An adaptive method for source-receiver Marchenko redatuming

Myrna Staring (Delft University of Technology), Roberto Pereira (CGG), Huub Douma (CGG), Joost van der Neut (Delft University of Technology) and Kees Wapenaar (Delft University of Technology)

This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.

Abstract

We propose an adaptive approach for the removal of internal multiples caused by an overburden using source-receiver Marchenko redatuming. Typically, a multi-dimensional deconvolution using the one-way Green's functions is performed to achieve redatuming, after these functions have been retrieved by solving the coupled Marchenko equations. However, this processing step is sensitive to imperfections in the data and the acquisition geometry as well as computationally expensive. We propose an adaptive redatuming method that is less sensitive to such imperfections and as such should be beneficial when attempting source-receiver Marchenko redatuming with field data. We show this using 2D synthetic data from the Santos basin offshore Brazil. As an added bonus, it is also computationally less expensive. A disadvantage of the proposed method is that the obtained reflection response exists in the physical medium, causing some interactions with the overburden to remain.

Introduction

In many places in the Santos basin in Brazil, the geology contains a highly reflective salt structure above the pre-salt reservoirs. Such salt is known to generate interbed multiples that interfere with the primaries in the target area (Cypriano *et al*. (2015)) (Figure 1a). Current imaging methods assume the recorded wavefields to have reflected only once, causing these internal multiples to appear as phantom reflectors in the image (Figure 1b). Therefore, it is essential that interactions with a complex overburden are accurately removed from the reflection response, such that we can obtain an image of the reservoir that is free from artefacts due to internal multiples.

Marchenko redatuming is a novel data-driven approach that requires a smooth velocity model and an accurate reflection response for the retrieval of one-way Green's functions at any depth level (Broggini *et al*. (2012); Wapenaar *et al*. (2014b)). The method achieves this by iteratively solving for the coupled Marchenko equations, resulting in one-way focusing functions and one-way Green's functions at specified focal points. Similar to internal multiple removal methods (Weglein *et al*. (1997); Jakubowicz (1998); Ikelle (2006)), Marchenko redatuming uses both convolutions and cross-correlations to construct internal multiples. However, unlike these methods, Marchenko redatuming in principle retrieves all orders of internal multiples at any desired depth level, without the need to resolve for the upper layers first.

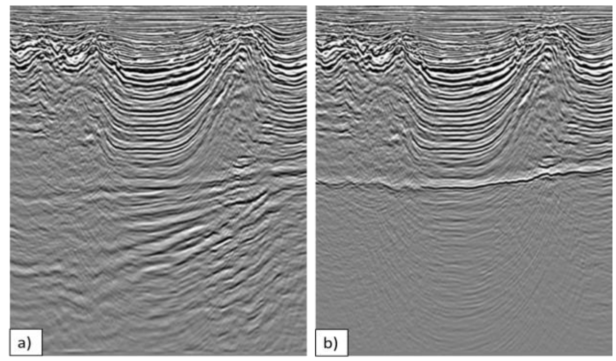

Figure 1 – *a) RTM Image for a 2D model of the Santos basin, b) same image but with the model being homogeneous below the base of salt, such that only the multiples generated in the overburden are visible*.

In order for Marchenko redatuming to be successful, certain requirements have to be satisfied. First, a broadband, well-sampled and noise-free reflection response is required. Second, the data should be free from ghosts, amplitude effects due to attenuation, free-surface multiples as well as horizontally propagating waves. Furthermore, source (and receiver) signatures have to be accurately removed (Wapenaar *et al*. (2014b); van der Neut and Wapenaar (2016)). In the method, evanescent waves are neglected. Finally, the acquisition geometry needs a large aperture and a dense grid of sources and receivers (Vasconcelos *et al*. (2014)). We mention that most of these requirements are also necessary for other internal multiple removal methods. While these assumptions hold for synthetic data, one or more of these assumptions will necessarily be violated for field data. Therefore, for field data, convergence of the iterative scheme that solves the coupled Marchenko equations is a valid concern (Ravasi *et al*. (2016)).

We propose an alternative redatuming approach that is less sensitive to imperfections in the data and the acquisition geometry, and that offers more flexibility for the application of source-receiver Marchenko redatuming to field data. We validate this method using 2D synthetic data from the Santos basin offshore Brazil.

