Target-oriented Marchenko imaging of a North Sea field

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SUMMARY
Seismic imaging provides much of our information about the Earth’s crustal structure. The principal source of imaging errors derives from simplicistically modeled predictions of the complex, scattered wavefields that interact with each subsurface point to be imaged. A new method of wavefield extrapolation based on inverse scattering theory produces accurate estimates of these subsurface scattered wavefields, while still using relatively little information about the Earth’s properties. We use it for the first time to create real target-oriented seismic images of a North Sea field. We synthesize underside illumination from surface reflection data, and use it to reveal subsurface features that are not present in an image from conventional migration of surface data. To reconstruct underside reflections, we rely on the so-called downgoing focusing function, whose coda consists entirely of transmission-born multiple scattering. As such, we provide the first field data example of reconstructing underside reflections with contributions from transmitted multiples, without the need to first locate or image any reflectors in order to reconstruct multiple scattering effects.

Key words: Inverse theory; Interferometry; Body waves; Computational seismology; Wave propagation.

1 INTRODUCTION
Imaging the geometry and properties of complex subsurface geology, identifying and characterizing subsurface reservoirs of hydrocarbons, minerals or water, as well as monitoring of waste products stored underground such as CO2 and nuclear waste, all require sophisticated seismic imaging and monitoring techniques. A crucial step for such imaging methods is the estimation of wavefields within the solid Earth’s interior where no direct observations are available. Standard estimation or ‘redatuming’ approaches based on time-reversal of data recorded along an open boundary of surface receivers (Berryhill 1984) fail to explain how energy propagates in the complex subsurface unless high-resolution seismic velocity models are available prior to imaging, as otherwise they cannot accurately predict multiply scattered waves (multiples) in the subsurface. This causes large errors in images and, crucially, in interpretation.

Marchenko redatuming (or autofocusing) is a novel technique to estimate acoustic wavefields within the subsurface including primary and multiple reflections, using seismic waves measured at the Earth’s surface and only a smooth estimate of the propagation velocity model (Rose 2002; Broggini et al. 2012; Wapenaar et al. 2013). Advantages over standard redatuming methods are that the multiply scattered wavefield coda is estimated at each subsurface image point, spurious arrivals due to multiples in the overburden are attenuated and the retrieved wavefields are naturally separated into their up- and downgoing components. The acoustic (fluid) Marchenko theory was extended to elastic (solid) media by da Costa et al. (2014), and by Wapenaar (2014), and by the elastic imaging of da Costa et al. (2015).

Standard migration techniques generate spurious structures in images as they do not correctly account for internal reflections. By contrast, Marchenko wavefields account for all multiples and Brog gini et al. (2014) and Slob et al. (2014) construct images free from internal multiple artefacts by cross-correlating (or deconvolving) the retrieved up- and downgoing fields at any subsurface image point. Wapenaar et al. (2014) limit the computation of Marchenko fields to a single depth level, then use multidimensional deconvolution (Wapenaar et al. 2011) to create redatumed reflection responses from and to that depth, which are free of spurious events related to internal multiples in the overburden. These responses can be used for imaging target areas of the subsurface below or above the depth level of interest. Such images can be more accurate than
those generated by standard reverse-time redatting followed by
cross-correlation of the subsurface responses (Dong et al. 2009) as
overburden multiples are removed.

This paper presents the first successful application of target-
oriented imaging using Marchenko redatting on real-field data.
We apply the method to reflection seismic data recorded by an
ocean-bottom cable (OBC) over the Volve oilfield, offshore Norway
in 2002. One of the main obstacles to the application of such novel
techniques to field data sets is the set of requirements for the reflection
data (explained below). We show that a wave-equation method to
redatting marine sources to the seabed, sea surface multiple re-
moval and seismic source designature, transforms ocean-bottom
data into a suitable estimate of the reflection response required
by the Marchenko scheme. We then produce images of target ar-
Eas of shallow and deep subsurface structures using Marchenko
wavefields, and compare these to images obtained from standard
reverse-time migration (RTM) of the same surface data.

