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Employing internal multiples in time-lapse seismic monitoring, using the Marchenko method

Kees Wapenaar and Johnno van IJsseldijk

Summary

Time-lapse seismic monitoring aims at resolving changes in a producing reservoir from changes in the reflection response. When the changes in the reservoir are very small, the changes in the seismic response can become too small to be reliably detected. In theory, multiple reflections can be used to improve the detectability of traveltimes changes: a wave that propagates several times down and up through a reservoir layer will undergo a larger time shift due to reservoir changes than a primary reflection. Since we are interested in monitoring very local changes (usually in a thin reservoir layer), it would be advantageous if we could identify the reservoir-related internal multiples in the complex reflection response of the entire subsurface. We introduce a Marchenko-based method to isolate these multiples from the complete reflection response and illustrate the potential of this method with numerical examples.

Introduction

Time-lapse seismic monitoring aims at resolving changes in a producing reservoir from changes in the reflection response. Time-lapse changes in the reflection response can consist of (angle-dependent) amplitude changes (Landrø, 2001), traveltimes changes (Landrø and Stammeijer, 2004), or a combination of the two. When the changes in the reservoir are very small, the changes in the seismic response can become too small to be reliably detected. In theory, multiple reflections can be used to improve the detectability of traveltimes changes: a wave that propagates several times down and up through a reservoir layer will undergo a larger time shift due to reservoir changes than a primary reflection. This is akin to the underlying principle of coda-wave interferometry (Snieder et al., 2002; Grêt et al., 2005), which employs time-lapse changes in the coda of a multiply-scattered signal to estimate changes in the background velocity. Since we are interested in monitoring very local changes (usually in a thin reservoir layer), it would be advantageous if we could identify the reservoir-related internal multiples in the complex reflection response of the entire subsurface. The aim of this paper is to introduce a Marchenko-based method to isolate these multiples from the complete reflection response.

A numerical time-lapse experiment

Consider a horizontally layered medium, of which the velocities and densities in the baseline and monitor states are shown in Figure 1. The reservoir layer is encircled. The thickness of the reservoir layer is 45 m and the velocities of this layer in the baseline and monitor states are 2055 m/s and 2150 m/s, respectively (the densities are the same in both states). Hence, the traveltimes shift for primary reflections from interfaces below the reservoir is -1.94 ms. The green arrows indicate two strong reflectors above and below the reservoir, at 1200 m and 1600 m, respectively. Figure 2 shows the baseline and monitor reflection responses $R(\mathbf{x}_R, \mathbf{x}_S, t)$ and $\bar{R}(\mathbf{x}_R, \mathbf{x}_S, t)$, respectively. Here \mathbf{x}_S and \mathbf{x}_R are the source and receiver coordinates and t denotes time. The green arrows in Figure 2(c) indicate the primary reflections of the two reflectors indicated in Figure 1. Note that the traveltimes shift of the reflector below the reservoir is hardly detectable. Multiples between these reflectors, which have larger traveltimes shifts, cannot be identified (they should occur at the traveltimes indicated by the red arrows).

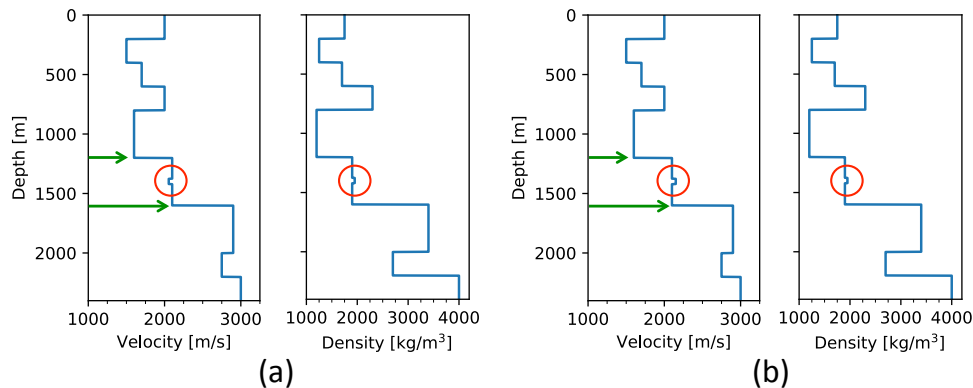


Figure 1 Velocities and densities of a horizontally layered medium. (a) Baseline state. (b) Monitor state.