Single-sided redatuming

Following Wapenaar *et al*. (2014b), we start by iteratively solving the coupled Marchenko equations for the one-way focusing and Green's functions. These iterations alternate between updating the upgoing focusing function and the coda of the downgoing focusing function. To initiate the scheme, the direct wave of the downgoing focusing function $\hat{\boldsymbol{f}}_0^+$ is needed. This can be obtained from a macro velocity model (Wapenaar *et al*. (2014a)). In this work, we will only use two of these fields: the upgoing Green's function $\widehat{\boldsymbol{G}}^{-+}$ and the downgoing focusing function $\hat{\boldsymbol{f}}^+$. The Green's function is measured as an upgoing field due to a downgoing source at the surface, as indicated by the superscripts. Since iterative substitution of the coupled Marchenko equations is equal to solving a Fredholm equation of the second kind, we can directly express the retrieval of our desired wavefields as a Neumann series (van der Neut *et al*. (2015b)):

$$\hat{G}^{-+}(\mathbf{x}_F,\mathbf{x}_S,t)=\sum_{i=0}^{\infty}\hat{G}_i^{-+}=\left\{\Psi R\sum_{i=0}^{\infty}\Omega^i\hat{f}_0^+\right\}(\mathbf{x}_F,\mathbf{x}_S,t), \tag{1}$$

and

$$\hat{f}^{+}(\mathbf{x}_S,\mathbf{x}_F,t)=\sum_{j=0}^{\infty}\hat{f}_j^{+}(\mathbf{x}_S,\mathbf{x}_F,t)=\sum_{j=0}^{\infty}\left\{\Omega^j\hat{f}_0^+\right\}(\mathbf{x}_S,\mathbf{x}_F,t), \tag{2}$$

Here $\hat{G}_i^{-+}$ and $\hat{f}_j^+$ represent initial estimates and updates of the upgoing Green's function and the downgoing focusing function respectively, where i and j indicate the number of iterations. The source signature as well as any surface-related multiples and ghosts are assumed to have been removed from the reflection response R. $\boldsymbol{x}_S$ and $\boldsymbol{x}_F$ indicate locations at the acquisition level and the focal level respectively. The band-limitation of the Green's function and focusing function is indicated by the ^ symbol. This band-limitation stems from convolving the time-reversed direct wave $\hat{f}_0^+$ with a zero-phase wavelet that covers the frequency content of the seismic data. The symbol $\Omega=\theta R^*\theta R$ represents an operator that applies a convolution and a cross-correlation with the reflection response R consecutively to $\hat{f}_0^+$. After every convolution or cross-correlation, a time-symmetric window θ is applied to the result to separate the focusing function from the Green's function. Application of the window function θ results in the focusing function, while the window $\Psi=\mathrm{I}-\theta$ is applied to obtain the Green's function. These truncations are Heaviside step functions θ_0 based on causality arguments and defined by the one-way traveltime t_d from the acquisition level to the focal points (Wapenaar *et al*. (2014b)). To correct for the finite frequency content of the data, we need to include a factor t_ε equal to half the wavelength of the wavelet when defining the window:

$$\left\{\theta\hat{P}\right\}(\mathbf{x}_F,\mathbf{x}_S,t)=$$
$$\left(\theta_0\left(t+t_d(\mathbf{x}_F,\mathbf{x}_S)-t_\varepsilon\right)-\theta_0\left(t-t_d(\mathbf{x}_F,\mathbf{x}_S)\right)+t_\varepsilon\right)\hat{P}(\mathbf{x}_F,\mathbf{x}_S,t). \tag{3}$$

In order for the Neumann series in equations 1 and 2 to converge, we must have $\left\|\Omega^k\hat{f}_0^+\right\|_2\to 0$ as $\mathrm{k}\to\infty$ (Fokkema and van den Berg (1993)). Here k represents either i or j in equations 1 and 2. This poses a challenge for field data, since for such data the recorded reflection response will be scaled by an unknown factor due to the acquisition geometry as well as pre-processing of the data (Ravasi *et al*. (2016)). Since in the case of field data, R might not satisfy all theoretically necessary requirements for Marchenko redatuming, the series might not converge to the correct solution.

Two-sided redatuming

Solving the coupled Marchenko equations for the upgoing Green's function results in a reflection response from a source $\boldsymbol{x}_S$ at the acquisition level to a receiver $\boldsymbol{x}_F$ at the focal point, which we can interpret as single-sided redatuming (see figure 2a). Since the reflection response has only been redatumed at the receiver-side, we now wish to also redatum at the source-side, such that we achieve two-sided redatuming (figure 2b). This step can be done in multiple ways, thereby allowing for a certain amount of freedom. Wapenaar *et al*. (2014b) suggest a multi-dimensional deconvolution (MDD) of the one-way Green's functions, that results in a reflection response in a truncated medium. This reflection response will not contain any interactions with the overburden. However, this processing step is computationally intensive as it uses an array of focal points as input. In addition, it is sensitive to amplitude errors in the data, which might occur due to attenuation and incomplete data (Wapenaar *et al*. (2014a); van der Neut *et al*. (2015a)).

