Data conditioning of legacy seismic using migration-driven 5D interpolation

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Abstract

Legacy seismic surveys cover much of the midcontinent USA and Texas, with almost all 3D surveys acquired in the 1990s considered today to be low fold. Fortunately, recent advances in 5D interpolation have not only enhanced the quality of structural and stratigraphic images, but they have also improved the data sufficiently to allow more quantitative interpretation, such as impedance inversion. Although normal-moveout-corrected, common-midpoint-based 5D interpolation does an excellent job of amplitude balancing and the suppression of acquisition footprint, it appears to misinterpolate undercorrected diffractions, thus smearing fault and stratigraphic edges. We described a least-squares migration-driven 5D interpolation workflow, in which data were interpolated by demigrating the current subsurface image to the missing offsets and azimuths. Such demigration accurately interpolates fault edges and other diffractors, thereby preserving lateral discontinuities, while suppressing footprint and balancing the amplitudes. We have applied this workflow to a highly aliased low-fold survey acquired in the early 1990s now of use in mapping the newly reinvigorated Mississippi Lime play. This workflow improves reflector continuity, preserves faults delineated by coherence, balances the amplitude, and provides improved well ties.

Introduction

Legacy seismic surveys cover much of the midcontinent USA and Texas, with almost all 3D surveys acquired in the 1990s considered today to be low fold. Low-fold data present multiple challenges. First, in the presence of random noise, the signal-to-noise ratio increases as the square root of n for n-fold data, such that low-fold data are noisier. Second, low-fold data are often spatially aliased. Although the signal is usually adequately sampled, noise such as low velocity ground roll is often undersampled and may leak through the stack array. Low fold diminishes the statistical power needed to select processing parameters, where it may be difficult to distinguish between the primary reflectors of interest and head waves, interbed multiples, converted waves, and other coherent "noise" events. Although a skilled interpreter may be able to accurately pick statics to properly align reflectors of interest in low-fold data, modern automated surface-consistent statistics-driven statics computations work better with high-fold data. Filters also suffer from low fold and aliasing. Modern $f - k_x - k_y$ filters work well on densely sampled, high-fold data, but they work poorly on coarsely sampled, low-fold data (Galibert et al., 2002).

Seismic migration is a linear filter that reads in one input data volume, outputs another with desired (focusing) enhancements, and suffers from "operator" aliasing (Biondi, 2001). The most common way to suppress operator aliasing is to limit the output high frequencies corresponding to the steeper dips. Finally, low-fold land surveys in general do not uniformly illuminate the earth's subsurface, giving rise to the acquisition footprint. In contrast, modern wide-azimuth, 400-fold surveys that more uniformly illuminate the subsurface exhibit only minimal acquisition footprint.

"High-resolution" Radon filters (e.g., Sacchi and Porsani, 1999; Trad et al., 2002) have had considerable success in filtering aliased data, and they are representative of a more general class of iterative least-squares filters. The objective in such filtering is to process or map different data components in a specific order, with (alternatively) the strongest, most coherent, or least aliased events being processed or mapped first and then subtracted from the original data, leaving a residual. This residual is then analyzed, with either the next strongest, most coherent, or least aliased events being processed or mapped next, with the criteria used in deciding which events to treat being relaxed at each iteration. Matching-pursuit spectral decomposition (Castagna et al., 2003) is one such filter. The filter that has perhaps best aided the analysis of low-fold legacy data over the past 10 years has been 5D interpolation. In the most common workflow, the processor carefully generates velocity and statics models that accurately flatten the

