Deconvolution of upgoing and downgoing wavefields: A data example from the NOAKA OBN experiment

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Summary

Ocean bottom node surveys are popular tools for both seismic exploration and monitoring due to the possibility for superior imaging and velocity model building compared to towed streamer surveys. In addition, the size of ocean bottom experiments has been increasing. This increase in frequency and survey size requires efficient processing solutions for attenuating free surface effects such as ghosts and multiples both in terms of usability and computing requirements. Traditionally, these processing steps were implemented by up-down wavefield separation to target the receiver-side effects, followed by separate source-side deghosting and demultiple. We have recently adopted the combination of up-down wavefield separation with up/down deconvolution or downgoing wavefield deconvolution as an alternative due to the simplicity of the process and the high quality of the results.

In this paper, we review up/down deconvolution as a demultiple and deghosting method for the upgoing wavefield and describe downgoing wavefield deconvolution as a similar process for the downgoing wavefield. Moreover, we perform both up/down deconvolution and downgoing wavefield deconvolution in a single processing flow. This combination simplifies the processing sequence, decreases the human effort, and reduces processing turnaround compared to our legacy solution. While being more user-friendly, our new solution has conserved the advantages of the legacy solution and delivers complimentary images using the up- and downgoing wavefields. Crucially for regions with a shallow seafloor, the downgoing wavefield permits superior imaging of the shallow subsurface.

Introduction

Compared to towed streamer experiments, ocean bottom node (OBN) surveys can deliver both higher quality imaging and superior velocity models. These properties can be better understood due to the larger offset, lower frequencies, higher signal/noise ratios, and better azimuthal coverage of seafloor experiments. The popularity of OBN acquisitions has created a need for an efficient processing solution to reduce the cost associated with processing steps such as deghosting and demultiple. For multi-component seafloor data, efficient processing solutions exist and usually involve the decomposition of the hydrophone and vertical geophone measurements into upgoing and downgoing wavefields (Wang et al., 2010). Following this step, we can effectively tackle free surface effects such as multiples and ghosts by using up/down deconvolution (UDD) or downgoing wavefield deconvolution (DGD). Compared to alternative deghosting/demultiple techniques for tackling the free surface effects, these deconvolution techniques are attractive due to their simplicity and robustness. The theoretical foundation of UDD and DGD is well established (Sonneland & Berg, 1987; Amundsen, 1993, 2020; Ziolkowski et al., 1999; Lokshtanov, 2005) and UDD has been used for demultiple and deghosting of the upgoing wavefield in many OBN processing projects. Until recently, less attention was paid to deconvolution methods for the downgoing wavefield. However, the recent introduction of down/down deconvolution (Hampson & Szumski, 2020) has sparked a renewed interest in DGD (Lokshtanov, 2021; Caprioli & Kristiansen, 2021). Most importantly, UDD and DGD deliver high quality results, which can be used for imaging using conventional and mirror migration.

In this study, we demonstrate that wavefield separation, UDD and DGD can be combined into a single flow to perform demultiple, deghosting and designature of the up- and downgoing wavefields. This combination reduces human effort and thereby benefits production turnaround. Furthermore, we demonstrate that mirror imaging using the DGD results delivers superior images of the shallow subsurface compared to conventional imaging of the upgoing wavefield, which greatly benefits acquisitions in shallow water environments.

In this paper, we first review the UDD and DGD methods and validate our implementations using a synthetic example. Next, we introduce our processing flow for wavefield separation and deconvolution and present preliminary results from the NOAKA experiment, acquired in the South Viking Graben of the Norwegian Continental Shelf. Finally, we conclude with a few observations about the benefits of UDD and DGD for shallow water OBN experiments.

Method

Both UDD and DGD are key elements of multi-component processing aiming to tackle free surface multiples/ghosts and deconvolve the source signature. UDD is commonly implemented as a spectral division in the frequency domain, where the earth impulse response X at the seafloor is related to the upgoing wavefield U and downgoing wavefield D (Lokshtanov, 2005):

$$X = UD^{*}/(DD^{*} + \varepsilon^{2})\ . \qquad (1)$$

Here, ε is a stabilization parameter. Similarly, for DGD the redatumed impulse response RZX is related to the

