Sub-seafloor reflectivity estimation by upgoing wavefield deconvolution

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Summary

Among other advantages, multicomponent seismic data acquired at the sea floor facilitate the separation of up- and downgoing wavefields. These separated components can then be used to reveal an estimation of subsurface reflectivity. The most used methods are up/down deconvolution, which uses the relationship between up- and downgoing signals, and down/down deconvolution, which uses the down going wavefield alone. Here we introduce a third alternative approach, which exploits the relationship between successive data terms in the upgoing wavefield.

Introduction

Multicomponent seismic data acquired at the seafloor, such as Ocean Bottom Node (OBN), Ocean Bottom Cable (OBC) or Ocean Bottom Seismometer (OBS) data, provide many advantages over both single and multi-component streamer data. Some of those advantages are listed below:

- Wider range of offsets and azimuths
- Richer range of illumination angles
- Quieter recording medium
- Higher S/N ratio at low frequencies
- Possibility of wavefield separation
- Higher quality of depth images
- More suitable for imaging with multiples
- More usable for full waveform inversion
- More appropriate for time lapse studies.

Ocean bottom data are usually acquired using receiver nodes. A typical node includes a hydrophone to record pressure wavefield (P), and three orthogonally oriented geophones to record particle velocity vector (V), of which the vertical component is known as Vz or Z. Seismic data acquired at the sea floor requires a specific processing workflow (Wang et al., 2010). A crucial part of that workflow is the wave field decomposition process. This process involves using both hydrophone and geophone data to estimate both upgoing and downgoing wave fields. These wavefields contain various orders of data, beginning with direct arrivals and continuing into primaries and various orders of multiples and ghosts (Figure 1). The upgoing wavefield (*U*) includes primaries and multiples, while the down going wavefield (*D*) involves direct arrivals and receiver-side ghosts. In other words:

$$U = SX_0 + SX_0\, RZX + SX_0\, (RZX)^2 + \cdots, \quad (1)$$

$$D = S \quad + S \quad RZX + S \quad (RZX)^2 + \cdots, \quad (2)$$

where S represents source signature, R is free-surface reflectivity, Z refers to two-way propagation in the water layer, X_0 is subsurface reflectivity according to primary reflections, while X is the reflectivity as observed by ghosts and multiples. The higher order terms usually correspond to ray paths with smaller ray parameters and narrower angles of incidence.

In this framework, for the purpose of simplicity some effects including energy partitioning, turning waves, head waves, converted waves, guided waves and Scholte waves are not considered. This conceptual perception can be used to explain the modern techniques that have evolved in recent years. From Equations (1) and (2) we obtain:

$$U = X_0\, (S + S\, RZX + S(RZX)^2 + \cdots), \quad (3)$$

$$U = X_0\, D. \quad (4)$$

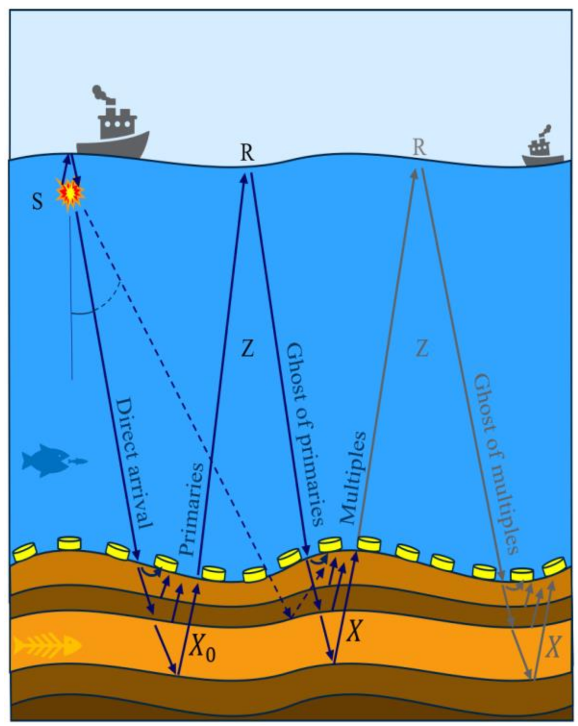

***Figure 1**– A schematic diagram showing data terms corresponding to both up- and downgoing wavefields. In a specific location, ghosts and multiples usually arrive with a tighter incidence angle than direct arrivals and primaries, leading to both richer illumination and finer sampling.*

