The role of FWI refining iterations in time-lapse nullspace shuttling - Implications for low-cost CO_2 monitoring

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Summary

Time-lapse nullspace shuttling is a post full waveform inversion optimization approach that can mitigate the effects of noise and non-repeated baseline and monitor acquisition geometries. It recovers a time-lapse difference that is less sensitive to the acquisition source effort and time-lapse strategy while maintaining the full waveform inversion data misfit. The size of the baseline and monitor nullspaces, which are related to the data misfit, must be sufficiently reduced prior to time-lapse nullspace shuttling such that no nullspace overlap exists. In a multi-scale full waveform inversion scheme an additional set of refining iterations over the full bandwidth is required to further reduce data misfit, separating the baseline and monitor nullspaces. While refining iterations have a minimal effect on the standard time-lapse difference there is significant improvement in the time-lapse shuttled difference, allowing temporal subsurface changes to be effectively identified using sparse monitor geometries and reducing monitoring costs.

Introduction

Land time-lapse surface seismic surveys are associated with high cost and large surface footprint. The replication of source and receiver geometries required by conventional methods is challenging due to variability in source and receiver positions, receiver coupling, and variations in near surface conditions between surveys (Yurikov et al., 2021). In addition, the requirement of long-offset data for surface seismic full waveform inversion (FWI) (i.e., diving waves or post-critical reflections) to update long wavelength features (Plessix and Cao, 2011), further extends the surface footprint and increases overall project costs. To mitigate costs, sparse time-lapse 3D seismic has been piloted at several CO_2 storage sites with some success (Ivandic et al., 2012; White et al., 2015).

Time-lapse vertical seismic profiles (VSP) are widely used in carbon capture and storage (CCS) projects. Time-lapse VSP reduces the surface footprint thus improving project economics, and the deployment of receivers in a borehole removes the variation of receiver position and near surface receiver effects (Yurikov et al., 2021). For VSP data, FWI makes use of compressional and shear waves and transmitted, converted, primary, and multiple reflected waves. The transmitted direct waves in VSP data facilitate the success of FWI as they partially mitigate the lack of low frequencies in reflected data (Owusu et al., 2016).

The use of targeted nullspace shuttles (NSS), initially developed for uncertainty quantification in FWI (Keating and Innanen, 2021) to estimate the minimal difference between monitoring and baseline FWI models, has recently been put forward as a potentially useful framework for time-lapse FWI (Keating and Innanen, 2024). Here we examine the framework in the context of severely constrained monitoring acquisition geometries. Targeted nullspace shuttling is a post-inversion optimization process which uses the model outputs from FWI. As such, certain aspects of the FWI implementation can impact the results of NSS, namely the time-lapse scheme (e.g., monitor survey starting model) and the level of ~~the reduction~~ of FWI misfit. ~~or objective function value~~. Pike et al. (2024) explored preliminary applications of timelapse nullspace shuttles to a synthetic VSP dataset but did not optimize the time-lapse FWI method to improve shuttling success. Here we explore the implications of FWI misfit on the traditional time-lapse difference and the time-lapse NSS difference for multiple acquisition geometries.

Method

Through numerical examples we assess the application of the time-lapse shuttling approach to variations in acquisition effort and method and its sensitivity to FWI refining iterations and the FWI time-lapse approach. Several plausible monitoring geometry scenarios are evaluated based on the field setup at the CMC Newell County Facility. For the multi-offset VSP geometry source arrays are centered on a hypothetical CO_2 injection well. A CO_2 plume is constrained to the injection zone at approximately 300 m depth and is modelled to be 10 m in thickness and 200 m in width.

We use a multiscale, frequency domain FWI approach to obtain parameter models for baseline and monitor surveys. After inversion for the highest frequency band, we refine the FWI model over the entire frequency range. The goal of this refining inversion is to further reduce the FWI misfit, thus shrinking the FWI nullspace. We illustrate this concept in Figure 1, using a two-parameter problem as an example. As the objective function decreases, the nullspaces of both baseline and monitor inversions shrink, potentially eliminating overlaps, and helping us to identify real time-lapse changes.

