Migration of surface multiples from conventional streamers

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Abstract

Theory for migrating multiples is for long established. However, only recently, imaging with surface multiples is getting more interest from the industry. This is because they present a different illumination pattern than that of primaries and in areas of complex geology, even using the state of the art in acquisition and processing, imaging with primaries still presents low-quality illumination-related images. Most of the current work on migration of multiples is focused on data registered by multicomponent streamers after wavefield separation. Here, migration of surface multiples registered by conventional streamers is addressed, by describing the theory, illustrating how crosstalk is formed, comparing the different illumination between primaries and multiples, and showing promising results on real data.

Introduction

Up until recently, multiple reflections had been considered unwanted noise, which motivated huge investments in multiple attenuation methods. Using multiple reflections to image the subsurface has been growing in interest because they have different illumination patterns from those of primaries. In the case of multi-component data, the downward wavefields which contain surface multiples are usually mirror-migrated (Godfrey et al., 1998) and yield an image of superior quality than that of the upward wavefields. This is especially true for shallow reflectors, but also valid for deep water settings. A shift towards using downgoing wavefields recorded by streamers to image the subsurface occurred after the work of Muijs et al. (2007). The authors work with data recorded by multi-component receiver cables. After wavefield separation, upgoing wavefields are input to shot-profile migration as the source wavefield, whereas downgoing wavefields are input as the receiver wavefield. In this case, illumination of the subsurface is enhanced, compared to imaging with primaries only, because the downgoing wavefields have a wider surface coverage than the point source used for migrating primaries. This issue is especially relevant in WAZ acquisition for azimuths perpendicular to the acquisition direction (Shaoping et al., 2014). Another reason is that, for one shot, a point in the subsurface can be reached more than twice by multiple reflections in contrast to the single hit for primaries.

Here, I explore this idea to image multiples from data recorded by a conventional streamer. Actually, Berkhout et al. (1993) formulated this problem, but using as the downgoing wavefield data containing primaries and multiples. Here, data after multiple suppression are input to shot-profile migration as the downgoing wavefield, whereas simulated (or even amplitude and phase adapted) surface multiples are input as upgoing wavefield. Under the approximation of the one-way wave equation, I discuss the theory, the crosstalk problem, and show tests on synthetic and field data, which results are promising. Most of the theory and examples also apply to the two-way wave equation.

Theory

The theoretical background for migrating surface multiples is similar to that for migrating primaries, which is the Born approximation. Let´s start by stating that, in the frequency domain, taking a Delta function as input, linearization of modeling with respect to velocity yields

$$d(\mathbf{x_s}, \mathbf{x_r}; \omega) = \int_A G_D(\mathbf{x_s}, \mathbf{x}; \omega) r(\mathbf{x}) G_U(\mathbf{x}, \mathbf{x_r}; \omega) d\mathbf{x} \quad , (1)$$

where ω is the radial frequency, $\mathbf{x_s}$, $\mathbf{x_r}$, and $\mathbf{x}$ are shot, receiver, and model position vectors, respectively. In the present case, G_D is the downgoing one-way Green´s function and G_U is the upgoing one-way Green´s function computed using some estimation of the migration velocity, r is the reflectivity, and A is the experiment aperture. Equation 1 is obtained after considering that a further interaction of the scattered wavefield d with reflectivity is negligible. Notice that, under this consideration, it is impossible to generate multiple reflections with Equation 1. Equation 1 can be written in matrix form as

$$\mathbf{d} = \mathbf{Lr} \quad , \qquad (2)$$

where the operator $\mathbf{L}$ encompasses the propagations with the Green´s functions and the integration.

Considering that surface multiples, m_{sup}, are generated after reflection of primaries at the sea surface and propagation in the subsurface again, one can use a version of Equation 1, having the scattered wavefield d as input, to model surface multiples. For a unique shot, this reads

$$m_{sup}(\mathbf{x_r}; \omega) = \int_A G_D(\mathbf{x_r}, \mathbf{x}; \omega) d(\mathbf{x_r}; \omega) r(\mathbf{x}) G_U(\mathbf{x}, \mathbf{x_r}; \omega) d\mathbf{x} \quad , (3)$$

which in matrix notation reads

$$\mathbf{m} = \underline{\mathbf{L}}\mathbf{r} \quad . \qquad (4)$$

Notice that the operator $\underline{\mathbf{L}}$ differs from that of Equation 2 only by the source term, which, for now, is the recorded data. Equation 3 applies to any acquisition configuration.

