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Parameterization, stacking, and inversion of locally coherent events with the Common-Reflection-Surface Stack method

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SUMMARY

The Common-Reflection-Surface Stack method relies on the presence of locally coherent reflection events in the seismic prestack data. Using a second-order traveltime approximation in an automated coherence analysis, such events are locally characterized by means of so-called kinematic wavefield attributes. The most important purpose of these attributes is velocity model building within as well as beyond the second-order assumptions inherent to the CRS approach.

Introduction. Locally coherent events have been playing an important role in seismic reflection imaging for decades. Although not being the first approach based on such events, the common-midpoint (CMP) stack method (Mayne, 1962) is the most successful approach: here, CMP gathers extracted from the prestack data are scanned for reflection events with hyperbolic moveout. These hyperbolas are parameterized in terms of zero-offset (ZO) time and stacking velocity. Assuming a 1D model, the latter coincides with the RMS velocity and can be easily inverted for interval velocity. The events described in this way can be considered as locally coherent as there is no need to track them contiguously across the entire prestack data. The CMP stack is based on the assumption that a reflection event in a CMP gather is associated with a common reflection point (CRP) in depth. Obviously, this only holds for 1D models. To apply this approach to models with lateral velocity variation, an additional dip-moveout (DMO) correction (e. g., Deregowski, 1986) is required in a way to precondition the data to meet the 1D assumption.

A different approach to generalize the CMP method to models with lateral variations is based on a simple consideration: we observe locally coherent events in the prestack data, not only in CMP gathers, but also in the perpendicular, off-CMP direction. Accordingly, we also expect locally coherent reflectors in the subsurface rather than isolated CRPs. Therefore, we can extend the CMP method to entire common reflection surfaces (CRS)[1]. The incorporation of neighboring reflection points in a certain vicinity is also supported by the concept of the interface Fresnel zone which defines the area around a reflection point from which we can expect constructive contributions. A more detailed discussion of the generalization from CMP to CRS can be found in Hertweck et al. (2007).

The reflection response of a CRS is not only a trajectory in the prestack data, but represents a spatial event which spreads in source/receiver offset and source/receiver midpoint direction. If we want to parameterize such an event in the same way as in the CMP approach, i. e., up to second order in traveltime, we have to replace the simple CMP hyperbola by a hyperbolic surface. In contrast to an event related to a CRP, the reflection response of a CRS also incorporates the local structure of the reflector. Again in terms of a second order approximation, this includes the local dip[2] and the local curvature of the reflector. In other words, the CRS stacking operator carries more information than the CMP operator. Most notably, this allows to introduce more general inversion schemes beyond Dix inversion. The determination of the CRS stacking parameters relies on coherence analysis along various CRS operators within the prestack data. In contrast to conventional stacking velocity analysis, this analysis is performed in an automated manner for each individual sample in the stacked section to be simulated.

Parameterization of the CRS operator. A hyperbolic surface like the CRS operator can be parameterized by means of the first and second spatial traveltime derivatives at the sample to be simulated. The number of required parameters depends on the dimension of the prestack data and the type of raypath to be simulated. In the most general case, the prestack data has five dimensions and we encounter four different first derivatives plus ten different second derivatives. For data with less dimensions like single-azimuth data or 2D data, the number of required derivatives reduces accordingly. The problem significantly simplifies if we consider classical stacking, i. e., the simulation of ZO data: in case the upgoing and downgoing raypaths coincide, all first derivatives with respect to offset vanish and only eight independent parameters remain for the 3D case. For 2D data, this further reduces to three parameters.

If the near-surface velocity is known and virtually constant within the stacking aperture, the traveltime derivatives can be expressed in terms of propagation directions and curvatures of hypothetical wavefronts at the acquisition surface. This provides a vivid geometric interpretation of the stacking parameters. This representation is mandatory for applications which explicitely rely on propagation directions, e. g. redatuming and topography handling (see, e. g., Heilmann

[1] A CRS might degenerate to a diffractor which can be regarded as a coherent reflector with infinite curvature.
[2] The dip also enters into the stacking velocity, but cannot be separated from the (zero-dip) NMO velocity.

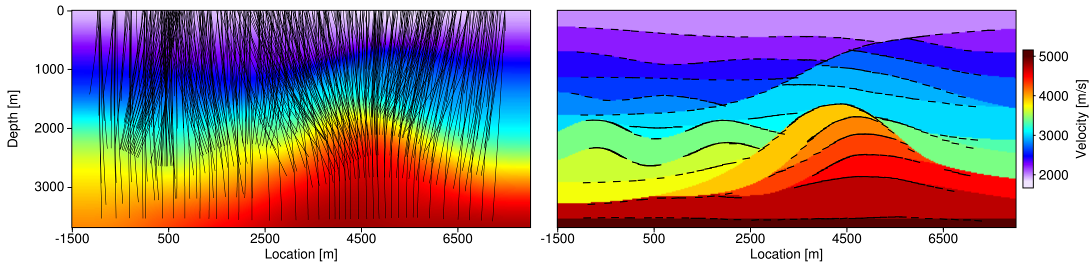

Figure 1: First synthetic data example for NIP-wave tomography by Duveneck (2003). Left: inverted velocity model and reconstructed normal rays. Right: inverted NIPs displayed as dip bars on top of the original blocky model.

