EAGE

A review of crosscorrelation and multidimensional deconvolution seismic interferometry for passive data

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Summary:

In the search for new hydrocarbon reservoirs a number of sedimentary basins have so far been underexplored. Not because they would not be prolific, but due to exploration challenges, like, e.g., difficult terrains to employ vibrator sources.

Instead of conducting an active seismic survey, the first exploration data could be delivered by using natural seismicity and seismic interferometry (SI). For this purpose, arrays with continuously recording receivers would need to be installed in the exploration area. With SI, seismicity due to natural sources in the subsurface can be remapped to receiver positions on the Earth's surface. The remapped responses can subsequently be used to create a (low-frequency) reflectivity image of the subsurface.

Initially, SI was proposed as a crosscorrelation (CC) of responses. Recently, an alternative remapping procedure for passive data was proposed, by performing a multidimensional deconvolution (MDD). We evaluate both methods.

We show that with both methods physical events can be retrieved correctly, also when there are moderate losses in the medium. In realistic situations, for both methods, additionally, specific artifacts are created, so-called internal events. We show how these artifacts could be recognized. In some cases, a hybrid approach can be applied in which MDD SI is used to account for losses in the medium and to correct for the effects of source irregularity and dual CC SI is applied to recognize spurious events in the MDD SI result.

Introduction

In the search for new hydrocarbon reservoirs a number of sedimentary basins have so far been underexplored, mainly because of exploration challenges. One example is the basins hidden under flood basalts. The heterogeneous and attenuating nature of the basalt make it extremely hard to look beneath.

The first exploration data for such basins could be delivered by using natural seismicity and seismic interferometry (SI). For this purpose, arrays with continuously recording receivers would need to be installed in the exploration area. With SI, seismicity due to natural sources in the subsurface can be remapped to receiver positions on the Earth's surface. The remapped responses can subsequently be used to create a (low-frequency) reflectivity image of the subsurface. In a desert setting, SI with natural sources has already been proven to be a valuable exploration asset (Draganov et al., 2007).

Initially, SI was proposed as a crosscorrelation (CC) of responses. Recently, an alternative remapping procedure for passive data was proposed, where instead of CC one performs a multidimensional deconvolution (MDD) (Wapenaar et al., 2008). In the following we will review the two approaches for the example of a sedimentary basin covered by flood basalts.

Seismic interferometry by Crosscorrelation (CC)

We consider a simplified flood-basalt setting as illustrated in Figure 1, which is based on the model discussed in Martini et al. (2005). The model consists of 4 layers: from top to bottom, a basalt-layer succession associated with continental break-up, a pre-existing sedimentary basin (2 layers), which might contain hydrocarbons, and a crystalline basement. As compared to a conventional sedimentary basin, the model has a sharp velocity decrease going from the basalt to the sediments and strong (scattering) losses in the basaltic package. The scattering losses are caused by the heterogeneous nature of the basalt, but this heterogeneity has not explicitly been built in to keep the model simple. Instead, a constant Q of 50 is used. For comparison reasons also a model without losses is used.

