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Retrieving reservoir-only reflection and transmission responses from target-enclosing extended images

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Summary

The Marchenko redatuming approach reconstructs wavefields at depth that contain not only primary reflections, but also multiply-scattered waves. While such fields in principle contain additional subsurface information, conventional imaging approaches cannot tap into the information encoded in internal multiples in a trivial manner. We discuss a new approach that uses the full information contained in Marchenko-redatumed fields, whose output are local reflection and transmission responses that fully enclose a target volume at depth, without contributions from over- or under-burden structures. To obtain the Target-Enclosing Extended Images (TEEIs) we solve a multi-dimensional deconvolution (MDD) problem that can be severely ill-posed, so we offer stable estimates to the MDD problem that rely on the physics of the Marchenko scheme. We validate our method on ocean-bottom field data from the North Sea. In our field data example, we show that the TEEIs can be used for reservoir-targeted imaging using reflection and, for the first time, local transmission responses, shown to be internal multiples retrieved by the redatuming scheme. Finally, we present local, TEEI-derived reflection and transmission images of the target volume at depth that are structurally consistent with a benchmark image from conventional migration of surface data.

Introduction

With the goal of achieving increased imaging resolution of reservoirs at depth and better quantitative reservoir characterisation, here we aim at retrieving the local reflection and transmission responses of a target volume at depth from surface seismic data, with no influence of over- or underburden geology. More importantly, we would like to achieve this using subsurface models that are no more complex than those used in conventional migration. A key enabler for our objective is the novel approach of Marchenko redatuming (Wapenaar et al., 2014; van der Neut et al., 2015; Ravasi et al., 2016): it allows us to obtain, from surface reflection data, subsurface redatumed waves that correctly handle internal multiples, while using conventional migration models. Combining this with the concepts of target-enclosing interferometry (van der Neut et al., 2013) and Reflectivity-based extended images (Vasconcelos et al., 2010; Thomson et al., 2016) we propose the new Target-Enclosing Extended Images. Here, we present this new concept, discuss how to estimate the associated fields, and support our claims with a field data example.

Target-Enclosing Extended Images (TEEIs) and Marchenko-redatumed fields

Retrieved from surface seismic data, extended images (EIs) can be thought of as local reflectivity responses of the subsurface, for pseudo-sources and receivers placed inside of the medium (Vasconcelos et al., 2010; Thomson et al., 2016). Here, we further extend this concept by defining the block system

$$\mathbf{F}_{out} = \mathbf{M}_{TE}\mathbf{F}_{in} \quad (1)$$

where the quantities involved are (Figure 1)

$$\mathbf{F}_{in} = \begin{bmatrix} \mathbf{P}^{+}_{top} & [\mathbf{P}^{-}_{top}]^{*} \\ \mathbf{P}^{-}_{bot} & [\mathbf{P}^{+}_{bot}]^{*} \end{bmatrix}, \ (2) \qquad \mathbf{F}_{out} = \begin{bmatrix} \mathbf{P}^{-}_{top} & [\mathbf{P}^{+}_{top}]^{*} \\ \mathbf{P}^{+}_{bot} & [\mathbf{P}^{-}_{bot}]^{*} \end{bmatrix} \ (3) \text{ and } \qquad \mathbf{M}_{TE} = \begin{bmatrix} \mathbf{R}^{+}_{TE} & \mathbf{T}^{-}_{TE} \\ \mathbf{T}^{+}_{TE} & \mathbf{R}^{-}_{TE} \end{bmatrix}$$

(4).

