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

A.S. Long* (PGS), S. Lu (PGS), D. Whitmore (PGS), H. LeGleut (PGS), R. Jones (Lundin Malaysia BV), N. Chemingui (PGS) & M. Farouki (PGS)

SUMMARY

A modified one-way equation pre-stack depth migration of up-going and down-going pressure wavefields was applied to two datasets derived from 3D towed dual-sensor streamer data in offshore Australia and Malaysia. The primary objective was to mitigate the well-known cross-line acquisition footprint effects upon shallow data quality and interpretability.

The new methodology introduced here 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, and angle gathers can be created to assist with velocity model building.

Introduction

Figure 1 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. Terminology used below describes the “up-going” pressure wavefield as that 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).

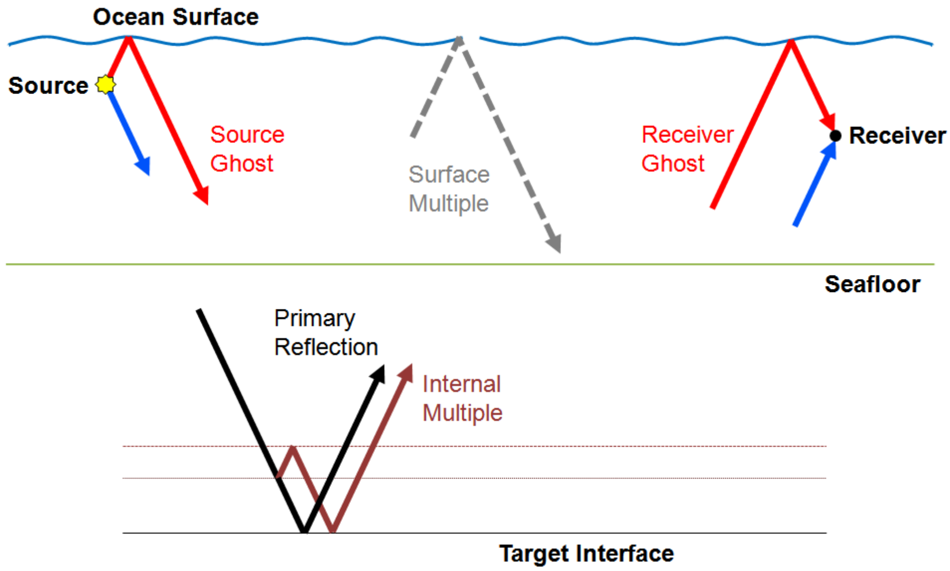

Figure 1 *Schematic diagram for various primary reflection and multiple reflection modes in towed streamer seismic data. Any multiple ray path that includes a reflection from the free-surface of the ocean is classified as a surface multiple. Internal multiples do not include any free-surface reflections. The light red ray paths indicate surface ghost events.*

Whitmore et al. (2010) published an approach whereby one-way wave equation pre-stack depth migration (WEM) is reconfigured to use the up-going and down-going wavefields to image the earth with surface multiple data that would historically be treated as unwanted noise. The 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 for imaging of separated wavefields using SEAM synthetic data and full-azimuth (FAZ) acquisition geometry. This paper presents the first-ever full-scale case study for imaging of separated wavefields with conventional towed streamer 3D acquisition geometry.

Figure 2 shows 3D ray tracing-based modelling of the illumination at a target surface roughly 500 m below the water bottom in a 3D model interpreted from real seismic data. In each case, 10 consecutive shots were modelled for three adjacent sail-lines. The dual-sensor 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 modelled using primary 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 (the cross-line receiver distribution), in contrast to the CMP-based illumination coverage of primaries which is generally about half the width of the streamer spread.

