2nd International KAUST-KACST-JCCP Workshop on Surface and Subsurface 4D Monitoring
King Abdullah University of Science and Technology (KAUST), Saudi Arabia, 4-6 March 2014

Marchenko redatuming below a complex overburden

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Summary

Complex overburdens can severely distort transmitted wavefields, posing serious challenges for seismic imaging. In Marchenko redatuming, we use an iterative scheme to estimate so-called focusing functions, which can be used to redatum seismic wavefields to a specified level below the major complexities in the subsurface. Unlike in conventional redatuming methods, internal scattering in the overburden is accounted for by this methodology. Through Marchenko redatuming, internal multiple reflections are effectively utilized and common artefacts that are caused by these multiples are suppressed. The redatumed data can be interpreted as if it were acquired at the redatuming level and as if the medium above this level were non-reflecting. We provide an interpretation of the iterative scheme that is used for Marchenko redatuming and we evaluate its performance in a medium with a strongly heterogeneous overburden.

Introduction

Strong heterogeneities in the near subsurface tend to distort transmitted wavefields, making it a severe challenge to image, characterize or monitor deep targets from the acquisition surface. In the Common Focal Point (CFP) method, the transmission response of the overburden is estimated from seismic reflection data (Al-Ali and Verschuur, 2007). This transmission response (commonly referred to as the CFP operator) is then used to redatum the seismic wavefield to a horizon below the major complexities. Although the CFP method addresses the propagation effects through the overburden, it does not eliminate internal multiple reflections from the data. Bakulin and Calvert (2006) revised the seismic redatuming problem, by deploying actual receivers below the overburden that measure the transmission response directly. In their so-called Virtual Source method, this transmission response is used for data-driven redatuming. Although the original aim of this method was to correct only for the transmission effects of the overburden, it was shown by Wapenaar and van der Neut (2010) that also internal multiple reflections can be eliminated, if redatuming is applied by an inversion process, commonly referred to as multidimensional deconvolution. Recently, a novel iterative scheme was presented to estimate the transmission response from reflection data and an estimate of the propagation effect of the direct wavefield through the overburden (Wapenaar et al., 2014). This estimate can be obtained from a background velocity model, but a CFP operator may also be used. In Marchenko redatuming, the estimated transmission response is used to redatum the seismic wavefield below the complex overburden. Since internal multiple reflections are included in the estimated transmission response, they can be effectively eliminated with this methodology. In this abstract, we explain the concept of Marchenko redatuming with simple diagrams. We show how multiply scattered waves are effectively predicted by the iterative scheme that lays at the basis this method. Finally, we demonstrate the application of Marchenko redatuming for imaging below an overburden with many point scatterers.

Marchenko redatuming

For a thorough derivation of the iterative scheme that undergirds Marchenko redatuming, we refer to Wapenaar et al. (2014). The purpose of the scheme is to estimate the upgoing (superscript -) and downgoing (superscript +) components of the focusing function $\mathbf{f}_1 = \mathbf{f}_1^+ + \mathbf{f}_1^-$. In our notation, these quantities are expressed as long vectors of concatenated traces in the time-space domain. The downgoing focusing function can be written as $\mathbf{f}_1^+ = \mathbf{f}_{1,d}^+ + \mathbf{f}_{1,m}^+$, where $\mathbf{f}_{1,d}^+$ is the initial focusing function and $\mathbf{f}_{1,m}^+$ is a coda. The initial focusing function is essentially the time-reversed direct field between the surface and the focal point, which can be obtained either through a velocity model or with the CFP method. The other components of the focusing functions can be computed with help of the scheme, consisting of the following two equations that can be iteratively updated (starting with equation 1 and $\mathbf{MRf}_{1,m}^+ = \mathbf{0}$):

$$\mathbf{f}_1^- = \mathbf{MRf}_{1,d}^+ + \mathbf{MRf}_{1,m}^+, \tag{1}$$

and $\mathbf{Zf}_{1,m}^+ = \mathbf{MRZf}_1^-$. (2)

