Target-Oriented Common Reflection Angle Migration

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Summary

A 2-D and 3-D ray-based migration/inversion approach for the construction of common image gathers (CIG) in the reflection angle domain is presented. We show that amplitudes and phases of the reflected events are preserved for a wide range of angles even in complex areas with multi-arrivals. The method can be used for detailed velocity-model determination and for accurate amplitude variation with angle (AVA) analysis in such areas. Our method is a target-oriented approach, based on shooting rays from the image points up to the surface. The migration aperture and density of rays per solid dip angle at the image points is chosen with the condition that we obtain optimal reconstruction of the migrated events, avoiding migration operator aliasing. However, using the whole migration aperture might be very time consuming, especially for steep angles, which require small angle step increments. We therefore present an implementation of a model-driven aperture migration, which makes the migration feasible and relatively fast even for large-scale complex 3-D models. The migration aperture is defined from information about the local directivity of the main reflectors, obtained from interpreted horizons. The implementation of the method for complex geological structures is demonstrated with the 2-D Marmousi dataset and with the 3D SEG/EAGE salt model.

Introduction

It has been shown that common image gathers (CIG) generated by common offset or common shot Kirchhoff depth migration contain unexpected kinematic and dynamic artifacts when applied in complex areas with strong lateral velocity variations (ten Kroode, 1994 and Nolan and Symes, 1996). In order to overcome these artifacts, de Hoop et al. (1994), Xu et al. (1998) and Brandsberg-Dahl et al (1999) suggested reconstructing the image gathers in the common diffracting/reflecting angle domain. Prucha et al. (1999) illustrated the kinematic problems of multi-arrivals in the shot and offset domains and presented the reconstruction of common image angle gathers using the wave-equation migration method. A comprehensive review of the problems encountered in the common offset and common shot domains is presented by Xu et al. (2001) and is also demonstrated in Koren and Kosloff (2001).

The method presented in this study follows the concept of working in the common-reflection angle domain where the implementation is for a target-oriented output driven approach. We propose to calculate the asymptotic migration/inversion operator (ray-paths, traveltimes, geometrical-spreading and phase rotation factors) from the image points up to the surface.

By shooting dense up-going rays with uniform emergence angle increments, we directly obtain a uniform illumination at the image points from all directions (dips and azimuths), which is essential for accurate reconstruction of the image gathers. Each event in the CIG is constructed by summing all seismic data-points reflected/diffracted from the image points with the same opening (reflection/diffraction) angle. The illumination of the image points from all directions ensures that all arrivals are taken into account. Since the migration is directly performed point by point in depth, migration operator factors like traveltimes, geometrical spreading, phase rotations and slowness vectors, are calculated along each ray and they are directly used in the migration without the need to store them on a disk. Thus, the proposed output-driven approach allows for directly applying the correct summation weighting factors, obtaining continuous amplitude and phase preserved image gathers for a wide range of reflection angles. The use of model-driven migration aperture makes it feasible to run even for large-scale 3-D datasets.

Construction of the Common Reflection Angle Gathers

Our procedure is carried out along the depth image points. From each point m we shoot a fan of up-going rays, with uniform emergence angle increment $\boldsymbol{d\nu}$. Traveltimes, geometrical-spreading and phase rotation factors (KMAH index, Chapman, 1985) are calculated for each ray segment. Each migrated reflected event at a given trace in the CIG is the result of a summation over seismic data points associated with ray pairs which emanate from the image points m, with different directions (dip angles ν), sharing the same diffracted/reflected angle θ (half the opening angle). The migration formula for the angle dependent reflectivity is given by,

$$R(\theta, m) = \int d\nu W(\nu, \theta, m) \mathrm{H}^{(1-n)}\{F[U(\boldsymbol{s}, \boldsymbol{r}, \tau_D)]\}$$