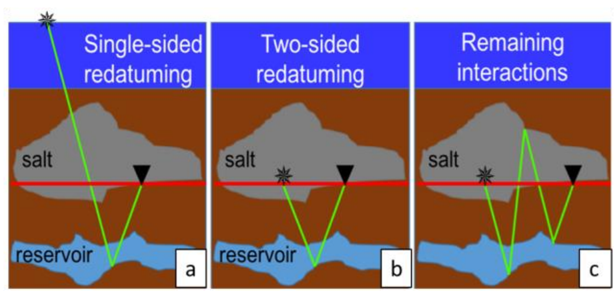

Figure 2 – *Illustration of a) single-sided redatuming, b) two-sided redatuming, and c) the remaining interactions with the overburden that result from redatuming in the physical medium instead of in the truncated medium.*

We desire to have an alternative that is more forgiving and less sensitive to imperfections in the recorded data and the assumptions of the medium. Van der Neut *et al*. (2015a) observed that the initial estimate of the upgoing Green's function $\widehat{\boldsymbol{G}}_0^{-+}$ already contains all correct physical arrivals. However, it also contains artefacts that we would like to see removed from this Green's function. The first update $\widehat{\boldsymbol{G}}_1^{-+}$ contains all the necessary counter-events to take care of these artefacts, just with the wrong amplitudes. The subsequent updates only correct the amplitudes of these counter-events until they match and completely eliminate the artefacts. The story is similar for the downgoing focusing function, where the first estimate $\hat{\boldsymbol{f}}_0^+$ already contains all physical information, while its first update $\hat{f}_1^+$ takes care of the artefacts due to internal multiples. Again, subsequent updates will only alter the amplitudes.

These properties are useful when considering an alternative for MDD. Convolving the downgoing focusing function at a virtual source location with the upgoing Green's function at a virtual receiver location creates downward-generating virtual sources and upward-measuring virtual receivers at the redatuming level, thereby achieving two-sided redatuming (see figure 2b). In addition, the properties of the upgoing Green's function and the downgoing focusing function allow us to write this equation as a series, using equations 1 and 2:

$$\begin{aligned}
&\hat{\hat{R}}_0(\mathbf{x}_H,\mathbf{x}_F,\omega) = \\
&\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\int_{-\infty}^{+\infty} d^2\boldsymbol{\chi}\,\hat{G}_i^{-+}(\mathbf{x}_H,\boldsymbol{\chi},\omega)\,\hat{f}_j^{+}(\boldsymbol{\chi},\mathbf{x}_F,\omega) \\
&\approx \int_{-\infty}^{+\infty} d^2\boldsymbol{\chi}\,\hat{G}_0^{-+}(\mathbf{x}_H,\boldsymbol{\chi},\omega)\,\hat{f}_0^{+}(\boldsymbol{\chi},\mathbf{x}_F,\omega) \qquad (4)\\
&+ \int_{-\infty}^{+\infty} d^2\boldsymbol{\chi}\,\hat{G}_1^{-+}(\mathbf{x}_H,\boldsymbol{\chi},\omega)\,\hat{f}_0^{+}(\boldsymbol{\chi},\mathbf{x}_F,\omega) \\
&+ \int_{-\infty}^{+\infty} d^2\boldsymbol{\chi}\,\hat{G}_0^{-+}(\mathbf{x}_H,\boldsymbol{\chi},\omega)\,\hat{f}_1^{+}(\boldsymbol{\chi},\mathbf{x}_F,\omega).
\end{aligned}$$

Here $\boldsymbol{x}_H$ and $\boldsymbol{x}_F$ represent locations at the redatuming level, while $\boldsymbol{\chi}$ indicates a position at the acquisition level. Note that the integral in this equation is over the acquisition surface, while MDD requires integration over the redatuming level. Therefore, the proposed method provides the flexibility to apply source-receiver redatuming to a single focal point only, which is useful for the parallelization of the algorithm. We have only included terms in this approximation for which the data has been correlated no more than twice, thus leaving out the term $\hat{G}_1^{-+}\hat{f}_1^{+}$. Correlating the data with itself rapidly degrades the quality of the updates, especially when the data contains a band-limitation or an unknown scaling factor.

