Highly aliased ground-roll suppression using a 3D multiwindow Karhunen-Loève filter: Application to a legacy Mississippi Lime survey

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ABSTRACT

Although modern recording capacity facilitates dense seismic acquisition, many, if not most, legacy 3D land surveys are spatially aliased with respect to ground roll. Irregular topography and weathering zones give rise to ground roll that has piecewise rather than continuous linear moveout (LMO). Dispersion often results in shingled events whose phase velocity cuts across the ground-roll noise cone. We have developed a workflow for the suppression of highly aliased broadband ground roll in which modern \(f-k\), \(f-kx\), \(f-kx\)-\(ky\) filters failed. Our workflow began with low-pass filtering and windowing the data, 3D patch by 3D patch. We then applied LMO corrections using an average phase velocity of the ground roll and improved these moveout corrections through the use of local three-shot by three-receiver 3D velocity scans about each sample to account for lateral changes in velocity, thickness, and weathering zone topography. Using a Kuwahara algorithm, we chose the most coherent window within which we applied a structure-oriented Karhunen-Loève filter to model the coherent noise. Finally, we removed the LMO correction and subtracted the modeled ground roll from the original data. We applied our workflow to a legacy data volume consisting of four merged 3D surveys acquired in the 1990s. Application of modern seismic attributes showed improved mapping of faults and flexures. We also validated our workflow using a synthetic gather having the same geometry as our field data.

INTRODUCTION

Ground roll is a general term that is used to describe relatively high amplitude seismic waves that travel along the earth's surface that provide little value in imaging deeper reflectors of interest. Although various modes of Rayleigh waves often form the most important components of ground roll measured on vertical component seismometers, ground roll may also include Love waves, reverberating refractions, and other phenomena that are guided by near-surface layering. In the presence of unconsolidated weathering zones, ground roll tends to be slow and at low frequency. In such cases, a low-cut filter (<15 Hz) sufficiently reduces the ground roll to provide high-quality images. Unfortunately, such low-cut filters reject information that is critical to impedance inversion. This problem is exacerbated when indurated Mesozoic and Paleozoic rocks outcrop on the surface. In many surveys in the Fort Worth Basin, strong ground roll persists up to 20 Hz. In surveys acquired over outcropping carbonates, the ground roll is still stronger (Regone, 1997).

If not suppressed, high-amplitude aliased ground roll leaks through the migration stack, thereby contaminating any subsequent attribute and inversion analysis. The software and workflow described in this paper were developed to suppress strong ground roll present in a suite of four surveys acquired over a hard surface in the 1990s. The target was shallow, such that high-amplitude ground roll overprinted the reflectors of interest. Irregularities in the relatively high velocity near surface and limited acquisition equipment resulted in aliased, piecewise coherent and dispersive ground roll ranging to 55 Hz.

Several techniques have been developed for coherent noise suppression during the last 30 years. Ground roll on 2D common-shot and common-receiver gathers acquired over flat topography often appears as low-frequency linear noise. Embree et al. (1963), Treitel et al. (1967), and Kirchheimer (1985) show that \(f-k\) fan filters can...
effectively remove unaliased ground roll on such 2D gathers. However, if the data are insufficiently sampled, ground roll will be aliased in the $k_x$ domain (Foti et al., 2002). The aliased component of ground roll may overlap the signal components of the spectrum and leak through the migration stack, thereby contaminating the resulting image. Radon, $\tau$-$p$, and radial transforms adapt to irregular source-receiver sampling and have also been applied to ground-roll suppression (Brysk and McCowan, 1986; Russell et al., 1990; Henley, 2003). Even with this flexibility over the $f$-$k$ filters of the time, Turner (1990) shows that spatial aliasing still exists in the $\tau$-$p$ domain. The introduction of high-resolution or sparse Radon transforms (Trad et al., 2003) ameliorates this problem, but they perform poorly when the irregular moveout due to irregular

topography and weathering zones is not well-approximated by the linear or parabolic Radon transform parameterization.

Liu (1999) models ground roll on common-shot gathers using a Karhunen-Loève (KL) transform, picking each 2D common-shot gather to flatten the ground roll. He then constructs covariance matrices about the flattened ground roll, computed eigenvectors, and eigenvalues and models the coherent ground roll using the first few eigenvalue-eigenvector pairs. After reversing the moveout correction, he subtracts the modeled ground roll from the original data to obtain a filtered result. Done (1999) improves on Liu’s (1999) workflow by defining different window sizes when forming the covariance matrix. Montagne and Vasconcelos (2006) add an alignment function to find the correct velocity to flatten the ground roll. In general, ground roll is dispersive, which makes flattening a human-labor-intensive process. Figueiredo et al. (2009) partially address this issue by muting the top and base of the ground-roll 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 up-coming P- and S-waves of interest on a VSP, Mulder et al. (2002) use an adaptation of structure-oriented filtering. Their version filters within coherent windows and avoids filtering in incoherent windows in which 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. Ground roll usually exhibits hyperbolic rather than linear moveout (LMO) on the receiver lines laterally offset from the shot location. The analogous problem arises for common receiver gathers. A more common approach is to sort a common-shot gather by unsigned offset, resulting in a densely, but irregularly, sampled gather. Gaiser (1995) addresses this unequal trace spacing by computing an $f$-$k$ domain fan filter using a least-squares approach. Galibert et al. (2002) apply a true $f$-$k_x$-$k_y$ filter to 3D seismic data to filter coherent noise. Unfortunately, neither of these methods work if the coherent noise is aliased. Liu and Marfurt (2004) find similar limitations using a 3D $\tau$-$p$-$q$ Radon transform to suppress coherent noise.

