Imaging of primaries and multiples using a dual-sensor towed streamer

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Summary

Multiple reflections are commonly treated as noise in one-way imaging methods. High effort is put into research and data processing worldwide in an effort to suppress this source of noise. In a new perspective multiples are treated as valuable imaging information. Based on dual-sensor towed streamer measurement, we decompose the wavefield and apply up/down imaging of primary and multiple reflections. This approach is tested using shallow water synthetic data and finally applied on dual-sensor field data.

Introduction

Conventional depth imaging by one-way wavefield extrapolation is based on the assumption that measured data represents an upward propagating primary reflected (scattered) wavefield. This assumption is solely fulfilled if the free-surface effects such as receiver ghosts, surface related multiples, and internal multiples are effectively suppressed.

Deghosting of seismic data is a nontrivial procedure, even for a flat sea surface and reflection coefficient of -1 (Ghosh, 2000). In order to move the spectral notches caused by receiver ghosts out of the main part of signal bandwidth, hydrophones are typically towed shallow in marine data acquisition. In recent years attempts have been made to introduce techniques for rough sea deghosting by using sea surface profile information (Amundsen, 2005). Kragh et al. (2002) derive the needed sea surface profile from very low frequency pressure fluctuations and Orji et al. (2009) image the sea-surface from below, using the decomposed wavefields of dual-sensor towed streamer data (Carlson, et al., 2007).

Removing the sea surface effects is the ultimate goal of SRME (Verschuur et al., 1991, Berkhout and Verschuur, 1997) and related methods of surface-related multiple suppression (Carvalho et al., 1991; Fokkema and van den Berg, 1993; van Borselen et al., 1996; Amundsen, 2001, Ikelle et al., 2003). Common feature of these methods is the independency of parameters characterizing the subsurface model. Söllner et al., 2007 and Frijlink et al., 2009 employ separated wavefields of a dual-sensor streamer in order to relax the sea surface assumption of SRME. However, the time varying sea-surface is not included in this concept.

From a different perspective, multiples may be treated as valuable information and as such be included in new imaging algorithms. Reiter et al., 1991 use a Kirchhoff approach to image water layer multiples. The two multiple generating boundaries need to be known in this approach before starting the imaging process. Berkhout and Verschuur (1994) and Guitton (2002) use one-way wavefield extrapolation for migrating surface-related multiples after explicitly separating from the data. In this case, the multiples are inverse extrapolated and the recorded data is forward extrapolated after multiplying with -1 (the reflection coefficient for calm sea). Muijs et al. (2007) employ OBC wavefield decomposition to migrate primaries and multiples in one step. This relates to the up/down imaging approach (Claerbout, 1976) and is not restricted to calm sea conditions.

In this work we adapt the up/down imaging approach of primaries and multiples to a dual-sensor towed streamer system by keeping the relaxed sea-surface condition.

Shot –profile wave-equation imaging conditions

In shot-profile wave-equation migration, an approximation of the reflection coefficient is given by (Claerbout, 1971)

$$\mathbf{I}_1(\mathbf{x}) = \sum_{\mathbf{x}_s}\sum_{\omega}\frac{\mathbf{R}(\mathbf{x},\mathbf{x}_s;\omega)}{\mathbf{S}(\mathbf{x},\mathbf{x}_s;\omega)} \qquad (1)$$

where $\mathbf{x} = (x,y,z)$ is each image position, ω is the angular frequency, and $\mathbf{x_s} = (x_s,y_s,z_s)$ is each source position. **R** and **S** denote the receiver and source wavefields, respectively. Physically, equation 1 states that a reflector exists where **R** and **S** coincide in time and space. Equation 1 will be numerically unstable wherever **S** equals (or is close to) zero. For this reason, it is customary to multiply both the numerator and the denominator by the complex conjugate of **S** (i.e. **S**') and add a stabilization parameter ε as follows:

$$\mathbf{I}_2(\mathbf{x}) = \sum_{\mathbf{x}_s}\sum_{\omega}\frac{\mathbf{S}'(\mathbf{x},\mathbf{x}_s;\omega)\mathbf{R}(\mathbf{x},\mathbf{x}_s;\omega)}{\mathbf{S}'(\mathbf{x},\mathbf{x}_s;\omega)\mathbf{S}(\mathbf{x},\mathbf{x}_s;\omega)+\varepsilon^2} \qquad (2)$$