In a simple two parameter case the FWI objective function can be approximated as a positive definite paraboloid in 3D space. A 2D level set defines the FWI nullspace at the corresponding objective function value. The baseline and monitor each have their own objective function paraboloid. If the baseline and monitor nullspaces overlap, as in Figure 1a, then the minimum difference between the baseline and monitor is zero, that is, the baseline and monitor could be equal without exceeding the misfit tolerance of our inversion. After shuttling the time-lapse difference will be zero. If we can reduce the value of the FWI objective function and shrink the nullspace, through refining iterations we can move down the paraboloid to a lower level set. After shuttling, the time-lapse difference will be non-zero and a minimum time-lapse estimate will exist (Figure 1b). So, by reducing the misfit tolerance of our inversion, we can eliminate overlaps between nullspaces.

Numerical Examples

To demonstrate the impact that the FWI objective function value has on reducing overlap in baseline and monitor nullspaces, and on recovering a time-lapse difference with certainty, we shuttle the dense baseline and monitor FWI models after a discrete number of refining iterations. As we increase the number of iterations we reduce the FWI objective function value, shrinking the nullspace. While we expect the nullspace to behave similarly for surface and VSP geometries, we expect the surface example to have a larger nullspace than the VSP geometry (i.e., fewer direct waves, receivers further away from zone, etc.), and have more overlap between baseline and monitor.

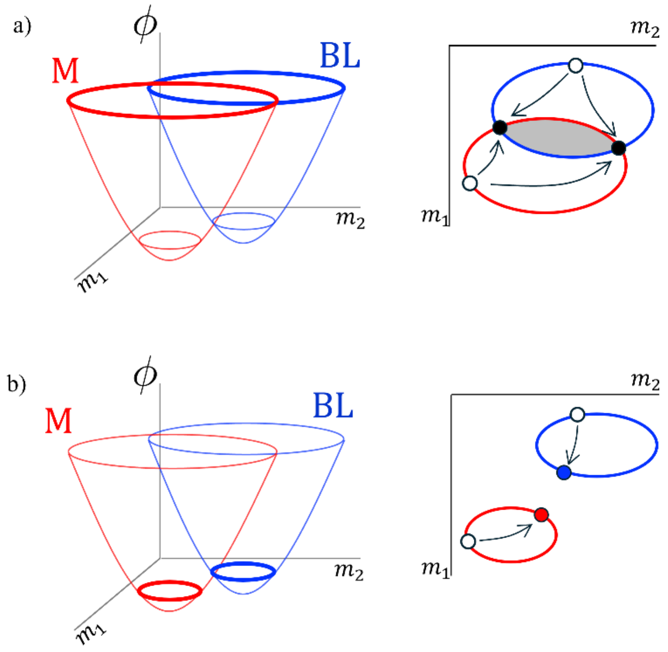

FIG 1. Conceptual illustration of FWI misfit and nullspace overlap for a two-parameter case. (a) The monitor and baseline nullspaces overlap at higher values of FWI misfit, resulting in zero minimum nullspace difference; (b) Separation exists between monitor and baseline nullspaces at lower values of FWI misfit, resulting in a minimum distance which can be found through nullspace shuttling.

Plots of FWI objective function value versus refining iteration for the baseline and monitor VSP examples are shown in the top two panels of Figure 2. The objective function decreases monotonically in both instances. We take the time-lapse and shuttled differences for baseline and monitor FWI models at refining iterations 1, 25 and 50, shown from left to right. The first iteration models are equivalent to the models obtained from multiscale FWI. There is no obvious improvement in the time-lapse difference with refining iteration. Any subtle changes are random and not organized about the plume. However, there is marked improvement in the shuttled difference. At refining iteration 1 a small, low amplitude plume is present. By refining iteration 25 the FWI misfit is reduced, and a larger, higher amplitude plume is recovered. There is marginal change in plume extent and magnitude by iteration 50.