At this point, we have a machinery to model surface multiples by wavefield propagation, which is the one formulated by Pica et al. (2008). From Equation 4, we can obtain an estimate of the reflectivity, $\underline{\mathbf{r}}$, by using the adjoint operator of $\underline{\mathbf{L}}$, $\underline{\mathbf{L}}^*$:

$$\underline{\mathbf{r}} = \underline{\mathbf{L}}^* \mathbf{m} \quad . \tag{5}$$

By applying $\underline{\mathbf{L}}^*$ on $\mathbf{m}$, we are downward propagating d as the downgoing wavefield, downward propagating m_{sup} as the upgoing wavefield, and crosscorrelating these wavefields at every depth to obtain $\underline{\mathbf{r}}$. Notice that surface multiples, $\mathbf{m}$, in Equation 5 can be estimated by any method, like SRME, or even that of Equation 4.

A drawback of this scheme for migrating multiples compared to migrating primaries is the crosstalk generation. In the migration of primaries with the one-way wave equation, a transmitted wave is propagated as the downgoing wavefield, whereas in migration of multiples the downgoing wavefield contains events other than the transmitted wave. In the proposed scheme, these events are primary reflections only, since we expect to have efficiently attenuated the surface multiples. The crosscorrelation of primary reflections with uncorrelated multiples generates crosstalk. In the following, using synthetics, I illustrate the crosstalk issue and compare the differences in illumination when migrating primaries and multiples.

Examples

Firstly, based on a simple model of constant velocity and three horizontal reflectors, in a shallow water context, I show the nature of the crosstalk between primaries and unrelated multiples. In Figure 1, we can see primary only reflections on the left and surface multiples including peg-legs on the right. The indexes of the multiples (M) are determined as follows: the first index relates to the generating primary (P) and the second index, to the reflector on which P is incident after reflecting back at the sea surface.

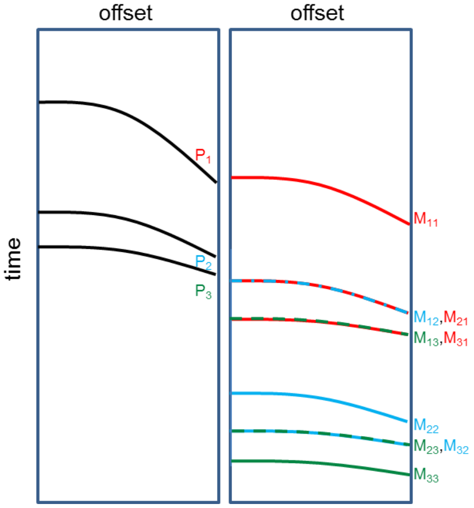

Figure 1 – Schematic for the nature of surface multiples in a model with three horizontal reflectors. The first index of multiples (M) relates to the generating primary and the second, to the generating reflector.

Considering Figure 1, an image I is produced by crosscorrelating primary and multiple wavefields. Any crosscorrelation term having one of the multiples index equal to the index of the crosscorrelating primary yields an estimate of the reflectivity in the correct position I_r. Otherwise, crosstalk I_c is generated. We can express this relation as

$$I = I_r + I_c; \begin{cases} I_r = P_i^* M_{jk}, \text{for } i = j \text{ or } i = k \\ I_c = \text{otherwise} \end{cases} \tag{6}$$

where the asterisk means correlation.

Figure 2 illustrates imaging by migration of multiples. For the sake of a better understanding, I show a time snapshot of the wavefields. Notice crosstalk generation when, for instance, P_1 correlates with M_{22}, M_{23}, M_{32}, and M_{33}.

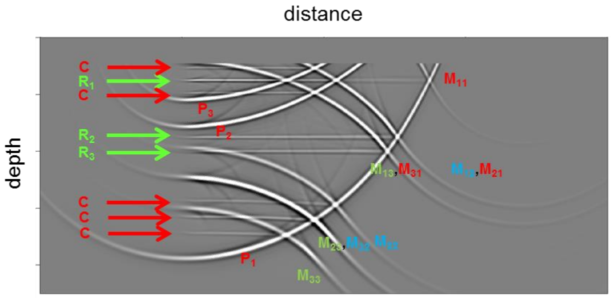

Figure 2 – Imaging by migration of multiples. Wavefields indicated with P and M correspond to the schematic of Figure 1. Correct reflectors are indicated with R, whereas crosstalk is indicated with C.

Another interesting feature in Figure 2, especially for reflector R_1, is that after correlation of P_1–M_{11} (rightmost part of the reflector), amplitude is reinforced with additional correlations between P_1–M_{12} and P_1–M_{21} (central part), and P_1–M_{21} and P_1–M_{31} (leftmost part). The same happens for reflectors R_2 and R_3, for subsequent instant times of propagation, revealing the advantage of the additional illumination reached by migrating multiples.

