By Andrew Long (Andrew.Long@pgs.com)

A Modern Perspective on Marine Multicomponent Seismic

The 'EAGE/SEG Workshop on Marine Multi-Component Seismic' in Kuala Lumpur on August 27-29 will discuss the current state of the art regarding OBS survey design, acquisition, processing, and interpretation — albeit all apparently in the context of traditional seismic imaging using primary reflections as compressional and converted-mode waves. In this paper, I will review the benefits of having access to separated wavefields — an outcome possible for both multisensor streamers and multisensor OBS receivers.

Introduction

Although 'multicomponent' seismic in the marine context is more commonly associated with retrievable receiver packages physically deployed along the seafloor (ocean bottom cables, OBC; ocean bottom nodes, OBN) or physically trenched into the seafloor for permanent reservoir monitoring (PRM) applications, the relative amount of 3D data acquired annually is trivial by comparison to the data volumes acquired each year with multisensor streamers. The key geophysical differences, however, are famously related to the following features:

- The sources and receivers are physically decoupled for ocean bottom seismic (OBS) methods, enabling more flexibility with survey design, and potentially, more uniform offset-azimuth acquisition than is possible using a conventional towed streamer vessel
- Receivers coupled to the seafloor record both compressional and shear-wave particle motion, thereby enabling both conventional and converted-wave seismic imaging

The issue of survey design is particularly relevant to a workshop that heavily features OBS methods, as operational inefficiency and high cost continue to be the greatest challenges to the expanded use of OBS. Limited equipment inventories coupled with slow deployment and retrieval typically translate to the receiver arrays deployed per shot being substantially smaller in area than the overall shot grid, and the spatial sampling between cables for OBC or between nodes for OBN being coarser than preferred. In addition to compromising spatial resolution, coarse receiver spacing also penalizes shallow image resolution. As discussed below, however, these challenges to OBS imaging can be largely mitigated by exploiting the benefits of separated wavefields. In the towed streamer context, Figure 1 provides a schematic illustration of a conventional 3D towed streamer vessel configuration, identifying another opportunity for multisensor acquisition to improve shallow image resolution and data quality.

Using the nomenclature of a common midpoint (CMP) occurring mid-way between every possible source and receiver surface coordinate, several CMP sublines are defined for the vessel configuration where (number of sublines) = (number of sources) x (number of streamers), the 'near offset' for each subline is the minimum distance between the respective source and streamer that contribute that that subline, and (nominal sail line separation) = 0.5 x (number of streamers) x (streamer separation). A series of parallel vessel passes along each sail line are used to acquire a contiguous 3D volume of seismic data from the survey area, with cross-line spatial sampling equal to the subline separation, where (subline separation) = 0.5 x (streamer separation) / (number of sources). As the near offset increases in response to wider streamer spreads being used in the pursuit of greater survey efficiency, the near-surface seismic images will be compromised by a 'cross-line acquisition footprint' between each sail line of data. Furthermore, seismic image resolution and quality improves as the subline separation decreases; encouraging the use of smaller streamer separation and / or more sources. It is shown below that the explicit measurement of cross-line particle velocity may facilitate the unwrapping of spatial aliasing in the cross-line direction, and may facilitate more accurate 3D deghosting for shallow depths. But there is more to the story than sampling on the receiver side, as it is the shot sampling that ultimately determines what level of spatial resolution can be achieved during seismic imaging.

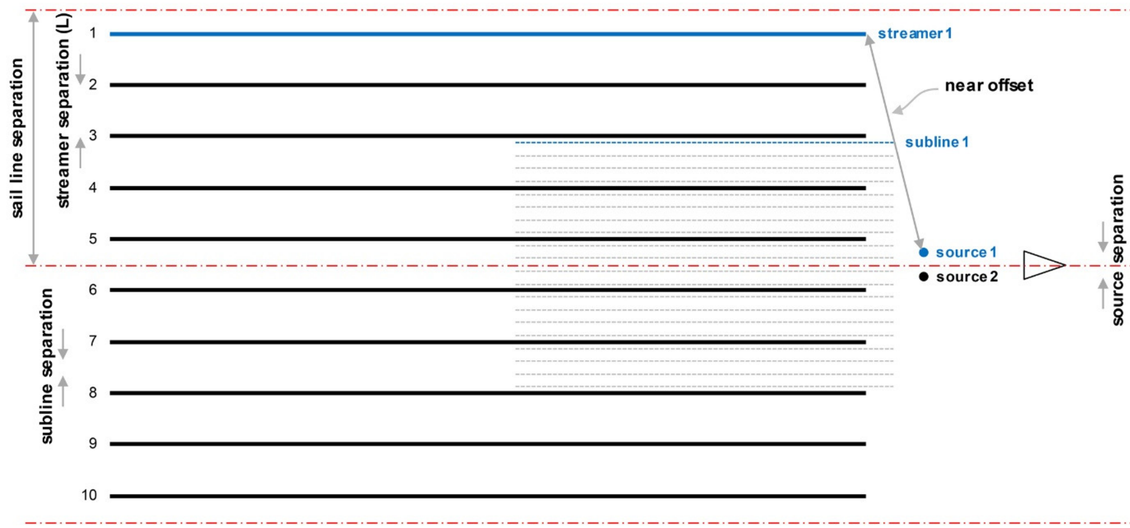

Figure 1. Nominal towed streamer acquisition geometry for dual-source shooting with 10 streamers.