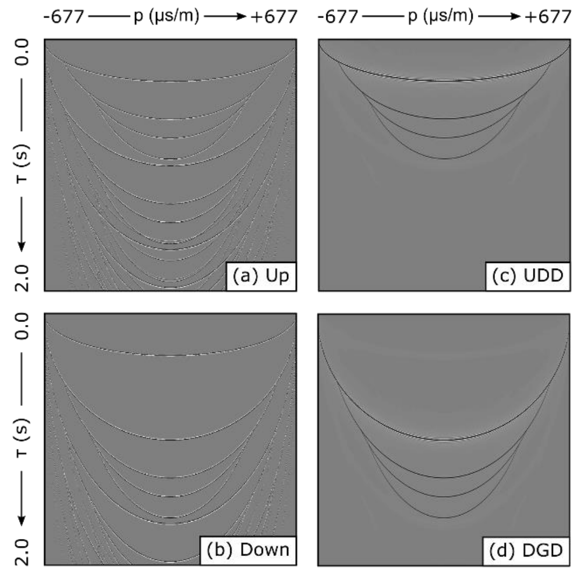

Figure 1: Synthetic data example showing the effect of UDD and DGD. Figures a&b show the input up- and downgoing data in the τ-p domain. Figures c&d compare the results of UDD and DGD.

downgoing wavefield D and the source wavefield S (Seher et al., 2022):

$$RZX = (D - S)D^*/(DD^* + \varepsilon^2) \ . \quad (2)$$

Here, Z is the round-trip operator in the water layer and R is the sea surface reflectivity. Critically, DGD requires an estimate of the source wavelet S. Hampson & Szumski (2020) suggested two methods. In the first method, a mute is applied around the direct arrival of the downgoing wavefield. In the second method, the source wavefield is derived using the cross-ghosting method (Soubaras, 1996). The first approach only uses the downgoing wavefield, whereas the second method requires both the up- and downgoing wavefields. If there exists a clear separation between direct arrivals and multiples, the first method is preferable because it is less sensitive to imperfections in the wavefield calibration. The second method, however, can be more suitable for shallow water surveys where the direct wave and its bubble interfere with the multiple arrivals.

Synthetic data example

To evaluate the efficiency of our new deconvolution algorithms, we created a simple synthetic dataset in the τ-p domain using the feedback model (Berkhout & Verschuur, 1997; Hampson & Szumski, 2020). Examining the data for a simple four layer over half-space model (figures 1a&b), we can discern the direct wave as well as four reflections and their respective multiples. The application of our UDD and DGD solutions to the up- and downgoing wavefields attenuates the multiples (figures 1c&d). Redatuming the receiver demonstrates that UDD and DGD deliver almost identical solutions and are consistent with each other.

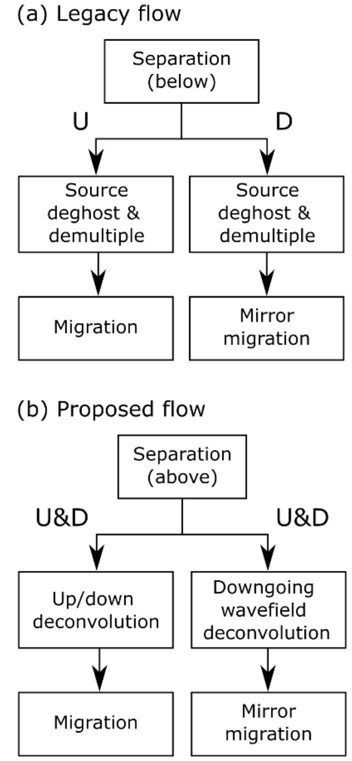

Figure 2: Illustration of two possible processing flows for OBN data (modfied after Wang et al., 2010).

Processing sequence

Multi-component seismic data can be processed using two different approaches (Wang et al., 2010). In the first approach, the hydrophone and vertical geophone data are separated below the seafloor into up- and downgoing wavefields. This process is followed by source designature, deghosting and demultiple (figure 2a). In the second approach, the wavefields are separated above the seafloor. The estimated up- and downgoing wavefields are subsequently used in UDD or DGD, which attenuates all surface multiples and ghosts and deconvolves the source signature (figure 2b). We note the symmetry of the two flows in treating the up- and downgoing wavefield for both the legacy and the proposed flow (i.e., a similar processing flow is applied to both wavefields). After preconditioning using either the legacy or novel flow, the data can be migrated using either conventional or mirror migration.

