# Separated Wavefield Imaging of Ocean Bottom Seismic (OBS) Data

S. Lu* (Petroleum Geo-Services), A.A. Valenciano (Petroleum Geo-Services), N. Chemingui (Petroleum Geo-Services) & D.B. Lecerf (Petroleum Geo-Services)

## SUMMARY

We discuss a depth imaging solution that uses primaries and all orders of multiple reflections to image seismic data from seabed acquisitions. The processing sequence starts by separating the up-going (P-UP) and down-going (P-DWN) wavefields from the seabed hydrophone and geophone measurements. The data are then organized into receiver gathers and the P-UP and P-DWN wavefields are migrated independently. By using the primaries and all orders of multiples in the migration, we greatly improve the resolution of the image and significantly expand the areal illumination of the survey. The improvements are not limited to the stack image; our imaging solution produces finely sampled angle gathers that could be further utilized for velocity model building or image enhancement post migration. We present a successful application of the technology to an Ocean Bottom Cable (OBC) recording system deployed for the Petrobras Permanent Reservoir Monitoring (PRM) pilot over the Jubarte field in the Campos basin offshore Brazil.

## Introduction

The use of Ocean Bottom Seismic (OBS) recording has become increasingly common in the oil industry for 3D and 4D seismic surveys. This technology promises good data repeatability and quality, especially in the presence of obstacles that can prevent the use of conventional streamers. However, one drawback of Ocean Bottom Cable (OBC) acquisition is that a large cable separation at the sea bottom delivers poor illumination for shallow targets. The industry has found a processing solution to this problem by using mirror migration (Grion et al., 2007). It consists of separating the seabed hydrophone and geophone data into up-going (P-UP) and down-going (P-DWN) wavefields. Then, the 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 sea 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. Nevertheless, the results from mirror migration can be further improved, since this method only uses the first-order multiples in the P-DWN wavefield to create an image.

A superior depth migration solution that uses all the recorded data, including primaries and all orders of multiples, can be adapted from towed streamer acquisition to OBC acquisition (Berkhout and Verschuur, 1994; Whitmore et al., 2010; Lu et al., 2014). Using this technology, we have imaged the multiples from deep-water Petrobras PRM datasets, reservoir-monitoring survey that was acquired over the Jubarte field in the north Campos basin. There, the images constructed from both primaries, and all orders of multiples, show enhanced angular illumination and improved subsurface coverage, when compared to images from primaries alone and/or mirror migration.

## Method

In OBC acquisition, both the primaries and the surface-related multiples are recorded by the seabed receivers, and both of these arrival types can be used for migration. To image the OBC data, the first processing step entails separation of the P-UP and P-DWN wavefields at the water bottom receiver locations. This can be accomplished using PZ-summation and PZ-subtraction processes respectively (Barr and Sanders, 1989). Seismic waves propagating upward (to the water bottom) constitute the P-UP wavefield and waves propagating downward compose the P-DWN wavefield. In addition to separating the P-UP and P-DWN wavefields, we invoke reciprocity in order to image the multiples. This is accomplished by interchanging the locations of sources and receivers. In the migration, the source and receiver wavefields are forward and backward extrapolated into the earth, and an image is constructed by applying the imaging condition. The same imaging principle can be used to image both primaries and multiples. However, while the P-UP wavefield contains both primary and multiple energy, the P-DWN wavefield contains only multiples.

The P-UP and P-DWN wavefields are migrated independently. When different source-receiver wavefield pairs are supplied as boundary data, there are resulting in four images:

(1) Imaging of primaries using P-UP wavefield [Figure 1A]: an impulse wavelet at the water bottom as source wavefield; and the recorded subsurface earth reflections (in P-UP) as receiver wavefield.
(2) Imaging of multiples using P-UP wavefield [Figure 1B]: the recorded sea surface reflected signals (in P-UP) as source wavefield; and the recorded subsurface earth reflections (in P-UP) as receiver wavefield.
(3) Mirror imaging using P-DWN wavefield (imaging of first-order multiples) [Figure 1C]: an impulse wavelet at the mirror position as source wavefield; and the recorded subsurface earth reflections (in P-DWN) as receiver wavefield.
(4) Imaging of multiples using P-DWN wavefield [Figure 1D]: the recorded sea surface reflected component (in P-DWN) as source wavefield; and the recorded subsurface earth reflections (in P-DWN) as receiver wavefield.

