Targeted nullspace shuttles as enablers of time-lapse CO2 monitoring with sparse acquisition

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Summary

Time-lapse seismic monitoring, when based on full waveform inversion methodologies, relies on both repeatability of baseline, and monitor survey geometries, and complete acquisition (i.e., dense sampling, and wide offsets and azimuths). The costs arising from this make it impractical for use in long-term CO_2 monitoring programs. Here we address this issue by examining targeted nullspace shuttles, which are FWI model updates designed to be applied post-convergence and to explore the space of models which conserve data misfit. If, as we assume, time-lapse model artifacts and 4D noise caused by sparse acquisition are not required to maintain data misfit, it follows that specially designed time-lapse nullspace shuttles might exist which suppress artifacts due to these low-cost acquisition geometries, opening them up to practical use. To test this idea, we set up numerical experiments in which we invert synthetic VSP data designed to mimic a time-lapse survey at the Carbon Management Canada Newell County Facility in Alberta, Canada. We vary the baseline and monitoring acquisition geometries, and compute shuttles designed to minimize model differences and maintain misfit with these varying datasets. Our observation is that, if the baseline acquisition is sufficiently complete, an extremely limited number of monitoring sources and sensors are needed to identify actual subsurface change and eliminate a large fraction of the acquisition artifacts.

Introduction

Time-lapse seismic surveying is a well-established technique that has been used for many decades in hydrocarbon reservoir monitoring and enhanced oil recovery (Greaves and Fulp, 1987; Wang et al., 1998; Lumley, 2001). 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. Previous authors have shown that time-lapse seismic is effective for monitoring injection of CO_2 into saline aquifers (Arts et al., 2004; Brevik et al., 2000; Chadwick et al., 2010; Pevzner et al., 2017).

Conventional time-lapse seismic methods require the replication of identical source and receiver geometries, and the use of the same source type and source parameters for baseline and monitor surveys in addition to careful simultaneous processing, to recover robust time-lapse changes (Porter-Hirsche and Hirsche, 1998; Lumley, 2001). This approach is time and resource intensive, implying substantial capital investment. While this approach may be economically feasible for hydrocarbon development projects, it may be prohibitive for CO_2 monitoring projects (Pevzner et al., 2017), especially when such programs must be set out for decades or longer. Controlling costs through sparse-acquisition time-lapse 3D seismic has been piloted at several CO_2 storage sites, including Ketzin, Germany (Ivandic et al., 2012), and Aquistore, Canada (White et al., 2015), with encouraging results.

To date, full-waveform technologies for seismic time-lapse inversion and difference model estimation have not been directly considered in low-cost, sparse-acquisition approaches. Indirectly, repeatability and 4D noise issues have driven the development of the range of differencing strategies for time-lapse FWI now in the literature (for a brief review see, e.g., Fu and Innanen, 2023), but we lack a coherent strategy for formulating time-lapse FWI when (say) monitoring surveys are by necessity restricted to small numbers of sources and receivers. The use of targeted nullspace shuttles, initially developed for uncertainty quantification in FWI (Keating and Innanen, 2021), to estimate minimal differences between monitoring and baseline FWI models, has been put forward as a potentially useful framework. Here we examine the framework in the context of severely constrained monitoring geometries.

Multiple time-lapse scenarios are modeled numerically, with the aim being to systematically assess the shuttling approach in the presence of evolving CO_2 plumes and sparse acquisition geometries. The geological model and acquisition scenarios considered are based on those implemented at Carbon Management Canada's (CMC) Newell County Facility, where CO_2 has been injected into the Late Cretaceous Basal Belly River Sand. One of the objectives of CMC is to evaluate and demonstrate accurate, cost-effective measurement and verification technologies. We explore the application of sparse FWI monitoring using targeted nullspace shuttling as a plausible, cost-effective, CO_2 plume detection method.

Theory and Method

The objective of full waveform inversion is to characterize the true properties of the subsurface, however it produces results that are also 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 dependence of FWI results on other factors also impacts any time-lapse differences.

The model, m, obtained from FWI corresponds to the solution with the lowest objective function value, ϕ, achieved during numerical optimization. This output is dependent 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. We accept our FWI output on the basis of the data- and prior-fit achieved as quantified by ϕ. 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 satisfy 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).

