ADVANCED RAY-BASED SYNTHETIC SEISMOGRAMS

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ABSTRACT

Ray-based seismic modeling methods can be applied at various stages of the exploration and production process, e.g., for comparison, simulation or representation of seismic data, to assess the ambiguity of interpretation or to make predictions. Ray tracing in its standard forms is not always able to produce complete synthetic seismograms, as may be required for processing tests. Standard reflection-based modeling gives good results in many cases, but could fail for some complex structures. For instance, in the presence of sharp edges and ripples on the modeled reflector or in the vicinity of caustics classical dynamic ray tracing (DRT) does not give reliable amplitude values. Therefore, we propose alternative approaches where reflection modeling is not used. Instead we use an optimized ray-based approach to calculate various types of Green's functions (GF), e.g., amplitudes and traveltimes, which will be applied within tailored modeling schemes, such as Kirchhoff modeling and modeling by demigration. Furthermore, we adapt the classical modeling by demigration approach using an alternative PSDM simulator. Even a simple two-layer model reveals the weaknesses of the standard ray tracing, and demonstrates on the contrary that the computed seismograms for the alternative methods are more complete and significantly improved. Finally, we document the applicability of all methods using a more complex model.

INTRODUCTION

Ray-based seismic modeling methods can be applied at various stages of the exploration and production process. The standard ray method has several advantages, e.g., computational efficiency. In addition ray tracing has an event-oriented nature, which means that specific arrivals of elementary waves (e.g., transmitted P and S waves, primary PP and PS reflected waves for selected horizons, multiples, etc.) can be labeled in synthetic seismograms or in computed sets of Green's function attributes. In early applications the focus was mostly on the calculation of raypaths and traveltimes (kinematic ray tracing), but throughout the seventies and eighties, numerical techniques were developed within dynamic ray tracing (DRT), giving fairly reliable estimates of amplitudes of both P and S waves. These amplitudes have a firm theoretical basis, being a high-frequency solution of the elastic wave equation (zeroth-order ray theory; Červený, 2001). The ray attributes become reasonably stable if velocity gradients and interface normals vary smoothly within the seismic wavelength. Comparisons with more complete (and much more time-consuming) techniques, like finite-difference schemes (FD), show that DRT-based theoretical seismograms can be very qualified if the model is prepared with the necessary smoothness.

The main weakness of the ray method applied to complex geological structures is due to the fact that the calculations along each ray is "super-local", that is, quite independent of the neighboring rays. One single ray "sees" only the velocity and interface behavior exactly along the raypath, and thus the stability across the rays depends on the assumption that these parameters are fairly representative for neighboring rays (at least within the Fresnel zone). Classical DRT traces continuous rays from source to receiver (two-point ray tracing), e.g., making use of the so-called shooting technique, adjusting the take-off direction of the ray and re-tracing until the ray hits sufficiently close to the receiver. For complex 3D models this technique may be very time consuming and can typically miss events (rays) in regions with large geometrical spreading. As an alternative, Vinje et al. (1993, 1996a,b); Gjøystdal et al. (2002, 2007) developed the wavefront construction method (WFC), which is a more robust ray tracing technique adapting the ray density to the model and interpolating the ray attributes. The reason for enhanced robustness lies in the fact that a continuous representation of the wavefront, with sufficiently dense sampling of ray points and slowness vectors, is established by interpolation after each time step. In this way, the sampling of parameters influencing the calculation of traveltimes, amplitudes, etc., is adapted to the complexity of the model of elastic parameters. Quite recently, the wavefront construction method has been further developed to include anisotropy (Mispel and Williamson, 2001; Gibson et al., 2005; Iversen, 2004). However, this method only partly solves the problem of lack of ray penetration into shadow zones.

In this paper we demonstrate new seismic modeling techniques that have been specifically developed to meet the demands of complex modeling in the petroleum industry. Given the objective of improving the applicability of the standard ray method, we define each ray-based process as an element of a system, which, as a composite process, is able to obtain better results than the ray-based process applied alone. They are, however, still firmly based on the basic WFC/DRT methodology, i.e., high-frequency approximation of the wave equation. We first demonstrate the pure DRT method and illustrate how some of the basic weaknesses can be reduced by applying the "DRT engine" in different ways, giving a more robust and realistic behavior. Therefore, we have implemented the Kirchhoff-Helmholtz (KH) modeling technique and the modeling-by-demigration approach.

The KH modeling technique should give more accurate and realistic reflection seismograms than those obtained by classical ray tracing in case of complex geological structures, because the KH integral consists of an integration along the reflector. By this, one sums the Huygens secondary-source contributions to the wavefield attached to the reflector at the observation point (Tygel et al., 1994, 2000).

Demigration itself can be defined as the inverse of migration (Hubral et al., 1996; Tygel et al., 1996; Santos et al., 2000). This involves nothing more than the formulation of a reflection imaging process by which one can return from a true amplitude depth migrated section to the original time section. Modeling by demigration represents a special implementation of the demigration concept, where the input is no longer standard migrated data but artificially migrated target geological structure(s) defined by the user. In this paper, the artificially migrated inputs are computed by employing both the standard approach (Tygel et al., 1996; Santos et al., 2000) and the PSDM simulator approach of NORSAR (SimPLI technology, Lecomte, 2006, 2008a). This PSDM simulator is used to directly produce simulated prestack depth migrated images of a given target, without generating synthetic traces and processing them (Lecomte et al., 2003; Lecomte, 2004; Lecomte and Pochon-Guerin, 2005).