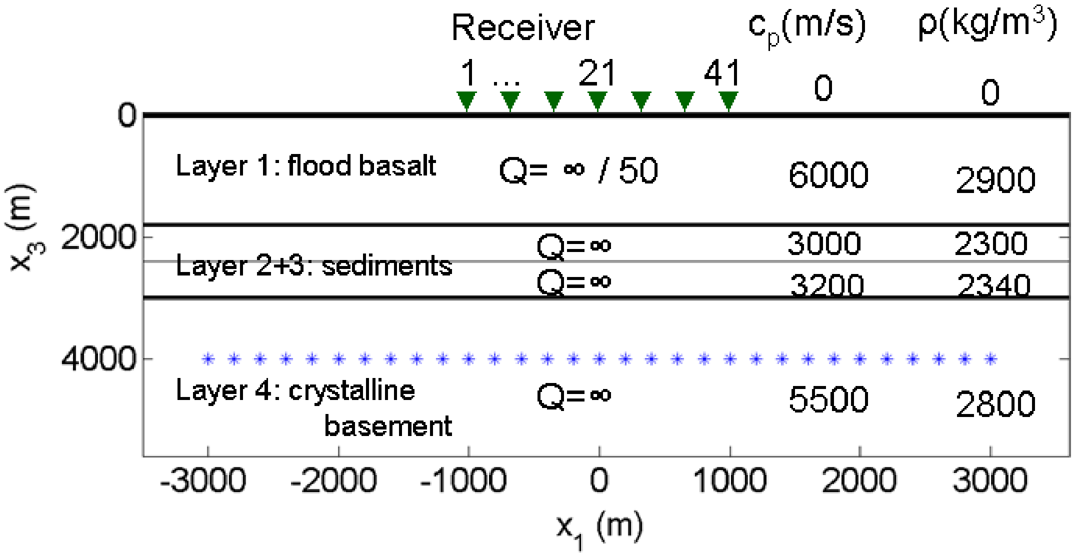

Figure 1: Model with a flood-basalt succession (layer 1) over a sedimentary basin (layer 2 and 3) with seismicity in the basement (layer 4). The responses initiated by the sources (blue stars) are recorded by receivers on the free surface (green triangles).

As sourcing mechanism we assume small abrupt displacements over faults in the crystalline basement. We assume an idealized seismic-source distribution, indicated with the blue stars in Figure 1. The sources are transients with a dominant frequency of 9 Hz. The responses due to all individual sources are recorded by a linear array of 41 receivers (green triangles) with a spacing of 50 m.

In Wapenaar and Fokkema (2006) exact relations are derived to retrieve a response between two receiver positions ($\mathbf{x}_A$ and $\mathbf{x}_B$), without having an actual source at one of the positions, assuming the medium is lossless. This process of crosscorrelation seismic interferometry (CC SI) can be summarized in a flow-chart as

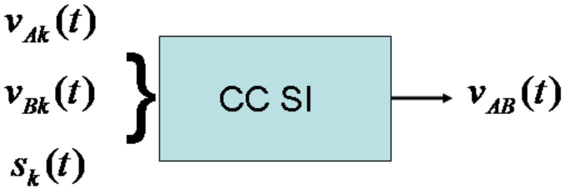

Chart 1

where $v_{Ak}(t)$ denotes the response measured at $\mathbf{x}_A$ due to the kth source in the subsurface and v_{Bk} (t) is the response due to the same source measured at $\mathbf{x}_B$. By crosscorrelating $v_{Ak}(t)$ and $v_{Bk}(t)$ and stacking for different sources k, we obtain $v_{AB}(t)$, which would be a good approximation of the response between $\mathbf{x}_A$ and $\mathbf{x}_B$ if the source distribution was favorable and no severe losses occurred. If a good dynamic retrieval of $v_{AB}(t)$ is required, also the source wavelet $s_k(t)$ of the tremors need to be well estimated.

In the first experiment we assume that there is no attenuation. We choose $\mathbf{x}_A$ and $\mathbf{x}_B$ to correspond with the location of receiver 21 in Figure 1. In Figure 2(left) the result of applying CC SI is shown (red trace) and compared with a modeled response for a source and a receiver at the location of receiver 21 (black dashed trace). The amplitudes before the arrival of the first reflection (the first 0.5 seconds) were muted and both traces were normalized with the maximum amplitude in the trace. On the directly modeled response, successively, the basalt-base reflection (Rbb), the sediment-sediment reflection (Rss), the first order multiple from basalt base (Mbs) and reflection from the basement (Rb) can be distinguished.

The retrieved response is almost identical to the directly modeled, but contains additionally one spurious event, a so-called internal event (IE), which occurrence will be explained later.

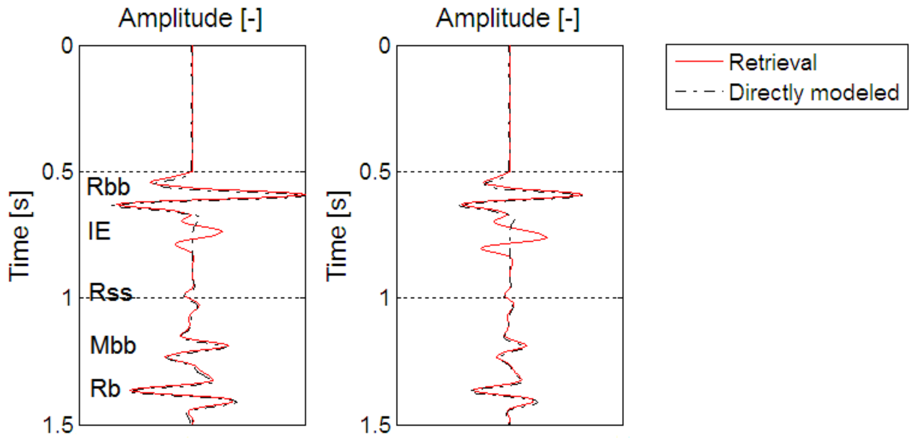

Figure 2: The directly modeled (black dashed trace) and the retrieved responses (red trace) for a model with no losses (left) and a model with losses (right).