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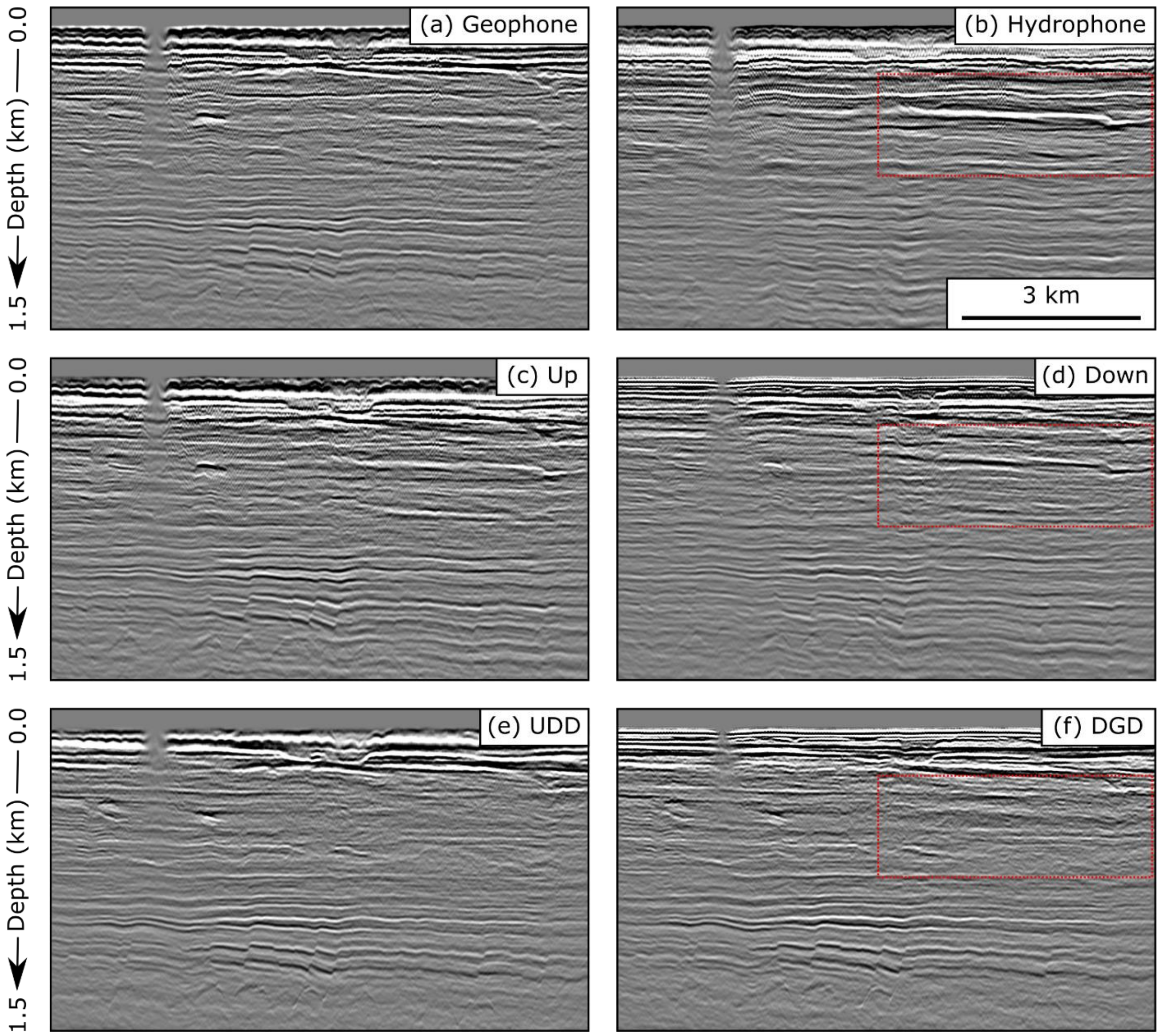

Figure 3: Data example from the NOAKA survey showing the impact of wavefield separation and deconvolution on Kirchhoff depth migration. Figures a&b show the depth migrated images for the input geophone and hydrophone data. Wavefield calibration and up-down separation transform the input data into the up- and downgoing wavefields (figures c&d). Finally, figures e&f show the data after UDD and DGD. The downgoing wavefield (figure d) and the DGD results (figure f) were migrated using mirror migration. All other images are obtained by conventional migration. All sections are scaled independently. The red rectangle marks the zoomed area shown in figure 4.

The simplicity and effectiveness of UDD have made it the preferred solution for preparing the upgoing wavefield for imaging. Prior to the introduction of DGD, separate source deghosting, designature and demultiple were required to prepare the downgoing wavefield for imaging. This has introduced an asymmetry in the processing sequence (i.e., different processing steps for the up- and downgoing wavefield) that complicated the seismic processing sequence. The introduction of DGD has allowed us to prepare the up- and downgoing wavefield for imaging using a single processing flow. This reduces the complexity of the processing sequence and improves processing turnaround.

