Simulated 2D/3D PSDM images with a fast, robust, and flexible FFT-based filtering approach.
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Summary

The “Simulated Prestack Local Imaging” method simulates Prestack Depth Migrated sections directly from angle-dependent reflectivity grids, without needing prestack synthetic traces (SimPLI, patent pending). Ray tracing techniques are used to generate, in a background model, scattering wavenumbers, i.e., the mandatory information for SimPLI. From that information, 2D/3D filters are built and the simulation process consists of applying these filters to reflectivity grids in the wavenumber domain. PSDM images are then obtained in space using FFT. The process is fast, robust and flexible, and is an extension of 1D convolution techniques in time-domain, but with 2D/3D convolution directly in space-domain. The filters built from the scattering wavenumbers contain lots of information such as the pulse, the overburden effects on the illumination of the targets, and 2D/3D resolution effects. Applications of SimPLI are multi-fold, with, among others, survey planning, interpretation analyses, and 4D seismics.

Introduction

When faced to complex reservoir models, modeling studies will either follow the heavy path of modeling synthetic data before applying PSDM, or use a short-cut by applying 1D convolution techniques to quickly get simulated time-migrated sections/cubes. The latter method is in favor in the production groups as the former requires expertise in seismic modeling and processing. But the 1D convolution method is assuming a stack of horizontal layers, which is a strong limitation as will be demonstrated. Research on a new PSDM approach (Lecomte et al., 2002) resulted in a new simulation process, giving a better alternative to 1D convolution users, i.e., the SimPLI method (Lecomte et al., 2003, Lecomte, 2004).

FFT-based filtering approach

The mandatory information for SimPLI is the scattering wavenumber, defined at a reference point as the local sum of two wavenumbers (Lecomte et al., 2002, 2003, Lecomte, 2004, Figure 1a): one for the incident wavefield and one for the scattered wavefield. The scattering wavenumber or K-vector, as it will be called in the following, is easily and quickly calculated by ray tracing techniques, especially when using Wavefront-Construction techniques. The slowness vectors necessary to calculate K are often calculated as part of the Green’s functions to be used for PSDM (summation or integral approaches). The calculation is performed in a smooth background velocity field.

The K-vector gives very fundamental information about PSDM processes. For instance, if there is a reflector perpendicular to K at that location, it will be illuminated (Figure 1b). The extension of the coverage spanned by the K-vectors in the wavenumber domain is inversely proportional to the resolution in the space domain in all directions. More specifically, the length of a K-vector, controlled by the local velocity, the frequency and the incidence-angle θs (Figure 1b), will determine the resolution across the corresponding potential reflector.

Figure 1: Scattering wavenumber definition.

Figure 2: Gullfaks model, survey and target.

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The black set of K-vectors corresponds to a 0 km offset selection of the data (see Figure 2 for the survey), and the blue one to a 4 km offset selection. The differences in K-vector coverage between 0 km and 4 km indicate a difference in illumination and resolution (Lecomte, 2004). As indicated earlier, the orientation of K-vectors gives the illumination: for point P1 (fault), the 4 km offset coverage does not cover the normal to the fault, while it is covered by the 0 km offset. The fault should therefore not appear on the PSDM image attached to the 4 km offset. In addition, the blue coverage is shorter vertically and narrower horizontally, which means poorer resolution, both horizontally and vertically. Figure 3 shows all these effects in a more comprehensive way by using the SimPLI method to simulate the corresponding PSDM sections.
From the model in Figure 2, a local reflectivity grid around point P1 has been created with constant reflection strength for all reflectors (Figure 3b). This local reflectivity is transformed into the wavenumber domain by FFT. The signature of the fault is identified. When applying the wavenumber filter deduced from the $K$-vectors ($K$-filter) of the 0 km offset selection, and for a given pulse (20 Hz Ricker), the fault is preserved but the spectrum is low-pass filtered due to the band-limited signal (Figure 3c). As a consequence, the SimPLI image shows all reflectors but they are less sharp than the input reflectivity. The $K$-filter built from the 4 km offset is different (Figure 3d). The signature of the fault in the wavenumber domain is now removed from the spectrum and the corresponding SimPLI image does not show anymore the fault (not illuminated). The resolution is also poorer, both across reflectors and along them, due to a smaller coverage in the wavenumber domain.

Note that the $K$-filters can be FFT-transformed into the spatial domain, thus giving the corresponding Point-Spread Functions (PSF, Figure 3). PSF is the PSDM response of a point scatterer. The SimPLI images can indeed be explained as the spatial convolution of the PSF with the reflectivity grid, each point of the latter being considered as a potential scatterer (Exploding Reflector concept). The validity of the SimPLI images has been demonstrated in Lecomte et al. (2003), Lecomte, (2004) by comparison with PSDM sections obtained from migrating prestack synthetic traces. The illumination and resolution effects mentioned above are also observed on reference PSDM sections.

