Attenuation of Diffracted Multiples in Angle Domain Common Image Gathers

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1 SUMMARY

We propose to remove diffracted multiples with an apex-shifted Radon transform in angle domain common image gathers (ADCIG). The complexity of the wavefield is handled by the migration provided reasonably accurate migration velocities are used. As a result, the moveout of the multiples is well behaved in the ADCIGs. For 2D data, the apex-shifted Radon transform maps the 2D image space into a 3D model space cube whose dimensions are depth, curvature and apex-shift distance. Well-corrected primaries map at or near the zero curvature plane and specularly-reflected multiples map to or near the zero apex-shift plane. The diffracted multiples map elsewhere in the cube according to their curvature and apex-shift distance. Thus, specularly reflected as well as diffracted multiples can be attenuated simultaneously. We illustrate our approach with an angle-domain common image gather under the edge of a large salt body in a 2D seismic line of the Gulf of Mexico. We show that ignoring the apex shift compromises the attenuation of the diffracted multiples, whereas our approach attenuates both the specularly-reflected and the diffracted multiples without compromising the primaries.

2 INTRODUCTION

Surface related multiple elimination (SRME) uses the recorded seismic data to predict and iteratively subtract the multiple series (Verschuur and Berkhout, 1992). 2D SRME can deal with all kinds of 2D multiples provided enough data are recorded given the offset limitations of the survey line. Diffracted multiples from scatterers with a cross-line component cannot be predicted by 2D SRME but in principle can be predicted by 3D SRME as long as the acquisition is dense enough in both in-line and cross-line directions. With standard marine streamer acquisition, the sampling in the cross-line direction is too coarse and diffracted multiples need to be removed by other methods (Hargreaves et al., 2003) or the data need to be interpolated and extrapolated to a dense, large aperture grid (van Dedem and Verschuur, 1998). Hargreaves et al. realized that the moveout of the diffracted multiples does not have its apex at zero offset and proposed a shifted hyperbola approach to attenuate the multiples in CMP gathers. This approach, however, relies on the moveout of the multiples to be well approximated by hyperbolas or parabolas, which is problematic in complex media.

An attractive alternative is to attenuate the diffracted multiples in the image space (i.e. on common image gathers). In most situations in which diffracted multiples are a serious problem, the wave propagation is rather complex, for example for multiples diffracted off the edge of salt bodies. Thus, the moveout of primaries and multiples tend to be very complex making the application of data-space moveout-based methods to the removal of multiples difficult. In ADCIGs, however, since the complexity of the wavefield has already been taken into account by prestack migration (to the extent that the presence of the multiples allows an accurate enough estimation of the migration velocity field), the residual moveout of multiples is smoother and better behaved (Sava and Guitton, 2003).

In this paper we attenuate the diffracted multiples in ADCIGs by redefining the tangent squared Radon transform of Biondi and Symes (2003) to add an extra dimension to account for the shift in the apexes of the moveout curves of the diffracted multiples. We show with a 2D seismic line from the Gulf of Mexico that our approach is effective in attenuating both, the specularly-reflected as well as the diffracted multiples. In contrast, ignoring the apex shift compromises the attenuation of the diffracted multiples.

The real impact of our method for attenuating diffracted multiples is likely to be in 3-D rather than in 2-D, though the results that we show in this paper are limited to 2-D. Biondi and Tisserant (2004) have presented a method for computing 3-D ADCIGs from full 3-D prestack migration. These 3-D ADCIGs are functions of both the aperture angle and the reflection azimuth. Simple ray tracing modeling shows that out-of-plane multiples map into events with shifted apexes (like the 2-D diffracted multiples) and different reflection azimuth than the primaries. Attenuation of these multiples from 3-D ADCIGs can be accomplished with a methodology similar to one we present in this paper.

3 DIFFRACTED MULTIPLES ON ADCIGS

Figure 1 shows a zero aperture angle migrated 2D line from the Gulf of Mexico over a large salt body. The presence of the salt creates a host of multiples that obscure any genuine subsalt reflections. Most multiples are surface-related peg-legs with a leg related to the water bottom or the top of salt. Below the edges of the salt, we also encounter multiples diffracted from the salt edges (CMP position 6000 m below 4000 m in Figure 1).

