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Probability density of spatially distributed soil moisture inferred from crosshole georadar traveltime measurements

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Geophysical models are increasingly used in hydrological simulations and inversions, where they are typically treated as an artificial data source with known uncorrelated "data errors". The model appraisal problem in classical deterministic linear and non-linear inversion approaches based on linearization is often addressed by calculating model resolution and model covariance matrices. These measures offer only a limited potential to assign a more appropriate "data covariance matrix" for future hydrological applications, simply because the regularization operators used to construct a stable inverse solution bear a strong imprint on such estimates and because the non-linearity of the geophysical inverse problem is not explored. We present a parallelized Markov Chain Monte Carlo (MCMC) scheme to efficiently derive the posterior spatially distributed radar slowness and water content between boreholes given first-arrival traveltimes. This method is called DiffeRential Evolution Adaptive Metropolis (DREAM_ZS) with snooker updater and sampling from past states. Our inverse scheme does not impose any smoothness on the final solution, and uses uniform prior ranges of the parameters. The posterior distribution of radar slowness is converted into spatially distributed soil moisture values using a petrophysical relationship. To benchmark the performance of DREAM_ZS, we first apply our inverse method to a synthetic two-dimensional infiltration experiment using 9421 traveltimes contaminated with Gaussian errors and 80 different model parameters, corresponding to a model discretization of 0.3 m $\times$ 0.3 m. After this, the method is applied to field data acquired in the vadose zone during snowmelt. This work demonstrates that fully non-linear stochastic inversion can be applied with few limiting assumptions to a range of common two-dimensional tomographic geophysical problems. The main advantage of DREAM_ZS is that it provides a full view of the posterior distribution of spatially distributed soil moisture, which is key to appropriately treat geophysical parameter uncertainty and infer hydrologic models.