The block matrix $\mathbf{M}_{TE}$ yields the desired Target-Enclosing Extended Images (TEEIs), containing $\mathbf{R}_{TE}$ and $\mathbf{T}_{TE}$, the local Reflection and Transmission responses corresponding only to the medium enclosed by the datums (Fig. 1b), with pseudosources both on the top (denoted by $\mathbf{R}^{+}$ and $\mathbf{T}^{+}$) and bottom ($\mathbf{R}^{-}$ and $\mathbf{T}^{-}$). In equation 1, the TEEIs are properties of the enclosed medium that take the input $\mathbf{F}_{in}$ fields into the output $\mathbf{F}_{out}$: the matrix blocks $\mathbf{P}^{+}$ and $\mathbf{P}^{-}$ are, respectively, down- and up-going wavefield matrices (Vasconcelos et al., 2010; van der Neut et al., 2013) due to sources on the acquisition surface, observed either on the top or bottom datums, as indicated by the subscripts *top* and *bot* (Fig. 1a). Throughout this paper all quantities are assumed to be in the frequency domain, though we point out that the block structure of the time domain equations is the same. The * superscript denotes complex conjugation in the frequency domain.

Here, the subsurface fields in eqs. 2 and 3 are retrieved from the observed surface reflection data $\mathbf{R}_{obs}$, by means of Marchenko redatuming (van der Neut et al., 2015), which for either top or bottom datums are given by:

$$\mathbf{P}^{-} = [\Psi\mathbf{R}_{obs}\Omega_{K}]\,[\mathbf{P}^{+}_{0}]^{*}, \ (5) \text{ and } \quad \mathbf{P}^{+}_{m} = [-\Psi\mathbf{R}_{obs}{}^{*}\Theta\mathbf{R}_{obs}\Omega_{K-1}]\,[\mathbf{P}^{+}_{0}]^{*} \ (6),$$

with $\mathbf{P}^{+} = \mathbf{P}_0^{+} + \mathbf{P}_m^{+}$. The $\mathbf{P}_0^{+}$ fields are the down-going fields (e.g., at *top* or *bot*) modelled with a known subsurface model (Fig. 1), and are used to initiate the Marchenko iterative scheme. After van der Neut et al. (2015), $\mathbf{\Theta}$ and $\mathbf{\Psi}$ are model-based, spatially-varying operators that perform windowing in the time domain. $\mathbf{\Omega}_K$ is an iterative operator containing $[\mathbf{\Theta}\mathbf{R}_{obs}]^{*}\mathbf{\Theta}\mathbf{R}_{obs}$ terms up to order K, where K is the number of iterations.

Note that Marchenko redatuming retrieves the full up-going fields $\mathbf{P}^{-}$, and the update to the modelled down-going $\mathbf{P}_0^{+}$ in the form of $\mathbf{P}_m^{+}$, which contains the transmission coda due to internal multiples.

Solving for the TEEIs by expansion of the blurring operator

Once the fields in eqs. 2 and 3 are estimated by redatuming, the next step is to invert for the desired $\mathbf{M}_{TE}$. For that purpose, we express the TEEI system in equation 1 in the normal equation form:

$$\mathbf{F}^{*}_{in}\mathbf{F}^{T}_{in}\mathbf{M}^{T}_{TE} = \mathbf{F}^{*}_{in}\mathbf{F}^{T}_{out}, \ (7) \text{ which we recast as } \quad \mathbf{B}_{in}\mathbf{M}^{T}_{TE} = \mathbf{G}_{out} \ .(8)$$

Now, the TEEI system can be treated as a multidimensional blurring problem, see Fig. 2. Due to the non-diagonal structure of $\mathbf{B}_{in}$ (Fig. 2), the inverse problem of solving for $\mathbf{M}_{TE}$ is highly ill-posed.

