Recent Advances in Reflection Seismic Imaging

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Summary

Kirchhoff migration is still the major tool in pre-stack seismic reflection imaging in 3-D media. Amplitude preserving Kirchhoff migration consists basically of four tasks: computation of diffraction traveltimes, traveltime interpolation, determination of migration weights, and the stack of weighted amplitudes of seismic traces along the diffraction surfaces which provides the image. Considerable progress was obtained in all these tasks which allows to carry out the Kirchhoff migration more effectively and with higher accuracy. A major role in traveltime interpolation is played by an extension of the well known $T^2 - X^2$ method to 3-D heterogeneous isotropic and anisotropic media. This extension also allows to compute migration weights which are related to geometrical spreading and to optimize migration aperture resulting in a new approach of *traveltime based amplitude preserving Kirchhoff migration* with optimized aperture. The extendended $T^2 - X^2$ method is also related to the Common Reflection Surface (CRS) stack which belongs to the new techniques of model independent imaging methods, i.e., the CRS may be applied to reflection data for any kind of subsurface structure. This new imaging tool does not only provide a stack superior to the classical CMP-stack but also provides certain attributes which are important for model building and interpretation. The developments mentioned above are presented in this contributions.

Traveltimes

The progress in traveltime computations concerns improved wave front construction (WFC) techniques for ray tracing in 3-D isotropic and anisotropic media and a perturbation finite difference (FD) solver for 3-D arbitrary anisotropic media. In the WFC approach ray tracing is performed such that a complete wave front is propagated through the medium. The sufficiency of illumination is checked at every time step by certain criteria. If these are not matched, a new ray is added to the wavefield by interpolation. The improved WFC technique traces these rays directly from the source without any interpolation which improves the accuracy of traveltimes.

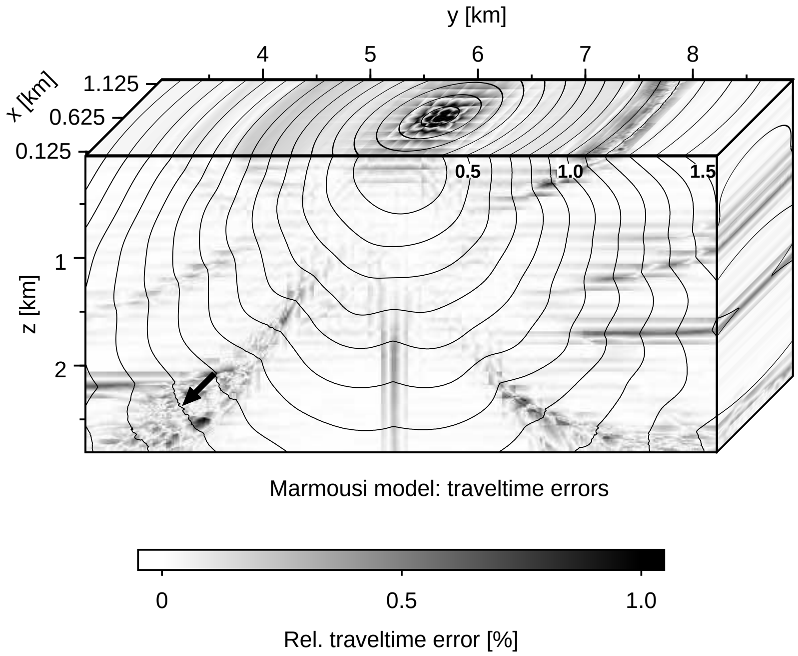

Figure 1: Relative errors for a 3-D version of the Marmousi model using hyperbolic traveltime interpolation. First arrival isochrons are given in seconds. Larger errors are related to "kinks" in isochrons, i.e., where later arrivals are present.

For arbitrary anisotropy the eikonal equation is coupled, i.e., it is not possible to derive an equation for each occurring wave separately. Since anisotropy in real rocks is usually small, a perturbation scheme can be applied to extend the isotropic eikonal equation for P-waves to arbitrary 3-D anisotropic media. This leads to a fast FD tool for first arrival traveltime computations of the Vidale type for 3-D arbitrary weakly anisotropic media.

Traveltime Interpolation and the Extended $T^2 - X^2$ Method

Traveltime interpolation is an important feature of Kirchhoff migration. The number of subsurface points for the migrated image is just too dense to compute the traveltimes directly to each of it. Usually traveltimes are computed on a coarse grid and interpolated onto the fine migration grid during the imaging process. In most implementation a linear interpolation (linear expansion) is used. This is sufficient if the grid spacing between coarse and fine grid is small, since wavefronts are curved.

However, if we take the wave front curvature into account, the difference in coarse and fine grid spacing may be considerably larger. This can be achieved by a hyperbolic, i.e., a 2nd oder expansion. We could have used a parabolic expansion too but in applied seismics we are inspired by hyperbolic traveltimes (simply speaking, by locally spherical wavefronts). This expansion corresponds to an extension of the $T^2 - X^2$ method to 3-D media. The coefficients of this expansion are determined by the traveltimes of the coarse grid by measuring squared traveltime differences (i.e. slopes) similar to the classical $T^2 - X^2$ approach.

