Deep Water Prestack Imaging With Primaries and Multiples

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Abstract

This paper discusses a deep water application of imaging of both primaries and multiples using the up and down-going wavefields obtained by processing dual-sensor towed streamer data. Seismic images are obtained by downward continuing the up and down-going wavefields and applying either cross-correlation of deconvolution imaging conditions. A shot profile framework is used to create depth images of primaries, multiples as a signal, and multiples as noise. The imaged multiple noise is then available for adaptive subtraction from the reflector images of the primaries and multiples. The imaging conditions include the generation of subsurface offset gathers, which are subsequently transformed to angle gathers. The gathers provide input for further offset or angle dependent processing**.**

Introduction

Primary imaging algorithms are based on the downward (forward) extrapolation or a source field and a downward (reverse) extrapolation of a receiver wavefield followed by an imaging principle. The source (downgoing) wavefield is generated from an analytical representation of the source field, whereas the receiver wavefield is assumed to be the upward traveling field when recorded at the surface. To accurately satisfy the assumption of up (or downgoing) wavefields at the surface a wavefield separation (deghosting) process must be applied to the recorded data. Wavefield separation of up and down-going wavefields of standard hydrophone seismic data is hampered by spectral notches caused by receiver ghosts that adversely affect the main part of signal bandwidth. These problems can be mitigated by acquisition and processing methods - one such method is dual-sensor towed streamer acquisition, followed by wavefield separation of the dual-sensor data (Carlson, et al., 2007).

Muiltiple reflections are generally treated as a form of noise that must be removed to properly construct images of the primary reflections. Attenuation of sea surface multiples is typically done in the data domain by a surface related multiple elimination process of SRME (e.g. Verschuur, 1991, van Borselen, et al, 1996). Altenatively, Artman, et al. (2007) demonstrate an image space multiple noise prediction and subtraction as an alternative to the data space SRME process.

Beyond extracting multiples as a source of noise, multiples may be also be used as valuable signal information and as such can be used for imaging (e.g. Guitton, 2002; Muijs et al. 2007; Verschuur and Berkhout, 2010, Whitmore, et.al. 2010).

In this paper, we extend the previous work on the imaging of primaries and multiples from dual-sensor data (Whitmore, et al., 2010). From a shot migration framework we image (1) primaries, (2) mulitples as signal and (3) multiples as noise that can be subtracted from signal images. We generate subsurface offset gathers and image gathers for each of these image types. In these extended domains we apply image space estimation of surface related multiple noise (Artman, et. al. 2007). This combination provides an image space framework for imaging and attenuation of multiples, and the generation of migrated subsurface offset or angle data.

Shot –profile wave-equation imaging and subsurface offset gathers

In shot-profile wave-equation migration, the imaging process is a combination of downward extrapolation and imaging. The can be done by extrapolation or reverse time imaging methods. In this paper we employ an extrapolation method based on Fourier Finite Difference (Valenciano, et al., 2009) and one of the two following offset dependent imaging conditions, which produce subsurface offset gathers:

Cross correlation:

$$\mathbf{I}_1(\mathbf{x},h)=\sum_{\mathbf{x}_s}\sum_{\omega}D'(\mathbf{x}-h,\mathbf{x}_s;\omega)U(\mathbf{x}+h,\mathbf{x}_s;\omega) \qquad (1)$$

Deconvolution:

$$\mathbf{I}_2(\mathbf{x},h)=\sum_{\mathbf{x}_s}\sum_{\omega}\frac{D'(\mathbf{x}-h,\mathbf{x}_s;\omega)U(\mathbf{x}+h,\mathbf{x}_s;\omega)}{\langle D'(\mathbf{x},\mathbf{x}_s;\omega)D(\mathbf{x},\mathbf{x}_s;\omega)\rangle_{(x,y)}+\varepsilon} \qquad (2)$$

where $\langle\ \rangle_{(x,y)}$ stands for smoothing in the image space in the x,y directions, $\mathbf{x}=(x,y,z)$ is each image position, ω is the angular frequency, and $\mathbf{x_s}=(x_s,y_s,z_s)$ is each source position. In general **h**=(hx,hy,hz), but in this paper we restrict **h** to be a function of lateral offset only. The **U** and **D** denote the up going and down going wavefields, respectively. Note, we obtain zero offset subsurface images when h=0.

