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Kirchhoff imaging as a tool for AVO/AVA analysis

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ABSTRACT

The methods of true-amplitude PreSDM and MZO can be used to perform an AVO/AVA analysis. By means of a simple but illustrative example, we discuss the advantages and disadvantages of both methods. For the sake of comparison, we have also considered the routinely applied method of deriving AVO information directly from CMP gathers. For a good velocity model, AVO/AVA using both, PreSDM and MZO, yield quite accurate results of comparable quality, even in the presence of caustics or diffractions. Apart from problems with aliasing, the cheaper MZO seems to provide as valuable AVO information as PreSDM.

INTRODUCTION

Kirchhoff-type weighted stacking methods are used in an ever more sophisticated way with the aim of aggregating amplitude information into imaged seismic sections. This is, for instance, the case of true-amplitude Pre-Stack Depth Migration (PreSDM), in which amplitudes of migrated primary reflections essentially represent a measure of offset-dependent reflection coefficients (Bleistein, 1987; Schleicher et al., 1993; Gray, 1997). Application of true-amplitude PreSDM to several individual common-offset sections give rise to an ensemble of migrated sections directly amenable to an Amplitude-Variations-with-Offset (AVO) analysis (Beydoun et al., 1993).

A more recent time-domain example for Kirchhoff stacking is provided by true-amplitude Migration to Zero Offset (MZO) (Tygel et al., 1998). With this imaging process, common-offset sections are transformed into corresponding simulated zero-offset sections, for which primary reflections have the same geometrical spreading as those that would be measured if an actual zero-offset experiment were performed. At the same time, offset-dependent reflection coefficients are preserved. As zero-offset geometrical-spreading factors can be well estimated from Normal-MoveOut (NMO) velocities, application of true-amplitude MZO to an ensemble of input common-offset input sections, provides an alternative way of estimating offset-dependent reflection

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coefficients. In this way, true-amplitude MZO sections are also directly amenable to an AVO analysis.

Processing an input section with a second true-amplitude PreSDM or MZO using slightly different weights, leads to the additional determination of the corresponding reflection angles. This means that AVO results can be turned into more informative Amplitude-Variations-with-Angle (AVA) data (Bleistein, 1987; Tygel et al., 1993; Bleistein et al., 1999).

In account of the said, we have at our disposal three different methods of doing AVO, these being conventional AVO in the CMP gather, AVO after migration in the migrated image gather, or AVO after MZO in the MZO image gather. This leads to the obvious questions of which are the advantages and disadvantages of one or the other. Disconsidering the possibility of tracing rays in the given macrovelocity model and deriving reflection angles from these, we still have the two possibilities of doing AVA after MZO or after migration. Which one is more suited in different practial situations?

As an initial guess, one would assume the following. Kirchhoff-type stacking methods, such as true-amplitude PreSDM and MZO, have the advantage of not requiring an identification of reflections prior to their imaging. On the other hand, they depend on an a priori given macro-velocity model, from which the stacking lines and weight functions are constructed. Thus, time-domain methods such as MZO should be less sensitive than depth-domain methods to errors in the given velocity model. However, diffractions and caustics are typical problems in time-domain data that should be better removed by a successful PreSDM.

In this paper, we discuss, by means of a simple but illustrative example, the methods of true-amplitude PreSDM and MZO to perform an AVO/AVA analysis on specific points of a target reflector. For the sake of comparison, we have also considered the routinely applied method of deriving AVO information directly from CMP gathers.

EARTH MODEL

Referring to Figure 1, we consider the seismic response of a single, target reflector overlain by a homogeneous acoustic medium of unit density and a velocity of 3.5 km/s. The medium below the reflector is also acoustic and homogeneous with unit density and a velocity of 4.5 km/s, except for a small reservoir zone inside the dome structure, where the velocity assumes the constant value of 2.0 km/s. The seismic line is a dip line and all point sources are reproducible. The multicoverage data that are acquired in this way can, on account of the 2-D model and the 3-D source and receiver characteristics, be modeled and imaged by what is commonly called 2.5-D methods.

