Separated Wavefield Imaging (SWIM) of Complex Structures

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SUMMARY

Dual sensor streamer acquisition allows the data to be accurately separated into upgoing and downgoing wavefields. The two components are used as input to migration that employs primaries and multiples for separated wavefield imaging (SWIM).
SWIM turns each receiver into a “virtual” source, therefore effectively increases the surface coverage and subsurface illumination. This principle is independent of the propagation algorithm, which can be based on one-way or two-way solutions to the wave equation. We find that SWIM based on reverse time migration (RTM) better handles 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 travel longer paths and illuminate wider areas than primaries. They 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). In principle, multiple-scattered energy can be kinematically transformed into primary reflections by cross-correlation. The synthetized 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) to avoid generating “virtual” shot-records before imaging.

The main advantage of using multiples for depth imaging comes from the fact that receivers are more densely sampled than sources in typical marine 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 Pdow 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 (Guitton et al., 2007). This reduces the cross-talk noise generated from unrelated correlation of up- and down-going wavefields.

Here we present a wave equation based depth migration toolbox for SWIM that makes 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

In shot-record wave-equation migration (RTM, and WEM), the reflection coefficient can be estimated as the deconvolution of the receiver by the source wavefield (Claerbout, 1971, Valenciano and Biondi, 2002). However, for practical reasons and primarily stability, the imaging condition is usually implemented as cross-correlation of the receiver and the source wavefields. While a cross-correlation imaging condition is customary in most RTM algorithms, a deconvolution can also be implemented (Valenciano and Biondi, 2002). Yet, applying an efficient deconvolution imaging condition in RTM requires few changes to the wavefields data management.

In practice, 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).

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 steeps deeps 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: a phase-shift, a 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 shares the angle limitation of 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.

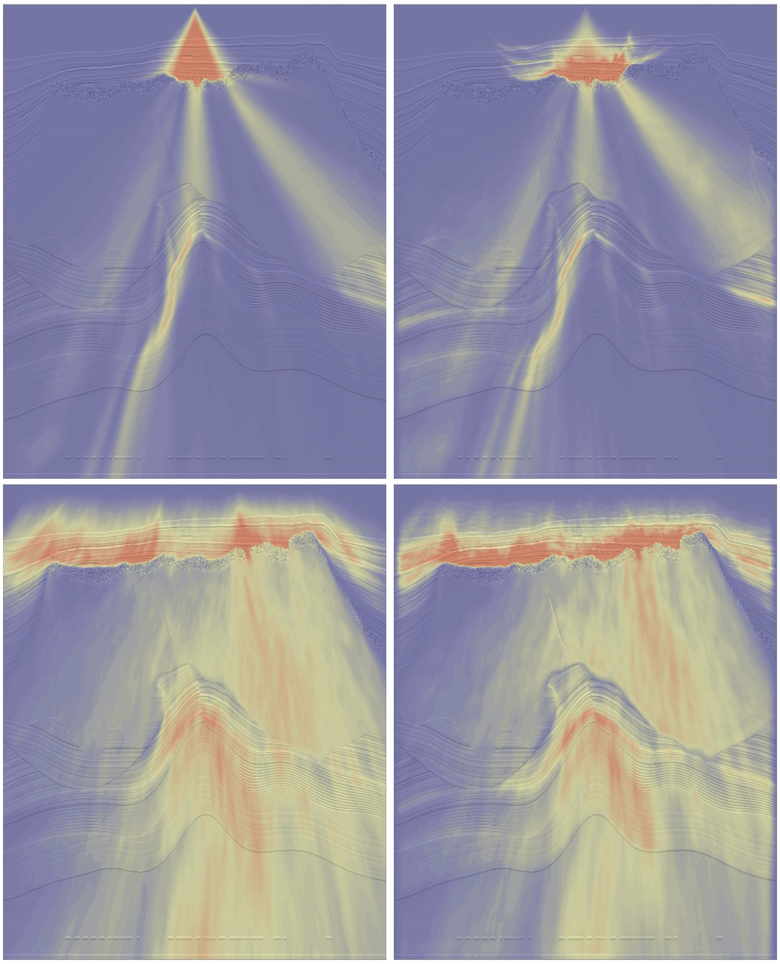

Figure 1: *Power spectra (illumination), created from one-shot, overlayed on SEAM reflectivity: point source WEM (top-left), point source RTM (top-right), Pdown as source wavefield WEM (bottom-left), and Pdown as source wavefield RTM (bottom-right).*

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. 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.
Figure 2 displays the migration results using primaries WEM (top left), primaries RTM (top right), SWIM WEM (bottom left) and SWIM RTM (bottom right), whereas Figure 3 represents a depth slice extracted from the four images at the depth of the SEG logo. As expected, RTM better preserve the steep dips in the image. 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.