Isolating the target response, using the Marchenko method

We define the target zone as the region between two relatively strong reflectors surrounding the reservoir layer. We propose a two-step method to isolate the target response, including internal multiples between the top and bottom of the target zone, from the complete reflection response.

Step 1: Removing the overburden response. We start with the baseline reflection response $R(\mathbf{x}_R, \mathbf{x}_S, t)$ at the acquisition surface \mathbb{S}_0 . We define a focus level \mathbb{S}_A at a small distance above the target zone. With the Marchenko method (Wapenaar et al., 2014; Slob et al., 2014), using a smooth model of the overburden (the medium between \mathbb{S}_0 and \mathbb{S}_A), we retrieve the downgoing and upgoing Green's functions $G^+(\mathbf{x}', \mathbf{x}_S, t)$ and $G^-(\mathbf{x}, \mathbf{x}_S, t)$, respectively, with observation points \mathbf{x}' and \mathbf{x} at \mathbb{S}_A . These Green's functions are related

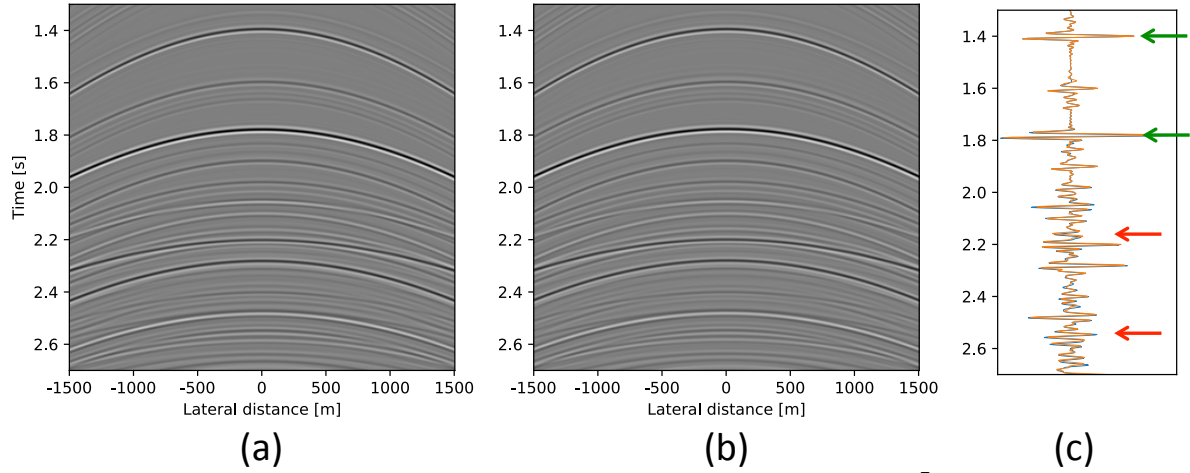


Figure 2 (a) Baseline reflection response $R(\mathbf{x}_R, \mathbf{x}_S, t)$. (b) Monitor reflection response $\bar{R}(\mathbf{x}_R, \mathbf{x}_S, t)$. (c) Overlay of central traces of (blue) baseline and (orange) monitor responses.

to each other via

$$G^-(\mathbf{x}, \mathbf{x}_S, t) = \int_{\mathbb{S}_A} R_A(\mathbf{x}, \mathbf{x}', t) * G^+(\mathbf{x}', \mathbf{x}_S, t) d\mathbf{x}', \quad (1)$$

where $*$ denotes convolution and $R_A(\mathbf{x}, \mathbf{x}', t)$ is the reflection response at \mathbb{S}_A of the medium below this surface. Assuming the Green's functions $G^+(\mathbf{x}', \mathbf{x}_S, t)$ and $G^-(\mathbf{x}, \mathbf{x}_S, t)$ are retrieved for many source positions \mathbf{x}_S at \mathbb{S}_0 , the redatumed reflection response $R_A(\mathbf{x}, \mathbf{x}', t)$ can be resolved from equation (1) by multidimensional deconvolution (MDD). To facilitate a good comparison with the original response $R(\mathbf{x}_R, \mathbf{x}_S, t)$ at the acquisition surface \mathbb{S}_0 , we project $R_A(\mathbf{x}, \mathbf{x}', t)$ to this surface, according to