Secondly, using a more complex velocity model, I explore the complementarity between images computed by migrating primaries and multiples. The 2D model consists of a complex allochthonous salt body embedded in a v_z model. Shot interval is 16 times greater than receiver interval and maximum offset is 6,000 m. Figure 3 shows the imaging of primaries at the top and some angle gathers from -40^o to 0^o on the bottom. Figure 4 shows the imaging of multiples. The strong reflector at the bottom is at 4,500 m. The image from migration of multiples is noisier than that from primaries consistent to the crosstalk issue. The shallower reflector presents an alternating pattern in the primary angle gathers related to the ratio between shot spacing and receiver spacing. This pattern is absent in the multiple angle gathers, which, in turn, present a narrower illumination range compared to primary angle gathers. For the deeper reflector, multiple angle gathers show more consistent amplitudes than the primary angle gathers in the second gather from the left and correct moveout for the last two gathers on the right, however there is a lack of illumination for mid angles in the last multiple angle gather. Notice that the moveout for the last two primary angle gathers is incorrect, which would lead to a wrong definition of the velocity model if we use only primary angle gathers for that. In contrast, multiple angle gathers show the correct moveout. Important to mention is that both images should be used in conjunction, since they show different characteristics, depending on the location.

In the examples above, surface multiples were synthesized using Equation 4, having the correct reflectivity as input. Otherwise, in the salt body example if we used the migration of primaries as input for reflectivity, the resulting multiples would be inaccurate in the regions of poor illumination. When working with real data, in a situation like that, to prevent such an inaccuracy multiples should be generated using a SRME-like strategy. Next, we will see results of the application on part of a sail line of a dataset from the Santos Basin, Brazil.

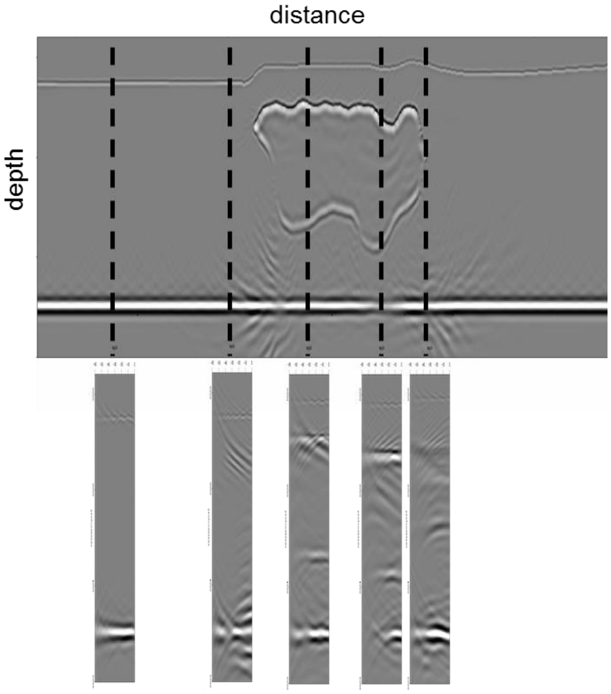

Figure 3 – Imaging primaries. Zero-offset at the top and angle gathers from -40^o to 0 ^{o} on the bottom. The deeper reflector is noisy in the second angle gather from the left and shows incorrect moveouts in the last two.

Results

Here, I show how the method performs on conventional streamer real data. I use part of a sail line of a 3D survey in the Santos Basin, Brazil. Water depth is about 2,100 m. Multiples were generated according to Equation 4, for which reflectivity is represented by a wide-frequency-band version of the depth–migrated full volume. Shot gathers after multiple attenuation and surface multiples (displayed in Figure 5) are input to migration as downgoing and upgoing wavefields, respectively.

To help identifying possible crosstalk in the migration of multiples, a fast 2D Born modeling/migration was performed, using only sea bottom, top and base of salt reflectors (Figure 6). In Figure 7 are shown the migration of primaries only and the migration of multiples. It is clear that the shallow part is better recovered by the migration of multiples than that of primaries, showing more continuous reflectors. Also, in the deeper part, reflectors in the migration of multiples show better continuity and less contamination of interbedded multiples. Interestingly, in this portion, migration of primaries and multiples show alternating and complimentary illumination patterns.

