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OBS wavefield separation and its applications

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Summary

This paper discusses present trends in ocean-bottom seismic (OBS) data processing. Current industrial practices for P-wave processing are described, discussed and exemplified using synthetic and real data examples. The discussion highlights the evolution of OBS processing techniques from inception to present time. Initially, specialized OBS processing aimed at the attenuation of water layer reverberations only. Later on, processing progressed towards a more complete wavefield separation approach and new applications emerged, such as more sophisticated P (pressure) and Z (vertical component) calibration, up-down deconvolution, and mirror imaging. The transition of these applications to standard practice is still ongoing but progressing rapidly, backed by theoretical correctness and the quality of practical results on field data.

Introduction

Ocean-bottom seismic data acquisition routinely employs hydrophones and three component (3-C) geophones or accelerometers embedded in an ocean bottom cable (OBC) or in individual ocean bottom nodes (OBN). The resultant recording of the pressure and particle motion components of the full elastic wavefield expands the scope of marine seismic data analysis and interpretation beyond conventional streamer data applications. There are two main categories of multi-component data processing applications: converted-wave processing and enhanced processing of pressure waves. This paper focuses on the latter, in particular on its evolution from the 1990s to the present time.

When pressure P and vertical particle velocity Z are simultaneously recorded, the elastic wavefield can be separated into its up and down-going parts. In the 1990s, processing efforts usually ignored the down-going wavefield and focused on up-going waves only. Depending on the separation level, upward-traveling waves are free of receiver-side multiples and facilitate further processing and conventional imaging. However, down-going waves have important applications. Mirror imaging of down-going waves (Grion et al., 2007) offer wider subsurface coverage than conventional migration of up-going waves. Additionally, up-down deconvolution combines both wavefields to completely remove free-surface effects (Amundsen, 2001). Figure 1 illustrates the current state-of-the-art choice of processing options which exploit the separation of up- and down-going waves. The choice of separation level, just below or just above the seabottom, is explained in the next section. The relative merits of the

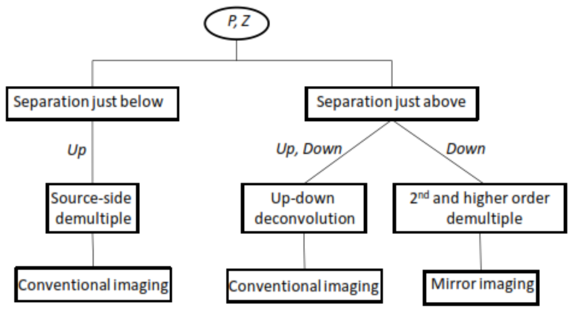

Figure 1 Three processing flows based on acoustic wavefield separation. Separation just below the sea bottom attenuates receiver side multiples while up-down deconvolution removes all multiples. Mirror imaging of the down-going receiver ghost provides better illumination in case of sparse receivers.

three processing flows are highlighted in the following sections. The flows in Figure 1 relate to cases when a low velocity layer at the seabottom allows for P-waves to be recorded essentially on the P and Z components and S-waves to be recorded on the horizontal components X and Y. In such scenarios, acoustic separation (involving only P and Z) is sufficient. For cases when all components record a mix of P and S modes, elastic separation is required (involving P, Z, X and Y) to separate not only upgoing from downgoing waves, but also P-waves from S-waves.

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Wavefield separation

Throughout the 1980s and most of the 1990s, acoustic wavefield separation for industrial purposes was aimed at multiple removal only. As such, only the up-going wavefield was calculated, and the wavefield separation process was usually referred to as “PZ summation” (See for example Barr and Sanders, 1989). This term makes explicit reference to the calculation of the up-going wavefield as a sum, after appropriate weighting, of the P and Z components but does not account for the calculation of the equally important down-going wavefield, which can be obtained as a weighted difference of P and Z.

During the 1990s wavefield separation became more precisely formalized in both acoustic and elastic terms, and more advanced PZ calibration methods were developed. (Amundsen, 1993; Soubaras, 1996; Schalkwijk et al., 1999; Osen et al., 1999). Wavefield separation can be thought of as occurring either infinitesimally below or infinitesimally above the seafloor.