In these equations, matrix $\mathbf{R}$ applies multidimensional convolution with the reflection response as recorded at the surface, matrix $\mathbf{M}$ truncates the output traces with arrival times larger or equal to the arrival time of the direct wavefield and matrix $\mathbf{Z}$ applies time-reversal. Once the focusing functions are found, we can compute the up- and downgoing Green's functions $\mathbf{g}^-$ and $\mathbf{g}^+$, respectively, by the following expressions:

$$\mathbf{g}^- = \mathbf{Rf}_{1,d}^+ + \mathbf{Rf}_{1,m}^+ - \mathbf{f}_1^-, \tag{3}$$

and $\mathbf{g}^+ = -\mathbf{RZf}_1^- + \mathbf{Zf}_{1,d}^+ + \mathbf{Zf}_{1,m}^+$. (4)

These Green's functions should be interpreted as if a receiver were positioned at the focal point, with sources at the surface. If we retrieve Green's functions at an array of focal points below the overburden, we can obtain a redatumed response by applying multidimensional deconvolution of the retrieved upgoing fields with the downgoing fields (Wapenaar and van der Neut, 2010). The redatumed response should be interpreted as if sources and receivers were located below the overburden and as if this overburden were non-reflecting. Finally, an image of the medium below the overburden can be created by migrating the redatumed data.

Retrieval of the upgoing field

To gain some intuitive understanding of the iterative scheme, we illustrate its action on a synthetic model that is shown in Figure 1a. From equation 3, we can see that the upgoing field is constructed by adding three terms. The first term ($\mathbf{Rf}_{1,d}^+$) predicts all the upgoing events with correct amplitudes. Essentially, the initial focusing function acts as an inverse wavefield extrapolator that redatums upgoing events in the reflection response back to the focal point. As an example, we show in Figure 2a how a particular upgoing internal multiple is retrieved. However, artefacts are also created by this extrapolation step. We recognise two types of artefact: type I arrives after the direct arrival, whereas type II arrives before the direct arrival. Examples of both types of artefacts are given in Figures 2b and 2c. The iterative scheme is designed such that the second term in equation 3 ($\mathbf{Rf}_{1,m}^+$) eliminates all artefacts of type I, whereas the third term in equation 3 ($-\mathbf{f}_1^-$) eliminates all artefacts of type II. For an illustration of how this is achieved, we refer to van der Neut et al. (2014).

Retrieval of the downgoing field

In the retrieval process of internal multiples in the downgoing field, $\mathbf{f}_1^-$ plays an important role. The dominant contribution of this quantity stems from the first term in equation 1, $\mathbf{MRf}_{1,d}^+$ that initiates the iterative scheme. In Figure 3a, we show how a particular type of event is created during this step. Through equation 4, this event is cross-correlated with the reflection response (i.e. $-\mathbf{RZf}_1^-$) , resulting in physical downgoing events, as illustrated in Figure 3b. A single evaluation of the iterative scheme is already sufficient to predict these events with relatively accurate amplitudes. During the next few iterations, amplitudes can be further balanced and higher-order multiples are predicted. The second term in equation 4 ($\mathbf{Zf}_{1,d}^+$) plays a role in the retrieval of the direct field. The last term ($\mathbf{Zf}_{1,m}^+$) eliminates artefacts that occur before the arrival time of the direct wave.

Redatuming below a complex overburden

We apply the iterative scheme to a model with multiple point diffractors in a homogeneous background, see Figure 1b. Sources and receivers are deployed at the surface and focal points are selected at a horizontal level at 800m depth. Below this level, we find three point scatterers that we aim to image. The iterative scheme is applied, using as input the reflection response at the surface and the direct wave between the surface and the focusing level (computed in a homogeneous model). Multidimensional deconvolution of the retrieved upgoing field with the retrieved downgoing field yields a redatumed response as if sources and receivers were located at 800m depth. The redatumed response is migrated below this level to obtain the image in Figure 4a. For comparison, we also show an image that is obtained by direct migration of the data from the surface, see Figure 4b. Note that the image in Figure 4a is less noisy than the image in Figure 4b, because we have successfully eliminated internal multiples from the data. However, the results are not perfect in this example. To understand these imperfections, we have to realise that the surface data has finite aperture, such that the required stationary points are not necessarily sampled (van der Neut et al., 2014). Moreover, the theory of Marchenko redatuming is based on the assumption that the direct wave is clearly separated in time and space from the internal multiple reflections. In smoothly varying media, this assumption is well fulfilled and accurate results could be achieved (Wapenaar et al., 2014). In media with point diffractors, waves that do not reverse their propagation after scattering (i.e. forward-scattered waves) conflict with this assumption. With the implementation of the current scheme, this can create incomplete retrieval and artefacts, as shown by van der Neut et al. (2014). However, despite these shortcomings of the current implementation, the image in Figure 4a shows already a clear improvement compared to Figure 4b.