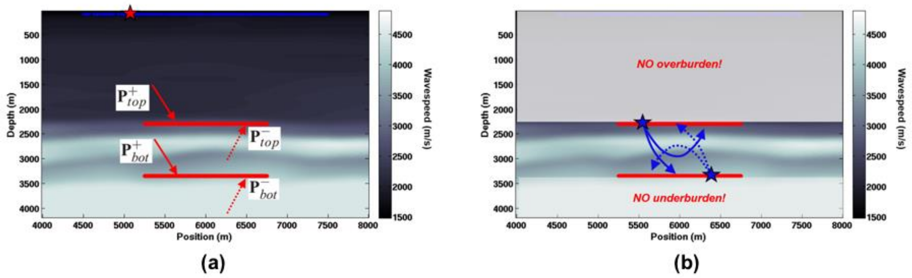

Figure 1 *The geometry of the TEEI concept: (a) shows the two chosen datums at depth (red lines) at which the up and down-going fields are retrieved, by means of redatuming, from the observed surface reflection data (indicated by the red source for a source location and blue triangles for the receivers). Panel (b) illustrates the responses retrieved in the TEEIs, i.e., two-sided reflection and transmission responses corresponding only to the medium enclosed by the two datums. The subsurface model shown here is the P-wave wavespeed model from the Volve field data used in this study.*

Thus, as an alternative to conventional regularisation approaches, here we offer a series-based solution to estimating the TEEI. To obtain this solution we first decompose $\mathbf{F}_{in}$ as the superposition of

$$\mathbf{F}_{in,0} = \begin{bmatrix} \mathbf{P}^{+}_{top,0} & \mathbf{0} \\ \mathbf{0} & [\mathbf{P}^{+}_{bot,0}]^{*} \end{bmatrix} \quad (9) \quad \text{and} \quad \mathbf{F}_{in,m} = \begin{bmatrix} \mathbf{P}^{+}_{top,m} & [\mathbf{P}^{-}_{top}]^{*} \\ \mathbf{P}^{-}_{bot} & [\mathbf{P}^{+}_{bot,m}]^{*} \end{bmatrix}. \quad (10)$$

This then implies a decomposition of the blurring operator, as

$$\mathbf{B}_{in} = \mathbf{B}_{in,0} + \mathbf{B}_{in,m}, \ (11) \text{ with } \mathbf{B}_{in,0} = \mathbf{F}^{*}_{in,0}\mathbf{F}^{T}_{in,0} \ (12) \text{ and } \mathbf{B}_{in,m} = \mathbf{F}^{*}_{in,m}\mathbf{F}^{T}_{in,0} + \mathbf{F}^{*}_{in}\mathbf{F}^{T}_{in,m}. \ (13)$$

If the power of the modelled down-going fields in $\mathbf{F}_{in,0}$ is significantly greater than that of the Marchenko-based fields in $\mathbf{F}_{in,m}$, an assumption already made by our redatuming scheme, then we obtain

$$\left[\mathbf{M}^{(N)}_{TE}\right]^{T} = \mathbf{B}^{\ddagger}_{in,0}\left[\mathbf{F}^{*}_{in,0}\mathbf{F}^{T}_{out}\right] + \sum_{n=1}^{N}\left(-\mathbf{B}^{\ddagger}_{in,0}\mathbf{B}_{in,m}\right)^{n}\mathbf{B}^{\ddagger}_{in,0}\left[\mathbf{F}^{*}_{in,0}\mathbf{F}^{T}_{out}\right] + \sum_{n=0}^{N}\left(-\mathbf{B}^{\ddagger}_{in,0}\mathbf{B}_{in,m}\right)^{n}\mathbf{B}^{\ddagger}_{in,0}\left[\mathbf{F}^{*}_{in,m}\mathbf{F}^{T}_{out}\right], \quad (14)$$

as an estimate for the TEEI response. Here, $\mathbf{B}^{\ddagger}_{in,0}$ denotes a pseudo-inverse of $\mathbf{B}_{in,0}$, and it is the only explicit matrix inverse required by this estimate of the TEEI. This is key for the numerical stability of our estimate, because, from equation 9, we see that $\mathbf{B}_{in,0}$ is inherently block diagonal and thus its numerical inverse is substantially more stable than that of the full $\mathbf{B}_{in}$. As such, an $\mathbf{M}_{TE}$ obtained with equation 14 is a stable estimate of the TEEI that relies on the same physical assumptions as those invoked by the Marchenko iterative scheme. We support this with field data below.