$$R_A^0(\mathbf{x}_R, \mathbf{x}_S, t) = \int_{\mathbb{S}_A} \int_{\mathbb{S}_A} G_d(\mathbf{x}_R, \mathbf{x}, t) * R_A(\mathbf{x}, \mathbf{x}', t) * G_d(\mathbf{x}', \mathbf{x}_S, t) d\mathbf{x} d\mathbf{x}' \quad (2)$$

(Meles et al., 2016; Van der Neut and Wapenaar, 2016). Here $G_d(\mathbf{x}', \mathbf{x}_S, t)$ is the (flux-normalised) direct-wave Green's function between \mathbb{S}_0 and \mathbb{S}_A . By defining it in the overburden model that is also used for Marchenko redatuming, traveltime errors of the Marchenko redatuming are compensated for by this projection. Applying a similar procedure to the monitor reflection response $\bar{R}(\mathbf{x}_R, \mathbf{x}_S, t)$, using the same overburden model, yields $\bar{R}_A^0(\mathbf{x}_R, \mathbf{x}_S, t)$. Figure 3 shows the result of applying this procedure to the responses in Figure 2. Note that the responses are cleaner. However, the multiples between the top and bottom reflectors of the target zone, indicated by the red arrows in Figure 3(c), are still contaminated by the primaries from deeper reflectors. This will be improved further in the next step.

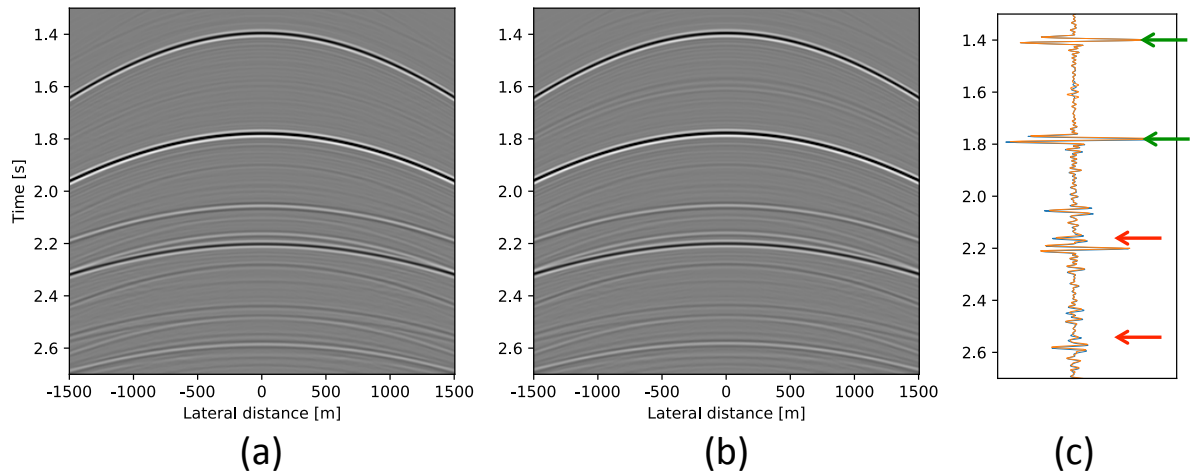


Figure 3 Results of removing the overburden response from the baseline and monitor data. (a) $R_A^0(\mathbf{x}_R, \mathbf{x}_S, t)$. (b) $\bar{R}_A^0(\mathbf{x}_R, \mathbf{x}_S, t)$. (c) Overlay of central traces of (blue) baseline and (orange) monitor responses.