2 MARCHENKO EQUATIONS

Marchenko redatting is based on two wave states which uniquely
relate subsurface wavefields from surfaces sources to so-called
focusing functions via the recorded seismic data (Wapenaar et al.
2014). The subsurface wavefields ($g^-$ and $g^+$) belong to the wave
state of the physical world in which data are acquired, while the
focusing functions ($f^-$ and $f^+$) are defined in a modified medium
that is homogeneous below a chosen subsurface level. These are
related by (van der Neut et al. 2014)

$$
g^- = Rf^+ - f^-
g^+ = -R^{+}f^- + f^+ \tag{1}
$$

Here $g^-$ and $g^+$ are matrices containing the time–space domain
up- and downgoing Green’s functions, with multiple sources at the
acquisition surface and receivers located at a desired subsurface
point. The focusing functions $f^-$ and $f^+$ are, respectively, up- and
downgoing acausal solutions to the wave equation that focus at zero-
time at the same subsurface point, and then down as downgoing
diverging fields into the homogeneous lower half-space. We suppose
that $f^- = f^0 + f_m^-$, that is, $f^-$ is composed of a direct wave
$f_0^-$ followed by a coda $f_m^-$; these quantities are also organized
in matrices with concatenated traces in the space–time domain.

The operator $R$ contains the real Earth’s reflection response from
vertical dipole sources to pressure receivers, and left multiplication
is equivalent to performing multidimensional convolution in the
space–time domain, while $*$ acts on a matrix by time reversing its
traces.

To obtain a system of coupled Marchenko equations, a muting
function $\Theta$ that removes the direct arrival and all subsequent events
is defined. Assuming that the muting function satisfies $\Theta g^- = 0,
\Theta g^+ = 0, \Theta f^- = f_0^-$ and $\Theta f^+ = f^-$ (Wapenaar et al. 2014), its
application to eq. (1) yields

$$
f^- = \Theta R f_0^+ + \Theta R f_m^- \tag{2}
$$

Starting from an initial focusing function $f_0^+$, obtained by inverting
(or time-reversing) an estimate of the direct wave $G_0$ from the
subsurface point to the surface and assuming a null coda ($f_m^- = 0$),
eq(2) can be iterated to convergence. As noted by van der Neut
et al. (2015) and Vasconcelos et al. (2015), the solution of the focusing
functions at iteration $K$ can be written in a compact form by
means of a Neumann series expansion:

$$
f^{-(K)} = \sum_{k=0}^{K} (\Theta R^+ \Theta R)^k f_0^+ 
$$

$$
f^{+(K)} = \Theta R \sum_{k=0}^{K} (\Theta R^+ \Theta R)^k f_m^- . \tag{3}
$$

where each term in the series represents an update to the focusing
function. Finally, up- and downgoing Green’s function can be
computed from eq. (1) using the estimated focusing functions $f^-$
and $f^+$.

3 MARCHENKO INPUTS AND
REDATUMED FIELDS

Marchenko redatting requires certain characteristics of the re-

fection response. $\mathbf{R}$ should be obtained from large aperture, fixed
receiver arrays with dense source coverage coinciding with the en-
tire receiver array, have broad bandwidth, and contain only pri-
mary reflections and internal multiples (i.e. be deprived of direct
waves, ghosts and surface-related multiples). Recorded reflection
response data therefore approximate $\mathbf{R}$ only after pre-processing.

If data are acquired with standard ocean-bottom acquisition sys-
tems, wave equation approaches to joint source redatting (to the
receiver level), demultiple and source designature (Amundsen 2001)
can transform recorded data into a suitable estimate of reflection re-

sponse $\mathbf{R}$. These methods solve the following integral relation by

means of multidimensional deconvolution (Wapenaar et al. 2011)

$$
\mathbf{p}^- = \mathbf{R} \mathbf{p}^+ \tag{4}
$$

where the recorded upgoing decomposed data ($\mathbf{p}^-$) is seen as the
result of multidimensional convolution of the downgoing data ($\mathbf{p}^+$)
and the desired reflection response ($\mathbf{R}$) that would be recorded in
a hypothetical seismic experiment with no sea surface present.
The decomposed data $\mathbf{p}^-$ and $\mathbf{p}^+$ are arranged in matrices contain-

ing responses from multiple sources to receivers at the acquisition
surface. The sought reflection response $\mathbf{R}$ is also a matrix with re-

sponses from vertical dipole virtual sources to pressure receivers at
the acquisition surface. Each frequency is inverted separately and the

time–space response $\mathbf{R}$ is obtained by combining solutions of each
inversion via an inverse Fourier transform.

For this study, we use data from an OBC on the seabed above
the Volve field located in the gas/condensate-rich Sleipner area of
the North Sea, offshore Norway. The receiver line contains 235 re-

ceivers spaced 25 m apart, and an overlying shot line of 241 sources
spaced 50 m apart (Fig. 1(a)). Noise suppression, vector-fidelity
corrections and initial source designature are applied to the data.
Further, we scale the data by $\sqrt{\lambda T}$ to account for 3-D geometrical
spreading and we calibrate the direct arrival of the particle veloc-

ty by the Marchenko scheme. We then produce images of target ar-

Eas of shallow and deep subsurface structures using Marchenko

wavefields, and compare these to images obtained from standard

reverse-time migration (RTM) of the same surface data.
amplitude for all offsets (Fig. 3a). Focusing functions \( f^+ \) and \( f^- \) estimated after two iterations of the Marchenko equations \((K = 2)\) in eq. 3 are shown in Figs 3(b) and (c) and are used in eq. (1) to compute Green’s functions \( g^+ \) and \( g^- \) (Figs 3d and e). Note that the iterative Marchenko scheme has retrieved the coda in the downgoing field: a wave with similar moveout to the direct arrival is visible at zero-offset around 1.5 s in Fig. 3(d), which may have experienced multiple bounces in the high velocity layer in between 2.6 and 2.85 km depth.

