Highly aliased groundroll suppression using a 3D multiwindow KL filter: Application to a legacy Mississippi Lime survey

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ABSTRACT

While modern recording capacity facilitates dense seismic acquisition, many, if not most, legacy 3D land surveys are spatially aliased with respect to groundroll. Irregular topography and weathering zones give rise to groundroll that has piecewise, rather than continuous linear moveout. Dispersion often results in shingled events whose phase velocity cuts across the groundroll noise cone. We present a workflow for the suppression of highly aliased broadband groundroll where modern $f$-$k_x$-$k_y$ filters failed. Our workflow begins with low-pass filtering and windowing the data, 3D patch by 3D patch. We then apply linear moveout corrections using the average phase velocity of the groundroll. We compute residual moveout components along the shot and channel axes to account for changes in velocity, thickness, and weathering zone topography about each sample. Using a Kuwahara algorithm, we choose the most coherent window within which we apply a structure-oriented Karhunen–Loève filter to model the coherent noise. Finally, we remove the linear moveout correction and subtract the modeled groundroll from the original data. We validate our workflow using a synthetic gathers having the same geometry as our field data we then apply our workflow to a merged legacy data volume consisting of four 3D surveys acquired in the 1990’s and evaluate its efficacy using modern seismic attribute to map faults and flexures.

INTRODUCTION
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Several techniques have been developed for coherent noise suppression in the last 30 years. Groundroll on 2D seismic shot gathers and receiver gathers acquired over flat topography often appears as low frequency noise exhibiting nearly linear moveout. Embree et al. (1963), Treitel et al. (1967) and Kirchheimer et al. (1985) used f-k fan filters to remove unaliased groundroll on 2D gathers. However, if the data are coarsely sampled (most legacy land surveys) the groundroll will be aliased in the $k_x$ domain (Foti et al., 2002), such that the aliased component of groundroll may overlap the signal components of the spectrum. Radon, $\tau$-$p$, and radial transforms have also been applied to groundroll suppression (Russell et al., 1990; Brysk and Mc Cowan, 1986, Henley, 2003). Turner (1990) showed the appearance of spatial aliasing in the $\tau$-$p$ domain. Trad et al. (2003) achieved reduced aliasing using a sparse Radon transform. Although recent developments in “high resolution” Radon transform algorithms have made improvements, irregular moveout of groundroll on rough topography limits their effectiveness even for 2D data.

Liu (1999) modeled groundroll on common shot gathers using the Karhunen-Loève (KL) transform. Liu first picked groundroll alignment functions on each 2D shot gather to flatten the groundroll. Coherent groundroll was then formed a covariance matrix about the flattened groundroll and computed its eigenvectors and eigenvalues. He reconstructed the coherent groundroll using the strongest eigenvalue eigenvector pairs, and removed the moveout correction. Finally, he subtracted the modeled groundroll from the original data to obtain a filtered result. Done (1999) improved the workflow by defining different window sizes while forming the
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covariance matrix. Montagne and Vasconcelos (2006) added an alignment function to find the
correct velocity to flatten the groundroll. In general, groundroll is dispersive which makes
flattening a human intensive process. Figueiredo et al. (2009) partially addressed this issue by
muting the top and base of the groundroll zone prior to flattening and application of the KL
transform, thereby minimizing any negative impacts on signal outside the noise cone. In a related
problem regarding high amplitude tube waves masking upcoming P- and S-waves of interest on a
VSP, Mulder et al. (2002) used an adaptation of structure-oriented filtering. Their version filtered
within coherent windows and avoided filtering in incoherent windows where the moveout of the
tube wave changes due to abrupt vertical changes in velocity. All these methods were applied to
2D data.

In general, simple 2D f-k and linear Radon filters do not work well on 3D data. Radon and f
- k filters can be extended to 3D seismic geometries. Gaiser (1995) sorted the 3D gathers by offset,
and accounted for unequal trace spacing by computing an f – x domain fan-filter using a least
squares approach. Galibert et al. (2002) applied a true f-kx-ky filter to 3D seismic data to filter
coherent noise. Neither of these methods work if the coherent noise is aliased. Liu and Marfurt
(2004) found similar limitations using 3D \( \tau-p-q \) Radon transform in suppressing coherent noise.
Short window, coherence-driven filters often work better in the presence of discontinuous changes
in moveout due to variations in topography, thickness and velocity of weathering zone. Using
commercial software, D’Agosto et al. (2003) sorted their 3D data by offset, flattened using an
average groundroll phase velocity, and then estimated the coherence and local residual moveout
of the groundroll by cross-correlating adjacent trace pairs. For those samples where the coherence exceeded a processor-determined threshold, the groundroll was estimated using the cross-correlation coefficient and subtracted.

