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Monitoring CO₂ Storage Using Seismic-interferometry Ghost Reflections

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SUMMARY

Time-lapse seismic monitoring is a fundamental part in most monitoring programmes involving CO₂ storage. Even though the seismic method has proven its applicability for monitoring, there are two major causes of uncertainty in the estimation of changes in the reservoir properties: non-repeatability of the source positions and the difficulty in distinguishing the time-lapse effect due to the overburden from that of the changes taking place in a CO₂ reservoir. We show that utilization of non-physical (ghost) reflections retrieved by seismic interferometry can address the two mentioned reasons of uncertainty. We apply this idea on numerically modelled data as well as on data from scaled laboratory experiment at ultrasonic frequencies.

Introduction

Application of seismic interferometry by cross-correlation (SI) to recordings at surface receivers from transient subsurface sources will retrieve the reflection response between the receivers as if one of them were a virtual source (Wapenaar and Fokkema, 2006). Most commonly, the sources are not in the subsurface, but at the surface, where they are not required by SI. Nevertheless, even surface sources can be used to retrieve the reflection response (see e.g. van Wijk, 2006), but in this case also many non-physical (ghost) reflections will be retrieved as well (Snieder et al., 2006). Still these ghosts can be very useful. King et al. (2011) showed that the ghost reflections can be used to obtain better estimates of the subsurface velocities during velocity analysis; King and Curtis (2012) showed that if identified, these ghosts can be used to estimate the layer-specific propagation velocities of the first few layers in the subsurface.

Figure 1 (a) Acoustic subsurface model used in the numerical experiment with indicated layer velocities (C_p) and densities (ρ). The black arrows indicate raypaths. (b) Reflection response retrieved by seismic interferometry as if from a virtual source at the surface at horizontal distance 4500 m. (c) Directly modelled reflection response for an actual source at the same place.

Results from numerically modelled data

We propose to use ghost reflections for monitoring changes in reservoirs. To show this can be done, we use data obtained from finite-difference modelling in acoustic mode (Thorbecke and Draganov, 2011). We consider a horizontally layered subsurface (Fig. 1(a)) derived from the model in Carcione et al. (2006), which is representative of the Sleipner field in the North Sea (Arts et al., 2004). We place impulsive sources at 1 m depth from 2000 m till 4400 m every 20 m and record the reflection responses at receivers between 4500 m and 5500 m every 10 m, placed also at a depth of 1 m. We do not include the shallow water layer, thus emulating data as if after application of surface-related multiple elimination. We model a base survey, with P-wave velocity and density in the reservoir (Utsira) layer as 2200 m/s and 2200 kg/m³, and a monitor survey after changing the velocity and density in the same layer to 2000 m/s and 1700 kg/m³, respectively.

We apply SI to these data to retrieve the reflection response at the receivers as if from a virtual source at 4500 m horizontal distance (Fig. 1(b)). Comparing the retrieved result with the directly modelled reflection response in Fig. 1(c), we see that the physical reflections are retrieved, but that there are also a lot of ghost reflections (some are indicated by the orange arrows). The physical primary reflections are retrieved from the correlation of a primary and a multiple, e.g. of the raypaths 1-2 and 1-2-3-4 retrieving the reflection at 0.55 s. The ghost primary reflections are retrieved from correlations of two primaries, e.g. of the raypaths 5-6-7-8 and 5-6-9-10-11-12. The correlation process removes the common travel path and we are left over with path 9-10, which is identical to a ghost reflection that would be recorded with ghost source and receiver placed directly at the top of the reservoir layer. This ghost is at 0.23 s in Fig. 1(b). The ghost reflection at 0.32 s is from inside the cap rock and can be explained in a similar way.

In Fig. 2(a) we show a zoomed-in section from Fig. 1(b) around the cap-rock and the reservoir ghost reflections. Comparing them with superimposed directly modelled reflections from only a reservoir layer and only a cap-rock layer, we see that kinematically they are the same. We then retrieve SI results for the monitor survey (Fig. 2(c)) and compare them again to directly modelled reflections (Fig. 2(d)) to see that these are also kinematically identical. Comparing the ghost reflections retrieved for the base and monitor surveys reveals that the only observed change is inside the reservoir layer. In Fig. 2(e) we show the ghost reflections retrieved for a monitor survey in which the active-source positions had random non-repeatability error of 5 m, 10 m, or 15 m around the position of the respective source in the base survey. Despite the positioning errors, the retrieved ghost reflections are like the ones in Fig. 2(c): in the retrieval process, SI has eliminated the non-repeatability errors by redatuming the active sources to the position of the ghost virtual source in the subsurface. This position is the same with and without non-repeatability errors in the surface sources.

The above example shows that ghost reflections can be used to monitor for layer-specific changes in the overburden and the CO₂ reservoir. As the method can remove the source non-repeatability, it could be especially advantageous for acquisitions with fixed receivers, e.g. OBS. Note, that some other retrieved events might overlay the ghost reflections we are interested in and thus hamper monitoring of velocity changes. To avoid this, the best would be before correlation to mute all arrivals in the recorded reflection panels except the once that will contribute to the retrieval of the ghost reflections of interest.

Figure 2 Retrieved ghost reflections from inside the reservoir (0.23 s) and the cap-rock (0.32 s) layers: (a) zoomed-in section from Fig. 1(b); (b) superimposed directly modelled reflections from only reservoir and only cap-rock layer for the base survey; (c) as in (a), but for the monitor survey; (d) as in (b), but for the monitor survey; (e) as in (d), but with random source non-repeatability error.