In other words, an upgoing signal is the result of a downgoing signal penetrating the earth and reflecting upwards after being convolved with subsurface reflectivity. Therefore, a deconvolution process is expected to reveal the desired reflectivity information (Amundsen, 1993, 2020; Lokshtanov, 2005, 2021; Sonneland & Berg, 1987; Ziolkowski et al., 1999):

$$X_0 = U/D. \quad (5)$$

This solution is known as up/down deconvolution or UDD. This method faces a few challenges, particularly in shallow water settings. The first practical obstacle is that node data sampling in the space domain is usually quite sparse. The second concern arises from the fact that achieving a flawless separation of the wavefield is nearly impossible. This is especially challenging in shallow water.
Aiming to enhance the image quality of shallow sediments, Caprioli & Kristiansen (2021) and Hampson & Szumski (2020) propose the deconvolution of receiver-side ghosts captured in the down going wavefield. Their method can be explained by using Equation (2) to write:

$$D - S = S\ RZX + S\ (RZX)^2 + \cdots, \tag{6}$$

$$D - S = RZX\ (S + S\ RZX + \cdots), \tag{7}$$

$$D - S = RZX\ D, \tag{8}$$

which means:

$$RZX = 1 - S/D. \tag{9}$$

This second solution is known as down/down deconvolution or DDD, also has been referred to as downgoing wavefield deconvolution or DGD (Caprioli & Kristiansen, 2021; Seher et al., 2022a; Seher et al., 2022b). This method faces a few practical challenges, the main concern is that an accurate estimation of the source wavefield is required.

Upgoing wavefield deconvolution

Here we propose an alternative approach using the multiples captured in the upgoing wavefield. Figure 2 aims to explain that the convolutional relationship between successive data terms is represented by two-way propagation in the water layer (*Z*), and reflections at both above and below the recording level (*R* and *X*). In other words:

$$Current\ term = Previous\ term * RZX. \tag{10}$$

From Equation (1) we obtain:

$$U - SX_0 = RZX\ (SX_0 + SX_0\ RZX + \cdots), \tag{11}$$

which means:

$$RZX = 1 - SX_0/U, \tag{12}$$

where X_0 is given by Equation (5). This third solution, which can be named either as up/up deconvolution (UUD), or upgoing wavefield deconvolution (UGD), also requires a good knowledge of source signature.

Data examples

We examine the methods explained above on both synthetic and real data. Our synthetic example is formed of a seabed event followed by three subsurface reflectors and their associated free-surface multiples. Figure 3 shows the effectiveness of all those methods in attenuating multiples and revealing primary reflections. These results exhibit a broadband wavelet as the deconvolution process cancels out the source signature.

Our real data example is from a 3D OBN survey recently acquired in the NOAKA oilfields in the North Sea. Figure 4 shows an image domain comparison both before and after various deconvolution methods. In the deep zone, UDD provides better resolution, whereas in the shallow zone both DGD and UGD results seem superior to UDD. This superiority is due to the finer sampling and richer illumination of downgoing ghosts in the case of DGD, and upgoing multiples in the case of UGD. Both DGD and UGD present clear images of shallow geology and the fault blocks around 1 km depth.

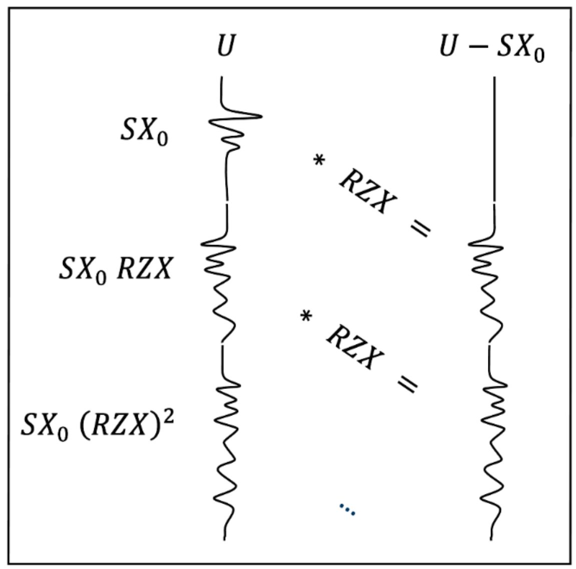

Figure 2 *– A demonstration of the convolutional relationship between successive data terms represented in an upgoing trace.*