We begin our paper with a description of the exploration objectives, data acquired and failure of conventional processing techniques (in piecewise continuous dispersive groundroll removal). We then address this problem by adapting a well-established edge preserving structure oriented filter (e.g. Marfurt, 2006) to enhance piecewise continuous dispersive groundroll, acquisition patch by acquisition patch. We apply this workflow to a legacy low fold merged survey contaminated by high amplitude, broadband, dispersive groundroll. We validate the efficacy of our algorithm by computing geometric attributes sensitive to noise and geologic discontinuities. We conclude with a summary of the value and limitations of this workflow.

**EXPLORATION OBJECTIVES AND DATA DESCRIPTION**

Our study area lies between the Midland Basin (Permian Basin) and Fort Worth Basin, Texas. In this area, there is no Barnett Shale, such that the Mississippi Lime lies directly above the Ellenburger Limestone at a depth of 6000-8000 ft (1825-2450 m). The target in our study area is shallow, at approximately $t = 1.2$ s., the surface infrastructure is in place, and many small operators already hold acreage from shallower or deeper production. Advancements in horizontal drilling, acidation, hydraulic fracturing, and efficient disposal of large volumes of water make these reservoirs economic. In contrast to some shale resource plays, the Mississippi Lime is highly
heterogeneous laterally. The major rock types are tripolitic chert, fractured tight chert, and tight limestone. The tripolitic and fractured chert have good porosity and good production in northern Oklahoma and southern Kansas.

Four seismic surveys were shot in the early 1990’s, three of which had EW receiver lines and one with NS receiver lines (Figure 1a). The merged surveys cover an area of 80 mi² (207 km²). Initially, we followed the conventional land processing workflow for Mississippian play after Dowdell (2013) and Aisenberg (2013) including iterative static and velocity analysis, and prestack time migration. Unfortunately, the resulting images were still contaminated by acquisition footprint (Figure 1b and 1c). The seismic data are very low fold (average fold ~15) (Figure 1a). Examination of the migrated gathers (not shown) reveals strong groundroll aliasing. On the original shot gathers, the groundroll appears as high amplitude, aliased, coherent events that persist up to 50 Hz (Figures 3a and 3b).

The four surveys were acquired using vibrator sweeps of 14-90 Hz and 12-85 Hz. The presence of groundroll up to 50 Hz (Figure 3b) precludes the use of a simple low-cut filter. The aliasing prevents the use of modern $f-k_x-k_y$ filtering.

In this paper we build on the coherent noise modeling concepts developed by Mulder et al. (2002), d’Agosto et al. (2003), Liu (1999), and Done (1999) as well as modern 3D edge preserving structure oriented filtering (Marfurt, 2006) and apply them to the 3D data volume, patch by patch. We recognize that the groundroll (1) is high amplitude, (2) is band limited ($f < 50$ Hz), (3) exhibits
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outgoing low group and phase velocity with few backscattered events, and (4) is piecewise coherent. We are also fortunate that our data were acquired in patches (Figure 2), facilitating the implementation of a 3D dip filter across channel number and shot number dimensions.

METHOD

Figure 4 summarizes our workflow. The seismic data includes geological reflections of all frequency ranges (12-85 Hz). Our first step is to apply a low pass filter (Figure 5a), $f < 50$ Hz (10-15-45-55 Hz) that removes the signal in the higher frequency range ($50 < f < 85$ Hz). The second step is to window the groundroll contaminated zone based on an average group velocity of 1000 m/s (Figure 5b). In this manner, subsequent filters will not impact reflection events outside the groundroll window. In the third step (Figure 5c), we apply a linear move out (LMO) correction using groundroll phase velocity $v = 1500$ m/s (5000 ft/s), thereby approximately flattening the shingled groundroll events and misaligning the higher apparent velocity geological reflections of interest. At this point, we have created a patch of data (Figure 2) that is amenable to 3D edge preserving structure-oriented filtering (Marfurt, 2006).