Imaging of primaries and multiples as signal

As a perquisite for imaging, we employ recordings from dual-sensor data consisting of hydrophone and vertical velocity sensors. This total pressure data can be separated into up and down-going pressure fields at a predefined horizontal datum by wavefield decomposition (e.g. Carlson, et al. 2007). After separation, the downward continuation and imaging process can produce either primaries or multiples, depending on the selection of the boundary data for the up and the down-going fields at $z = 0$ (Guitton, 2002; Muijs et al. 2007, Verschuur and Berkhout, 2010, Whitmore, et al., 2010).

In the imaging of primaries and multiples the following data is used as boundary data:

$$D([x,y,z=z_S],\mathbf{x_s};\omega) = \begin{cases} \mathbf{S}^D([x,y.z=z_S];\omega) & (3.1) \\ \mathbf{P}^D([x,y,z=z_S],\mathbf{x_s};\omega) & (3.2) \end{cases}$$

$$\mathrm{U}([x,y,z=z_R],\mathbf{x_s};\omega) = \mathbf{P}^U([x,y,z=z_R],\mathbf{x_s};\omega) \quad (4)$$

When imaging primaries, **D** is typically an analytically defined source, $\mathbf{S}^D$, with a specified wavelet or possibly the downward traveling direct arrival wavefield. When imaging multiples as signal, **D** is the down-going pressure derived from wavefield separation of dual sensor data. The up-going field, **U**, is the up-going pressure field, regardless of imaging primaries or multiples. The **U** and **D** wavefields can be extrapolated to any depth where the imaging principle is applied.

Image space estimation of multiple noise

The above imaging formulations above assume that we have an up and down-going fields (or source) at the surface. If these data have free surface multiples remaining then the subsequent images will have image of surface related multiples as a form of noise. The usual approach for attenuating multiples is to apply SRME + adaptive subtraction in the time domain followed by depth imaging. We discuss here an alternative image space estimate of the multiple noise discussed by Artman, et al. (2007), which employs convolution of the up-going data with itself during the downward continuation process. The image space gathers of the multiple noise in the image space is computed by:

$$\mathbf{I}_5(\mathbf{x},h) = \sum_{\mathbf{x_s}} \sum_{\omega} U(\mathbf{x}-h,\mathbf{x_s};\omega) U(\mathbf{x}+h,\mathbf{x_s};\omega) \quad (5)$$

So in the same imaging framework, the primaries and the multiples are imaged as signal (with boundary conditions (3) and (4) and imaging conditions (1) or (2)) and the multiples are imageds as noise by using only the extrapolated **U** wavefield and the imaging conditions in equation 5.

Offset and Angle gathers:

The equations (1), (2), and (3) produce the subsurface offset gather of the primaries or multiples whereas the h=0 is the special case of zero subsurface offset for either the primaries or multiples. Given offset gathers of either the signal images defined by the imaging conditions in equations (1) or (2) and of the multiple noise estimates given by equation (5), we can generate angle gathers by simple offset to angle transforms (Ricket and Sava, 2002), which applies a local slant stack to the subsurface offset gathers (or radial trace extraction in the (K_z, K_h) domain).

DeSoto Canyon Imaging Example

In previous work, (Whitmore, et al., 2010) the imaging of both primaries and multiples was applied to dual-sensor data in the North Sea, which was in relatively shallow water. This paper discusses the application of these methods to dual-sensor data acquired in DeSoto Canyon in deep water Gulf of Mexico. A near offset section from the hydrophone component of the dual-sensor data is shown in Figure 1. (Note the data display starts at 1.8 sec. and the strong surface related multiples.) Typical shots of up-going pressure obtained from dual-sensor processing are shown in Figure 2.