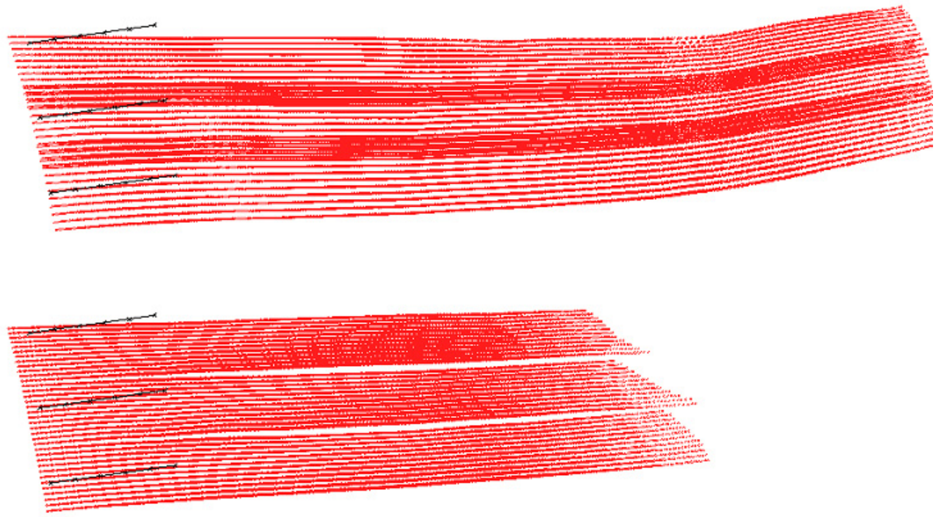

Figure 2 *Modeling of the illumination (reflection points) for three adjacent sail-lines, and primary reflections (lower) and first order surface multiples-only (upper). Note the overlapping illumination between adjacent sail-lines in the upper panel, removing the far offset gaps seen on the lower panel.*

Hence, some of the major contributors to the shallow cross-line acquisition footprint (loss of surface fold and target illumination coverage in particular) 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).

Method and Results

The forward propagated source wavefield in one-way shot profile WEM was replaced with the down-going wavefield derived from wavefield separation, and the back propagated receiver wavefield was replaced with the up-going wavefield. A deconvolution imaging condition (modified from Guitton et al., 2007) can be used to construct the subsurface image:

$$R(x) = \sum_{x_s}\sum_{\omega}\frac{D'(x,x_s;\omega)U(x,x_s;\omega)}{\langle D'(x,x_s;\omega)D(x,x_s;\omega)\rangle_{(x,y)}+\varepsilon}$$

where ***U*** and ***D*** represent the up-going and down-going wavefields at the imaging point $\mathbf{x}(x,y,z)$, initiated from the same source at $\mathbf{x_s}(x_s,y_s,z_s)$. Wavefield propagation is formulated in the frequency (ω) domain. By multiplying the down-going wavefield with its conjugate ***D'*** and adding a damping parameter ε to the denominator the smoothed deconvolution imaging condition is used. Smoothing is applied in the space domain ($\langle\rangle_{(x,y)}$).

All processing and imaging applied here followed a simple workflow. Wavefield separation was applied in the shot domain, followed by simple noise attenuation, shot profile separated wavefield WEM, and then fast-tracked to stack. As an initial test, five adjacent sail-lines from a 3D dual-sensor towed streamer dataset in the Browse Basin, Australia, were imaged over a time window of 0-3 seconds and up to a maximum frequency of 30 Hz. The dual-sensor streamer spread was 10 x 8,100 m streamers at 100 m separation, 15 m streamer depth and with dual-source shooting. Note how the cross-line acquisition footprint has been mitigated in Figure 3 when the surface multiple illumination is imaged.

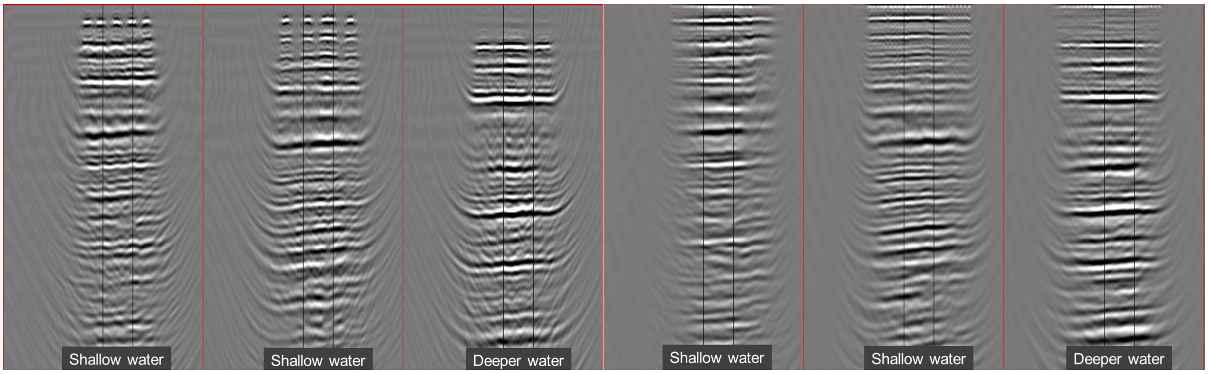

Figure 3 *Prototype brute stacks for imaging of separated wavefields applied to five adjacent sail-lines from a 3D dual-sensor streamer dataset in the Browse Basin, Australia. Vertical scale is 0 – 3 s TWT. The left panel is imaging the illumination related to primary reflections using a conventional implementation of WEM; only the up-going (separated) wavefield is used in the imaging condition. The right panel is imaging the illumination related to surface multiples only; both the up-going and down-going wavefields are used in the imaging condition. Note the significant differences in the shallow data. The first event imaged in the right panel is the free-surface of the ocean.*