The model is made more realistic by building in an effective attenuation in the basalt layer. In Figure 2 (right) the directly modeled response (black dashed trace) and the retrieved response (red trace) for the model with losses is shown. Again, there is a very good correspondence between the directly modeled and retrieved trace, but again, additionally, an internal event has been retrieved. In comparison with the response in the model with no losses (left), the drop in relative amplitudes can be noted.

Comparing the left-hand side with the right-hand side of Figure 2 it can be concluded that also with losses the physical events are retrieved almost perfectly, but the artifact – the internal event – becomes relatively stronger.

The spurious event has previously been noted and explained in Ruigrok et al. (2008). It is called an internal event because it appears as if the event was both initiated as well as recorded at a boundary within the Earth (Figure 3, box I). In the crosscorrelation process both internal events with positive phase (Figure 3, box II) and with negative phase (Figure 3, box III) are created. Only if the requirements for CC SI are perfectly satisfied, the positive-phase and negative-phase internal events cancel each other.
For the retrieval in Figure 2 (left), the cancellation is not perfect due to suboptimal illumination. For the retrieval in Figure 2 (right), the cancellation is not perfect, both due to suboptimal illumination and due to losses.
The internal events can be both a merit and a defect. A defect, since they might well be misinterpreted to be primary reflections. A merit, since they contain additional information. In Draganov et al. (2008) an approach is suggested to identify and use these internal events to estimate a Q model of the subsurface. Here, our aim is to remove the internal events and thus create an artifact-free reflection response. Next, we evaluate whether with MDD an artifact free-response can be retrieved.

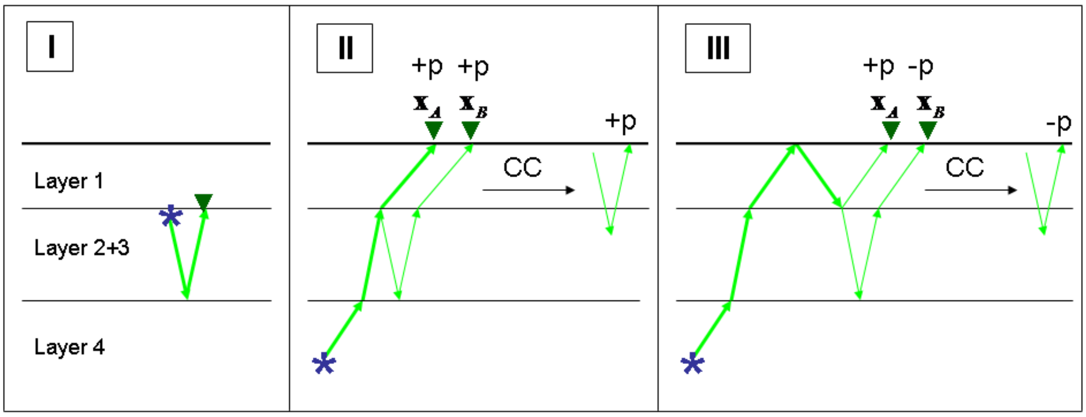

Figure 3: In box I the main internal event is depicted. In box II and III the creation of this internal event with positive phase (+p) and opposite phase (-p) is shown, respectively. The green lines depict rays. In box II, if the source sends a positive spike, than the two rays arriving at $\mathbf{x}_A$ *and* $\mathbf{x}_B$ *will still be positive spikes and also the crosscorrelation of both events will be a positive spike. In box III, a ray will reach* $\mathbf{x}_A$ *as a positive spike, whereas the other ray will reach* $\mathbf{x}_B$ *as a negative spike and therefore the crosscorrelation will give a negative spike.*

Seismic interferometry by Multi-Dimensional Deconvolution (MDD)

Recently, seismic interferometry for passive data by multidimensional deconvolution (MDD SI) was introduced (Wapenaar et al., 2008). In a flow chart it can be summarized as

Chart 2

where $v_{ak}(t)$ denotes the particle-velocity response measured at an array of receivers due to the kth source in the subsurface, $\bar{v}_{ak}(t)$ is the response at the same array of receivers, but without free-surface interaction and $\bar{p}_{bk}(t)$ is the acoustic pressure of that same response, for the same (or a nearby) array. For a single source and receiver, $v_{ak}(t)$ and $\bar{v}_{ak}(t)$ are visualized in Figure 4. Given a favorable source distribution and given that a proper stabilization for the MDD is chosen, $v_{ab}(t)$ is a good approximation of a set of responses between all receiver positions within the array.