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primary reflections of interest. Unfortunately, such accurate velocity and statics analysis of low-fold data can take considerable care and skill. Once flattened, supergathers are fit by local $f - k_x - k_y - k_h - k_{\varphi}$ (or other parameterizations of the five dimensions) transforms, where the offset h, and azimuth ϕ , dimensions are incompletely populated. Liu and Sacchi (2004) use a minimum weighted norm interpolation algorithm, Xu et al. (2005) use an antileakage Fourier transform algorithm, and Abma and Kabir (2006) use a projection onto convex sets algorithm. Variations of these methods are reported by Stein et al. (2010) and Wojslaw et al. (2012). Many commercial 5D interpolation workflows use high-resolution Fourier transforms (e.g., Trad, 2009), in which the strongest events are transformed first in an iterative least-squares filter to minimize aliasing. Chopra and Marfurt (2013) use a commercial implementation of Trad's (2009) method and illustrate the significant reduction in acquisition footprint on volumetric coherence and curvature images. However, although the resulting images were more continuous, they also showed lower lateral resolution about faults and stratigraphic edges. Chopra and Marfurt (2013) show that some of this loss of resolution can be ameliorated by applying a shorter wavelength curvature algorithm, but little other than subsequent passes of image



Figure 1. Workflow showing the first iteration of the migration-driven 5D interpolation workflow. In the first iteration, there are no interpolated data. However, the migrated images are demigrated (modeled) to the desired interpolated $(x, y, h, and \varphi)$ bins, such that interpolation is done using the diffraction hyperbolae. The real and interpolated data are then used for subsequent iterations, updating the interpolated data each time. The objective (data misfit) function is computed only at the measured surface bins, not on the interpolated bin locations.

SG32 Interpretation / May 2016

processing filters could repair the smeared coherence images.

The authors of this paper hypothesize that the loss of such lateral resolution is an artifact of interpolating normal-moveout (NMO)-corrected specular reflections. The diffractions needed to resolve edges are only partially corrected by NMO and are thus misinterpolated, or smeared, by the 5D planar interpolation process. We therefore follow Trad (2003) and propose 5D interpolation of the data using the demigration operator rather than the NMO operator as part of an iterative leastsquares migration workflow.

We begin by reviewing the physics of least-squares migration, the use of prestack structure-oriented filtering (SOF) to avoid interpolation of operator aliases, and demigration to a more uniform surface grid to 5D interpolate the surface data. We then apply this workflow to a highly aliased legacy Mississippi Lime data set acquired over north Texas. We demonstrate the value of each step of this workflow through vertical slices through the seismic amplitude and time slices through coherence at the objective level. We conclude by showing the improvement in poststack inversion over the original data volume.

Method

Figure 1 shows our migration-driven 5D interpolation workflow. The first step of the first iteration is to prestack Kirchoff time migrate the data. These data are then subjected to edge-preserving prestack SOF (Guo, 2014; Zhang et al., 2015), using a three-trace by three-trace by three-offset Kuwahara alpha-trimmed mean filter. In general, nonlinear median, alphatrimmed mean, and lower-upper-middle filters are more robust than mean and principal component filters in the presence of high-amplitude aliased noise spikes that often occur in prestack migration. The objective of this edge-preserving structure-oriented filter is to suppress steeply dipping coherent noise that crosscuts the reflectors and diffractors of interest. The next step in leastsquares migration is to demigrate (or forward model) the subsurface reflectivity to the original surface source-receiver locations. These modeled data are then subtracted from the measured surface data, resulting in a data residual. The amplitude of the reflectivity image is properly scaled, and the residual data migrated, beginning the second iteration of a "preconditioned" leastsquares migration (Guo et al., 2012). To interpolate the data, at subsequent iterations, we predict the data not only at the measured surface locations, but also at the surface locations that were not occupied (Figure 2).

