Introduction

Each carbon capture, utilization, and storage (CCUS) site requires a measurement, monitoring, and verification (MMV) plan, which provides assurance regarding the conformance and containment of the stored CO_2 and ensures compliance with regulations.

Time-lapse (4D) seismic monitoring is a proven technology for characterizing subsurface changes due to reservoir production and will play a significant role in demonstrating that the CO_2 plume is in conformance (or otherwise) with the MMV plan. However, costs associated with the acquisition, processing, and interpretation of conventional time-lapse seismic are high, and a step change in the cost of CO_2 monitoring, versus conventional reservoir monitoring, is a common goal across the industry.

One route to achieve this cost reduction is through the incorporation of dynamic modelling, survey design, history matching and automation to facilitate verification and update of the subsurface model (Branston et al., 2024).

In this paper, we demonstrate that by adopting a 4D detection objective, rather than a 4D imaging/characterization objective, we can exploit data redundancy in conventional 4D seismic. We propose to use the output of dynamic subsurface modelling, to design 4D surveys that target specific changes in a known subsurface model. This is done using a perturbation analysis, based on full-waveform inversion (FWI), that allows the model and perturbation to be synthetically probed with different acquisition geometries, to determine which geometry provides the most cost-effective solution to detect and localise the targeted change.

In this way, we create a 4D FWI workflow, where the acquisition effort is adapted to the evolution of the plume, through the connection to dynamic modelling.

Method

A conventional 4D monitoring approach will typically involve acquiring a high-density baseline survey, with monitoring surveys of an equivalent density acquired at defined intervals. The baseline and monitor data are processed rigorously to minimise acquisition-related differences, before isolating the 4D difference through seismic imaging. An alternative approach is to use FWI to directly find the 4D difference in the model domain. For example, Dutta et. al. (2023) introduced a 4D FWI approach that requires minimal data preprocessing and minimises acquisition-related differences by solving for both the baseline and the monitor models in a joint inversion.

An FWI based approach to 4D seismic may be carried out as sketched in Figure 1a. A dense baseline survey is acquired over the site of interest, a starting model is generated (e.g., from legacy data or tomography), and a baseline model is generated from this starting model through FWI. At some later time, a repeat monitor survey is acquired, and the model is updated using FWI to derive the 4D model update. Note that the sketched workflow has two parallel branches for baseline and monitor surveys, but following Dutta et al. (2023), the 4D update may be directly derived by a joint inversion.

In this workflow, when conducting the monitor survey, we already have a good understanding of the subsurface from our baseline model. For a CCUS project, dynamic subsurface modelling can indicate the expected behaviour of the CO_2 plume within this baseline model. If our 4D objective is to prove that the plume conforms to the subsurface modelling (as part of the MMV plan), then our requirement of 4D FWI is to detect and localise the plume.

We propose a model probing strategy that aims to determine the minimum acquisition effort required to meet this CCUS monitoring objective. This adaptive 4D FWI workflow is sketched in Figure 1b. The same baseline survey as in Figure 1a is carried out, along with the associated baseline model building. However, instead of acquiring a dense monitor survey, the 4D objective (an expected model update, or risk to monitor) is used to perturb the baseline model, and this perturbed model is synthetically probed with a set of candidate monitor surveys of varying coverage and density. A metric-driven approach enables selection of the most cost-effective geometry that meets the 4D objective. This may include metrics that quantify each candidate geometry's ability to illuminate and resolve/detect the targeted change, as well as metrics to assess the sensitivity to the signal-to-noise ratio and 4D repeatability.

Note that there may be multiple subsurface updates or risks to monitor for, or overburden changes to consider, and the adaptive design can be extended for those situations. The survey design will adapt as the subsurface model is updated through the lifecycle of the storage site.

