True-amplitude CRS-based Kirchhoff time migration for AVO analysis

Miriam Spinner and Jürgen Mann, Geophysical Institute, University of Karlsruhe, Germany*

Summary

The achievable image quality and the reliability of amplitudes in Kirchhoff migration strongly depend on the selection of the migration aperture. Our aim is to use CRS-based minimum apertures in Kirchhoff prestack time migration to obtain the best possible input for AVO/AVA analyses. The basic idea is demonstrated for a synthetic data set which contains events from a common sequence of gas/water/oil contacts. We discuss the determination and extrapolation of stationary points and projected Fresnel zones based on CRS wavefield attributes, as well as a simple and efficient way to set up a migration velocity model. The first results show a significant reduction of amplitude dispersion in common-image gathers as well as in the zero-offset section, thus providing superior input to AVO/AVA analyses.

Introduction

The Common-Reflection-Surface (CRS) stack method as highly automated imaging process has been successfully applied to various data sets. Its implementation for zero-offset (ZO) simulation was initially mainly considered as an alternative to stacking procedures like NMO/DMO/stack. Meanwhile, the stacking parameters of the CRS stack, the so-called kinematic wavefield attributes, turned out to be extremely useful for various purposes: estimation of projected Fresnel zones and geometrical spreading factors, tomographic velocity model determination, etc.

Pruessmann et al. (2004) presented a first approach to perform CRS-based AVO analysis in the *unmigrated* time domain. For complex media, a migration prior to AVO analysis might, however, be inevitable.

For optimum amplitude behavior in the migrated image, Kirchhoff migration should be restricted to the projected Fresnel zone, only (Schleicher et al., 1997). In conventional migration the stationary point where the operator is tangent to the event and the projected Fresnel zone are unknown prior to migration. Thus, the aperture has to be centered around the operator's apex and has to be chosen sufficiently large to preserve steep events. As a consequence, a lot of noise off the event and possibly other events contribute to the stack and deteriorate the amplitudes. In addition, the risk of operator aliasing is increased. In contrast, the minimum-aperture operator avoids these problems as its location and size fits the constructively contributing part of the reflection event. Jäger (2005) employed the CRS attributes in pre- and poststack Kirchhoff depth migration to estimate the size and location of this minimum aperture.

As depth migration is quite sensitive to velocity model errors and costly in terms of inversion, we propose to transfer the concept to the time domain. There, we benefit from reduced sensitivity to model errors, and the model building is much simpler and may be highly automated. Working with the straight ray approximation, we obtain smooth, analytic migration operators and operator slopes, and the consistent true-amplitude weight factors can also be calculated analytically.

Basics of CRS stack

The CRS method is based on a second-order approximation of the kinematic reflection response of an arbitrarily curved reflector segment in depth. This approximation can be entirely expressed in terms of so-called kinematic wavefield attributes defined at the acquisition surface rather than in the subsurface. In 2D, the commonly used hyperbolic approximation reads (see, e. g., Schleicher et al., 1993):

$$
\begin{aligned}
t^2(x_\mathrm{m},h) = &\left[t_0 + \frac{2\,\sin\alpha\,(x_\mathrm{m}-x_0)}{v_0}\right]^2 \\
&+ \frac{2\,t_0\,\cos^2\alpha}{v_0}\left[\frac{(x_\mathrm{m}-x_0)^2}{R_\mathrm{N}} + \frac{h^2}{R_\mathrm{NIP}}\right].
\end{aligned} \tag{1}
$$

It describes the traveltime along a paraxial ray characterized by source/receiver midpoint x_m and half-offset h in terms of the traveltime t_0 along the central normal ray emerging at x_0, the near-surface velocity v_0, and the wavefield attributes α, R_NIP, and R_N. The latter three are related to the propagation direction and wavefront curvatures of two hypothetical waves, namely the so-called NIP and normal wave, respectively (Hubral, 1983).