The mathematically rigorous way to apply filters internal to least-squares migration is represented by early applications by Nemeth et al. (1999) and Duquet et al. (1999), who construct filters that are mathematical adjoints of each other, with the mathematical adjoint of smoothing being sharpening. When combined with Kirchhoff migration and Kirchhoff demigration (which are also mathematical "adjoints" of each other), these processes form a constrained least-squares migration that obeys a mathematical "dot-product" test (Claerbout and Fomel, 2014). We choose to be less rigorous by breaking the least-squares migration into the steps shown in Figure 1, allowing us to apply any filter appropriate to address the signal and noise of the specific data set. In Figure 1 and in the following example, we will use a nonlinear prestack structure-oriented filter; however, in other applications, one may wish to use a high-resolution Radon transform to remove multiples (e.g., Duquet and Marfurt, 1999). The price of such flexibility is that we may no longer obey the dot-product test that guarantees convergence to the correct answer. Nonlinear alpha-trimmed mean filters and Radon transforms with mutes have no adjunct and hence fail the dot-product test. We therefore need to validate our results by confirming that our last iteration least-squares fits the measured signal of the surface gathers to the desired accuracy.

Although most processors migrate data to the natural bin size, one might accept an increase in computational cost and define a finer output bin size, with the output data being "interpolated" by the migration impulse response, or Green's function. Similarly, one can demi-

grate the current reflectivity image to a denser distribution of source-receiver pairs. In our case, we wish to demigrate to the locations of missing sourcereceiver offsets and azimuths, thereby regularizing the fold for each common offset-azimuth volume (Figure 2). The demigration operator considers each voxel to be a point scatterer, generating a diffraction impulse response. The response from adjacent voxels along a smooth reflector constructively and destructively interferes to produce a specular reflection. The demigrated energy from edges in the reflectivity image undergoes less interference and appears as diffractions in modeled, interpolated data.

Guo (2014) applies 5D interpolation to a Mississippi Lime survey acquired in Ness Co., Kansas, where the offsets and azimuths of the original data (Figure 3a) are augmented to generate a more regular interpolated survey (Figure 3b). Figure 4a and 4c shows the image resulting from a conventional Kirchhoff migration algorithm after prestack SOF, or simply, the first iteration of preconditioned least-squares migration shown in Figure 1. Figure 4b and 4d shows the same vertical slices after three iterations of preconditioned leastsquares migration. Red arrows indicate the top Mississippi Lime formation. Note the improved amplitude balancing toward the left side of each image from least-squares migration and 5D interpolation. Also note the improved vertical resolution in the deeper Arbuckle Formation below the target. Although older (acquired in 2003), these data were acquired at an 25.14×25.14 m (82.5×82.5 ft) nominal bin size and were not highly



Figure 2. Cartoon showing the binning of a common midpoint gather with two offsets and four azimuthal sectors with (a) data before 5D interpolation showing two bins containing two traces, two bins containing one trace, and four bins containing no traces. (b) The goal of 5D interpolation is to fill each bin with at least one trace. In our implementation, we will compensate for a variable number of traces per bin through the use of least-squares migration.



Figure 3. Fold map of the Dickman Field, KS, survey (a) before and (b) after 5D migration-driven 5D interpolation. The nominal bin size was 25.14×25.14 m (82.5×82.5 ft; data are courtesy of Mull Drilling Co.).

aliased. In contrast, our primary objective is to image four highly aliased (merged) surveys acquired in the early 1990s with natural bin sizes of 33.5×33.5 m (110×110 ft).

Application

Our objective is to map the Mississippi Lime and potential chert sweet spots in a vintage survey acquired in north central Texas (Figure 5). In this area, the Mississippi Lime lies directly above the Ellenburger Limestone (Arbuckle equivalent to the Kansas data shown in Figure 4) at a depth of 1825-2450 m (6000– 8000 ft). The Mississippian target in our study area is shallow (at approximately t = 1.2 s). Costs to small operators playing the Mississippi Lime are reduced due to an abundance of preexisting surface infrastructure (such as previously drilled wells) and their current acreage leaseholds. Advancements in technology of horizontal drilling, acidation, hydraulic fracturing, and advanced methods of disposal of large volumes of



Figure 4. Vertical slices along line AA' and BB' through the migrated volumes generated (a and c) without and (b and d) with migration-driven 5D interpolation. Note the better amplitude balancing at the Mississippi Lime target on the lines AA' and BB' (location shown in Figure 3). Note also that strongly dipping migration artifacts in panel (c) due to the edges of the data are reduced in panel (d). The vertical resolution below the target Mississippian is also significantly improved in panel (d) when compared with panel (c). The amplitude balancing is due to the least-squares construct that compensates for the irregular fold.

