

Robust estimation of primaries by sparse inversion and Marchenko equation-based workflow for multiple suppression in the case of a shallow water layer and a complex overburden: A 2D case study in the Arabian Gulf

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ABSTRACT

Suppression of surface-related and internal multiples is an outstanding challenge in seismic data processing. The former is particularly difficult in shallow water, whereas the latter is problematic for targets buried under complex, highly scattering overburdens. We have developed a two-step, amplitude- and phase-preserving, inversion-based workflow that addresses these problems. We apply robust estimation of primaries by sparse inversion (R-EPSI) to solve simultaneously for the surface-related primaries Green's function and the source wavelet. A significant advantage of the inversion approach of the R-EPSI method is that it does not rely on an adaptive subtraction step that typically limits other demultiple methods such as surface-related multiple elimination. The resulting Green's function is used as the input to a

Marchenko equation-based approach to predict the complex interference pattern of all overburden-generated internal multiples at once. In this approach, no a priori information about the subsurface is needed. In theory, the interbed multiples can be predicted with correct amplitude and phase and, again, no adaptive filters are required. We illustrate this workflow by applying it on an Arabian Gulf field data example. It is crucial that all preprocessing steps are performed in an amplitude-preserving way to restrict any impact on the accuracy of the multiple prediction. In practice, some minor inaccuracies in the processing flow may end up as prediction errors for which corrections will be needed. Hence, we conclude that the use of conservative adaptive filters were necessary to obtain the best results after interbed multiple removal. The obtained results indicate promising suppression of surface-related and interbed multiples.

INTRODUCTION

Marine seismic processing and imaging can be very challenging in settings with shallow water and a complex overburden. Typically in these settings, many orders of strong surface-related and internal multiples interfere with the primary reflections in the target area. This interference results in an image that may no longer be suitable for structural or quantitative interpretation. This is a well-recognized issue in various areas around the world, e.g., in Norway (Rønholt et al., 2014), the West Central Graben of the North Sea

(Yanez et al., 2018), or offshore Middle East (Belonosov et al., 2019). The multiples problem in the latter area is particularly challenging due to a strongly scattering overburden (El-Emam et al., 2011, 2015). Addressing this issue in a fit-for-purpose and practically achievable demultiple workflow poses important technical and practical challenges.

Geophysicists discriminate between surface-related and internal multiples based on the location of sources and receivers relative to the multiple generator (an interface creating downward reflections) as well as on the amount of a priori assumed or available informa-

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tion. Surface-related multiples have a known generator — a stationary and flat water-air interface at $z = 0$ with a reflectivity of about $r_0 = -1$, with some deviations in rough sea conditions (Kryvohuz and Campman, 2019). Internal multiples are generated by any reflector in the subsurface, with unknown position and reflectivity.

These differences make the two kinds of multiples, depending on the geologic setting, very different in terms of their strength, character, and removal in subsequent processing. Surface-related multiples tend to be much stronger (*the first-order demultiple problem*). However, internal multiples, though always individually weaker, are more numerous. Collectively, they often result in a complex, hazy, and, on occasion, strong interference pattern, rather than individual, easy-to-discriminate events. In contrast, individual internal multiples tend to stand out more when two dominant reflectors (e.g., the water bottom or a salt body interface) are present in the subsurface. A wide range of potential purpose- or area-specific demultiple approaches exist. One that is commonly applied to both internal and surface-related multiples is a two-step approach of (1) prediction and (2) in the absence of a good wavelet estimate (a source and a receiver response), adaptive subtraction. However, the latter step in that approach does not offer any guarantees of successful multiple attenuation (Verschuur, 2013) and should be applied with great care.

Many approaches exist aimed at tackling surface-related multiples. Moveout discrimination between high velocity primaries and lower velocity surface-related multiples is still used frequently, although this approach is only applicable in simple-enough geologic settings. These techniques result in many artifacts and damage to the primary reflections, and they fail in shallow water where the water column does not result in a sufficient moveout difference between surface-related multiples and surface-related primaries (primary reflections and internal multiples). Predictive deconvolution approaches, with their many intrinsic assumptions about the medium, have been proposed and tested in a shallow water setting (Biersteker, 2001). Unfortunately, they may be unsuitable in combination with more advanced internal demultiple schemes because they tend to artificially whiten (or otherwise alter) the surface-related primaries' output amplitude spectrum.

More sophisticated approaches aim to predict the multiples using either model-based methods (Lokshtanov, 1999; Jahdhami et al., 2017) that require a priori knowledge of the subsurface or data-driven methods such as surface-related multiple elimination (SRME) (Verschuur et al., 1992). Both of these rely on some implementation of adaptive subtraction, and they may also impact primary reflections and hence result in images that may not be suitable for amplitude variation with offset analysis. An improved multiple model can be obtained if a good source wavelet estimate is available. This estimate can be obtained explicitly by modeling airgun arrays, by reading it off a simple and well-consolidated water bottom reflection, or by simultaneously solving for it (van Groenestijn and Verschuur, 2009a; Savelis et al., 2011). Unfortunately, these approaches no longer work in the shallow-water environment (Hargreaves, 2006; Hung et al., 2010; Barnes et al., 2014) due to the interference (and thus inseparability) of primaries and the first (few) order(s) of (short-period) surface-related multiples, and missing near-offset data.

In general, internal multiple removal tends to be more challenging and, to this day, there have only been a few approaches with limited applicability. The use of moveout discrimination between primary reflections and internal multiples is impossible in practice due to relatively small timing differences. Predictive deconvolution

or filtering approaches (Lesnikov and Owusu, 2011) can fail in sufficiently complex settings (Brookes, 2011; Griffiths et al., 2011) because the periodicity that they assume is not necessarily physical. Applications of poststack dip filtering tend to affect anticlines and low-relief structures (Retailleau et al., 2014) for flat, strongly scattering overburdens. Model-based (Lokshtanov, 1999; Jahdhami et al., 2017) or data-driven (e.g., Weglein et al., 1997; Jakubowicz, 1998) wave-equation-based methods predict kinematically accurate individual events. However, they rely on an understanding of the interbed generation mechanisms or on the separability of individual primary reflections (internal multiple generators). Failure to do so results not just in amplitude but more importantly in phase prediction errors. Layer stripping can be used to account for more generation mechanisms; however, this approach tends to be more computationally expensive (even in 2.5D media), and it can result in amplitude damage to deeper primaries resulting in a downward-cascading, and likely cumulative, prediction-and-subtraction error. Ways of partially mitigating this problem have been suggested by Ypma and Verschuur (2013).