Conclusion

We have analysed an iterative to retrieve the up- and downgoing components of a Green's function in an unknown medium from single-sided reflection data and an estimate of the direct wave. During each iteration, an update of a so-called focusing function is cross-correlated with the reflection response. By adding and subtracting traveltimes along stationary raypaths, we could explain how the scheme allows us to retrieve particular multiply scattered events. By retrieving Green's functions below a complex overburden and applying multidimensional deconvolution of the upgoing components of these Green's functions with the downgoing components, a redatumed response could be retrieved that is free from internal multiples in the overburden.

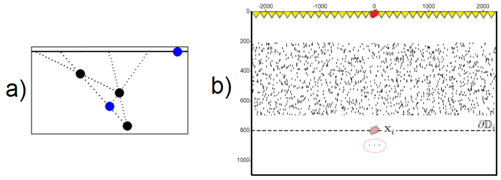

Figure 1. a) Model with three point diffractors (black dots). Our aim is to retrieve a Green's function between the two blue dots, being a location at the surface (black solid line) and the focal point. The black dashed lines represent stationary raypaths that play a role in the retrieval process. b) Model with multiple point scatterers in a homogeneous background. Sources and receivers are laid out at the surface and focal points are selected along a horizontal level at 800m depth. Our aim is to image three point scatterers (indicated by the red ellipse) below this level.

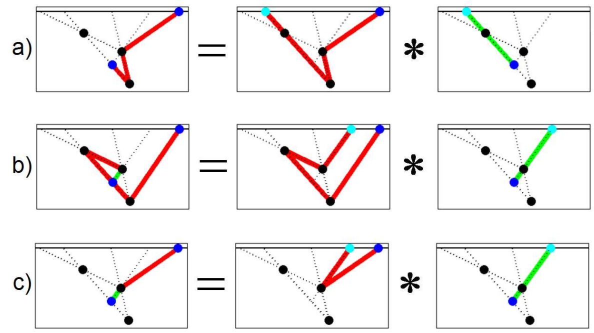

Figure 2. a) Example of an upgoing event (left) that is successfully retrieved by the multidimensional correlation of an event in the reflection response (middle) with the initial focusing function (right). b) Example of an artefact of type I (arriving after the direct wave). c) Example of an artefact of type II (arriving before the direct wave). Red raypaths have positive traveltimes and green raypaths have negative traveltimes. Blue dots are the source and receiver (focal point) of the retrieved Green's function. The cyan dot is a stationary point.

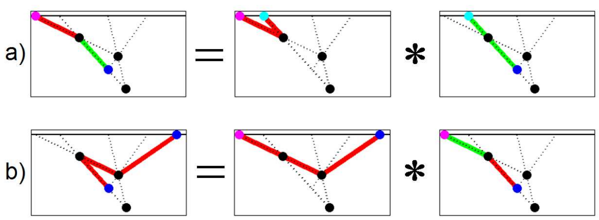

Figure 3. Illustration of the retrieval of a downgoing event in two steps. a) Through equation 1, an event is formed by the multidimensional correlation of an event in the reflection response (middle) with the initial focusing function (right). The traveltime of this event is obtained by subtracting the traveltime along the green raypath from the traveltime along the red raypath. B) Through equation 4, this event (shown after time-reversal in the right panel) is cross-correlated with the reflection response (middle) to retrieve a downgoing event. Blue dots are the source and receiver (focal point) of the retrieved Green's function. The cyan and magenta dots are stationary points.

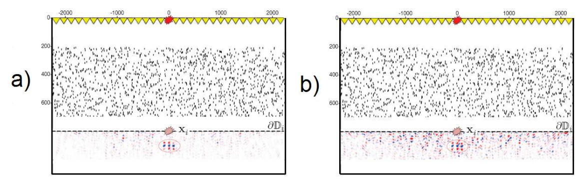

Figure 4: a) Image (below 800m) obtained by Marchenko redatuming to a level at 800m and conventional migration below this level. b) Image (below 800m) obtained by conventional migration of the surface data.

Acknowledgements

The research of J. van der Neut was sponsored by the Technology Foundation STW, applied science foundation of NWO (project 13078).

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