et al., 2006). In the general case of finite-offset simulation, two-way experiments are required to describe all stacking parameters (Zhang et al., 2002). For the simpler case of ZO simulation which will be considered in the following, two one-way experiments are sufficient: an exploding reflector experiment and an exploding point source experiment with the source located at the (unknown) NIP. Evidently, the latter experiment is related to a hypothetical diffractor in depth such that a second-order approximation of the diffraction traveltimes of a hypothetical diffractor at the NIP is readily available.

A third alternative to express the stacking parameters was proposed by Hertweck et al. (2007): to highlight the relation between CRS stack and the classic CMP method, the familiar (azimuth-dependent) stacking velocity is pertained as parameter. In addition, the horizontal slowness (vector) and a second (azimuth-dependent) imaging velocity named curvature-moveout velocity are introduced to fully describe the CRS stacking operator. The latter is not associated with a physical velocity, but simultaneously depends on the reflector's curvature and its overburden. The terms in parentheses refer to the 3D case.

Inversion with analytic diffraction traveltimes. According to the NIP-wave theorem (see, e. g., Hubral, 1983), the CMP traveltimes for an actual reflector coincide with the ZO diffraction traveltimes of a hypothetical diffractor at the same NIP up to second order. In turn, ZO diffraction traveltimes can be combined to calculate the diffraction traveltimes for any arbitrary offset. As already mentioned, this implies that the parameters of the CRS operator can be directly used to obtain a data-derived approximation of diffraction traveltimes. This is very attractive to set up an inversion scheme as diffraction traveltimes are independent of the reflector structure.

In addition, we have to consider that we are dealing with specular reflections. Thus, Snell's law has to be satisfied at the reflector. As the ZO CRS stack is based on central rays with normal incidence on the reflector, this condition is implicitly met by the central ray. Therefore, it is near at hand to invert for the normal rays together with the approximate diffraction traveltimes. Duveneck and Hubral (2002) introduced this concept in the framework of the CRS method which is now often referred to as NIP-wave tomography: with the geometric interpretation of the CRS stacking parameters in terms of propagation directions and curvatures of hypothetical wavefronts, this inversion scheme has a very vivid imaging condition: if the NIP wavefront is propagated from the surface along the normal ray in a consistent velocity model, it will focus at zero time in the corresponding NIP.

The actual inversion scheme is based on forward-modeling of the NIP wavefront in a smooth macro-velocity model parameterized in terms of B-spline coefficients: for an initial velocity model and an initial set of NIPs, the CRS parameters are determined by dynamic ray tracing. The misfit between the forward-modeled parameters and the data-derived parameters is used to iteratively update the velocity model and the NIPs (see Figure 2 left).

Figure 1 shows the first application of the NIP-wave tomography to synthetic seismic data. For this inversion method, picking is only required in the CRS-stacked section. Due to the higher

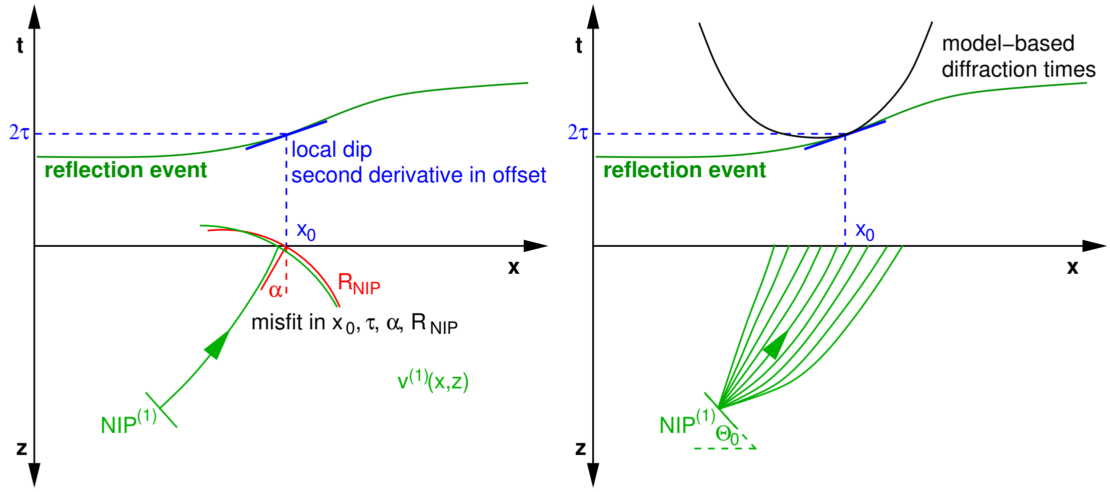

Figure 2: Transition from the inversion with approximate, analytic diffraction times (left) to inversion with exact, model-based diffraction times (right) for 2D data. In the first case, the diffraction traveltimes and the normal rays are parameterized in terms of one-way traveltime τ along the normal ray, its emergence angle α, its emergence location x_0, and the radius of curvature R_{NIP} of the NIP wavefront.