Recently, two new demultiple technologies have been proposed that aim to address many of the aforementioned issues. First, Lin and Herrmann (2013) propose robust estimation of primaries by sparse inversion (R-EPSI), which simultaneously solves for the source wavelet and the surface-related primaries' Green's function. This approach had been tested on field data (Czyczula-Rudjord et al., 2015), and it was deemed well-suited for shallow water (Belonosov and van Borselen, 2017). Second, recently proposed Marchenko equation-based approaches (henceforth referred to as the *Marchenko methods*) could be seen as a form of internal demultiple, in which the entire overburden is treated as a single collective internal multiple generator (Slob et al., 2014; Wapenaar et al., 2014; van der Neut and Wapenaar, 2016). The Marchenko methods, by solving an underconstrained inverse problem, produce an inverse transmission response of the overburden. The latter are then (indirectly) used in an Amundsen et al. (2001)-like multidimensional deconvolution (MDD) to remove the effect of overburden-borne reverberations on the target primary reflections. Thus far, the Marchenko equation-based approach had been tested in settings in which source signature estimation was not a limiting factor (Pereira et al., 2018, 2019; Staring et al., 2018). Alternatively, given multicomponent data, Ravasi et al. (2016) suggest deconvolving the up- and downgoing wavefields, which results in data free from (1) surface-related multiples and (2) the source signature.

Both demultiple problems could, in principle, be handled by merging SRME- and Marchenko-type methods. This requires some modifications to the Marchenko equation (Ware and Aki, 1969; Singh et al., 2016). Unfortunately, these approaches are not likely to work very well in practice because not only do they struggle converging in the presence of strong multiples (Dukalski and de Vos, 2017), but, more importantly, they still need a good wavelet estimate on input. To address this point, Ravasi (2017) proposes an alternative approach that merges Amundsen et al. (2001)-like MDD with the Marchenko equations. However, this approach requires up- and down-going field measurement and relative hydrophone and geophone amplitude calibration. In addition, in a shallow-water setting, this scheme might be more difficult to implement due to the limited (or saturated) dynamic range of the receivers by the direct (downgoing) wave. Having exhausted the list of available possibilities, perhaps the combined R-EPSI and Marchenko equation-based approaches could work together in theory and, more importantly, *in practice*.

This work is structured as follows. The “Theory” section briefly discusses a Marchenko equation-based method and studies its strengths and limitations. For more detail, readers can refer to existing literature on the topic. We propose a practical shortcut to predict (and later adaptively subtract) internal multiples and avoid the post-Marchenko equation MDD step. Then, we explain why the R-EPSI output could be a very good fit to be the input to the Marchenko equation. We then show how the proposed workflow can be applied to field data from the Arabian Gulf. Finally, we discuss the results and some open questions.

THEORY

In a traditional processing workflow, surface-related multiples are treated first (to our knowledge, the only notable exceptions are deepwater settings with subsalt targets) and dominant internal multiples are typically handled afterward. This sequence is also often assumed by most internal demultiple schemes, the Marchenko method being no exception. At the cost of stringent input data quality (i.e., the output of the surface-related demultiple), the Marchenko method can simultaneously handle internal multiples due to the entire overburden. To better understand this process, we take an antichronological approach and first explain the internal demultiple before we show how the surface-related demultiple of our choice fits the Marchenko method.

Marchenko equation-based multiple elimination

The method proposed by [van der Neut and Wapenaar \(2016\)](#) removes the internal multiples generated by the overburden from the surface reflection data. By staying at the surface, this method is independent of background velocity information and helps in gaining a better understanding of the imprint of internal multiples as compared to Marchenko redatuming ([Wapenaar et al., 2014](#)). Moreover, much like [Jakubowicz internal multiple elimination \(IME\)](#), it only uses convolutions, correlations, and temporal windowing of the reflection data. We propose to combine the method of [van der Neut and Wapenaar \(2016\)](#) with the double-focusing approach proposed by [Staring et al. \(2018\)](#). Moreover, we suggest a viable quality control (QC) step to increase confidence in the data preprocessing.

The reflection data R_0 contain the target reflection response R_{tar} past a specified source- and receiver-dependent onset time $t_2(x_r, x_s)$. Due to the overlying overburden, the latter response is not only covered by overburden-only multiple reflections, but it is also dressed with overburden-borne internal-multiple-coda reverberations, which we denote with $(v^+)^{-1}$. [Van der Neut and Wapenaar \(2016\)](#) and [Elison et al. \(2020\)](#) show that v^+ , a Marchenko focusing function f_1^+ that is “propagated” or “projected” to the surface, is a solution to the (here, already reduced) coupled set of Marchenko equations:

$$\Theta_\epsilon^{t_2}[v^+] - \Theta_\epsilon^{t_2}[R_0^* \Theta_\epsilon^{t_2}[R_0 v^+]] = 0. \quad (1)$$

Above, we use a detail hiding notation, in which “multiplications” denote the Rayleigh integrals ([Berkhout, 1982](#); [van der Neut et al., 2015](#)). Moreover, $\Theta_\epsilon^{t_2}$ is a source- and receiver-dependent mute that preserves the signal inside the $[e, t_2(x_r, x_s)]$ time window, i.e., after a small time interval e (discussed later) and before t_2 , i.e., the onset of target primaries from R_{tar} . Given $v_\epsilon^+ = v^+ - \Theta_\epsilon^{t_2}[v^+]$, equation 1 is easily solved using the nested series

$$v^+ = \sum_{k=0}^{\infty} \Omega_k[v_\epsilon^+], \quad (2)$$

where $\Omega_k[A] = \Theta_\epsilon^{t_2}[R_0^* \Theta_\epsilon^{t_2}[R_0 \Omega_{k-1}[A]]]$, $\Omega_0[A] = A$, and, *in theory*, the first term in the series v_ϵ^+ is given by an identity (in practice convolved with a user-defined wavelet — see the discussion on practical limitations below).

The aforementioned authors then proceed to derive auxiliary fields U^\pm , where U^- is a reflection response — one without overburden-only multiples and source-side reverberations. The MDD inversion of $U^- = R_{\text{tar}} U^+$ recovers a target-only reflection response (as if the overburden was transparent). [Van der Neut and Wapenaar \(2016\)](#) calculate a low-order series expansion to obtain R_{tar} . However, [Elison et al. \(2020\)](#) show that in the presence of more complex internal multiple scattering, more terms need to be computed in equation 2 and hence in U^\pm . Note that, in general, each term provides amplitude and phase corrections instead of predictions of individual events or their specific order. Individual terms may correspond to predictions of individual events in cases in which multiple scattering is dominated by only a few reflectors. In such a case, only the leading order terms will be the most relevant and then one could attempt to adaptively subtract them.