For MDD SI a response needs to be detected at a regularly sampled array of receivers, whereas CC SI can be performed for a single receiver pair. On the other hand, for CC SI the source distribution needs to be regularly sampled, whereas MDD SI can correct for the effects of source irregularity. For MDD SI losses are taken into account correctly, whereas for CC SI losses lead to small amplitude deviations and the occurrence or amplification of internal events.

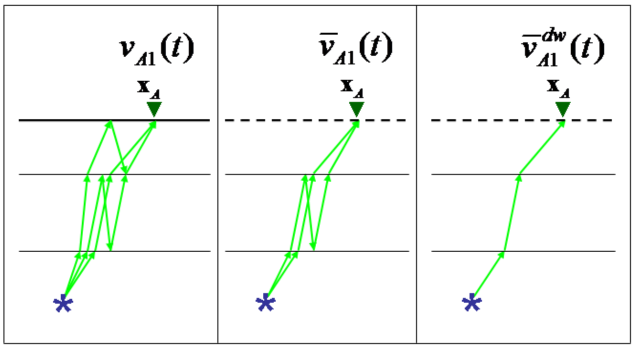

Figure 4: Ray visualization of the particle-velocity response at $\mathbf{x}_A$ *due to a subsurface source; the complete response (left), the response without free surface interaction (middle) and the direct-wave response without free-surface interaction (right).*

For the model discussed in Wapenaar et al. (2008), an MDD SI is performed for which all the required input is available. The result is depicted in Figure 5 (left) in red and compared with a directly modeled response in dashed black. It can be noted that the response is perfectly retrieved.

A problem is that in practical situations $\bar{v}_{ak}(t)$ (Figure 4 (middle)) cannot easily be separated from $v_{ak}(t)$ (Figure 4 (left)) and hence also $\bar{p}_{bk}(t)$ cannot easily be estimated from $v_{bk}(t)$. If the responses due to different sources are well separated in time, at least the direct-wave arrival without free surface interaction, $\bar{v}_{ak}^{dw}(t)$ (Figure 4 (right)), can be separated by time-windowing and a division by 2.

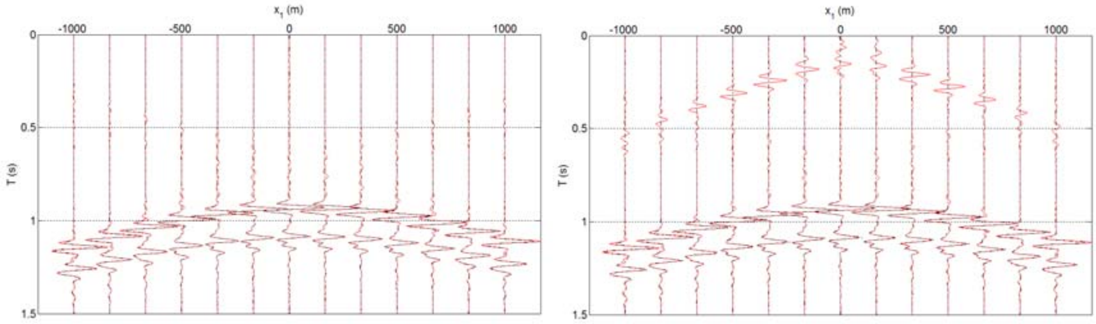

Figure 5: A response retrieved with MDD SI for which all the requirements are met (left) and a response retrieved when $\bar{v}_{ak}(t)$ *and* $\bar{p}_{bk}(t)$ *are approximated by* $\bar{v}_{ak}^{dw}(t)$ *and* $\bar{p}_{bk}^{dw}(t)$ *(right) are depicted in red and compared with directly modeled responses in black dashes.*

Figure 5 (right) depicts the MDD SI result when using $\overline{v}_{ak}^{dw}(t)$ and $\overline{p}_{bk}^{dw}(t)$ instead of $\overline{v}_{ak}(t)$ and $\overline{p}_{bk}(t)$. Still the events are retrieved well, but additionally a spurious event is retrieved.
From a further analysis (which is not shown here) we know that this spurious event is an internal event. This internal event has the kinematics as if there was a source and a receiver at an interface within the Earth (Figure 3 (left)).
In conclusion, also MDD SI, for realistic passive seismic settings, cannot be applied without the occurrence of internal events.