Here, we make use of a specific type of nullspace shuttle, namely that which maximally reduces the impact of non-reproducible effects in our time-lapse estimate. 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 which solves 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 nullspace of 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 valid FWI model solution. Through targeted shuttling, we can directly search the nullspace for the 'optimal' or minimum difference between

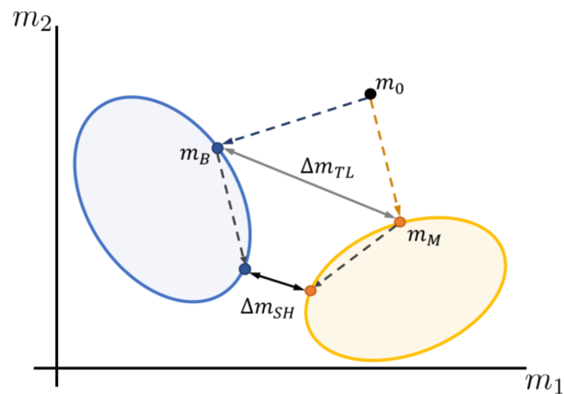

Figure 1: Conceptual diagram of the time-lapse inversion nullspaces. The blue and orange ellipses represent the baseline and monitor FWI nullspaces, respectively. The baseline and monitor P-wave velocity models after FWI are m_B and m_M and their time-lapse difference is Δm_{TL}. Through shuttling we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

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.

To test the targeted nullspace shuttling approach, acoustic FWI datasets for baseline and monitoring scenarios are created. A synthetic true baseline P-wave velocity model is generated by blocking compressional sonic well log data at geological interfaces. A true monitor P-wave velocity model is approximated using elastic parameters modeled from a reservoir simulation study presented in Macquet et al. (2019). Using a semi-patchy saturation model to replace 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% within the basal Belly River sand. To simulate the true monitor velocity model for this study the P-wave velocity of the baseline model is reduced by 950 m/s within the injection interval.

A CO_2 injection scheme is modeled using a 2D VSP acquisition geometry with borehole receivers and surface sources considered. Receiver locations remain constant for baseline and monitor models, while multiple source geometry configurations, from densely sampled, to single source point, are considered. FWI is then 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).

Examples

To evaluate the utility of targeted nullspace shuttling to isolate minimum time-lapse changes we first consider the ideal case where the baseline and monitor acquisition geometries are repeated exactly, with sources at every surface grid cell (i.e., every 5 m) and no additional noise added. The baseline and monitor FWI results, their time-lapse difference, and the difference after targeted nullspace shuttling is shown in Figure 2. In this figure and the next figure, baseline source locations are shown in red, monitor source locations are shown in cyan and receiver locations are shown in white.

The CO_2 plume can be clearly identified in the simple time-lapse difference, given the sampling conditions and lack of noise. The shuttled difference, corresponding to the minimum time-lapse difference that preserves data-fit, is nearly identical in lateral extent. All non-CO_2 injection related changes have been removed, providing a more definitive plume geometry.

To assess the effectiveness of targeted nullspace shuttling to a sparse, low-cost time-lapse monitoring survey we consider the case of a less dense baseline survey with sources located every 50 m and a monitor survey with a single surface source located at approximately 110 m from the CO_2 injection well. The objective of this model is to simulate a plausible low-cost monitoring scenario. The FWI results, time-lapse difference and shuttled difference are shown in Figure 3.

In this example the baseline FWI result is noisy, but comparable to that obtained in the ideal case. The monitor FWI result is uninterpretable. No discernable geological or fluid related features can be identified. Two horizontal, coherent, low-velocity features exist on the time-lapse difference, but cannot be confidently attributed to the CO_2 plume. After nullspace shuttling a single, small anomaly