Similar to a conventional stacking velocity analysis, the optimum wavefield attributes for each location (x_0,t_0) are determined automatically by means of coherence analysis. The final results are entire sections of the wavefield attributes α, R_NIP, and R_N, as well as coherence section.

Determination of stationary points

In Kirchhoff migration, the main contribution to the diffraction stack stems from the region where the reflection event is tangent to the migration operator. As the CRS operator (1) is already tangent to an reflection event in the data, this tangency condition can be directly evaluated by a comparison of CRS operator slope and migration operator slope. This is particularly easy for the ZO case where the CRS operator simplifies. In case of Kirchhoff depth migration, the migration operator slope has to calculated numerically from the Greens function tables (Jäger, 2005). For time migration with straight rays as considered here, the operator as well as its derivatives are given by analytic expressions.

In practice, we calculate the modulus of the difference between these two slopes and choose the location of the minimum as stationary point. The associated coherence values help to decide whether the stationary point is reliable by applying a user-given threshold.

Estimation of minimum aperture

By definition, the point (x_0, t_0) in operator (1) is the stationary point for ZO in the context of Kirchhoff migration. The concept of the *Common-Reflection-Point (CRP) trajectory* allows to extrapolate this stationary point to finite offset. Its projection onto the acquisition surface reads (Höcht et al., 1999):

$$x_{\mathrm{m}}(h) = x_0 + r_{\mathrm{T}} \left(\sqrt{\frac{h^2}{r_{\mathrm{T}}^2} + 1} - 1 \right) , \qquad r_{\mathrm{T}} = \frac{R_{\mathrm{NIP}}}{2 \sin\alpha} . \tag{2}$$

The final information relevant for minimum migration apertures which can be gained from the attributes is the size of the projected ZO Fresnel zone W_{F}. In terms of CRS attributes, it can be approximated as (see, e. g., Mann, 2002)

$$\frac{W_{\mathrm{F}}}{2} = |x_{\mathrm{m}} - x_0| = \frac{1}{\cos\alpha} \sqrt{\frac{v_0 \, T}{2 \left| \frac{1}{R_{\mathrm{N}}} - \frac{1}{R_{\mathrm{NIP}}} \right|}} , \tag{3}$$

where T denotes some measure of the wavelet length. Unfortunately, an extrapolation of the ZO Fresnel zone to finite offset is not supported by the attributes alone, but requires additional assumptions. For the data example below, we simply used a constant extrapolation to finite offset, an approximation which appears to be reasonably accurate to obtain reliable amplitudes.

Model determination

The wavefield attributes are attached to the stationary point for ZO, i. e., (x_0, t_0). Kirchhoff time migration, however, is usually parameterized in terms of RMS velocities defined at the operator apices.

As the NIP wave does not depend on the reflector curvature and orientation, it allows to approximate the ZO *diffraction* response of a diffractor located on the (unknown) reflector segment in depth. Expressing this diffraction response in the coordinates of the apex location $(x_{\mathrm{apex}}, t_{\mathrm{apex}})$ yields the poststack time migration operator parameterized with a migration velocity v_{c} in terms of CRS wavefield attributes (Mann, 2002).

Each set of (reliable) CRS attributes can now be related to a migration velocity value and its corresponding location in the time domain. To end up with a smooth velocity model covering the whole target zone, this values have firstly been smoothed along the reflection events in an event-consistent manner (Mann and Duveneck, 2004). In a subsequent infill procedure, the migration velocities are inter- and extrapolated using a distance weighted polynomial interpolation. This approach has, so far, no sound physical justification.

Synthetic data example

To demonstrate the potential of the true-amplitude CRS-based Kirchhoff time migration for AVO analysis we generated a synthetic prestack data set for the model shown in Figure 1a. The target region for the amplitude extraction is the horizontally layered structure beneath the uppermost dome-like interface. The elastic parameters are chosen such as to mimic a sequence of gas/oil/water contacts. The primary P-waves have been modeled by means of a wavefront construction method using a zero-phase Ricker wavelet with a dominant frequency of 40 Hz. Edge diffractions have not been considered. Colored noise was added; a representative common-offset section is shown in Figure 2.

