Mitigation of the 3D Cross-line Acquisition Footprint Using Separated Wavefield Imaging of Dual-sensor Streamer Seismic Data

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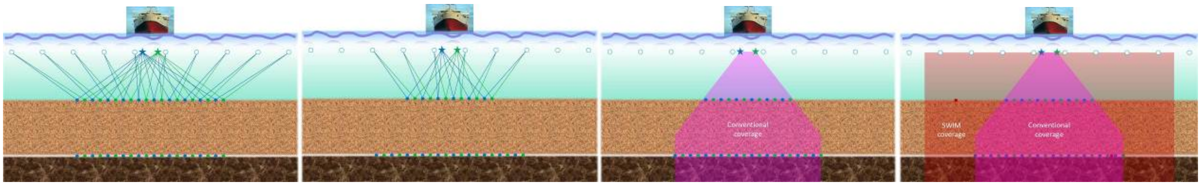
SUMMARY

Lundin Malaysia BV completed the first-ever application of separated wavefield PSDM imaging to 3D dual-sensor streamer seismic data as a test to improve shallow geological interpretation. The methodology exploits the illumination corresponding to surface multiple energy, and thus exploits what has historically been treated by the seismic industry as unwanted noise. Whereas a strong cross-line acquisition footprint affected the very shallow 3D data using conventional processing and imaging, the new results yield spectacular continuous high resolution seismic images, even up to and including the water bottom. One implication of these results is that very wide-tow survey efficiency can be achieved without compromising shallow data quality if dual-sensor streamer acquisition and processing is used, even in very shallow water areas such as that discussed here. The imaging methodology can account for all degrees of lateral variability in the velocity model, full anisotropy can be accounted for, and angle gathers can be created to assist with velocity model building

Introduction

Whilst 3D seismic surveys can be acquired efficiently using wide-tow streamer configurations, a 3D cross-line acquisition footprint develops which can degrade the shallow data, to the extent that the water bottom may not be imaged continuously and shallow targets may be recorded with insufficient coverage. Figure 1 illustrates the cross-line acquisition footprint problem. Figure 1a shows the nominal cross-line subsurface illumination for a 10 streamer configuration operating in dual-source mode. However, for shallow events and at large offsets a frequency distortion occurs as a result of Normal Moveout Correction (NMO), and a mute is required to remove this 'NMO stretch'. The useful recorded data for a shallow target is therefore limited to smaller offsets (Figure 1b) and a narrow cone of penetration for the shallow layers results (Figure 1c). For certain shallow events, the critical angle for reflection recording will be the limiting factor. Data recorded by outer streamers may not contribute to the shallow 3D seismic image.



Figures 1a,b,c,d *Figure 1a: The nominal cross-line subsurface coverage for wide-tow streamer acquisition. Figure 1b: The useful subsurface coverage for shallow events at far offsets is limited due to the effects of NMO stretch and the critical angle of recording, giving rise to a narrow cone of pentration for the shallow section as in Figure 1c. Figure 1d: Separated wavefield imaging exploits the surface multiple raypaths to provide illumination of the shallow section that extends to almost the entire streamer spread width.*

The design of a 3D seismic survey requires the positioning of adjacent sail lines such that the subsurface coverage in the cross-line direction is continuous for deeper targets; this means that, for the reasons described above, a cross-line acquisition footprint results with a periodic loss of coverage for the shallower horizons. This effect is seen clearly in the left and right sections of Figure 4.In this paper we show that the 3D cross-line acquisition footprint may be mitigated using separated wavefield imaging of dual-sensor streamer seismic data. The improved subsurface coverage for the shallow section that results from this approach will extend to almost the entire streamer spread width (Figure 1d).

