Noise suppression using preconditioned least-squares prestack time migration: Application to the Mississippian Limestone

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Summary

Conventional Kirchhoff migration often suffers from artifacts such as aliasing and acquisition footprint, which come from sub-optimal seismic acquisition. The footprint can mask faults and fractures, while aliased noise can focus into false coherent events which affect interpretation and contaminate AVO, AVAz and elastic inversion. Preconditioned least-squares migration minimizes these artifacts.

We can implement least-squares migration by minimizing the difference between the original data and the modeled demigrated data using an iterative conjugate gradient scheme. Unpreconditioned least-squares migration better estimates the subsurface amplitude, but does not suppress aliasing. In this paper, we precondition the results by applying a structure-oriented prestack LUM filter to each common offset and common azimuth gather at each iteration. The preconditioned algorithm suppresses aliasing of both signal and noise, and improves the convergence rate.

We apply the new preconditioned least-squares migration to a survey acquired over a new resource play in the Mid-Continent, USA. Acquisition footprint in shallow targets is attenuated and the signal-to-noise ratio is enhanced. To demonstrate the impact on interpretation, we generate a suite of seismic attributes to image the Mississippian limestone, and show that karst-enhanced fractures in the Mississippian limestone can be better illuminated.

Introduction

Conventional Kirchhoff migration can be regarded as the adjoint of the seismic forward modeling operator (Claerbaut, 1992). Chavent and Plessix (1996) used standard migration as the zeroth iteration, and then used a conjugate gradient scheme to compute the Hessian matrix. They then used a least-squares formulation to obtain an optimized image. Schuster (1993) added constraints to the objective function. Following Nemeth (1996), he used least-squares migration to overcome uncompensated migration artifacts due to incomplete data, which can give rise to acquisition footprint.

Least-squares migration may require many iterations to reach convergence, consuming significant computer resources. For this reason, significant effort has focused on preconditioning the input data to decrease the number of iterations. Wei and Schuster (2009) and Aoki and Schuster (2009) preconditioned the data by using a deblurring filter, thereby reducing the number of iterations needed. Wang and Sacchi (2009) evaluated running average and prediction filter constraints to improve the convergence rate of a 2D least-squares migration algorithm. Cabrales Vargas (2011) used mean and median filters as constraints in 3D preconditioned least-squares migration in his master thesis.

Post-stacked structure-oriented filtering is commonly used in conditioning stacked volumes after migration to facilitate interpretation (Fehmers and Höecker, 2003). Luo et al. (2002) extended Kuwahara et al. (1976) algorithm to 3D seismic data as an alternative edge-preserving smoothing algorithm. Marfurt (2008) proposed a modification of Luo et al.’s (2002) technique. First, he used coherence rather than the standard deviation to choose the most homogeneous window. Then, instead of using the mean, median or the $\alpha$-trimmed mean, he used a principal component (or Karhunen-Loève) filter to that more fully uses trends in the analysis window to replace the amplitude at the analysis point. Corrao et al. (2011) showed how an LUM-based structure-oriented filter can reject outliers, yet better retain the original character of the seismic data. Kwiatkowski and Marfurt (2011) showed how such filters can be applied to prestack time-migrated common-offset-azimuth gathers. To suppress aliasing within the conjugate gradient PLSM algorithm, we apply LUM-based structure-oriented filters to the common-offset-azimuth gathers, which reduces the number of iterations needed by PLSM.

In this paper, we begin our discussion by examining the role of Kirchhoff migration as the adjoint of the seismic modeling operator and demigration as the seismic modeling operator in a PLSM algorithm. Next, we will introduce the mathematics of the PLSM algorithm. I demonstrate the value of my PLSM algorithm and workflow to one prestack data volumes from Ness Co., Ok and illustrate the effectiveness by analyzing seismic attributes computed along the top of the Gilmore City horizon.

Theory

We can express modeling (demigration) in matrix notation as:

$$d = Lm,$$  \hspace{1cm} (1)
where \( L \) constitutes the forward modeling operator (in this thesis prestack time demigration), \( m \) is the reflectivity model, and \( d \) is the modeled data.

We define migration as
\[
\begin{align*}
m' &= L^T d, \\
\end{align*}
\]
(2)

Where \( L^T \) is the adjoint operator of \( L \), (in this paper is prestack), and
\( m' \) is the migration approximation to the Earth's reflectivity.

Standard migration \( L^T \) is the adjoint of the forward modeling operator \( L \).