These terms use the fields $\hat{G}_0^{-+}$, $\hat{G}_1^{-+}$, $\hat{f}_0^{+}$ and $\hat{f}_1^{+}$ that include all the events needed for Marchenko redatuming, except with the wrong amplitudes. The first term contains the result of conventional redatuming (using the direct wave $\hat{f}_0^{+}$) including both primaries and internal multiples, while the second and third terms contain the first-order predictions of multiples at the receiver and source sides respectively, with opposite polarity compared to the first term. In order to avoid needing the amplitude updates from the higher order terms, we add the three terms with an adaptive filter. Throughout this work, we have used an adaptive subtraction in the curvelet domain (e.g., Wu and Hung (2015)), because curvelets provide extra flexibility when multiples coincide with primaries in time and space, but not in slope. We expect this method to be less sensitive to imperfections in the data and the medium assumptions than MDD, since the adaptive filter can correct for the amplitude mismatch of the updates. In addition, the proposed method is computationally cheaper. A disadvantage is that the redatumed response exists in the physical medium, as opposed to the truncated medium that results from MDD. Therefore, waves that propagate from the virtual source downwards into the target, back up into the overburden, back down into the target, and then again up to the virtual receiver will not be removed (see figure 2c).

Comparison of methods: a 2D synthetic data example

To illustrate the workings of the proposed method, a 2D synthetic dataset from the Santos basin is used. Synthetics were generated in a model obtained from an acoustic inversion of field data. As such it can be considered a realistic model that generates realistic internal multiples that would be observed on field data from this area (Cypriano *et al*. (2015)). The reflection response was generated on a line with 601 sources and receivers with a spacing of 25 m. The first redatuming step is initiated by the direct wave $\hat{f}_0^{+}$, which is obtained from a macro velocity model. An Ormsby wavelet with a central frequency of 35 Hz is applied to impose a band-limitation. After two iterations of solving the coupled Marchenko equations, convolving the individual updates of $\hat{G}^{-+}$ and $\hat{f}^{+}$ with each other, and only keeping the terms that have been convolved no more than twice, the three terms of equation 4 result. An example of these terms is shown in Figure 3, for a virtual source location in the middle of the array at the redatuming level. It can clearly be seen that the second and third terms contain counter-events for the artefacts in the first term $\hat{G}_0^{-+}\hat{f}_0^{+}$.

Figure 4 shows a comparison between MDD and our adaptive redatuming. On the left is the result of modeling a reflection response in a medium with a homogeneous overburden above the redatuming level. As such it can be used as a guide to see how well both methods work. MDD uses the upgoing and downgoing one-way Green's functions that result from two iterations of solving the coupled Marchenko equations. We apply a mute (indicated by the white lines in figure 4) to both the MDD and the adaptive results to remove the acausal parts. When comparing the MDD and adaptive result to the modeled result, it is clear that the adaptive redatuming is capable of producing an improved result over MDD, even though a medium truncation is not achieved. This implies that multiples due to remaining interactions between the overburden and the target area are negligible in this example.

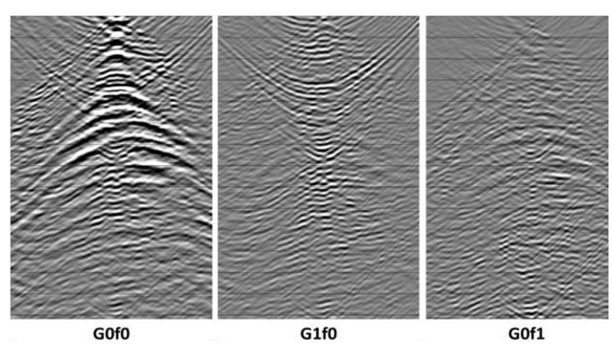

Figure 3 – *Examples of the individual terms from equation 4 in the synthetic example from the Santos basin, for a source in the middle of the array.*