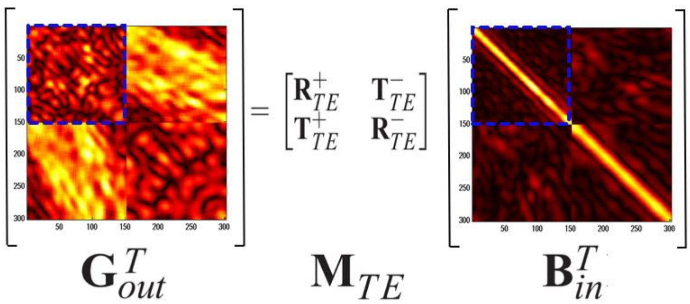

Figure 2 *Illustration of the full TEEI system in the form of normal equations, where the input* $\boldsymbol{G}_{out}$ *is the desired* $\boldsymbol{M}_{TE}$ *blurred by the operator* $\boldsymbol{B}_{in}$*. Here the coloured maps show the absolute values of the corresponding frequency-domain matrices from the field data example, for the datums as shown in* ***Fig 1****, at 40 Hz.*

North Sea field data example

In this paper, we use the same 2D OBC data set from the Volve field, North Sea, as do Ravasi et al. (2016). For details on the data pre-processing, and more importantly for a discussion on the results of Marchenko redatuming using those data, we refer the reader to Ravasi et al. (2016): here we rely on the results of that study as the input data to retrieve the TEEI responses. Da Costa Filho et al. (2017) present alternative Marchenko-based imaging approaches using these same data. In Figure 1, we show both the depth and lateral extent of the chosen depth datums (red lines). In Figure 3, we show selected pseudosource gathers from the TEEI responses $\mathbf{R}^+_{\mathbf{TE}}$ and $\mathbf{T}^+_{\mathrm{TE}}$, that are representative of the quality of the overall TEEI estimates. The gathers in Figs. 3a and 3b display considerably fewer artefacts and overall higher signal-to-noise ratio than those in Figs. 3c and 3d: thus supporting our claim that our blurringbased expansion provides a noticeably more stable estimate of $\mathbf{M}_{\mathbf{TE}}$ than does a conventional Tikhonov Least-Squares (TLS) approach. More importantly, we successfully retrieve not only local reflection responses from the TEEI (Fig. 3a) but also a coherent, physically plausible transmission response of the target volume (Fig. 3b) which includes internal transmitted multiples. Here, both over- and underburden geology effects are suppressed, so the fields correspond only to the medium in the target volume. In Figure 4, we provide images from 151 pseudo-sources and receivers extracted from the TEEI responses, corresponding to the target area between the chosen datums (Fig. 1). We provide a windowed RTM image of the surface data input to redatuming and TEEI inversion as a benchmark to the imaging results: comparing it to the image from TEEI reflection (Fig. 4b), we see that the images are structurally consistent, with elative amplitude differences, and shifts in deeper reflectors in the TEEI image. The image from the transmission TEEI data (Fig. 4c) is also structurally consistent with the benchmark RTM: this validates that the transmission coda retrieved in the TEEIs contains geologically meaningful subsurface information. Figure 3 Field-data time-domain TEEI responses, after inversion, corresponding to a fixed pseudosource placed at the centre of the top datum in Figure 1. The responses in (a) and (c) are reflection responses (i.e., for receivers on the top datum), and the responses in (b) and (d) are retrieved transmission responses (i.e., for receivers on the bottom datum). The gathers in (a) and (b) are the result of the blurring-based expansion of the TEEI solution, whereas (c) and (d) are their Tikhonov Least-Squares (TLS) counterparts.