Here, we propose an approach combining the strongest points of the methods by [van der Neut and Wapenaar \(2016\)](#) with insights from the double-focusing method by [Staring et al. \(2018\)](#). We propose a method called “double dereverberation,” which evaluates

$$v^{+T} U^- = v^{+T} \Theta_{t_2}^\infty[R_0 v^+], \quad (3)$$

where left multiplication with v^{+T} (the source-receiver swapped version of v^+) amounts to removing receiver-side reverberations, such that the result contains the target reflection response R_{tar} and the later-arriving internal multiples generated by scattering between the overburden and the target. We can also isolate the multiples predicted by this scheme via

$$v^{+T} \Theta_{t_2}^\infty[R_0 v^+] - \Theta_{t_2}^\infty[R_0], \quad (4)$$

which we later adaptively subtract, bearing in mind that the term on the right (left) needs to be convolved (deconvolved) with the user-defined wavelet used inside the Marchenko equation solver (equation 2). We wish to note that collecting the $k \leq 1$ terms in equation 2, plugging them into equation 3, and ignoring terms higher than third order in R_0 , yields two terms, where one conforms with the term suggested by [van der Neut and Wapenaar \(2016\)](#).

There are two major, somewhat hidden, assumptions in the scheme presented above, which are very likely to be violated by real complex finely layered overburdens. First, equation 1 (and hence its solution equation 2) only holds if the time pick t_2 does not cut into either a target or an overburden primary. In the event that this assumption is not satisfied, the magnitude of the resultant artifact is expected to be proportional to the magnitude of the cut-into primary event and will be spread over the entire multiple prediction rather than localized. Second, the (infinitesimal in theory) ϵ parameter delineating the boundary between the initial guess v_ϵ^+ and the rest of the v^+ solution needs to be set to about half-wavelet length when the scheme is applied to band-limited data. This means that in the presence of short-period internal multiples (SPIMs — those generated by reflectors spaced by less than the dominant wave-

length anywhere in the overburden), the estimate v_e^+ also needs to contain part of the solution responsible for attenuating them (Slob et al., 2014). Although the scheme is somewhat robust to these challenges (Elison et al., 2020) and currently no suggestions have been proposed to address the first problem, the SPIM challenge can be mitigated in cases in which the overburden is sufficiently flat (Dukalski et al., 2019; Elison et al., 2020), but this will not be considered here. Finally, our Marchenko method is acoustic and its extensions to include elastodynamic effects are even more sensitive to the aforementioned effects (Reinicke et al., 2019). Even though we may express the extent of the expected artifacts qualitatively and quantitatively (Reinicke et al., 2020a), they still require further development and further tests on sufficiently complex synthetics.

Marchenko equation-based methods are made up of the same fundamental building blocks as many other demultiple methods; however, the inverse-problem-type approach involving the summation of many terms (see equations 1–3) requires a specific reflection data format for the equation to hold. Ravasi et al. (2016) show that a reflection response R_0 satisfying the Marchenko equation requirements can be extracted from multicomponent up- P^\uparrow and down- P^\downarrow separated measurements by inverting the MDD relation $P^\uparrow = RP^\downarrow$. In other words, the data have to be defined on a grid of colocated sources and receivers (with some spacing Δx) at the same depth level. In addition, the data need to be wavelet-free, dipole-source, monopole-receiver, and multiplied by $2\Delta x$ for equation 1 to be satisfied. In the absence of reliable multicomponent data that had been accurately up- and down-decomposed, this can be challenging. Therefore, the main challenge is finding the correct wavelet. Its shape can be well-approximated by modeling or by any of the methods mentioned in the introduction; however, getting the correct scale tends to be much harder. However, we know that the series (equation 2) is unconditionally convergent (Dukalski and de Vos, 2017), thus accidentally overscaling the data might result in a divergent behavior (runaway solutions). This helps impose an upper, but not a lower, limit on a typically unknown scaling. As first suggested by Elison et al. (2020), in the presence of additional information (e.g., regional geology or well-log information), one can

build a (well-log-based) 1D synthetic, determine the expected convergence rate, and compare it to one obtained using field data to approximately verify whether the data were appropriately scaled. However, this only helps to determine a single (for the whole data set) frequency-independent scalar. In the next section, we show how the reflection response obtained on output from R-EPSI fits the above requirements. In the “Case study in the Arabian Gulf” section, we show how this works in practice and compare the Marchenko equation convergence curve against that obtained from a synthetic showing a good match.

Basics of R-EPSI

R-EPSI estimates a surface-related primaries’ Green’s function directly from the data, without any additional knowledge of the subsurface properties. In a very shallow-water setting, the method produces a high-fidelity result and outperforms common practice approaches (Belonosov et al., 2019). Hence, its output is a good candidate for input to the aforementioned Marchenko approach. In this section, we briefly outline the R-EPSI method.

The method assumes a grid of seismic dipole sources colocated with monopole receivers at the sea surface, a water surface reflection coefficient of -1 , and a source signature that is the same for all sources. Then, a monochromatic component of the upgoing data R_{-1} (the subscript denotes the reflection coefficient at the free surface) can be explained by (Berkhout, 1982)

$$R_{-1} = R_0 S - R_0 R_{-1}, \quad (5)$$

where R_0 is the unknown surface-related primaries’ Green’s function, i.e., the input for the Marchenko method, whereas S is the unknown effective source wavelet. The first term on the right side, $R_0 S$, represents the primaries and internal multiples, and the second term represents the surface-related multiples.

R-EPSI solves equation 5 in the time domain to find R_0 and S given R_{-1} . This problem is unconstrained, and to tackle this issue R-EPSI imposes conditions on the unknowns. Sparsity is often used as an assumption in geophysical field data applications (van Groenestijn and Verschuur, 2009b) and, as a good approximation of this assumption for the Green’s function, the candidates for R_0 are restricted to solutions with an L_1 -norm time-domain minimum. The source wavelet is estimated as a function that has a limited temporal support, i.e., the length of the wavelet.

To solve equation 5, R-EPSI applies an automatic iterative process with only one input parameter that is the level of noise in the data. For the details of this iterative process, we refer to Lin and Herrmann (2013). As mentioned, R-EPSI produces highly accurate surface-related primaries in a very shallow water situation in which conventional methods such as SRME, based on prediction plus subtraction, may fail (Hung et al., 2010). As a disadvantage, R-EPSI is much more computationally expensive. For each iteration, the method takes the computational runtime of several SRME processes (i.e., several convolutions). The output Green’s function R_0 is used directly as input for the Marchenko equation-based approach, explained in the previous section.

