

Imaging complex structures with separated Up- and Down-going wavefields

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Summary

Dual sensor streamers record the total pressure and the particle velocity of the seismic wavefields. They allow the data to be accurately separated into up-going and down-going pressure. These two components can be input to a depth migration that uses primaries and multiples for Separated Wavefield IMaging (SWIM).

SWIM increases the surface coverage and subsurface illumination by turning each receiver into a “virtual” source. This principle is independent of the wave equation propagation algorithm, which can be based on one-way or two-way solutions. SWIM with reverse time migration (RTM) better images the steep dips of the data. On the other hand, SWIM using one-way wave equation migration (WEM) provides an efficient alternative for high-resolution high-frequency imaging.

Introduction

Multiples can be used for imaging the subsurface instead of being discarded as noise (Berkhout and Verschuur, 1994, Guitton, 2002, Shan, 2003, Muijs et al., 2007, Whitmore et al., 2010). They travel longer paths and illuminate wider areas than primaries. In principle, multiple-scattered energy can be kinematically transformed into primary reflections by cross-correlation. The synthesized data can be treated as acquired from “virtual” sources at the surface (Claerbout, 1968). The same principles apply when the cross-correlation is performed during migration (Berkhout and Verschuur, 1994, Guitton, 2002).

The main advantage of using multiples for depth imaging comes from the fact that receivers are more densely sampled than sources in typical marine towed-streamer acquisition. Migrating the multiples effectively creates “virtual” sources at each receiver position, potentially enhancing illumination and resolution in the subsurface. This is especially important in the case of shallow targets as multiples illuminate the subsurface at smaller reflection angles than primaries.

Conventional shot-record migration of primaries backward extrapolates the deghosted Pup wavefield as receiver wavefield, and forward extrapolates a synthetic point source. In the case of dual sensor streamer acquisition, the data can be accurately separated into Pup and Pdown components (Carlson, et al., 2007). A shot record migration that images separated wavefields, the down-going wavefield as source, and the up-going wavefield as receiver

turns each receiver into a “virtual” source, and effectively increases the source sampling and coverage at the surface. We refer to such solution as Separated Wavefield IMaging (SWIM). Because of the complexity of the up- and down-going wavefields interaction, a deconvolution imaging condition is often necessary. This reduces the cross-talk noise generated from unrelated correlation of up- and down-going wavefields.

Here we present two wave equation based depth migration alternatives for SWIM that make use of one-way (WEM) and two-way propagators (RTM). If the objective is to image high-resolution shallow targets a WEM algorithm is ideal (Lu et al., 2013). This class of algorithms is efficient and accurate especially for high resolution imaging in anisotropic, and visco-acoustic media (Valenciano et al., 2011). On the other hand, when the objective is to image structurally complex areas, a migration algorithm based on two-way propagation, e.g. RTM, would be the preferred tool. Our pseudo analytical TTI RTM implementation (Crawley et al., 2010) has proven to be more accurate than WEM in imaging steep deeps and subsalt structures, when provided with an accurate velocity model.

Each SWIM solution, WEM or RTM, has its advantages and disadvantages. They range from the complexity of the propagated wavefields and the handling of the cross talk noise, to the implementation of the imaging conditions and the computational costs. We illustrate their differences using two examples: the SEAM wide azimuth benchmark model, and a deep-water wide azimuth field data.

Separated Wavefield Imaging with WEM and RTM

The reflection coefficient, in RTM or WEM, can be estimated as the deconvolution of the receiver by the source wavefield (Claerbout, 1971). However, for practical reasons and primarily stability, the imaging condition is usually implemented as cross-correlation of the receiver and the source wavefields as follows:

$$I_c(\mathbf{x}) = \sum_{\mathbf{x}_s} \sum_i S^*(\mathbf{x}_s, \mathbf{x}, i) R(\mathbf{x}_s, \mathbf{x}, i) \quad (1)$$

where $\mathbf{x} = (x, y, z)$ is each image position, i can be either angular frequency (ω) or time, depending on the propagation algorithm, and $\mathbf{x}_s = (x_s, y_s, z_s)$ is the source position. R and S denote the receiver and source wavefields, respectively.

While a cross-correlation imaging condition is customary in most RTM algorithms, a deconvolution can also be implemented (Valenciano and Biondi, 2002). A stable

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deconvolution imaging condition was proposed by Guitton et al. (2007) as:

$$I_o(\mathbf{x}) = \sum_{\mathbf{x}_s} \sum_{\omega} \frac{S^*(\mathbf{x}_s, \mathbf{x}, \omega) R(\mathbf{x}_s, \mathbf{x}, \omega)}{\langle S^*(\mathbf{x}_s, \mathbf{x}, \omega) S(\mathbf{x}_s, \mathbf{x}, \omega) \rangle_{(x,y)}} \quad (2)$$

where $\langle \rangle_{(x,y)}$ stands for smoothing in the image space in the x, y directions. Yet, applying an efficient deconvolution imaging condition in RTM requires few changes to the wavefields data management.

