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Marchenko redatuming by adaptive double-focusing on 2D and 3D field data of the Santos basin

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SUMMARY

The Santos basin in Brazil suffers from strong internal multiples that overlap with primaries from the pre-salt reservoirs. We propose an adaptive double-focusing method for the removal of these multiples to obtain a correct image of the target area. The proposed method applies a form of source-receiver Marchenko redatuming to the reflection response. The Marchenko method is used to achieve single-focusing, after which we convolve the retrieved downgoing focusing function and the upgoing Green's function to create double-focusing. This results in a base image that contains both primaries and internal multiples, and two models that predict the strongest internal multiples. Next, adaptive subtraction in the curvelet domain is used to remove these multiples from the base image. Some multiple interactions between the target area and the overburden remain, but we gain a robust method that is capable of dealing with a sparse acquisition geometry and imperfections in the (pre-processed) data. Also, this method is straightforward to implement and can be parallelized over pairs of focal points. These properties make adaptive double-focusing particularly suitable for the application to large volumes of field data. Tests on 2D field data and 3D field data show that the proposed method correctly predicts and removes the strongest internal multiples from the overburden, resulting in a clear improvement of the geological interpretability in the target area.

INTRODUCTION

The Marchenko method recovers one-way Green's functions between any two locations inside a medium, in principle including all orders of internal multiples (Broggini et al. (2012); Wapenaar et al. (2014)). The method is completely data-driven, only the reflection response at the acquisition surface and a smooth velocity model are needed. The Marchenko method has a range of applications, for example in homogeneous Green's function retrieval, in (target-oriented) imaging or in monitoring (Brackenhoff et al. (2018); Ravasi et al. (2016); Wapenaar and Staring (2018)), but we use it here to achieve source-receiver redatuming below a complex overburden. First, we solve the multi-dimensional coupled Marchenko equations and thereby create virtual receivers at the desired depth level. Next, we create virtual sources at that same depth level. The strength of the Marchenko method is that we can directly redatum to the desired depth level without needing to resolve overlying layers first.

The second redatuming step can be performed in a variety of ways. Single-focusing with the Marchenko method results in up- and downgoing Green's functions and up- and downgoing focusing functions. Typically, the one-way Green's functions are multi-dimensionally deconvolved to achieve source redatuming (Wapenaar et al. (2014)). This results in a medium that is homogeneous above the redatuming level, such that all overburden interactions are removed. However, the multi-dimensional deconvolution (MDD) solves $\hat{G}^- = \int R * \hat{G}^+$, which is equal to solving an inverse problem for finding redatumed reflection response R inside the integral. This inversion is fundamentally ill-posed and should be correctly stabilized (Minato et al. (2013)). Also, artefacts due to incomplete illumination can appear (van der Neut et al. (2011)). As a result, it is sensitive to sparse acquisition geometries and imperfections in the (pre-processed) data (Staring et al. (2017)). This is not a problem for synthetic data, but it becomes an issue when applying the method to field data.

Therefore, we propose adaptive double-focusing as an alternative. Instead of performing a multi-dimensional deconvolution with the one-way Green's functions that result from the Marchenko method, we now perform a multi-dimensional convolution of the upgoing Green's function and the downgoing focusing function. Here we demonstrate the successful application of the proposed method to 2D and 3D field data, where we can observe a clear improvement in the geological interpretability. We use a dataset from the Santos basin in Brazil, known for its pre-salt reservoirs, where accurate imaging of the targets is hindered by strong internal multiples generated in the overburden (Cypriano et al. (2015)). The multiples are clearly visible (see figure 1), thus making it a suitable dataset to test adaptive double-focusing.

