci[1]
[1]Ankara University, Faculty of Engineering, Geophysical Engineering Department, Geophysical Modelling Group, Ankara, TURKEY. E-mail: idemirci@eng.ankara.edu.tr

SUMMARY

In last decades, thanks to the developed semi-airborne/airborne geophysical measurement methods and data acquisition systems, it is aimed to make the data acquisition possible and increase the data acquisition speed in areas where working condition is difficult. Airborne geophysical studies have generally focused on Magnetic methods, transient Electromagnetic methods and Very Low Frequency Electromagnetic methods. However, due to the weakness of the methods in terms of depth information, the use of airborne-based controlled-source electromagnetic methods has gained importance in recent years. The realization of geophysical studies in forested and mountainous areas depends not only on the development of measurement acquisition systems, but also on the development of software to be used in the evaluation processes of the measurements taken. In this study, 3D forward solution algorithm is developed to use for inversion stage of natural and controlled source electromagnetic data collected on ground and airborne studies. In addition, direct and iterative solution methods are used in the software developed during the study, and their performance is tested in CPU-GPU platforms and the results are discussed.

Keywords: Airborne Electromagnetic, Modeling, Three-Dimensional, Graphical Processing Unit

INTRODUCTION

In recent years, studies have done on aerial measurement methods for many geophysical methods (Radiometric, Magnetic and Electromagnetic methods, etc.). Thanks to the developed airborne-based geophysical measurement methods and measurement taking systems, it is possible to work in topographic conditions where it is not possible or difficult to take measurements from the land, covered with dense vegetation and where it is not possible to carry the equipment for measurement taking. However, due to the weakness of methods such as Radiometric and Magnetic methods in terms of depth information, the use of electromagnetic methods measured from the air vehicle has gained importance. Airborne EM methods are used in many subjects such as environmental problems (Doll et al., 2001), infrastructure surveys (Pfaffhuber et al. 2010), groundwater and pollution (Gunnink et al., 2012), geological mapping (Steuer et al., 2009) and mineral surveys (Wolfgram and Golden, 2001).

In parallel with the developments in the measurement methods and applications of airborne EM methods, the development of 3-D modeling and inversion algorithms used in the evaluation of data has accelerated. 3-D forward solution algorithms are the most important part of inversion algorithms used to obtain reliable 3-D underground models. Therefore, the development of stable and fast 3-D forward solution algorithms is vital for obtaining more reliable underground models.

In recent years, there are many studies on 3-D forward solution in frequency domain EM methods. Finite Differences (Newman and Alumbaugh, 1995, 2002; Streich, 2009), Finite Elements (Badea et al., 2001; Mitsuhata and Uchida, 2004; da Silva et al., 2012), Finite Volume (Mackie et al., 1994; Haber and Ascher, 2001; Constable and Weiss, 2006) and Integral Equation (Wannamaker, 1991; Avdeev et al., 2002) methods are generally used for forward solution methods. Finite element method is the most flexible method in terms of defining model geometry (Avdeev, 2005, Erdoğan et al. 2008, Demirci et al., 2012). Although integral equation methods are very useful for simple models, there are difficulties in computation for complex models (Mackie et al. 1993). For this reason, the Finite Difference method and the closely related Finite Volume method are preferred because of their ease of calculation and application and solution stability. In addition, there are a limited number of studies on modeling 3-D airborne-based EM methods (Newman and Alumbaugh, 1995; Avdeev, 2005; Cox et al., 2010; Liu and Yin, 2014), and the finite difference method was generally preferred in the studies. During this study, airborne and land-based CSEM 3-D forward modeling algorithm was developed by using Finite Difference method.