We call equation 2 the damping imaging condition. Note that equation 2 is equivalent to equation 1 multiplied by an optimal Wiener filter, assuming that the spectrum of the noise is white. Equation 2 poses a serious problem to practitioners: how do we estimate the damping parameter ε? Since stability is often more important than mathematical accuracy, the imaging condition is usually implemented by using crosscorrelation between **R** and **S** as follows:

$$\mathbf{I}_3(\mathbf{x}) = \sum_{\mathbf{x}_s}\sum_{\omega}\mathbf{S}'(\mathbf{x},\mathbf{x}_s;\omega)\mathbf{R}(\mathbf{x},\mathbf{x}_s;\omega) \qquad (3)$$

We call equation 3 the crosscorrelation imaging condition. Jacobs (1982) analyzes in detail the differences between equations 3 and 2.

Guitton et al. (2007) proposed approximating the deconvolution imaging condition in equation 2. The main goal of their method is to emulate the deconvolution while being practical and robust filling the zeros in the denominator in equation 2. Therefore, they proposed the following:

$$\mathbf{I}_4(\mathbf{x}) = \sum_{\mathbf{x}_s}\sum_{\omega} \frac{\mathbf{S}'(\mathbf{x},\mathbf{x}_s;\omega)\mathbf{R}(\mathbf{x},\mathbf{x}_s;\omega)}{\langle \mathbf{S}'(\mathbf{x},\mathbf{x}_s;\omega)\mathbf{S}(\mathbf{x},\mathbf{x}_s;\omega)\rangle_{(x,y)}} \qquad (4)$$

where $\langle\ \rangle_{(x,y,)}$ stands for smoothing in the image space in the x,y directions. Equation 4 was called the smoothing imaging condition. In this paper, a triangle function is used as the smoothing function. Valenciano et al. (2003), and Muijs et al. (2007) discussed the use of more dimensions in the imaging condition; but the computational cost the extension required makes it less attractive in a production environment. This method is used as the deconvolution imaging condition in the examples below.

Imaging of primaries and multiple reflections

Equations 1 to 4 can be used to image either primaries or multiples depending on the data used to fill the boundary, at $z = 0$, for the receiver and the source wavefields (Verschuur and Berkhout, 1995; Guitton, 2002; Shan, 2003; Berkhout and Verschuur, 2006; Muijs et al. 2007). For imaging of primaries, a point (or areal) source is used as the boundary condition; for imaging of multiples a generalized source is necessary.

Dual-sensor data consisting of pressure and vertical velocity sensors is decomposed at a predefined horizontal datum in up going and down going pressure fields (Claerbout, 1976; Fokkema and van den Berg, 1993; Carlson, 2007). The separation level serves as initial boundary condition for imaging the primaries and multiple reflections, as sketched in Figure 1. Based on the concept that every up going wave branch is generated from a forward propagated down going wave branch, we use the direct down going wavefield for imaging the primaries and the scattered down going wavefield for imaging all surface related multiples.