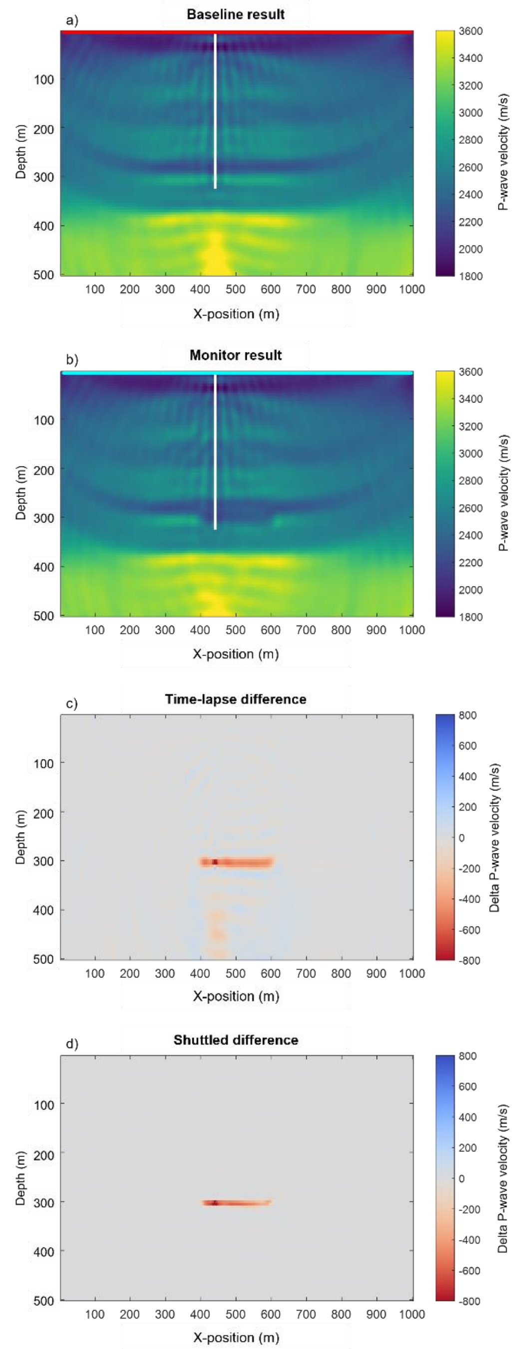

Figure 2: a) Baseline inversion, b) monitor inversion, c) time-lapse difference and d) shuttled difference for the CO_2 injection case of dense, exactly matched acquisition geometries.

remains in the location of the injected CO_2 plume, suggesting the minimum time-lapse difference; all other noise is removed. This is remarkable, given the poor monitor survey FWI result.

Conclusion

The results of targeted nullspace shuttling applied to time-lapse FWI for sparse CO_2 monitoring are encouraging, based on these synthetic examples. An appropriately defined hypothesis function, based on an understanding of the expected elastic response to CO_2 injection, provided an estimate of the minimum time-lapse difference between baseline and monitor surveys while preserving data-fit. When applied to sparse acquisition scenarios this method was able to effectively isolate a minimum time-lapse difference due to CO_2 injection. This may reduce the costly requirement of repeatability in baseline and monitor survey geometry enabling low-cost, sparse monitoring for CCS projects. An appropriately posed hypothesis function may allow for the detection of time-lapse changes, even when a traditional FWI time-lapse difference does not.

Acknowledgements

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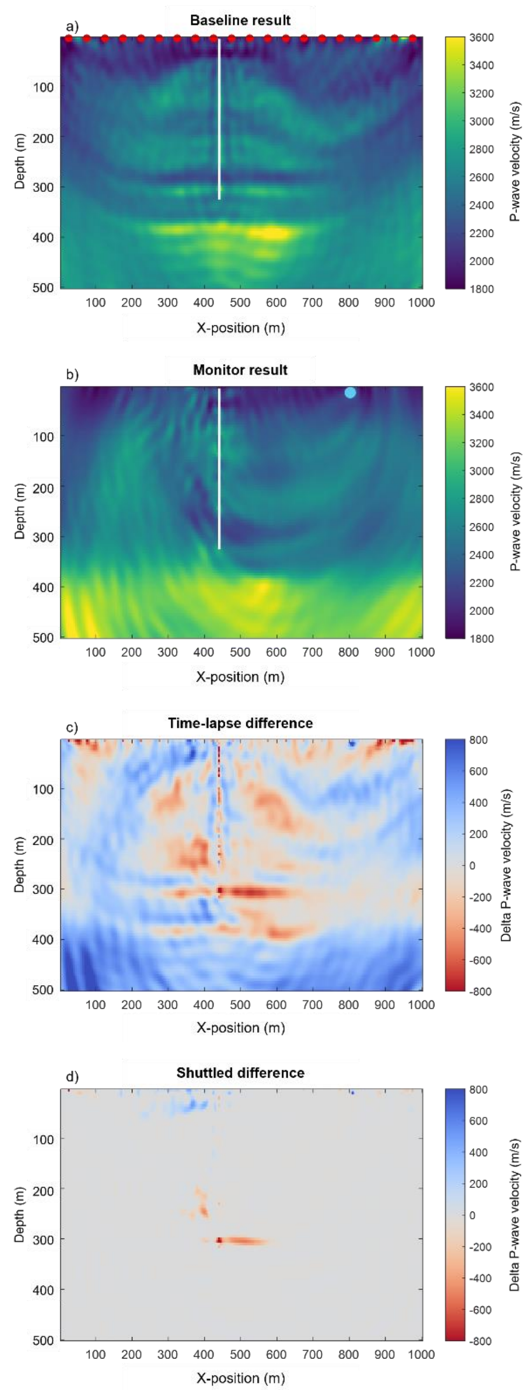

Figure 3: a) Baseline inversion, b) monitor inversion, c) time-lapse difference and d) shuttled difference for the CO2 injection case of a single source point located at 810 m x-position, with added noise.