Real data example

To illustrate the impact of our proposed processing flow (figure 2b) on the depth migrated images we applied our processing sequence to a subset of the recently acquired

NOAKA OBN experiment and migrated the data at various stages of the processing sequence. The test dataset comprised a total of 177 multi-component receivers spaced 50 m apart along a single receiver line and shots in a 3D shot carpet (25 m by 50 m). The data preparation involved shear wave noise attenuation (Ren et al., 2020; Yang et al., 2020) as well as shot carpet regularization to a regular grid of 12.5 m by 12.5 m. These regularized data were transformed into the τ-p domain and calibrated using the cross-ghosting technique (Soubaras, 1996). After calibration, the data were separated into up- and downgoing wavefields and subsequently processed using either DGD or UDD.

Examining the migrated images for both hydrophone and geophone data shows multiples in the near surface that obscure shallow structures (figures 3a&b). The process of calibration and wavefield separation attenuates some of the ghosts/multiples and delivers clearer images for both up- and downgoing wavefields (figures 3c&d). Finally, we applied both UDD and DGD to our test dataset, which mitigates the remaining free surface effects (i.e., source-side ghosts & multiples) as well as the source signature (figures 3e&f).

The mirror migration results (figures 3d&f) show a better image of the seafloor and shallow subsurface than the images derived from conventional upgoing migration (figures 3a-c&e). Comparing the deeper subsurface, the images of UDD and DGD are similar (figures 3e&f). Furthermore, comparing the images before and after deconvolution (figures 3c&e and 3d&f) demonstrates that UDD and DGG successfully attenuate free surface multiples and source ghosts. Finally, we have shown that wavefield decomposition and DGD play a key role in attenuating multiples and allow high quality imaging with the downgoing wavefield (figure 4).

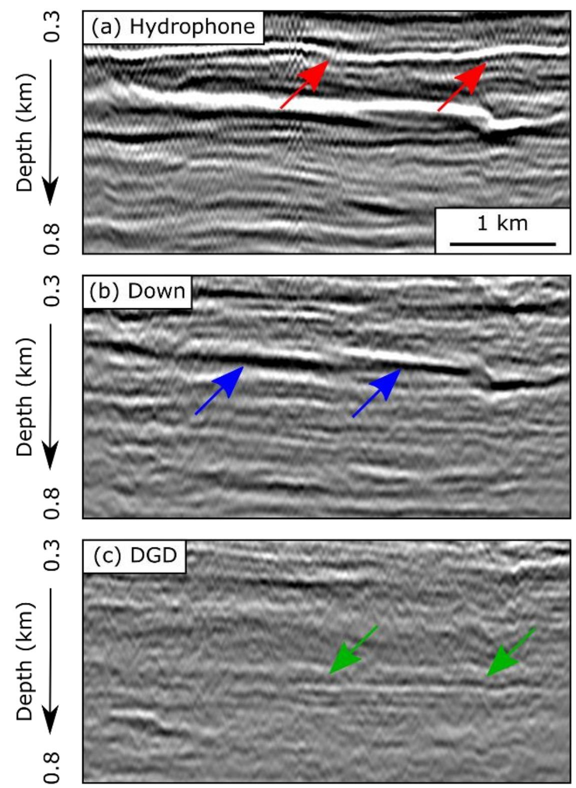

Figure 4: Zoom of the shallow subsurface for the data example in figure 3. The red arrows mark a receiver side multiple, the blue arrows show a source side multiple, and finally the green arrows highlight a weak reflector.

Discussion and Conclusions

Efficient demultiple, deghosting and designature of both up- and downgoing wavefields are required steps for the processing of large multi-component OBN experiments. In this study, we have described how UDD and DGD can be used to achieve this efficiency by simultaneously processing both up- and downgoing wavefields. Most importantly, this simultaneous processing can improve the productivity of production teams and benefit processing turnaround through a simplification of the processing sequence. Furthermore, we have applied the proposed processing flow to a subset of the recently acquired NOAKA OBN dataset from the North Sea. Here, we demonstrated the impact of each processing step on Kirchhoff depth migration by showing how each processing step attenuates free surface effects present in ocean bottom experiments and delivers a progressively clearer image of the shallow subsurface.

For shallow water regions like the North Sea, combining UDD and DGD is particularly appealing because of the complimentary information derived from the up- and downgoing wavefields. This is most striking for the shallow subsurface, where the DGD image is clearly superior to the UDD image. This observation can be explained by smaller reflection angles and a larger number of pre-critical input traces. Consequently, combined imaging with UDD and DGD data can greatly enhance both characterization and understanding of the shallow subsurface.

Acknowledgements

This work was made possible through the help of numerous TGS colleagues. We are grateful to Eddie Cho, Peter Lee, and Jan Gromotka. We would like to thank TGS management for permission to show the NOAKA field data. Finally, we acknowledge Magseis Fairfield for the acquisition of this survey.

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