S/N ratio compared to the prestack data, this can be realized in a highly automated manner. There is no need to match the forward-modeled data with the seismic prestack data such that this inversion scheme is highly efficient. However, due to the employed dynamic ray tracing, it is inherently limited to a second-order approximation, thus not allowing for arbitrary complexity of the model. The individual picks are fully independent of each other.

Inversion with model-based diffraction traveltimes. NIP-wave tomography is well-suited to obtain a high-quality initial macro-velocity model. To overcome its second-order limitation, Klüver (2006) proposed a more general inversion scheme to refine the results of NIP-wave tomography: the analytic approximation of diffraction traveltimes is replaced by exact, model-based diffraction traveltime as schematically shown in Figure 2 (right). These diffraction traveltimes can be used to time-shift the prestack data to residual time Δt as a function of illumination angle Θ and scattering angle Φ. Two subsets of such a prestack data volume in residual time are displayed in Figure 3: a common-illumination-angle (CIA) gather and a common-scattering-angle (CSA) gather.

The imaging conditions for this inversion scheme are as follows: for a consistent model consisting of the macro-velocity model and the NIPs with their dips coinciding with the respective specular illumination angles Θ_0, the event in the corresponding CIA gather appears at zero residual time, i. e. flattened. Accordingly, the traveltime misfits in the CIA gathers enter into the inversion scheme. This replaces the misfit in the NIP-wavefront parameters in NIP-wave tomography. The second imaging criterion again has to ensure that we are satisfying Snell's law. Instead of using the normal rays only, we can now consider this boundary condition for various different scattering angles (or offsets): a CSA directly reflects Fermat's principle of stationary traveltime. In a consistent model, the traveltime is stationary for the specular illumination angle Θ_0, i. e., $\partial/\partial\Theta\ \Delta t(\Phi)|_{\Theta_0} = 0$ for any scattering angle Φ. Thus, the residual slope as shown in Figure 3 (right) enters into the inversion scheme.

This inversion scheme is far more demanding than NIP-wave tomography because we have to match the forward-modeled traveltimes to the prestack data in each iteration. However, two facts facilitate this task: NIP-wave tomography is based on data-derived diffraction traveltimes. Therefore, we can expect that the event to be flattened is already centered around zero time in the prestack data volumes in residual time obtained with the initial model. Thus, a local migration

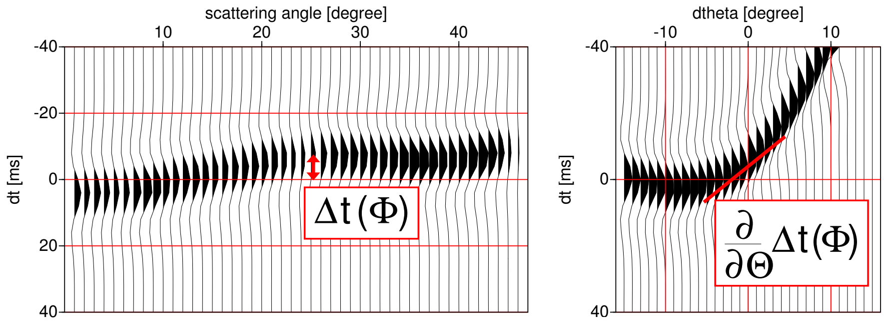

Figure 3: Imaging conditions for the inversion with model-based diffraction times: time misfits in the common-illumination-angle gather in residual time (left), slope in a common-scattering-angle gather for relative illumination angle $\Delta\Theta = \Theta - \Theta_0$. Source: Klüver (2007).

to residual time within a small time window is sufficient. In addition, the CRS-stacked trace is available as high-quality pilot trace to determine the time misfits by means of cross-correlation with the prestack traces in residual time. Finally, the residual slopes in the CSA gathers can be determined by coherence analysis similar as in the CRS stack itself. The main advantage of NIP-wave tomography, i. e., completely independent picks, is fully retained in this generalized inversion scheme.

Conclusions. The use of locally coherent events in the CRS stack method provides powerful tools to detect and parameterize reflection events in the prestack data: the generalized velocity analysis provides more parameters compared to conventional CMP methods. Apart from a superior stack section, these parameters serve for the highly automated NIP-wave tomography which, in turn, provides the initial model for an inversion scheme beyond the second order limitations inherent to the CRS stack approach.

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