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Targeted nullspace shuttles of time-lapse full waveform inversion with application to CO_2 plume monitoring

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Summary

Time-lapse seismic monitoring is a proven technique in hydrocarbon reservoir monitoring and optimization. Traditional time-lapse implementations detect changes in the subsurface through differencing baseline and monitor surveys and relies on the repeatability of baseline and monitor survey geometries. While time-lapse monitoring can also be extended to full waveform inversion, the models obtained from full waveform inversion are non-unique, and therefore absolute inferences about time-lapse differences are difficult to make. We implement a numerical optimization strategy, targeted null space shuttling, to explicitly navigate the inversion nullspace to find unique baseline and monitor models which minimize the time-lapse difference and preserve the data-fit. Using synthetic examples, this approach demonstrates the ability of nullspace shuttling to detect minimum CO_2 time-lapse changes and reduce unwanted noise without the traditional time-lapse requirement of replicated acquisition geometries.

Introduction

Time-lapse seismic surveying is a well-established technique that has been used for many decades in the monitoring and optimization of hydrocarbon production (Greaves and Fulp, 1987). More recently, the time-lapse seismic method has been used in the monitoring, measurement, and validation (MMV) of CO_2 sequestration projects to characterize CO_2 plume migration, plume geometry, and plume containment.

To recover robust time-lapse changes using seismic monitoring, it is important that the baseline and monitor seismic surveys be repeated in as similar a manner as possible. This requires the replication of identical source and receiver geometries, and the use of the same source type and source parameters, for the baseline and monitor surveys. Conventional time-lapse seismic methods also require careful simultaneous processing of baseline and monitor surveys to enable meaningful time-lapse changes to be recovered. This approach takes considerable time and economic investment and may be prohibitive for CO_2 monitoring projects.

Most time-lapse inversion methods are based on either differencing a baseline and monitor inversion result or inverting the difference between baseline and monitor data sets. These approaches can be effective in simple, noise-free models but are challenging in realistic data sets in which non-repeatable effects such as noise and differences in acquisition geometry are present. In addition, the FWI results of the baseline and monitor inversions are non-unique and are dependent on the initial model and numerical optimization scheme used in the inversion. Consequently, the time-lapse difference is also non-unique. An approach for nullspace shuttling in FWI uncertainty analysis was introduced by Keating and Innanen (2021). Targeted shuttling can be used to explicitly navigate the FWI nullspace with respect to a user-defined scalar function of model-space location.

Theory

Full waveform inversion seeks to characterize the true properties of the subsurface but produces results that are highly dependent on the acquisition geometry, initial model, optimization strategy used and noise. A time-lapse inversion difference ideally identifies real temporal changes in the subsurface without identifying any changes due to differences in acquisition geometry between baseline and monitor surveys, or noise in the data.

The model, m, obtained from FWI corresponds to the lowest value of the objective function, ϕ, which was achieved during numerical optimization but not the exact, or global minimum. The inversion output depends on the specific optimization parameters used and is inherently distorted due to noise in the data and approximations in the theory. In addition, measurement errors contribute to differences in baseline and monitor data sets, meaning that many possible models fit the data as well, or better than, the true model. Another model, m^*, with objective function value ϕ^*, could be an equally plausible output of the inversion, provided that $\phi^* \leq \phi$. The FWI problem, then, has a set of acceptable solutions, **m**, containing all possible models $m^*$for which $\phi^* \leq \phi$, that satisfies the inversion conditions equally well. We refer to this set of possible models as the nullspace of the inversion problem, and the objective function-preserving model-space steps as 'nullspace shuttles' (Deal and Nolet, 1996).

The method of time-lapse targeted nullspace shuttling is fully described in Keating and Innanen (2022) and summarized as follows. We begin by defining a hypothesis that the shuttling will attempt to violate. Here we use the hypothesis that the baseline and monitor models differ from one another. The shuttling process will then be used to find the time-lapse change which most violates this hypothesis (that is, to find the most similar models) while still fitting the data acceptably well. This hypothesis function is small when the difference between baseline and monitor surveys is also small, and large otherwise. In this context the time-lapse difference can be presented as a multi-stage shuttling optimization problem in which solve for the minimum difference:

$$\Delta m_{SH} = (m_M + \delta m_M^*) - (m_B + \delta m_B^*) \qquad (1)$$

where Δm_{SH} is the optimal time-lapse difference, m_B and m_M are the baseline and monitor FWI results, and δm_B^* and δm_M^* are the optimal shuttled updates.