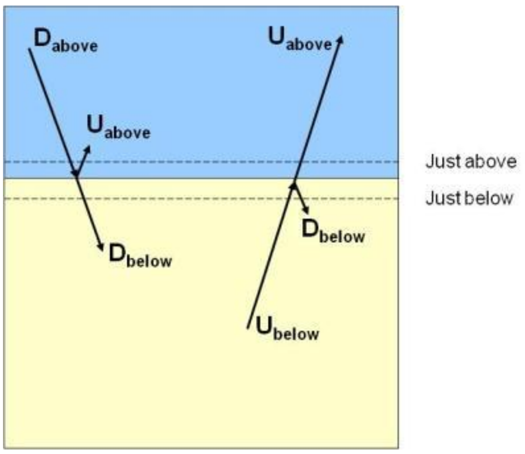


Figure 2 Up-going and down-going events just above and just below the seabottom. The left part of the diagram considers an event arriving at the seabottom receiver from above, such as for example the direct arrival, or a water-layer multiple. Such event is purely down-going just-below the seabottom, but just above the seabottom it incurs reflection and is therefore simultaneously up- going and down-going. Similarly, the right part of the diagram considers an event arriving from below, such as a primary event, source-side multiple or internal multiple. Such event is purely up- going just above, but is both up- and down-going just below.

The difference between separation above and below the seabed is highlighted in Figure 2. There are two contributions to Uabove, one from the earth (right side) and one from the seabottom bounce (left side). However, wavefield separation at a location just below the seabottom estimates Ubelow, which does not contain the seabottom bounce and is therefore free from receiver-side multiples. Ubelow is the wavefield obtained through PZ summation in a conventional processing flow (left flow of figure 1).

Separation below the seabottom can be performed using either an acoustic or an elastic approximation. PZ summation is an acoustic separation. Elastic separation combines all four recorded components: P and Z as well as the horizontal components X and Y. It offers the additional benefit of separating P from S waves, as well as upgoing from downgoing waves. It can be beneficial in cases where a high velocity layer near the seabottom causes substantial P-wave energy to be recorded on the horizontal components, as well as S-wave energy to be recorded on the vertical component.

Up-down deconvolution

At first sight the upgoing wavefield above the seabottom appears of limited use: it still contains receiver-side multiple-energy. However, once the recorded wavefield is separated into its up-going and down-going parts above the

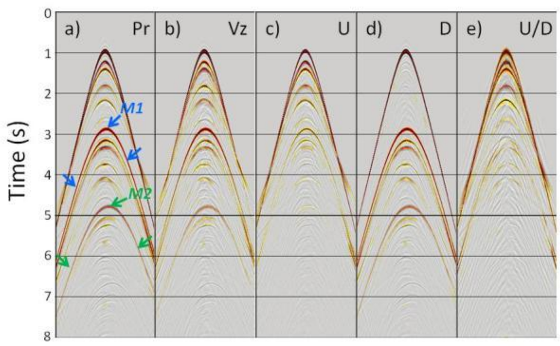


Figure 3 A hydrophone (P) and calibrated vertical component of particle velocity (Z) common receiver gather is shown in a) and b). Events M1 and M2 are the first and second order water-layer multiples. The up-going and down-going wavefields just above the sea bottom are shown in c) and d). Notice that the upgoing wavefield contains both primaries and multiples, while the down- going contains only multiples. The up-down deconvolution result is in e). The downgoing wavefield acts as a successful, deterministic multi-dimensional deconvolution operator for the upgoing.