Method

Figure 2 is a schematic illustration of various primary reflection, surface ghost, and both surface and internal multiple ray paths for towed streamer seismic data. In the historically ideal scenario, primary reflection data is recovered that includes no surface ghost effects and no multiple reflections from the earth. The "up-going" pressure wavefield is that which is scattered up from the earth and yet to encounter the free-surface of the ocean. The "down-going" pressure wavefield is the time-delayed version of the up-going wavefield that is reflected downwards from the free-surface of the ocean with opposite polarity (also referred to as the "receiver ghost" version). Conventional hydrophone-only streamers record a continuously interfering combination of the up-going and down-going pressure wavefields – the total pressure wavefield (Carlson *et al*., 2007).

Whitmore et al. (2010) published an approach whereby one-way wave equation pre-stack depth migration (PSDM) is reconfigured to use up-going and down-going wavefields to image the earth with surface multiple data that would historically be treated as unwanted noise (refer also to Figure 3). These up-going and down-going wavefields are derived from wavefield separation of dual-sensor streamer data (Carlson et al., 2007). Surface multiples provide laterally more extensive illumination of the earth than primary reflections for a conventional 3D towed streamer geometry, particularly for shallower geology. Lu et al. (2011) demonstrated the greater lateral extent of imaging using separated wavefields using SEAM synthetic data and full-azimuth (FAZ) acquisition geometry. This paper presents the first-ever case study of imaging using separated wavefields using conventional towed streamer 3D acquisition geometry.

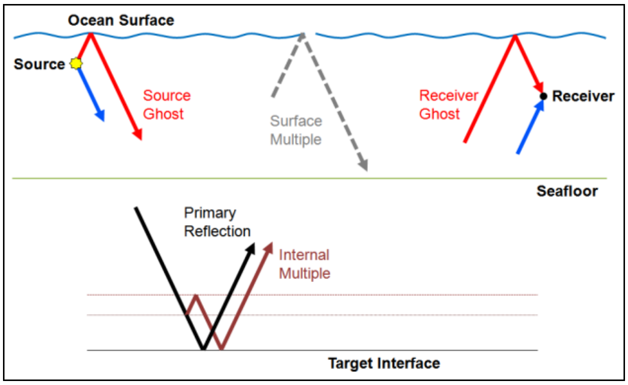


Figure 2 *Schematic diagram for various primary reflection and multiple reflection modes in towed streamer seismic data. Any multiple ray path that includes a reflection from the free-surface of the ocean is classified as a surface multiple. Internal multiples do not include any free-surface reflections. The red ray paths indicate surface ghost events.*

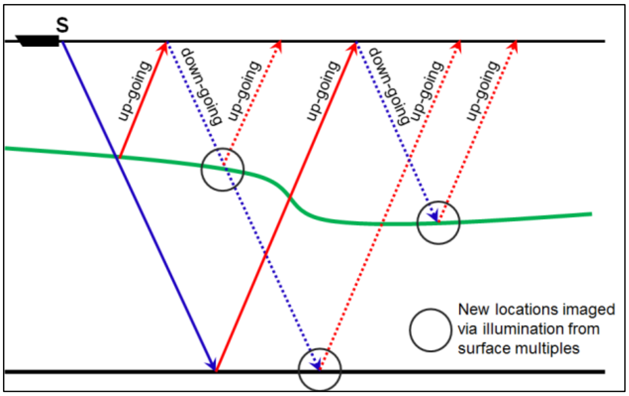


Figure 3 *Schematic diagram for primary reflections (solid lines) and first-order surface multiples (dotted lines) from two subsurface interfaces. In the context of dual-sensor wavefield separation, the dotted red ray paths represent the up-going wavefield and the dotted blue ray paths represent the down-going wavefield. Separated wavefield imaging uses the up-going and down-going wavefields to image either the illumination corresponding to primary reflections or surface multiples. Surface multiples typically have a greater lateral extent of illumination.*