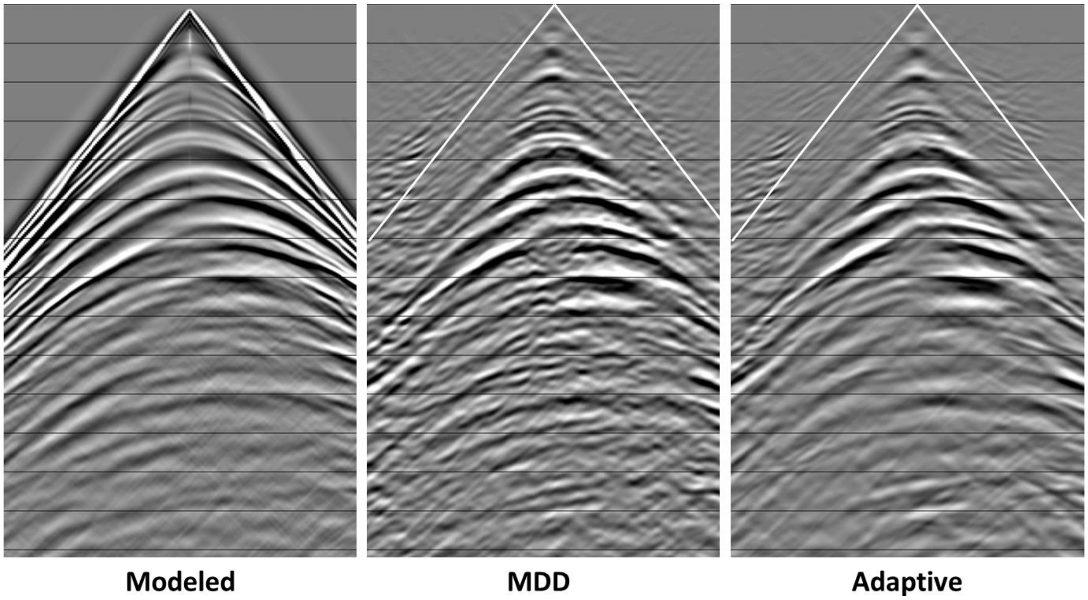

Figure 4 – *Comparison of the result of modeling a reflection response at the redatuming level in a medium with a homogeneous overburden above the redatuming level (left), the MDD result (middle), and the result of the proposed two-sided adaptive redatuming (right).*