CASE STUDY IN THE ARABIAN GULF

Data from the Arabian Gulf provide an excellent illustration of the challenges stemming from a shallow water environment com-

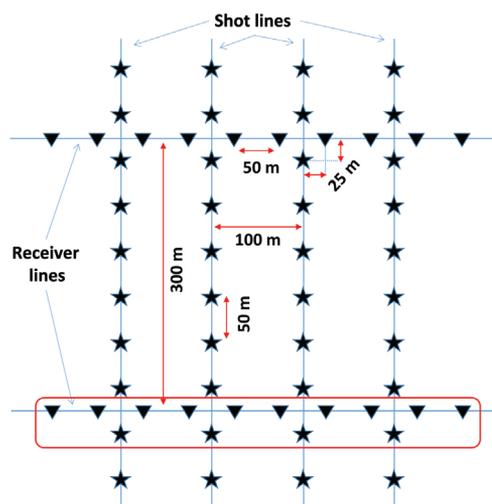


Figure 1. OBC acquisition geometry for the Arabian Gulf data. Receivers (triangles) are located at the sea bottom, whereas sources (stars) reside just below the water surface. The red box indicates the 2D line selected from this 3D survey.

bin with a complex overburden. The water bottom itself shows little variation in depth and contrast (Alá'i et al., 2002). The subsurface consists of a fairly strong sea-bottom reflector at depths between 25 and 35 m followed by a thick package of thinly layered deposits of anhydrites, carbonates, and various clastic sediments and subsequent high impedance contrasts (El-Emam et al., 2011), with just minor undulations across larger distances. Hence, the velocities vary primarily vertically.

Acquisition of towed marine streamer data is difficult in shallow water, and the associated large gap in the near offsets would have presented an additional challenge for our demultiple workflow. However, in the area, a 3D wide-azimuth ocean bottom cable (OBC) data set had been acquired with minimum inline and crossline offsets of only 25 m. Extracting a single 2D line of shots and inline receivers makes an ideal data set for this test case. Further details of the acquisition geometry are provided in Figure 1 in which the red box indicates the extracted 2D line. A raw split-spread shot gather with the ground roll typical for the survey area and various kinds of other noise is shown in Figure 2a (gained and clipped for display). Despite the noise, the effects of shallow-water depth and thin layering are already evident in the multitude of similar reflection events in the background. Related images of shot gathers will be shown for some key points of the processing workflow. Later, some reverse time migration (RTM) images will be shown.

Figure 3 shows a workflow of the processing steps performed in this section. Preprocessing stage 1 started with a standard debubble. The data were converted from three dimensions to two dimensions by applying a \sqrt{t} gain, followed by the application of water-column-related static corrections. High-amplitude (linear) noise and mud roll were filtered out in the frequency domain. The data were decomposed in up- and down-going wavefields by a data-driven method similar to that described by Soubaras (1996). The upgoing pressure wavefield is selected for further processing to make this workflow also suitable for streamer data (in theory). An example of the resulting upgoing pressure wavefield is shown in Figure 2b. The noise introduced above the first break and the effects of one or more dead channels, as indicated by the arrow, need to be addressed. Nevertheless, the overall quality and continuity of the reflection events has improved. Source ghosts were left in the data to mimic the effect of dipole sources required by R-EPSI and Marchenko, which is reasonable given a source depth of 7 m and mild weather conditions. However, the initial 100 m shot and 50 m receiver spacing along the line did not fulfill their requirements. Hence, the data were regularized and interpolated to a 25 m grid and fixed spread of 239 colocated sources and receivers, thereby removing any acquisition-

related gaps (see Figure 2c), and muted. This step further reduces random noise. During the full preprocessing sequence, particular attention was given to each step to ensure that the amplitude and phase fidelity were maintained.

Stage 2 starts by applying a band-pass filter (2–6–38–42 Hz) to avoid aliasing-related effects during subsequent processing. The data are now suitable as input for surface-related multiple suppression with R-EPSI. Before its application, and to suppress the artifacts related to the limited aperture available, we also applied cosine-squared tapers for 15 traces at each edge. We tested this taper width and chose the smallest value for which the artifacts became negligible. We used 80 ms as the wavelet length. This estimate is

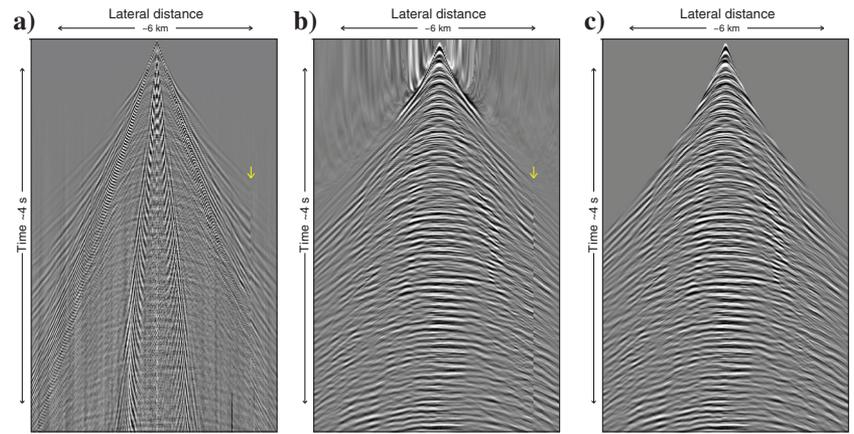


Figure 2. Shot gather of (a) raw hydrophone data (with a $t^{1.5}$ gain), (b) upgoing pressure wavefield, and (c) result after regularization of the wavefield in (b). The yellow arrows point to an acquisition gap that was resolved by regularization.

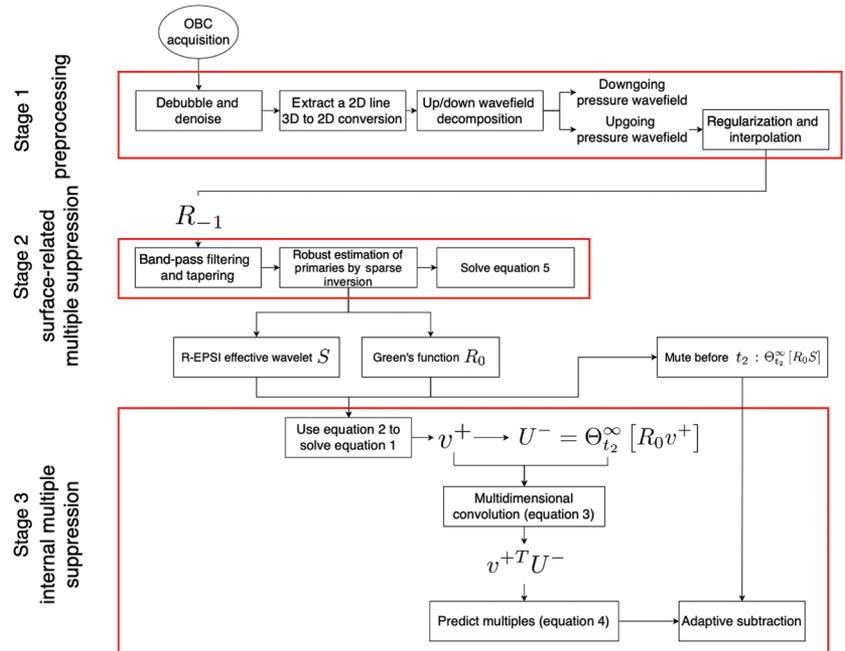


Figure 3. Workflow showing the different stages involved in the processing of our data set. Stage 1 deals with preprocessing, stage 2 performs surface-related multiple suppression, and stage 3 uses the proposed Marchenko method for internal multiple suppression.

based on the interpretation of the first arrivals in the data as well as a basic dominant frequency analysis. In all of our tests, R-EPSI was insensitive to small deviations in the range of approximately 20 ms to this parameter. As for the noise level in the data, we tried different values starting from 20% and smaller. We noticed that the residual did not change below a noise level of 15%. Hence, we set this parameter to this value. The method converged after approximately 250 iterations of the spectral projected gradient for L1 minimization (SPGL1) solver (van den Berg and Friedlander, 2008, 2019), i.e., mostly updates of the Green's function because the wavelet was updated only 30 times.