These four migrations can be used to build either pre-stack or post-stack images. Results from the four migrations can also be combined after imaging.

**A field data example: Jubarte PRM pilot**

In 2012, Petrobras installed the first deep-water optical permanent reservoir monitoring system on the Jubarte field in the north Campos basin. The project covers 10km$^2$, with 712 seismic recording stations. The receivers are positioned every 50m along the cable array that consists of 11 receiver lines nominally separated by 300m. A source grid covering an area of 11km by 11km was acquired with sources located every 25m in orthogonal directions.

Images were constructed for both primaries, and all orders of surface-related multiples, using the method discussed above. Since each order of multiple has different reflection points, the illumination area is significantly extended compared to the coverage from migrating either P-UP, primary events or mirror-derived images for the first-order, P-DWN multiples. By imaging the multiples, the areal illumination is defined by the surface distribution of the seismic source and the maximum order of recorded multiples. Figure 2 compares an image derived from the P-UP primary reflections (2A), an image computed from all orders of multiples available in the P-UP wavefield (2B), an image created from mirror migration of the first-order multiples in the P-DWN wavefield (2C) and an image generated from all recorded multiples in the P-DWN wavefield (2D). It is evident that the P-UP, primary image is limited by the receiver array, while the mirror migration expands the image to the first order multiple covered area. Images constructed from higher-order multiples show further improvement in the illumination. Vertical sections of the four migrations in Figure 3 also demonstrate the improved areal illumination by imaging multiples.

Pre-stack images also benefit from imaging surface-related multiples. Since the angular illumination is controlled by the source density, images from multiples display finer sampling over angle [Figure 4]. Consequently, angle gathers derived from surface-related multiples display higher resolution than those obtained from either primaries or the mirror imaging of first-order multiples [Figure 5]. When imaging with primaries, we can usually generate adequate angle gathers in the direction for which OBC receivers are properly sampled (cable direction). However, the receiver sampling along the cross-line direction is often large, as dictated by the cable separation at the sea bottom. This separation is typically of the order of several hundred meters. Consequently, it is difficult to produce densely populated angle gathers from primaries or first-order multiples (mirror) along the ninety-degree azimuth, as demonstrated in Figures 5A and 5C. On the other hand, by imaging all the multiples, we can create densely-populated angle gathers, even along the cross-line direction [Figures 5B and 5D]. The poorer angular illumination from the imaging of primaries is particularly problematic for shallow reflections, as demonstrated in Figure 5. Here, the dense sampling over angle that is provided by multiples, improves migration resolution at each image point.

**Conclusions**

Imaging all orders of multiples in ocean bottom seismic (OBS) data improves areal coverage and angular illumination when compared to imaging primaries and/or mirror migration. The angle gathers from imaging of multiples can be utilized for AVA analysis or velocity model building. The methodology may affect the OBS acquisition design in the future.