In time-lapse FWI there is a nullspace for the baseline, and a separate nullspace for the monitor. Figure 1 illustrates, in two dimensions, a simplistic time-lapse FWI approach. The orange ellipse corresponds to the nullspace of the monitor inversion, and the blue ellipse corresponds to the baseline inversion. The FWI results, m_B and m_M, are simply differenced to find a traditional time-lapse difference, Δm_{TL}. These inversion results are determined by the starting models used for each inversion. Hypothetically, any point on either nullspace is an equally possible FWI model solution. Through targeted shuttling, we can directly search the nullspace for the 'optimal' or minimum difference between baseline and monitor, Δm_{SH}. This minimum difference will not provide the absolute time-lapse change, but it will provide an estimate of the minimum difference that meets the data-fit obtained through FWI.

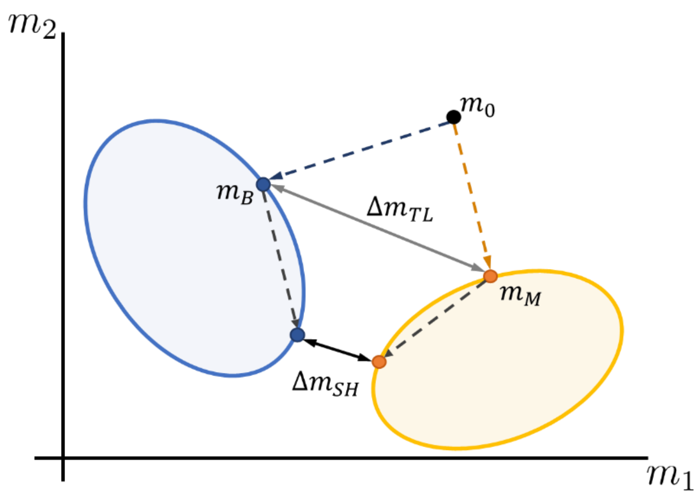

FIG. 1. Conceptual diagram of the time-lapse inversion nullspaces. The blue and orange ellipses represent the baseline and monitor FWI nullspaces, respectively. The baseline and monitor P-wave velocity models after FWI are m_B, and m_M, and their time-lapse difference is Δm_{TL}. Through shuttling, we seek, Δm_{SH}, minimum difference between baseline and monitor FWI models.

Method

Synthetic baseline and monitor models were created using well log data acquired by Carbon Management Canada (CMC) at their field research facility in Newell County, AB, where CO_2 is being injected into the Basal Belly River Sandstone. The true baseline P-wave velocity model was created by blocking the compressional sonic log at geological interfaces. A true monitor P-wave velocity model was created using elastic parameters modeled from a reservoir simulation study presented in Macquet et al. (2019). Assuming a semi-patchy model and fluid replacement of brine with up to 50% CO_2 saturation, and pore pressure increases of up to 2.7 MPa, Macquet et al. estimated a reduction of P-wave velocity between 20-32%. To simulate a true monitor velocity model the P-wave velocity of the baseline model was reduced by 950 m/s within the injection interval.

To approximate a CO_2 monitoring scheme a 2D VSP acquisition geometry, using parameters based on those used at the CMC site, with borehole receivers and surface sources is considered. FWI is implemented using a 2D, acoustic, frequency-domain, multi-scale approach to obtain predicted baseline and monitor P-wave velocity models.

To estimate the minimum time-lapse changes between baseline and monitor FWI models the inversion results serve as optimization parameters in the objective function of the targeted nullspace shuttling scheme. The aim is to find baseline and monitor models that minimize all differences unrelated to true subsurface changes, while preserving the FWI objective function values of the baseline and monitor inversions. A targeted shuttling objective function is constructed, using the Huber norm, with inputs of baseline and monitor inversion models as the optimization parameters, to estimate the optimal models. The complete nullspace shuttling algorithm is described in detail in Keating and Innanen (2021).