This particular form of the reflector was chosen to study the results of an AVO/AVA analysis at four characteristic points for seismic imaging while leaving all other pos-

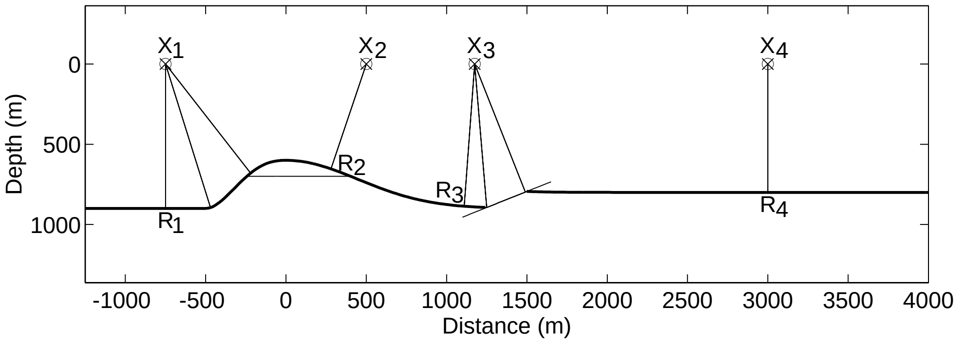

Figure 1: Earth model for the synthetic examples. The AVO and AVA analysis was carried out at the four reflection points R_1 to R_4 that are shown here with their respective normal rays.

sible complications out of consideration. Point R_1 lies within a caustic zone due to a strongly curved left flank of the dome. Point R_2 is located above the reservoir, slightly dislocated from its top. Point R_3 is positioned close to a fault where diffractions originate, and point R_4 is a reference point in an uperturbed area on a flat reflector. In spite of its apparent simplicity the present model contains, in its fundamental form, some of the main structural difficulties faced by all migration and imaging methods when amplitudes are of prime interest.

The multicoverage reflections from the target reflector were computed by a 2.5-D Kirchhoff-Helmholtz forward modeling algorithm and are organized as an ensemble of common-offset sections for the offsets $2h = 400$ m to $2h = 2400$ m in steps of $2\Delta h = 100$ m. White noise was added with a signal-to-noise ratio of three with respect to the mean amplitude in the section for $2h = 200$ m. The phenomenon of a caustic to the left of the dome, as well as the phenomenon of diffractions occurring close to the fault are present in all common-offset sections.

FORMULATION OF THE PROBLEM

Given the multicoverage data as described, a velocity model of the overburden of the target reflector and CMP points X_1 to X_4, to obtain the AVO/AVA responses at the corresponding points R_1 to R_4 at the target reflector.

Below we present the results of two true-amplitude imaging methods designed to solve the above problem. At first, we show the AVO results obtained using Kirchhoff true-amplitude PreSDM and MZO algorithms, respectively. These are directly compared to the ones obtained by the application of conventional AVO directly on the CMP gather. Thereafter, we show the corresponding AVA results after PreSDM and MZO, respectively.

AVO BY TRUE-AMPLITUDE PRESDM AND MZO

We apply a true-amplitude PreSDM algorithm to an ensemble of individual common-offset sections extracted from the multicoverage data. This leads to the corresponding ensemble of common-offset migrated images. From all migrated common-offset sections, we have extracted the image gathers that include the reflector points R_1 to R_4. As a result of the true-amplitude migration, the amplitudes in the image gathers are free from geometrical-spreading losses, thus being a direct measure of the of offset-dependent reflection coefficients. In practice, the true-amplitude output would still suffer from other wave-propagation effects, not removed from the true-amplitude migration algorithm. These includes, e.g., attenuation along the ray paths and transmission losses accross interfaces. For most AVO purposes, these quantities do not show significant lateral variation, being taken as fixed scaling factors in each image gather. As we are here mainly interested in the differences between AVO/AVA after migration and MZO, we neglect these effects, which would affect migration and MZO in the same way.

We next apply a true-amplitude MZO algorithm to the same ensemble of individual common-offset sections. This results in a corresponding ensemble of simulated zero-offset sections. As a result of the application of true-amplitude MZO, simulated zero-offset primary-reflection amplitudes are given by the original offset-dependent reflection coefficients divided by the zero-offset geometrical spreading. The latter can, however, be readily removed using classical formulas based on NMO velocities and zero-offset traveltimes. In the present case of a homogeneous overburden, the geometrical-spreading factor is the product of the overburden (constant) velocity by the zero-offset traveltime. As before, we extract of all simulated zero-offset section the MZO image gather at the selected CMP points X_1 to X_4.