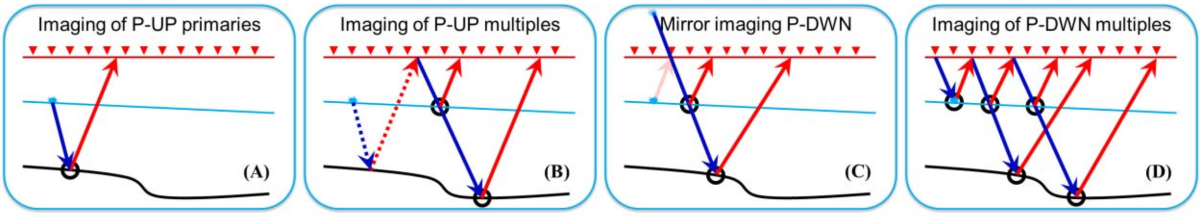


***Figure 1*** *Schematic ray diagrams for imaging using OBS data: (A) imaging of primaries using P-UP wavefield; (B) imaging of multiples using P-UP wavefield; (C) mirror imaging using P-DWN wavefield; (D) imaging of multiples using P-DWN wavefield. The blue arrows are source wavefield and red arrows are receiver wavefield. Black circles are imaging points.*

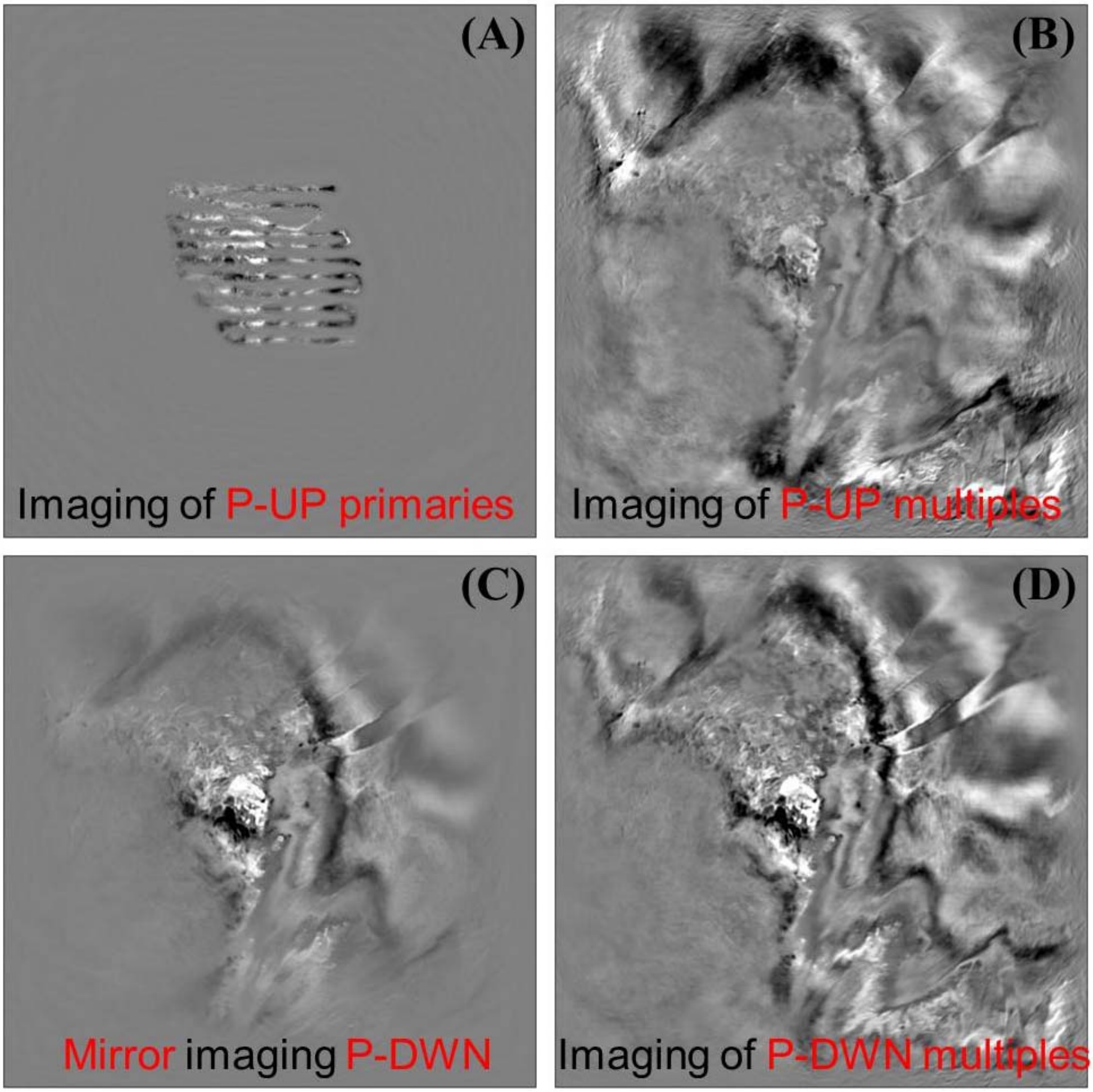


***Figure 2*** *Depth slices right below the water bottom (1355m depth from sea surface) from imaging of Jubarte OBC data (10km by 10m area).*

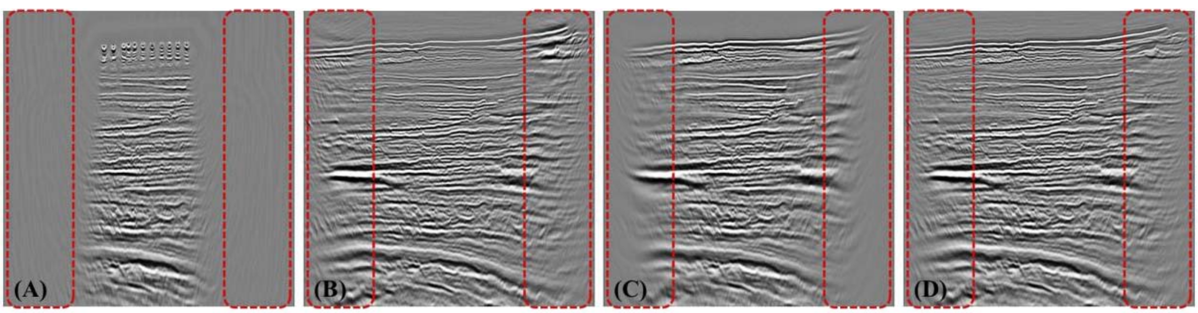