METHODOLOGY

In this section, we give an overview and brief introduction to the methodology to be applied. For all methods Green's functions (Aki and Richards, 1980) are needed and as mentioned above, calculated by ray tracing. The Green‘s functions (GF) represent the wave field propagation between two points in a given velocity model. However, in our case, in practice, one of these points is a source or receiver of a seismic survey, and as such often near the surface (not true for the VSP case). Besides the traveltimes, ray tracing calculates amplitudes and other parameters (e.g., polarization, attenuation factor, etc.) which could be used as well, specially for an "amplitude-preserving" type of modeling or imaging (Schleicher et al., 1993). Regarding the ray tracing strategy, we use DRT in a model adaptive wavefront construction (WFC) approach, which is much more robust with respect to model details than conventional DRT based on single rays. Depending on the needs for the different approaches the WFC process can be applied to calculate reflected ray attributes or to compute one-way traveltimes and amplitudes, e.g., needed for Kirchhoff-Helmholtz modeling. WFC is particularly efficient for calculating both surface-type (interface) and volume-type Green‘s functions since ray attributes are interpolated and single rays to each point do not have to be calculated.

Standard ray-based seismogram

The ray-tracing technique is based on a high-frequency approximation of the elastic wave equation. As such the synthetic seismograms at a given receiver can be computed by :

$$u_{RT}(t) = cU_0[s(t-T)\cos(\phi) - h(t-T)\sin(\phi)], \tag{1}$$

where, U_0 and ϕ are modulus and phase of the complex amplitude coefficient of a given event, T is the traveltime, and $s(t)$ and $h(t)$ are the source wavelet and its Hilbert transform, respectively. Here, c is a general amplitude scaling factor. The amplitude coefficient is in general a complex number calculated along the ray. It results from the fact that DRT keeps track of geometrical spreading, transmission and reflection loss, phase changes of the wavefield due to focal points (caustics) and overcritical reflections occurring along the raypath. If no phase change occurs, we can see from equation 1 that the contribution of one single event to the ray-based seismogram is simply a scaled version of the source pulse. Optionally, the effect of anelasticity in the layers can be estimated, causing a frequency filtering of the wavelets s and h. Note also that the amplitude coefficient is tied to a coordinate system, so that U_0 can typically be a component in a given direction, i.e., in the case of multi-component data, equation (1) should be used for each component. Figure 1 shows wavefront propagation trough a salt subsurface model and one common shot seismogram.

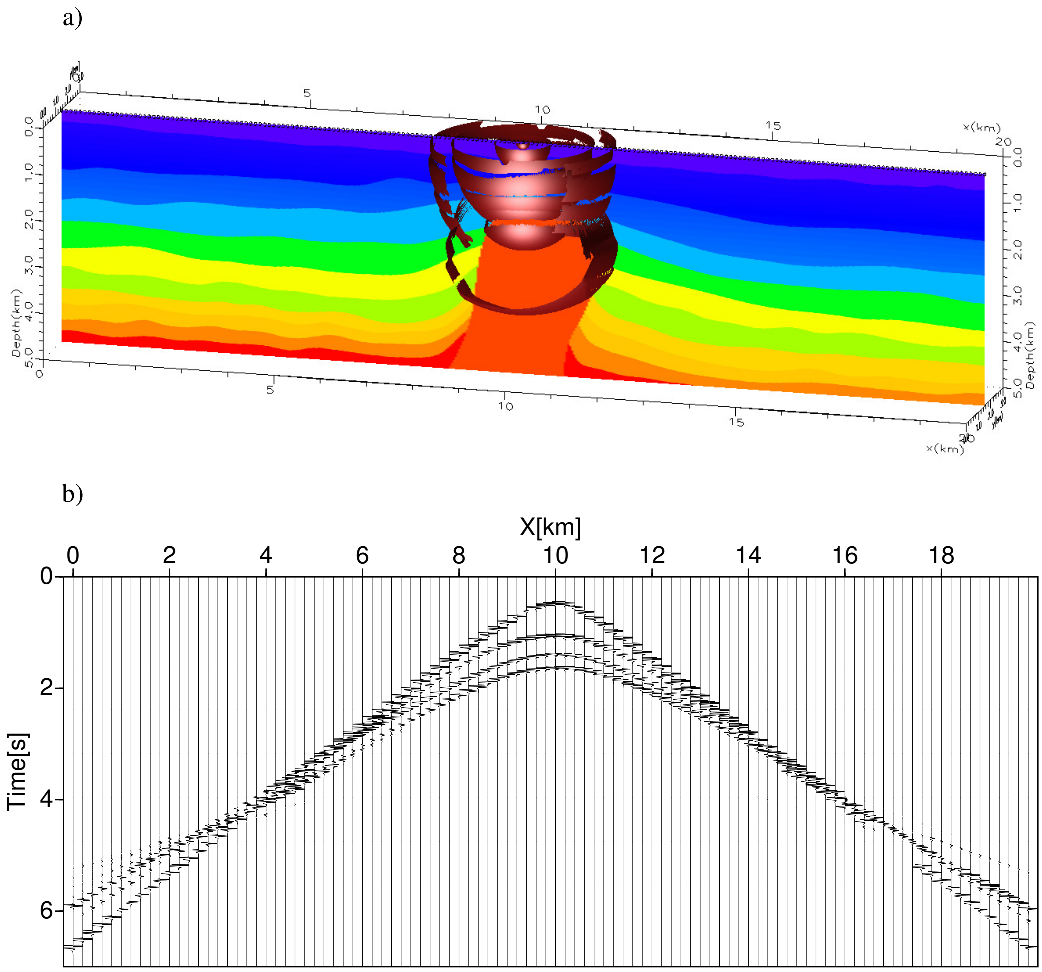

Figure 1: Wavefront propagation within a saltdome model (a) and one corresponding common shot seismogram.

The question to be addressed is: can we apply the ray method in a more robust way, i.e., to make it respond better to sharper details of the model horizons? One solution that we will explain in the next section is to use DRT in combination with the Kirchhoff integral.

