Robust Numerical Spectral-Domain Modeling of Subsurface EM Sensors in Planar-Layered Media based on the Complex-Plane Method of Weighted Averages

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Summary: We present a robust numerical spectral-domain methodology for the modeling of subsurface electromagnetic (EM) sensors traversing planar-layered media of general anisotropy and loss. Subsurface sensor modeling, in a manner that is *robustly* accurate and fast versus environment and sensor properties, is important both for improving fundamental understanding about subsurface sensor geophysics as well as aiding rapid inversion of subsurface anisotropic conductivity profiles to expedite characterization of hydrocarbon reservoirs. Although numerical spectral-domain techniques have many advantages versus more brute-force techniques such as FEM and FDTD, they have well-known drawbacks that until recently have not been adequately addressed. The present algorithm robustly achieves exponential-cum-algebraic convergence of the EM field solution. Applying the algorithm to tri-axial subsurface sensors traversing layered biaxial-conductive media, we observe excellent agreement with past published results, as well as observe differing sensitivity of the sensor's tensorial measurements to the components of a formation's conductivity tensor.

Background: Subsurface EM remote sensors, consisting of multiple, differently-oriented loop antennas wound around a central resistive mandrel, are routinely used as part of a multi-physics sensor instrument suite to characterize hydrocarbon reservoirs. The sensor depth-dependent scattered EM field signal aids in reservoir detection, location, and imaging to determine productivity potential. However, many interacting factors (e.g., sensor orientation, sensor frequency, layer thickness, and layer anisotropic conductivity) can lead to similar sensor readings. Full-wave numerical EM modeling can aid in predicting and understanding such confounding scenarios, as well as inform the design of more complex sensors (e.g., tri-axial sensors featuring three orthogonally-oriented transmitters and receivers) that aid in resolving sensor response ambiguities. Numerical spectral-domain EM techniques are particularly desirable since they exhibit low-frequency stability and the capability to model geophysical media of diverse anisotropic conductivity, which can arise from fracturing, alternating sand/shale micro-laminate depositions, and so on.

Challenges and Methodology: Numerical spectral-domain techniques have long been known to possess several practical issues impeding robustly accurate and rapid evaluation of the radiated EM field. Particularly, as the observation and source points approach nearer in depth, the spectral-domain integrand (when integrated along the classical real-axis path) becomes increasingly oscillatory and/or more slowly decaying. One strategy to overcoming these problems is to appropriately deform the integration path along a linear path bent away from the real axis (i.e., a source and observation position-dependent deformation angle), which ideally would asymptotically eliminate integrand oscillation and result in an optimal rate of exponential convergence. The other key ingredient in our methodology is to apply, along the deformed path, the Method of Weighted Averages of Mosig and Michalski to further impart algebraic integral convergence acceleration. The latter technique, which when now applied to said *deformed* integration paths we name the "Complex-Plane Method of Weighted Averages," results in robustly high accuracy and rapid exponential-cum-algebraic convergence.