***Figure 3*** *Crossline images from depth 1km to 3km, lateral range 10km. (A) Imaging of P-UP primaries; (B) Imaging of P-UP multiples; (C) Mirror imaging using P-DWN wavefield; (D) Imaging of P-DWN multiples. Imaging all orders recorded surface-related multiples in P-UP and P-DWN wavefields improves areal illumination (the red-boxed areas) when compared to imaging primaries and/or mirror migration.*

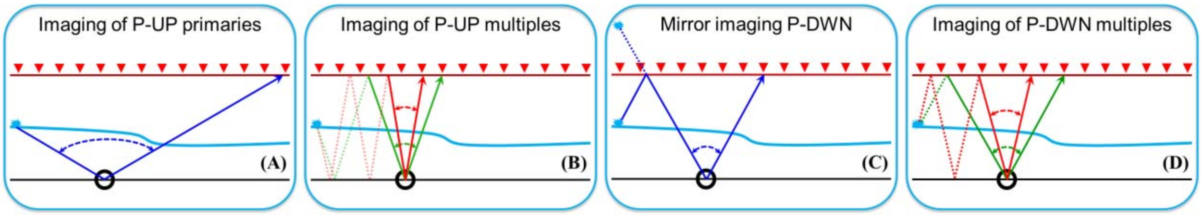


***Figure 4*** *Schematic ray diagrams for indicating angular illumination at one subsurface reflector from using one shot. Imaging of multiples improves angle density.*