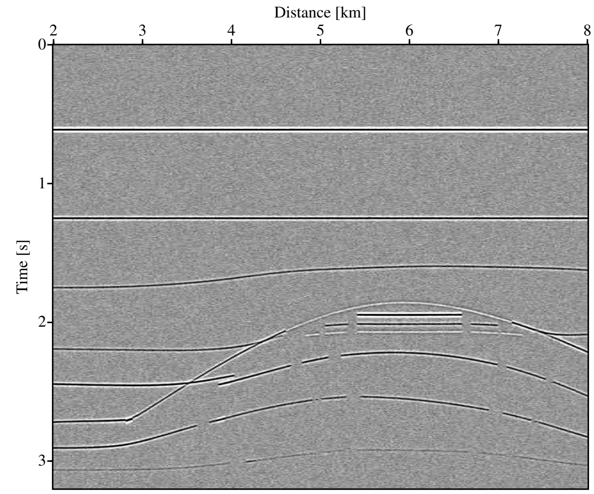

Fig. 2: Representative common-offset section ($h = 100$ m) extracted from the synthetic prestack data.

The CRS stack has been applied to simulate a ZO section in a fully automated way. More relevant in this context are the CRS wavefield attribute sections and the associated coherence section. Based on the coherence values which indicate the location of the reflection events and the reliability of their wavefield attributes, an automated picking process was employed to extract the wavefield attributes along the reflection events. These attributes have been used to determine all relevant informations for the minimum-aperture migration (the ZO location of the stationary point, its extrapolation to finite offset, and the size of the projected ZO Fresnel zone) as well as the time-migration velocity values. The interpolated smooth time-migration velocity model shown in Figure 1b is based on these velocity values. The model is kinematically consistent with the data as can be seen from the set of common-image gathers (CIGs) displayed in Figure 3.

The time migration was performed twice: on the one hand in a conventional way with user-given aperture, on the other hand with the minimum aperture given by the (extrapolated) projected Fresnel zone. The user-given aperture was chosen such that the steep flanks of the dome-like structure has been imaged. The projected ZO Fresnel zone is shown in Figure 4 for those locations where stationary points have been detected. As expected, its size increases with increasing traveltime and increasing curvature of the reflection events.

Stacks of the two true-amplitude prestack migration results are depicted in Figure 5. For Figure 5b, the minimum-aperture migration was only performed at locations where stationary points