Figure 2 shows two ADCIGs obtained with wave-equation migration as described in Sava and Fomel (2003). Figure 2a corresponds to a lateral position directly below the salt body (CMP position 12000 m)

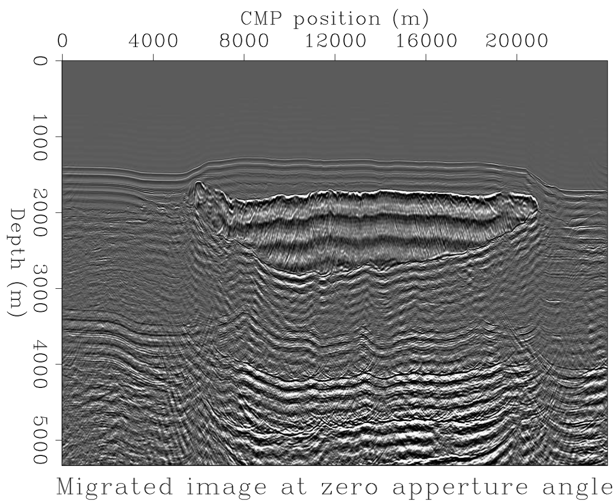


Figure 1. Migrated image at zero aperture angle of 2D seismic line in the Gulf of Mexico. Notice that multiples below the salt obscure any primary reflections.

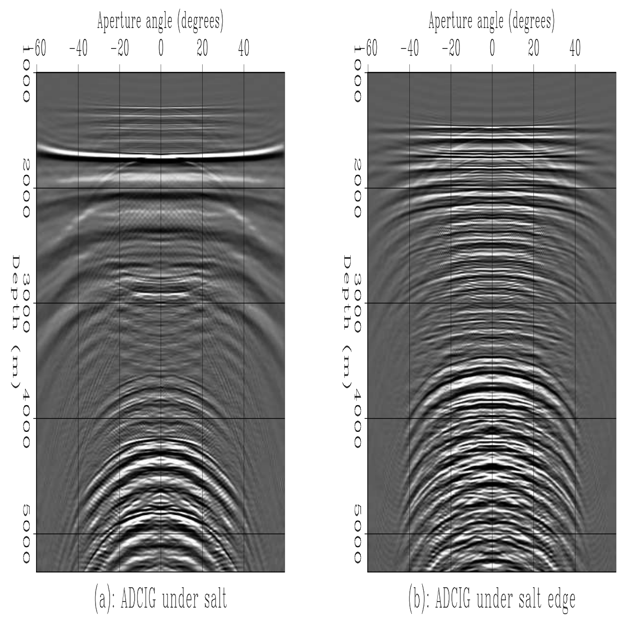


Figure 2. Comparison of angle-domain common image gathers under salt (a) and under the edge of salt (b). Note the presence of the diffracted multiples on (b) below 4000 m.

whereas Figure 2b corresponds to a position below the left edge of the salt (CMP position 22056 m). While the residual moveout of the specularly-reflected multiples shown on Figure 2a have their apexes centered at zero offset, the diffracted multiples on Figure 2b have their apexes shifted away from the zero-offset line (e.g., around 4600 m). Notice that although the data is marine, the ADCIGs show positive and negative aperture angles. We used reciprocity to simulate negative offsets and interpolation to compute the two shortest-offset traces not present in the original data. The offset gathers were then converted to angle gathers. The purpose of having both positive and negative aperture angles is to see more clearly the position of the apexes of the diffracted multiples.

4 APEX-SHIFTED RADON TRANSFORM

To account for the apex-shift of the diffracted multiples (h), we define the forward and adjoint transforms as a modified version of the "tangent squared" Radon transform introduced by Biondi and Symes (2004). We define the transformation from data space (ADCIGs) to model space (Radon-transformed domain) as:

$$m(h,q,z') = \sum_{\gamma} d(\gamma, z = z' + q\tan^2(\gamma - h)),$$

and from model space to data space as

$$d(\gamma, z) = \sum_{q}\sum_{h} m(h,q,z' = z - q\tan^2(\gamma - h)),$$

where z is depth in the data space, γ is the aperture angle, z' is the depth in the model space, q is the moveout curvature and h is the lateral apex shift. In this way, we transform the two-dimensional data space of ADCIGs $d(z,\gamma)$ into a three-dimensional model space $m(z',q,h)$.

In the ideal case, the primaries would be perfectly horizontal in the ADCIGs and would thus map in the model space to the $q = 0$ plane (a plane of (h,z')) whereas the specularly-reflected multiples would map to the $h = 0$ plane (a plane of (q,z')). The diffracted multiples map elsewhere in the cube depending on their curvature and apex shift.