We compute the residual inline (Figure 6a) and crossline components of linear moveout as well as coherence (Figure 6b) within each and every 3 channel by 3 shot by 0.020 s analysis window. Each sample forms part of 9 spatial by 21 vertical (or 189) windows. The most coherent Kuwahara (1976) window (i.e. the one that best represents moderately dipping coherent groundroll) is used for subsequent analysis (Figure 7). If the window is sufficiently coherent ($c >$
0.3) we apply a Karhunen–Loève (KL) filter to model the strongest event (the moveout-corrected groundroll) at the current sample of interest. If the window is incoherent \((c < 0.2)\), only misaligned signal (or random noise) exists, and no filter is applied. We blend the modeled noise and signal for value of \(0.2 < c < 0.3\).

We apply inverse linear moveout after the KL filter (Figure 6c) to obtain the modeled groundroll (Figure 8a). Finally we subtract the modeled groundroll from the original data. A major advantage of KL filtering is that the scale of the seismic amplitude does not change. A simple subtraction therefore is effective and sufficient (Figure 8b). In this workflow, the most important parameters are the high cut frequency, linear moveout velocity, window size, and the threshold values of coherence. We obtain the high cut frequency by simply applying bandpass filters to the gather to determine at which frequency band the groundroll is sufficiently low in amplitude. Since we know our data are dispersive and will need to search for residual linear moveout we only need an approximate phase velocity of groundroll. The size of vertical analysis window used in the KL filter should be smaller than the dominant groundroll period to avoid vertical mixing of events. If the widow is too large, vertical samples that correspond to different groundroll phase velocities will be smeared, reducing the amount of noise that can be modeled. When using a nine-trace (three shots into three channels) window, we find that the first two eigenvectors (rather than simply the first eigenvector) better estimate the groundroll. Coherence is computed as the ratio of the energy represented by the first two eigenvectors to that of the original data. After linear moveout using the groundroll group velocity, reflection events are in general strongly overcorrected and aliased such that this appears as low coherence zones in the flattened data volume. By co-rendering
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coherece plotted against a polychromatic color bar with seismic amplitude data plotted as a gray scale one can easily choose a cut off value of coherence below which there is no significant groundroll present.

VALIDATION WITH A SYNTHETIC PATCH

We generated prestack synthetic data to validate our groundroll suppression workflow. First we created a model with very shallow layers and velocity increasing with depth, in order to generate dispersive groundroll. We then created a second model with deeper layers to generate reflections. We combined the results of the two models to generate the final synthetic. We then generated a synthetic 3D patch using geometry representative of our real seismic data (Figure 9 a). We implemented the groundroll suppression workflow described in this paper to remove the dispersive groundroll. Figure 9b shows that most of the dispersive groundroll was removed while the reflections were preserved. It is important to notice that the groundroll at near offsets appears to be an incoherent event and could not be removed by this technique.

APPLICATION

Comparing the shot gathers before (Figure 3a) and after groundroll suppression (Figure 8b) shows that we remove the highly aliased groundroll and preserve the reflection events of interest. When sorted to CMP super gathers, the filtered data provides significantly improved velocity spectra.
Calculating coherence attribute after groundroll suppression (Figure 10b), we observe that the footprint is minimized and geological structures are enhanced.

**DISCUSSIONS**

If backscattered groundroll were a problem (Strobbia et. al, 2014), a more computationally intensive search about a 3D moveout cone rather than within the source-receiver sagittal plane would be required.

**CONCLUSIONS**

We have adopted concepts of edge preserving structure oriented filtering commonly used to improve the continuity of reflectors in 3D migrated data volumes to modeling groundroll in LMO corrected acquisition patches. Through shot and channel 3D residual moveout search, within overlapping windows we are able to model piecewise continuous, dispersive noise trains.

We show by application to two data volumes that our workflow provides excellent results when applied to aliased groundroll suppression where \(f-k_x-k_y\) techniques fail. The explicit search for sample-by-sample phase velocities allows the filter to adapt to dispersive groundroll wave trains. The short, overlapping 3D window implementation allows the filter to model piecewise continuous groundroll events that are broken by irregular topography and discontinuities in the weathering zone. The suppression of groundroll makes it possible to obtain more accurate velocity
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analysis and preconditions the data for subsequent 5D interpolation. Coherence slices show that random noise is suppressed while edges are preserved. Our surveys are dominated by radially-traveling groundroll, allowing us to approximate the moveout using a user defined velocity and the source-receiver offset.

FIGURES

Figure 1. (a) Fold Map of the four merged surveys. Before reprocessing (b) vertical section of seismic amplitude (c) time slice at $t = 1.1$ sec at the level of Mississippian chert for coherence. Note the strong EW and NS footprint in both images (indicated by yellow arrow).