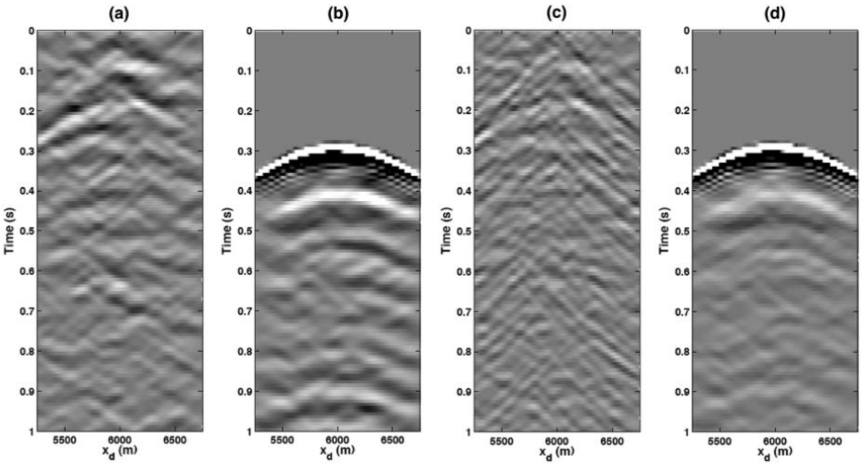

Figure 3 *Field-data time-domain TEEI responses, after inversion, corresponding to a fixed pseudosource placed at the centre of the top datum in* ***Figure 1****. The responses in (a) and (c) are reflection responses (i.e., for receivers on the top datum), and the responses in (b) and (d) are retrieved transmission responses (i.e., for receivers on the bottom datum). The gathers in (a) and (b) are the result of the blurring-based expansion of the TEEI solution, whereas (c) and (d) are their Tikhonov Least-Squares (TLS) counterparts.*

Conclusions

In this paper, we present a new definition for the so-called Target-Enclosing Extended Images (TEEIs): these are local, two-sided, Reflection and Transmission responses corresponding only to the subsurface properties within a target volume defined by two chosen depth datums. In practice, this is only achievable with a redatuming scheme that accounts not only for primaries but also internal multiples: here we rely on the method of Marchenko redatuming. We present a stable estimate for the TEEIs based on a physical expansion of the system's blurring operator: whose increased stability we support with a field data example. With these field data, we show that we retrieve geologically consistent TEEI reflection data, and, for the first time, make local transmission images of a target volume from surface reflection data.

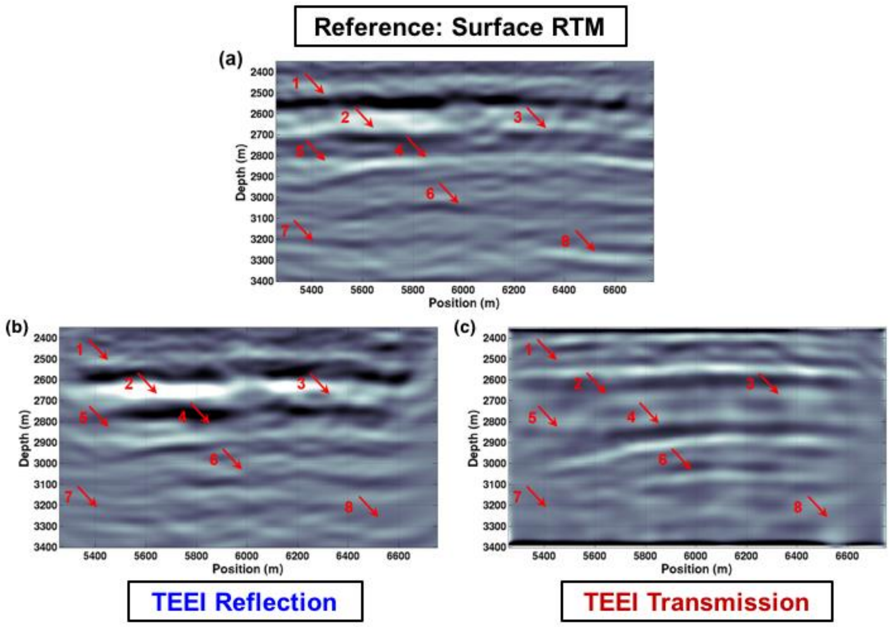

Figure 4 *Imaging of the structure within the target volume between the two chosen datums (**Figure 1**) from (a) conventional RTM of the surface reflection data, (b) local migration of the TEEI Reflection responses and (c) local imaging of the TEEI Transmission responses. The red arrows provide reference points for comparison between the images.*

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