So I redefine the benefits of multicomponent marine seismic as follows, and address each category in the text below:

- Access to separated wavefields, creating opportunities to use the full seismic wavefield for more efficient survey design, how the data are imaged, and how the data may be used
- Measurement of vector particle velocity wavefields, creating opportunities to improve shallow spatial resolution when imaging primary reflections
- Where the receivers are coupled to the seafloor, converted-wave seismic imaging of the full wavefield is possible, as well as more uniform offset-azimuth acquisition than is possible using a conventional towed streamer vessel

Much of the discussion below relates to multisensor streamer acquisition, but I mention multisensor OBS wherever appropriate too.

Access to Separated Wavefields

The theory of how multisensor data can be used to separate the recorded seismic wavefield into its up- and down-going parts has been discussed in detail by several authors (e.g., Claerbout, 1976; Fokkema and van den Berg, 1993). The recorded data have sea-surface 'ghosts', or reflections from the sea surface, at the source and receiver side. In the case in which the sea surface is assumed to behave as a flat free surface, and it is assumed that the signal undergoes no modification on traveling to the sea surface and back again, the recorded pressure signal from the sea-surface ghost is a polarity-reversed time-delayed copy of the recorded primary pressure signal. On the source side, the copy is of the down-going source energy, and on the receiver side, the copy is of the up-going primary energy ('P-UP') scattered from the subsurface below ('P-DWN'). The time delay of the ghost results in constructive and destructive interference at frequencies imposed by the source and receiver depths. Although the applications to dual-sensor (a hydrophone complemented by a vertically-inclined velocity sensor or accelerometer) were already well established, when dual-sensor streamers were first commercialized in 2007 the benefits for isolating P-UP from P-DWN, and hence removing the effects of the receiver-side ghost (refer to Figure 2), spawned an entire 'broadband seismic' industry for towed streamer data (Carlson et al., 2007). In addition to fundamental improvements in the resolution and interpretability of towed streamer seismic images, access to P-UP also facilitates efficiency gains during acquisition (Widmaier et al., 2015), quantitatively more accurate and robust reservoir characterization (Reiser et al., 2015a,b), and represents the preferred platform for highly repeatable time-lapse 3D ('4D') surveys (Lecerf et al., 2018).

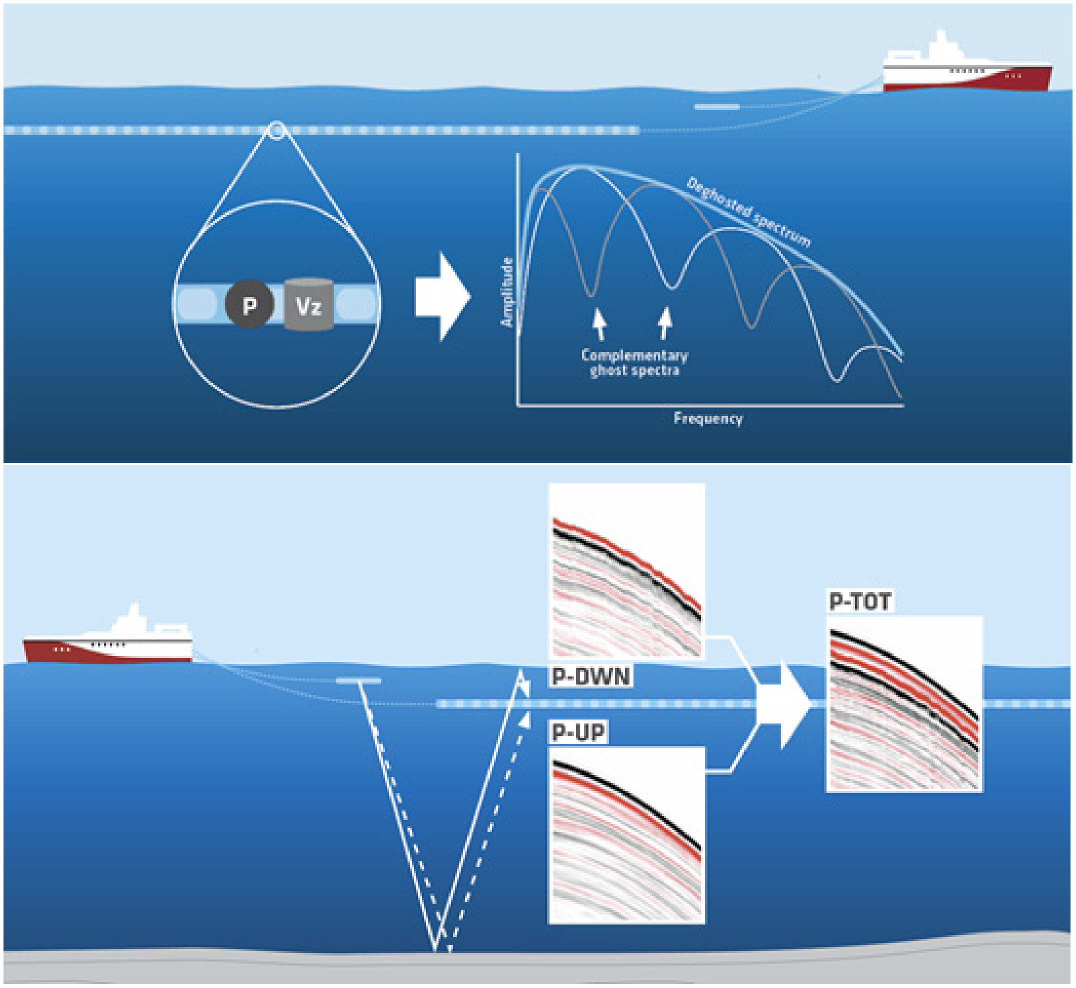

Figure 2. (upper) Principles of how collocated dual-sensor receivers in a towed streamer enable cancellation of the receiver-side ghost notches in the recorded amplitude spectrum; (lower) Principles of wavefield separation: a hydrophone can only record the total pressure wavefield (P-TOT), whereas dual-sensor acquisition enables the separation of P-UP and P-DWN.