5 SPARSITY CONSTRAINT

As a linear transformation, the apex-shifted Radon transform can be represented simply as $\mathbf{d} = \mathbf{L}\mathbf{m}$ where $\mathbf{d}$ is the image in the angle domain, $\mathbf{m}$ is the image in the Radon domain and $\mathbf{L}$ is the forward apex-shifted Radon transform operator. To find the model $\mathbf{m}$ that best fits the data in a least-squares sense, we minimize the objective function:

$$f(\mathbf{m}) = \|\mathbf{L}\mathbf{m} - \mathbf{d}\|^2 + \frac{\epsilon^2}{b^2}\sum_{i=1}^{n} \ln\left(1 + \frac{m_i^2}{b^2}\right), \qquad (1)$$

where the second term is a regularization that enforces sparseness in the model space. Here n is the size of the model space, ϵ controls the amount of sparseness in the model space and b relates to the minimum value below which everything in the Radon domain should be zeroed (Sava and Guitton, 2003). The least-squares inverse of $\mathbf{m}$ is

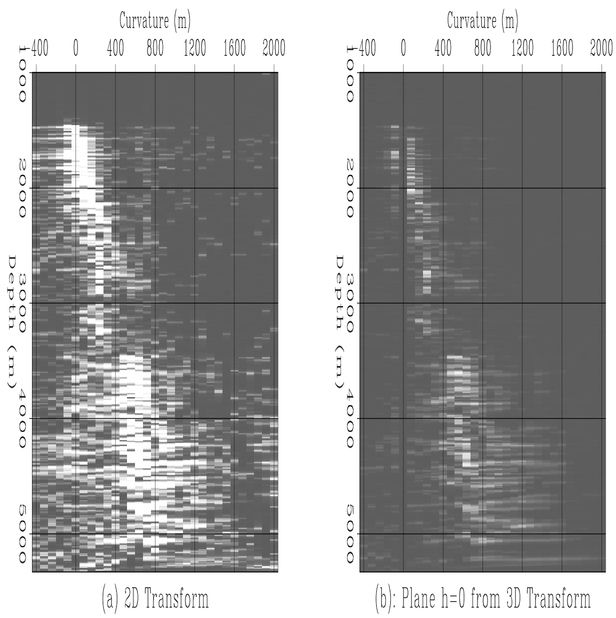


Figure 3. Radon transforms of the ADCIG in Figure 2b. (a): 2D transform. (b): $h = 0$ plane of the apex-shifted 3D transform.

$$\hat{\mathbf{m}} = \left[\mathbf{L}'\mathbf{L} + \epsilon^2 \mathbf{diag}\left(\frac{1}{1 + \frac{m_i^2}{b^2}} \right) \right]^{-1} \mathbf{L}'\mathbf{d}, \tag{2}$$

where **diag** defines a diagonal operator. Because the model space can be large, we estimate $\mathbf{m}$ iteratively. Notice that the objective function in Equation (1) is non-linear because the model appears in the definition of the regularization term. Therefore, we use a limited-memory quasi-Newton method (Guitton and Symes, 2003) to find the minimum of $f(\mathbf{m})$.

Figure 3a shows the 2D tangent-squared transform of the ADCIG in Figure 2b and Figure 3b shows the $h = 0$ plane of our 3D apex-shifted transform. The primaries are mapped near the zero curvature in both Figures although not with the same amplitudes since in the 3-D transform part of their energy is mapped near the zero curvature in other h planes (not shown). The specularly-reflected multiples are mapped away from the zero curvature line and are better focused with the 3D transform (Figure 3b). The diffracted multiples are mapped as unfocused events in the 2D transform in particular at the largest and smallest curvature values. In the 3D transform, these events are mapped to planes other than the $h = 0$ plane and are therefore not seen in Figure 3b. The absence of the background noise produced by the diffracted multiples in the 2D transform makes the specularly reflected multiples stand out better in the $h = 0$ of the 3D transform.

6 ATTENUATION OF DIFFRACTED AND SPECULARLY-REFLECTED MULTIPLES

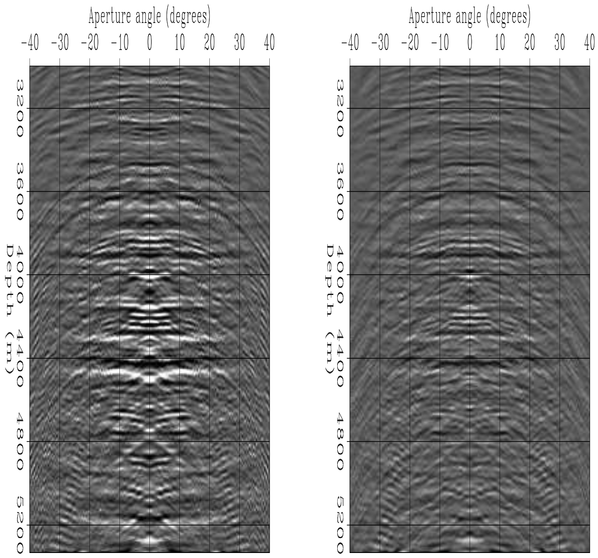
With ideal data, attenuating both specularly-reflected and diffracted multiples could, in principle, be accomplished simply by zeroing out (with a suitable taper) all the q-planes except the one corresponding to $q = 0$ in the model cube $m(z', q, h)$ and taking the inverse apex-shifted Radon transform. In practice, however, the primaries may not be well-corrected and primary energy may map to a few other q-planes. Energy from the multiples may also map to those planes and so we have the usual trade-off of primary preservation vs. multiple attenuation. The advantage now is that the diffracted multiples are well focused to their corresponding h-planes and can therefore be easily attenuated. Rather than suppressing the multiples in the model domain, we chose to suppress the primaries and inverse transform the multiples to the data space. The primaries were then recovered by subtracting the multiples from the data.