There are few differences between SWIM and the most established imaging of primaries. Being the main modification in a shot-record migration implementation that for imaging of primaries a point source is used to simulate the source wavefield; while for SWIM the down-going wavefield is necessary (Whitmore et al., 2010). Using the down-going wavefield improves illumination of the subsurface, but increases the complexity of the source wavefield. In the case of RTM it can boost the low wavenumber noise related to the correlation of backscattered waves in the sharp boundaries of the model. It can also augment the crosstalk noise characteristic of imaging with multiple reflections. In contrast, a one-way propagator does not produce backscattered waves in the velocity interfaces but cannot accurately propagate waves in the horizontal direction.

The RTM examples in this paper were computed using the pseudo-analytic method (Crawley et al., 2010). The pseudo-analytic solution provides accurate, nearly non-dispersive wave propagation with a simple 2nd-order time-stepping scheme. It preserves steep dips in the images, as it doesn't impose limitations on the angle of propagation of the wavefields.

The WEM examples were generated using a Fourier Finite-Difference (FFD) algorithm (Valenciano et al., 2011). This migration by wavefield continuation consists of three parts: phase-shift, thin-lens, and finite-differences. The 3D finite-differences operator was implemented using multi-way splitting that employs a different set of optimized coefficients along each splitting direction. The FFD migration operator presents similar angle limitations as other one-way propagators, but it is extremely efficient especially in the case of TTI anisotropy. The efficiency feature makes the algorithm well suitable for high-resolution imaging.

SEAM benchmark model

The SEAM benchmark model was generated based on the geology of deep-water Gulf of Mexico. We used the full-azimuth classic data set with sparse shot spacing of 600 m in the in-line and cross-line directions. Several orders of multiples are recorded in the data.

Figure 1 shows a comparison of the power spectra of the source wavefield generated from a point source (top panels, WEM and RTM), and the power spectra from using Pdown as source wavefield (bottom panels, WEM and RTM). The results are very similar with the exception of small differences due to angle limitation of the one-way propagator in WEM when imaging steep dips. The results clearly illustrate the concept of improved illumination by the generation of "virtual" sources in SWIM. Moreover, the improved illumination is independent of the wavefields extrapolation algorithm.

Figures 2 and 3 display the migration results using primaries WEM, primaries RTM, SWIM WEM and SWIM RTM. As expected, RTM better preserve the steep dips in the image. Figure 4 represents a depth slice extracted from the four images at the depth of the SEG logo. Both the RTM and WEM SWIM images can resolve the SEG lettering. Overall the results from both propagation methods are similar, even at the depth of the SEG logo. Generally, SWIM provides a complementary result to the imaging of primaries.

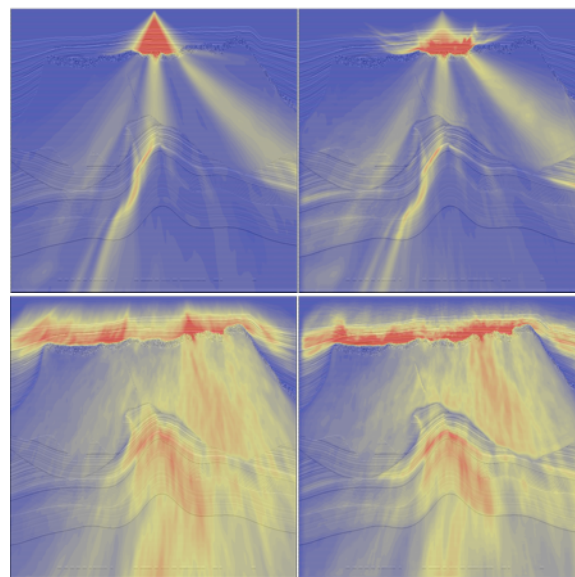


Figure 1: Power spectra (illumination), created from one-shot, overlaid on the SEAM model reflectivity: point source WEM (top-left), point source RTM (top-right), Pdown as source wavefield WEM (bottom-left), and Pdown as source wavefield RTM (bottom-right).