(see also Miller et al., 1987, using the generalized Radon transform (GRT)), where $s(\nu,\theta,m)$ and $r(\nu,\theta,m)$ are respectively the shot and receiver locations near the ray arrival points on the surface, and $\tau_D(\nu,\theta,m)$ is the two-way traveltime of the reflecting/diffracting rays. $W(\nu,\theta,m)$ is the amplitude-weighting factor, given by

$$W(\nu,\theta,m) = \frac{\cos\theta}{A(\boldsymbol{s},m)A(m,\boldsymbol{r})} S$$

where $A(\boldsymbol{s},m) = \sqrt{\dfrac{c(m)}{8\pi\,|\,J(\boldsymbol{s},m)\,|}}$

Here, *c(m)* is the velocity at the image point and *J(s,m)* denotes the geometrical spreading. H denotes the Hilbert transform and *n* is the KMAH index (i.e., the sum of all phase rotations along a ray), which accounts for the total phase shift caused by caustics. For the 2.5-D case, S represents the out-of-plane spreading factor,

$$S = \sqrt{\sigma(\boldsymbol{s}, m) + \sigma(m, \boldsymbol{r})}$$

where σ is the out of plane spreading defined by the integral along the ray $\sigma = \int ds \; c$ with s being the arc length. For the 2-D and 3-D situations, S=1. Finally, *U* is a time filter applied to the pre-stack input traces. In the 3-D situation, *F* is simply the time derivative, where in 2.5-D and 2-D cases, *F* represents the anti-casual half-derivative with respect to time.

Generally, all seismic events of shot-receiver pairs in the vicinity of the ray arrivals with the given reflecting/diffracting angle contribute to the corresponding imaged trace within the migrated gather. However, for a reflection event, the main contribution to the image comes from seismic events, which are in the vicinity of the stationary phase rays (or specular rays), i.e., reflected rays that obey Snell's law at the reflecting horizons. A model-driven migration aperture per each image point can be defined by adding a-priori information about the general direction of the normal vector of the reflectors (Kosloff et al., 1997). This information is obtained from interpreted horizons along the main reflectors. It enables to define a local system of assumed specular rays around the normals. A small migration aperture with respect to the assumed specular rays can be defined. The minimum migration aperture can be derived from paraxial ray theory (Schleicher et al., 1997) as a projection of the first Fresnel zone from the target image to the data space. It can also be determined directly in time as the duration of the source pulse (the minimum time difference allowed between central reflected and diffracted rays). By using a small aperture, the migration process is much faster, which is especially important in large-scale 3-D imaging.

The migration summation is performed over selected seismic events in which the source and receiver locations and the traveltimes are functions of uniform dip and reflecting angles at the image points. The method therefore takes into account all relevant arrivals under the condition that the image points are illuminated from all directions.

Technically, the output-driven, upward-shooting approach enables one to calculate all the migration operator factors and apply them directly in the migration. In the case of a standard input driven approach, the migration operator factors are usually stored on a disk before applying the summation. In large-scale 3-D projects the amount of migration-operator factors that has to be stored is huge, which makes the implementation of true amplitude migration non-feasible. The problem of the output driven approach is obviously transformed to the problem of I/O, where input traces are read randomly according to the ray arrivals on the surface. Note that the proposed output driven approach requires fewer events to be migrated.

Application to the Marmousi Dataset

The main features of the proposed method are illustrated first with the 2-D Marmousi dataset, which presents a challenging imaging algorithm. The Marmousi dataset has been considered as a reference test for imaging in complex areas where multi-arrivals and ray caustics are present. Figures 1a and 1b are the result of applying our imaging approach, where the only difference is that in (1a) the KMAH index is taken into account and in (1b) it is ignored. A significant improvement in the image (especially at the area marked by the rectangle) can be seen. The strong lateral and vertical velocity variations above the marked area causes multi-arrivals and ray caustics that require correct application of the phase rotation factors. Figure 2 shows examples of common reflection angle gathers at three different locations. Note that even the CIG in figure 2b, which is located at the complex area, contains coherent and continuous events for a wide range of reflection angles.