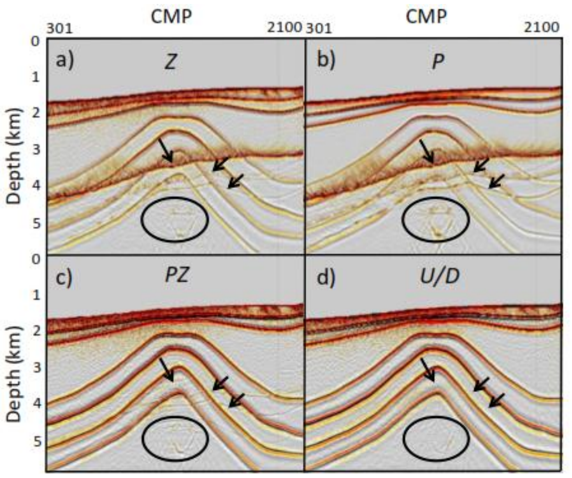


Figure 4 Depth migrated stacked sections for the vertical component a), hydrophone b), a conventional PZ summation approach c), and up-down deconvolution d). The arrows point to multiple events and the circles highlight an area where multiple energy tends to focus, creating undesired artifacts. For illustration purposes no demultiple is applied to the data in a) and b). The PZ summation image in c) is obtained by migration of the upgoing wavefield just below the seabottom, with no additional source-side demultiple applied.

seabottom, up-down deconvolution can be used to attenuate all free-surface multiples and simultaneously designature the data (central flow in figure 1). Moreover, the overall water-layer effect is attenuated, with important implications for 4D processing (Wang et al., 2010b). The theory of using up-down deconvolution to address surface-related water-column multiples in a horizontally-layered medium is well known (see, for example, Sonneland and Berg, 1987). Amundsen (2001) discusses the method in detail and extends the method to more complex geology. This simple deconvolution approach implicitly assumes a 1-D earth (i.e. a horizontally-layered medium. On the other hand, practical experience has repeatedly proven that the method is robust in the presence of structure. Wang et al. (2010) have recently investigated the reasons for this success under violation of the assumptions.

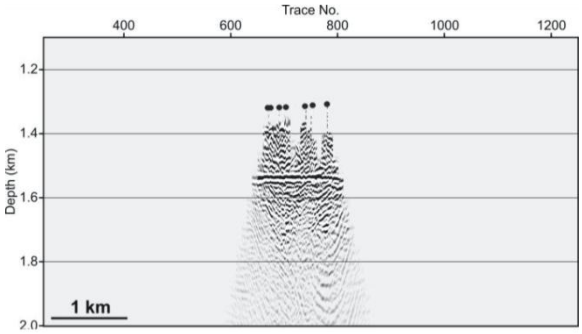
As an example, consider the finite-difference synthetic dataset presented in Wang et al. 2010. It consists of 170 OBS nodes at depths between 1375 and 1837m, and 1,280 shots. Shot and receiver sampling is 12.5m and 100m, respectively. The sea bottom is gently dipping, with an average dip of 1.6 degrees, but significant subsurface structure is present. Up- and down-going waves just above the seabed are shown in Figure 3c and 3d. After wavefield separation the next step is to deconvolve the down-going waves from the up-going waves for each receiver. The up-down deconvolution result clearly shows that all free-surface multiples are successfully attenuated (Figure 3e).
For comparison purposes the data is also processed using a conventional PZ summation approach (Figure 4).

Mirror imaging

The down-going wavefield just-above the seabottom does not contain any primary reflected energy, see for example Figure 3d. However, down-going receiver ghosts bounce from the same reflectors as the primary waves. In fact, the sea surface acts as a mirror reflecting the image of subsurface structure and receiver ghosts can be used for "mirror imaging" (Grion et al., 2007). This imaging approach is appropriate for either node surveys or cable surveys with significant cable separation. In either case, the acquisition geometry is in general characterized by a sparse and localized receiver spread in conjunction with a wider and denser shot grid.

With such geometry, down-going waves provide better subsurface illumination then up-going waves, especially for shallow events. This is an important factor for ocean-bottom operations, where receiver deployment is significantly more costly and time consuming than operating air guns at the sea surface. In other words, mirror imaging allows a shift in acquisition effort from the receiver side to the shot side.