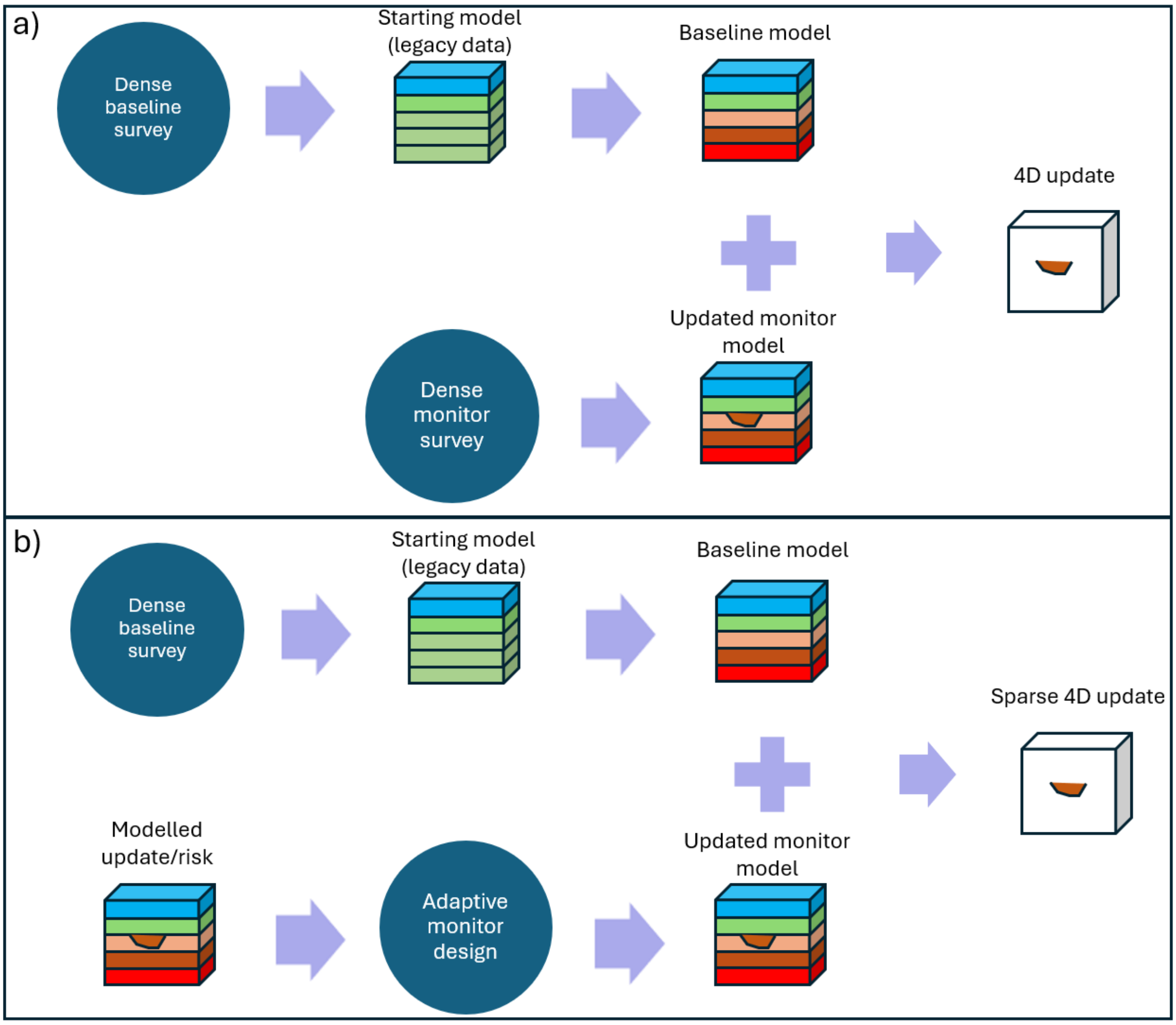

Figure 1 *(a) FWI based approach to 4D seismic. A dense baseline survey is acquired over the site of interest, and a baseline model is generated from a known starting model through FWI. At some later time, a repeat monitor survey is acquired, and the model is updated using FWI to derive the 4D model update. (b) The adaptive design workflow proposed in this abstract. Instead of conducting a repeat survey, a targeted update/risk is used to identify a sparse monitoring geometry.*

Example

A 3D static and dynamic earth model built as an analogue of the Southern North Sea (SNS) subsurface is used as a platform for the experiment (Chapelle et. al., 2024). The model is in shallow water (water depth varies between 20 m and 60 m). A dynamic flow simulation simulates CO_2 injection in a saline aquifer reservoir located at ~1.2 km depth. After a decade, the resulting CO_2 plume has a diameter of

5.4 km and presents an acoustic impedance change of 15% and a velocity decrease of about 10% (Harrington et al., 2024).

2D elastic data are generated for the model before and after the 10 years of injection. Data are modelled for a pressure sensor located on the seabed with 5-m sampling, with sources located in the water layer. The source wavelet has a maximum frequency of 60 Hz.

We first build a velocity model using the baseline data. While the input data are elastic, we use acoustic diving wave FWI to build the velocity update. Using 180 sources spaced at 125 m (indicated by the stars at the top of Figure 2a) we build the velocity model by running FWI across four frequency bands. The result is presented in Figure 2a with the top and bottom of the reservoir layer shown by the solid and dashed line respectively.

We then repeat this exercise using the monitor data modelled after 10 years of injection. The baseline model is used as the input model to FWI, and the data are modelled in the same locations as in Figure 2a. The resulting model is shown in Figure 2b, with the change to the model due to the injection seen in the dashed box.

The same result is created but using only the sparse set of sources defined by the adaptive monitor design. In this case only 10 sources are used, spaced at 500 m and with a gap of 3000 m. The gap is centred on the injection site, and since only diving waves are used, the adaptive design indicates that sources in this gap do not contribute to detecting and resolving the plume. The resulting velocity model is shown in Figure 2c.