Application to the 3-D SEG-EAGE Salt Model Dataset

The second example is from the 3-D SEG-EAGE salt model, inline 360, which is located along the main dip fault and therefore considered as the most difficult line for imaging. The main problem of imaging below the salt is poor-illumination from certain directions; especially dip directions in the vicinity of the specular rays. Figure 3 is a preliminary result of the proposed method to obtain a depth image along in-line 360. Down to the base of the salt, the result is very clean and all reflectors are imaged correctly. There are however sub-salt areas that are not fully imaged, mainly due to the lack of illumination.

Conclusions

We have presented an output-driven target-oriented approach for generating common reflection angle gathers. The main advantages are: 1) illumination of the image points from all directions, 2) the use of multi-arrivals which causes continuous migrated events for a wide range of angles, 3) preservation of amplitudes and phases even in complex areas that cause triplicated rays and caustics, 4) target-oriented, 5) model-based migration aperture which allows to use only data points that are in the vicinity of the specular rays and therefore makes the migration process much faster, and 6) the angle domain CIG are less affected by migration stretch. The method is designed for detailed velocity-model determination, for target-oriented high-resolution reservoir imaging and for accurate AVA.

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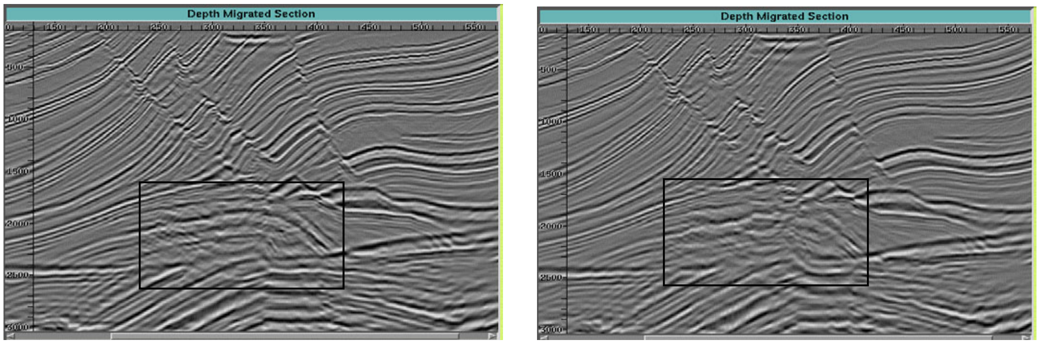
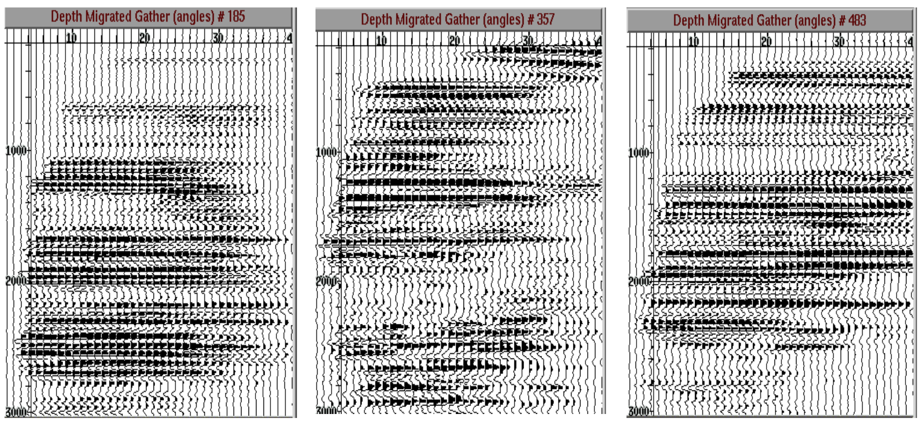


1a **1b**

Figure 1: Marmousi model depth image using the Common Reflection Angle Migration.
a) Applying the KMAH index b) Without applying the KMAH index. Note the differences in the marked area due to ray-caustics.