AVO ANALYSIS

For an AVO analysis, we pick the amplitudes within the CMP section, the MZO image gather and the migrated image gather. To be able to compare the results, the CMP and MZO amplitudes are subjected to the corresponding geometrical-spreading correction, i.e., multiplication by traveltime and migration velocity. Plotting the resulting amplitude values as a function of the offset $2h$ for which they were obtained, results in a standard AVO analysis. This is shown in Figure 2 for the four reflector points R_1 to R_4.

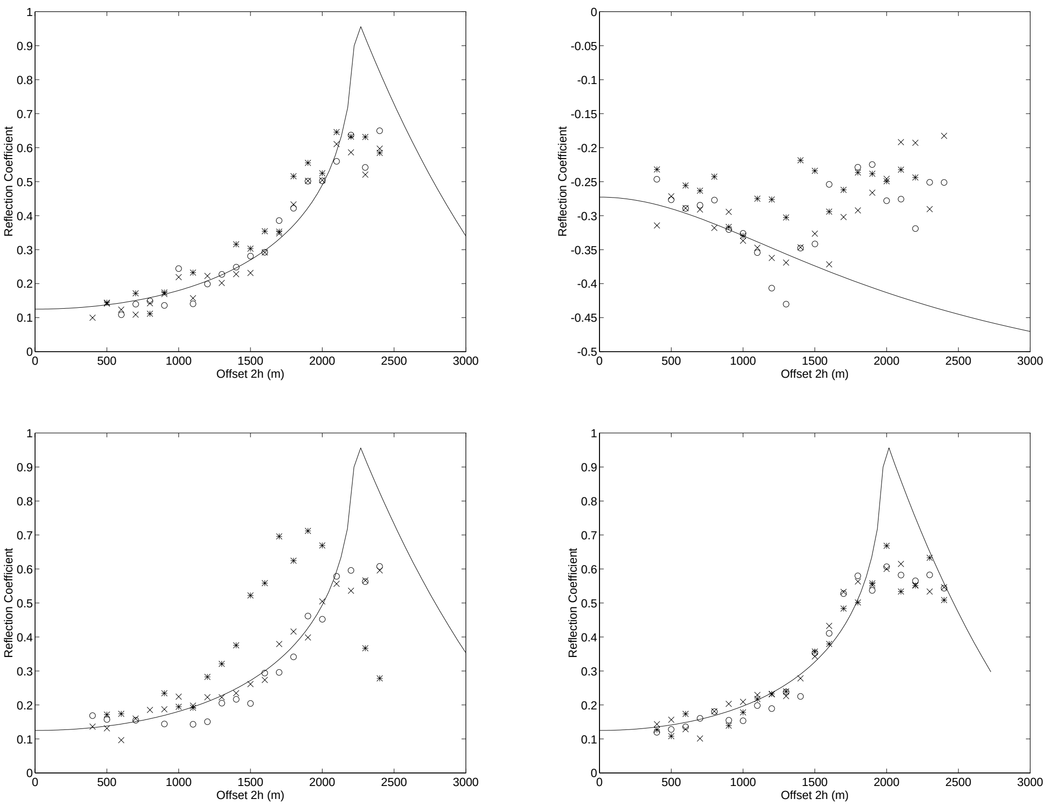

Figure 2: Comparison of amplitudes of CMP (asterisks), MZO (circles), and migration (crosses) with the exact reflection coefficient (solid line) as a function of offset $2h$.

TRANSFORMING AVO INTO AVA

As explained above, reflection coefficients, as a function of offset, can be directly estimated by one application of true-amplitude PreSDM (or MZO). It can be shown, however, that, in addition to the reflection coefficient, the corresponding reflection angle can be also estimated. All that is needed for that purpose is an additional application of the same PreSDM (or MZO) algorithm using slightly different weight functions. By relating the two PreSDM (or MZO) stacking results to each other, one can determine the reflection angle and, thus, one can transform AVO into AVA (Bleistein et al., 1999).