Discussions

We have demonstrated that subsurface reflectivity can be estimated using multiples in the upgoing wavefields. For this purpose, we first estimate $\boldsymbol{X_0}$ as an initial solution obtained from up/down deconvolution, then we calculate $\boldsymbol{U - SX_0}$, which represents surface related multiples captured in the upgoing record. Finally, we divide that content by *U* to collapse the chain of multiples into $\boldsymbol{RZX}$, which represents the receiver-side ghost of all primary events. For a sparse OBN survey, both UGD and DGD provide superior images of the shallow structure than UDD. That is because compared with primaries, both multiples and ghosts provide richer ranges of illumination angles and finer data sampling.

The process of deconvolution explained above is usually performed in the tau-p domain. That is because in a flat earth scenario, multiples are expected to be periodical for plane wave components. However, a challenge associated with this type of operations in the tau-p domain is related to the inherent flat-earth assumption. In a complex geology that notion breaks down, leading to a misrepresentation of slowness traces. Meanwhile, the deviation from the 1D assumption can be tolerated to some extent because the earliest generations of multiples have travel paths situated in the nearby neighbourhood.

Each of the above-mentioned approaches requires some data preparations. Generally, those seismic events that are not in agreement with Equations (1) and (2) should be excluded from the data. In that respect, shear wave contamination, guided waves, clipped amplitudes, noise spikes, residual blending noise and so on need to be addressed beforehand. After those preparations, the data still needs to be preconditioned to reduce the artefacts expected from a roundtrip tau-p transformation. This may include regularization, interpolation, extrapolation, spatial tapering at offset edges, and temporal tapering at end of traces. For the UDD process, we may apply tapers at both top and bottom of slowness traces in the tau-p domain. Meanwhile we may note that the upgoing wavefield should be terminated at an earlier time than in the downgoing wavefield, so that the expression of $D - S = RZU$ remains valid.

With regards to post deconvolution processing, it is worthwhile to mention that all the methods discussed here are expected to provide broadband reflectivity data with absolute amplitudes smaller than unity. Therefore, any changes to either amplitude or phase spectrum introduced by the inverse tau-p transform should be compensated for. Moreover, these methods can be altered to predict surface related multiple models for either the up- or downgoing wavefield. In case a multiple subtraction workflow is chosen instead of a deconvolution workflow, further processing efforts will be required to address the source issues including source-side ghost, bubble effect and source signature. In either case, further processing steps remain due to address further outstanding concerns including absorption effects and internal multiples.

