Aperture optimized two-pass Kirchhoff migration

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Summary

The migration aperture is a parameter often difficult to set in Kirchhoff PSDM and on which the final quality of the migrated image depends strongly. It may take a lot of tests to determine the best possible aperture for a given dataset. We propose here a method to avoid migration tests and to optimize the aperture with a spatially variable function of data.

Our workflow first consists in a coarse grid PSDM where aperture is migrated as an attribute. We have developed an algorithm which uses this result to extract and interpolate an aperture zone for each final PSDM depth point. This information is then used to optimize the second fine grid final PSDM aperture.

This automatic data driven aperture optimization algorithm has been successfully tested on real marine and land datasets. With no human interaction it was possible to improve the quality of the migrated images, in some cases in a very significant way.

Introduction

The migration aperture is a critical parameter in Kirchhoff PSDM to obtain the best image quality from a given dataset. Reducing the migration aperture generally enhances the signal/noise ratio and reduces computation time but to the detriment of dipping events imaging. Aperture is the result of a compromise. Moreover a constant aperture can never be optimal in complex media. We must use a spatially variable aperture to optimize the image quality in complex media.

In a standard PSDM workflow, the aperture is often selected after several migration tests. We propose here a method to avoid migration tests and to optimize aperture thanks to a fully data driven processing.

Theory and Method

1. *Aperture attribute migration*

1.1. What is migration aperture?
The Kirchhoff migration algorithm basically consists in spreading out each trace sample amplitude on the isochron surface related to the trace sample time, and the trace source and receiver positions. If we repeat this process for all traces, the sum of all single trace migration images constructs the total reflectivity image. However, in practice, we only spread out the amplitudes on a part of the isochron centered on the trace CMPs. This is the aperture (figure 1).

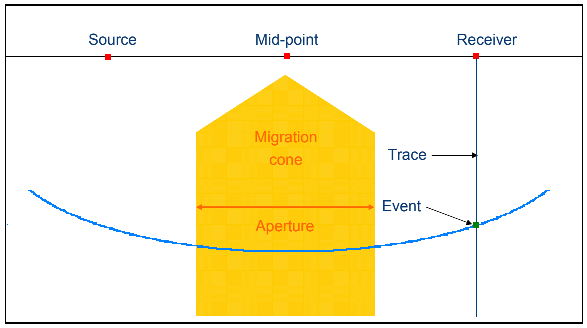


Figure 1: Migration aperture definition

1.2. How do we choose migration aperture?
The first obvious criterion is that Kirchhoff migration computation cost is directly related to the aperture size.

The second criterion for aperture selection is the signal/noise ratio. The larger the aperture is, the more noise we add to the image. Ideally, aperture should be limited to the Fresnel zone around the specular reflection.

Finally, the third criterion is dipping events imaging.

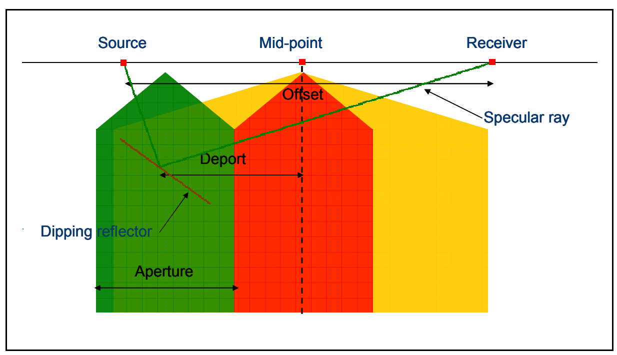


Figure 2: Dipping events imaging

Using the red aperture cone we cannot image the dipping reflector (figure 2). With the yellow aperture cone, we image the reflector but we add noise to the image. Ideally, we would like to use the green cone. As can be noticed on this figure, the “best” aperture cone is not centered on the CMP but rather on the depth specular reflection point. In the rest of this paper, we will call “deport” this horizontal vector linking the CMP position to the current imaged depth point position: $deport = \begin{pmatrix} dep_x \\ dep_y \end{pmatrix} = \begin{pmatrix} x - xm \\ y - ym \end{pmatrix}$, where (xm,ym) are the CMP coordinates and (x,y) are the current depth point coordinates.