Kirchhoff-Helmholtz modeling

Kirchhoff Helmholtz (KH) modeling (Eaton and Clarke, 2000; Schleicher et al., 2001) is employed in areas which are geologically complex. Compared with standard ray tracing, the method has the potential of giving more accurate results on the expense of computational speed. Ray theory still forms the basis of the modeling, and hence many advantages are inherited, such as the selection of specific events. In order to model the reflection response of a chosen interface, rays are traced to that interface from the sources and receivers (i.e., Green‘s functions computations, see Figure 2).

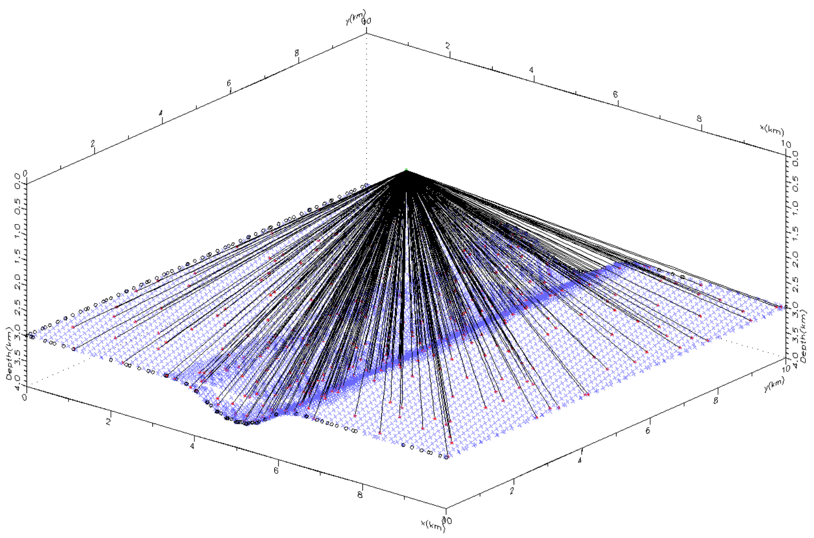

Figure 2: Rays are traced to each interface from each source and receiver position, here selected rays for one shot position are displayed.

Following Santos et al. (2000), the locations of (S, G) are assumed not to be independent but to pertain to a certain measurement configuration described by a 2-D parameter vector ξ, i.e., $S = S(\xi)$ and $G = G(\xi)$. Therefore, the approximate Kirchhoff modeling integral (Frazer and Sen, 1985; Tygel et al., 1994) can be used to define the modeled synthetic seismogram:

$$u_{KH}(\xi, t) = \frac{1}{2\pi} \int\int d^2\mathbf{x}\, W(\mathbf{x}, \xi, P_\Sigma) \partial_t F[t - \tau(\xi, P)]|_{z=\Sigma(\mathbf{x})}, \tag{2}$$

where $z = \Sigma(\mathbf{x})$ is the reflector that gives the integration surface. $P(\mathbf{x}, z)$ is an arbitrary point in depth, with $P_\Sigma = P|_{z=\Sigma(\mathbf{x})} = (\mathbf{x}, \Sigma(\mathbf{x}))$. Moreover, $W(\mathbf{x}, \xi, t)$ is a weight function consisting of an obliquity factor, the specular plane-wave reflection coefficient of the incident wave at the reflector, and two Green‘s function amplitudes. Here, $\partial_t F[t]$ is the time derivative of the analytic pulse chosen to represent the source wavelet. The total traveltime

$$\tau(\xi, P_\Sigma) = T(S(\xi), P_\Sigma) + T(G(\xi), P_\Sigma), \tag{3}$$

is the sum of traveltimes along the two paths of propagation $\overline{SP_\Sigma}$ and $\overline{GP_\Sigma}$, where $S(\xi)$ and $G(\xi)$ are fixed and P_Σ varies along the reflector. The approximate Kirchhoff modeling integral 2 must be evaluated along each reflector within the given model.
Spencer et al. (1997) proposed an efficient algorithm to evaluate such integrals on triangulated interfaces.

The algorithm performs the integral over stripes within the triangles, assuming that the traveltimes and weights can be interpolated linearly.
In order to prepare for the Kirchhoff modeling approach, we use DRT to calculate the so-called Green's functions. Consider a source position, a receiver position, and a target reflector in a model. Instead of calculating wavefronts from source via the target reflector and back to the receiver in one operation, we perform one-way WFC from source S and receiver R to a dense grid of points on the target reflector P_Σ. These points are now acting as 'receivers' in the WFC.

Modeling by demigration

Demigration is a seismic forward-modeling scheme based on seismic imaging, it is a 'forward' technique, due to the fact that a velocity model needs to be specified. On the other hand, demigration can be considered as the inverse of migration. The true amplitude reflector image can directly be constructed from a given reflector and a chosen source pulse. Then in a second step, the true-amplitude demigration can be performed, thus offering a new seismic modeling method, i.e., modeling by demigration (see Figure 3).