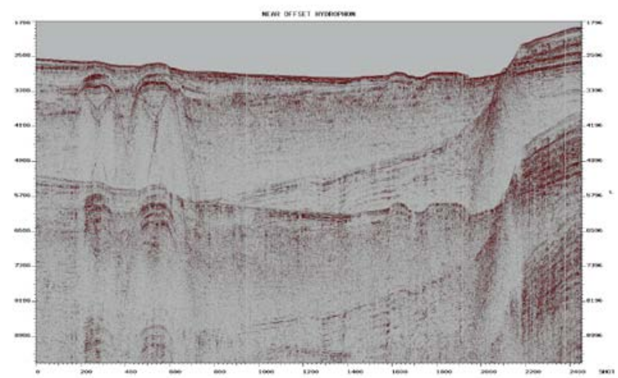

Figure 1. Near offset hydrophone section from Desoto Canyon dual-sensor data (1.8s to 9.5s)

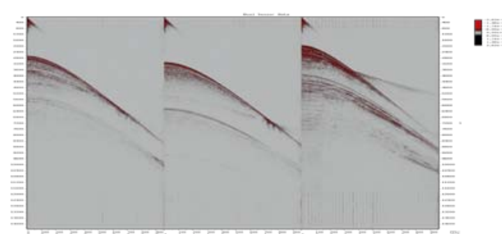

Figure 2. Typical shot records of up-going pressure obtained from dual-sensor processing

Imaging Results

These data were imaged by extrapolating the up-going and source field as in (3.1) and (4) respectively and using the imaging condition (equation 2). The primary image of the data with a velocity is shown in Figure 3. The imaged data within the highlighted box is shown in Figure 4. All of the next displays are referenced to this region within the box. The image of the primary (zoomed) is in Figure 5. To image the multiples as signal, the D wavefield is the down-going wavefield at the surface. These results are shown in Figure 6. Finally, we can generate an image space estimate of the multiple noise by applying the imaging condition in equation 5 to the extrapolated U wavefield. These results are shown in Figure 7.

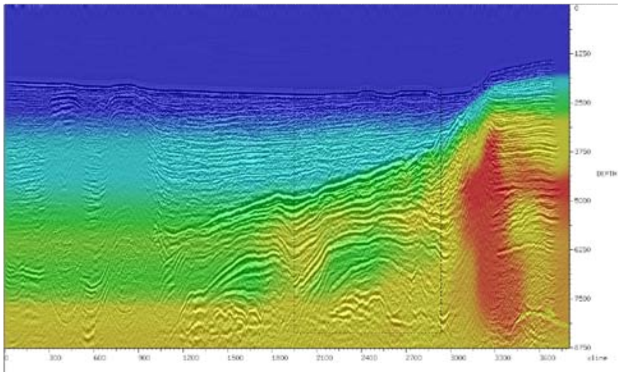

Figure 3. Primary Image with Velocity Model

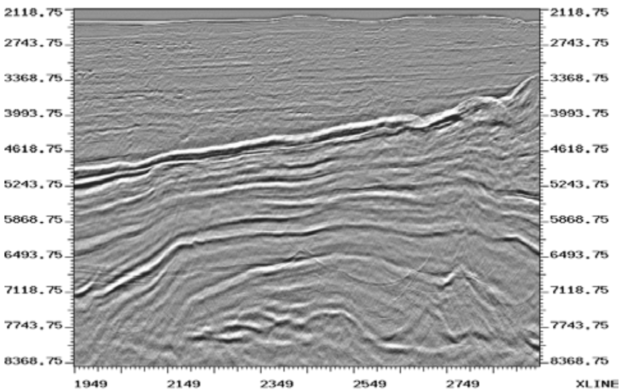

Figure 4. Primary Image from Source & Upgoing Wavefields (zoomed from insert box)

