Integration of closed-loop surface-related multiple estimation and full wavefield migration for shallow water

Zhang, D.; Verschuur, E.

DOI
10.3997/2214-4609.201900779

Publication date
2019

Document Version
Final published version

Published in
81st EAGE Conference and Exhibition 2019

Tu_R01_03

Integration of Closed-Loop Surface-Related Multiple Estimation and Full Wavefield Migration for Shallow Water

D. Zhang[1]*, E. Verschuur[1]

[1] Delft University of Technology

Summary

Reliably estimating primary reflections in a shallow-water scenario remains a challenge. Therefore, we introduce the integration of closed-loop surface-related multiple estimation (CL-SRME) and full wavefield migration (FWM). Multiples present in the seismic data can help infill the acquisition imprint of the FWM image. With the image as constraint, we are capable of reconstructing the data at smaller offsets, which is crucial for CL-SRME. Therefore, in the proposed framework, we use the image to back-project the information from multiples to primaries with the physical constraint of all information belonging to the same earth model. We utilize a cascaded approach, which first involves reconstructing incomplete data via FWM and then uses the fully-sampled reconstructed data as the desired input for CL-SRME. Applications to both synthetic and field data demonstrate the good performance of the proposed framework in a shallow-water scenario.

Introduction

Closed-loop SRME (CL-SRME) is an inversion-based primary estimation approach, in which the primaries are directly estimated via full waveform inversion in a fully data-driven manner (Lopez and Verschuur, 2014). To maximize the performance of CL-SRME for coarsely sampled data, the focal transform (Berkhout and Verschuur, 2006) was adopted to overcome the large missing data problem, which is called focal CL-SRME (Lopez and Verschuur, 2015). In a shallow-water scenario, both undersampling and missing near-offsets data are common, while strong surface-related multiples are typically present. As a result, we cannot capture enough information for the highly-curved water bottom reflection events which, however, make significant contributions to surface multiple prediction.

Despite all the efforts, shallow water still remains challenging. Therefore, in order to allow focal CL-SRME to better handle the difficult shallow-water scenario, we need to add a stronger constraint. Currently, imposing sparseness in the focal domain is not sufficient to achieve a good-quality reconstruction for a challenging shallow-water scenario. Many depth levels are, thus, required in the focal domain and an accurate velocity model is also necessary for keeping the reflection information close to the focal point. In the limit, with a focal domain at every depth level, the focal transform becomes a least-squares imaging algorithm. To further exploit data redundancy, simultaneous migration of primaries and all multiples, the full wavefield migration (FWM) (Berkhout, 2014b), will use all available data information. Therefore, we introduce the integration of CL-SRME and FWM for shallow water. By combining the primary estimation ability of CL-SRME (Lopez and Verschuur, 2015) with the strong interpolation power of FWM (Nath and Verschuur, 2017) we achieve a better separation between primaries and multiples. Thus, in the proposed framework, we use the image to back-project the information from multiples to primaries with the physical constraint of all information belonging to the same earth model.

Closed-loop SRME

Let $\mathbf{P}$ represent the monochromatic total upgoing wavefields from all sources recorded at the surface, and primary wavefields can be denoted by $\mathbf{P}_0$. Both $\mathbf{P}_0$ and $\mathbf{P}$ are in the detail-hiding notation (Berkhout, 1982), where vectors (the columns of the matrix) represent monochromatic shot records. CL-SRME proposes to estimate primary wavefield $\mathbf{P}_0$ from the recorded data $\mathbf{P}$ in a fully data-driven manner that can avoid the adaptive subtraction. In the CL-SRME framework an objective function is minimized when the inversion parameters $\hat{\mathbf{P}}_0$ and $\hat{\mathbf{A}}$, known as the surface operator, precisely explain the input dataset $\mathbf{P}$. The objective function J, based on a Frobenious L2 norm, can be expressed as:

$$J = \sum_{\omega} \|\mathbf{P} - \hat{\mathbf{P}}_0(\mathbf{I} + \hat{\mathbf{A}}\mathbf{P})\|^2. \tag{1}$$

The updates of the inversion parameters are obtained using a descent method in a flip-flop manner, alternating the estimation of $\mathbf{P}_0$ and $\mathbf{A}$ as the algorithm progresses (Lopez and Verschuur, 2015).