Figure 2d shows the true velocity change in the model due to the injection (top), the detected change using 4D FWI with a dense monitor survey (middle), and the detected change using the sparse monitor survey (bottom). With a significant reduction in source effort, we have been able to detect and resolve the shape of the plume in this synthetic scenario, with only the addition of some noise in the imaging system due to the sparse input data.

Conclusions

We have introduced a workflow to determine the sparsest acquisition geometry required to meet a known 4D monitoring objective. This workflow exploits the presence of a high-quality baseline model, together with dynamic subsurface modelling carried out to determine subsurface changes or risks that are identified as part of the MMV plan. A perturbation-based approach is then used to determine the minimum geometry required to illuminate and detect that change.

We have demonstrated the approach using 2D synthetic data, modelled for an analogue of the Southern North Sea, showing that the adaptive design can provide sparse 4D FWI updates using a significantly lower source effort than a conventional 4D monitor survey.

The design is tied to the monitoring plan, associated dynamic modelling and the evergreening of the subsurface model. This means that it is adaptive, and the design will vary proportionally as the understanding of the injection site evolves. For example, there may be additional risks to monitor, the overburden may need updated and so on.

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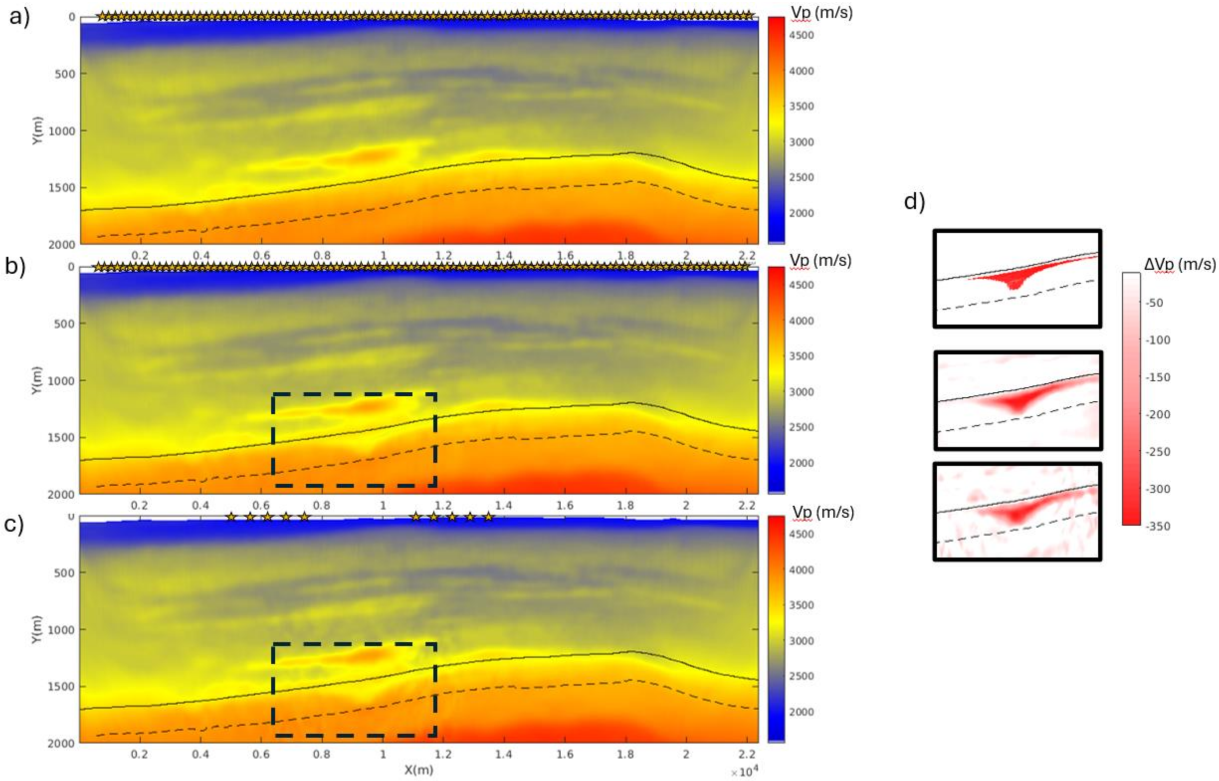

Figure 2 *(a) Velocity model generated from acoustic diving-wave FWI using a full coverage of shots (180 shots at 125 m intervals). (b) The velocity model updated using the same shot sampling after 10 years of injection. Dashed box indicates the region of interest. (c) The velocity model updated using only 10 shots, located at optimal locations, after 10 years of injection. (d) The true modelled velocity change (top), the change extracted from the dashed box in (b) (middle), and the change extracted from the dashed box in (c) (bottom). Stars indicate the source positions used for input to FWI.*

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