The effect of the method on the field data is illustrated in Figures 4, 5, and 6. The shot gather in Figure 4a shows the difficulty of identifying primaries when there is heavy contamination by shallow-water reverberations, which are of comparable strength. The result of R-EPSI in Figure 4b is much improved in that respect. The surface-related multiples are generated by the shallow water bottom, and they are thus present mostly in the near offsets before spreading out as the difference panel shown in Figure 4c. The multiples also appear to be concentrated in a certain frequency band, which is clearly visible on the corresponding f - k spectra shown in Figure 5.

The RTM images in Figure 6 show that the local geology is almost horizontally layered. The result after R-EPSI, Figure 6b,

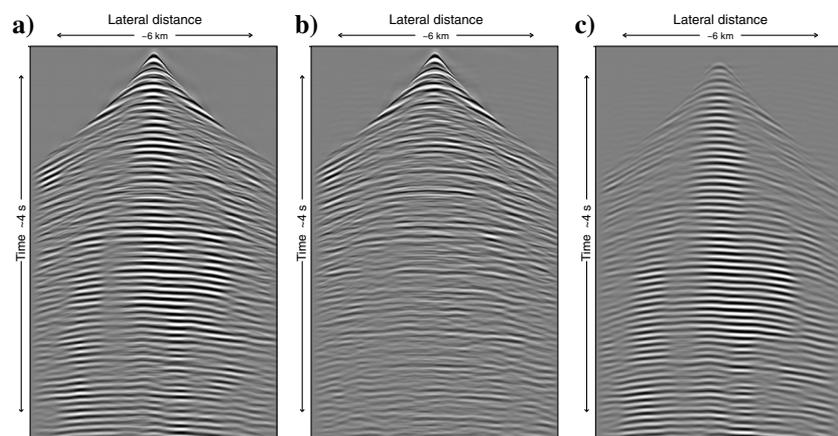


Figure 4. Fixed-spread common-shot gather (a) before R-EPSI, (b) after R-EPSI (i.e., R_0), and (c) their difference.

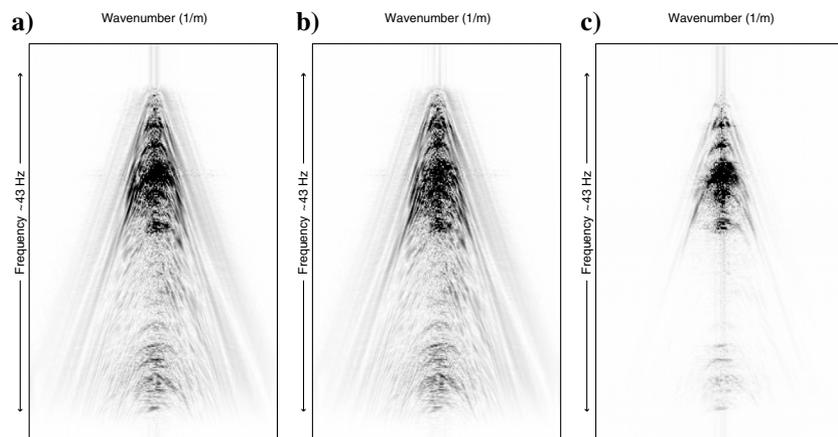


Figure 5. The f - k spectra for each gather in Figure 4 (a) before R-EPSI, (b) after R-EPSI, and (c) their difference.

reveals likely primary reflection events that stand out at later times. The upper shallow part appears to show a package of many thin layers. Finally, note that in Arabian Gulf-like synthetics with a water layer depth of 25 m (the water depth varied between 25 and 35 m in the field data), the R-EPSI primaries are almost identical to the true primaries (Belonosov et al., 2019). This fact gives us great confidence in the R-EPSI result obtained.

Following the above preprocessing and correction steps, the output of stage 2 (the R-EPSI method) satisfies the input data requirements of stage 3 (our Marchenko equation-based method): the Green's function is wavelet-free, its dipole sources and monopole receivers are collocated at the same datum, and the wavefield is properly scaled. We use the effective wavelet output by R-EPSI such that the data can be compared with the other stages of the processed workflow. Alternatively, a Ricker wavelet that fits the frequency spectrum or bandwidth of the data can be used.

We were provided with a rough estimate of the top of the target area based on knowledge of the regional geology and an initial stack. Subsequently, we identified a strong reflection event on the shot gathers, which allows us to determine the traveltimes t_2 separating the overburden and target. This event was handpicked and auto-tracked on each gather, whereby smoothing was applied to remove any remaining jumps in the traveltimes curve between shots. If a velocity model were available, then this curve could also be modeled instead of being picked. Finally, the curve was shifted up to exclude the event itself from the truncation and to avoid cross-cutting into a target primary. Figure 7b shows the effect of using the t_2 curve to mute a shot gather in the middle of our 2D line. We also define the time horizon ϵ , which is a hyperbola with an apex at half the R-EPSI wavelet length with a moveout approximately corresponding to the first event in the data.

Combining R_0 with the mutes, the series in equation 2 can be evaluated to obtain the v^+ . The value and change in the L_2 norm of the individual terms, $\|\Omega_k[v_e^+]\|_2$, are used to determine convergence. Provided that the Green's function derived by R-EPSI was scaled correctly, this value should decrease continuously. At some point, it will become negligible and the corresponding term is unlikely to still be relevant. In addition, the total required number of terms or iterations will depend on the geologic setting (Elison et al., 2020). For example, Staring et al. (2018) only use two iterations to predict internal multiples for a target area in deepwater Brazil. In contrast, 20 iterations were needed in our case as shown in Figure 8. This (perhaps slow) convergence is supported by a well-log-based synthetic test and other synthetic studies from the Middle East (Elison et al., 2020). Because the subsurface of the Arabian Gulf generates highly complex interference patterns, convergence is of the utmost importance to avoid missing important amplitude and phase updates and thus to ensure that the internal multiple predictions match the data.