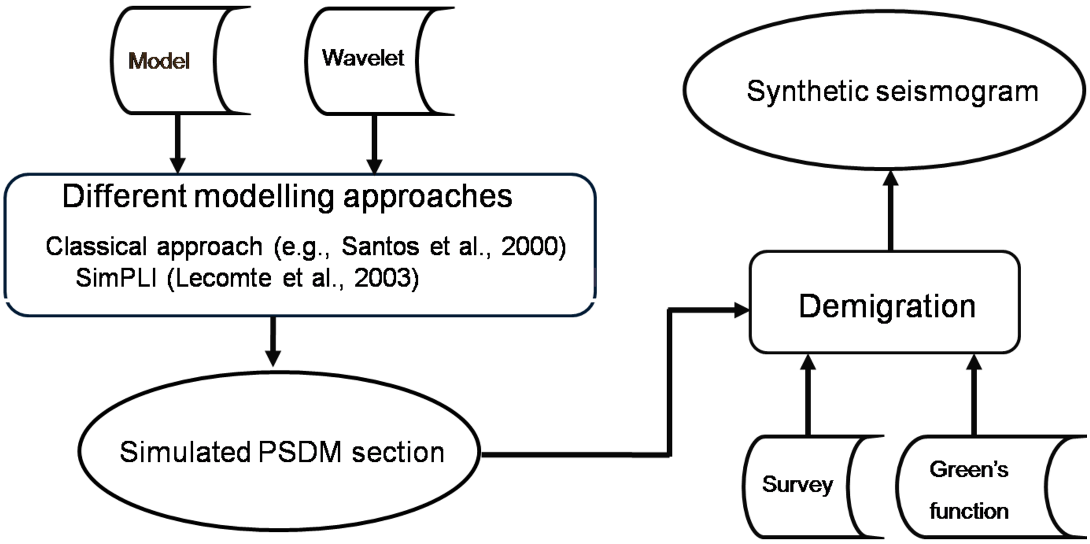

Figure 3: Schematic overview of the modeling by demigration concept.

Similar to the arguments that lead to the Kirchhoff migration formula, a structurally equivalent integral can be set up for its inverse operation (Hubral et al., 1996; Tygel et al., 1996). The idea is to stack along a certain surface in the depth-migrated data volume in such a way that any migrated events that possibly pertain to a certain, fixed point (ξ, t) in the demigrated section are summed together. This leads to the following expression for the Kirchhoff demigration integral (Santos et al., 2000):

$$u_D(\xi, t) = \frac{1}{2\pi} \int\int d^2\mathbf{x}\, W_D(\mathbf{x}, \xi, t) \partial_z M(\mathbf{x}, z)|_{z=\zeta(\mathbf{x},\xi,t)}, \tag{4}$$

where $u_D \xi, t)$ denotes the demigrated data, $W_D(\mathbf{x}, \xi, t)$ is a true-amplitude weight function to treat amplitudes correctly, and $M(\mathbf{x}, z)$ is the migrated data to be demigrated. The stacking surface, $z = \zeta(\mathbf{x}, \xi, t)$, is implicitly given by

$$t = \tau(\xi, \mathbf{x}, z = \zeta(\mathbf{x}, \xi, t)) = T(S(\xi), P) + T(G(\xi), P) \tag{5}$$

i.e., by the same sum of traveltimes as used in Kirchhoff forward modeling (3) and Kirchhoff migration. In other words, $z = \zeta(\mathbf{x}, \xi, t)$ describes the surface of equal reflection time or isochron pertaining to the pair S and G and a given time t. Thus, the stack contains all contributions that come from the Fresnel zones surrounding the specular reflection points.

To use the demigration integral model for each given subsurface reflector, its corresponding true-amplitude, depth-migrated reflector image as if obtained from a Kirchhoff migration is given by:

$$M(\mathbf{x}, z) = \mathcal{A}(\mathbf{x})F[\mathcal{P}(\mathbf{x})(z - \Sigma(\mathbf{x}))]. \tag{6}$$

We may say that this is obtained by placing the correctly scaled and stretched source pulse $F[t]$ along the reflector. Here, the amplitude factor $\mathcal{A}(x)$ and the prestretch factor $\mathcal{P}(x)$ have yet to be chosen in such a way that, at the stationary point $x^* = x^*(\xi)$, they match the correct (plane-wave) reflection coefficient $\mathcal{R}(\xi)$ and the correct pulse stretch factor $\mathcal{S}(x^*(\xi))$, respectively:

$$\mathcal{A}(x^*) \approx \mathcal{R}(\xi) \text{ and } \mathcal{P}(x^*) \approx \mathcal{S}(\xi) \tag{7}$$

For our comparison we consider a zero offset survey. Here, the idea of modeling by demigration can be applied directly. All necessary quantities to construct the migrated image for each reflector are physical parameters directly available from the a priori specified earth model, which is assumed here to be isotropic. For any arbitrary zero-offset reflection, the stretch factor at the stationary point on the reflector is given by Tygel et al. (1994):

$$S(x^*) = \frac{2\cos\beta_R}{v_R} \tag{8}$$

and the normal-incidence reflection coefficient is given by

$$R(\vec{\xi}) = \frac{\tilde{\rho}_R\tilde{v}_R - \rho_R v_R}{\tilde{\rho}_R\tilde{v}_R + \rho_R v_R} \tag{9}$$

Here, β_R is the local reflector dip, and v_R, $\tilde{v}_R$ and ρ_R, $\tilde{\rho}_R$ are the velocities and densities above and below the considered target reflector at the reflection point. Therefore, S and R can be directly computed for any given reflector point.

The fact that the familiar Kirchhoff migration integral seems to have two inverse integrals in an approximate sense (i.e., the Kirchhoff Helmholtz modeling integral (2) and the Kirchhoff demigration integral (4) leads inevitably to the question whether the two processes described by these integrals are identical. The answer is that, although closely related, they are different processes. Their close relationship, however, leads to the conclusion that it should be possible to use Kirchhoff demigration to achieve the goals of Kirchhoff forward modeling .

