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Hamiltonian Tomography

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We present a new approach to the solution of tomographic inverse problems. It rests on the construction of an artificial Hamiltonian system where a model is treated as a high-dimensional particle moving along a trajectory in an extended model space. Both a probabilistic and a deterministic mode of operation are possible.

The probabilistic mode consists of Hamiltonian Monte Carlo (HMC) solutions to linear and nonlinear seismic tomography. HMC provides the complete posterior distribution, i.e. full uncertainty information, for order of magnitude 10'000 model parameters using not more than a standard laptop in the case of 2D traveltime inversion. Using derivatives of the forward equations, HMC is able to make long-distance moves from the current towards a new independent model, thereby promoting model independence, while maintaining high acceptance rates.

Following a brief description of HMC concepts in geophysical language, we provide an analysis of linear (tomographic) problems. Though these may not be the main target of Monte Carlo methods, they provide valuable insight into the geometry and the tuning of HMC, including the design of suitable mass matrices, and the length of Hamiltonian trajectories. With a series of tomographic/imaging examples we illustrate (i) different variants of HMC, such as constrained and tempered sampling, (ii) the independence of samples produced by the HMC algorithm, and (iii) the effects of tuning on the number of samples required to achieve practically useful convergence. Most importantly, we demonstrate the combination of HMC with adjoint techniques. This allows us to solve a fully nonlinear, probabilistic traveltime tomography without any need for supercomputing resources.

The deterministic mode is a new method to explore the effective nullspace of nonlinear inverse problems without Monte Carlo sampling. Depending on its initial momentum and mass matrix, the artificial particle (tomographic model) evolves along a trajectory that traverses the effective nullspace, thereby producing a series of alternative models that are consistent with observations and their uncertainties. Variants of the nullspace shuttle enable systematic hypothesis testing, e.g., by adding features or by producing smoother or rougher models. Furthermore, the Hamiltonian nullspace shuttle can serve as a tunable hybrid between deterministic and probabilistic inversion methods: Choosing random initial momenta, it resembles Hamiltonian Monte Carlo; requiring misfits to decrease along a trajectory, it transforms into gradient descent. We illustrate the concept with a low-dimensional toy example and with high-dimensional nonlinear inversions of seismic traveltimes, respectively.