Once the operator v^+ was obtained, we evaluate the right side of equation 3 to obtain the target response without source- and receiver-side overburden-borne internal multiples. Then, those multiples are isolated according to equation 4 thereby providing us with the prediction (similar to Figure 7d). Clearly, we observe a complex interference pattern, instead of a multitude of distinct events. This matches the pattern in the data very well; thus, only a very conservative or mild adaptive filter could be used to subtract the predictions from the muted reflection response $\Theta_2^\infty R_0$. The parameterization used a filter length of just five samples, windows of 100 samples by 25 traces, and L_2 minimization. Figure 7c shows the actual result after adaptive subtraction of the internal multiple predictions given this parameterization. A clear difference is visible when compared to Figure 7b. Some events that were not visible previously have emerged, and the continuity of the reflections has improved. By studying the f - k spectra in Figure 9, the effect of the subtraction of the internal multiples is also noticeable. The f - k spectrum after adaptive subtraction (Figure 9c) does look more balanced, indicating that perhaps this complex overburden generates mainly low-frequency internal multiples. Note that the internal multiple predictions seem

to be even more concentrated in a shorter range of low frequencies when compared with the surface-related multiples (Figure 9d versus Figure 5c).

Figure 10 contains the RTM images corresponding to Figure 7a, 7c, and 7d. The white boxes indicate the target, where a difference due to the removal of internal multiples generated by the overburden can be observed. Note that a difference is also seen below the area of interest. Internal multiples generated by the overburden itself are removed; however, those generated within the target or by scattering between the target and the overburden remain in the data. Figure 11a–11c shows a magnification of the target area to study some of its details. A significant reduction of internal multiple energy is visible in the yellow circles. In addition, conflicting seismic events have been resolved, leading to improved visibility of certain known horizons (the green circles). Furthermore, the images now have a better definition of faulty structures (the red circles). We studied the amplitude spectra of the RTM images before and after internal multiple removal (Figure 12). These spectra confirm that the removed interference pattern mainly had low frequencies and also some higher frequencies were attenuated (which are perhaps not easily observed in the RTM images). This observation is supported by detailed synthetic controlled experiments (Reinicke et al., 2020b).

As final remarks, we did test two different target boundaries, but the effect was rather insignificant suggesting that the separability issue is not too essential. We also tested a variety of adaptive filter parameter settings, such as window sizes and filter lengths, which had hardly any impact on the result; thus, we settled on the values considered the least invasive or mildest.

DISCUSSION

We presented a case study that introduced a two-step approach to handle surface-related and internal multiples in a shallow-water environment with a complex overburden. The R-EPSI

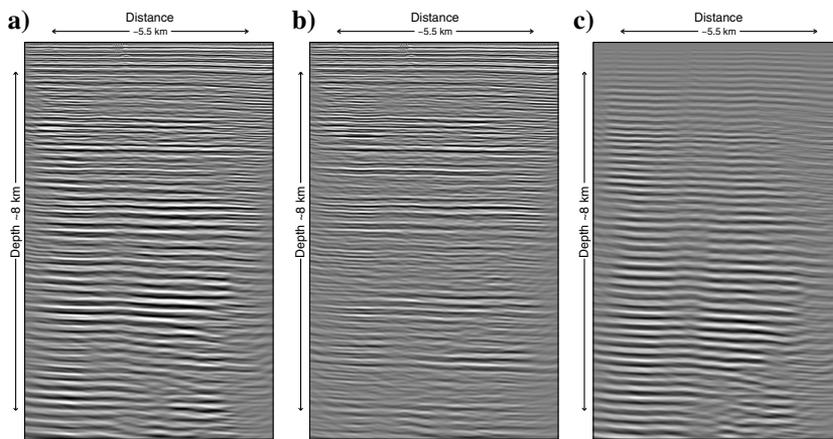


Figure 6. RTM of data (a) before R-EPSI, (b) after R-EPSI, and (c) their difference.

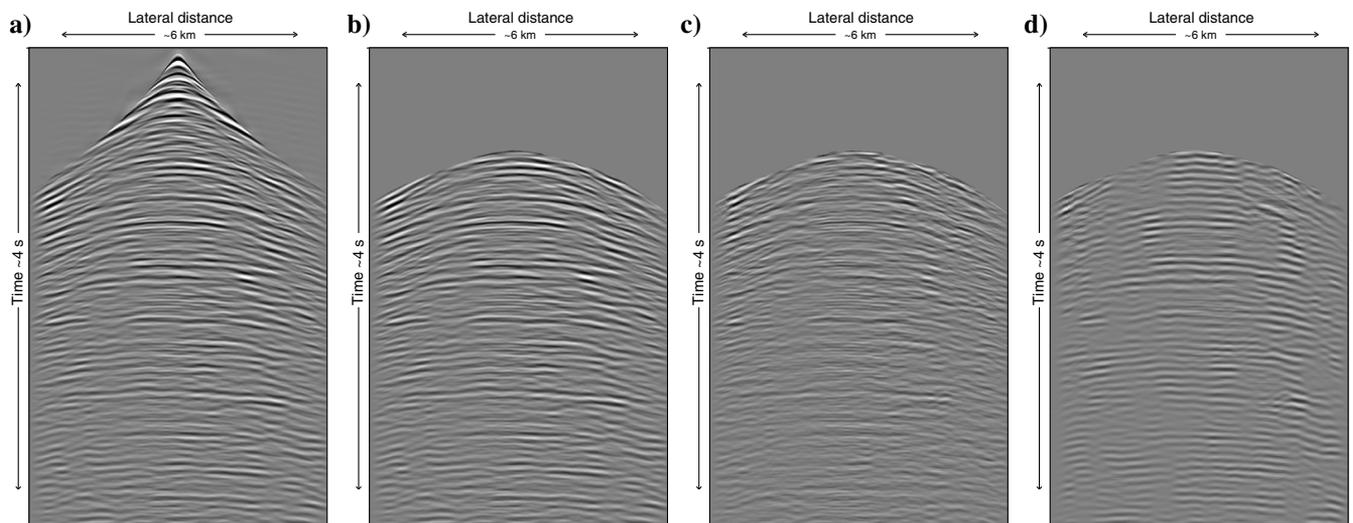


Figure 7. Shot gather of data (a) after R-EPSI (the same as Figure 4b), (b) after the t_2 mute, (c) after Marchenko, and (d) the difference between (b) and (c).

method not only offers a solution to the shallow water surface-related demultiple problem but also provides the correct Green's function R_0 required for the Marchenko IME approach.

The results presented in this paper are encouraging for the surface-related multiple and the interbed multiple attenuation.