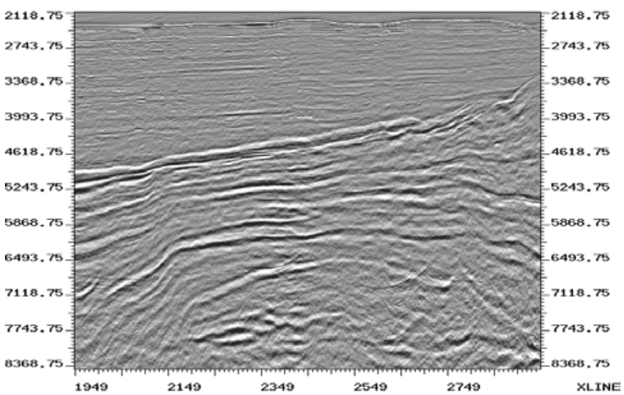

Figure 5. Multiple Image from Up and Downgoing Wavefields

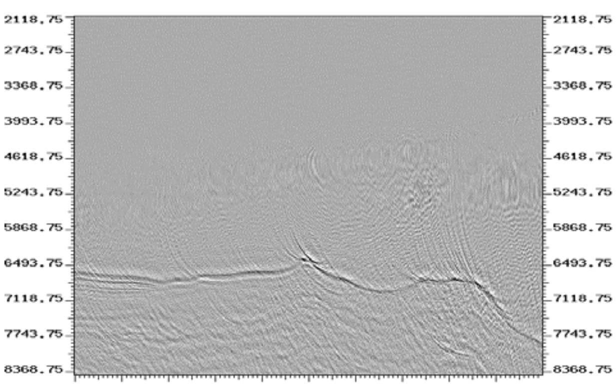

Figure 6. Image Space Multiple Noise

The preceding images are for a subsurface offset h=0. The imaging conditions in equations 1, 3, and 5 can be applied to non-zero offset. Representative subsurface offset gathers for each case are shown in Figures 6, 7 and 8. Due to the accuracy of the velocity model, the primaries and multiple signal images focus near zero offset, whereas the surface related multiples are not focused near zero subsurface offset (they would focus at water velocity – not the imaging velocity).

Although not shown here, It is important to note that the image space estimate of the multiple noise can be adaptively subtracted from both the primary and multiple images.

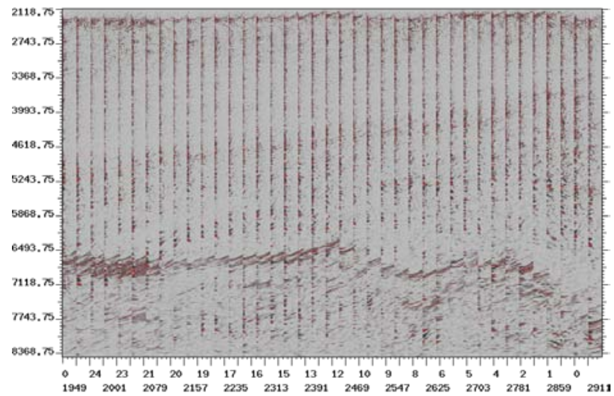

Figure 7. Subsurface Offset Gathers - Primaries

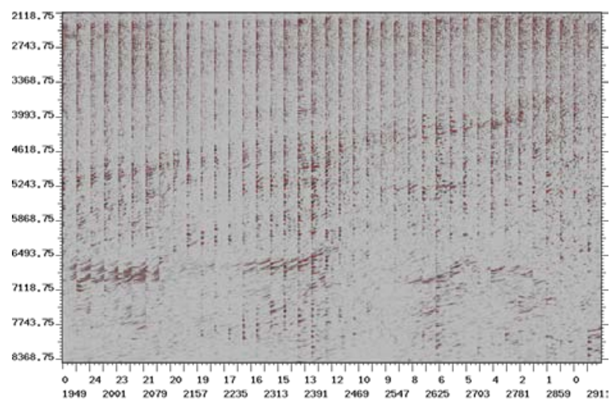

Figure 8. Subsurface Offset Gathers – Mulitple Image

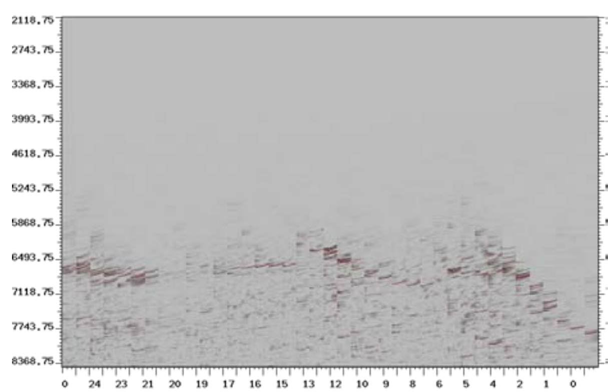

Figure 9. Offset Gathers – Image Space Multiple Noise

The subsurface offset gathers can be mapped to angle gathers by an offset to angle transform. These gathers can then be analyzed for subsurface angle information. The mapping of the offset to angle gathers is applied to the gathers from the primary, multiple signal and multiple noise images. The angle gathers for each case are shown in the Figures 10, 11, and 12 respectively.