Substituting equation 1 into equation 2, I obtain
\[
\begin{align*}
m' &= L^T L m. \\
\end{align*}
\]
(3)

We can regard the matrix \( L^T L \) as a linear filter applied to \( m \). If \( L^T L \) approximates the identity matrix. Unfortunately, due to sparse surface acquisition, \( L^T L \) is almost never diagonal such that \( m' \) has migration artifacts (Nemeth, 1996).

Schuster (1997) attenuated these artifacts by making \( L^T L \) closer to the identity matrix. In this work, we add a preconditioner \( F \) to obtain:
\[
\begin{align*}
e &= \|L m F\|^2 + \|C m\|^2, \\
\end{align*}
\]
(4)

where \( e \) is the objective function to be minimized, the first term on the right-hand side of the equation is the misfit function, and \( C \) is the constraint matrix. Multiplying both sides of equation 4 by \( L^T \), I form the normal equations and minimize the function:
\[
\begin{align*}
[L^T L + C] m &= m' = L^T d. \\
\end{align*}
\]
(5)

We will solve equation 5 for \( m \) using a conjugate gradient scheme, giving rise to an iterative method that constitutes a preconditioned least-squares migration algorithm (Schuster, 1997).

**Example**

Dickman field, located in Northern County, Kansas, as shown in Figure 1, is a typical super mature Mississippian reservoir, which has produced approximately 1.7 million barrels of oil. In the field, Pennsylvanian strata unconformably overlie the Mississippian reservoir rocks of the Meramecian Spergen and Warsaw limestone. The Mississippian reservoir in Dickman field is composed of shallow-shelf carbonates. Karst-enhanced fractures have been documented to extend several meters below the regional unconformity surface. The Western Interior Plains aquifer system acts as a very strong bottom water drive for the reservoir, which in turn is underlain by the low porosity and low permeability Gilmore City limestone.

Figure 1: Map of the Mississippian subcrop in Kansas. Black box outlines Ness County, and the white block arrow indicates the location of Dickman Field. Black dots represent oil production. (After Nissen et al., 2009).

Figure 2: Time-structure map of the top of the Gilmore City horizon. The white block arrows indicate collapse features.

Figure 3a shows vertical slices through seismic amplitude along profiles AA’ of conventional migration, the low signal-to-noise ratio causes the poor illumination for the layers, and random noise masks subtle geological features. After two and three iterations of PLSM in Figures 3b and 3c, the signal-to-noise ratio is enhanced and there is less noise contamination, which interferes with the main reflected energy from conventional migration.

Figure 4a shows a time slice at \( t=0.406s \) of the stacked volume after conventional migration. The white block arrow indicates footprint, its contamination interferes with interpretation of subtle geological features. After two and three iterations of PLSM in Figure 4b and Figure 4c, the footprint is almost eliminated and the structural features are retained.

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Figure 3: Vertical slice through seismic amplitude along profiles AA’ as shown in Figure 2: (a) using conventional migration, and after (b) two, and (c) three iterations of PLSM. The white block arrows indicate collapse features. The red block arrows indicate Gilmore City horizon.

Figure 4: Time slice at $t=0.406s$ through stacked amplitude volumes after (a) conventional migration and after (b) two, and (c) three iterations of CLSM. The white block arrows in (a) and (b) indicate footprint.

Figure 5a shows coherence horizon slices through coherence volumes along the Gilmore City after conventional migration. The red block arrow denotes karst collapse features. Note the contamination of random noise on the coherence attribute. After two and three iterations of PLSM in Figure 5b and Figure 5c, contaminating noise is suppressed. The red block arrows highlight the karst features clearly in form of collapse character.
Figure 5: Horizon slices along the Gilmore City through coherence volumes computed from seismic amplitude: (a) using conventional migration, and (b) two, and (c) three iterations of PLSM. Red block arrows indicate the karst collapse features.

Figure 6a shows the common reflection point (CPR) prestack gathers from conventional migration. After CSLM, same events in Figure 6c and Figure 6d show more continuation and less noise contamination.

Figure 6: A representative conventionally migrated CRP gathers (a) after muting, (b) two, and (c) three iterations of PLSM. The white block arrow in (a) indicates noise. The white block arrows in (b) and (c) indicate noise attenuated.

Conclusions

Application of PLSM to the Gilmore City limestone shows a rapid improvement of signal-to-noise ratio for CRP gathers and significant attenuation of footprint and random noise, which impedes interpretation from conventional migration. PLSM provides significant improvement in the quality of subsequent seismic attributes. PLSM eliminates random noise and coherent noise that is inconsistent with the subsurface geology on prestack gathers. For this reason, we anticipate that preconditioned least-squares migration will result in improved prestack inversion and AVAz analysis.

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EDITED REFERENCES
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