2D versus 1D: illumination and resolution effects

To illustrate the risk of using blindly 1D-convolution, a special reflectivity model was used, i.e., the SEG logo (Figure 4). 1D convolution is assuming all reflectors in each column to be horizontal, i.e., no dip information about the structure. To simulate the effects of 1D reflectivity, an equivalent $K$-filter can be built, containing the pulse and a mean incidence angle, but no directivity (circular filter, Figure 4a). Applying this 1D-filter, the image is still giving the SEG logo with all characters but with only the borders because the DC component is removed by the filter. If we now apply the actual seismic filters to get realistic PSDM images, with dip and incidence-angle effects, totally different images are obtained. In addition, the images change with respect to the selected survey, both in terms of illumination and resolution.

Angle-dependent simulations

The $K$-filter can also be decomposed as a function of the incidence-angle $\theta$ (Figure 1b). This is indeed necessary because elastic reflectivity is angle-dependent. The 4 km offset selection of the Gullfaks model contain angles...
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varying from 14° to 45° (Figure 4b). 4 filters were built from different angle selections, and the resulting SimPLI images show how the illumination of the logo is different (same amplitude scale for all images). The 40° to 45° range is the dominating one at 4 km offset but gives mostly the horizontal components of the logo. Even if the other angle ranges give weaker contributions, the summation of all these images is necessary to get a more complete logo, though the image is not as good as with the 0 km offset (compare with the sum image of all the angles given in Figure 4a, bottom left).

Applications and further developments

Different applications have already been tested, especially in 4D seismics (Drottning et al, 2004). Figure 5 shows a synthetic reservoir model, built from an actual geological site at the Svalbard islands. The reservoir model in Eclipse format was used, as well as rock physics constrains from wells (field example from the Norwegian Continental Shelf), to estimate elastic parameters (P-velocity in Figure 5a as an example). From the elastic parameters, the angle-dependent elastic reflectivity is calculated using Zoeppritz equations (Figure 5a) and SimPLI can be applied. The K-vectors coverage for a 0-120 Hz frequency-band is given in Figure 5b but using band-limited pulses will further restrict that coverage (Figure 5c). The effect of various pulses on PSDM images is easily analyzed through the resulting SimPLI images in depth (Figure 5d). Depth-to-time conversion can also be included in the workflow to allow comparisons with real data in time-migrated domain when no PSDM results are available.

The real earth structures being 3D, the SimPLI method is under development to take into account angle-dependent 3D reflectivity grids as input (the K-vectors are already calculated in 3D models). Preliminary results are given in

Figure 6. The Gullfaks model is once more used and a 2.5D local reflectivity grid has been generated for the sake of the testing. Later on, complex 3D reservoir models will be studied but the technology is already demonstrated. The K-filter is built from the same 4 km offset selection of Figure 3a, hence 2.5D (Figure 6b). The corresponding 3D PSF is also given, showing no resolution along the Y-axis, as expected due to the 2.5D filter used here (Figure 6c). Even if the reflectivity and the filter are 2.5D in that specific example, the computing time is the same as for 3D structures, the process working already with 3D grids.

Conclusions

The SimPLI method gives the opportunity to survey planners, interpreters, reservoir engineers, 4D analyzers and PSDM users to play quickly with many parameters in a robust and interactive manner. The initial cost of calculating the K vectors is low (a few min at maximum) due to efficient ray tracing technology, and the SimPLI process itself is fast due to FFT filtering (predictable computing time). The efficiency is mostly dependent on the FFT cost, i.e., negligible computing time in 2D and reasonable in 3D. This filtering approach in the wavenumber domain (convolution in the spatial domain) is much more complete than the standard 1D convolution, and almost as fast, with automatic integration of illumination, resolution and amplitude effects, with propagation effects through 2D-3D overburden models and angle-dependent reflectivity as input. Other parameters can be included in the K-filters, especially by sorting the K-vectors (maximum traveltime, maximum migration aperture, wave type, etc). The method is also working for converted PS waves or others, and is expected to work as well in anisotropic media. Amplitude effects can be analyzed, either for PSDM quality control (true-amplitude versus simple amplitude compensation) or for AVO/AVA effects,
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because using angle-dependent reflectivity models (later, azimuth-dependent as well for anisotropy). Other amplitude effects such as source and receiver directivity are also easy to integrate.

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References


Figure 5: Storvola reservoir model 8500 m x 550 m. a) Model properties. b) K-coverage and pulse spectrum. c) K-filters and SimPLI images.

Figure 6: Gullfaks model: preliminary 3D example using the 4 km offset K-vectors coverage and the true local reflectivity grid.