Removal of the internal event

Since also for MDD SI, the occurrence of an internal event cannot be circumvented in realistic settings, another solution is sought. We replace $v_{Ak}(t)$ in the input for CC SI (chart 1) with $2\,v_{Ak}^{dw}(t)$; that is, from the response recorded in $\mathbf{x}_A$ we only use the direct wave, whereas still the complete response recorded in $\mathbf{x}_B$ is used. Figure 6 shows the CC SI results for retrieving a response as if there was a source and receiver at the location of receiver 21 in Figure 1. On the left-hand side, the result when using $v_{Ak}^{dw}(t)$ instead of $v_{Ak}(t)$ (green trace) is compared with the result of applying CC SI with complete responses (red trace). On the right-hand side the results are compared for the model with losses.

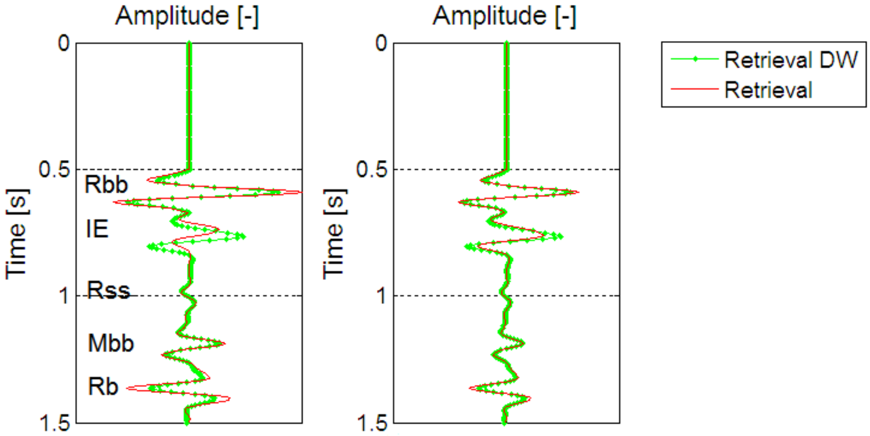

Figure 6: *The CC SI retrieved response when using full responses (red) and when replacing one of the responses with only the direct wave (green) for a model with no losses (left) and a model with losses (right).*

In Figure 6 it can be seen that the same events are still retrieved well when $v_{Ak}(t)$ is replaced by $v_{Ak}^{dw}(t)$. The amplitude of the physical events (Rbb, Rss, Mbb and Rb) has decreased slightly, because all correlations between higher-order events are left out when only the direct wave is used for one of the responses. The amplitude of the internal event (IE), on the other hand, has increased significantly, both for the model without (left) and for the model with (right) losses. This can be understood by looking again at Figure 3. The creation of the negative-phase internal event as depicted in box III cannot occur when only $v_{Ak}^{dw}(t)$ is used. The creation of the positive-phase internal event (box II) still occurs. The net-effect is an increase of amplitude of the internal event.
As illustrated in Figure 6, the execution of both CC SI with full responses and CC SI with a full response and only a direct wave, can be used to distinguish internal events. The increase in amplitude, which only occurs for the internal event, might be significant enough to recognize internal events, also when additional noise is added. In Figure 6 the internal event is separated in time from the physical events. Therefore it is easy to remove the internal event

after recognition. In the general case of interfering internal and physical events, it will be a bigger challenge to recognize and remove the internal events.

Conclusion

For CC SI, moderate losses in the medium do not pose a severe problem for the retrieval of physical events, but specific artifacts, so-called internal events, are amplified due to the losses. With MDD SI, losses in the medium are treated correctly, given that the required wavefield responses can be collected. Practically, it will be especially hard to get the required response without free-surface interaction. When this response is approximated by the direct wave, still the physical events are retrieved correctly but, additionally, internal events appear. These internal-events can be recognized by applying both CC SI with full responses and CC SI with a full response and only a direct wave. After recognition, the internal event can be removed from either the MDD SI or the CC SI result. Thus, in some cases, a hybrid approach can be applied in which MDD SI is used to account for losses in the medium and to correct for the effects of source irregularity and a dual CC SI is applied to recognize spurious events in the MDD result.

Acknowledgements

This work is supported by the Netherlands Research Centre for Integrated Solid Earth Science (ISES), the Netherlands Organization for Scientific Research (NWO, Toptalent 2006 AB), the Dutch Technology Foundation STW, applied science division of NWO and the Technology Program of the Ministry of Economic Affairs (grant DCB.7913).

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