Figure 4 shows 3D ray tracing-based modeling of the illumination at a target surface roughly 500m below the water bottom in a 3D model interpreted from real seismic data. In each case, 10 consecutive shots were modeled for three adjacent sail-lines. The streamer spread was 10 x 6,000 m streamers at 100 m separation and with dual-source shooting. First order surface multiples from the target interface remove the classic far offset illumination gaps modeled using primary-only reflections. Higher order multiples will illuminate the area between adjacent sail-lines with even higher density. The imaging process described here exploits exactly this illumination, but provided by all orders of surface multiples – not only the first-order multiples. In principle, the cross-line illumination extent for surface multiples can be almost as large as the streamer spread width itself, in contrast to the CMP-based illumination coverage of primaries which is generally about half the width of the streamer spread. Hence, some of the major contributors to the shallow cross-line acquisition footprint (loss of fold and illumination coverage) are mitigated with the 3D imaging solution described here. Another attractive aspect for the near-term development of this solution is that the cross-line acquisition footprint generally affects only shallow data (0-1 seconds at most, even for ultra wide-tow spreads), so the target depth range of interest is unlikely to be affected by cross-talk imaging artifacts associated with very high order surface multiples (refer to Lu *et al*., 2011).

Considerable flexibility exists within the imaging methodology being used. The operator can be adjusted in terms of numerical complexity according to the lateral variability of the velocity model, full anisotropy can be accounted for, and angle gathers can be created to assist with velocity model building. The only assumption is that true wavefield separation of dual-sensor streamer data has been completed in pre-processing.

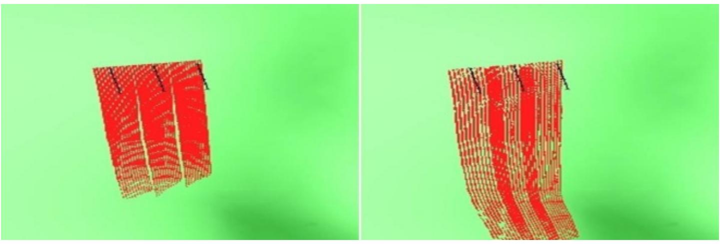


Figure 4 *Modeling of the illumination (reflection points) for three adjacent sail-lines, and primary-only reflections (left) and first order surface multiples-only (right). Note the overlapping illumination between adjacent sail-lines on the right, removing the far offset gaps seen on the left.*

Malaysia Data Example

The data set used was a roughly 400 km² extract from a dual-sensor streamer survey over the Tenggol Arch area in offshore Peninsula Malaysia, in approximately 70m water depth. This survey was acquired in 2011 using a 12 x 4050 m dual-sensor streamer spread with 75m separation and 15 m depth. The data were processed through a simple workflow using the modified one-way wave equation migration. Imaging was pursued up to 60 Hz, ramping off to 80 Hz maximum. This choice was made simply because of the experimental nature of the test. A deconvolution imaging condition was used to separately image the illumination of primary reflections only and the illumination of surface multiples only.

Results and conclusions

Figure 5 shows a comparison of depth slices at 70m. The one-way separated wavefield wave equation PSDM of primaries only (left) contains a pronounced cross-line acquisition footprint that precludes shallow geohazard interpretation. In contrast, one-way separated wavefield wave equation PSDM of surface multiples (right) yields a remarkably continuous and high resolution image because of the superior illumination from surface multiples.

Figure 6 shows a comparison of cross-line stacks displayed for 0.0 to 0.5 s TWT. One-way separated wavefield wave equation PSDM of multiples only (upper panel) and conventional Kirchhoff PSTM of primaries only (lower panel) illustrate how imaging with the surface multiple illumination mitigates the cross-line acquisition footprint. In the upper panel the water bottom reflector is fully preserved. The PSDM image was stretched to TWT for comparison with the PSTM result.

The results are very encouraging. Not only has the water bottom been recovered, but the significantly improved fold and illumination from the PSDM of surface multiples yields a near surface volume which is of sufficiently high resolution to serve as a basis for a regional geohazard study.