In this paper we compare the results of using different imaging conditions, and different data as boundary condition for the source wavefield

$$\mathbf{S}(x,y,z=z_S,\mathbf{x}_s;\omega) = \begin{cases} \mathbf{S}^D(x,y,z_S,\mathbf{x}_s;\omega) & (5.1) \\ \mathbf{P}^D(x,y,z_S,\mathbf{x}_s;\omega) & (5.2) \end{cases}$$

and the receiver wavefields,

$$\mathbf{R}(x,y,z=z_R,\mathbf{x}_s;\omega) = \begin{cases} \mathbf{P}(x,y,z_R\mathbf{x}_s;\omega) & (6.1) \\ \mathbf{P}^U(x,y,z_R,\mathbf{x}_s;\omega) & (6.2) \end{cases}$$

When imaging primaries, $\mathbf{S}^D$ can be a point source with a specified frequency domain wavelet or the downward traveling direct arrival, if recorded. $\mathbf{P}^D$ and $\mathbf{P}^U$ are the separated down and up going data derived from deghosting the dual-sensor components. When we include wavefield extrapolation in the wavefield separation process, the source and receiver depths and be chosen at a z=0 or a depth equal to or greater than the cable depth, to avoid the effects of a rough sea surface.

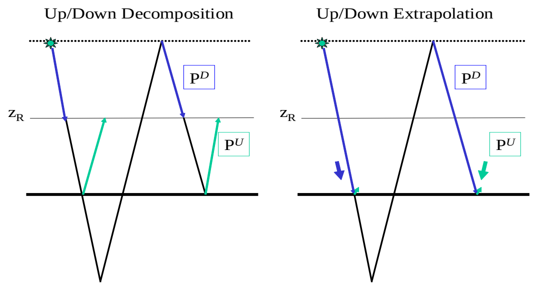

Figure 1: Up Down Separation and Extrapolation

Shallow water Sigsbee2B example

The Sigsbee2B model simulates the geological setting interpreted at the Sigsbee escarpment in the deep-water Gulf of Mexico. The model was designed to test surface-related demultiple algorithms, thus a free surface boundary condition was used. In addition, a “hard” water bottom was included in the velocity model.

Since our interest is to use the multiples and not remove them we created a new dataset with similar geometry to the original SMAART distribution. The goal was to record in the new model data as many orders of multiples as possible in a 12 seconds recording time. To achieve that goal, we stripped 5000 feet of the water column from the velocity model (Figure 2).

For this model we tested imaging of primaries and multiples - with both crosscorrelation and deconvolution imaging conditions. For example, Figure 3 shows an example of typically employed imaging process for primaries with a deconvolution imaging condition: the source field was an analytical point source with a flat spectrum and the receiver field was initiated by injecting the total pressure at the surface as described in equations (5.1) and (6.1). This image can be compared with a multiple image generated from deconvolution imaging conditions. In this example, the multiple image was generated by downward continuing $\mathbf{P}^D$ as the source field and $\mathbf{P}^U$ as the receiver field, as described in equations (5.2) and (6.2) and then applying deconvolution imaging conditions. The results are shown in Figure 4. Note that the structural image from primaries and multiples are similar. However, the basic wavelets of the images are different This is is due to the fact that the primary image was generated with a flat spectrum and that P-total has a different spectrum than the P-up.

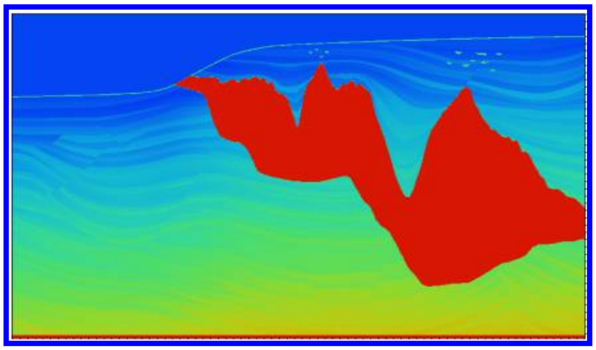

Figure 2: "Shallow Water" Sigsbee2b Model

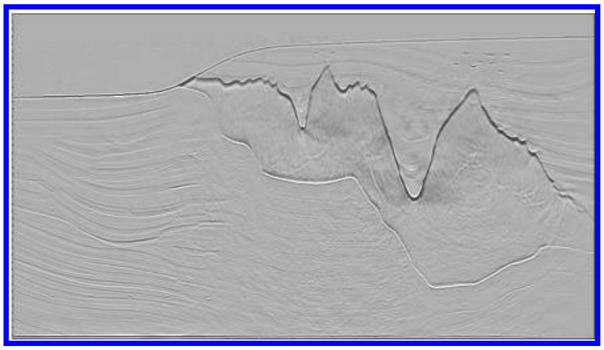

Figure 3: Deconvolution Image of Primaries (P total)