Whitmore et al. (2010) showed how access to both P-UP and P-DWN enables each receiver to act as a virtual source, thereby allowing the illumination surface multiples to yield complementary separated wavefield imaging (SWIM) of the earth. The spatial aperture imaged for each shot is greatly extended, most notably for shallow depths, very small incidence angles can be recorded from very shallow reflectors for each streamer in modern wide-tow streamer spreads, and therefore, acquisition footprint effects can be mitigated (Long et al., 2013); velocity model building integrity is improved at all depths (Rønholt et al., 2014); shallow AVO inversion becomes feasible (Feuilleaubois et al., 2017). Lu et al. (2018) also demonstrate how full wavefield migration (FWM) of both primary reflections and surface multiples within an iterative least squares migration scheme (LS-FWM) can attenuate the cross-talk noise that historically challenged the applicability of SWIM beyond moderately shallow depths, and enables deep seismic imaging with optimized illumination and spatial resolution.

Lecerf et al. (2015a,b) and (Martin et al., 2018) extended SWIM to OBC and OBN data. The historical processing used to mitigate poor shallow illumination from coarsely-sampled OBC and OBN data was ‘mirror migration’; wherein first-order multiples in the P-DWN wavefield are imaged by treating them as though they had been recorded above the sea surface at an elevation equal to the seafloor depth. This procedure generates better images than those produced conventionally from the P-UP primary wavefield because it expands the area of illumination for shallow targets. The obvious restriction, however, is that mirror migration only uses the first-order multiples in the P-DWN wavefield to create an image. In contrast, SWIM uses every shot as virtual receivers, and therefore the source-side free-surface multiple reflections are treated as signal. The resulting image has a greater spatial extent than the one obtained with conventional imaging, thanks to the dense and wide distribution of sources. Furthermore, in shallow water environments, the angular diversity provided by multiples means that the recovered reflectivity sections are free of traditional distortions observed in conventional imaging. Recent applications of SWIM and LS-FWM have also produced data suitable for geohazard assessment on conventionally-acquired OBS (and deep tow multisensor streamer) data, mitigating the additional expenditure associated with performing this kind of analysis using site survey acquisition and processing (refer to Figure 3). There is no theoretical limit on how many orders of surface multiples can contribute to SWIM, and it can be demonstrated that the density of seafloor receivers deployed can be decimated quite substantially without unacceptably compromising the image quality and resolution of OBC/OBN SWIM images, thereby promising efficiency and cost gains during acquisition (Lecerf et al., 2017).

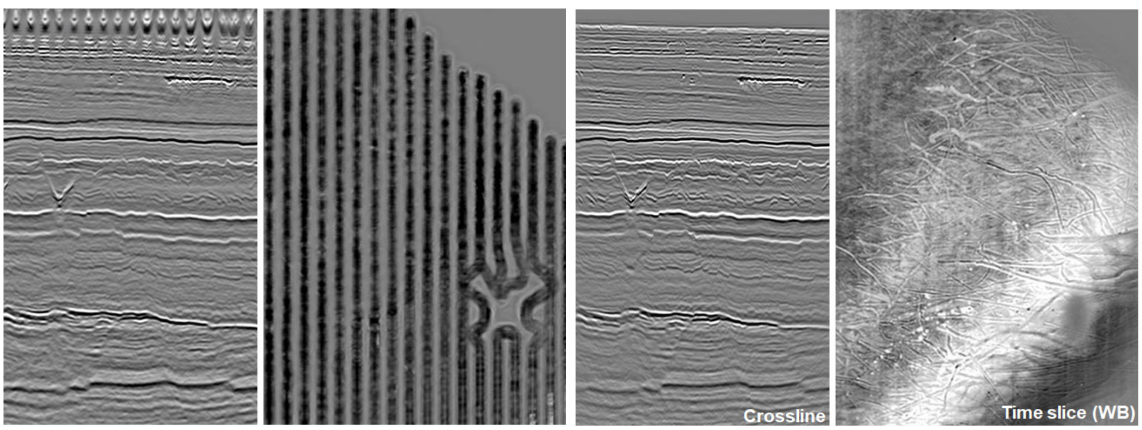

Figure 3. (left) Cross-line migrated stack and time slice at the seafloor level for Kirchhoff PSTM of multisensor OBC data; and (right) SWIM shallow hazard (SHAZ) product using the same data. Note how the acquisition footprint and the receiver coverage hole below a production platform in the second panel is mitigated by SWIM in the fourth panel.

