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Shape-based 4D Full Waveform Inversion

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Introduction.

Full Waveform Inversion (FWI) is a powerful method for retrieving subsurface velocity and other physical properties by inverting the seismic waveform data. As a high-dimensional inverse problem, FWI is typically formulated as a gradient-based optimization. However, the quality of the FWI gradient is strongly influenced by the distribution of sources and receivers, as well as by noise in the data. To mitigate these issues, regularization terms are often added to the FWI objective function. These terms constrain the inversion to favor certain characteristics, such as smoothness or blockiness, in the resulting velocity model. Another strategy is to incorporate prior knowledge about the expected shape of geological structures. In 2D and 3D inversions, this is challenging due to the complexity and variability of subsurface geometries. In contrast, in 4D (time-lapse) inversion, we can often leverage prior information about the location and shape of anomalies, such as changes induced by injection wells in a reservoir. Based on this idea, we propose a 4D FWI approach that, instead of inverting for velocity at every point in the model, inverts for a set of shape parameters that define the 4D anomalies. This parametrization allows us to focus the inversion on meaningful changes in known regions of interest.

Method and/or Theory

To implement our shape-based 4D FWI, we reformulate the gradient computation to work in terms of anomaly shape parameters. Specifically, we compute the FWI gradient as the product of the conventional velocity gradient and the Jacobian of the velocity field with respect to the shape parameters. We begin with synthetic tests using simple Gaussian-shaped anomalies, which are described by six parameters: maximum amplitude, center coordinates (x and z), horizontal and vertical radii, and slope. The inversion experiments are conducted using a synthetic 4D OBN (Ocean Bottom Node) acquisition simulated on a velocity model typical of the Brazilian pre-salt region. The anomalies are located in the subsalt formations, where hydrocarbon reservoirs are commonly found.

Results and Conclusions

We are currently testing the method on both Gaussian and more realistic, non-Gaussian anomalies modeled from real data. The goal is to compare the performance of shape-based FWI with that of conventional 4D FWI. For the Gaussian case, we expect the shape-based inversion to yield more accurate results due to the explicit parametrization of the anomaly. For non-Gaussian cases, we anticipate that shape-based FWI will still provide valuable insights into the amplitude and spatial extent of the reservoir changes. Additionally, we are evaluating the robustness of the proposed method under non-repeatability conditions, where acquisition differences between baseline and monitor surveys may affect the inversion quality.