A PSDM simulator

In this paper, we also use an alternative approach to calculate the artificial migrated image (6) based on a ray-based PSDM simulator called in the following SimPLI (Simlated Prestack Local Imaging; Lecomte et al., 2003; Lecomte, 2004; Lecomte and Pochon-Guerin, 2005; Lecomte, 2006, 2008a). SimPLI directly produces simulated prestack depth migrated images of a given reservoir model, without generating synthetic traces and processing them. This approach makes use of the PSDM resolution (inverse problem), i.e., applying the calculated ray-based point-spread functions (PSF Lecomte and Gelius, 1998) in a background velocity model to the reflectivity of a superimposed target (e.g., reservoir). This is done by either convolution in the depth domain, or multiplication in the scattering-wavenumber domain, and using fast FT (FFT) to perform the depth-to/from-wavenumber conversions. SimPLI acts as a signal- or image-processing method, distorting the actual reflectivity to reproduce the effects of seismic imaging. This is comparable to what is done in PSDM, where a seismic data set is used to retrieve the unknown reflectivity (only a filtered version, as suggested earlier). This distorted reflectivity is superimposed by PSDM to the (smooth) background velocity field used for the propagation effects (traveltimes). In the simulator approach, which is a modeling one, we know the reflectivity in depth, so there is no need for the back propagation of the migration method, but we simulate instead the focusing effect (imaging) by distorting the true reflectivity according to the PSF. Other approaches are also possible (Toxopeus et al., 2008), but the ray approach provides a flexible, interactive and robust concept for PSF estimation (Gjøystdal et al., 2007).

To illustrate the PSDM simulator, Lecomte (2008b) consider the SEG logo as the input reflectivity grid, which is then transformed to the scattering-wavenumber domain (Figure 4).

Figure 4: Illumination and resolution effects on the SEG logo. (a) SEG logo taken in as input to the PSDM simulator and transformed to the wavenumber domain. (b) Simulated PSDM for a near-offset selection. (c) Simulated PSDM for a far-offset selection. (d) Simulation of 1D convolution effect. (b), (c), and (d) show from left to right the corresponding wavenumber filter, then the result of applying that filter to the SEG logo, still in the wavenumber domain, and finally the resulting simulated PSDM image in the space (depth) domain (Lecomte, 2008b).

Using ray tracing in a given background model, two wavenumber filters were obtained for two constant-offset survey selections and a 20-Hz zero-phase Ricker wavelet (Figure 4b and c, left). These filters are then applied in the wavenumber domain to the input reflectivity grid and finally an inverse FFT gives the simulated PSDM images (Figure 4b and c, right). The SEG logo is distorted as a result. The zero-offset image is best but it is missing the steep contours of the characters due to limited illumination, as is the case in actual seismic acquisition. The 4-km offset shows both a decrease in resolution and stronger limitation in illumination. The PSDM simulator can also be used to simulate a 1D convolution for the sake of comparison (Figure 4d). A 1D-convolution simulator corresponds indeed to a perfect illumination of all reflector dips and azimuths, which is equivalent to a circular wavenumber filter (Figure 4d, left). A cross-reflector resolution effect is introduced by taking into account the band-limited pulse and a pulse stretch factor (like in equation 8). However, no lateral resolution effects (Fresnel zones) can be reproduced due to the circular shape of the filter. As a result, the obtained SEG logo image is not realistic, showing all 'dips' with just a certain thickness of the contours (Figure 4d, right).

NUMERICAL RESULTS

In this section, we will give a brief overview of the methodology to be applied, illustrated by some very simplistic modeling examples, in order to grasp the basic principles, limitations, and differences between the approaches. In these examples we have chosen to keep the velocity field constant and focus on the shape of the reflector(s), since this turns out to be the factor causing most problems in practical situations.

Single horizon model

Consider the model in Figure 5. It consists of one syncline structure that separates two homogeneous isotropic layers. In this (and all following examples) a 30 Hz zero phase Ricker wavelet was used as the source pulse. P-velocities above and below the horizon are 2000 and 2500m/s respectively, P/S velocity ratio is 2, and density is 2.0 g/cm^3. Now consider a zero offset survey along a line in the x direction, with shot/receiver spacing of 50m and the shot/receivers are located between 1 and 9km. For illustration, Figure 5 shows some raypaths resulting from WFC. Noted that all WFC/DRT calculations are performed in 3D, even if the following examples show simulations for shot/receiver lines in the x-direction.

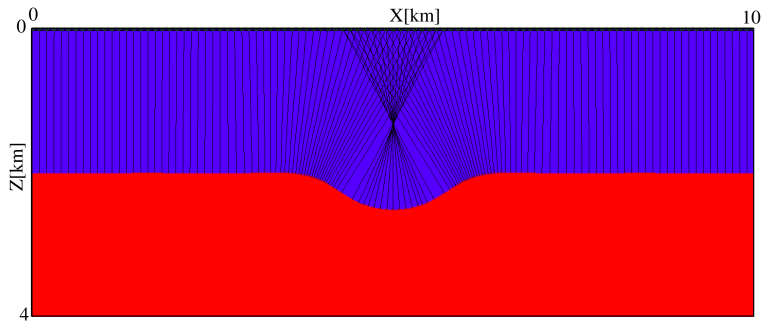

Figure 5: First example consisting of a syncline structure that separates two homogeneous isotropic layers.

Figure 6 shows the different modeling results calculated for the syncline structure by all four presented modeling approaches. By comparing all seismic sections quantitatively it can be seen that all results bear resemblance for the center part of the structure. However, typical deficiencies that can be observed in DRT-based seismograms (Figure 6b) are some unrealistically high amplitudes close to the cusps of the caustics, and the lack of a gradual decay in the form of diffracted energy. Here, the fish tail is less prominent than the ones obtained by Kirchhoff Helmholtz modeling (Figure 6a) and modeling by demigration (Figures 6c and 6d). We observe that KH modeling automatically simulates edge diffractions and is much more stable than simple DRT. However, the KH seismic data comprises residual noise which could basically be controlled by the sampling of the modeled interface. Consequently, increasing the sampling density leads to less noise in the obtained seismogram.