FWM using surface-related multiples

Recently, FWM using surface-related multiples was proposed to better illuminate the subsurface (Davydenko and Verschuur, 2017). Instead of using only the source wavefield $\mathbf{S}^+(z_0)$ excited at the surface, the total downgoing wavefield $\mathbf{Q}^+(z_0)$ is regarded as the incident wavefield for migration:

$$\mathbf{Q}^+(z_0) = \mathbf{S}^+(z_0) + \mathbf{R}^\cap(z_0, z_0)\mathbf{P}^-_{obs}(z_0), \tag{2}$$

where $\mathbf{P}^-_{obs}(z_0)$ is the observed wavefield at the acquisition surface and $\mathbf{R}^\cap(z_0, z_0)$ represents the downward reflectivity at the surface, usually considered as $\mathbf{R}^\cap(z_0, z_0) = -\mathbf{I}$. This total downward wavefield is then forward extrapolated to every depth level, while the recorded total upgoing wavefield is inverse extrapolated to every depth level. Reflectivity is then extracted by the imaging condition, via the cross-correlation of downgoing and upgoing wavefields. In this way, the primaries and multiples are migrated simultaneously. Nevertheless, direct imaging by cross-correlation is not accurate enough, which can be improved by the inversion approach in FWM (Berkhout, 2014b). Note that using equation 2 requires a high receiver coverage and density, which is often not met in reality. Therefore, we suggest using the surface-related multiples in a non-linear way (Nath and Verschuur, 2017).

FWM as the interpolation engine

During the FWM process, we can estimate the subsurface reflectivity, which in turn is highly useful for helping us generate complete modeled data. Both the surface multiples and the internal multiples contribute to a more accurate estimation of the subsurface reflectivity.

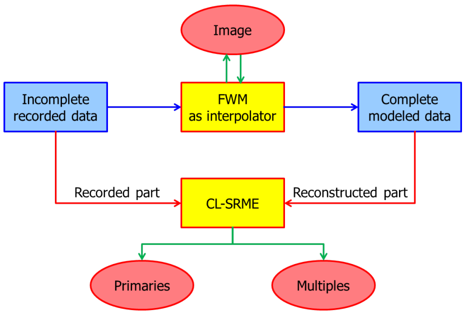


Figure 1 *The proposed integrated workflow of primary estimation for shallow water.*

Figure 1 demonstrates the workflow for our proposed framework. From the top part, we can see that the incomplete recorded data $\mathbf{P}^-_{obs}$ are considered as input for the FWM process, which functions as an interpolation operator. Note that the FWM process contains a closed-loop least-squares migration procedure and both image (or reflectivity) $\mathbf{R}$ and modeled data $\mathbf{P}^-_{mod}$ are updated in a flip-flop manner during FWM iterations. Essentially, the image $\mathbf{R}$ acts as a strong constraint for the modeled complete data $\mathbf{P}^-_{mod}$. After the whole FWM process, the output is the final modeled complete data $\mathbf{P}^-_{mod}$, which can be combined with the incomplete recorded data $\mathbf{P}^-_{obs}$ as:

$$\mathbf{P} = \mathbf{P}^-_{obs} + \mathscr{M} \circ \mathbf{P}^-_{mod}, \tag{3}$$

where $\mathscr{M}$ denotes the sampling operator that selects the traces at missing positions of the observed data and $\circ$ indicates the Hadamard product or the entry-wise product. Now $\mathbf{P}$ is our desired complete data set with missing parts reconstructed by the FWM process and is transferred to the subsequent CL-SRME process in the second part, after which the estimated primaries and multiples can be obtained.

