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Inference of multi-Gaussian property fields by probabilistic inversion of crosshole ground penetrating radar data using an improved dimensionality reduction

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Deterministic inversion procedures can often explain field data, but they only deliver one final subsurface model that depends on the initial model and regularization constraints. This leads to poor insights about the uncertainties associated with the inferred model properties. In contrast, probabilistic inversions can provide an ensemble of model realizations that accurately span the range of possible models that honor the available calibration data and prior information allowing a quantitative description of model uncertainties. We reconsider the problem of inferring the dielectric permittivity (directly related to radar velocity) structure of the subsurface by inversion of first-arrival travel times from crosshole ground penetrating radar (GPR) measurements. We rely on the DREAM_(ZS) algorithm that is a state-of-the-art Markov chain Monte Carlo (MCMC) algorithm. Such algorithms need several orders of magnitude more forward simulations than deterministic algorithms and often become infeasible in high parameter dimensions. To enable high-resolution imaging with MCMC, we use a recently proposed dimensionality reduction approach that allows reproducing 2D multi-Gaussian fields with far fewer parameters than a classical grid discretization. We consider herein a dimensionality reduction from 5000 to 257 unknowns. The first 250 parameters correspond to a spectral representation of random and uncorrelated spatial fluctuations while the remaining seven geostatistical parameters are (1) the standard deviation of the data error, (2) the mean and (3) the variance of the relative electric permittivity, (4) the integral scale along the major axis of anisotropy, (5) the anisotropy angle, (6) the ratio of the integral scale along the minor axis of anisotropy to the integral scale along the major axis of anisotropy and (7) the shape parameter of the Matérn function. The latter essentially defines the type of covariance function (e.g., exponential, Whittle, Gaussian). We present an improved formulation of the dimensionality reduction, and numerically show how it reduces artifacts in the generated models and provides better posterior estimation of the subsurface geostatistical structure. We next show that the results of the method compare very favorably against previous deterministic and stochastic inversion results obtained at the South Oyster Bacterial Transport Site in Virginia, USA. The long-term goal of this work is to enable MCMC-based full waveform inversion of crosshole GPR data.