Field data example

A deep-water wide azimuth (WAZ) field data was used to compare SWIM WEM and SWIM RTM. Both migrations used a tilted transverse isotropic (TTI) model. Figure 5 and

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6 show the migrated SWIM images at two different locations. Figure 5 compares a 20 Hz SWIM WEM, a 20 Hz SWIM RTM. While, figure 6 shows results for a 20 Hz SWIM WEM, a 20 Hz SWIM RTM, and a 35 Hz SWIM WEM (right). The field data results corroborate the observations on the SEAM benchmark model; SWIM RTM better images the steep dips. Meanwhile, using a broader frequency band of 35Hz, SWIM WEM has produced a higher resolution image particularly of the shallow sediments and the top of the salt body. The efficiency of the WEM solution makes it an attractive extrapolator for high-resolution imaging using SWIM.

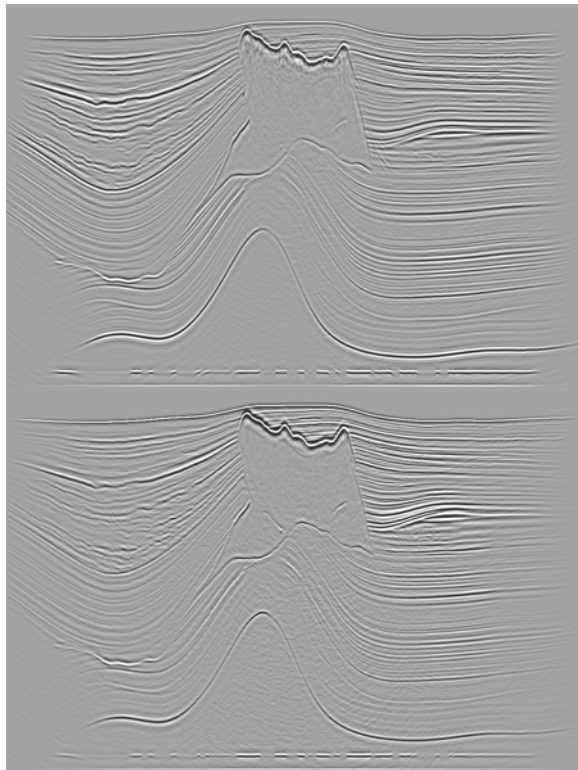


Figure 2: Depth migrated images: primaries WEM (top) and SWIM WEM (bottom)

Conclusions

We presented two alternatives for separated wavefields imaging (SWIM) based on two different classes of wave equation migration propagators. Using wide azimuth field data and the SEAM benchmark model, we showed that RTM based SWIM better preserves the steep dips in the image. In low relief structures the SWIM WEM and SWIM RTM images are equivalent. The broader frequency band SWIM WEM provided a cost effective solution for high-frequency high-resolution imaging suitable for reservoir

studies. We conclude that the choice of the extrapolator in SWIM should be tailored to the imaging problem to be solved.

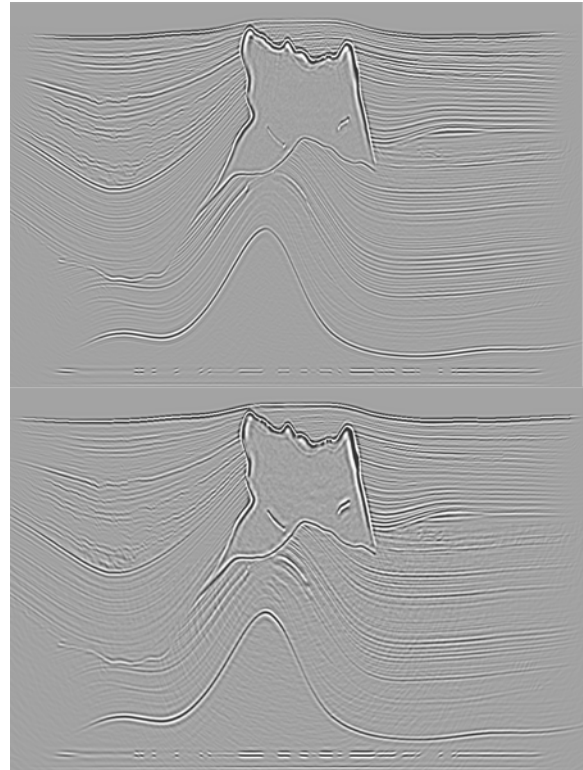


Figure 3: Depth migrated images: primaries RTM (top), and SWIM RTM (bottom).



Figure 4: Depth migrated images of the SEG logo: primaries WEM (top-left), primaries RTM (top-right), SWIM WEM (bottom-left), and SWIM RTM (bottom-right).