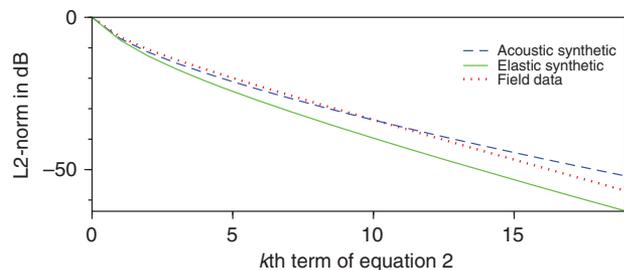


Figure 8. The L_2 norm of the individual terms in the series of equation 2. The convergence curve for the acoustic synthetic is in dashed blue, that for the elastic synthetic is in continuous green, and that for the Arabian Gulf field data is in dotted red.

However, proper QC of the results on this complex shallow-water field data example is very difficult because we did not have well logs to which to tie our results. Part of the ongoing work is to apply the proposed workflow on data on which well-log information is readily available. In parallel, additional controlled experiments are being conducted to verify if and to what level the observations that we gathered from this initial field data experiment are valid. This will help us to understand if the amount and complexity of the predicted multiple patterns are realistic, or if the observed dominant low-frequency content of the interbed multiples can be explained better. On the one hand, the amplitude- and phase-preserving characteristics of the approach are one of its main advantages. These characteristics allow the removal of the complex interference pattern of all overburden-generated internal multiples in a fully data-driven way and without (too much) dependence on any a priori information (e.g., generation mechanism identification for multiple prediction). On the other hand, they also put stringent conditions on all (pre)processing steps to maintain amplitude and phase validity. Therefore, it makes sense to revisit the processing flow used

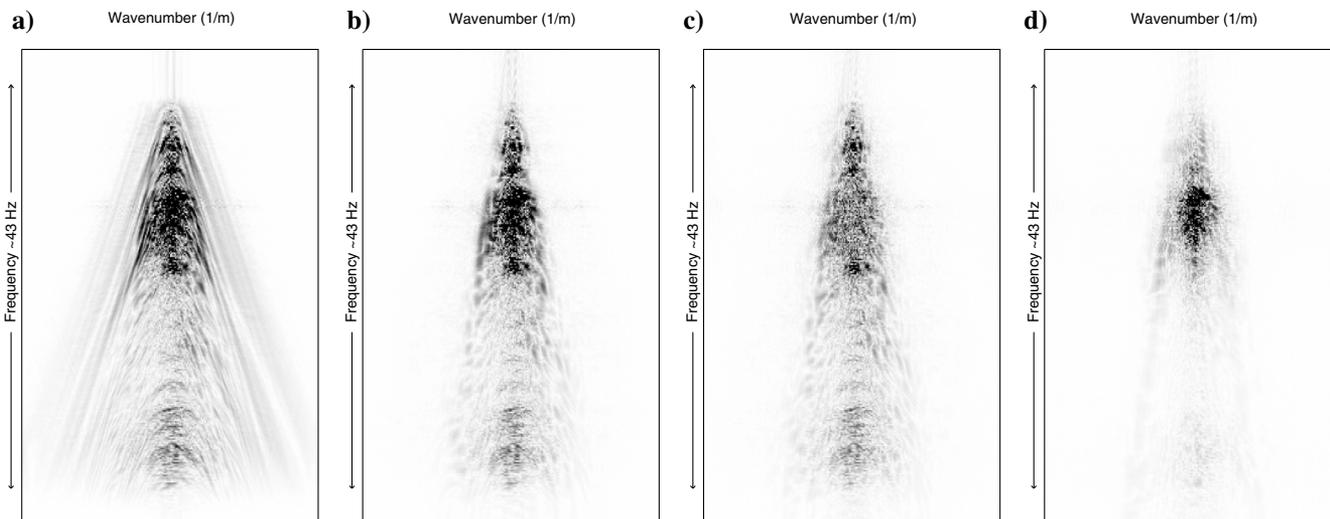
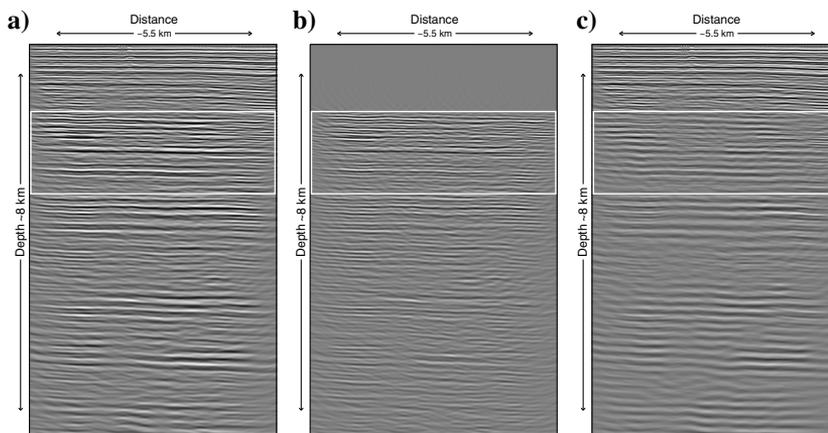


Figure 9. The f - k spectra corresponding to data shown in Figure 7 (a) after R-EPSI, (b) after the t_2 mute, (c) after Marchenko, and (d) their difference.

Figure 10. RTM of data (a) after R-EPSI (the same as Figure 6b), (b) after Marchenko, and (c) their difference. The white boxes indicate the target area.



for the 2D field data exercise and discuss where more attention might be required for future projects.

The first point of attention is the 3D-to-2D conversion, which could influence the correct amplitude balance between primaries and multiples. In future work, other approaches can be used, which are expected to predict generally more reliable amplitudes and produce exact results for horizontally layered 1.5D media (Wapenaar et al., 1992). Sensitivity tests were not part of the scope of the work, but given the convergence of the R-EPSI and Marchenko methods

and a relatively flat vertical effective velocity profile, the impact is believed to be minimal.

Another aspect that could affect the proposed amplitude- and phase-sensitive workflow is the quality of the up-down decomposition, which is not always straightforward for complex field-data situations as used in this paper. More synthetic and well-controlled field data exercises are recommended to test how sensitive this will be on the final demultiple results. In addition, instead of applying the up-down decomposition to the P and V_z data, alternative methods could be investigated. For instance, van Groenestijn and Ross (2011) discuss how the upgoing wavefield can be obtained by applying EPSI to the hydrophone-only data instead.

For this case study, a 2D subset of the data was selected. This subset was reasonably regular (not many gaps in the acquisition), had only limited crossline offsets, and was band-pass filtered to avoid any aliasing effects. All of this minimized the dependence of the interpolation/regularization on our demultiple results. Further research is needed to determine how sensitive the R-EPSI and Marchenko methods are to data regularization in case of realistic scenarios in which sparse crossline spacing, irregular sampling, larger and more data gaps, and higher frequencies will play an important role.

