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Analytical modeling of electromagnetic wave propagation and fracture scattering in dielectric media using discretized dipole distributions

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Accurate characterization of flow and transport in fractured media is both challenging and fundamental for many applications in the Earth Sciences. We are currently developing a framework to couple hydrological data from single-well injection-withdrawal and near-natural gradient tracer tests with single-hole Ground Penetrating Radar (GPR) monitoring data. Probabilistic inversion schemes will be developed to obtain multiple realizations of conditioned discrete fracture networks. To make such an approach tractable, it is essential to develop efficient, robust and accurate GPR forward solvers for arbitrary discrete fracture networks. Here, electromagnetic wave propagation is modeled analytically in the frequency domain using symbolic programming. The scattering of electromagnetic waves from a surface (fracture) is modeled as a distribution of infinitesimal dipoles on that surface (both in transverse electric and transverse magnetic modes). The complete representation of the dipole radiation field (near, intermediate and far field) arising from both the source and the scattering surface is taken into account. The thin bed approximation is used to model the effect of fluid-filled fractures with apertures that are considerably smaller than the dominant wavelength. Frequency dependence on wave propagation (necessary to model attenuation and dispersion effects) is taken into account by introducing a frequency dependent wavenumber. The following assumptions are made: (1) the host rock is homogeneous, (2) the fractures are assumed planar and thin (millimeter scale apertures), and (3) secondary reflections are ignored. As a preliminary test, predicted responses were compared with those from a well-established finite-difference code (GprMax) for a reflection from a large perfectly conducting plane. We also considered a 5-millimeter fracture in a homogeneous granitic matrixand compared our results to laboratory measurements. Our results are both accurate and efficient when a sufficiently close dipole separation is used and computation times that are considerably less than for the finite-difference simulation, often upt o two orders of magnitude but depending on the number of dipoles used to discretize the discontinuities. Numerical dispersion and boundary effects are avoided and the inclusion of the analytic thin-bed response allows for spatially varying fracture properties. We also evaluate how the algorithm performs when considering many fractures (>30) and its suitability for field applications.