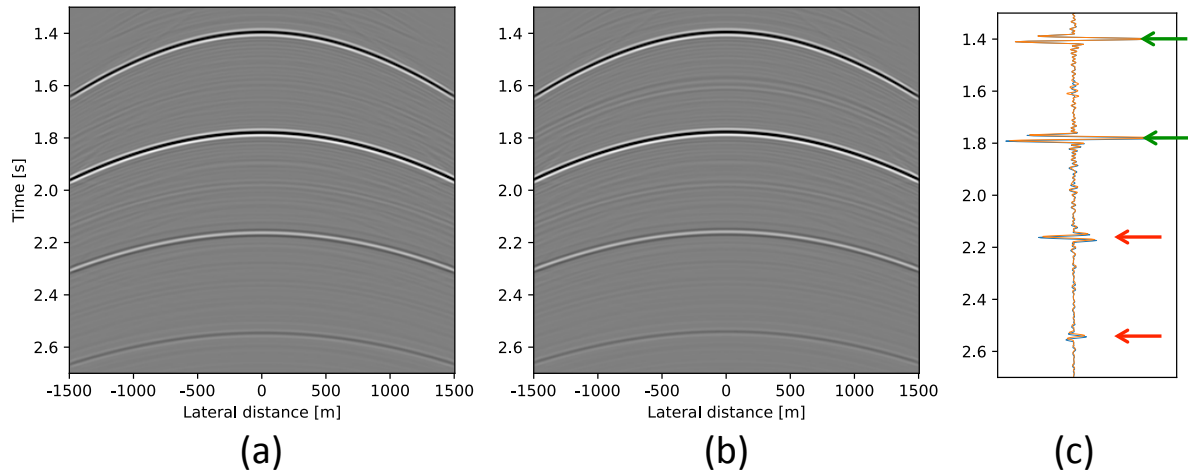


Figure 4 Results of removing the underburden response from the baseline and monitor data. (a) $R_{AB}^0(\mathbf{x}_R, \mathbf{x}_S, t)$. (b) $\bar{R}_{AB}^0(\mathbf{x}_R, \mathbf{x}_S, t)$. (c) Overlay of central traces of (blue) baseline and (orange) monitor responses.

Step 2: Removing the underburden response. We continue with the baseline response $R_A^0(\mathbf{x}_R, \mathbf{x}_S, t)$ of the medium below \mathbb{S}_A , projected to the acquisition surface \mathbb{S}_0 . We define a focus level \mathbb{S}_B at a small distance below the target zone. With the Marchenko method, using a smooth model of the overburden and target zone (the medium between \mathbb{S}_0 and \mathbb{S}_B), we retrieve the downgoing and upgoing focusing functions $f_1^+(\mathbf{x}_S, \mathbf{x}, t)$ and $f_1^-(\mathbf{x}_R, \mathbf{x}, t)$, respectively, with the focal point \mathbf{x} at \mathbb{S}_B . These focusing functions are related to each other via

$$f_1^-(\mathbf{x}_R, \mathbf{x}, t) = \int_{\mathbb{S}_0} R_{AB}^0(\mathbf{x}_R, \mathbf{x}_S, t) * f_1^+(\mathbf{x}_S, \mathbf{x}, t) d\mathbf{x}_S \quad (3)$$

(Wapenaar and Staring, 2018), where $R_{AB}^0(\mathbf{x}_R, \mathbf{x}_S, t)$ is the reflection response at \mathbb{S}_0 of the medium between \mathbb{S}_A and \mathbb{S}_B (i.e., the target zone). Assuming the focusing functions $f_1^+(\mathbf{x}_S, \mathbf{x}, t)$ and $f_1^-(\mathbf{x}_R, \mathbf{x}, t)$ are retrieved for many focal point positions \mathbf{x} at \mathbb{S}_B , the reflection response $R_{AB}^0(\mathbf{x}_R, \mathbf{x}_S, t)$ can be resolved from equation (3) by MDD. Applying a similar procedure to the monitor reflection response $\bar{R}_A^0(\mathbf{x}_R, \mathbf{x}_S, t)$, using the same overburden and target model, yields $\bar{R}_{AB}^0(\mathbf{x}_R, \mathbf{x}_S, t)$.