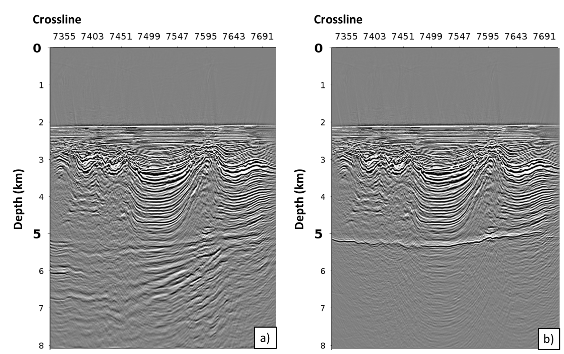

Figure 1: a) Santos basin RTM image, b) same image in which the model is homogeneous below the base of salt, in which only the multiple reflections generated in the overburden are visible. Note the half-circle appearance of the artefacts, we will find them again in the images of the field data.

ADAPTIVE DOUBLE-FOCUSING

We start by performing the Marchenko method using the reflection response and a smooth velocity model. This results in directionally-decomposed focusing functions and Green's functions. Next, we select the downgoing focusing function at a virtual source location and the upgoing Green's function at a virtual receiver location and convolve them (Wapenaar et al. (2016); Singh et al. (2016)):

$$\hat{\hat{G}}^{-+}(\boldsymbol{x}_{vr},\boldsymbol{x}_{vs},t) = \int_{\partial \mathbf{D_0}} \hat{G}^{-}(\boldsymbol{x}_{vr},\boldsymbol{x},t) * \hat{f}^{+}(\boldsymbol{x},\boldsymbol{x}_{vs},t)\, d^2\boldsymbol{x} \quad (1)$$

Thus, downward-radiating virtual sources $\boldsymbol{x}_{vs}$ and upward-measuring virtual receivers $\boldsymbol{x}_{vr}$ are created at the redatuming level in the physical medium. Positions at the acquisition surface are denoted by $\boldsymbol{x}$. The $\hat{}$ symbol indicates the band-limitation of the Green's functions and focusing functions. The result of double-focusing is wavefield $\hat{\hat{G}}^{-+}$: the upgoing Green's function measured by an upward-measuring receiver due to a downward-radiating source. Note the integral over the acquisition surface $\partial\mathbf{D_0}$. This integral allows us to parallelize over pairs of focal points, which is a great advantage when applying the method to large volumes of 3D data.

The wavefields $\hat{G}^{-}$ and $\hat{f}^{+}$ can be retrieved using the Marchenko scheme (van der Neut et al. (2015)):

$$\hat{G}^{-}(\boldsymbol{x}_{vr},\boldsymbol{x},t) = \sum_{i=0}^{\infty} \hat{G}_i^{-} = \Psi R \sum_{i=0}^{\infty} \Omega^i \hat{f}_0^{+}, \quad (2)$$

and

$$\hat{f}^{+}(\boldsymbol{x},\boldsymbol{x}_{vs},t) = \sum_{j=0}^{\infty} \hat{f}_j^{+} = \sum_{j=0}^{\infty} \Omega^j \hat{f}_0^{+}. \quad (3)$$

The symbols $\hat{G}_i^{-}$ and $\hat{f}_j^{+}$ represent updates of the upgoing Green's function and the downgoing focusing function respectively, where i and j indicate the iteration number. Finite-difference modeling or an Eikonal solver are used to retrieve the direct wave of the downgoing focusing function $\hat{f}_0^{+}$ that initiates the Marchenko scheme. The operator $\Omega = \theta R^{\star}\theta R$ consecutively applies a convolution and a cross-correlation with reflection response R to $\hat{f}_0^{+}$. The time-symmetric window θ separates the focusing function from the Green's function. Application of θ results in the focusing function, while application of $\Psi = I - \theta$ results in the Green's function.