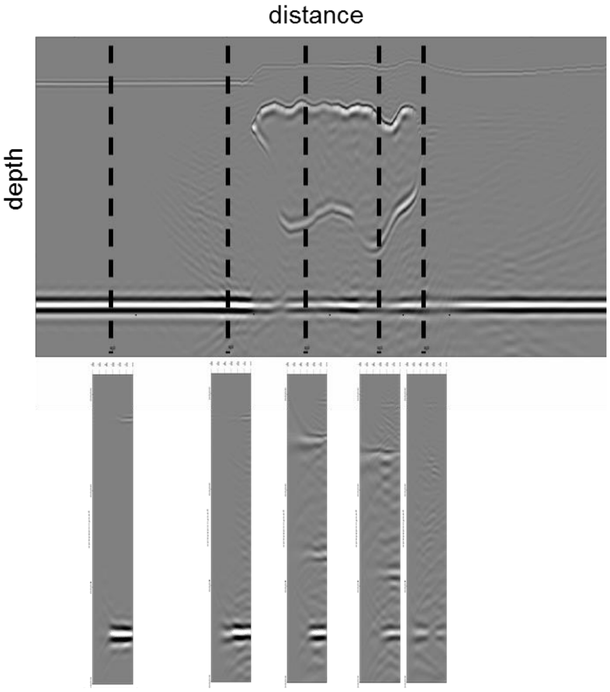

Figure 4 –Imaging multiples. Zero-offset at the top and angle gathers from -40^o to 0 ^{o} on the bottom. Comparing to Figure 3, the deeper reflector is cleaner in the second angle gather from the left and presents correct moveouts on the last two.

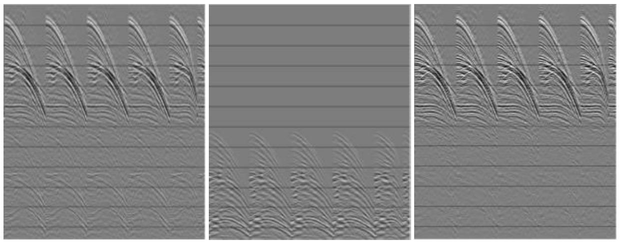

Figure 5 – Generation of surface multiples. Portion of a 3D shot record is shown. Left: original shot gathers; center: multiples modeled with Equation 4; right: shots after multiple attenuation.

Notice that crosstalk it is not clear in the migration of multiples. With the help of the synthetic of Figure 6, we can track events which possibly correspond to crosstalk (red arrows in Figure 7).

Conclusions

Migration of multiples from conventional streamers provides images of good quality that can be used in conjunction with the conventional image computed by migrating primaries to crosscheck interpretation and to define velocity model. We showed that crosstalk is not a big issue for deep water real data, however can be strong in shallow water as the test with synthetics showed. The input to the algorithm are shot gathers after multiple attenuation and surface multiples computed by Born modeling or, in the case of severe illumination unbalancing, computed with SRME.

Acknowledgments

I would like to acknowledge Petrobras for allowing publication.

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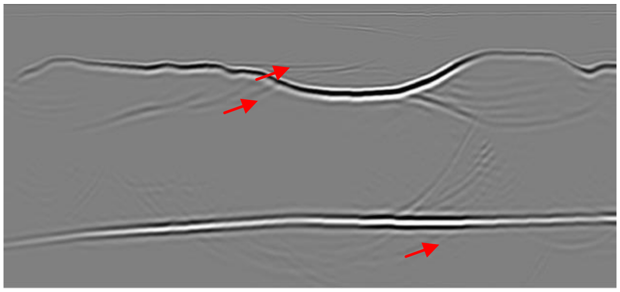

Figure 6 – 2D Born modeling/migration of multiples to evaluate crosstalk in real data.

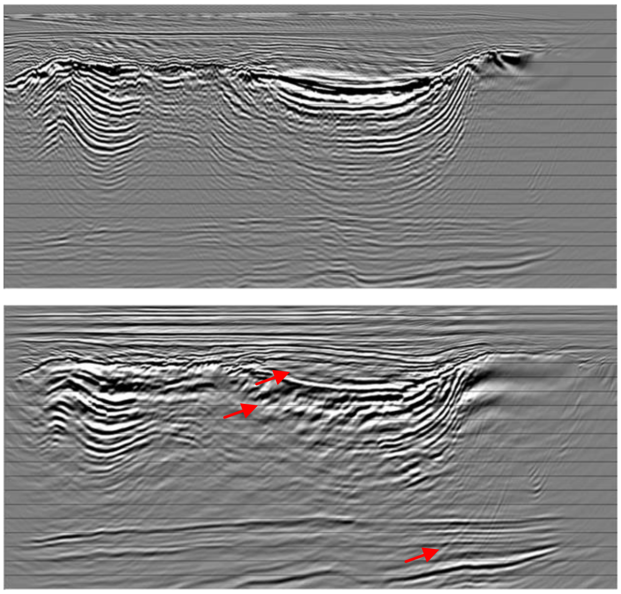

Figure 7 – Depth migration of a sail-line. Top: migration of primaries. Bottom: migration of multiples