Figure 5. (a) Location of study area (modified after Pollastro, 2007). Note that the red rectangle in the northwest of the map indicates the study area. (b) A typical log showing the target Mississippian chert.



water make these reservoirs economic. In contrast to some shale resource plays, the Mississippi Lime is highly heterogeneous laterally. High-porosity tripolitic chert, fractured tight chert, and tight limestone are the major rock types. The tripolitic and fractured chert have good porosity and good production in northern Oklahoma and southern Kansas.

In the study area, four seismic surveys were shot in the early 1990s, three of which had east-west receiver lines and one with north-south receiver lines (Figure 6a). The merged 15-fold surveys cover an area of 207 km^2 (80 mi²). Initially, the data were processed with a conventional workflow that worked very well on an Osage Co., OK, 60-fold Mississippi Lime survey acquired in 2012 (Dowdell et al., 2013). The resulting images were strongly contaminated by the acquisition footprint (Figure 7), much of it due to highly aliased broadband groundroll. Given the success reported by Chopra and Marfurt (2013), we applied a commercial Fourier-based 5D interpolation workflow to the NMO and static corrected data and migrated the result. In retrospect, we should have anticipated that 5D interpolation would misinterpolate the steeply dipping ground roll before ground-roll suppression, resulting in the inferior images seen in Figure 8.

The use of a coherence-based ground-roll suppres-

sion workflow described by Verma et al. (2016) shown in Figure 9 provided an improvement over the images in Figure 7. Migrating these data (without 5D interpolation) reduces the footprint and provides an acceptable image of faults F1 and F2 present in the eastern part of the survey. Following Figure 1, we applied three passes of prestack SOF, to suppress cross-cutting noise (Figure 10). The vertical seismic section displayed in Figure 10a shows improved reflector continuity in the green ellipse, whereas Figure 10b shows an overall increase in coherence (a whiter image) and enhanced delineation of faults F3 and F4.

After ground-roll suppression and prestack SOF, we interpolated missing offsets and azimuths via demigration (i.e., migration-driven 5D interpolation), resulting in the fold map shown in Figure 6b. The misfit between the demigrated data and the measured data form the minimization function, whereas the interpolated data that correspond to missing traces do not. This migration-SOF-demigration process is iterated three times, providing acceptable convergence of the least-squares misfit function (see Guo et al. [2012] for such analysis). We observed that in Figure 10a, a low-amplitude strip exists in



Figure 6. (a) Fold map of the four merged surveys showing an average fold of 12. (b) After 5D interpolation, the fold will be a more uniform 35.



Figure 7. Images after a conventional Mississippi Lime processing flow (given by Dowdell et al., 2013) showing (a) a vertical line through the prestack time-migrated data and (b) a horizon slice along the top Ellenburger through coherence volume. The coherence image is particularly noisy.

Figure 8. The same images as shown in the Figure 7, but now after 5D interpolation of the input NMO-corrected gathers. The resulting (a) vertical slice through seismic amplitude and (b) Ellenburger horizon slice through coherence are now worse. We interpret this failure to be due to strong residual groundroll in the data.



Figure 9. The same image as shown in Figures 7 and 8, but now computed after modeldriven groundroll suppression. (a) The vertical slice through amplitude shows a reduction of coherent noise and better alignment of reflectors (e.g., within the green ellipse). (b) The Ellenburger horizon slice through coherence preserves the faults, whereas the groundroll noise bursts that gave rise to organized low coherence impulse responses are now significantly reduced.