Following these preliminary test results, a full-scale test for imaging of separated wavefields was pursued with a 400 km² extract from a 3D dual-sensor towed streamer survey over the Tenggol Arch area in offshore Peninsula Malaysia. Water depth is approximately 70 m. This survey was acquired in 2011 using a 12 x 4050 m dual-sensor streamer spread with 75 m separation, 15 m streamer depth and with dual-source shooting. Imaging was pursued up to 60 Hz, ramping off to a maximum of 80 Hz. This choice was made simply because of the experimental nature of the test, and a much higher frequency range could be selected instead. A final Kirchhoff pre-stack time migration (PSTM) volume was already available, so the depth imaged results were stretched back to two-way time (TWT) for comparison (refer to Figure 4).

All the results presented here are very encouraging. Considerable flexibility exists within the methodology being used for imaging of separated wavefields. 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. Thus, a simple V(z) velocity model can be used for a robust first-pass imaging effort applied to raw field gathers after wavefield separation. Consequent iterations would benefit from velocity model building in the image domain. The only assumption is that true wavefield separation of dual-sensor streamer data has been completed in pre-processing. Although not shown here, a shallow window from the depth imaged results were stretched back to time and successfully merged with time domain Kirchhoff migrated results from conventional imaging. The resultant 3D data cube therefore was achieved cost effectively and with negligible acquisition footprint effects all the way up to, and including, the seafloor reflection event.

Conclusions

Imaging of separated wavefields 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 Australian and Malaysian examples 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! The operator complexity can be automatically determined 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, Imaging of separated wavefields potentially meets all exploration, appraisal and production requirements regarding seismic-based discovery and recovery.

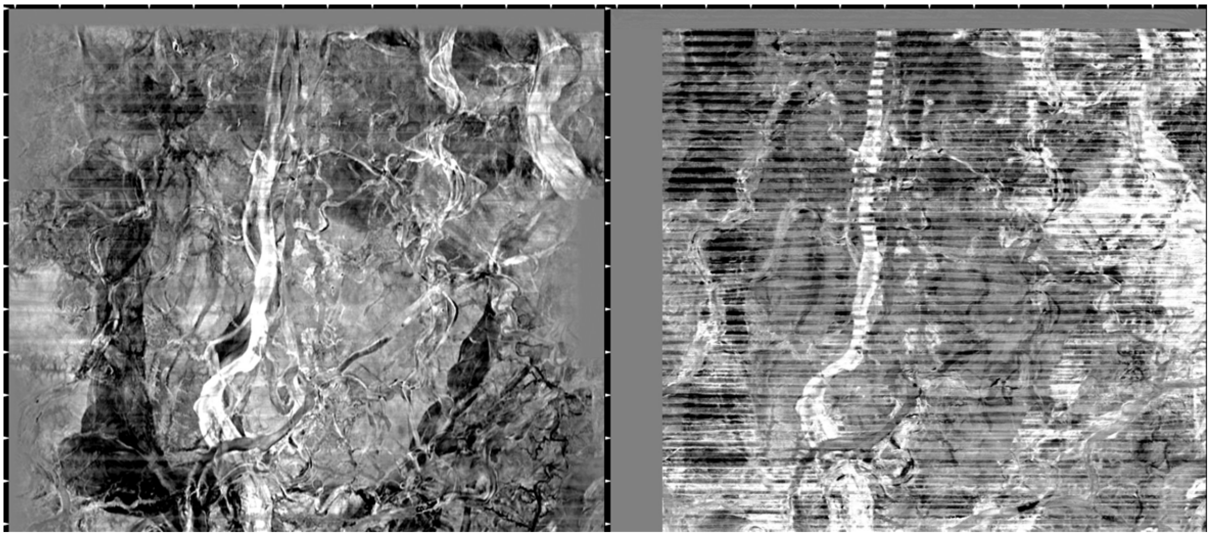

Figure 4 *Comparison of two time slices at 120 ms TWT. Water depth is 70 m. Imaging of separated wavefields for surface multiples (left) yields a remarkably continuous and high resolution image because of the superior illumination (refer also to Figure 3). In contrast, conventional Kirchhoff PSTM of primaries (right) contains a pronounced cross-line acquisition footprint that precludes shallow geohazard interpretation. The PSDM image on the left was stretched to TWT for comparison with the PSTM result on the right.*

Acknowledgements

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