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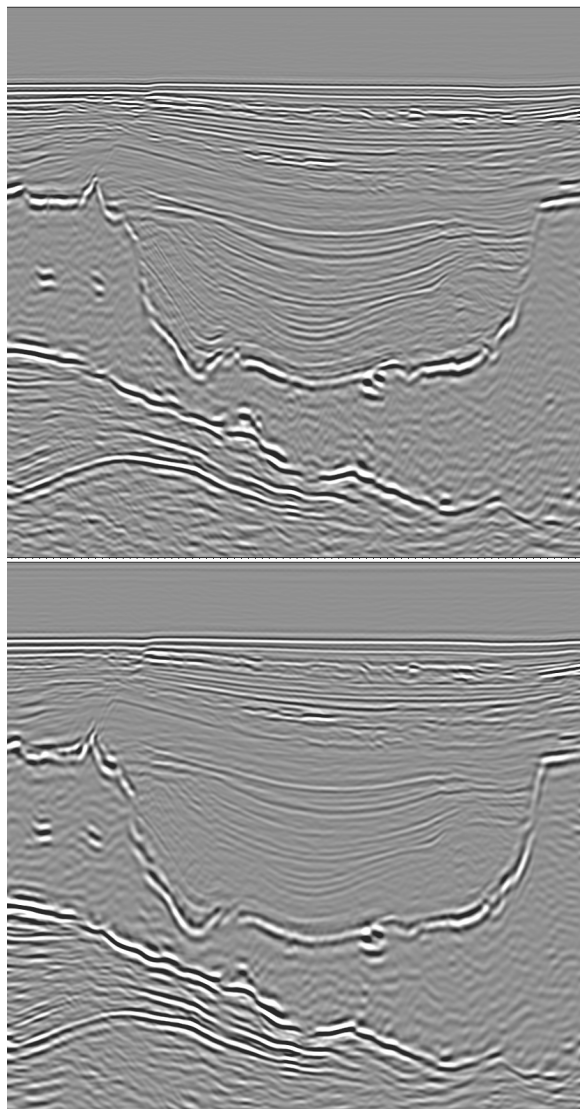


Figure 5: Depth migrated images: 20 Hz SWIM WEM (top), 20 Hz SWIM RTM (bottom). Note the better imaging of the steep deeps by the RTM based SWIM.

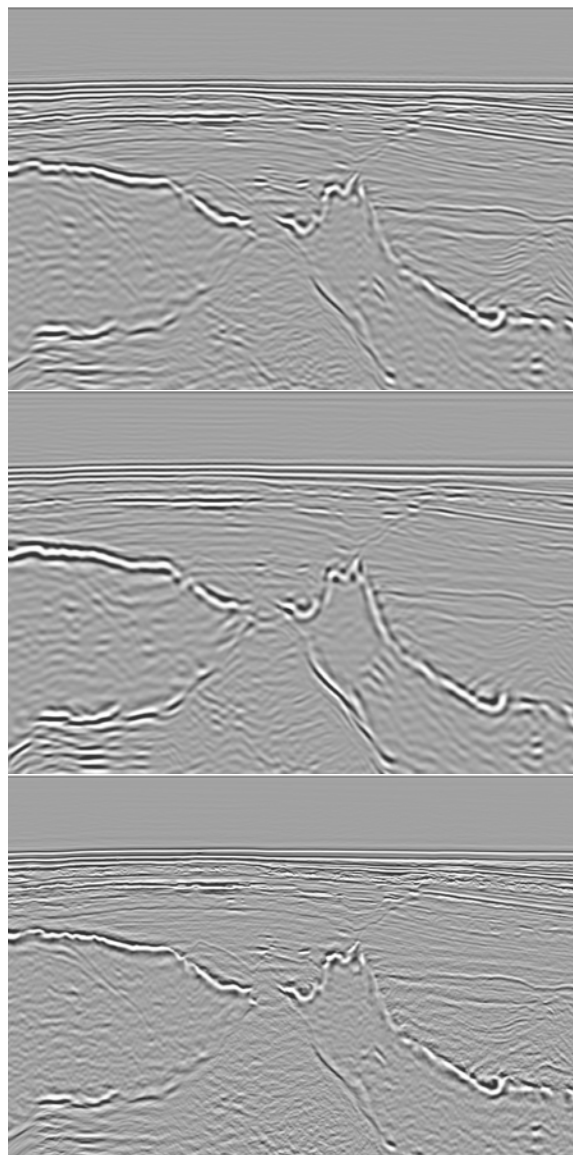


Figure 6: Depth migrated images: 20 Hz SWIM WEM (top left), 20 Hz SWIM RTM (bottom left), and 35 Hz SWIM WEM (right). Note the better imaging of the steep deeps by the RTM based SWIM.

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EDITED REFERENCES

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