Figure 2. A representative receiver patch. These 18 sources into 360 channels forms an 18x360 trace 3D seismic volume (we can also call it 3D patch). If we flatten the noise in this 3D patch using linear moveout, we can use multiwindow structure oriented filters to model it.

Figure 3. (a) A representative shot gather (sorted by shot vs channel) before ground roll suppression. Figure 4 shows the geometry of receiver lines R1-R6 for this shot. (b) Bandpass filtered $40 \text{ Hz} < f < 50 \text{ Hz}$ image shows ground roll having high frequency components masking the target zone (indicated by the green rectangle).

Figure 4. The groundroll suppression workflow presented in this paper.
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Figure 5. (a) Common shot gather sorted by absolute offset $x$ after a high cut filter removing reflections with $f > 50$ Hz, strong ground roll window indicated by top and base mutes parallel to the group velocity of approximately 1000 m/s. (b) Windowed data shown sorted by common shot vs channel number. (c) The same gather after linear moveout using a phase velocity of $v=1524$m/s (5000 ft/s). Note the ground roll events are relatively flat while the underlying signal is steeply dipping.

Figure 6. (a) Local residual linear moveout (dip) in Inline direction, where increasing channel numbers are “in-line” and increasing shot numbers are “cross-line” in reference to the 18x360 trace patch geometry. Crossline dips are computed but not shown. (b) Coherence computed on the windowed, flattened patch, high coherence indicates coherent ground roll. (c) Modeled ground roll using a Karhunen-Loeve filter within those windows exhibiting a coherence, $c > 0.3$.

Figure 7. A simplified cartoon showing a suite of nine overlapping 3 shot by 3 receiver Kuwahara (1976) windows used to filter the ground roll. The red star and triangle indicate the target trace to be filtered such as the blue shot point into a channel on receiver line R5 in Figure 4. First we compute the coherence along local 3D dip for each of the nine windows. The window with the highest coherence value best represents the coherent ground roll. Within this window, we then apply a 9-trace Karhunen Loeve filter along dip to model the desired ground roll for the red source-receiver pair. In actual implementation, we also allow our windows to vary vertically over ±10.
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samples, such that we search $21 \times 9 = 189$ windows, all of which include the target time sample at the target shot-receiver trace.

Figure 8. A shot vs channel gather (a) with modeled ground roll with dominant frequency of 25-40Hz, after reverse linear move on the gather shown in Figure 7c, and (b) after ground roll suppression, subtraction of modeled ground roll (Figure 9a) from the original gather (Figure 3a). (c) Amplitude spectrum of the same shot gather before (in blue) and after (in red) ground roll suppression.

Figure 9. Synthetic prestack gather data generated with 18 sources and 360 channels, the acquisition patch is shown in the upper right corner of the figures. Shot vs channel gather for blue source (a) before ground roll suppression (b) after ground roll suppression (c) removed coherent noise.

Figure 10. After ground roll suppression (a) vertical section of seismic amplitude (b) time slice at $t = 1.1$ sec at the level of Mississippian chert for coherence. Compare this figure with the Figure 1, to see improvements after ground roll suppression.
ACKNOWLEDGEMENTS

We acknowledge Clear Fork Inc. for data support. ProMAX (by Haliburton) and VISTA (by Schlumberger) software were used for seismic data processing. Bo Zhang, Mark Aisenberg and Marcus Cahoj provided valuable insight in seismic processing. Finally, thanks to the industry sponsors of the AASPI Consortium for their financial support.

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Figure 3 (b)

The diagram shows a time-frequency representation with multiple frequency bands. The time axis is labeled as "Time (s)" with values ranging from 0.5 to 2.0 seconds, and the frequency bands are marked as "High frequency" and "Ground Roll." The signal of interest is highlighted with a green box, and two arrows indicate the separation between high frequency and ground roll components.
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Figure 6

Figure 7. (b)
Figure 6

Figure 7. (c)
<table>
<thead>
<tr>
<th>Process</th>
<th>Run Time per 2 processors per patch (= 6480 traces)</th>
<th>Survey parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual dip search</td>
<td>135 sec</td>
<td>No. of Shots per patch</td>
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<tr>
<td>Coherence</td>
<td>120 sec</td>
<td>No. of Samples per trace</td>
</tr>
<tr>
<td>K-L Filter</td>
<td>105 sec</td>
<td>Total no. of receivers for each shot</td>
</tr>
</tbody>
</table>

Table 1: Computation cost for the processes.
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Figure 8

Figure 8. (b)
Figure 8

c) Before ground roll suppression

After ground roll suppression

Figure 8. (c)
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Figure 10. b
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