For a more detailed investigation, in Figure 7 we show one single trace location at $x = 5$km. For both modeling by demigration results the seismic sections contain high-frequent noise due to the summation process (Figures 7c and 7d). However, this residual noise could be significantly reduce applying a low-frequency filter after the actual modeling process.

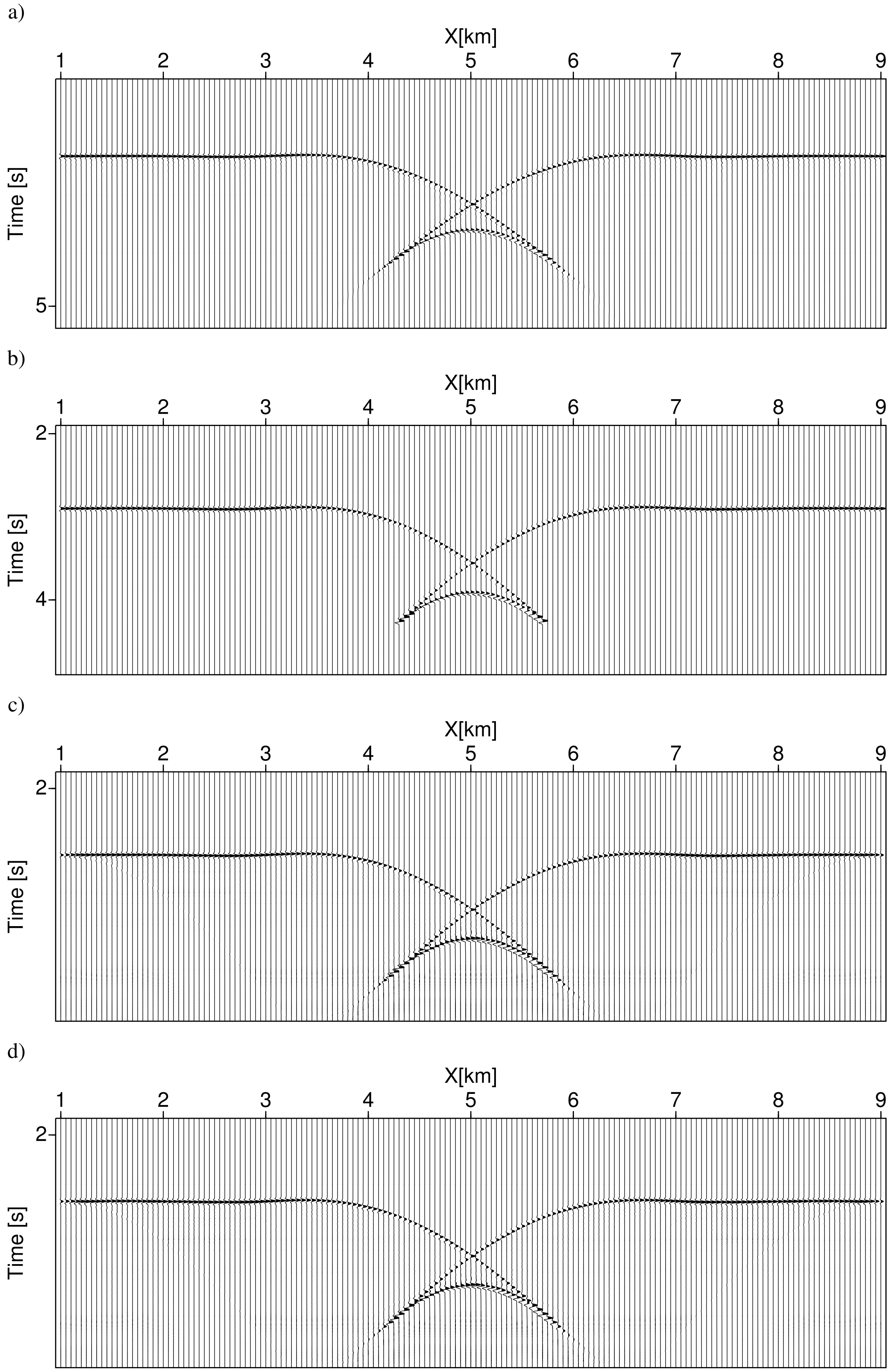

Figure 6: Computed synthetic seismograms for different modeling techniques: (a) Kirchhoff Helmholtz modeling, (b) standard ray-tracing, (c) classical modeling by demigration and (d) SimPLI demigration.