Lens-shaped synthetic data example

Based on the scheme in Figure 1, we test our proposed framework on a 2D synthetic lens-shaped model given in Figure 2(a), which consists of a shallow water layer, a high velocity lens-shaped body and two deep target layers. The water depth is 80 m. Sources and receivers are placed covering the whole surface with the lateral interval of 20 m, and the depth interval for imaging is 10 m. For this 2D synthetic model, full wavefield numerical data are produced using full wavefield modeling (FWMod) (Berkhout, 2014a). Figure 2 also presents the modeled shot gathers as the ground truth. We can clearly see that the shallow water bottom reflection event is highly curved and relatively strong, so it is an important event for predicting the multiples via CL-SRME.

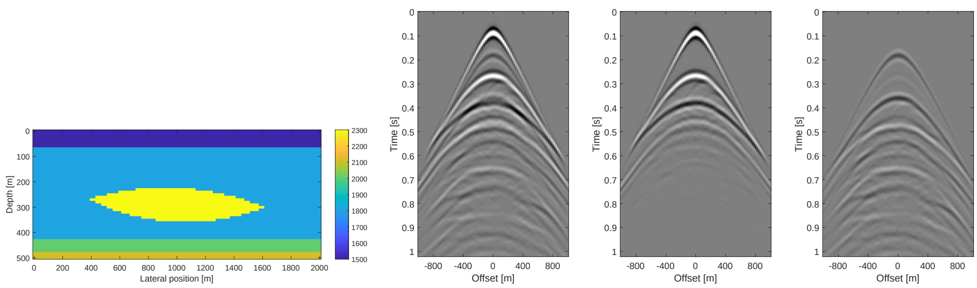


Figure 2 *(a) 2D velocity model. (b) True full wavefield. (c) True primaries. (d) True multiples.*

We consider a typical shallow-water scenario with a 200 m data gap and we compare FWM-based framework with the parabolic Radon transform (PRT) (Kabir and Verschuur, 1995). Figure 3 demonstrates the shot gather reconstruction and primary estimation comparison for the near-offsets missing data. We can clearly see the obvious amplitude difference around 0.1 s from the PRT reconstructed shot gathers in Figure 3(b) and the reconstruction error section in Figure 3(c). In contrast, the reconstruction errors for the proposed framework in Figure 3(h) are much smaller, which is also very obvious from the zero-offset trace comparison in Figure 3(f). For data reconstructed by the PRT, the primaries after CL-SRME contain multiple leakage around 0.2 s and 0.6 s shown in Figure 3(d). Also, the amplitude for the water bottom reflection is obviously mismatched. In contrast, the primaries are clean using the proposed FWM-based framework shown in Figure 3(i) with more accurate multiples in Figure 3(j).