AVA ANALYSIS

We apply the above mentioned technique to the previous PreSDM and MZO AVO image gathers. The results are the corresponding PreSDM and MZO AVA panels of Figure 3, into which we have superimposed the exact angle-dependent reflection co-

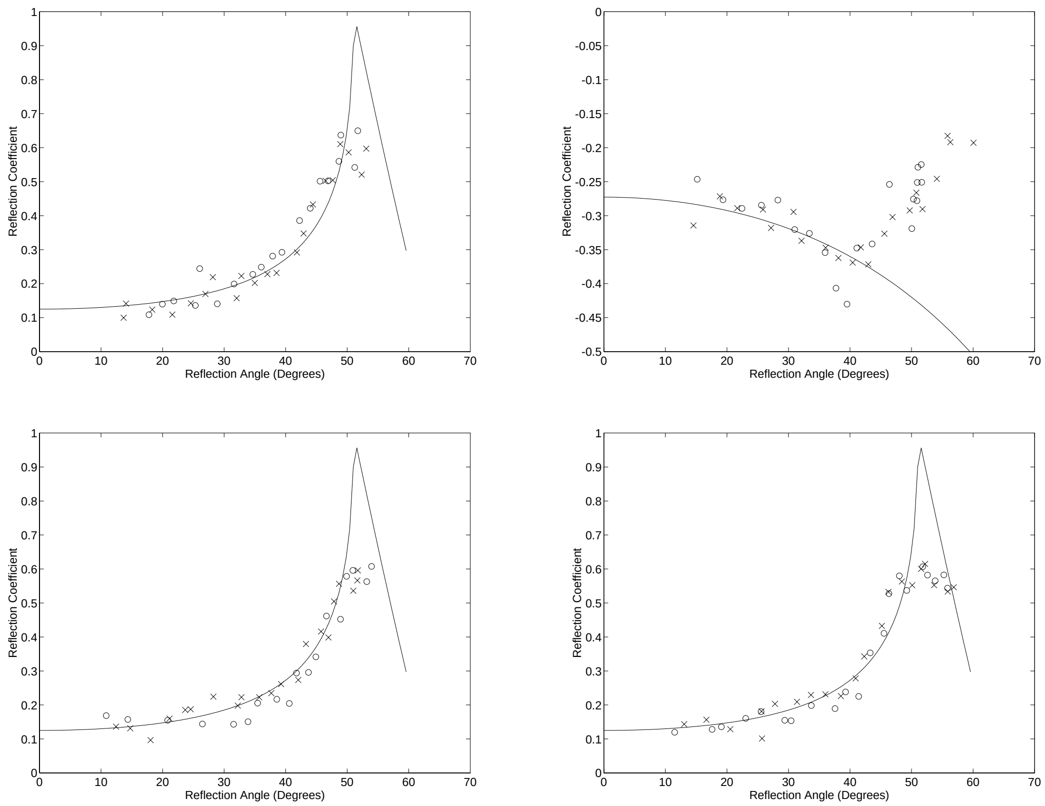

Figure 3: Comparison of amplitudes of MZO (circles) and migration (crosses) as a function of the determined reflection angle with the exact angle-dependent reflection coefficient (solid line).

efficient function directly computed from the model. Apparently we obtain a good match if we use the exact migration velocity.

DISCUSSION OF RESULTS

Starting with the simplest situation of point R_4 on the flat and undisturbed part of the target reflector, we observe from the AVO graphs of Figure 2 an excellent agreement between the directly obtained CMP amplitudes with the ones resulting from the application of true-amplitude PreSDM and MZO amplitudes. All values closely match the correct reflection coefficient. The same is true in the AVA graph of Figure 3 corresponding to PreSDM and MZO data. This indicates that, not only amplitudes, but also angles are extracted very accurately in this simple situation. We may conclude that in such a situation, conventional AVO within the CMP gather is quite sufficient to determine the AVO trend.

Interestingly enough, things do not worsen too much at point R_3, located near the fault. The diffraction events do not seem to disturb the application of the true-amplitude PreSDM and MZO algorithms, good results being obtained both in the AVO or AVA domains. Also the direct AVO method directly applied on the CMP gather gave rise of comparable resuts. In the caustic region at point R_1, the CMP-AVO gets a little worse than the corresponding results from true-amplitude PreSDM and MZO, but still recovers the AVO trend quite well, although the triplication of events in the bow-tie structure of the caustic is not completely resolved.

Finally, at point R_2 located almost on top of the reservoir low-velocity zone, we see the most dramatic difference between CMP-AVO and that of true-amplitude PreSDM or MZO. Whereas the latter two remain close to the theoretical curve for about ten offsets, the CMP amplitudes remain so for the first five offsets only, thus making an AVO analysis much more difficult. The deviation of all amplitudes from the theoretical curve at larger offsets is due to the larger Fresnel zone, which includes part of the target reflector away from the top of reservoir. The effective velocity below the reflector for these offsets is some weighted mean of the velocities within and outside the reservoir zone.