We have chosen to write the retrieval of the wavefields $\hat{G}_i^{-}$ and $\hat{f}_j^{+}$ as a Neumann series in equations 2 and 3 . We have done so in order to explain why double-focusing is particularly suitable for an adaptive implementation. Of both series, the first estimate already contains all the correct physical arrivals and all the internal multiples. The first update already contains counter-events for the dominant multiples, only with incorrect amplitude. Further updates provide amplitude updates for these counter-events, such that they correctly remove the original internal multiples. Based on these dynamics, adaptive subtraction can be applied to the first estimate and the first update. An adaptive filter substitutes for the amplitude updates that would otherwise be provided by further iterations. This is advantageous since further iterations convolve and correlate the data with itself more, which rapidly degrades the data quality. In addition, adaptive filters add an extra robustness to the method, since they might be able to correct for attenuation, an amplitude mismatch due to incomplete data or inaccurate removal of the source signature (van der Neut and Wapenaar (2016)). We performed 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.

The following equation results by inserting the series notations of equations 2 and 3 into equation 1:

$$\begin{aligned}
&\hat{\hat{G}}^{-+}(\boldsymbol{x}_{vr},\boldsymbol{x}_{vs},t) = \\
&\sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \int_{\partial \mathbf{D_0}} \hat{G}_i^{-}(\boldsymbol{x}_{vr},\boldsymbol{x},t) * \hat{f}_j^{+}(\boldsymbol{x},\boldsymbol{x}_{vs},t)\, d^2\boldsymbol{x} \\
&\approx \int_{\partial \mathbf{D_0}} \hat{G}_0^{-}(\boldsymbol{x}_{vr},\boldsymbol{x},t) * \hat{f}_0^{+}(\boldsymbol{x},\boldsymbol{x}_{vs},t)\, d^2\boldsymbol{x} \qquad (4)\\
&+ \int_{\partial \mathbf{D_0}} \hat{G}_1^{-}(\boldsymbol{x}_{vr},\boldsymbol{x},t) * \hat{f}_0^{+}(\boldsymbol{x},\boldsymbol{x}_{vs},t)\, d^2\boldsymbol{x} \\
&+ \int_{\partial \mathbf{D_0}} \hat{G}_0^{-}(\boldsymbol{x}_{vr},\boldsymbol{x},t) * \hat{f}_1^{+}(\boldsymbol{x},\boldsymbol{x}_{vs},t)\, d^2\boldsymbol{x}.
\end{aligned}$$

This approximation only contains the terms that were obtained by convolving and correlating the reflection response no more than twice. The first term on the right-hand side of equation 4 is similar to the result of conventional redatuming, since the wavefield $\hat{f}_0^{+}$ is used for both source and receiver redatuming. It has all primaries and all internal multiples. This is the base image from which we will subtract the multiples. The second term has counter-events for multiples on the receiver side, while the third term has counter-events for multiples on the source side. These are the models that we will subtract. Note that adaptive double-focusing does not aim to remove all internal multiples, but only the multiples that typically generate the most dominant artefacts in the target area. We redatum in the physical medium instead of in the truncated medium achieved by MDD (see figure 2). Thus, some interactions between the target and the overburden remain. Waves that propagate downwards into the target from the virtual source, upwards into the overburden, back down into the target zone, and then up again to the virtual receiver (see figure 2c) are not removed. In addition, similar to the MDD method, we do not remove internal multiples generated in the target area.

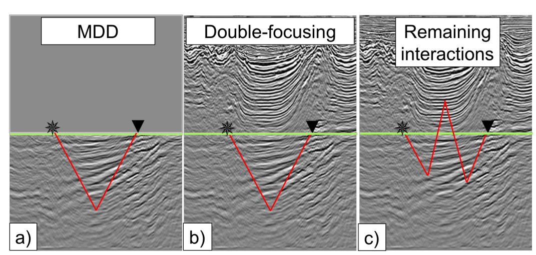

Figure 2: Illustration of a) source-receiver redatuming using MDD, where a medium truncation is achieved, b) source-receiver redatuming in the physical medium using the double-focusing method, and c) the remaining interactions with the overburden that result from redatuming in the physical medium instead of in the truncated medium.