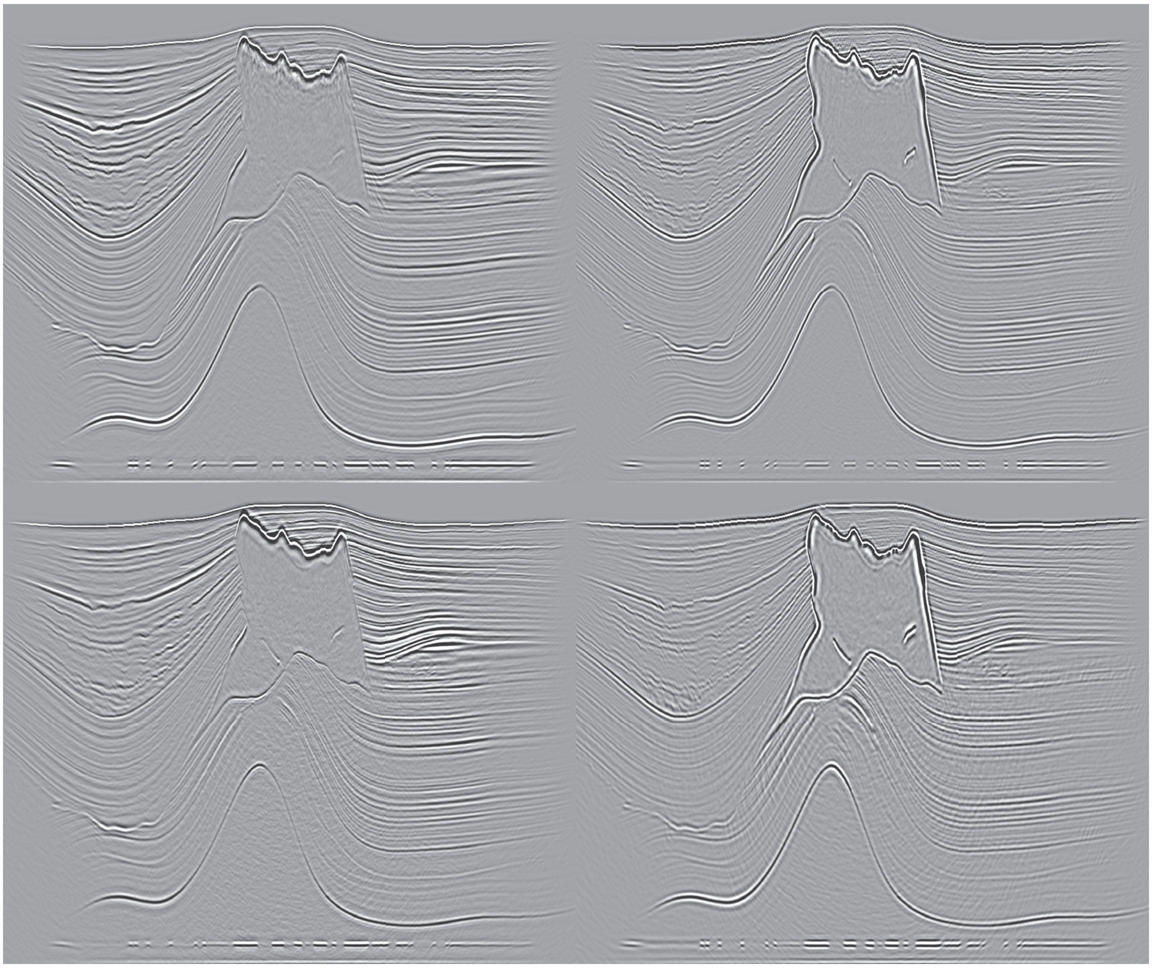

Figure 2 *Depth migrated images: primaries WEM (top-left), primaries RTM (top-right), SWIM WEM (bottom-left), and SWIM RTM (bottom-right).*

Figure 3 *Depth migrated images of the SEG logo, from left to right: primaries WEM, primaries RTM, SWIM WEM, and SWIM RTM.*

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 tranverse isotropic (TTI) model. Figure 4 shows the migrated results for a 20 Hz SWIM WEM (left), a 20 Hz SWIM RTM (center), and a 35 Hz SWIM WEM (right). The field data results corroborate the observations on the SEAM benchmark model; the steep deeps are better imaged by SWIM RTM. 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.

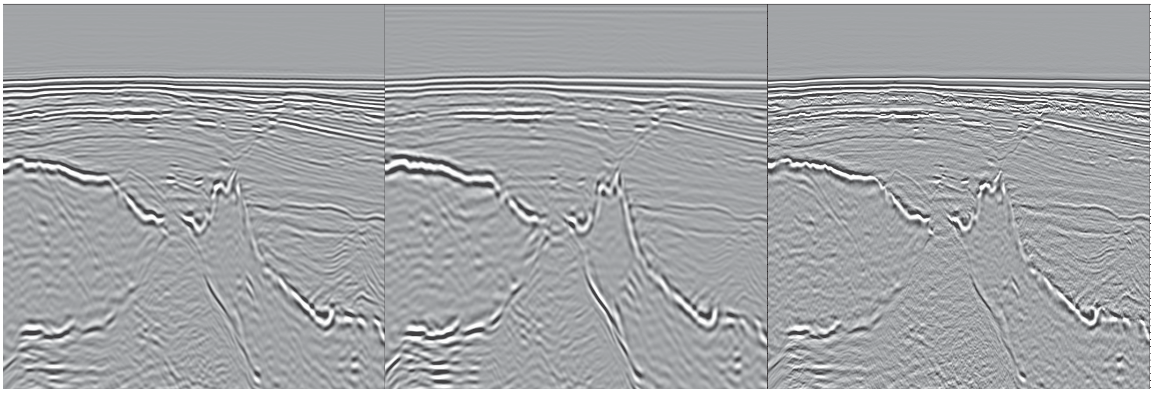

Figure 4 *Depth migrated images: 20 Hz SWIM WEM (left), 20 Hz SWIM RTM (center), and 35 Hz SWIM WEM (right).*

Conclusions

We presented a SWIM toolbox based on different classes of wave equation migration extrapolators. 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.

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