METHOD

In EM methods, to calculate model responses, we solve the vector Helmholtz equation for the secondary electric field $\mathbf{E}^S$

$$\nabla \times \nabla \times \mathbf{E}^s + i\omega\mu_0\sigma^*\mathbf{E}^s = -i\omega\mu_0\mathbf{J} \quad (1)$$

where $\mathbf{J} = (\sigma^* - \sigma^{P*})\mathbf{E}^P$ define source term, ω denotes angular frequency, the complex conductivity σ* = σ + *j*ωε includes conductivity σ and permittivity ε, μ_0 denotes free-space magnetic permeability and σ^{P*} is the conductivity of a layered background model. If the source term on the right hand side of the equation is used, the methods are defined as controlled source, otherwise natural source methods. The primary electric field $\mathbf{E}^P$ is computed for conductivity σ^{P*} using quasi-analytic expressions for 1D media (Streich & Becken 2011). The Helmholtz equation given above cannot be solved analytically for complex models. For this reason, one of the numerical solution methods should be used in the solution of the equation. Finite Difference method (Newman and Alumbaugh, 1995; Alumbaugh et al., 1996; Champagne II et al., 2001; Weiss and Newman, 2002, Streich, 2009) is one of the most preferred methods due to its ease of application and speed of solution. In this study, Finite Difference method is preferred in the solution of the Helmholtz equation.

The Finite Difference expression of Eq.1 is obtained using Yee(1966)'s staggered grid approach, scaled symmetrically, and Dirichlet boundary conditions (usually Dirichlet boundary conditions have been used in previous studies so that the resulting equation is symmetrical, see Newman and Alumbaugh, 1995; Streich, 2009) is used, a system of linear equations is obtained in the form given below.

$$\mathbf{K}\mathbf{E}^S = \mathbf{S} \qquad (2)$$

where **K** defines a hermitian and sparse matrix with at most 13 nonzero elements in each row, and **S** defines the source term. **E** field values are obtained by solving the system of equations, and **H** fields can be derived from electric fields by using auxiliary equations. In order to solve the system of equations, it is necessary to invert the matrix **K** (direct methods) or to solve the system of equations with Krylov space solvers (iterative methods).

Recently, direct solvers have used for relatively small modeling meshes. Since the inverse of the matrix is taken with direct solvers, there is no need to solve the equation again for each source and polarization, and the solution speed increases. Depending on the developments in computer technology, the use of direct solution methods has increased in the last decades and the use of Multifrontal methods in the CPU environment has become widespread (Streich, 2009; da Silva et al., 2012; Kordy et al., 2015; Puzyrev et al., 2016; Mütschard et al., 2017 ; Liu et al., 2018). Although the RAM usage of direct solvers are reduced with Multifrontal methods, it is not preferred for large model meshes. During the study, Multifrontal methods are used to compare solution speeds for small model meshes.

The number of rows or columns of the K matrix in the equation system to be solved can be expressed in hundreds of thousands or even millions, depending on the number of elements in the designed 3-D model mesh. For this reason, stationary and fast solvers used in the solution of the system of equations directly affect the speed of the method. Krylov space solvers are often preferred because RAM usage is much lower than direct solvers. In the 3-D EM method, the main Krylov space solvers used in the forward solution are CG (Zhdanov et al., 2000; Haber, 2004; Zhdanov et al., 2011), BICG (Sasaki et al., 2010; Farquharson ve Miensopust, 2011; Sasaki, 2012), BICGSTAB (Xiao et al., 2018; Singh et al., 2017; Plessix ve Mulder, 2008), QMR (Kelbert et al., 2014; Tang et al.,2015; Wang ve Tan, 2017) and GMRES (Cox et al., 2010; Grayver, 2015; Grayver and Kolev, 2015). Hursan and Zhdanov (2002) compared the methods and said that BICGSTAB, QMR and GMRES methods are the most effective solvers in their study. These three methods are often preferred in the solution of the equation.

These solvers are used in the developed algorithm and CPU performances are tested in the solution of frequency domain CSEM 3-D modeling algorithm. Using the results obtained, it is preferred to use BICGSTAB in GPU. The results of the algorithm and comparison of the solvers are discussed and their results presented in the following section.