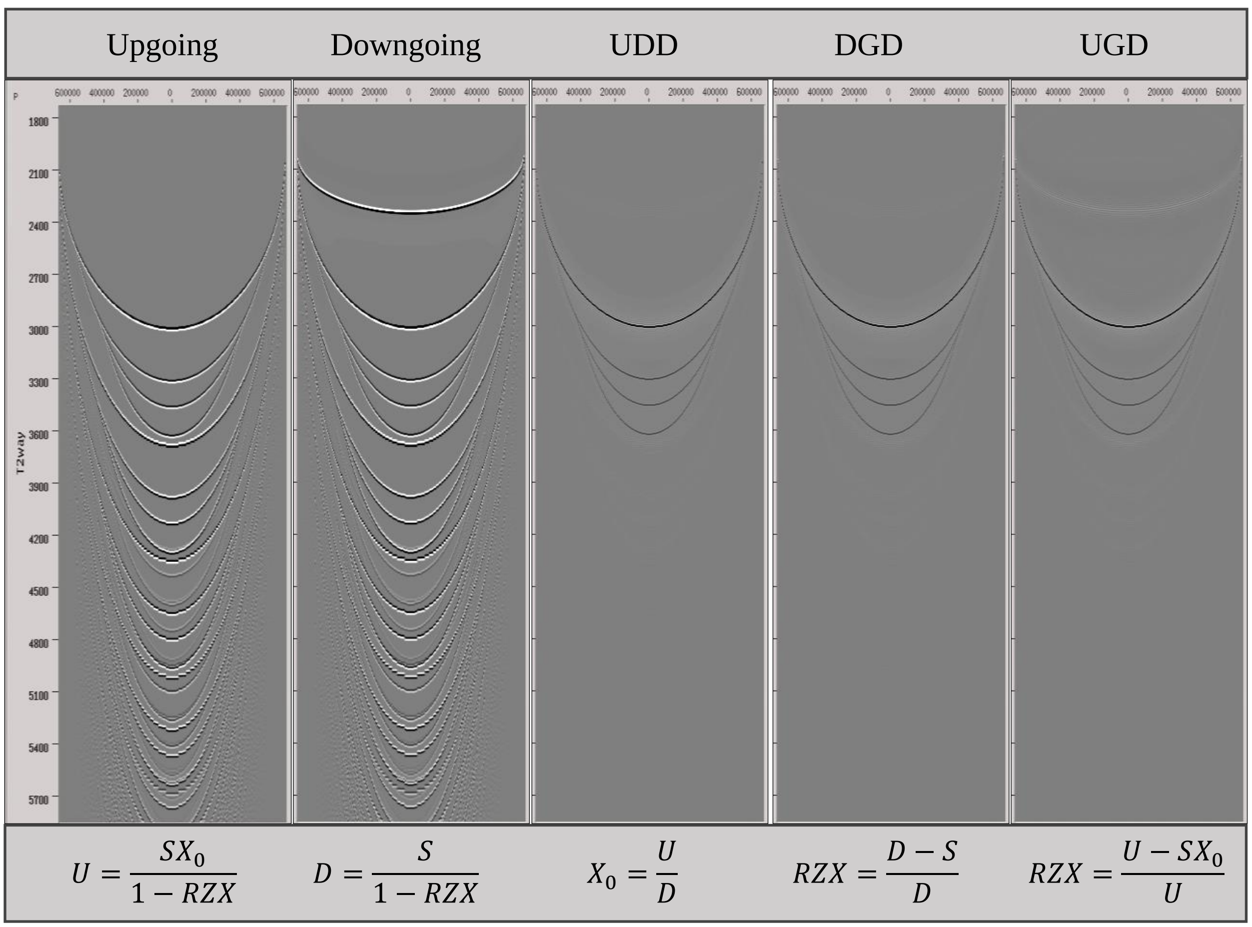

***Figure 3**– Synthetic data example representing a seabed event followed by 3 primary reflections and their surface related multiples in the upgoing wavefield, and direct arrival and ghosts in the downgoing wavefield, presented in the tau-p domain with unified datum and polarity. Alternative deconvolution methods can successfully suppress surface related multiples and ghosts to reveal desired broadband primary events.*

Conclusions

The combination of both hydrophone and geophone data acquired in OBN surveys facilitate effective separation of up- and downgoing wavefields. However, primary reflections from shallow interfaces may not be well represented due to poor illumination caused by sparse spatial sampling. Fortunately, both receiver-side ghosts in the downgoing wavefield and multiples in the upgoing wavefield may capture a portion of that valuable narrow angle information. Those separated wavefields can then be used in a deconvolution scheme to reveal subsurface reflectivity.

For deep geology, conventional imaging of the UDD result provides highly focused depth images. For shallow sediments however, we may prefer using either UGD or DGD results and mirror imaging. However, both approaches require a precise knowledge of the source signature. Therefore, they may be more applicable for surveys where near-field hydrophone data have been acquired.