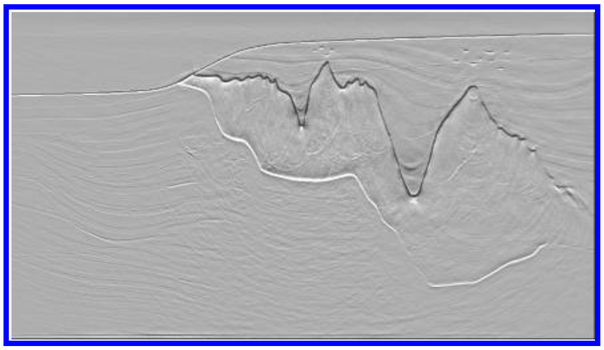

Figure 4: Deconvolution Image of Multiples

This demonstrates that the primaries and multiples can be imaged. However, it is important to properly incorporate the source wavelet when comparing or perhaps combining primary and multiple images.

North Sea dual-sensor streamer example

The second application for the imaging of primaries and multiples uses a 3D data set from the North Sea acquired with dual-sensor streamers comprised of hydrophones and vertical geophones. Dual-sensor deghosting and extrapolation was applied to these data to produce upgoing and downgoing pressure. A subset of upgoing pressure shot records are shown in Figure 5.

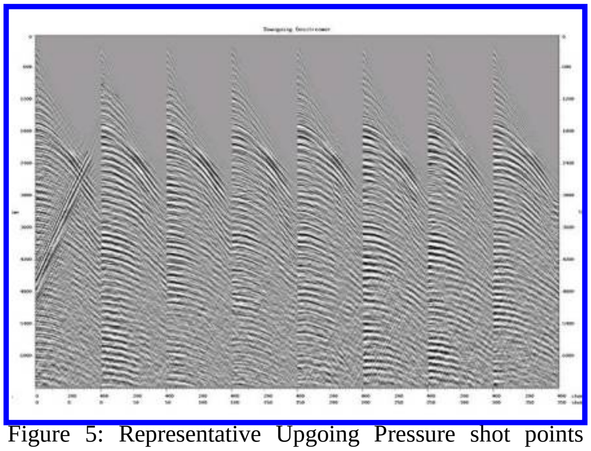

Figure 5: Representative Upgoing Pressure shot points generated from dual-sensor deghosting – no multiple attenuation has been applied.

The original streamer depth for this data was 15 meters. As it can be seen in the shot records, this data contains significant short period and long period multiples. This is due to a hard water bottom and other major impedance changes. As a result, both the upgoing and downgoing wavefields contain several orders of multiples. To address the multiples when imaging the primaries, the upgoing data is typically subjected to a cascade of short and long period multiple removal (e.g. tau-p decon + surface SRME, whereas the multiple imaging uses the multiples as signal.

Imaging of Primaries:

Imaging of the primaries was done for this data by downward continuing and imaging the surface source and receiver wavefields as defined by equations (5.1) and (6.1). The source field is an analytical point source and the receiver field is the upgoing P wavefield with a simple gap decon applied to reduce some of the short period multiples. The imaging condition was cross correlation. This primary image with the velocity model is shown in Figure 6.