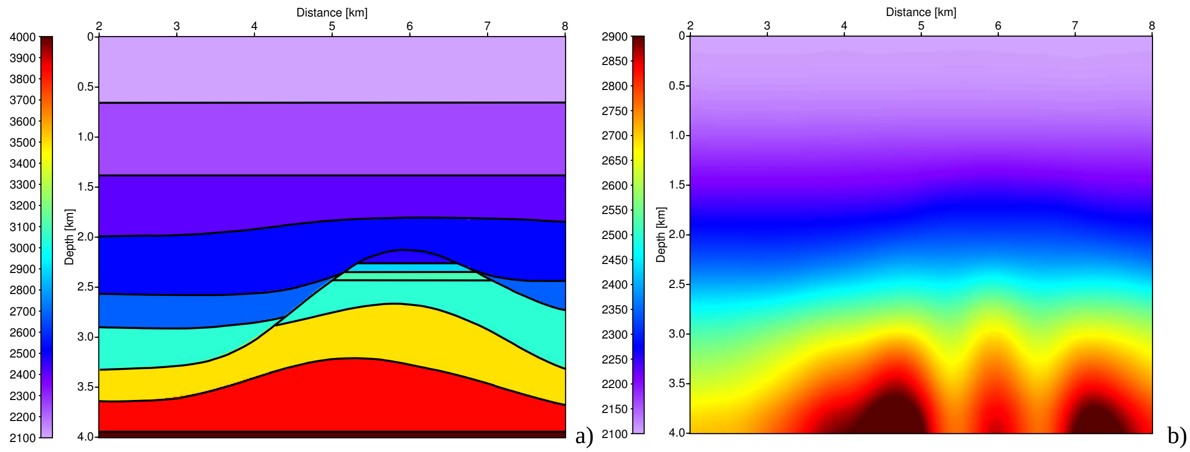

Fig. 1: a) Interval P-wave velocity model [m/s] used to generate the synthetic data, b) time migration velocity model [m/s] determined from CRS wavefield attributes. Note the different color scales.

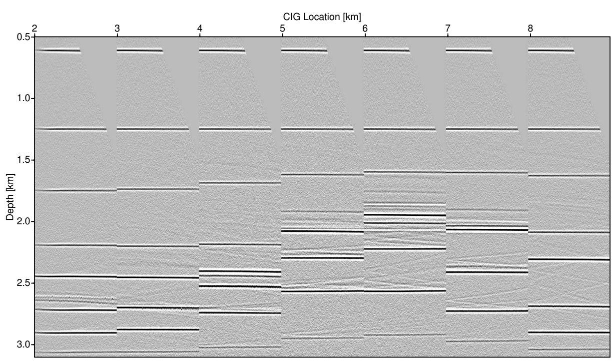

Fig. 3: Several common-image gathers extracted from the time-migrated prestack data.

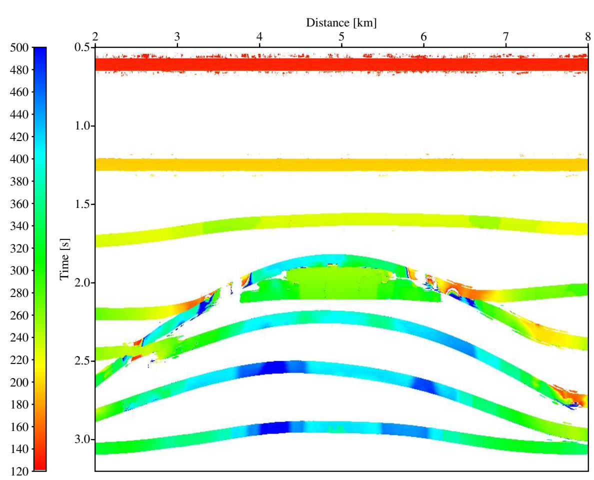

Fig. 4: Size of projected first ZO Fresnel zone [m] estimated from the CRS attributes. Only locations with identified stationary points have been considered.

have been detected. This removes many of the artifacts due to modeling deficiencies, but might cause gaps along weak events: stationary points might not be detected along an entire reflection event. In practice, we use the user-given aperture at all other locations to obtain a fully covered image without gaps.

Finally, we extracted the amplitudes along the images of the target reflectors. Figure 6 shows the amplitude along the uppermost target reflector (directly beneath the dome-like interface) for one of the CIGs (Figure 6a) and for offset zero (Figure 6b). The amplitudes are shown for both aperture definitions applied to the noisy data. In addition, the minium-aperture migration has been applied to the same data without noise to obtain reference values. Obviously, the CRS-based results are closer to the reference values and far more contiguous compared to their conventional counterparts. Thus, they provide superior input to any kind of AVO/AVA analysis.

Conclusions

Jäger (2005) successfully applied CRS wavefield attributes to estimate the location of stationary points and the projected Fresnel zone required for minimum-aperture Kirchhoff depth migration. We demonstrated that this CRS-based minimum aperture concept can be transferred back to the time domain. In the time domain, not only the sensitivity to model errors is reduced, but the time migration velocity model building can be performed in a highly automated and simple way. The entirely analytic migration operators and their corresponding derivatives allow an efficient implementation, especially concerning the determination of stationary points. Due to the reduced sensitivity to model errors and the optimum migration aperture we obtain more reliable amplitudes for AVO/AVA analyses compared to conventional approaches.