Acknowledgements

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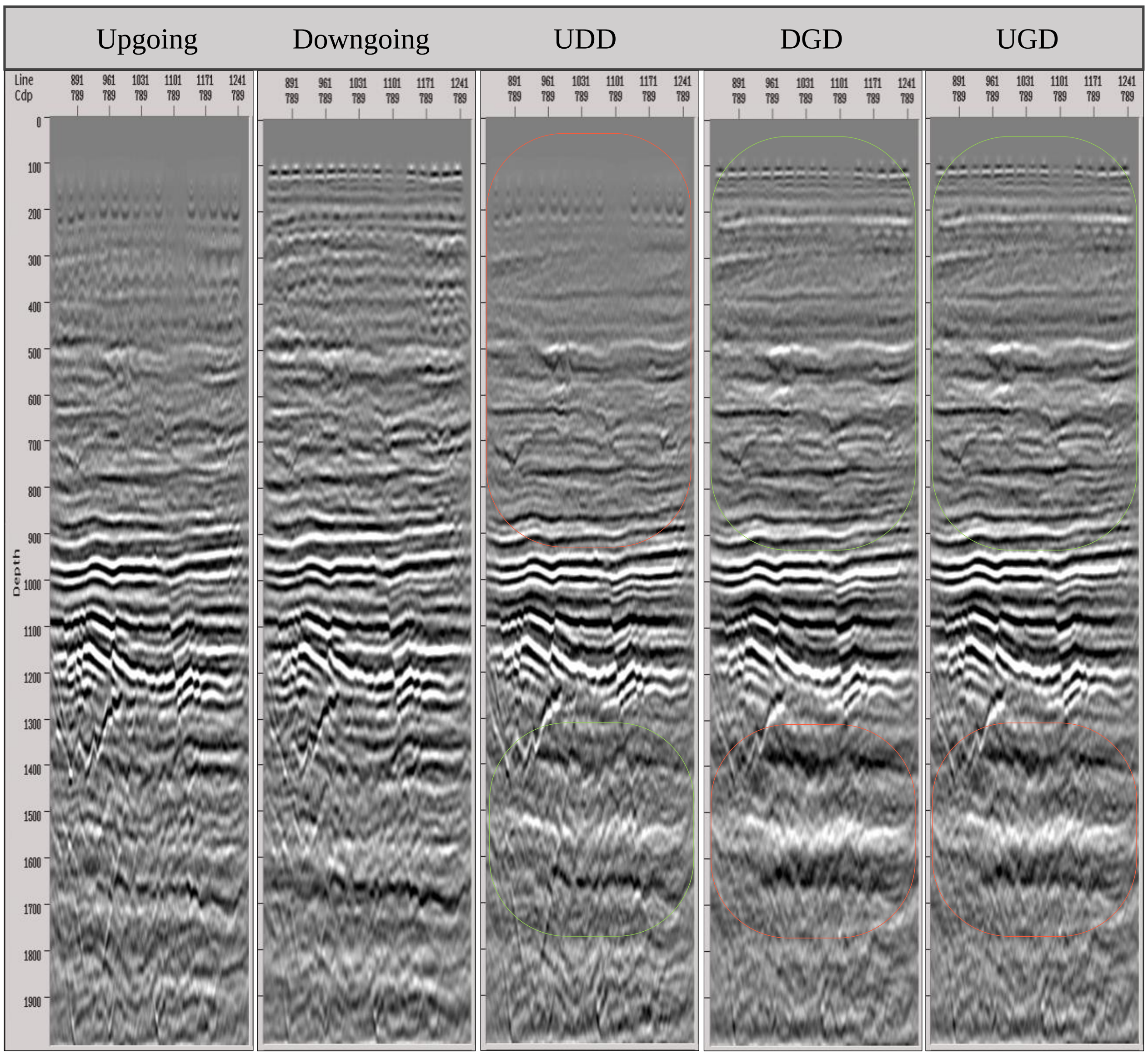

Figure 4– *Real data example from a recent OBN survey showing crossline images both before and after alternative deconvolution methods. The UDD image is quite weak in the shallow zone, due to a lack of illumination, but it is quite sharp and clear in the deep zone. Meanwhile, DGD and UGD images are superior in the shallow zone but less impressive in the deep zone. The low frequency appearance can be attributed to the imperfections in the source signature estimation process, particularly the bubble effect.*