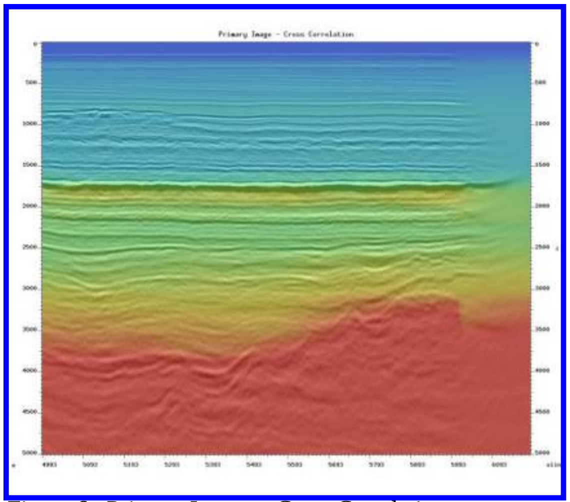

Figure 6; Primary Image - Cross Correlation

Imaging of Multiples:
The major complication in the imaging of multiples in this data case is that the multiples in the data are very complex. Because of this the imaging condition is critical in obtaining a useful image of the multiples. As discussed earlier to obtain a multiple image the downgoing pressure and upgoing pressure are injected as the source and receiver fields at datums as described in (5.2) and (6.2). We applied two different imaging conditions – deconvolution and cross correlation (equations 3 and 4) – and these results are shown in Figures 7 and 8.

As can be seen from these results, the deconvolution imaging condition produces an image comparable to the primary image, while the cross-correlation image is riddled with multiple reverberations. This indicates that the deconvolution imaging condition was essential for the imaging of multiples.

Conclusions

In this paper we have demonstrated the imaging of primaries and multiples using dual-sensor data. The dual-sensor data facilitates the proper separation of upgoing and downgoing pressure at the acquisition surface. The imaging process incorporates dual-streamer wavefield separation, downwared extrapolation and the application of an imaging condition. Cross correlation and smoothed deconvolution imaging conditions were applied to both primaries and multiples and the results were compared.

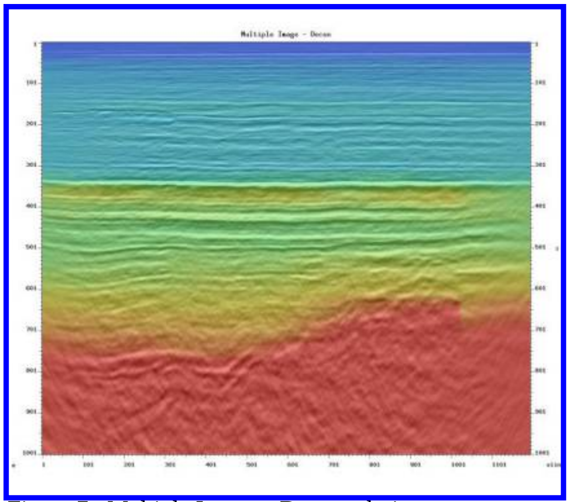

Figure 7: Multiple Image – Deconvolution

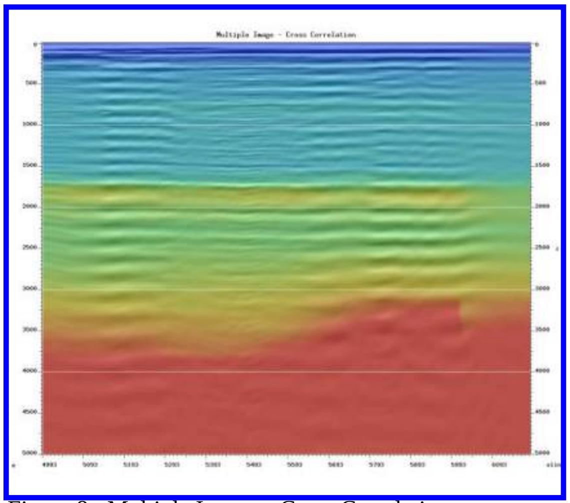

Figure 8: Multiple Image – Cross Correlation

The deconvolution imaging conditions were essential in producing a good images from the multiples, particularly in the case of shallow to mid water depths with complex multiples. Understanding of the effects of the source wavelet and multiple generators are necessary for a direct comparison of primary and multiple images. We treat multiples not only as a source of noise that needs to be removed, but also as a signal that can complement the imaging of primaries.

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