Measurement of Vector Particle Velocity Wavefields

As discussed earlier, the particle velocity for a seismic wavefront corresponds to the normal outward derivative of the pressure for that wavefront, and taken together, a knowledge of the pressure and particle velocity (specifically, the vertical component of the particle velocity, Vz) enables wavefield separation of P-UP and P-DWN. The same physical principles discussed in Carlson et al. (2017) have been used to develop inversion-based approaches to deghosting and data reconstruction that additionally take advantage of recorded crossline particle motion data (Robertsson et al., 2008; Özbek et al., 2010; Vassallo et al., 2010) and can theoretically enable accurate wavefield separation for higher emergence angles in the cross-line direction than can be recovered using dual-sensor streamers. Note that their methodology assumes that the horizontal wavenumber in both the inline and cross-line direction is known for all (three-dimensional) angles of emergence and temporal frequencies of interest, and signals are recorded by the cross-line accelerometers with adequate signal-to-noise ratio (Day et al., 2013). In practice, the latter assumption generally only follows for moderately shallow depths where the cross-line emergence angle exceeds several degrees. Tiegen et al. (2012) also show that additional modes of noise can be recorded by multisensor streamers that incorporate cross-line axis sensors, necessitating finer spatial sampling in the inline direction than historically used as most mechanical streamer noise is slower than the speed of sound through water. Nevertheless, if successfully recorded, a knowledge of the second-order crossline derivatives of pressure in the horizontal direction allows at least one order of aliasing to be removed; effectively enabling higher spatial resolution in the cross-line direction (Robertsson et al., 2008).

The use of vector measurements of particle velocity in effect enable the determination of vector pressure gradients; also determinable in a specific direction using two receivers with known separation. One such approach is based on recording data with multiple streamers at different constant depths (e.g., Sønneland, et al., 1986; Hill et al., 2006; Moldoveanu et al., 2007). If the same wavefield is recorded by receivers at two different depths, the receiver-side ghost effects for each depth will be different. Provided the depths are chosen such that there are no common spectral notches within the usable bandwidth, then, wherever there is a spectral notch for one depth, good SNR will be recorded at the other depth, thereby increasing the usable bandwidth compared to a single depth. Similar approaches have also been proposed for extending the usable bandwidth emitted by the source (e.g., Egan et al., 2007; Cambois et al., 2009; Parkes and Hegna, 2011).

Furthermore, where adequate phase control of a towed marine vibrator sweep exists over all frequencies of interest, laterally-separated marine vibrators at a common depth sweeping simultaneously with opposite polarity sweeps can in principle enable the spatial sampling of the receiver wavefield to be decimated in the cross-line direction without aliasing—in the same manner claimed by Robertsson et al. (2008), courtesy of cross-line particle velocity sensors.

So overall, the deployment of ‘multiple sensors’ to measure vector pressure gradients, or the use of multisensor receivers to measure vector particle velocity, present opportunities for wavefield interpolation/reconstruction beyond the Nyquist limits of the natural receiver interval in the cross-line direction, and therefore, may also provide opportunities for more efficient acquisition with coarser receiver sampling in the cross-line direction. It is worth noting, however, that Figure 4 illustrates how the denser illumination provided by several orders of surface multiples, by comparison to primary reflections, enables SWIM to yield higher resolution shallow images—without acquisition footprint effects—than can be achieved using multisensor wavefield reconstruction methods such as described in Robertsson et al. (2008). The acquisition footprint in the upper panel of Figure 4 primarily arises because the near offset becomes large for the outermost streamers (as shown in Figure 1), and shallow CMP fold on the relevant sublines correspondingly becomes negligible after the application of the outer mute in processing. The input data in the upper panel of Figure 4 were interpolated from a natural cross-line bin size of 25 m to only 6.25 m using the methodology described in Robertsson et al. (2008), whereas the input data in the lower panel of Figure 4 used the natural cross-line bin size of 25 m, but SWIM still achieves comparable spatial resolution, and with superior contiguous image quality!

Figure 4 alludes to an issue perhaps not obvious in the previous discussion that the spatial sampling in the shot domain is just as critical as spatial sampling in the receiver domain for maximizing the wavenumber content of the data and therefore the maximum spatial resolution achievable in seismic imaging. Shot sampling is typically coarse and highly non-uniform for towed streamer 3D acquisition, but the receiver sampling, especially for high-density 3D (HD3D) surveys with dense streamer spacing, is far denser and relatively uniform. In contrast, shot sampling is typically dense and uniform for OBS 3D, but the receiver sampling is coarse, highly non-uniform in the case of OBC (reasonably inline receiver spacing, coarse cable spacing), and areally limited by comparison to the shot grid. But SWIM enables every receiver to act as a virtual source for towed streamer 3D, and every shot to act as a virtual receiver for OBS 3D, so there is tremendous scope when using the full wavefield to improve spatial resolution in both acquisition scenarios. In the case of Figure 4, as the average receiver spacing is 12.5 x 75 m, now the virtual source spacing, the benefits to shallow spatial resolution and image quality are far more compelling than any ability to improve cross-line spatial sampling when imaging only primary reflections.