Finally, a few topics that were not addressed in the current paper are worth mentioning. These topics were discussed already in other papers or are being addressed in ongoing research projects. A known problem with the R-EPSI method is that the approximation of the Green's function sparsity with an L_1 -norm may lead to some scaling ambiguity between the estimated wavelet and the Green's function (Esser et al., 2015). Nevertheless, so far this problem was not encountered in other R-EPSI applications (Belonosov and van Borselen, 2017). For the purpose of this paper, we expect that the potential impact of this scaling ambiguity is limited because we saw that the Marchenko Neumann series expansion converged at a rate nearly identical to the synthetic based on the well log from the region.

The proposed Marchenko approach only attenuates internal multiples generated while passing through the overburden and ignores the overburden-target reverberations. In many cases, this will be sufficient to sweep the target area of most internal multiples thereby leading to improved interpretation. Therefore, it would be worthwhile to compare the numerical efficacy of this method on a larger section of field data using the MDD step as in van der Neut and

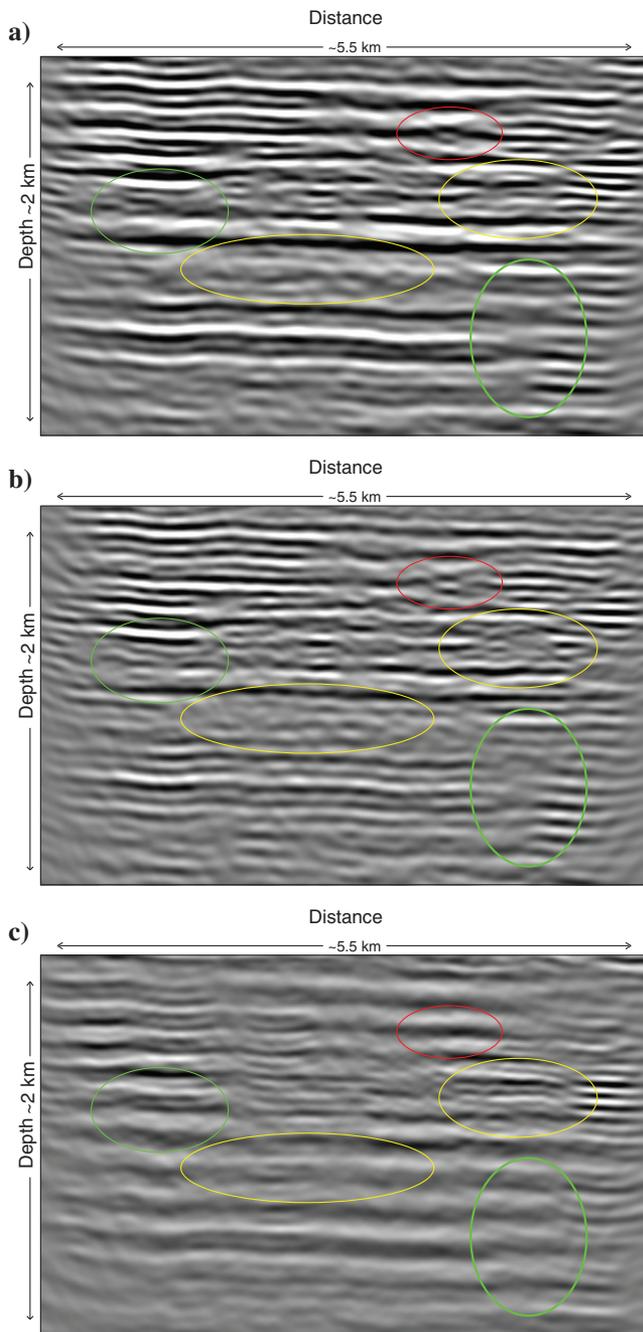


Figure 11. Magnification of RTM in Figure 10 (a) after R-EPSI, (b) after Marchenko, and (c) their difference.

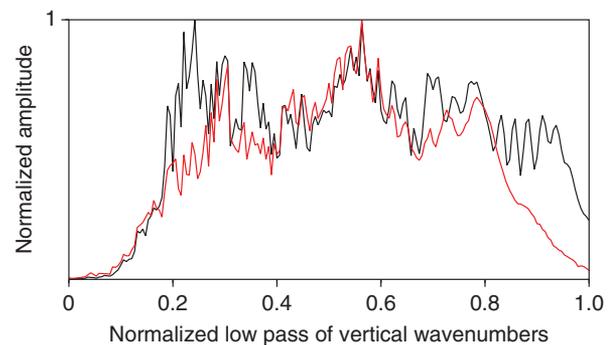


Figure 12. Spectral analysis of vertical wavenumbers for the magnified area of RTMs of data before (red) and after (black) Marchenko.

Wapenaar (2016) or by using an extended method proposed by Dukalski and de Vos (2020).

In this paper, SPIMs have not been considered nor they have been addressed by the proposed method here. Dukalski et al. (2019) and Elison et al. (2020) discuss a method to handle these short-period multiples in one dimension and for media with flat overburdens, respectively. Part of our ongoing work is on validating this method on synthetic data sets. The relatively horizontal layered character of the Arabian Gulf area makes the data example used in this paper a good candidate for testing this method also.

CONCLUSION

We demonstrated an amplitude- and phase-preserving seismic processing workflow for shallow-water environments with a complex overburden on an OBC data set acquired in the Arabian Gulf. The workflow addresses the challenge of removing surface-related multiples without using any a priori information about the subsurface when the water bottom and shallow subsurface boundaries are not represented in the recorded data due to the shallow water depth. In addition, the proposed workflow provides a solution for predicting interbed multiples at target levels that have been generated by a complex, thin-layered overburden. R-EPSI proved to be successful in simultaneously removing the surface-related multiples and predicting the source wavelet. The double dereverberation Marchenko method is subsequently applied to the resulting surface-related primaries' Green's functions to suppress the interbed multiples generated by the thin-layered overburden. The predictions contain a complex interference pattern as opposed to a set of separate events that are typically observed when dealing with interbed multiples for less-complex, and generally deeper water, environments. Given the number of closely spaced internal multiple generators in the complex overburden of the Arabian Gulf and the interference of various dominant orders of these multiples, this predicted pattern is very complex, demonstrating that this problem can only be fully addressed with truly physics-based approaches such as the double dereverberation Marchenko method.

In ongoing research, we aim to work toward a better understanding of the robustness of this method. One issue to address is the current use of, although very conservative, adaptive filters to better match the predicted interbed multiples with the data. Theoretically, no adaptive filters are required. Sensitivity studies for the individual (pre)processing steps will help us to obtain further understanding of the proposed workflow when applied to data representing challenges similar to the Arabian Gulf data used in this paper. These studies should include controlled experiments on synthetic data from realistic complex models and the use of various QC tools, such as well-log matching, to verify whether the obtained predictions on field data are accurate.

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DATA AND MATERIALS AVAILABILITY

Data associated with this research are confidential and cannot be released.

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Biographies and photographs of the authors are not available.