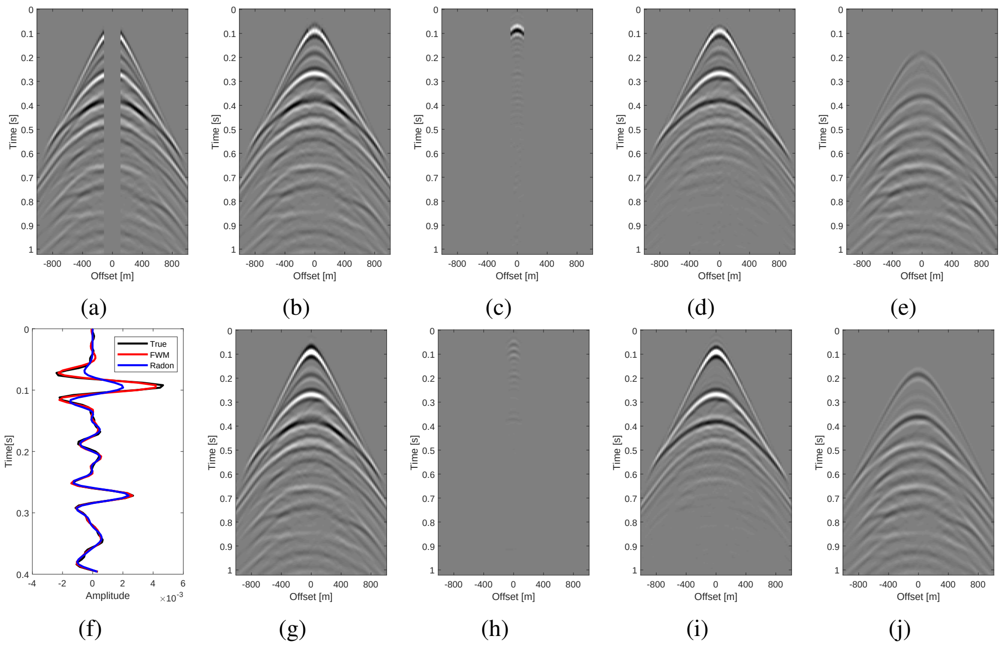


Figure 3 *(a) Decimated data. (b) & (c) Reconstructed data and errors using the parabolic Radon transform. (g) & (h) Reconstructed data and errors using FWM as the interpolation engine. (f) Zoomed zero-offset trace comparison of (b) & (g) with ground truth. (d) & (e) Estimated primaries and multiples based on (b). (i) & (j) Estimated primaries and multiples based on (g).*

Field data example

Next, we applied the proposed FWM-based framework to a North Sea data set. The data are extracted from a 2D line. By using reciprocity and regularization, a fixed spread data set is obtained with 201 sources and 201 receivers. Both source and receiver spacing are 12.5 m. In this data set, we have manually cut out the top part of near-offsets with a 200 m gap as shown in Figure 4(a).

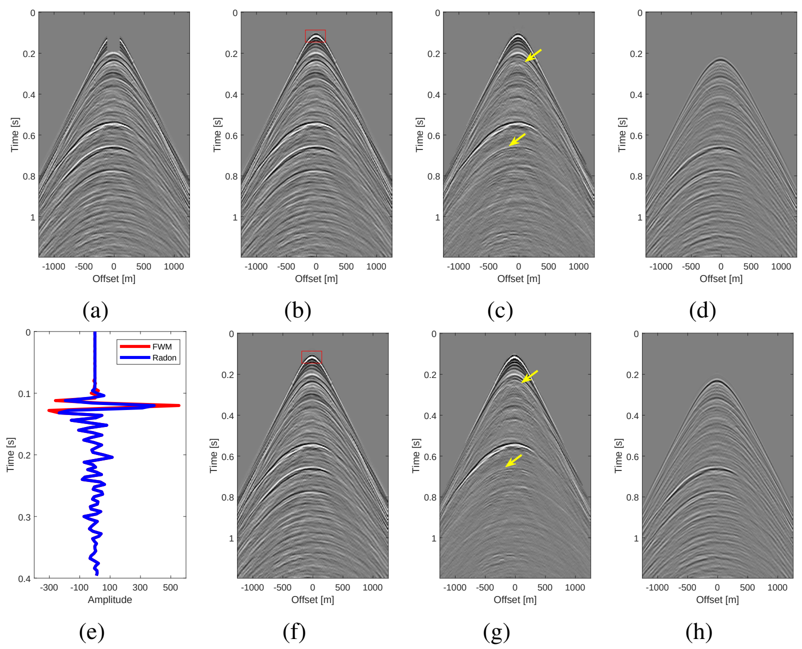
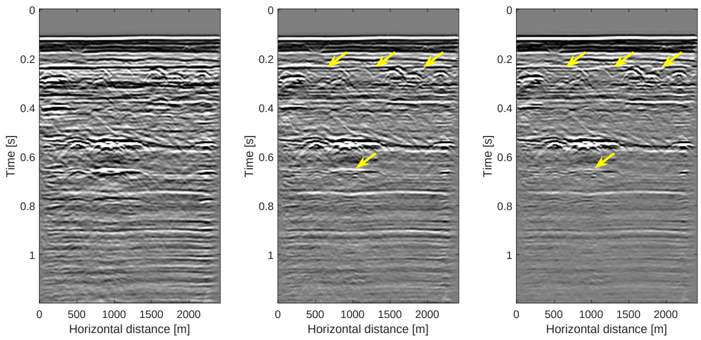


Figure 4 *(a) Decimated data. (b) & (f) Reconstructed data using the PRT and FWM, respectively. (e) Zoomed zero-offset trace comparison of (b) & (f). (c) & (d) Estimated primaries and multiples based on (b). (g) & (h) Estimated primaries and multiples based on (f).*