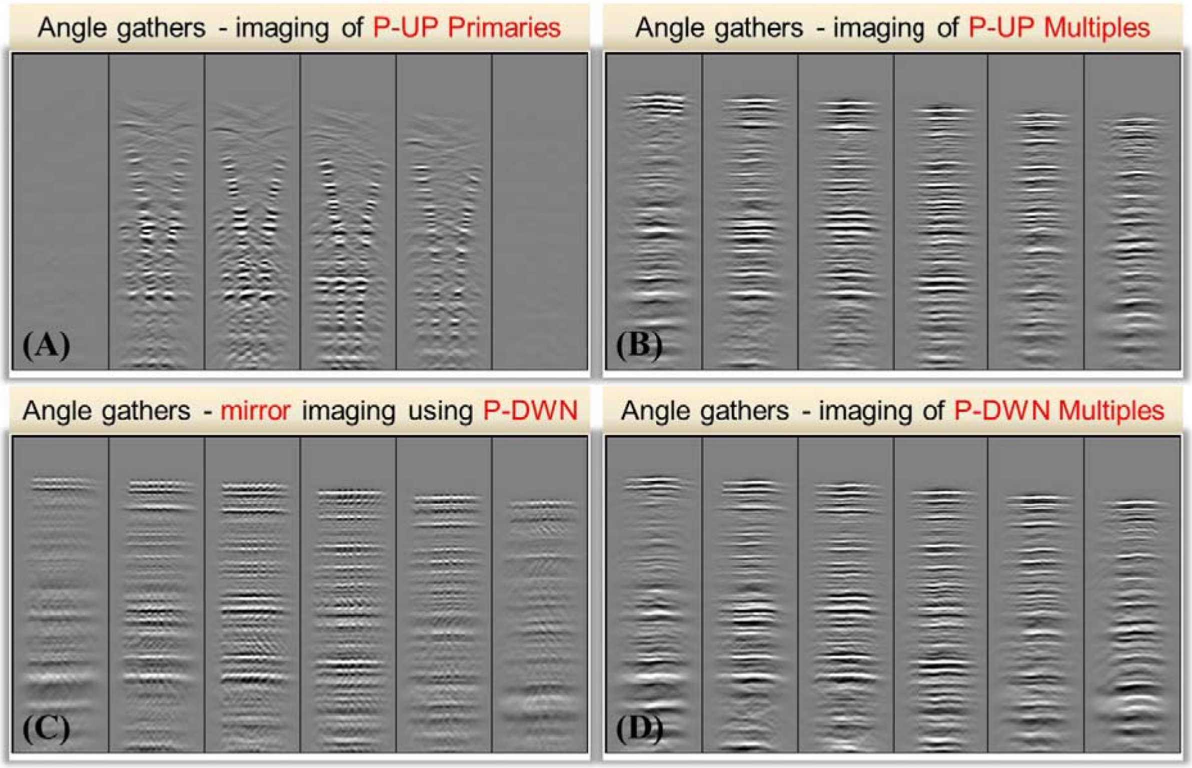


***Figure 5*** *Angle gathers of 90$^o$ azimuth: depth from 1km to 2.5km, angle range from -50$^o$ to +50$^o$.*

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**References**

1. Barr, F.J. and Sanders, J.I. [1989] Attenuation of water-column reverberations using pressure and velocity detectors in a water-bottom cable. *59$^{th}$ Annual International Meeting,* SEG *Expanded Abstracts*, 653-655.
2. Berkhout, A.J. and Verschuur, D.J. [1994] Multiple technology: Part 2, migration of multiple reflections. *64$^{th}$ Annual International Meeting, SEG Expanded Abstracts*, **23**, 1497-1500.
3. Grion, S., Exley, R., Manin, M., Miao, X., Pica, A., Wang, Y., Granger, P., and Ronen, S. [2007] Mirror imaging of OBS data. *First Break*, **25**, 37-42.
4. Lu, S., Whitmore, N.D. Valenciano, A.A. and Chemingui, N. [2014] Enhanced subsurface illumination from separated wavefield imaging. *First Break*, **32**, 87-92.
5. Whitmore, N.D., Valenciano, A.A., Söllner, W. and Lu, S. [2010] Imaging of primaries and multiples using a dual-sensor towed streamer. *80$^{th}$ Annual International Meeting, SEG Expanded Abstracts*, **29**, 3187-3192.