A concern about the application of Marchenko redatuming to a field data is whether the iterative scheme presented above converges. Since we do not have direct access to the real Earth’s reflection response \( \hat{R} \), it is inevitable that the processed version of the recorded data \( \hat{R} \) will be scaled, such that \( \hat{R} = c_g \hat{R} \). Here, \( c_g \) is at best an unknown scalar (or, more likely, a compact filter varying in time and space) that depends on the acquisition and processing chain. In this application, we have taken advantage of the observation that \( \| (\Theta \hat{R} \Theta^T) f_d \| \rightarrow 0 \) as \( k \rightarrow \infty \) needs to hold for the Neumann series in eq. (3) to converge (see Supporting Material). While meeting this condition does not guarantee that each update has the correct amplitude and may not allow complete cancellation of spurious arrivals in the upgoing field, we show here that after two iterations of the Marchenko scheme this method produces a coda in the downgoing focusing function (Fig. 3b) and Green’s function (Fig. 3d) with non-negligible amplitudes.

An accurate deconvolution of the source wavelet from the data is required for a correct summation of various updates of the Neumann series. In fact, each iteration of the Marchenko scheme involves one convolution and one correlation with reflection response \( \hat{R} \) to obtain \( f^+ \), and a further convolution to construct \( f^- \) (eq. 3); an unbalanced frequency response may enhance some frequencies relative to others, rendering the focusing function updates from different iterations incompatible. In this study, we mitigate the effect of the source signature from the data using the wave-equation demultiple approach of Amundsen (2001). While it is not possible to directly verify that the source wavelet has been fully deconvolved from the reflection data \( \hat{R} \), we note that the original upgoing data show a much higher energy content at low frequencies (see insert in Fig. 1b) while the reflection response obtained from multidimensional deconvolution has a better equalized amplitude spectrum (see insert in Fig. 1d). However, since other factors such as frequency-dependent attenuation, imperfect deghosting, or noise affect the quality of the updates, an adaptive scheme may further improve the robustness of Marchenko redatuming (van der Neut et al. 2014).

4 MARCHENKO IMAGING

Marchenko redatuming produced up- and downgoing Green’s functions for 151 subsurface points forming a 1.5 km wide array ranging from 6.7 to 8.2 km horizontally, at a depth of 2.5 km (lower

Figure 1. (a) Migration velocity model, source array at depth \( z_S = 6 \) m (red line) and receiver array at \( z_R = 90 \) m (white line) in the ocean-bottom cable acquisition. A grey dot represents the subsurface point where Marchenko fields shown in Fig. 3 are computed using eqs (1) and (3), while two white boxes indicate the target areas where Marchenko imaging is performed. Single common-shot gather of the (b) upgoing pressure data \( p^+ \), (c) downgoing pressure data \( p^- \) and (d) estimate of the reflection response \( \hat{R} \). Inserts in (b) and (d) show the average amplitude spectra of the gathers.

Figure 2. Subsurface image obtained by applying standard RTM to the estimate of the ideal reflection response \( (\hat{R}) \) shown in Fig. 1(d).
target box in Fig. 1a). From these fields we obtain an estimate of the reflection response from above the target ($R_\cup$) as if both sources and receiver were located along the array of subsurface points, within a modified medium with the same properties as the physical medium below the array but which is homogeneous above. We do so by solving the following equation by means of multidimensional deconvolution (Wapenaar et al. 2014):

$$g^- = g^+ R_\cup.$$

The estimate of $R_\cup$ for a source in the centre of the subsurface array is shown in Fig. 4a. As discussed in Wapenaar et al. (2014), the redatumed reflection response can be used as input for standard imaging in a target zone just below the redatumed level (Fig. 4c). Comparison with standard RTM of our estimate of $R_\cup$ shows that Marchenko imaging from above is able to produce an image comparable to that from RTM (Fig. 4e), perhaps improving details between the main reflectors at 2.6 and 2.9 km, and limiting the required (expensive) finite-difference computation for RTM to a smaller subsurface target zone.