We observe that in the present model, the velocity contrast along the reflector remains constant, with the exception of the top of reservoir. In a practical situation, with the contrast varying along the target reflector, CMP-AVO should be expected to yield accordingly worse results. This is because of the reflection-point smear, namely different reflection points for different offsets.

VELOCITY DEPENDENCE

To study the quality of AVO and AVA analysis in dependence on the migration velocity, we have repeated the above experiment with a 10% too low migration velocity, 3.15 km/s.

Figure 4 shows the corresponding AVO panels. The match between the amplitudes of CMP, MZO as well as migration and the theoretical reflection coefficient remains quite well. As before, at the reservoir reflection point R_2, the results are worst. Again, migration yields better amplitudes than MZO or CMP. At the other three reflection points, the results of all three methods match the theoretical curve comparably well. The amplitude does not seem to be greatly affected by the incorrect migration velocity.

Finally, looking at the AVA graphs in Figure 5, we observe a shift to greater angles. This is a reasonable effect since geometrically, a shallower reflector involves greater reflection angles than a deeper-down one. We conclude that the angle is the quantity most sensible to velocity inaccuracies. However, as one would surely process in practice only flat image gathers, velocity inaccuracies are not expected to be greater than

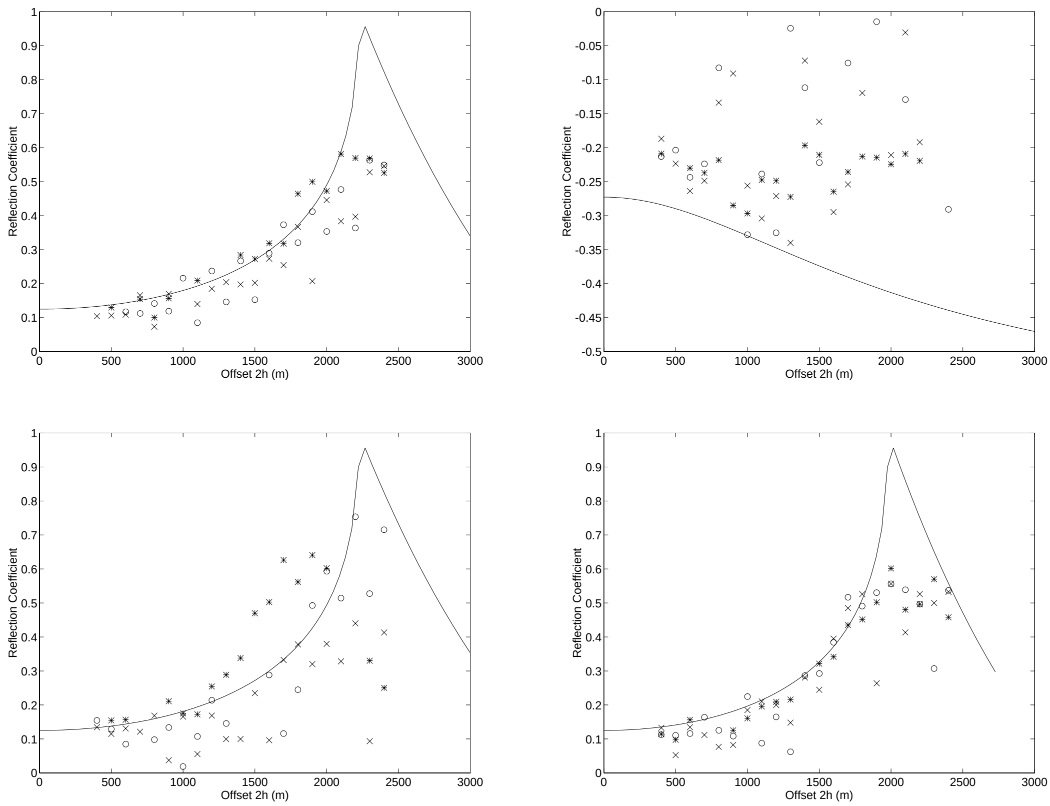

Figure 4: Comparison of amplitudes of CMP (asterisks), MZO (circles), and migration (crosses) with the exact reflection coefficient (solid line) as a function of offset $2h$ for migration velocity 3.15 km/s.

ten percent, such that an AVA analysis remains possible. Comparing the AVO and AVA results of MZO to those of migration, we observe that they present more or less the same stability with respect to migration velociy. Only at supercritical angles, where AVO failed in all of our examples, MZO amplitudes were more strongly affected by the inaccurate velocity than migration amplitudes.