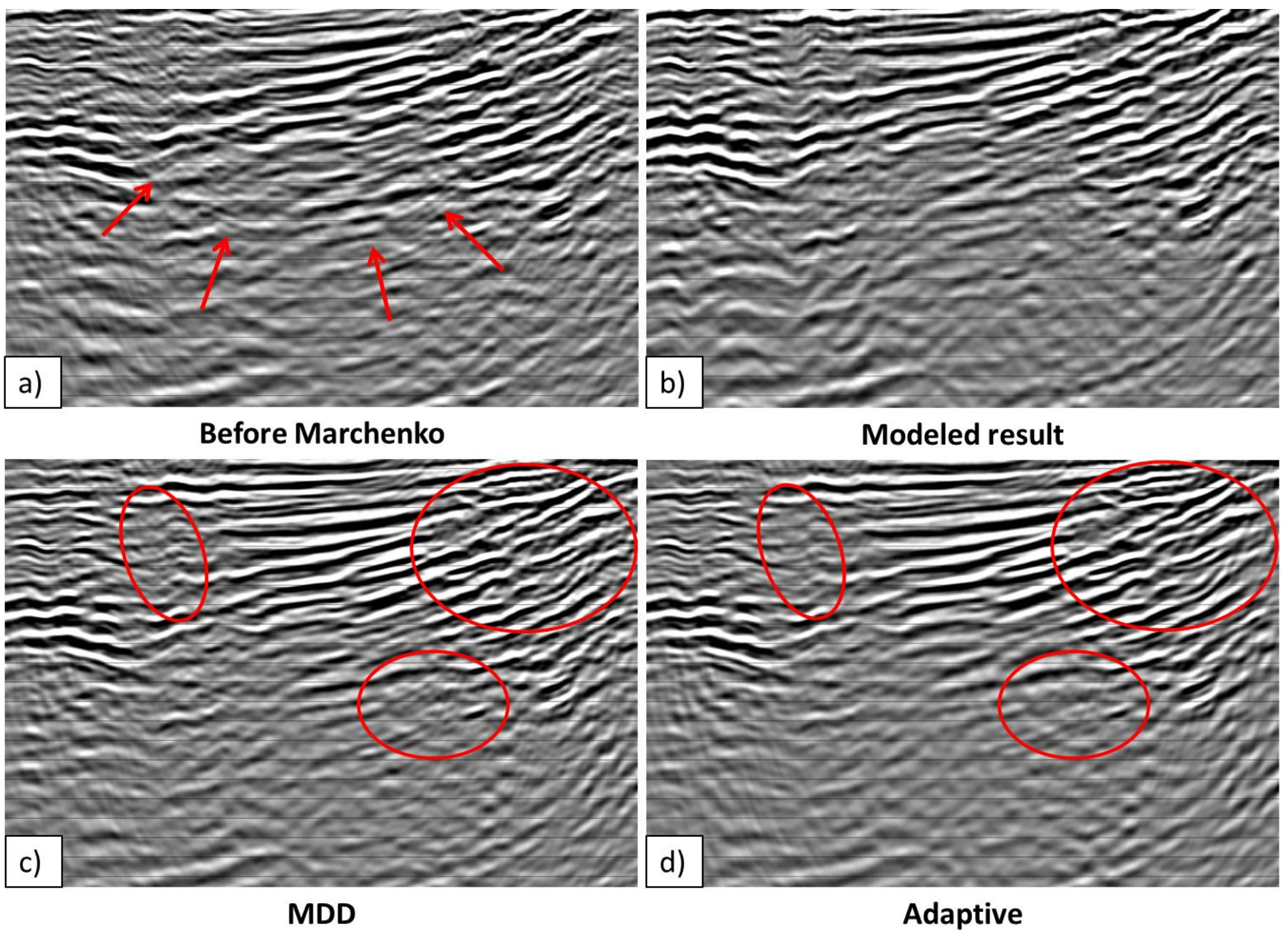

Figure 5 – *a) RTM from the surface before applying Marchenko redatuming, including all the artefacts due to internal multiples, b) RTM of a reflection response modeled at the redatuming level in a medium with a homogeneous overburden above the redatuming level, c) RTM of the MDD result, d) RTM of the two-sided adaptive redatuming result.*

Figure 5 shows the images obtained after RTM. Figure 5a shows the result before Marchenko redatuming to allow comparison with the image obtained when migrating the data including all internal multiples from the surface. Both the MDD and the adaptive method in Figures 5c and 5d remove multiples well (cf. Figure 5a), while the adaptive method produces a somewhat improved result that compares better to the modeled result in Figure 5b. For convenience of the reader, we have indicated the multiples in Figure 5a by arrows. See also Figure 1b for an example of what the artefacts due to internal multiples look like in the image domain for this synthetic example. In addition, the circles in Figures 5c and 5d highlight a few areas with the largest differences.

We proceed to verify if the proposed method is indeed less sensitive to imperfections in the data with two simple examples. Two shortcomings that are typically found in field data are chosen: a reflection response scaled by an unknown factor and a less dense acquisition geometry. First, we test the effect of a single scalar, the simplest possible error in the scaling of the reflection response. We scale the reflection response by 50% and 200% of the true value. Figure 6 shows the performance of both redatuming approaches. As anticipated, the adaptive method perfectly corrects for the incorrect amplitudes. However, the MDD result clearly has difficulties removing the internal multiples when the reflection response is scaled by an erroneously low factor. For an erroneously large factor, it adds multiples instead of removing them. In principle, the MDD result can be improved by finding an optimal scalar. However, it is not obvious how to accurately do this. In contrast, the adaptive method is not affected at all by the presence of such an unknown scalar.

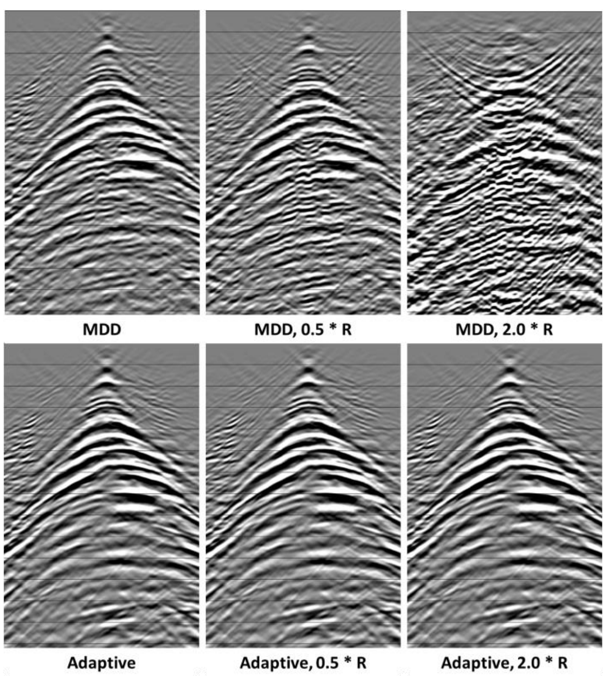

Figure 6 – *Performance of the MDD versus the two-sided adaptive redatuming for a reflection response multiplied with a scaling factor. The two-sided adaptive redatuming is not affected at all by the presence of such a scalar, while the MDD result is.*