MODEL STUDY

The initial results of the developed algorithm has been tested for the resistivity model given in Table-1 with using 1-D semi-analytical straight solution algorithm (Streich and Becken, 2011) and the previously developed 3D CSEM forward modeling algorithm (CUSTEM- Rochlitz et al., 2019). The E and H field amplitudes of the developed algorithm were compared with the CUSTEM and semi-analytical solution algorithm for the 1Hz frequency on each measurement point, which were obtained as a result of the resistivity model given in table-1 (Figure 1). The source used in the study is located at y=-3km and parallel to the x-axis. The dipole length of the source is used as 1 Km. The result of developed algorithm coincides with the results obtained with both the analytical solution and the CUSTEM algorithm. The performances of the solvers are tested on the CPU and it is seen that the BICGSTAB solver was the fastest and most stable solver (Figure 2). However, it is seen that direct solvers reach the solution in the most effective solution time when more than one source is used. In Figure 2, the results are given according to the use of a single source. In iterative solvers, it is necessary to recalculate for each source, while in direct solvers, there is no significant increase in computation time when more than one source is used. Therefore, as a result of the study, it is concluded that using direct solvers would be efficient in case of using multiple sources for small model meshes. When the CPU and GPU performances of the BICGSTAB algorithm, which is the chosen iterative solver, are examined, it is observed that the acceleration in the solver is 2,5 times higher, especially at low frequencies, and the algorithm developed on the GPU platform is more efficient (Figure 3).

Table 1. 1-D resistivity model used in the test study

	z (m)	Resistivity (Ωm)
B 1	0 to 300	100
B 2	300 to 700	10000
B 3	700 to infinity	1000

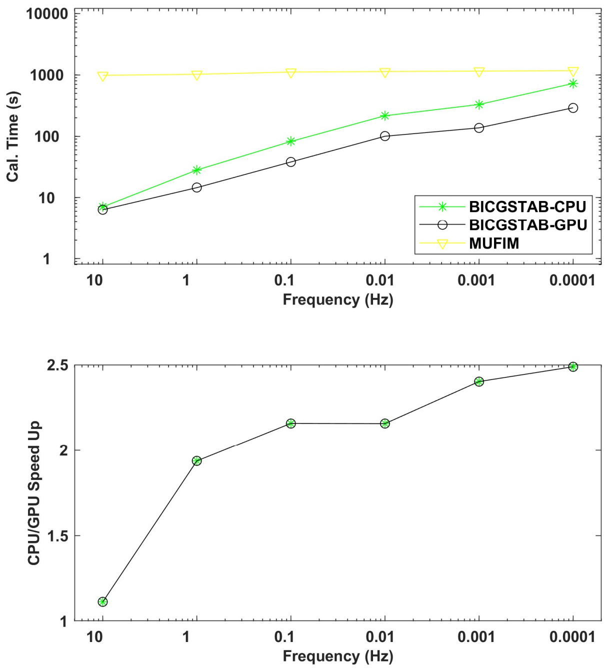

Figure 3. CPU and GPU performances and relative acceleration graphs of the selected iterative solver (BICGSTAB)

Conclusions

The findings obtained on the CPU revealed that the BICGSTAB algorithm is an efficient algorithm for 3D CSEM forward modeling. Therefore, it was also coded in the GPU environment. In this way, it has been observed that the algorithms coded on the GPU reach a solution 2.5 times faster, especially at low frequencies. In the case of multiple sources, multifrontal methods is converging to the solution faster for high frequencies and for small model networks. It is thought that the selection of the solvers in the developed algorithm chosed as hybrid in the light of the information obtained, which will increase the solution speed. For this purpose, in order to optimize the solution speed, the use of BICGSTAB at high frequencies and the multifrontal method at low frequencies is recommended in cases where the number of sources is more than one.

Acknowledgements

This work was supported within the scope of TÜBİTAK BİDEB with grant no 1059B191800610.

References

Avdeev DB, Kuvshinov AV, Pankratov OV, Newman GA (2002) Three-dimensional induction logging problems, Part I: An integral equation solution and model comparisons. Geophysics, 67(2), 413-426.

Badea EA, Everett ME, Newman GA, Biro O (2001) Finite-element analysis of controlled-source electromagnetic induction using Coulomb-gauged potentials. Geophysics, 66(3), 786-799.

Constable S, Weiss CJ (2006) Mapping thin resistors and hydrocarbons with marine EM methods, Part II—Modeling and analysis in 3D. Geophysics, 71(6), G321-G332.

da Silva NV, Morgan JV, MacGregor L, Warner M (2012) A finite element multifrontal method for 3D CSEM modeling in the frequency domain. Geophysics, 77(2), E101-E115.

Demirci I, Erdoğan E, Candansayar ME (2012) Two-dimensional inversion of direct current resistivity data incorporating topography by using finite difference techniques with triangle cells: Investigation of Kera fault zone in western Crete. Geophysics, 77(1), E67-E75.