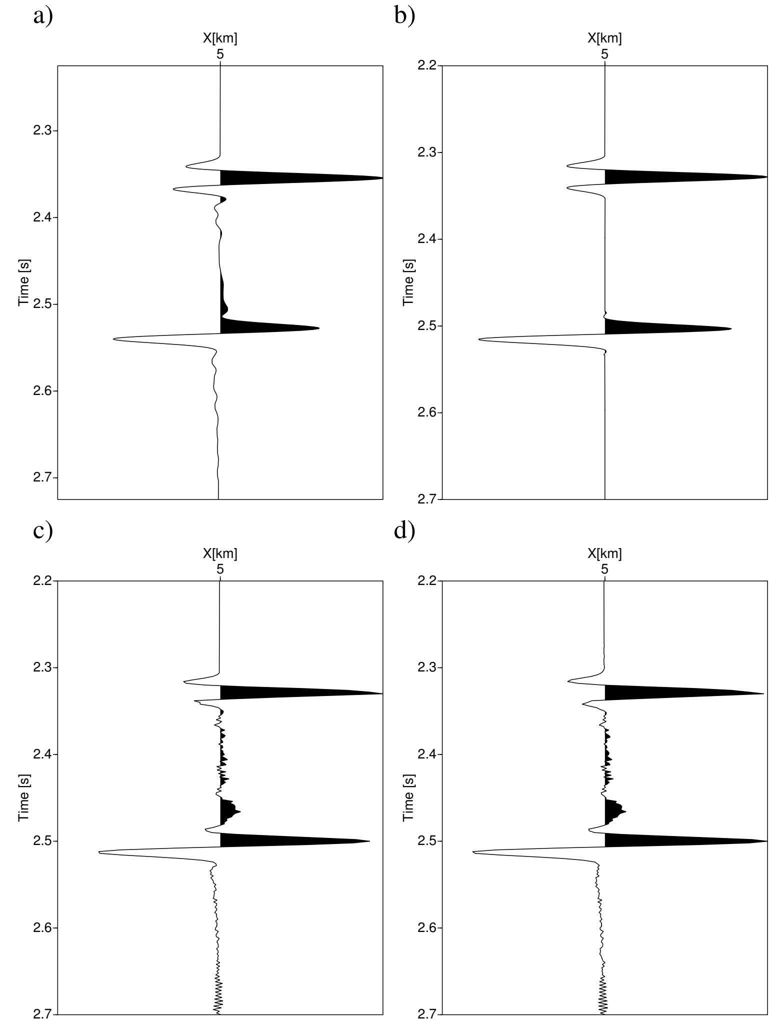

Figure 7: One synthetic trace for different modeling techniques: (a) Kirchhoff-Helmholtz modeling, (b) standard ray-tracing, (c) classical modeling by demigration and (d) SimPLI demigration.

Multi-horizon model

The second example contains three horizons, see Figure 8. The first reflector is a simple horizontal plane, the second a syncline structure as in the previous example and the deepest represents a (slightly smoothed) fault structure. For computational simplicity, we chose a 2.5D situation which means that 3D amplitude effects of in-plane propagation are correctly considered. In most ray-tracing applications for such a heterogeneous subsurface, model smoothing is a key problem, and it is not always an easy task to determine the proper smoothing procedure. Consequently, we would need a smooth version of the given model to produce proper GF‘s for KH modeling and modeling by demigration which is in practice usual available as it is needed for migration anyway. Nevertheless, the obtained modeling result would be slightly different depending on the smoothing level and thus, would make a comparison with the DRT results more difficult. Therefore, we separate our layers by varying the densities and keep the velocities constant ($v_P = 2.0$km/s and $v_S = 1.0$km/s). The density is given by $\rho_1 = 1.0$ g/cm^3, $\rho_2 = 1.5$ g/cm^3, $\rho_3 = 2.0$ g/cm^3 and $\rho_4 = 2.5$ g/cm^3, respectively.
Gjøystdal et al. (2007) demonstrated that sharp edges on an interface can be smoothed slightly to produce a diffraction-like DRT response, which is closer to reality than if keeping them sharp. Therefore, we employed a smoothing operator to the fault interface, to obtain the best possible DRT synthetic seismogram for this example.

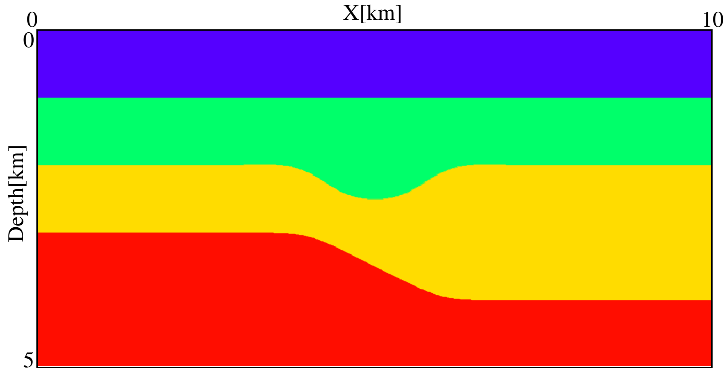

Figure 8: Second model consists of four layer, separated e.g, by a simple horizontal plane, a syncline structure as in the previous example and a slightly smoothed fault structure.

As demonstrated for the first example, both demigration results show strong similarities, thus here we restrict ourselfs to the new SimPLI demigration approach. Again we consider a zero-offset survey along a line in the x direction, with shot/receiver spacing of 50m and the shot/receivers being located between 1 and 9km. The synthetic section resulting from modeling by demigration has been compared in Figure 9 to the corresponding sections obtained by conventional seismic modeling schemes. Figure 9a shows the modeled traces computed by standard ray tracing; Figure 9b contains the corresponding seismogram resulting from KH modeling with integral (2) and Figure 9c shows the new SimPLI demigration result. As expected, we observe differences between the standard ray tracing results and the ones obtained by both summation processes. As in the previous example, the diffracted events, i.e., the caustic tails in the triplication , are not present in the former. In this respect, the modeling by demigration approach is more accurate than the standard ray tracing because it includes diffracted-wave contributions as does the KH modeling. However, there are no significant differences between the KH seismogram and the one obtained by SimPLI demigration. To suppress the residual noise in the modeling by demigration result, we applied a high-frequency filter after the actual modeling process. However, the Simpli demigration yields practically the same pulse as standard ray tracing and KH modeling.

CONCLUSIONS

A major challenge in the development of ray-tracing technology is to achieve more robust applications of the ray method at the various stages of the seismic value chain - from acquisition to time lapse interpretation. In this respect, one may either select a strategy based on specifically extending the validity area of the standard ray method itself, or one may follow the red line of this paper, which is to consider ray tracing as only one constituent of a composite system of processes.

The combination of the standard ray method with the wavefront construction method serves a variety of purposes, e.g., simulation of large realistic 3D surveys and modeling the reflected wavefield for predefined targets and wave modes, as well as efficient generation of Green‘s function attributes needed for real data imaging, simulated local imaging, and Kirchhoff modeling. The last technique turns out to be a very interesting candidate for effectively extending the limits of ray theory, since it dramatically reduces the need for reflector smoothness, thereby modeling both edge and caustic diffractions. Although more time consuming, it is quite feasible to perform Kirchhoff modeling in three dimensions today, having an efficient wavefront construction tracer running in parallel, even on small clusters.