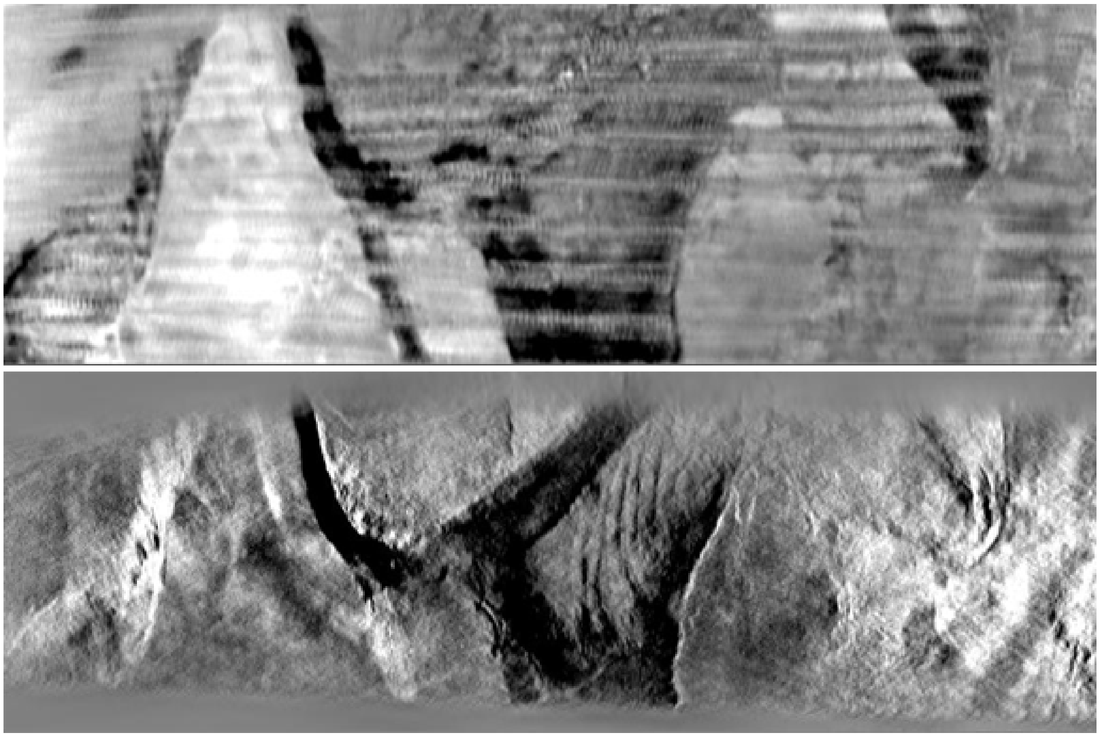

Figure 4. (upper) Conventional Kirchhoff PSTM migration at 92 m depth below MSL of 10 adjacent sail lines of multisensor towed streamer data with 75 m streamer separation reconstructed to 6.25 m cross-line bin size; and (lower) SWIM image at the same depth of the same data, but with the natural cross-line bin size of 25 m as input.

Measurement of Shear Waves

Shear waves cannot be propagated through a fluid, hence, shear waves can only be recorded by OBC and OBN receivers directly coupled to the seafloor. In fact, what is recorded by OBC/ OBN sensors is typically converted waves as the source is traditionally an air gun array towed through the water and therefore incapable of emitting shear waves. Ozasa et al. (2016, 2017) conceptually demonstrate how dipole marine vibrators operating a short distance above the seafloor can generate shear waves below the seafloor, but this is beyond the discussion here.

The kinematics of converted wave propagation are complex and asymmetric with respect to each subsurface reflection point. For example, because shear wave velocity is inevitably slower in any formation than the compressional wave velocity, the angle of reflection will be smaller than the angle of incidence, and the ratio of angles varies with depth. Therefore, processing steps such as trace binning and velocity analysis become interdependent, and an iterative approach to cascaded binning and velocity analysis is pursued in practice. Horizontal records from multisensor OBS data are seldom used in imaging. However, mode-converted waves propagate significant distances in the subsurface as purely compressional waves, and this information can be isolated and recovered by the use of the deconvolution imaging condition in SWIM; thereby providing complementary target illumination.

The image parameters of OBC/OBN data are fundamentally dictated by the receiver deployment. Cost considerations typically mean that receiver separation is between 25 and 50 m along each OBC cable, and the separation between each OBC cable (or the separation in all directions between each OBN receiver) may be several hundreds of meters. Furthermore, limited equipment inventories typically mean that the spatial area of the receivers deployed at any moment in time is far smaller than the area of the shot grid recorded for each receiver configuration. For conventional imaging of primary reflections and converted wave reflections this means that the spatial aperture of the migration image roughly corresponds to the spatial area described by the receiver deployment, and the spatial resolution (and in turn, temporal resolution) is limited by Nyquist limits related to the receiver separations. However, Lecerf et al. (2015a) demonstrate that the application of SWIM to OBC/OBN data enable high-order multiples to extend reservoir illumination to the spatial aperture of the surface shot point grid; a ten-fold increase in the imaged area in the deepwater case example used, and applicable to time-lapse (4D) acquisition. Furthermore, van den Berg et al. (2018) also demonstrate how significant decimation of the receiver sampling can often be pursued, thereby saving acquisition effort and cost, without compromising the resolution of quality of SWIM images (refer to Figure 5).