Doll WE, Nyquist JE, Beard LP, Gamey TJ (2000) Airborne geophysical surveying for hazardous waste site characterization on the Oak Ridge Reservation, Tennessee. Geophysics, 65(5), 1372-1387.

Erdoğan E, Demirci I, Candansayar ME (2008) Incorporating topography into 2D resistivity modeling using finite-element and finite-difference approaches. Geophysics, 73(3), F135-F142.

Gunnink JL, Bosch JHA, Siemon B, Roth B, Auken E (2012) Combining ground-based and airborne EM through Artificial Neural Networks for modelling glacial till under saline groundwater conditions. Hydrology and Earth System Sciences, 16(8), 3061.

Haber E, Ascher UM (2001) Fast finite volume simulation of 3D electromagnetic problems with highly discontinuous coefficients. SIAM Journal on Scientific Computing, 22(6), 1943-1961.

Mackie RL, Smith JT, Madden TR (1994) Three-dimensional electromagnetic modeling using finite difference equations: The magnetotelluric example. Radio Science, 29(4), 923-935.

Mitsuhata Y, Uchida T (2004) 3D magnetotelluric modeling using the T-Ω finite-element method. Geophysics, 69(1), 108-119.

Newman GA, Alumbaugh DL (1995) Frequency-domain modelling of airborne electromagnetic responses using staggered finite differences. Geophysical Prospecting, 43(8), 1021-1042.

Newman GA, Alumbaugh DL (2002) Three-dimensional induction logging problems, Part 2: A finite-difference solution. Geophysics, 67(2), 484-491.

Pfaffhuber AA, Grimstad E, Domaas U, Auken E, Foged N, Halkjaer M (2010) Airborne EM mapping of rockslides and tunneling hazards. The Leading Edge, 29(8), 956-959.

Rochlitz R, Skibbe N, Günther T (2019) custEM: Customizable finite-element simulation of complex controlled-source electromagnetic data. Geophysics, 84(2), F17-F33.

Steuer A, Siemon B, Auken E (2009) A comparison of helicopter-borne electromagnetics in frequency-and time-domain at the Cuxhaven valley in Northern Germany. Journal of Applied Geophysics, 67(3), 194-205

Streich R (2009) 3D finite-difference frequency-domain modeling of controlled-source electromagnetic data: Direct solution and optimization for high accuracy. Geophysics, 74(5), F95-F105.

Streich R, Becken M (2011) Electromagnetic fields generated by finite-length wire sources: comparison with point dipole solutions. Geophysical Prospecting, 59(2), 361-374.

Wannamaker PE (1991) Advances in three-dimensional magnetotelluric modeling using integral equations. Geophysics, 56(11), 1716-1728.

Wolfgram P, Golden H (2001) Airborne EM applied to sulphide nickel-examples and analysis. Exploration Geophysics, 32(3/4), 136-140.