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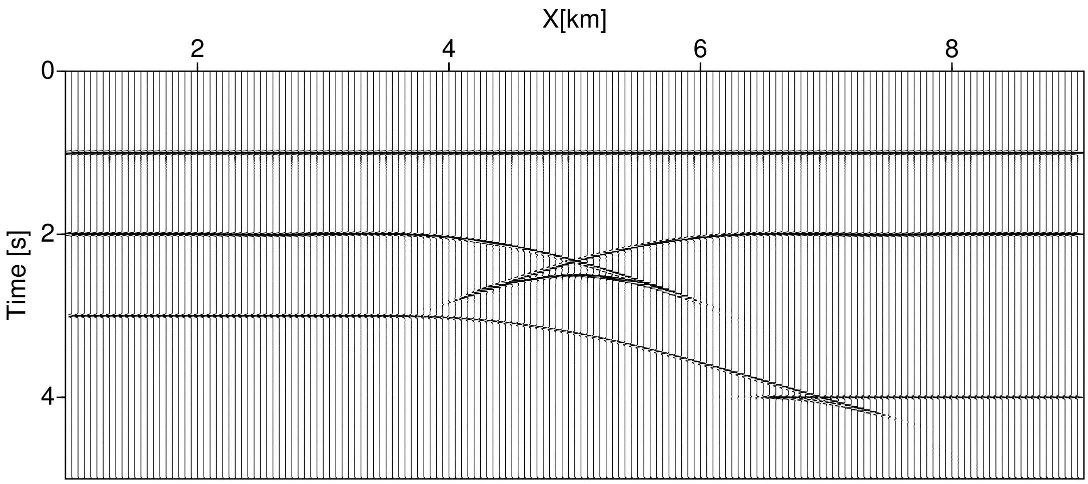
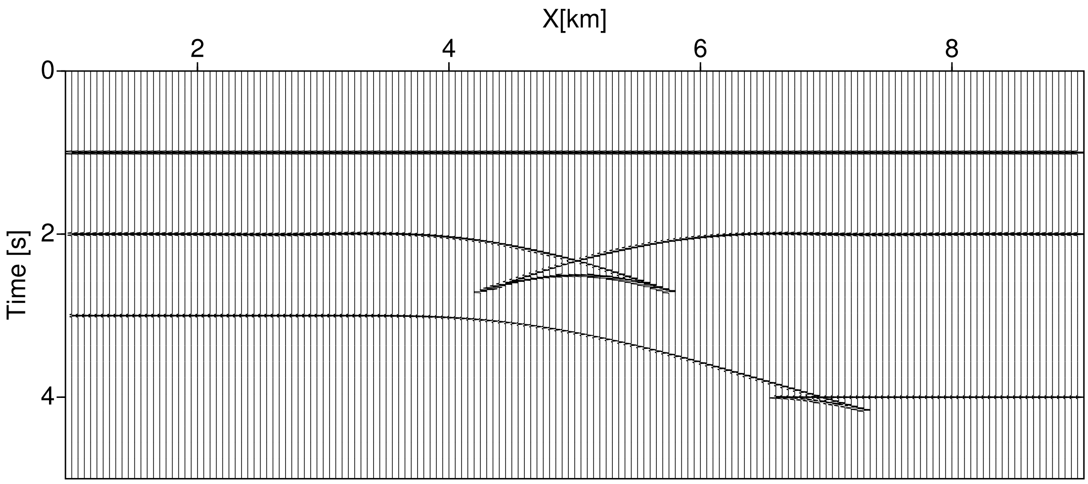
b)



a)



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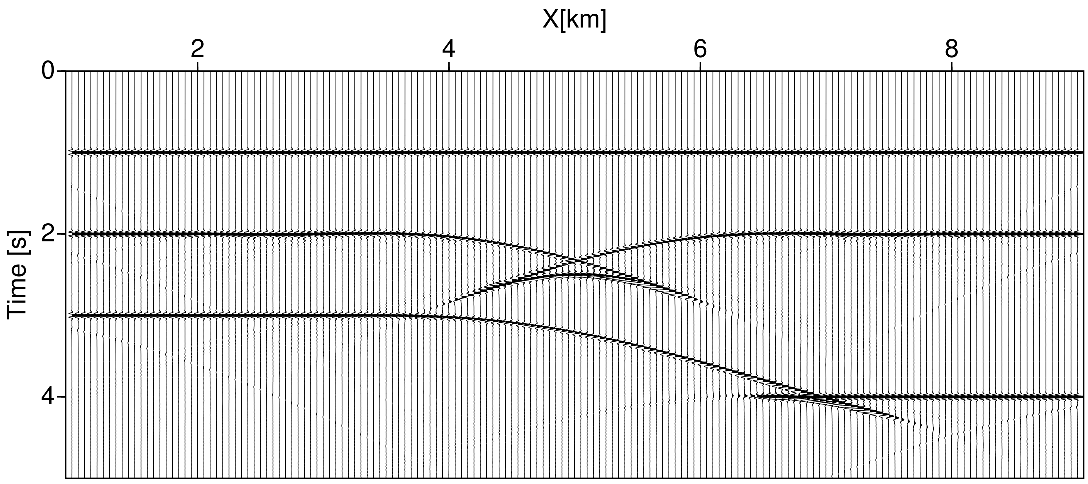

Figure 9: Computed synthetic seismograms for different modeling techniques: (a) Kirchhoff Helmholtz modeling, (b) standard ray-tracing and (c) SimPLI demigration.

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