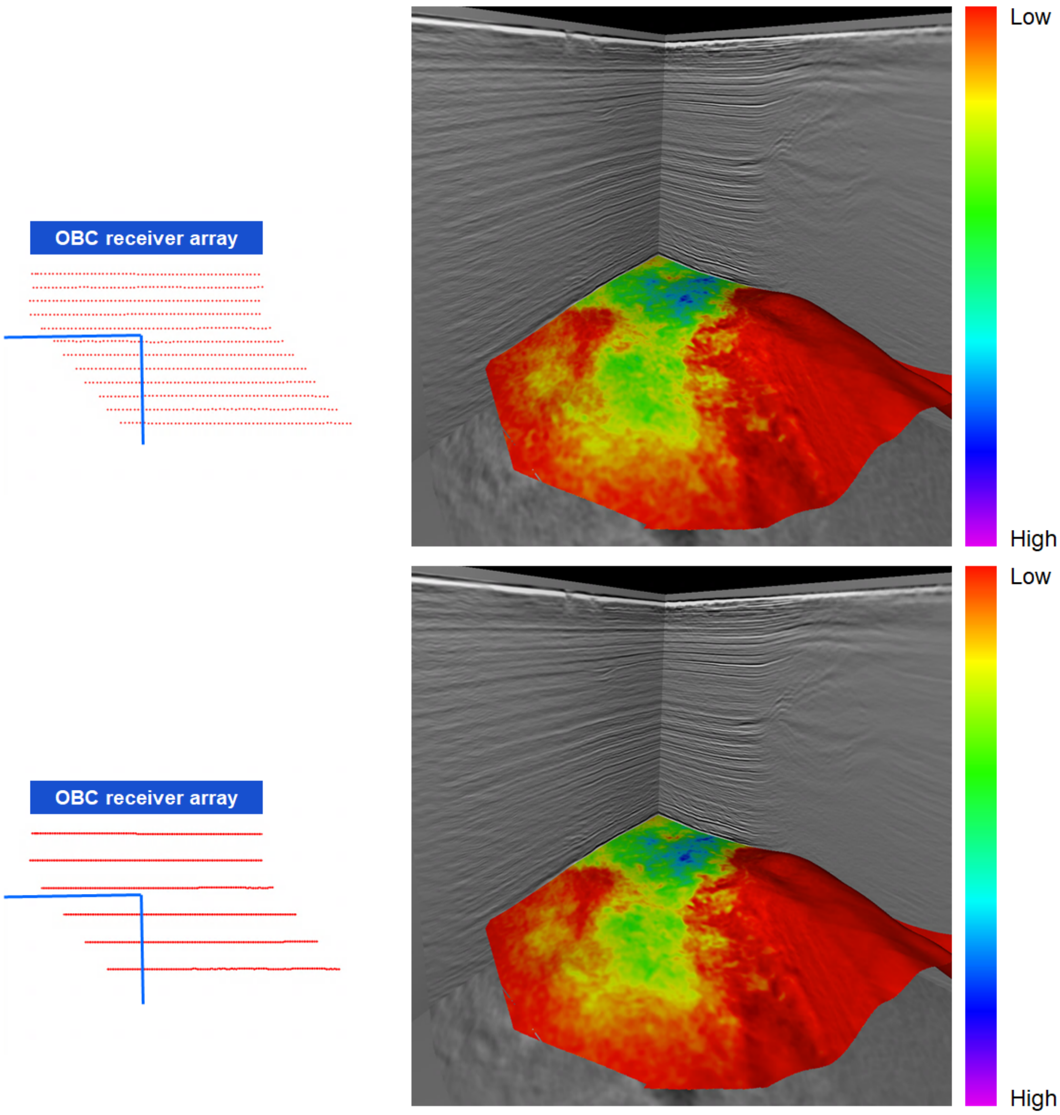

Figure 5. (upper) Inline and cross-line migrated stacks from an undecimated multisensor OBC volume imaged with SWIM, plus an amplitude extraction at an interpreted horizon; and (lower) The equivalent SWIM images after every second OBC cable was dropped. The blue lines superimposed on the survey map show the locations of the extracted vertical seismic sections.

Image domain 4D reflectivity inversion using multi-dimensional point spread functions (PSFs) has been shown to be able to compensate for significant illumination differences and to recover the full signal bandwidth when substantially different survey geometries such as towed streamer and OBS are used for 4D imaging (Lecerf and Besselievre, 2018), thereby extending the relevance of SWIM and LS-FWM.

Summary

A common theme that emerges through the use of both deep tow multisensor streamers and multisensor OBC/OBN data is access to separated wavefields, and the associated opportunities for new survey designs, improved operational efficiency, and high resolution seismic imaging at all depths. From an efficiency perspective, SWIM and LS-FWM enable SHAZ processing products to be produced from both exploration towed streamer data and OBC/OBN data, thereby mitigating the additional expenditure associated with site survey acquisition and processing; and OBC/OBN receiver deployment may be reduced without compromising image quality, thereby providing opportunities for flexible and cost effective survey designs. Although methods have been published that use cross-line particle motion measurements to increase the Nyquist wavenumber and therefore, the theoretical spatial resolution of multisensor seismic images, such methods rely upon interpolating data between the physical measurement points of primary reflections. In contrast, the illumination of the full seismic wavefield is far denser, so both SWIM and LS-FWM improve spatial resolution using real physical data measurements. Finally, new seismic imaging methods can also improve the integration of multisensor streamers and multisensor OBC/OBN data for both 3D and 4D seismic applications. OBC/OBN data have the benefit of recording shear and converted waves, and SWIM is now starting to create new opportunities to exploit the complementary illumination of mode-converted events recorded by horizontal particle velocity sensors.

References

Barros, C., Burren, J., Hodges, E. and Lecerf, D. [2014] The impact of the receiver-side ghost on 4D monitoring using broadband seismic. 2nd EAGE/SBGf Workshop on Broadband Seismic, Extended Abstracts, We D04. (https://www.pgs.com/globalassets/technical-library/whitepapers-library/2014nov_pgs_barros_etal_4d.pdf)

Caprioli, P.B.A., Özdemir, A.K., Özbek, A., Kragh, J.E., van Manen, D.J., Christie, P.A.F. and Robertsson, J.O.A. [2012] Combination of multicomponent streamer pressure and vertical particle velocity – Theory and application to data. 74th EAGE Conference & Exhibition, Extended Abstracts, A033.