The only problem is that the specular reflection position is related to the geological dips which are unknown before migration.

1.3. “Deport” attribute migration

The adopted strategy consists in migrating the X and Y components of the deport vector as attributes. The migration process will focus the specular reflection deport values.

The attribute migration consists in computing three images instead of the single Kirchhoff PSDM image. The three migrated images can be written as:

$$I(x,y,z,h) = \sum_{xs,ys,xr,yr} G_{xs,ys}(x,y,z) G_{xr,yr}(x,y,z) D(xs,ys,xr,yr)$$

$$I_{dep\_x}(x,y,z,h) = \sum_{xs,ys,xr,yr} G_{xs,ys}(x,y,z) G_{xr,yr}(x,y,z) D(xs,ys,xr,yr)(x - xm)$$

$$I_{dep\_y}(x,y,z,h) = \sum_{xs,ys,xr,yr} G_{xs,ys}(x,y,z) G_{xr,yr}(x,y,z) D(xs,ys,xr,yr)(y - ym)$$

where (xs,ys) and (xr,yr) are the trace shot and receiver coordinates. $xm = \frac{xs + xr}{2}$ and $ym = \frac{ys + yr}{2}$ are the CMP coordinates. $G_{xs,ys}$ and $G_{xr,yr}$ are the source and receiver Green’s functions. D is the seismic data.

This attribute migration is computed on a coarse grid for obvious cost reasons. We can chose to only migrate low frequencies in the data, in order to avoid too much aliasing and to reduce noise.

2. *Deport and aperture extraction*

A specific algorithm has been developed to extract specular deport and aperture X and Y components from the coarse grid attribute migrated images and to interpolate it to the second migration fine grid.

2.1. Specular deport extraction

To extract the specular deport X and Y components, the basic idea is to compute the following ratios:

$deport_x = {I_{dep\_x}}/{I}$ and $deport_y = {I_{dep\_y}}/{I}$,using the same notations.

In practice, to stabilize the attributes computation, for each image point, we compute a spatially weighted average of I_{dep_x}, I_{dep_y} and I before doing the division.

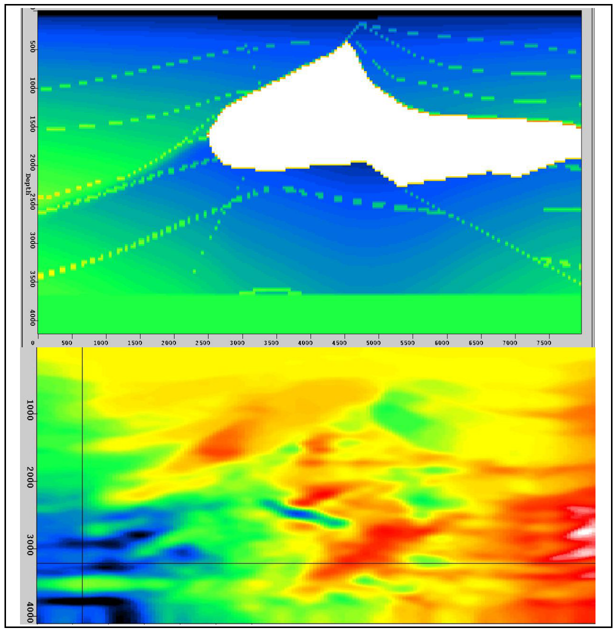


Figure 3: Deport attribute extracted on an SEG salt dome model inline.

The extracted deport values are spatially coherent on the seismic reflectors.

2.2. “Optimal” aperture computation

Once the specular deport has been computed for each fine image depth point, the next step is to determine the fine grid migration aperture. This aperture should be equal to the size of the Fresnel zone. This size is related to the curvature radius of the migration operator. Schematically, we can write:

$ap = \sqrt{\lambda R / 2}$, where ap is the half aperture, λ is the wavelength and R is the curvature radius.

However, computing the two main curvature axes and radii of the migration operator is long and complicated and it must be done for each single seismic trace sample, which would seriously slow down the second migration. In a homogeneous medium, the migration operator is a simple ellipsoid. This allows an analytical approximation of the “optimal” aperture.