THE APPLICATION TO 2D FIELD DATA

We tested the adaptive double-focusing method on 2D field data acquired by 6 streamers with a cable length of 6000 m and a cable spacing of 150 m. The data was pre-processed using de-ghosting, de-signature, de-noise and the removal of surface-related multiples. We regularized shots and receivers on the same line with a 25 m spacing. Figure 3 shows a comparison of the images obtained by applying an RTM directly to the reflection response acquired at the surface (we call this conventional imaging), the base term of the adaptive double-focusing method ($\hat{G}_0^- \hat{f}_0^+$) that includes all primaries and all internal multiples (this is comparable to conventional imaging), the image obtained by using single-focusing and the MDD method, and the result of the adaptive double-focusing method. The white lines indicate the half-circles created by internal multiples, comparable to the ones seen in figure 1. The white circles highlight an area in which the internal multiples mask the real structure of the reservoir and thereby give the encircled section a different appearance. Here the improvement due to multiple removal can be most clearly seen. The adaptive double-focusing method does not only outperform the MDD method in predicting and removing internal multiples, but it was also able to remove the internal multiples in the encircled area, thereby making the masked structure visible and improving the geologic interpretability in the target area.

THE APPLICATION TO 3D FIELD DATA

Next, we test the adaptive double-focusing method on 3D field data. The acquisition consisted of 6 streamers with a cable length of 6000 m and a cable spacing of 150 m. The sailline spacing is 450 m and the shot spacing is 50 m. We interpolated to a receiver/shot grid of 50 m by 75 m. The grid of focal points in the subsurface is 25 m by 37.5 m. Figure 4 shows the result of directly taking an RTM of the reflection response at the surface, and the result of adaptive double-focusing. Below these images are depth slices at 5100 m depth, also clearly showing the multiples and their removal. The white dotted line indicates the intersection between the two images. The white stripes highlight the multiples that are visible as half-circles, while the encircled areas show the most significant improvements in geologic interpretability. In addition, a clear overall improvement due to the removal of multiples is visible in the image. This can also be observed in the depth slices. We believe that this example can be improved by adding more lines (we now used 24 lines).

CONCLUSION

We presented the theory and the application of the adaptive double-focusing method on field data. Based on the Marchenko scheme, this method performs redatuming by creating virtual sources and virtual receivers at any desired depth level. It redatums in the physical medium and thereby predicts the most dominant internal multiples. An adaptive filter in the curvelet domain is used to ensure complete and correct removal of these predicted multiples. The method is robust and capable of dealing with sparse acquisition geometries and imperfections in the (pre-processed) data. The implementation is straightforward and allows for parallelization by pairs of focal points, which makes it particularly suitable for the application to large volumes of field data. The application to both 2D and 3D field data was succesful and demonstrates a clear improvement in geological interpretability. Therefore, we conclude that the adaptive double-focusing method is an effective tool for the prediction and removal of internal multiples from field data.