Cambois, G., Long, A., Parkes, G., Lundsten, T., Mattsson, A., and Fromyr, E. [2009] Multi-Level airgun array: A simple and effective way to enhance the low frequency content of marine seismic data. 79th Annual SEG International Meeting, Expanded Abstracts, 152-156.

Carlson, D., Long, A., Söllner, W., Tabti, H., Tenghamn, R. and Lunde, N. [2007] Increased resolution and penetration from a towed dual-sensor streamer. First Break, 25(12), 71-77. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_carlson_etal_dec2007_increasedresolutionandpenetration.pdf)

Claerbout, J.F. [1976] Fundamentals of geophysical data processing. Blackwell Scientific Publications, 289 p.

Day, A., Kluver, T., Söllner, W., Tabti, H. and Carlson, D. [2013] Wavefield-separation methods for dual-sensor towed-streamer data. Geophysics, 78(2), WA55-WA70. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/geophysics_day_etal_2013_wavefiledseparation.pdf)

Egan, M., El-Kasseh, J.G. and Moldoveanu, N. [2007] Full deghosting of OBC data with over/under source acquisition. 77th Annual SEG International Meeting, Expanded Abstracts, 31–35.

Feuilleaubois, L.O., Charoing, V., Maioli, A. and Reiser, C. [2017] Utilizing a novel quantitative interpretation workflow to derisk shallow hydrocarbon prospects – a Barents Sea case study. First Break, 35(3), 85-92. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_feuilleaubois_etal_march2017_utilizinganovelquantitative.pdf)

Fokkema, J.T. and van den Berg, P.M. [1993] Seismic applications of acoustic reciprocity: Elsevier Science Publishing, 352 p.

Hill, D., Combee, C. and Bacon, J. [2006] Over/under acquisition and data processing: The next quantum leap in seismic technology? First Break, 24(6), 81–95.

Lecerf, D., Valenciano, A,. Chemingui, N., and Lu, S. [2015a] Using high-order multiples to extend reservoir illumination for time-lapse monitoring - Application to Jubarte PRM. 77th EAGE Conference and Exhibition, Extended Abstracts, Tu N101 03.

Lecerf, D., Hodges, E., Lu, S., Valenciano, A., Chemingui, N., Johann, P., and Thedy, E. [2015b] Imaging primaries and high-order multiples for permanent reservoir monitoring: Application to Jubarte field. The Leading Edge, 34(7), 824-828. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/tle_lecerf_etal_july2015_imagingprimaries.pdf)

Lecerf, D., Barros, C., Hodges, E., Valenciano, A., Lu, S., Chemingui, N., Johann, P. and Thedy, E. [2017] Very sparse seabed seismic acquisition for 3D/4D reservoir imaging with high-order multiples. Application to Jubarte PRM. 79th EAGE Conference & Exhibition, Extended Abstracts, Tu A1 12. (https://www.pgs.com/globalassets/technical-library/whitepapers-library/2017June_Lecerf_etal_VerySparse.pdf

Lecerf, D., and Besselievre, M. [2018] A new approach to compensate for illumination differences in 4D surveys with different individual acquisition geometries. First Break, 36(2), 71-76. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_lecerf_etal_feb2018_4dsynthetic.pdf)

Lecerf, D., Raistrick, D., Caselitz, B., Wingham, M., Bradley, J., and Moseley, B. [2018] 4D broadband towed-streamer assessment, West Africa deep water case study. 80th EAGE Conference and Exhibition, Extended Abstracts, Tu A15 09.

Long, A., Lu, S., Whitmore, D., LeGleut, H., Jones, R., Chemingui, N. and Farouki, M. [2013] Mitigation of the 3D cross-line acquisition footprint using separated wavefield imaging of dual-sensor streamer seismic. 75th EAGE Conference & Exhibition, Extended Abstracts, Th 01 05. (https://www.pgs.com/globalassets/technical-library/whitepapers-library/2013june_pgs_long_etal_swim.pdf)

Lu, S., Whitmore, D., Valenciano, A. and Chemingui, N. [2014] Enhanced subsurface illumination from separated wavefield imaging. First Break, 32(11), 87-92. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_lu_etal_nov2014_enhancedsubsurface_swim.pdf)

Lu, S., Valenciano, A.A., Chemingui, N. and Lecerf, D.B. [2015] Separated wavefield imaging of ocean bottom seismic (OBS) data. 77th EAGE Conference and Exhibition, Extended Abstracts, WE N106 08. (https://www.pgs.com/globalassets/technical-library/whitepapers-library/2015june_pgs_lu_etal_swim-obc.pdf)

Lu, S., Liu, F., Chemingui, N., Valenciano, A. and Long, A. [2018] Least-squares full-wavefield migration, The Leading Edge, 37(1), 46-51. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/tle_lu_et_al_jan2018_ls-fwm.pdf)

Martin, T., van der Burg, D., Fasterling, J. and Musser, J. [2018] Separated wavefield imaging for shallow geohazard analysis - An ocean bottom study on a North Sea dataset. 80th EAGE Conference & Exhibition, Extended Abstracts, Th P8 16. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/eage2018_pgs-maersk_martin_etal_june2018_obs-swim-geohazards.pdf)

Moldoveanu, N., Combee, L., Egan, M., Hampson, G., Sydora, L., and Abriel, W. [2007] Over/under towed-streamer acquisition: A method to extend seismic bandwidth to both higher and lower frequencies. The Leading Edge, 26(1), 41–58.