Figures 4(b) and 4(f) show the reconstructed data using PRT and FWM, respectively. Note that for the very critical shallow part of the data, we only utilize the FWM reconstructed water bottom reflection indicated by the red box in Figure 4(f), while the rest is taken from PRT reconstructed data. Figure 4(e) also demonstrates this issue by displaying the zero-offset trace comparison between Figures 4(b) and 4(f). It is clear that the only difference is the water bottom reflection, in which the FWM reconstructed data (red line) have much higher amplitude than the conventional PRT reconstructed data (blue line). This amplitude difference corresponds to the result from the synthetic data example. Figures 4(c) and 4(d) show the estimated primaries and multiples using CL-SRME based on the PRT reconstructed water bottom reflection, while Figures 4(g) and 4(h) present the estimated primaries and multiples using CL-SRME based on the FWM reconstructed water bottom reflection. We are certain about two first-order multiple leakages in this data set as indicated by the yellow arrows in Figure 4(c). From the primaries we can clearly see that with the FWM-based method the multiple leakages have been suppressed (Figure 4(g)). Also, we can observe the same phenomenon from the stacked section comparison in Figure 5. From these results we can see that the tiny part of water bottom reflection has a huge influence on primary estimation. At the same time, we need to mention that the primary model that has the least multiple leakage may not be the best model for primary amplitude preservation in the deeper area due to the fact that 3D data can never be perfectly represented by a 2D theory. The energy lost in the deeper area is because of the balancing process inside the CL-SRME inversion scheme.



(a) (b) (c)

Figure 5 *(a) Stacked input section. (b) Stacked primary section based on PRT reconstructed water bottom reflection. (c) Stacked primary section based on FWM reconstructed water bottom reflection.*

Conclusions

We have introduced a new framework for better primary and multiple prediction, which aims to provide high-quality fully-sampled data for CL-SRME in order to avoid primary estimation failure that typically occurs in shallow-water environments. The core is to utilize full wavefield migration as the interpolation engine for providing the complete reconstructed data. Applications on 2D synthetic and 2D field data demonstrate the good performance of the proposed framework in a shallow-water scenario.

Acknowledgements

The authors thank the Delphi Consortium members for support and PGS for providing the field data.

References

Berkhout, A.J. [1982] *Seismic migration, imaging of acoustic energy by wave field extrapolation, A: theoretical aspects*. Elsevier (second edition).

Berkhout, A.J. [2014a] Review Paper: An outlook on the future of seismic imaging, Part I: Forward and reverse modelling. *Geophysical Prospecting*, **62**, 911–930.

Berkhout, A.J. [2014b] Review Paper: An outlook on the future of seismic imaging, Part II: Full-Wavefield Migration. *Geophysical Prospecting*, **62**, 931–949.

Berkhout, A.J. and Verschuur, D.J. [2006] Focal transformation, an imaging concept for signal restoration and noise removal. *Geophysics*, **71**(6), A55–A59.

Davydenko, M. and Verschuur, D.J. [2017] Full-wavefield migration: using surface and internal multiples. *Geophysical Prospecting*, **65**, 7–21.

Kabir, M.M.N. and Verschuur, D.J. [1995] Restoration of missing offsets by parabolic Radon transform. *Geophys. Prosp.*, **43**(3), 347–368.

Lopez, G.A. and Verschuur, D.J. [2014] Closed-Loop SRME - A New Direction in Surface Multiple Removal Algorithms. EAGE, Eur. Ass. of Expl. Geophys., Expanded abstracts, Amsterdam, We E102 02.

Lopez, G.A. and Verschuur, D.J. [2015] Closed-loop surface-related multiple elimination and its application to simultaneous data reconstruction. *Geophysics*, **80**(12), V189–V199.

Nath, A. and Verschuur, D.J. [2017] Using surface-related multiples in imaging for data with large acquisition gaps. SEG, Soc. Expl. Geophys., Expanded abstracts, Houston, 4768–4772.