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Can you trust your uncertainties? Improving Bayesian earthquake source inversions using simulation-based inference

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This work introduces a novel framework for full-waveform seismic source inversion using simulation-based inference (SBI). Traditional probabilistic approaches often rely on simplifying assumptions about data errors, which we show can lead to inaccurate uncertainty quantification. SBI addresses this limitation by building an empirical probabilistic model of the data errors using machine learning models, known as neural density estimators, which can then be integrated into the Bayesian inference framework. We apply the SBI framework to point-source moment tensor inversions as well as joint moment tensor and time-location inversions. We construct a range of synthetic examples to explore the quality of the SBI solutions, as well as to compare the SBI results with standard Gaussian likelihood-based Bayesian inversions. We then demonstrate that under real seismic noise, common Gaussian likelihood assumptions for treating full-waveform data yield overconfident posterior distributions that underestimate the moment tensor component uncertainties by up to a factor of 3. We contrast this with SBI, which produces well-calibrated posteriors that generally agree with the true seismic source parameters, and offers an order-of-magnitude reduction in the number of simulations required to perform inference compared to standard Markov chain Monte Carlo techniques. Finally, we apply our methodology to a pair of moderate magnitude earthquakes in the North Atlantic. We utilise seismic waveforms recorded by the recent UPFLOW ocean bottom seismometer array as well as by regional land stations in the Azores, comparing full moment tensor and source-time location posteriors between SBI and a Gaussian likelihood approach. We find that our adaptation of SBI can be directly applied to real earthquake sources to efficiently produce high quality posterior distributions that significantly improve upon Gaussian likelihood approaches.