Results from laboratory data

We now apply the above method to a scaled laboratory experiment. The laboratory sample is shown in Fig. 3 and consists of a top layer of epoxy, representing a cap rock, and a bottom layer of Bentheimer sandstone, representing the reservoir rock. The sandstone has a porosity of 21.7 %, permeability of 1.34 D (1.34E-12 m²) and density of 2080 kg/m³. As sources and receivers we use 1-MHz P-wave transducers from Panametrics directly glued to the sample using acoustic couplant. The sources are fixed at the top of the cap rock. When they are excited, the reflection response is measured at a receiver position. After that the receiver is moved approximately, but not exactly, 2.5 mm and new measurements from each of the sources is taken. Applying source-receiver reciprocity, we can look at the acquisition geometry as having fixed receivers at positions S1 and S2 and non-repeatable source positions. We record a base survey when the sandstone is fully saturated with brine. We then record three monitor surveys when the brine has been displaced by injection of ethanol equal to about 1/3, 2/3, and the complete calculated pore volume. Note that as the ethanol dissolves in water, we are not sure how much brine is actually displaced. We use ethanol instead of supercritical CO₂, as encountered at the Sleipner field, due to the ethanol's easy handling at room conditions. Furthermore, the seismic characteristics of ethanol are between those of brine and supercritical CO₂.

Figs. 3(b,c) show the recorded common-source gathers or, after application of source-receiver reciprocity, the common-receiver gathers at S1 and S2 when ethanol quantity of about the complete calcu-

Figure 3 (a) Cartoon of the laboratory sample consisting of an epoxy plate at the top, representing a cap rock, and a plate of Bentheimer sandstone, representing a reservoir rock. The P-wave sources S1 and S2 are indicated by the red stars, while the blue triangles represent P-wave receiver transducers; the green star and triangle represent, respectively, the locations of the ghost source GS and the ghost receiver GR. (b) Common-source gather for S1. (c) Common-source gather for S2. (d) Combined common-source gather from (b) and (c). The red lines indicate interpreted arrivals.

lated pore volume is injected. In Fig. 3(d) we show the combined common-receiver gather obtained by taking the recordings till 50 mm distance from the panel in (b) and the complete panel in (c). This helps interpret the recorded arrivals. Arrival Arr1 is the P-wave reflectoin from the bottom of the cap rock; Arr2 is the converted reflection; Arr3 is the multiple of Arr1; Arr4 is the S-wave reflection from the bottom of the cap rock; and Arr5 is the P-wave reflection from the bottom of the sandstone. For monitoring the layer-specific velocity changes inside the reservoir, we need to apply SI to retrieve the ghost reflection from inside the sandstone. This ghost is retrieved from the correlation of Arr1 in Fig. 3(b) with Arr5 in Fig. 3(c) followed by summation over the source positions. Because of this, we keep only Arr1 in the common-receiver panel at S1 and only Arr5 in the gather at S2; all the rest is muted. After application of SI, we retrieve the desired ghost reflection as if from a ghost source GS and ghost receiver GR placed directly at the top of the sandstone. We do this for the base and the three monitor surveys. The results are shown in Figs. 4(a-d). Following the strongest negative peak, we see that the P-wave velocity inside the reservoir increases when ethanol is injected. As both layers are horizontal and assuming lateral homogeneity, the distance between GS and GR is equal to the distance between S1 and S2. This allows us to convert the obtained two-way travel times in Fig. 4(a-d) to velocities from inside the reservoir (using the sandstone's thickness) – 2544 m/s, 2558 m/s, 2611 m/s and 2616 m/s, respectively.

For an independent estimate of the velocities, we also make transmission measurements from S1 to a receiver at T2 (Fig. 3(a)). We calculate the velocity inside the epoxy cap rock for the case before brine injection by dividing the epoxy's thickness by the traveltime difference between the first arrival and its multiple after internal reflection inside the epoxy. We obtain 2727 m/s. We calculate the velocity inside the sandstone for the base and the three monitor surveys using the first arrivals, the thicknesses of both plates and the velocity inside the epoxy. The estimated values are 2520 m/s, 2607 m/s, 2594 m/s, and 2596 m/s, respectively. Comparing these values with the ones we estimate from the ghost reflections, we see that they follow the same trend and the respective differences are very small.

Resa et al. (2005, Table 3) showed for a binary mixture water-ethanol that for low concentrations of ethanol the velocity of the mixture increases, reaches a maximum at around 20 % ethanol (with velocity

about 100 m/s higher than that of pure water) and then decreases again. At around 50 % ethanol, the mixture's velocity is with about 50 m/s lower than that of pure water. Using these observations, we might interpret the estimated velocities from the ghost reflections to indicate that for the three monitor surveys the concentration of the ethanol is about 20 %.

Conclusions

We proposed the use of non-physical (ghost) reflections retrieved from seismic interferometry with surface reflection data for monitoring layer-specific changes in CO₂ reservoirs. The ghost reflections represent arrivals from inside separate subsurface layers as if measured with sources and receivers directly at the top of each of these layers. We showed how to apply the method using numerically modelled data for a horizontal subsurface. We then applied the method to ultrasonic laboratory data and estimated the P-wave velocity inside the reservoir layer when the reservoir was fully saturated with brine and for three cases of displacement of the brine with ethanol. The estimated velocity values follow the same trend as values obtained from transmission measurements and the respective differences are very small.

Figure 4 Retrieved ghost reflection from the bottom of the sandstone reservoir as if measured with ghost source and receiver placed directly at the reservoir's top: (a) when the reservoir is fully saturated with brine; after injection of ethanol quantity equal to about (b) 1/3, (c) 2/3 and (d) the complete calculated pore volume.

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