The focusing functions $f^-$ and $f^+$ can also be combined to obtain a second estimate of the reflection response which illuminates the target area from below ($R_\cap$) (Wapenaar et al. 2014):

$$-f^- = f^+ R_\cap.$$

The estimate of $R_\cap$, shown in Fig. 4b for a source in the centre of the subsurface array at a depth of 3.3 km, is used to image the target zone just above the lower redatumed level (Fig. 4d) producing a similar image to panel c. Reflections $R_\cap$ illuminating this portion of the subsurface from below contain complementary information to $R_\cup$, at least when the lateral extension of the arrays of subsurface points used for imaging from above and below is the same. It is however important to note that the reflection $R_\cap$ does not contain information from the portion of the subsurface below the focusing level: this is because $R_\cap$ originates from focusing functions in a

![Figure 3. Marchenko redatuming. (a) Forward-modeled first arriving wave. (b) Down- and (c) upgoing focusing functions and (d) down- and (e) upgoing redatumed fields at $x_F$. All panels are displayed with 50 per cent clipping of absolute amplitudes.](image)

![Figure 4. Marchenko imaging. Multidimensional deconvolution estimates of (a) reflection response from above $R_\cup$ at depth level $z = 2.5$ km and (b) reflection response from below $R_\cap$ at depth level $z = 3.3$ km. Images of the target zone from (c) above and (d) below, compared to that obtained from (e) standard RTM of the reflection response $R$. (f), (g) and (h) are same as (b), (d) and (e) for a shallower depth level ($z = 1.13$ km).](image)
medium that is homogeneous below the focusing level (Wapenaar et al. 2014).

Similarly, Marchenko fields were computed along a line at 1.13 km depth (upper box in Fig. 1a) to image the complex stratigraphy in the shallow subsurface from below (Figs 4f and g). Spatial aliasing occurs in the standard RTM image (Fig. 4h) as this was originally sampled every 10 m to save on computational cost. The Marchenko image may be sampled relatively cheaply every 5 m due to the limited area of finite-difference modeling required, and compares favourably to that from RTM.

Marchenko imaging from below is performed for two additional subsurface lines with interreceiver spacing of 10 m: the first ranges from 5.4 to 6.9 km horizontally at depth 3.4 km, while the second is at 3.41 km depth and extends from 4.1 to 5.6 km horizontally. The resulting images are located either side of that in Fig. 4(d), and all three are merged to form Fig. 5(b). Note that since each of the reflection responses \( R \) is obtained using multidimensional deconvolution, the aperture of the subsurface array should not exceed that of sources at the acquisition surface for a successful inversion of eq. (6). Additionally, sparse (rather than dense) subsurface points will result in spatial aliasing, making the inversion unstable. With the choice of the extension and sampling of the subsurface array being limited by these constraints, it is important to assure that images obtained independently from different subsurface responses \( R \), at different depth levels show consistent structures. Green arrows in Fig. 5(b) indicate near-perfect continuity of reflectors between the various images, thus showing that we may design short-aperture, finely sampled subsurface arrays that prevent spatial aliasing in subsequent imaging. Finally, Marchenko imaging from below reveals structural features (blue arrows in Fig. 5b), which are not present in our surface RTM image of the reflection response \( R \) (Fig. 5a). While our interpretation of these events is that of physical structures that are perhaps hidden under coherent noise in the RTM image, they could also represent artificial structure arising from a suboptimal choice of the scaling \( c_R \) that overpredicts spurious events in the upgoing field (see Supporting Material).

5 CONCLUSIONS

The novel technique of Marchenko redatuming applied to an ocean-bottom seismic data acquired over the Volve North Sea field, produces encouraging results of target-oriented imaging of both shallow and deep structures. Although a by-product of the information contained in the original data, Marchenko focusing functions contain sufficient information to directly image the subsurface using reconstructed underside reflections. Such images reveal coherent features beneath strongly reflecting interfaces, which are distorted or invisible when imaging directly with surface data. This coherence supports the observation that the information in the retrieved focusing functions recasts that in the original data in a manner which is both nontrivial and useful. As such, we envisage that other practices that require wavefield focusing such as microseismic source localization, seismic time-lapse monitoring and non-destructive testing may also benefit from estimates of focusing functions from Marchenko redatuming.

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REFERENCES


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper.

Figure S1. (a) Energy of \((\Theta\tilde{R}^\ast\Theta\tilde{R})^j_\alpha f^j_\alpha\) (in logarithmic scale) versus number of iterations. (b) Energy of \(g + g^\ast\) within the region where the window \(\Theta\) equals one (in logarithmic scale) versus number of iterations. (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggv528/-/DC1).

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