# Determining changes in $CO_2$ saturation from time-lapse measurements using ghost reflections retrieved by seismic interferometry

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## SUMMARY

One of the targets of time-lapse seismic monitoring of CO<sub>2</sub> sequestration is to determine the parts of the reservoir reached by the injected CO<sub>2</sub> and to estimate their saturation. Such information could be extracted from the time-lapse measurement using AVO or impedance information. But non-repeatability of the source positions and time-lapse changes in the overburden could lower the accuracy of the estimation of saturation. We propose the utilization of non-physical (ghost) reflections retrieved by seismic interferometry to estimate the CO2 saturation inside the reservoir. We use the ghost reflections to directly estimate the layer specific velocities inside the reservoir and the cap rock and thus eliminate the two mentioned causes of inaccuracies. We apply this idea and demonstrate its added value and potential using numerically modelled data for a simplified model based on the Sleipner underground storage site in the North Sea.

## INTRODUCTION

Time-lapse seismic measurements have proven their merit in monitoring changes in the reservoirs layer during  $CO_2$  sequestration (Arts et al., 2002; Chadwick et al., 2010; Lumley, 2010; Ivanova et al., 2012). Results at the Sleipner underground storage site in the North Sea show a very strong time-lapse seismic response, both in terms of high seismic amplitudes as well as strong timeshifts (Arts et al., 2004b). Matching injected volumes of  $CO_2$  with seismically derived volumes leads to uncertainties in the order of 30% (Chadwick et al., 2004). This is essentially due to uncertainties in the underlying rock-physics model and to the saturation distribution in the reservoir, as well as to the resolution of the seismic surveys and the associated structural uncertainties in the geological model. In fact, the solution within the given constraints is non-unique.

The injection of CO<sub>2</sub> in the reservoir results in time-lapse changes in the seismic velocity and density. These changes are attributable to a combined effect of changes in CO<sub>2</sub> saturation and pore pressure in the reservoir. The latter is expected negligibly small at Sleipner (Arts et al., 2004a). Nevertheless, an independent verification from the seismic data would be extremely valuable. Landrø (2001) proposed to use this relationship and to invert for the saturation and pore-pressure changes inside the reservoir layer from the AVO time-lapse information. For that, the author derived a relationship between the reflection coefficients and the relative changes  $\Delta V_P/\langle V_P \rangle$  and  $\Delta V_S/\langle V_S \rangle$  in the P-wave and S-wave velocities  $V_P^{r,c}$  and  $V_S^{r,c}$  inside the reservoir (r) and the caprock (c), where  $\langle V_P \rangle = (V_P^r + V_P^c)/2$ ,  $\langle V_S \rangle = (V_S^r + V_S^c)/2$ ,  $\Delta V_P = V_P^r - V_P^c$ , and  $\Delta V_S = V_S^r - V_S^c$ . For the derivation, the author assumed that  $\Delta V_P / \langle V_P \rangle < <$ 1 and  $\Delta V_S / \langle V_S \rangle \ll 1$ . Such an assumption is not always fulfilled and this might lead to errors in the estimated changes in the saturation and the pore pressure. Further uncertainties result from changes in the overburden between the base and the monitor survey and due to non-repeatability errors in the source and receiver positions. If a permanent network of seismic sensors is installed for monitoring purposes, the receiver non-repeatability is minimized to almost zero (in reality there always remains some uncertainty in the instrument and in coupling), but the source non-repeatability errors would remain. In the following, we propose to minimize the uncertainties due to possible changes in the overburden and the source non-repeatability by utilization of non-physical (ghost) reflections retrieved by seismic interferometry (SI). The reflection ghosts provide layer-specific information of the seismic velocities. In this study, we propose to evaluate the added value of this method on a simplified synthetic model of Sleipner, neglecting in this first step the multiple stacked CO2 layers in the reservoir. Obtained velocity changes are used to estimate the saturation in the reservoir layer from its relation to  $\Delta V_P / \langle V_P \rangle$ .