Next, we increase the spacing of the sources and receivers from 25 m to 50 m and 100 m. Figure 7 shows the redatumed gathers that were obtained by applying either the MDD or the adaptive redatuming. Although the adaptive method deteriorates as sources and receivers are being removed, it is still capable of obtaining a significant amount of primary energy. In contrast, the MDD greatly suffers and does not contain any recognizable signal when increasing the spacing to 100 m. This difference is particularly visible in the image domain after applying RTM to the results for a 50 m source and receiver spacing (Figure 8). With a coarser acquisition geometry, the proposed adaptive method still removes a significant amount of multiples compared to the dense geometry (cf. Figure 5d), while the MDD clearly suffers substantially more (cf. Figure 5c).

Conclusion

A method to apply two-sided adaptive redatuming was presented and tested on 2D synthetic data. Comparison with the MDD indicates that the adaptive method is less sensitive to imperfections in the data and the acquisition geometry. It manages to obtain a cleaner redatumed reflection response using the same amount of iterations, and it is computationally cheaper than MDD. In addition, it provides more flexibility since it can be applied to a single focal point only, allowing for parallelization per focal point. A disadvantage is that the redatumed response exists in the physical medium, such that some interactions with the overburden remain. Overall, we conclude that the performance of the adaptive redatuming is better than the

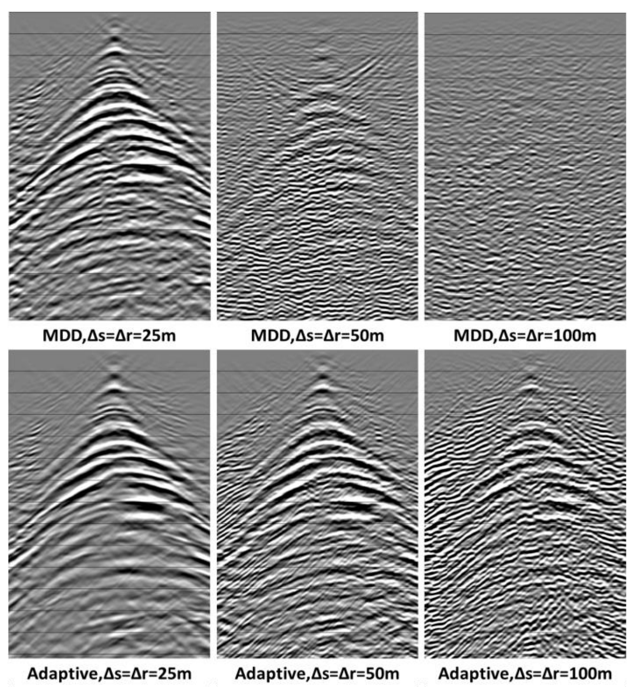

Figure 7 – *MDD versus the adaptive redatuming for a coarser acquisition geometry. Both methods suffer, but the adaptive redatuming is less sensitive.*