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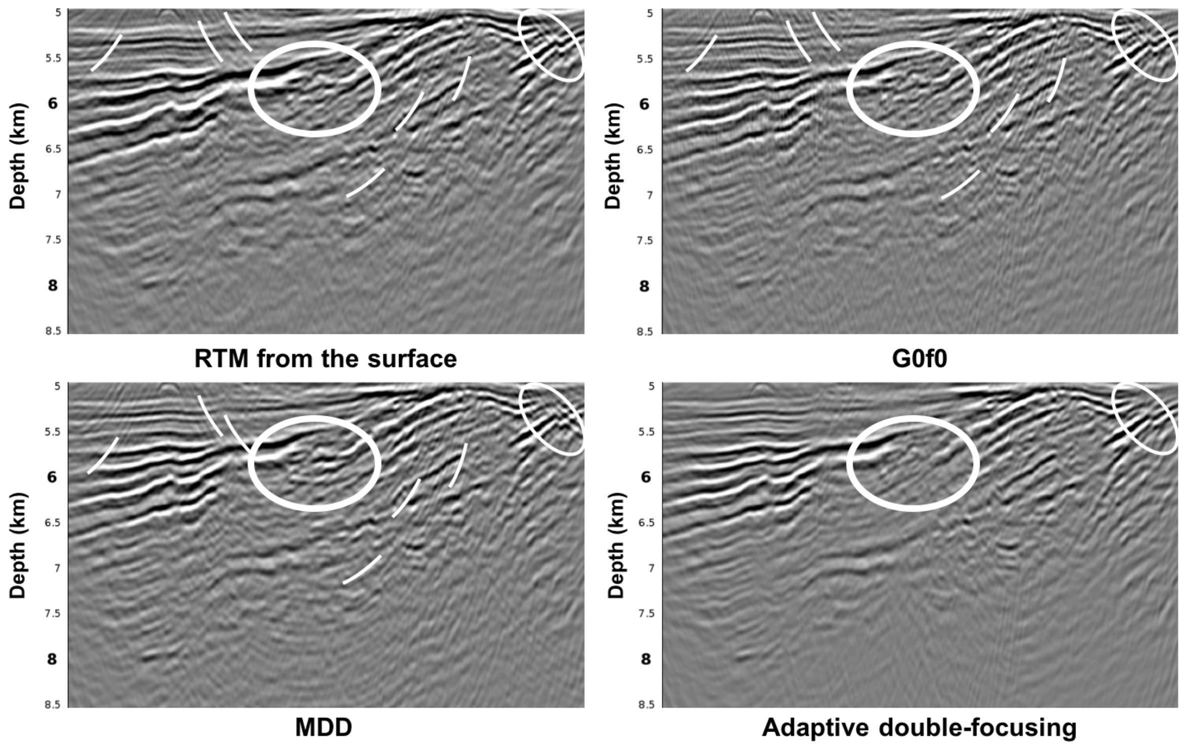

Figure 3: Images showing the result of applying the MDD method and the adaptive double-focusing method to 2D field data of the Santos basin. The top images also show the RTM from the surface and the base term of the adaptive double-focusing method that contains both primaries and internal multiples.

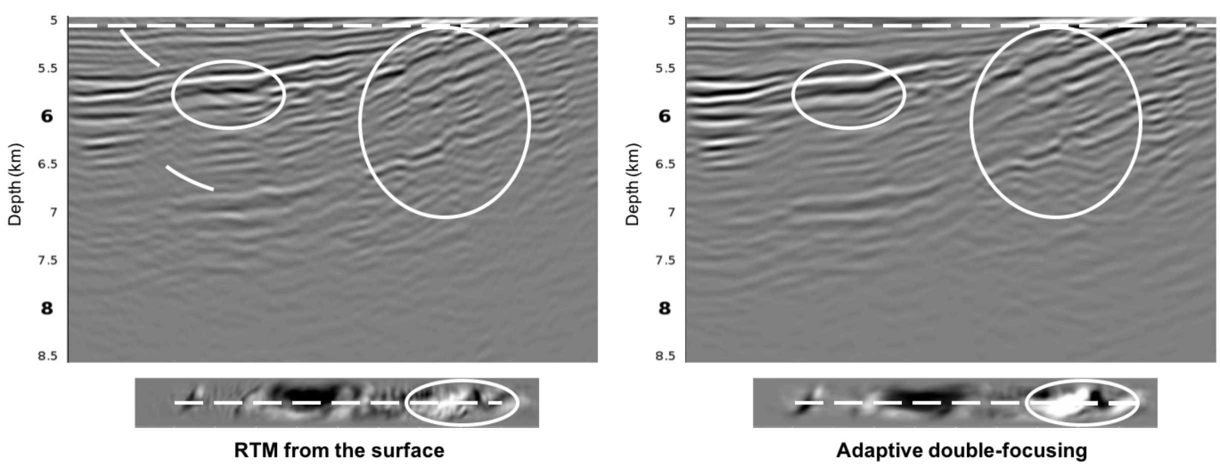

Figure 4: Images showing the result of applying the adaptive double-focusing method to 3D field data of the Santos basin.

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