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# Comparative Study of Full-Waveform Inversion (FWI) Approaches for 4D Seismic Monitoring in Complex Acquisition Scenarios

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## Introduction.

Time-lapse or 4D seismic analysis is an essential tool for monitoring changes in reservoirs caused by production activities or other geological events, such as fault activation or modifications in the geometry or properties of specific geological areas. Identifying zones with remaining oil within the reservoir is particularly critical for guiding production and injection strategies, maximizing reservoir exploitation, and optimizing recovery efforts in the oil and gas industry. In recent years, Carbon Capture, Utilization, and Storage (CCUS) has emerged as another significant application of the methodologies discussed in this work. This is especially relevant when utilizing sparse acquisition geometries to minimize monitoring costs while ensuring the integrity and safety of the storage process.

This study analyzes and compares different strategies for generating responses related to full-waveform inversion (FWI) in time-lapse (4D seismic) analysis. Five distinct strategies are concisely presented. The first is the **Parallel Inversion**, in which the base and monitor datasets are treated independently, and at the end of the inversion cycle, the 4D FWI response is obtained by subtracting the two velocity models. The second is the **Sequential Inversion**, also known as Cascaded Inversion, where the monitor dataset is inverted sequentially after the base dataset is inverted, and the 4D FWI response is subsequently derived. The third strategy is the **Sequential Difference Cross-Updating**, in which two sequential inversions are applied consecutively, resulting in a total of four inversions following the sequence base → monitor → base → monitor. Each inversion uses the velocity model obtained in the previous step as the starting point for the subsequent inversion, with the 4D FWI response extracted at the end. The fourth approach is the **Central Difference**, where two independent cascaded inversions are performed—one starting with the base dataset and the other with the monitor dataset. The 4D response is obtained by averaging the results from the two cascaded inversions. Finally, the fifth approach is the **Simultaneous or Joint Inversion**, where both datasets are inverted simultaneously using a single objective functional. Regularization terms and a coupling term could be included to impose shared characteristics on the final inverted models, such as smoothness or sparsity. The coupling term can also penalize 4D anomalies outside the reservoir areas. To conclude, the 4D FWI response is obtained at the end of the joint inversion.

To further enhance the challenge of obtaining a reliable 4D response in a pre-salt environment—where expected impedance changes are on the order of a few percent and the reservoir overburden exhibits significant geological complexity—this study considers entirely different acquisition types for the base and monitor datasets. Specifically, the base dataset consists of streamer data, while the monitor dataset employs ocean-bottom nodes (OBN). These distinct acquisition geometries result in vastly different illumination and coverage patterns, posing significant challenges for achieving a reliable 4D response in this scenario.

## Results and Conclusions

To illustrate the methodologies, evaluate their strengths and limitations, and assist decision-makers in selecting the most suitable approach for a real-world 3D application, a realistic synthetic 2D geological model based on the Brazilian pre-salt is utilized. Despite the considerable challenges, the study concludes that there are strong prospects for success when the appropriate methodology is applied with meticulous care, incorporating robust quality control measures during the processing and inversion stages—even in such a complex environment with distinct acquisition geometries.