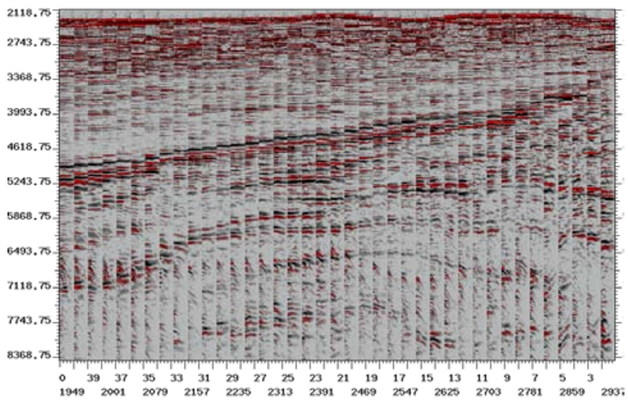

Figure 10. Angle Gathers for Primary Image

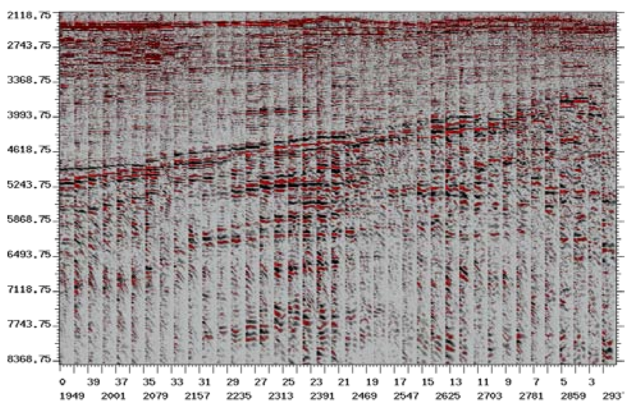

Figure 11. Angle Gathers for Multiple Image

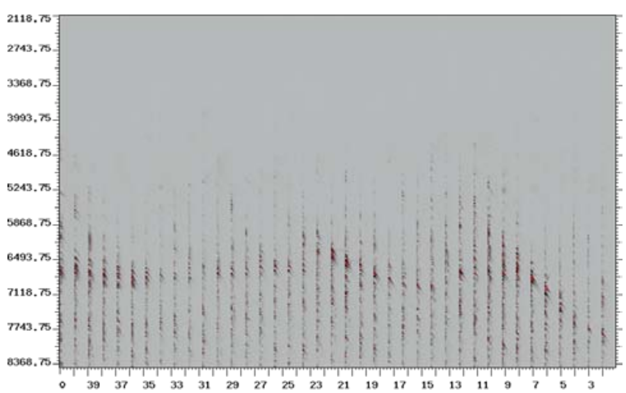

Figure 12. Angle Gathes for Image Space Multiple Noise

Conclusions

This paper demonstrates the application of depth imaging of both primaries and multiples in a deep water environment. Dual-sensor processing was applied to separate up and down-going wavefields at the surface. Two forms of multiple images are produced - one which provides an image of the reflectors, and the other an image of surface related multiple noise that can be adaptively subtracted from the reflectivity images. The standard imaging conditions can be applied to both the zero offset (h=0) images as well as the subsurface offset (or angle) gathers for primaries and multiples (both the reflection image and the surface related multiple noise image). This provides a unified framework for the imaging and analysis of primaries and multiples in the prestack domain. The subsurface offset and angle domains can be used for velocity estimation and angle dependent processing.

The example shown here was for a 2D line from a 3D survey. Generation of image space multiple noise estimates and offset and angle gathers depend on adequate source and receiver sampling in acquisition and data regularization methods in 3D.

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