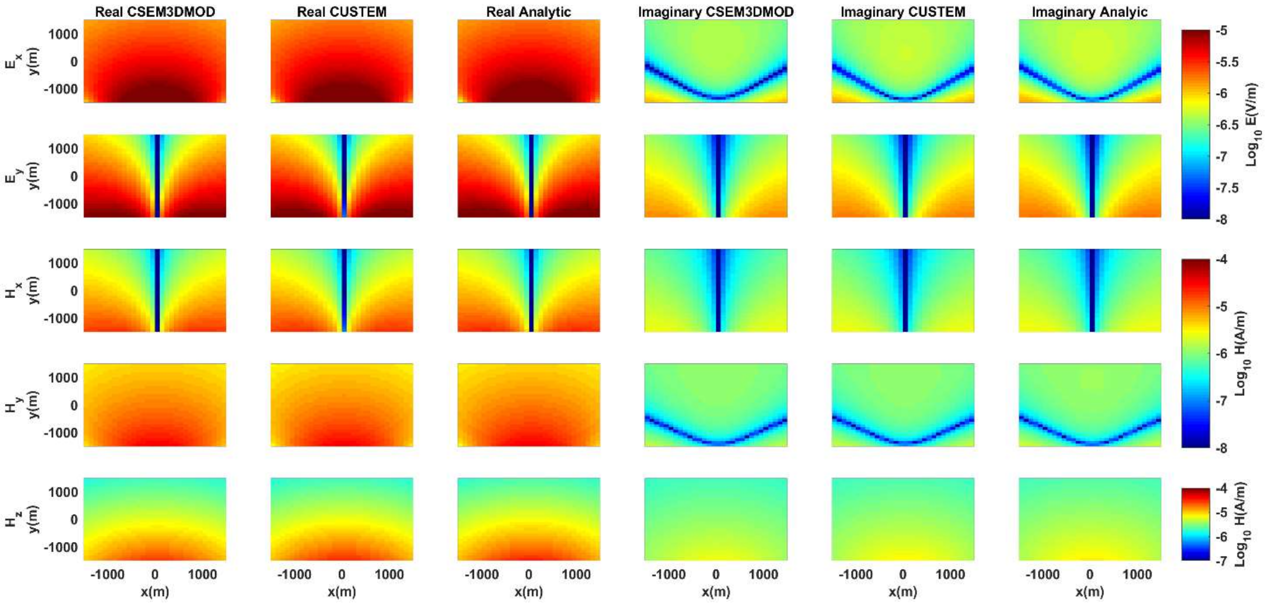

Figure 1. Comparison of our algorithm electric and magnetic field results (Ex, Ey, Hx, Hy, Hz) with CUSTEM and Semi-analytic solution for 1 Hz

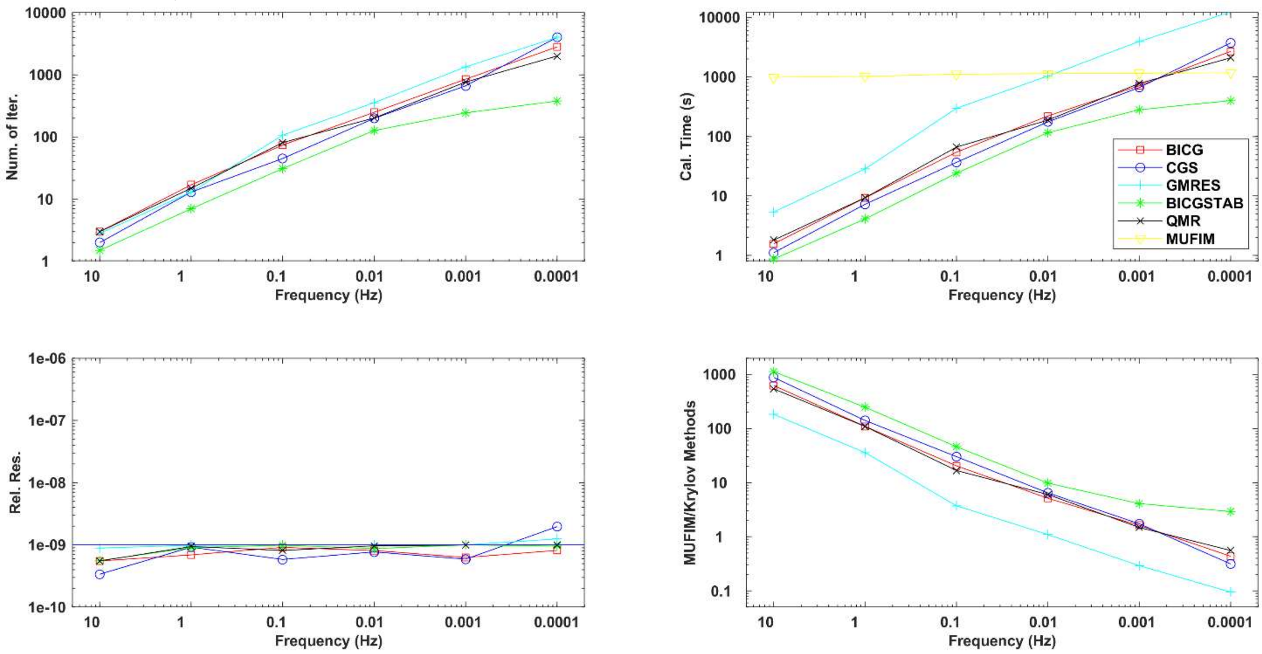

Figure 2. Comparison of iterative solvers in terms of iteration number, computation time, relative error and speed-up relative to direct solvers