## **RETRIEVAL OF GHOST REFLECTIONS**

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SI commonly refers to the process of retrieving the Green's function between two stations from the crosscorrelation and summation of recordings at these stations from surrounding sources. For a lossless acoustic medium, after making high-frequency and far-field approximations, the SI relation is (Wapenaar and Fokkema, 2006)

$$(\mathbf{x}_B, \mathbf{x}_A, t) + G(\mathbf{x}_A, \mathbf{x}_B, -t) \propto \oint_{\partial \mathbb{D}} G(\mathbf{x}_B, \mathbf{x}, t) * G(\mathbf{x}_A, \mathbf{x}, -t) d^2 \mathbf{x}, \quad (1)$$

where the source-boundary surface  $\partial \mathbb{D}$  effectively surrounds the two receivers positioned at  $\mathbf{x}_A$  and  $\mathbf{x}_B$ . When the retrieval is performed with receivers at the Earth's surface, only sources in the subsurface are required.  $G(\mathbf{x}_B, \mathbf{x}_A, t)$  is the Green's function between a source at  $\mathbf{x}_A$  and a receiver at  $\mathbf{x}_B$  and \* denotes convolution. The right-hand side of relation 1 is the crosscorrelation of recordings at the points  $\mathbf{x}_A$  and  $\mathbf{x}_B$  from sources at positions  $\mathbf{x}$  on  $\partial \mathbb{D}$ .

In a normal seismic survey, the active sources are at the Earth's surface instead of in the subsurface. Nevertheless, using stationary-phase arguments, it can be shown (Halliday et al., 2007) that

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Figure 1: (a) Subsurface acoustic model used for the numerical examples. The layers' velocities  $V_P$  are given in m/s and the densities  $rho - \ln kg/m^3$ . Base and a monitor surveys are modelled, between which the velocity and density inside the reservoir and the top layer have changed. The colored arrows illustrate travel raypaths: the light blue color is for the part of the ray inside the top layer, the dark blue – inside the second (caprock) layer, and the magenta – inside the third (reservoir) layer. (b) Modeled reflection response at the receiver array (from 4500 m to 5500 m with a receiver interval of 10 m) for a source at 4400 m during the base survey. (c) As in (b), but during the monitor survey. The color arrows indicate the primary reflections from the top (light blue), the caprock (dark blue) and reservoir (magenta) layers.

also in this situation the desired Green's function (the reflection response) is retrieved (van Wijk, 2006). The lack of sources in the subsurface, though, causes also retrieval of extra nonphysical reflection events (Snieder et al., 2006), which we call ghost reflections. To explain how such ghosts are retrieved, we use a horizontally layered subsurface model as illustrated in Figure 1(a). A correlation of the reflection from the top layer with a reflection from the bottom of the second (caprock) layer and summation over the available active source at the surface (equation 1) will result in the elimination of the common travelpaths (the light blue parts in Figure 1(a)) and retrieve an arrival that is kinematically identical to a reflection from the bottom of the caprock measured with a source and receiver directly at the caprock's top (the dark blue part). In a similar way, correlation of the primary reflection from the bottom of the caprock with the primary from the bottom of the third (reservoir) layer and summation over the surface sources will eliminate the common travel path (the light and dark blue parts) and retrieve an arrival kinematically identical to a reflection from inside the reservoir measured at the reservoir's top (the magenta part). As such retrieved reflections are not possible to measure with sources and receivers at the Earth's surface, they are non-physical. Draganov et al. (2012) showed how that such ghost reflections eliminate the uncertainty due to surface-source non-repeatability errors. Furthermore, as the ghost reflections are indicative of velocities only inside a single layer, Draganov et al. (2012) used the ghost reflections to monitor layer-specific changes inside a reservoir between a base

and a monitor survey, with a very high accuracy.

## MONITORING SATURATION CHANGES USING RE-FLECTION GHOSTS

To demonstrate the potential of ghost reflections for monitoring saturation changes inside a reservoir during CO<sub>2</sub> sequestration, we make use of the model in Figure 1(a). The model follows the one in Carcione et al. (2006) and represents a simplification of the Sleipner site (Arts et al., 2004b). (The seismic velocities we use here differ slightly from those in Arts et al. (2004b) due to utilization of different values for the bulk and shear moduli of the rock skeleton.) CO2 is being sequestrated inside the field's Utsira formation (the reservoir - a highly permeable porous sandstone lying 800 m below the sea floor). The P-wave velocity and density values for the top and the caprock layers during the base and the monitor surveys are based on the values in Table 3 in Carcione et al. (2006). We make use of impulsive sources and receivers placed 1 m below the surface. For the base survey, the sources are placed from 2000 m till 4400 m with a spacing of 20 m. For the monitor survey, the sources are placed around the positions of the sources from the base survey, but with a random non-repeatability error of 5, 10, or 15 m. The receivers are placed from 4500 m till 5500 m every 10 m. We do not include the shallow water layer in the modeling, emulating a reflection dataset after application of the water-bottom multiple elimination. We