2a **2b** **2c**

Figure 2: Example of common reflection angle gathers used to create the depth image above (figure 1) in three different locations: a) CIG 185, b) CIG 357 and c) CIG 483. Note, that although CIG-357 is located at the complex area, the migrated events are relatively continues for large range of reflection angles (up to 40 deg.).

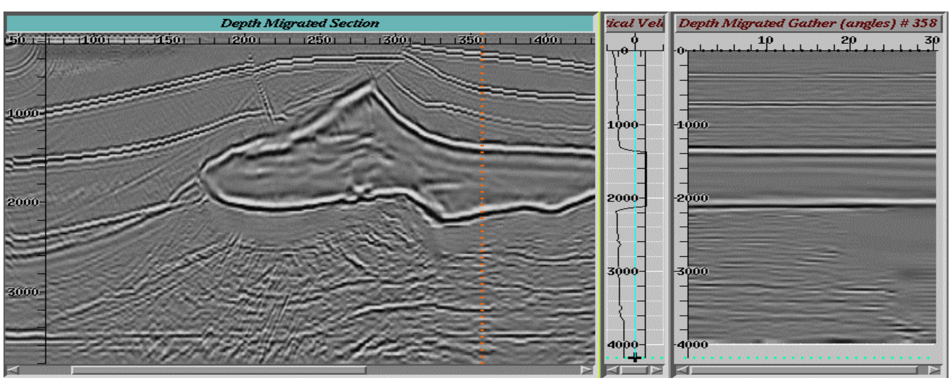


Figure 3: Result of 3-D depth imaging from the 3-D SEG-EAGE salt model, inline 360, with an example of an angle domain CIG.

References

Brandsberg-Dahl, S., de Hoop, M. V., and Ursin, B. (1999). Velocity analysis in the common scattering-angle/azimuth domain. *In Expanded Abstracts*, pages 1715-1718. Soc. Expl. Geophys.

de Hoop, M., Burridge, R., Spencer, C., and Miller, D. (1994) *GRT/AVA migration/inversion in anisotropic media*, volume 2301, pages 15-27. SPIE-The International Society of Optical Engineering.

Koren, Z., and Kosloff, D, (2001), Common reflection angle migration, a special issue of the JSE, Seismic True Amplitudes, edited by Martin Tygel.

Kosloff, D., Meshbey, O., Koren, Z. and Litvin, A., (1997), Migration process using a model based aperture technique, United State Patent, 5,629,904.

Miller, D., Oristaglio, M., and Beylkin, G. (1987). A new slant on seismic imaging: Migration and integral geometry. Geophysics, 52(7):943-964.

Nolan, C. and Symes, W. (1996). Imaging in complex velocities with general acquisition geometry. *Technical Report, TRIP, The Rice Inversion Project (Rice University).*

Prucha, M., Biondi, B., and Symes, W. (1999) Angle-domain common image gathers by wave-equation migration. In *Extended Abstracts*, pages 824-827. Soc. Expl. Geophys.

Schleicher, J., Hubral, P., Tygel, M. and Makky, S. J., (1997), Minimum apertures and Fresnel zones in migration and demigration: Geophysics, 62, 183-194.

ten Koode, A. P. E., Smit, D.J., and Verdel, A.R. (1994). Linearized inverse scattering in the presence of caustics. *In Expanded Abstracts.* SPIE.

Xu, S., Chauris, H., Lambare', G., and Noble, M. (1998). Common angle image gather: a strategy for imaging complex media. In Extended Abstracts Book, Boussens, page X012. S.E.G./E.A.G.E.

Xu, S., Chauris, H., Lambaré, G., and Noble, M. (2001). Common angle image gather: a strategy for imaging complex media. Geophysics in press.