We add to this aperture value a factor which is proportional to the standard deviation of the deport attribute. This factor represents the uncertainty in the determination of the specular ray deport. In this way, in areas where signal is poor, we open more the migration aperture and we do not risk choosing to enhance some coherent noise instead of the true reflection.

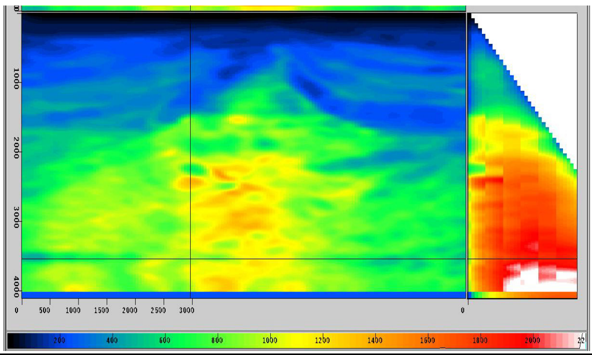


Figure 5: Aperture computed on the same SEG salt dome inline

To summarize, in this phase, for each (x,y,z,h) depth point of the optimized aperture PSDM image, we compute the four following values: dep_x and dep_y, the X and Y components of the specular deport and ap_x and ap_y, the X and Y half aperture.

3. Optimized aperture migration

The optimized aperture migration consists in weighting the migration operator:

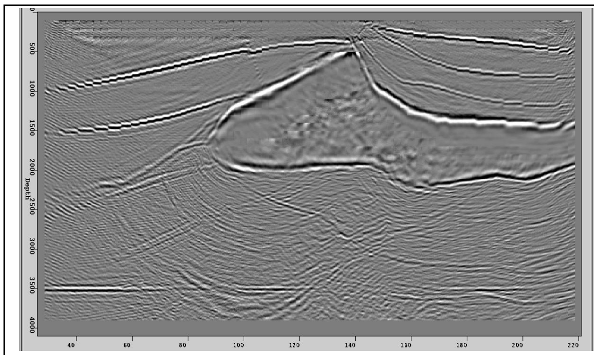
$$I(x,y,z,h) = \sum_{xs,ys,xr,yr} G_{xs,ys}(x,y,z) G_{xr,yr}(x,y,z) D(xs,ys,xr,yr) w_x w_y$$

with

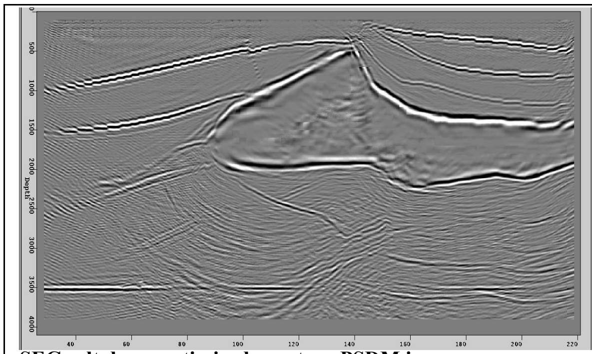
$$w_x = e^{-\left(\frac{x - x_m - dep_x(x,y,z,h)}{ap_x(x,y,z,h)}\right)^p} \quad w_y = e^{-\left(\frac{y - y_m - dep_y(x,y,z,h)}{ap_y(x,y,z,h)}\right)^p}$$

p being an even integer.

To reduce the second PSDM cost, the data is only migrated when $\frac{x - x_m - dep_x}{ap_x} \le 5$ and $\frac{y - y_m - dep_y}{ap_y} \le 5$.