Acknowledgments

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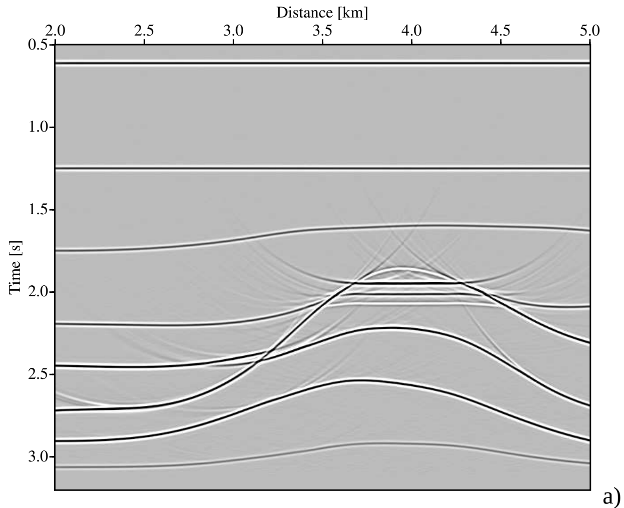

Fig. 5: Stacks of the time-migrated prestack data with a) conventional user-defined aperture and b) CRS-based minimum-aperture. In the latter case, only locations with identified stationary points have been considered. The artifacts mainly visible in the conventional result are due to missing edge diffractions and gaps in the modeled prestack data.

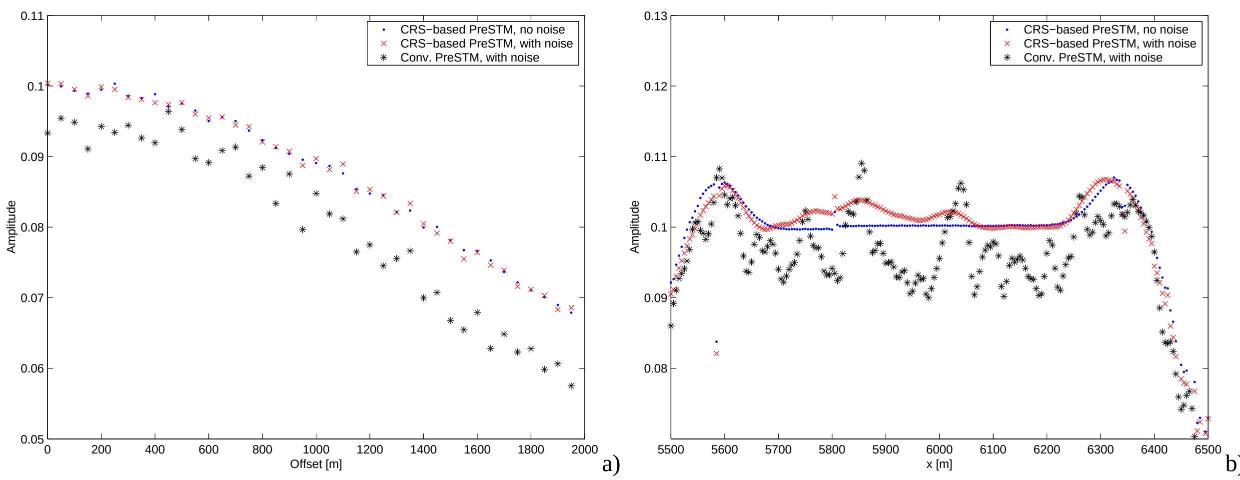

Fig. 6: Amplitudes along the first target reflector extracted from the time-migrated prestack data a) for a CIG ($x = 5900$m) and b) for ZO. Note the significant differences in dispersion.

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