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Figure 2: Dependance of the relative velocity changes  $\Delta V_P / \langle V_P \rangle$  on the brine-to-CO<sub>2</sub> saturation ratio.

calculate the P-wave velocity and density inside the reservoir using the Gassmann equation (Mavko et al., 2009) for brineto-CO<sub>2</sub> saturation ratio equal to 0.98 (as already mentioned, to decrease the contrast in velocity) during the base survey and 0.8 during the monitor survey (see Figure 1(a)). The relative changes  $\Delta V_P / \langle V_P \rangle$  in the P-wave velocities calculated using the Gassmann equation are given in Figure 2 for different brine-to-CO<sub>2</sub> saturation ratios. The value of the ratio of 1 means that the reservoir is fully saturated with brine, while ratio 0 means that the reservoir is fully saturated with supercritical CO2. As mentioned above, changes in seismic velocities and densities due to pore-pressure changes are expected negligible for Sleipner, so we use  $\Delta V_P / \langle V_P \rangle$  as a direct indicator for changes in the saturation. Note that to decrease the velocity contrast between the initial and time-lapse situation in our study, a starting velocity corresponding to 2% of CO2 has been selected. This is done on purpose to test the performance of the method on more common velocity differences than the extremely large one observed at Sleipner of about 30% (Arts et al., 2004a). For the sake of demonstration of the method, further the multiple stacked CO<sub>2</sub> layers in the reservoir have been neglected and a single accumulation is assumed.

We use the subsurface velocity and density models in a finitedifference modeling scheme (Thorbecke and Draganov, 2011). Figures 1(b,c) show the recorded reflection response during the base and monitor surveys, respectively, for a source at the Earth's surface at 4400 m (for the monitor survey due to the random non-repeatability error, the source is actually at 4410 m). The light blue, dark blue, and magenta arrows indicate the primary reflections from the bottom of the top, caprock, and reservoir layers, respectively. We apply SI equation 1 to retrieve a reflection common-source gather as if from a virtual source at the position of the first geophone, i.e., at 4500 m. For this, we extract the trace at that position from the panel in Figure 1 and correlate it with the complete panel. This is repeated for the common-source gathers for each source position from the base survey and the individual correlation results are summed. The resulting retrieved common-source gather for a virtual source at 4500 m is shown in Figure 3(a). The same procedure is applied to the measurements from the monitor



Figure 3: Retrieved common-source gather for a virtual source at position 4500 m using the data from (a) the base and (b) the monitor surveys. The orange arrows indicate the retrieved ghost reflections from inside the caprock, while the red ones – from inside the reservoir.

survey and the retrieved common-source gather for the same virtual-source position is shown in Figure 3(b). The orange arrow indicate the retrieved ghost reflections from inside the caprock, while the red ones - from inside the reservoir. As the ghost reflections represent arrivals from the bottom of a layer as if measured with ghost source and receivers placed directly at the top of that layer, the retrieved two-way traveltimes depend only on the P-wave velocity within the layer. Comparing the retrieved ghost reflections for the base and the monitor surveys, we can see that the ghost reflection from inside the reservoir indicates clearly that there were changes inside the reservoir between the two surveys. On the other hand, the ghost reflection from inside the caprock is retrieved at the same two-way travel time and that shows that no changes have occurred inside the caprock. Note that between the two surveys, the P-wave velocity inside the top layer was changed, but that change was eliminated by the SI redatuming and as a result the two-way travel times of the ghost reflections form inside the caprock are the same, as expected from the used subsurface models.