These coefficients are used to interpolate traveltimes from the coarse to the fine grid. It also includes the interpolation of entire shots. This and the fact that much larger differences between fine and coarse grids (compared to linear interpolation) are possible leads to considerable savings in storage and computing time. In the example shown in Fig.1 the coarse grid spacing is 125m and the fine grid spacing is 12.5m. This would lead to a factor of 10^5 in storage compared to no interpolation at all. It includes the reduction of 10^2 in shots which also reduces the amount of computational time for traveltime generation.

Migration Weights and Migration Aperture

The benefits of the coefficients determined from the hyperbolic expansion for traveltime interpolation is multifold. They can also be used to compute geometrical spreading and migration weights, which are closely related. Migration weights are needed for amplitude preserving migration in order to reconstruct the reflection coefficient for an imaged reflector. Such images are vital for amplitude versus offset (AVO) studies. Moreover, the coefficients can also be applied to determine Fresnel volumes and to compute an optimized migration aperture. The optimized migration aperture leads to a decrease in computational time since it is considerably smaller than the full registration aperture which is usually used. This aperture considers only the traces, which really contribute to the image point under consideration. It therefore also helps to reduce migration noise. The application of the extended $T^2 - X^2$ method for Kirchhoff migration leads to a traveltime based strategy for amplitude preserving migration. This strategy needs only coarsely gridded traveltime tables as input and, of course, the seismic reflection data.

Common Reflection Surface Stack

With a few manipulations it can be shown that the hyperbolic expansion of the extended $T^2 - X^2$ method corresponds to the recently developed common reflection

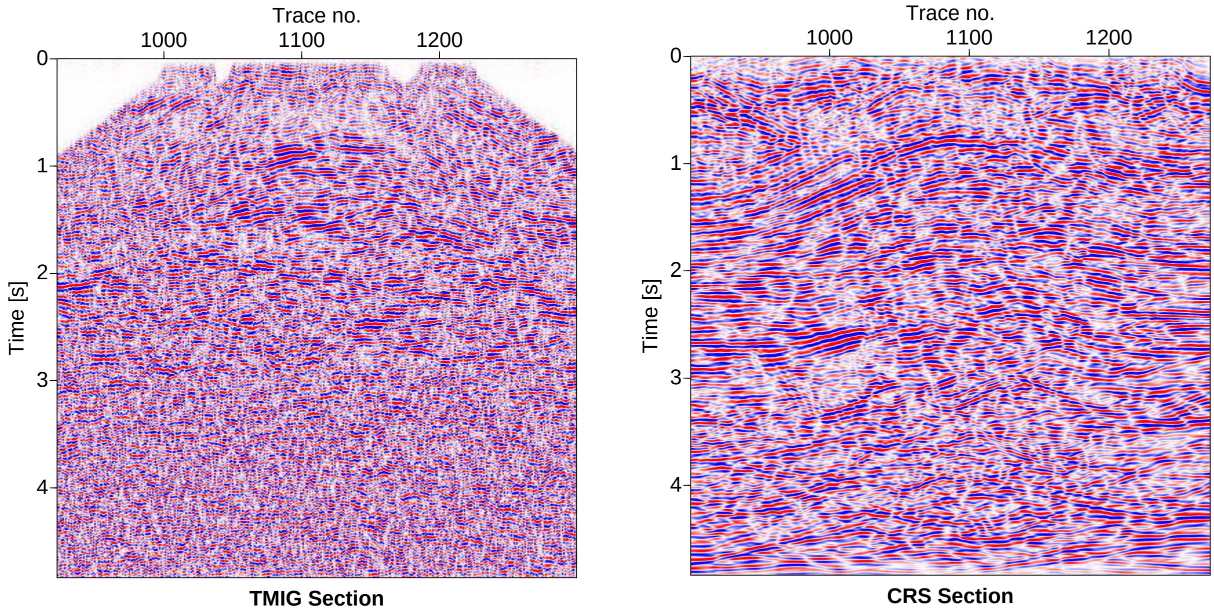

Figure 2: Time migrated seismic sections of reflection data from the Donbas Basin, Ukraine: left CMP section, right CRS section. Note the higher signal to noise ratio and the improved continuity of events in the CRS result.

surface (CRS) stack. The CRS stack is a multi-parameter stack. For the classical CMP stack we search for the stacking velocity. For the zero offset CRS stack in 2-D a 3-parameter search is required. Compared to the classical CMP stack more traces contribute to the CRS stack since a surface element of the reflector is considered. This larger number of traces increases the signal-to-noise ratio of the CRS stacked section when compared to the CMP stack (see Fig. 2).

The CRS-stack is a data-driven automatic procedure and therefore belongs to the model independent techniques of reflection imaging. It does not only provide a stacked section but also so called CRS attributes which are related to the above mentioned 3 search parameters. These attributes are important for model building, i.e., inversion, and interpretation. Among others, they can be used to determine RMS-velocities. They also provide a technique to distinguish reflections from diffractions in the pre-stack data. This, e.g., allows to obtain a stacked section which contains only diffractions. Such sections are important for post stack velocity refinements.