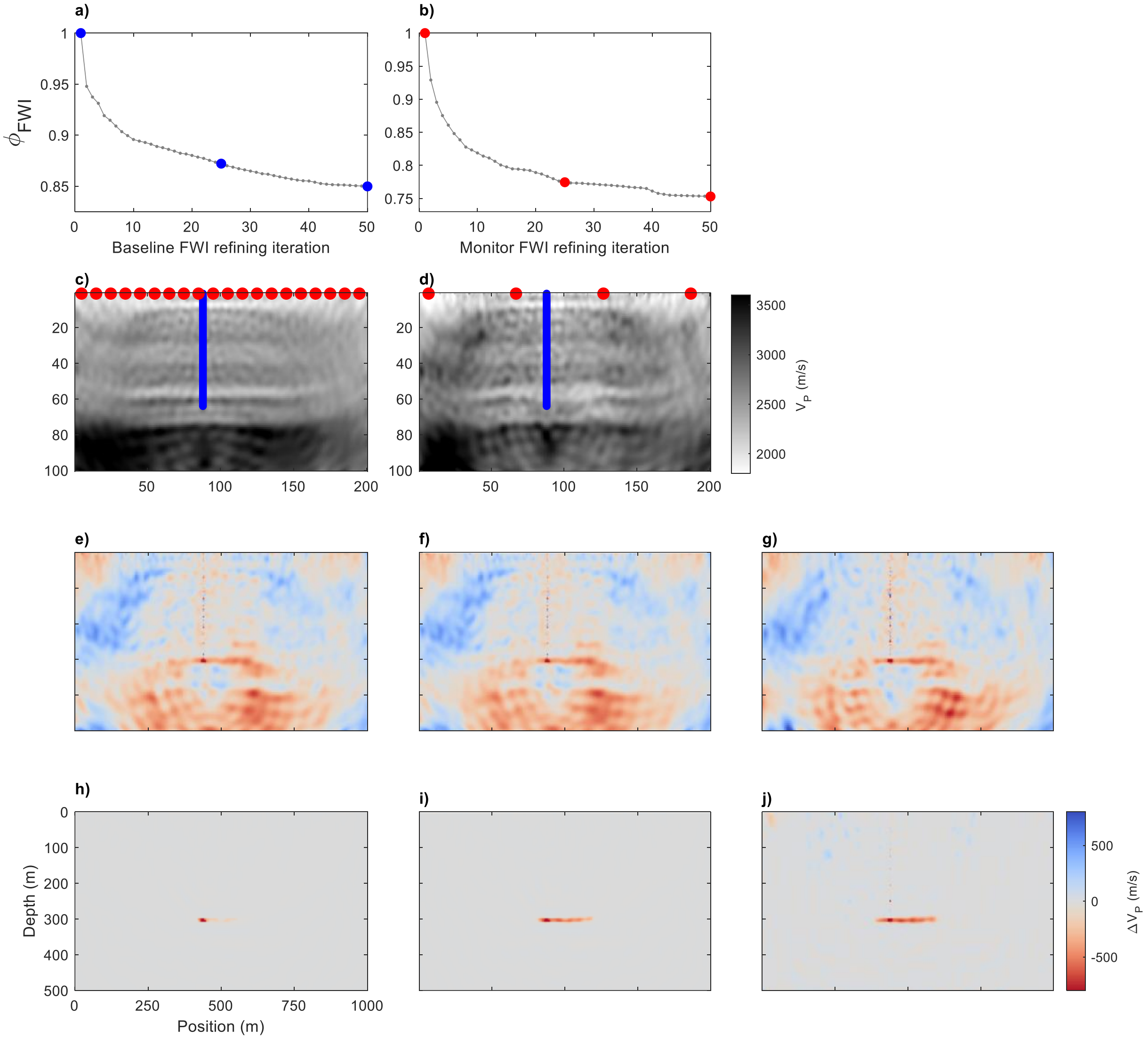

Figure 2. Normalized FWI misfit versus refining iterations for VSP acquisition (a) baseline and (b) monitor inversions; (c) dense baseline FWI model, (e) sparse monitor FWI model; (e) FWI time-lapse difference after 1 refining iteration, (f) 25 refining iterations, and (g) 50 refining iterations; (h) Time-lapse shuttled difference after 1 refining iteration, (i) 25 refining iterations, and (j) 50 refining iterations.

Discussion and Conclusions

While time-lapse nullspace shuttling can be successfully applied to VSP and surface acquisition geometries, as demonstrated by these numerical examples, the FWI approach implemented prior to shuttling data contributes directly to its success. To obtain a timelapse shuttled anomaly the baseline and monitor FWI nullspaces must have separation. Otherwise, the minimum difference solved for during shuttling will be zero. To obtain this separation we reduce the data misfit by further reducing the FWI objective function through an additional pass of FWI, referred to as refining iterations. This refining step over the entire frequency range reduced the misfit by 15-25% which, in the examples shown, eliminated overlap in the baseline and monitor nullspaces.

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