Figure 4 shows the result of applying this procedure to the responses in Figure 3. Note that the responses are again cleaner. In particular, the multiples between the top and bottom reflectors of the target zone, indicated by the red arrows in Figure 4(c), are now clearly identifiable. The subtle shifts between the baseline and monitor responses are now also visible. Coda-wave interferometry can now be used to estimate the changes in the reservoir. To this end we apply cross-correlation of the baseline and monitor responses in a time window from 2.0 to 2.2 s, around the first multiple, see Figure 5(a). The green curve is the result obtained from the original data (Figure 2(c)), the orange curve from the data with the overburden response removed (Figure 3(c)), and the blue curve from the data with the overburden and underburden responses removed (Figure 4(c)). Note that from the blue curve in Figure 5(a) we infer a time shift of -4 ms. The expected time shift for this multiple is twice the expected time shift of -1.94 ms for the primary, hence, the retrieved time shift is quite accurate. Figure 5(b) shows the cross-correlations in a time window from 2.4 to 2.6 s, around the second multiple. The time shift inferred from the blue curve is -6 ms, which corresponds accurately with three times the expected time shift of -1.94 ms for the primary.

Conclusions

We have proposed a Marchenko-based procedure to remove the overburden and underburden responses from the seismic reflection response of a producing reservoir. This method isolates the response of a target zone, including the multiple reflections between the top and bottom reflectors of the target zone. Since these multiples propagate several times down and up through the reservoir layer (which is included in the target zone), they are more sensitive to time-lapse changes in the reservoir than primaries. Hence, these multiples can be used to infer time-lapse changes in the reservoir.

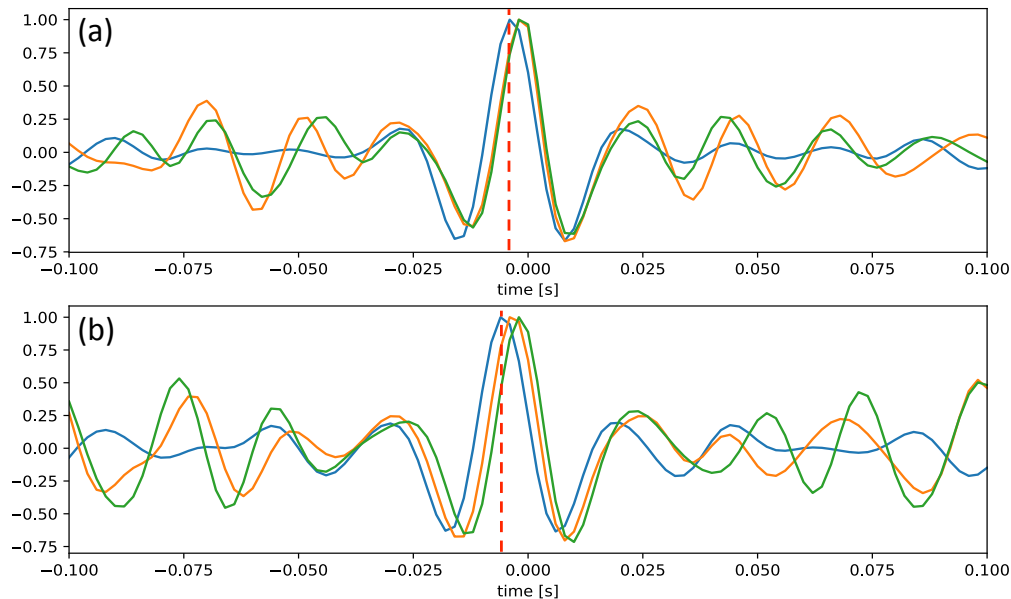


Figure 5 Cross-correlations of the baseline and monitor responses in a time window (a) from 2.0 to 2.2 s around the first multiple and (b) from 2.4 to 2.6 s around the second multiple. The traveltimes shifts inferred from the blue curves (-4 ms and -6 ms, respectively) correspond accurately with the expected time shifts for the first and second multiple (i.e., two times and three times, respectively, the expected time shift of -1.94 ms for the primary).

To infer small traveltimes changes in time-lapse seismic data, a high degree of repeatability is required. When the baseline and monitor surveys are carried out with different acquisition conditions (different sources and/or receivers, different source wavelets, etc.), the differences between these surveys due to changes in acquisition may be larger than those due to changes in the reservoir. We note that the proposed method (in particular the MDD process) has the potential to reduce the acquisition imprint on the time-lapse response. This is subject of current investigations.

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