Separated wavefield WEM imaging is an innovative new one-way wave equation depth migration solution that uses seismic data acquired with dual-sensor streamers and images seismic multiples, delivering broadband and continuous seismic images all the way up to, and including, the seafloor seismic event – even in areas with very shallow water and where the 3D seismic surveys have towed a very large streamer spread to optimize survey efficiency. Although the maximum frequency imaged in the Malaysian example presented here was 60 Hz, there is no theoretical upper limit. High-order multiples introduce increasing levels of cross-talk noise, but this can be ignored for the depth range affected by the cross-line acquisition footprint – even for shallow water. The paradigm shift is that 3D marine seismic survey efficiency can be increased (at much lower cost) whilst the very shallow seismic images are in fact improved in terms of both vertical and lateral resolution! Considerable flexibility exists within the imaging methodology being used, including automatic operator complexity according to the lateral variability of the velocity model, full anisotropy capability, and the generation of angle gathers. When pursued in tandem with broadband amplitude recovery, the solution described here potentially meets all exploration, appraisal and production requirements regarding seismic-based discovery and recovery.

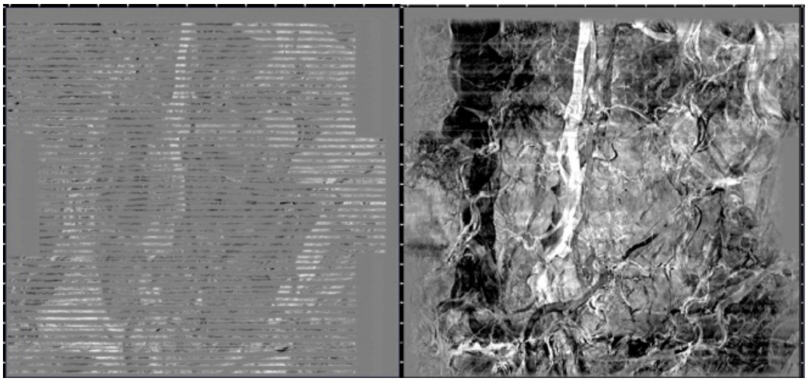


Figure 5 *Comparison of depth slices at 70m. One-way separated wavefield wave equation PSDM of primaries only (left) contains a pronounced cross-line acquisition footprint. In contrast, one-way separated wavefield wave equation PSDM of surface multiples (right) yields a remarkably continuous and high resolution image because of the superior illumination from surface multiples.*

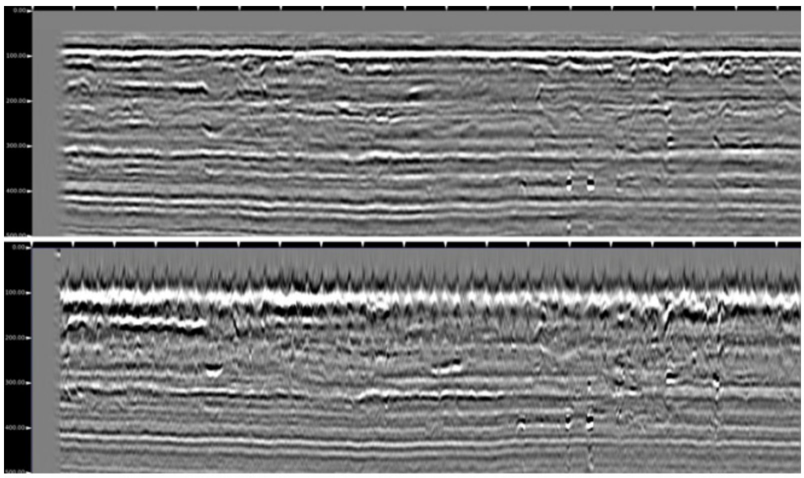


Figure 6 *Comparison of cross-line stacks displayed for 0.0 to 0.5 s TWT. One-way separated wavefield wave equation PSDM of multiples only (top) and conventional Kirchhoff PSTM of primaries only (bottom) illustrate how imaging with the surface multiple illumination mitigates the cross-line acquisition footprint.*

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