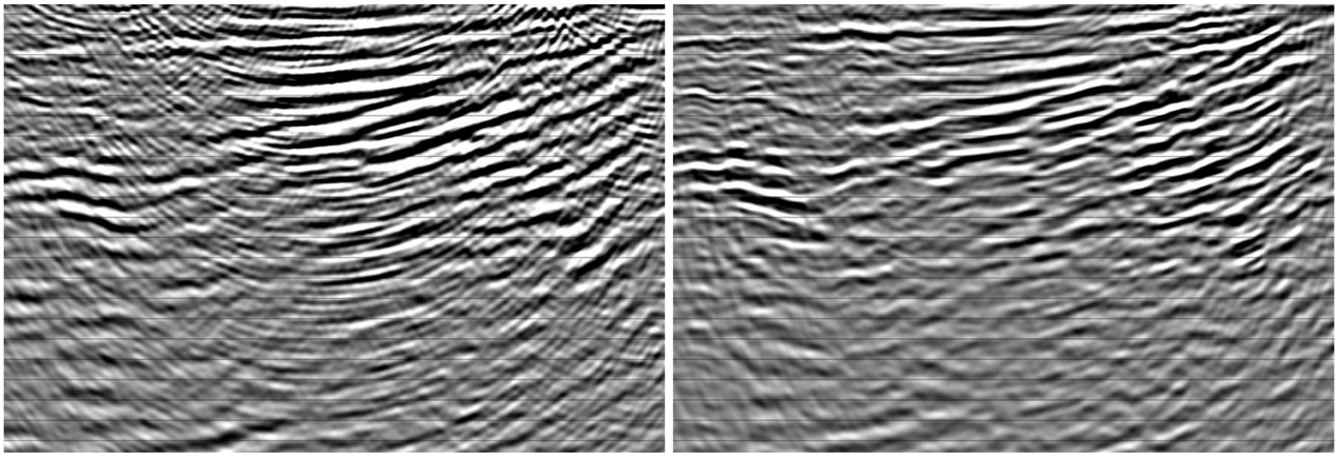

Figure 8 – *Images resulting from performing an RTM on the reflection responses for both cases obtained by MDD and adaptive redatuming. The source and receiver spacing is 50 m.*

MDD, which holds promise for the application of Marchenko redatuming to field data.

Acknowledgments

This research has been performed in the framework of the project "Marchenko imaging and monitoring of geophysical reflection data", financially supported by the Dutch Technology Foundation STW, applied science division of NWO and the Technology Program of the Ministry of Economic Affairs. We thank CGG Rio de Janeiro for a fruitful collaboration, and Manuel Peiro (CGG Rio) for preparing the model used to create the synthetic 2D data for the tests.

References

BROGGINI, F., R. SNIEDER, & K. WAPENAAR, 2012, Focusing the wavefield inside an unknown 1d medium: Beyond seismic interferometry: Geophysics, 77, A25–A28,

CYPRIANO, L., F. MARPEAU, R. BRASIL, G. WELTER, H. PRIGENT, H. DOUMA, M. VELASQUES, J. BOECHAT, P. DE CARVALHO, C. GUERRA, et al., 2015, The impact of inter-bed multiple attenuation on the imaging of pre-salt targets in the Santos basin off-shore Brazil: Presented at the 77th EAGE Conference and Exhibition 2015.

FOKKEMA, J. T. & P. M. VAN DEN BERG, 1993, Seismic applications of acoustic reciprocity: Elsevier.

JAKUBOWICZ, H., 1998, Wave equation prediction and removal of interbed multiples: Presented at the 60th EAGE Conference and Exhibition,

RAVASI, M., I. VASCONCELOS, A. KRITSKI, A. CURTIS, C. A. DA COSTA FILHO & G. A. MELES, 2016, Target-oriented Marchenko imaging of a North Sea field: Geophysical Journal International, 205, 99–104.

VAN DER NEUT, J., J. THORBECKE, K. MEHTA, E. SLOB & K. WAPENAAR, 2011, Controlled-source interferometric redatuming by crosscorrelation and multidimensional deconvolution in elastic media: Geophysics, 76, SA63–SA76,

VAN DER NEUT, J., I. VASCONCELOS & K. WAPENAAR, 2015a, On Green's function retrieval by iterative substitution of the coupled Marchenko equations: Geophysical Journal International, 203, 792–813,

VAN DER NEUT, J. & K. Wapenaar, 2016, Adaptive overburden elimination with the multidimensional Marchenko equation: Geophysics, 81, T265–T284,

VAN DER NEUT, J., K. WAPENAAR, J. THORBECKE, E. SLOB & I. VASCONCELOS, 2015b, An illustration of adaptive Marchenko imaging: The Leading Edge, 34, 818–822,

VASCONCELOS, I., VAN MANEN, D.-J., RAVASI, M., WAPENAAR, K. & VAN DER NEUT, J., 2014, Marchenko redatuming: advantages and limitations in complex media, 84th annual SEG meeting, Denver, Workshop W-11: Using Multiples as Signal for Imaging,

WAPENAAR, K., J. THORBECKE, J. VAN DER NEUT, F. BROGGINI, E. SLOB & R. SNIEDER, 2014a, Green's function retrieval from reflection data, in absence of a receiver at the virtual source position: The Journal of the Acoustical Society of America, 135, 2847–2861,

WEGLEIN, A. B., F. A. GASPAROTTO, P. M. CARVALHO & R. H. STOLT, 1997, An inverse-scattering series method for attenuating multiples in seismic reflection data: Geophysics, 62, 1975–1989.

WU, X. & B. HUNG, 2015, High-fidelity adaptive curvelet domain primary-multiple separation: first break, 33, 53–59.