Mirror imaging is not restricted to a particular imaging algorithm, it can be used in a basic NMO and stack process for rapid quality control of noise levels and clock drifts of autonomous OBS nodes. It can also be used for migration



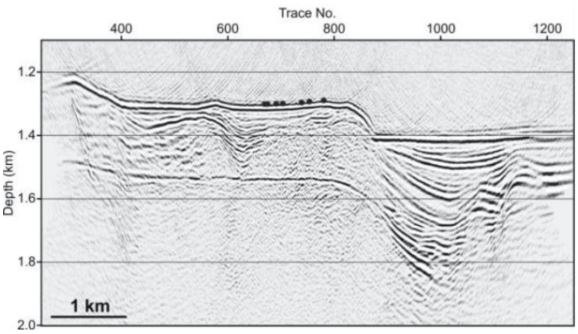


Figure 5 Seven OBS were successfully deployed on the ocean bottom at an average depth of about 1300 m with variable inline separation (100-300m). The data was acquired over the Northern Cascadia continental margin offshore Vancouver Island, British Columbia, Canada. The OBS line was 1 km long while the shot line was15 km long. With mirror imaging, illumination is mostly determined by the extent of the shot line and is therefore much wider than for conventional imaging. With conventional imaging illumination is mostly determined by the extent of the receiver line.

using any algorithm, including beam migration and RTM. The extended illumination that the method allows is exemplified in Figure 5. Mirror imaging of this data is thoroughly discussed in Dash et al., 2009.

In current practice mirror imaging uses not the entire down-going wavefield but the 1st order multiple only, sometimes also referred as the receiver ghost. Therefore, after wavefield separation, 2nd and higher order multiples have to be attenuated from the down-going wavefield. Conventional demultiple algorithms can be used for this purpose, as well as an adaptive up-down decon approach. However, in complex scenarios the model-based SRME method discussed in Pica et al. (2006) can give significant advantages and is generally preferred.

Discussion

Processing ocean-bottom data through a conventional PZ summation approach (left flow of figure 1) is attractive for its simplicity and can indeed lead to satisfactory results when receiver sampling is sufficiently dense and source-side demultiple carried out by statistical methods or by a modeling and adaptive subtraction approach is sufficient.

When a source side multiple overlays a primary reflection of particular interest that can not be precisely removed by adaptive subtraction or predictive deconvolution, up-down deconvolution (central flow in figure 1) can be beneficial. It achieves a complete demultiple by deterministic means, without need for adaptive subtraction or move-out discrimination. Additionally, it performs an automatic directional source designature. This is a powerful technique, with substantial advantages over a PZ summation approach. However, to be effective it requires unaliased wavefields and excellent separation, as well as a flat or moderately dipping seabottom. In general, up-down deconvolution is more sensitive to noise and aliasing than PZ summation.

The result of up-down deconvolution is a designatured upgoing wavefield free of all free-surface multiples. This wavefield may therefore have illumination issues, in cases where receiver sampling is sparse. In such situations, the mirror imaging flow (on the right in figure 1) can provide substantial structural imaging benefits, typically up to a depth below the seabottom approximately equal to the receiver spacing. Additionally, the downgoing wavefield can facilitate shallow velocity model building, thereby providing structural imaging benefits also where upgoing illumination is sufficient. For cases where illumination and accurate demultiple issues coexist, mirror imaging and up-down deconvolution can be used jointly. For example, the downgoing wavefield can be used for shallow velocity model building and imaging, while up-down deocnvolution can be used for demultiple and imaging of the target area.

Conclusions

PZ summation is aimed at the attenuation of receiver side multiples and is widely used in the industry. It consists of calculating the upgoing wavefield just below the seabottom using an acoustic assumption and often assuming vertical propagation only. Recently, a number of applications for the down-going wavefield have also emerged, and the processing of ocean-bottom data has shifted towards a more complete wavefield separation approach. Current separation methods are 3D and either acoustic or elastic depending on the exploration scenario. In particular, a hard seabottom with substantial S-wave energy recorded on the Z component and P-waves on X and Y can benefit from elastic separation. After wavefield separation, up-down deconvolution is an effective, deterministic and automatic free-surface demultiple and designature method, with important implications for 4D data processing. Additionally, mirror imaging of down-going waves allows for increased illumination of the subsurface and is rapidly becoming standard for OBS acquisitions.

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