Figure 10. The same images shown in Figure 9, but computed after three passes of prestack SOF of the migrated images showing (a) a vertical slice through amplitude and (b) the Ellenburger horizon slice through coherence. Note the reduction of steeply dipping noise in panel (a) and the significant increase in coherence in panel (b), except about the faults, which are well preserved. There is still a zone of anomalously low amplitude associated with edges of the component surveys (block arrow).

Figure 11. The same images as in Figure 10, but now after migration-driven 5D interpolation. After groundroll suppression and three passes of SOF and 5D interpolation: (a) stacked seismic data cross section and (b) coherence on horizon slice at Ellenburger surface. Notice the reduction of noise, as well as the balancing of amplitude. The coherence image is sharper than in Figure 10b, indicating that the migrated-driven 5D interpolation did not smear lateral discontinuities. We hypothesize that this improvement is through the use of demigration diffractions as the interpolator.

Figure 12. Ellenburger horizon slices through acoustic impedance corendered with coherence (a) computed from the data shown in Figure 7a and (b) computed from the data shown in Figure 11a, which was subjected to groundroll suppression, prestack SOF, and migration-driven 5D interpolation.





Figure 13. Well to seismic tie on well indicated by the white star in Figure 12b: (a) before 5D interpolation and (b) after 5D interpolation. The synthetic to seismic correlation before 5D interpolation was 38%, whereas after 5D interpolation, it is 53%. You can observe by the red arrow that the well synthetic shows two reflectors and the seismic after 5D interpolation has better resolved the two reflectors.

a)

the middle of the vertical section because of the anomalously low fold at survey boundaries. After 5D interpolation and least-squares migration, the amplitude is balanced (Figure 11a). Coherence in Figure 11b is increased still further (overall appears whiter), whereas faults F1, F2, F3, and F4 retain their values (the same level of black), indicating that we have done a good job of edge preservation.

To further evaluate the impact of seismic data conditioning, we performed model-driven acoustic impedance inversion before ground-roll suppression using a conventional inversion workflow and after the coherency-based ground-roll suppression (Verma et al., 2016), SOF, and migration-driven 5D interpolation workflow. The impedance computed from the conventional imaging workflow shown in Figure 12a exhibits rapid lateral variation and is geologically unreasonable. In contrast, the impedance computed from the more aggressive processing shown in Figure 12b is geologically reasonable.

Figure 13 shows the well synthetic to seismic correlation at well A. The synthetic to seismic correlation with seismic data after groundroll suppression and before 5D interpolation shows an acceptable correlation in the zone of interest. However, if we look closely, the correlation is improved significantly after migrationdriven 5D interpolation. For the larger window beyond the target, the correlation increases from 38% to 53%. This improvement was seen on the other four wells with P-wave sonic logs falling within the survey.

Conclusion

Many parts of Texas and the Midcontinent are covered by low-fold 3D surveys acquired in the 1990s. In general, these data suffer from strong acquisition footprints, operator aliasing, and (in the example described here) insufficiently attenuated coherent noise. Unfortunately, limitations in budget or recently constructed infrastructure may prohibit reshooting a modern wide-azimuth, high-density survey. Five-dimensional interpolation does not suppress and can exacerbate the effects of coherent noise. Such noise needs to be attenuated prior to subsequent processing and imaging. Least-squares migration-driven 5D interpolation provides the advantages of improved continuity, reduced acquisition footprint, and amplitude balancing while retaining sharp fault edges and improving well ties.

The major limitation of migration-driven 5D interpolation is increased computation (but not human interpreter or processor) cost. First, the cost of each demigration is equivalent to a migration, such that three iterations of least-squares migration along with demigration for 5D interpolation cost six times as much as a conventional migration. Second, increasing the density of the surface data (but not the subsurface image) through 5D interpolation of missing offsets and azimuths increases the cost by another factor of three to four, such that the total runtime increases by a factor of 18–24. Obviously, if one were to reshoot a denser survey, one would encounter the same increase in imaging cost. In situations in which such acquisition is not practical, we feel that least-squares migration driven 5D interpolation provides a good alternative.

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