Results

To evaluate the effectiveness of targeted nullspace shuttling to isolate the minimum time-lapse changes while preserving data-fit, multiple numerical examples with varying signal-to-noise ratios (SNR) and baseline and monitor acquisition geometry parameters are considered. The traditional time-lapse difference and targeted nullspace shuttled difference are compared for each scenario. In the example shown in Figure 2 we consider the case of different SNR between baseline and monitor surveys and non-repeated acquisition geometries. In the monitor survey a CO_2 plume has been modeled as a velocity decrease at approximately 300 m depth. While this plume cannot be easily interpreted on the monitor FWI result (Figure 2b), an anomaly along with extraneous noise is observed in the time-lapse difference (Figure 2c). After targeted nullspace shuttling the noise has been removed, and a minimum estimate of the CO_2 plume remains (Figure 2d).

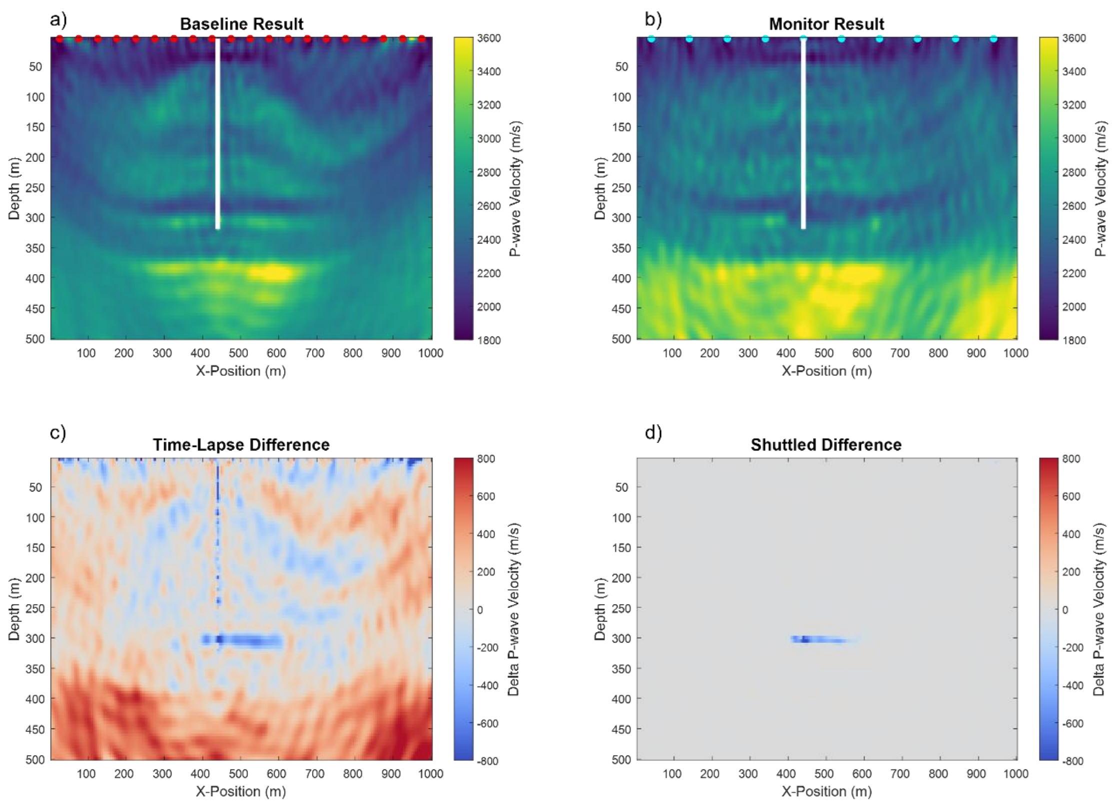

FIG. 2. a) Baseline inversion, source points in red, b) monitor inversion, source points in cyan, c) time-lapse difference and d) shuttled difference for the CO_2 injection case of offset and unequally spaced source geometry, with added noise. VSP receiver locations in white.

Conclusions

The application of nullspace shuttling to time-lapse FWI based on these synthetic models continues to show promise. The objective of nullspace shuttling in this report was to provide the minimum time-lapse difference between baseline and monitor, while remaining in the baseline and monitor nullspaces. In the synthetic case considered, nullspace shuttling effectively isolated a minimum time-lapse difference due to CO_2 injection, and successfully removed noise unrelated to subsurface changes.

Acknowledgements

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