Figure 4: Retrieved common-source gather with the caprock ghost reflection for a virtual source at position 4500 m using the muted data from the (a) base and (b) monitor surveys. Retrieved common-source gather with the reservoir ghost reflection for a virtual source at position 4500 m using the muted data from (c) the base and (d) the monitor surveys.

As can be seen from Figures 3(a,b), apart from the desired ghost reflections from inside the caprock and the reservoir, there are also other non-physical arrivals. To make the comparison and the extraction of velocity information easier, we could retrieve only the desired ghost reflections. To active this, instead of correlating the complete common-source panels, we could correlate only the arrivals that contribute to the retrieval of the ghost reflections. To retrieve the caprock ghost reflection, we correlate only the primary reflection from the bottom of the top layer (light blue in Figures 1(b,c)) with the primary reflection from the bottom of the caprock (dark blue in Figures 1(b,c)); all other arrivals are muted. The results are shown in Figure 4(a,b). Similarly, to retrieve that reservoir ghost reflection, we correlate only the dark blue and the magenta arrivals in Figures 1(b,c) and the results are shown in Figures 4(c,d). Comparing the caprock ghost reflections from Figures 4(a) and 4(b), we can see that indeed they are retrieved at the same twoway traveltimes and thus no changes have occurred inside the caprock between the two surveys. On the contrary, comparison of the retrieved reservoir ghost reflections shows clearly that changes inside the reservoir did occur between the two surveys. To quantify these changes in terms of changes in the saturation using  $\Delta V_P / \langle V_P \rangle$ , we need to calculate the velocities inside the caprock and the reservoir for both the base and the monitor surveys. As the subsurface layers are horizontally

layered, the distance between the ghost source and receivers at the top of the caprock and reservoir layers are equal to the distances in the retrieved common-source gathers between the virtual source and receivers at the surface (Draganov et al., 2012). Thus, using the two-way traveltimes measured at different offsets between the ghost source and receivers at the top of the caprock and the reservoir, we can calculate the velocities inside the two layers for both the base and the monitor surveys. Even though this calculation could be performed for any of the available offsets for the caprock reflection, only a limited number of offsets for the reservoir reflection are retrieved correctly. Looking at Figures 4(c,d), we can see that for larger offsets the moveout of the reservoir ghost reflection appears to be linear instead of hyperbolic. This is a result of the subsurface models and the surface source-receiver geometries, which limit the available travel paths that fulfill the requirements as sketched by the colored rays in Figure 1(a). Because of that, we limit our analysis to offsets up to 300 m for both the base and the monitor surveys. Taking the two-way travel times for offsets 100 m, 200 m, and 300 m, we calculate  $\Delta V_P / \langle V_P \rangle$  for the base survey of -0.0914, -0.0883, and -0.0890, while for the monitor survey we calculate -0.1355, -0,1349, and -0.1343 for the respective offsets. The average value from the three offsets are -0.0895 for the base survey and -0.1349 for the monitor survey. Using these estimates and the graph in Figure 2, we estimate the brine-to-CO<sub>2</sub> ratio to be 0.9797 for the base survey and 0.77 for the monitor survey. The actual values for  $\Delta V_P / \langle V_P \rangle$ calculated using the model velocities from Figure 1(a) are -0.0890 for the base survey and -0.1341 for the monitor survey and the respective saturation ratios are 0.98 and 0.80.

## CONCLUSIONS

We showed how changes in saturation in the reservoir layer during CO<sub>2</sub> sequestration can be monitored using seismic interferometry. For this we made use of non-physical (ghost) reflections retrieved by seismic interferometry. These reflections provide layer-specific velocity information and eliminates the uncertainties due to source non-repeatability and due to changes in the overburden. We retrieved ghost reflections from numerically modeled data for a simplified model of the Sleipner underground storage site in the North Sea for a base and a monitor survey. Using the ghost reflections, we estimated the velocities inside the caprock and the reservoir laver. We used the estimated velocities to calculate the changes in the brineto-CO<sub>2</sub> saturation ratio inside the reservoir between the base and the monitor surveys. The calculated ratios are very close to the actual saturation ratios used in the models for the base and the monitor surveys. As a next step, we intend to test the method taking into account the multiple stacked CO2 accumulations in the reservoir and finally to apply the method on the real time-lapse seismic data.

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### **EDITED REFERENCES**

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