CONCLUSIONS

Having ignored the generally very complex overburden of a target reflector in the real Earth, we have on a simple, but very illustrative example, discussed the application of true-amplitude PreSDM and MZO as tools for AVO/AVA analysis. For a relatively accurate reflector overburden velocity model, true-amplitude PreSDM and MZO have presented good results even in the vicinity of caustics and diffractions. It should be mentioned that MZO appeared more sensible to aliasing than PreSDM. For a larger trace distance, results of PreSDM were not much different, as oppose to the ones of

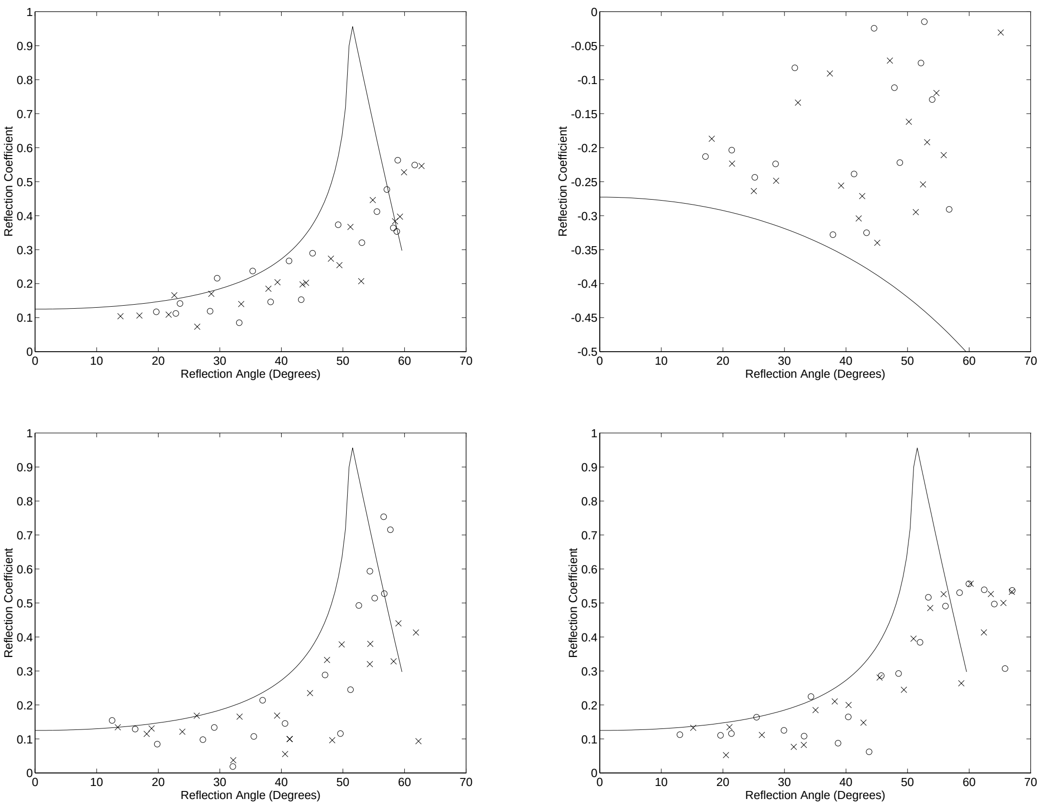

Figure 5: Comparison of amplitudes of MZO (circles) and migration (crosses) as a function of the determined reflection angle with the exact angle-dependent reflection coefficient (solid line) for migration velocity 3.15 km/s.

MZO that suffered strongly from aliasing.

Contrary to intuition, both methods have shown to work equally well in the presence of caustics and diffractions and were equally sensitive to a incorrect velocity model. Mostly affected by the latter were the reflection angle as determined by the use of a double application of the PreSDM (or MZO) algorithms.

In conclusion, the choice between true-amplitude PreSDM or MZO as the tool to an AVO/AVA analysis should be based on the following observations. Because of the smaller operator size, MZO is a faster method. In our simple analytic examples, MZO was about a factor two faster than PreSDM. On the other hand, without an amplitude-preserving anti-alias filter, MZO will certainly run into problems when applied to field data with insufficient trace spacing. Complexities in the wave field such as diffractions and/or caustics do not seem to severely affect any of the methods.

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PUBLICATIONS

A paper containing these results has been published in The Leading Edge (Tygel et al., 1999).