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Forward Modeling Study of Controlled-Source Electromagnetic Based on the FEMTIC Program

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The Controlled-Source Electromagnetic (CSEM) method is a geophysical technique that uses an artificial electromagnetic source to investigate subsurface electrical conductivity variations. It operates in both marine and land environments and is particularly effective in inverting shallow targets, especially thin resistors compared to magnetotelluric (MT). In CSEM surveys, a known time-varying current—often from grounded electric dipole or current wire, which is injected into the Earth or ocean, generating primary electromagnetic (EM) fields. These primary fields interact with subsurface conductivity structures, inducing secondary electric currents whose associated EM fields can be measured at the surface or seafloor.

Forward modelling predicts the EM response for a given conductivity model and survey configuration, forming the foundation for interpretation and inversion. In realistic 3D geological settings, Maxwell's equations cannot be solved analytically, necessitating numerical approaches such as finite-element (FE), finite-difference (FD), finite-volume (FV), or integral-equation (IE) methods. In this study, we conduct forward modeling research on CSEM based on the open-source edge-based FE method MT program FEMTIC (Usui, 2015, 2017, 2021). The FEMTIC is particularly powerful for CSEM modelling because it can handle arbitrarily complex geometries through unstructured tetrahedral meshes. In the frequency domain, the Helmholtz equation for the electric field can be solved directly using edge-element basis functions, which ensure tangential field continuity. The FE approach involves discretizing the computational domain into tetrahedral elements, applying the Galerkin weighted-residual formulation, and assembling a sparse linear system representing the governing equations.

We use the total field equation as the governing equation for CSEM. Unlike the scattered field (secondary field) equation, the advantage of the total field equation is that it does not require the additional calculation of background electric field values. Its electric and magnetic field derivative matrices are consistent with those of MT (Since the source term is independent of the subsurface model conductivity), eliminating the need for further modifications. At the same time, it can better simulate field sources of arbitrary shapes. Correspondingly, to avoid computational singularities, we need to refine the mesh near the source to ensure the accuracy of the field source integration terms. We employ an accurate equivalent source method to discretize arbitrarily shaped sources. Unlike approaches that map current lines onto the edges of grid cells, our method identifies the actual contact relationship between the real field source and the grid elements. This allows us to determine the length, coordinates, and orientation of each wire segment passing through a certain grid cell, thereby enabling the simulation of arbitrarily shaped wires. In the program, we provide three types of field sources: (1) infinitesimally small magnetic dipole source with arbitrary orientation; (2) infinitesimally small electric dipole source with arbitrary orientation, (3) arbitrarily shaped wire (simulated using a polyline composed of multiple segments). By using the pseudo-Dirac function, we parameterize the field source. Leveraging the integral properties of the Dirac function, we achieve the calculation of the source integration term on the right-hand side of the governing equation. After incorporating the source term integration, by setting all outer boundary conditions in the CSEM simulation to the Dirichlet zero boundary condition, the forward modeling of CSEM can be achieved.

After modifying the CSEM forward modeling equations, we designed numerical experiments to demonstrate the accuracy of the CSEM forward modeling based on FEMTIC. The subsurface medium was modeled as a homogeneous half-space with a resistivity of 100 Ω· m. Sixty observation points were evenly spaced along the y-axis at 150 m intervals in the east – west direction. The source was positioned at the center of the model (origin of the coordinate system), implemented as both a 1 A· m moment electric dipole and a 1 m long current-carrying wire with a current of 1 A, both oriented in the due north direction. The analytical solution was computed using Dipole1D (Key, 2009). By comparing the CSEM results simulated with FEMTIC to the 1D analytical solutions, the average errors were found to be less than 1%, demonstrating the accuracy of the CSEM forward modeling based on FEMTIC. This lays a solid foundation for the subsequent development of the CSEM inversion module.