



Imaging the Plume, Testing the Physics: Context-Aware Digital Twins for CO₂ Storage

Reliable geological carbon storage requires digital twins that track CO₂ saturation and pressure from time-lapse observations while quantifying uncertainty. Our earlier work introduced an uncertainty-aware digital shadow that uses machine learning to assimilate seismic and well data despite nonlinear reservoir dynamics and seismic observations. However, its reliability depends on how accurately the assumed rock physics represents the reservoir. We address this limitation by replacing conventional migrated images with common-image gathers, which retain offset- and angle-dependent information, are less sensitive to background-velocity errors, and help distinguish changes in density and velocity. We also condition the learned model explicitly on rock-physics parameters describing the transition between uniform and patchy saturation and the pressure dependence of seismic velocity. Synthetic experiments demonstrate improved joint estimates of CO₂ saturation and pressure, with the largest gains for pressure. The resulting context-aware framework enables rock-physics “what-if” analyses without retraining, providing a step from uncertainty-aware digital shadows towards digital twins for risk-aware monitoring and operational control.