Figure 4 shows a close-up comparison of the primaries extracted with the standard 2D transform (Sava and Guitton, 2003) and with the apex-shifted Radon transform. The standard transform (Figure 4a) was effective in attenuating the specularly-reflected multiples, but failed at attenuating the diffracted multiples (below 4400 m). This is a consequence of the apex shift of these multiples. There appears to be only one clearly visible subsalt primary in this ADCIG (just above 4000 m) since it is located exactly below the edge of the salt. This primary was preserved with both transformations.

Figure 5a shows the multiples obtained with the 2D Radon transform whereas Figure 5b shows those obtained with the 3D transform. Notice how the diffracted multiples look almost as specularly-reflected multiples in Figure 5a whereas they they show their characteristic apex-shift in Figure 5b. That some of the multiples in this ADCIG are actually diffracted multiples is further emphasized in Figure 6. The specularly-reflected multiples (Figure 6a) have been separated from the diffracted multiples (Figure 6b) emphasizing their shifted moveout even between 4000 and 4400 m where they were not so clearly visible in Figure 5b.

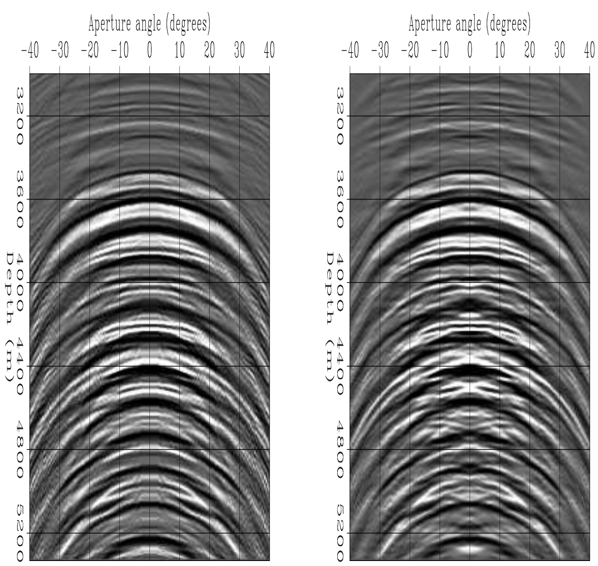
7 CONCLUSIONS

The combination of choosing the image space in the form of ADCIGs and the apex-shifted tangent-square transformation from (z, γ) to (z', q, h) has proven to be effective in attenuating both, specularly-reflected and diffracted multiples in 2D marine data. The residual moveout of both multiples in ADCIGs is well-behaved and the extra dimension provided by the apex-shift allows the attenuation of the multiples without compromising the integrity of the primaries.



(a) Primaries 2D transform (b) Primaries 3D transform

Figure 4. Comparison of primaries extracted with the 2D Radon transform (a) and with the apex-shifted Radon transform (b). Notice that some of the diffracted multiples remain in the standard result).



(a): Multiples 2D transform (b): Multiples 3D transform

Figure 5. Comparison of multiples extracted with the 2D Radon transform (a) and with the apex-shifted Radon transform (b).

ACKNOWLEDGMENTS

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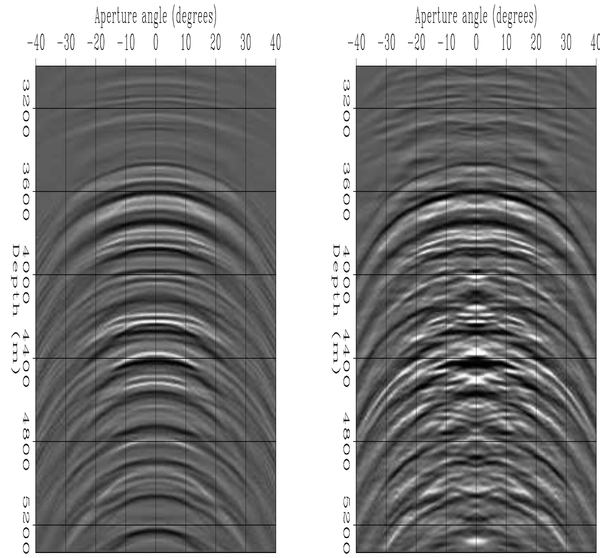

(a) Specularly-reflected multiples (b) Diffracted multiples

Figure 6. Specularly-reflected multiples (a) and diffracted multiples (b) extracted with the 3D transform.

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