Ozasa, H., Sato, F., Asakawa, E., Murakami, F., Hondori, E.J., Takekawa, J. and Mikada, H. [2016] Development of marine seismic vibrator towards realization of shear wave source with no touch-down to seafloor. IPTC, Bangkok, IPTC-18903-MS.

Ozasa, H., Hatanaka, H., Nagai, Y., Asakawa, E., Murakami, F., Hondori, E.J., Takekawa, J. and Mikada, H. [2017] Realization of offshore shear-wave survey with marine vibrator and interferometric approach. 87th Annual SEG International Meeting, Expanded Abstracts, 2523-2527.

Özbek, A., Vassallo, M., Özdemir, K., van Manen, D.-J. and Eggenberger, K. [2010] Crossline wavefield reconstruction from multicomponent streamer data: Part 2—Joint interpolation and 3D up/down separation by generalized matching pursuit. Geophysics, 75(6), WB69–WB85.

Parkes, G. and Hegna, S. [2011] An acquisition system that extracts the earth response from seismic data. First Break, 29(12), 81–87. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_parkes_etal_dec2011_anacquisitionsystem.pdf)

Posthumus, B.J. [1993] Deghosting using a twin streamer configuration. Geophysical Prospecting, 41, 267–286.

Reiser, C., Bird, T. and Whaley, M. [2015a] Interpretation and reservoir properties estimation using dual-sensor streamer seismic without the use of well. EAGE Workshop on Broadband Seismic. - A Broader View for the Middle East, Extended Abstracts, BS22. (https://www.pgs.com/globalassets/technical-library/whitepapers-library/2015nov_pgs_reiser_etal_qi.pdf)

Reiser, C., Bird, T. and Whaley, M. [2015b] Reservoir property estimation using only dual-sensor seismic data – a case study from the West of Shetlands, UKCS. First Break, 33(10), 93-101. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_reiser_etal_october2015_reservoirpropertyestimation.pdf)

Robertsson, J.O.A., Moore, I., Vassallo, M., Özdemir, K., van Manen, D.-J. and Özbek, A. [2008] On the use of multicomponent streamer recordings for reconstruction of pressure wavefields in the crossline direction. Geophysics, 73(5), A45–A49.

Rønholt, G., Korsmo, Ø, Brown, S., Valenciano, A., Whitmore, D., Chemingui, N., Brandsberg-Dahl, S., Dirks, V. and Lie, J.-E. [2014] High-fidelity complete wavefield velocity model building and imaging in shallow water environments – A North Sea case study. First Break, 32(6), 127-131. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_ronholt_etal_jun2014_highfidelity.pdf)

Sønneland, L., Berg, L.E., Eidsvig, P., Haugen, A., Fotland, B. and Vestby, J. [1986] 2-D deghosting using vertical receiver arrays. 56th Annual SEG International Meeting, Expanded Abstracts, 516–519.

Teigen, O., Ozdemir, K., Kjellesvig, B.A., Goujon, N. and Pabon, J. [2012] Characterization of noise modes in multicomponent (4C) towed-streamer. 74th EAGE International Conference and Exhibition, Extended Abstracts, Z013.

van der Burg, D., Martin, T., Asnaashari, A., Perrier, S., Fasterling, J., and Musser, J. [2018] Separated wavefield imaging for ocean bottom surveys – Feasibility study of receiver decimation on a North Sea dataset. 80th EAGE Conference & Exhibition, Extended Abstracts, Tu A10 11. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/eage2018_pgs-maersk_vanderberg_etal_june2018_swim-obn-decimation.pdf)

Vassallo, M., Özbek, A., Özdemir, K. and Eggenberger, K. [2010] Crossline wavefield reconstruction from multicomponent streamer data: Part 1 — Multichannel interpolation by matching pursuit (MIMAP) using pressure and its crossline gradient. Geophysics, 75(6), WB53–WB67.

Whitmore, N.D., Valenciano, A.A., Sollner, W. and Lu, S. [2010] Imaging of primaries and multiples using a dual-sensor towed streamer. 80th SEG Technical Program, Expanded Abstracts, 3187-3192. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/seg2010_whitmore_etal_sept2010_imagingofprimaries_swim.pdf)

Widmaier, M., Fromyr, E. and Dirks, V. [2015] Dual-sensor towed streamer: from concept to fleet-wide technology platform. First Break, 33(11), 83-89. (https://www.pgs.com/globalassets/technical-library/tech-lib-pdfs/fb_widmaier_etal_nov_2015_dual-sensor_towed_streamer.pdf)

PGS Links

Acquisition Calculator (https://www.pgs.com/marine-acquisition/tools-and-techniques/acquisition-solutions/calculator/acquisition-calculator/)

Acquisition Solutions (https://www.pgs.com/marine-acquisition/tools-and-techniques/acquisition-solutions/)

GeoStreamer (https://www.pgs.com/marine-acquisition/tools-and-techniques/geostreamer/)

GeoStreamer Infographic (https://www.pgs.com/publications/infographics/geostreamer/)

SWIM (https://www.pgs.com/marine-acquisition/tools-and-techniques/geostreamer/technology/imaging-with-separated-wavefields/)

SWIM Infographic (https://www.pgs.com/publications/infographics/extending-illumination-and-angular-diversity/)