SEG salt dome reference image



SEG salt dome optimized aperture PSDM image

Figure 6: Aperture optimized PSDM on the same SEG salt dome inline

4. *Cost*

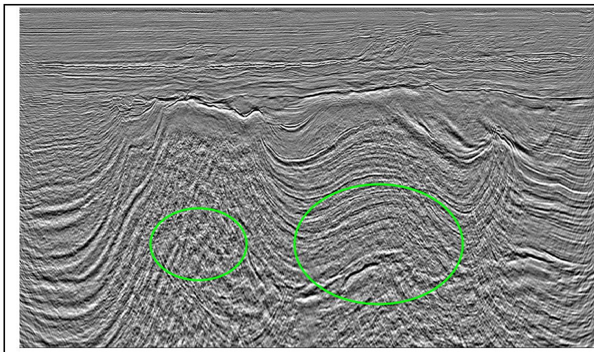
The first attribute PSDM is computed on a coarse grid. Its cost should only be a fraction (typically 1/16 or 1/32) of the cost of a regular migration. Unfortunately, our Kirchhoff PSDM is not optimally implemented for coarse grid migrations. Deport and aperture computation and interpolation algorithm are about 10 times faster than a migration. For the time being, the optimized aperture second migration has approximately the same cost as a regular migration.

However, the aperture attribute migration method can potentially reduce significantly the migration computation cost: if we migrate the data on 2000 meters instead of 10000, the migration could be 5 times faster. To fully beneficiate of the first coarse migration to reduce the dense migration time, we would have to implement a parsimonious migration in our Kirchhoff migration code.

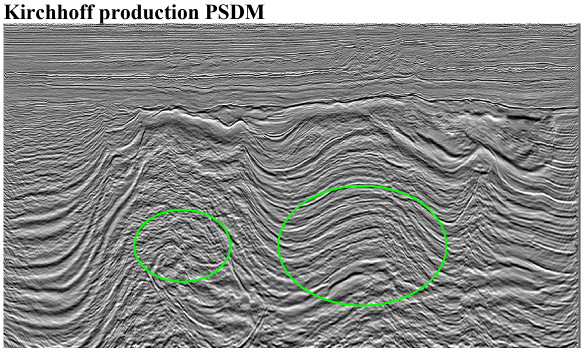
For the time being, we benefit of the information extracted from the coarse migration to improve the dense migration image quality. If we also use this information to reduce the second migration cost, the total cost of the two migrations would still be 4 times cheaper than a regular Kirchhoff migration.

Real Data Examples

Example 1: Automatic migration aperture optimization on real 3D marine data.

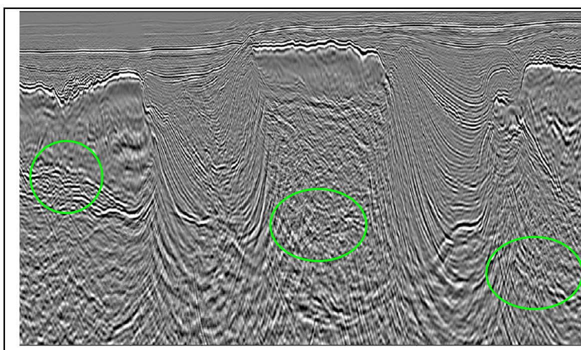


Kirchhoff production PSDM

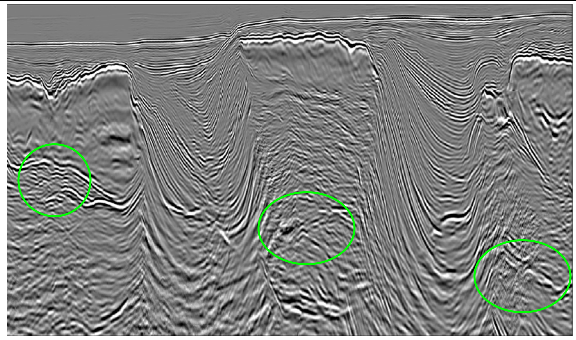


Kirchhoff aperture optimized PSDM

Example 2: Automatic migration aperture optimization on real 3D marine data with salt structures.



Kirchhoff reference PSDM



Kirchhoff aperture optimized PSDM

Conclusions

Migration aperture in the traditional Kirchhoff implementations has always been a difficult parameter to choose but on which can rely the quality of the final migrated image, especially with noisy data. It is normally set after several migration tests, which can be time consuming and still lead to some bad surprises if the strongest dips are not present on the tested areas.

We have proposed here a realistic cost effective way to deal with the aperture problems in Kirchhoff migration. The automatic aperture optimization was successfully tested on several datasets. It drastically improved the signal/noise ratio on noisy images. Some strong dipping events were sometimes partially attenuated.

EDITED REFERENCES

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