Figure 1. (a) Fold map of the four merged surveys. Before reprocessing (b) vertical section of seismic amplitude and (c) time slice at $t = 1.1$ s at the level of Mississippian chert for coherence. Note the strong east–west and north–south footprint in both images (indicated by the yellow arrow).

Figure 2. A representative receiver patch. These 18 sources into 360 channels form an $18 \times 360$ trace 3D seismic volume (we can also call it a 3D patch). If we flatten the noise in this 3D patch using linear moveout, we can use multiwindow structure-oriented filters to model it.
In contrast to $f$-$k$ filters that operate on the entire gather, short window and coherence-driven filters often work better in the presence of discontinuous changes in moveout due to the variations in topography, thickness, and velocity of the weathering zone. Using commercial software, D’Agosto et al. (2003) sort their 3D data by offset, flatten using an average ground-roll phase velocity, and then estimate the coherence and local residual moveout of the ground roll by crosscorrelating adjacent trace pairs. For those samples in which the coherence exceeded a processor-determined threshold, the ground roll is estimated using the crosscorrelation coefficient and subtracted.

In this paper, we exploit recent software developments made in 3D edge-preserving structure-oriented filtering to generalize the approach used by D’Agosto et al. (2003) and Mulder et al. (2002) to work on patches of 3D data. For our problem, 3D will be acquisition patches comprising a suite of seismic sources measured by a suite of live receiver lines. The structure oriented will be a computation of residual ground-roll moveout about an average LMO correction. The edge preservation will be the preservation of discontinuous ground-roll events due to irregular topography and weathering zones, similar to that used by Mulder et al. (2002). Finally, the filtering will be a 3D $5 \times 5$ trace KL filter similar

![Figure 3](image3.jpg)

**Figure 3.** (a) A representative shot gather (sorted by shot vs channel) before ground-roll suppression. Figure 2 shows the geometry of receiver lines R1–R6 for this shot, the blue dot represents the location of this shot gather. (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). The seismic gather was sorted by shot vs absolute offsets domain and was transformed to (c) Frequency-wavenumber ($f$-$k$).

![Figure 4](image4.jpg)

**Figure 4.** The ground-roll suppression workflow presented in this paper.

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to that of Embree et al. (1963) and Done (1999). This filter will be applied only when the noise is considered to be sufficiently coherent, as determined by the percentage of energy measured by the first eigenvector. We begin our paper with a description of a legacy low-fold merged survey contaminated by high-amplitude, broadband, dispersive ground roll. We then describe our workflow, showing step-by-step results. Finally, we validate the efficacy of our algorithm by computing geometric attributes.

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 the top and base mutes parallel to the group velocity of approximately 1000 m/s. (b) The windowed data shown are sorted by common shot versus channel number. (c) The same gather after linear moveout using a phase velocity of $v = 1524$ m/s (5000 ft/s). Note that the groundroll events are relatively flat, whereas the underlying signal is steeply dipping.
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 targeted Mississippi Lime lies directly above the Ellenburger Limestone at a depth of 1825–2450 m (6000–8000 ft) or at a two-way traveltime of $t = 1.2$ s.

Four seismic surveys were shot in the early 1990s for shallower objectives, in which three had EW receiver lines and one had north–south receiver lines (Figure 1a). The merged surveys cover an area

Figure 6. (a) Local residual linear moveout (dip) in the inline direction, in which increasing channel numbers are “inline” and increasing shot numbers are “crossline” in reference to the $18 \times 360$ 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-Loève filter within those windows exhibiting a coherence $c > 0.3$. 

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of 80 mi² (207 km²). Initially, we followed a successful processing workflow used to image Oklahoma Mississippian plays developed by Dowdell (2013) and Aisenberg (2013), which included iterative static and velocity analysis, followed by prestack time migration. Unfortunately, the resulting images were highly contaminated by the acquisition footprint (Figure 1b and 1c). Limitations in recording capacity (Figure 2) at the time resulted in a low (approximately 15) fold (Figure 1a) with ground roll leaking through the migration stack array that gives rise to artifacts in the coherence images (Figure 1c). On the original shot gathers, the ground roll appears as high-amplitude, aliased, coherent events that persist up to 50 Hz (Figure 3a and 3b).

The four surveys were acquired using vibrator sweeps of 14–90 and 12–85 Hz. The presence of ground roll up to 50 Hz (Figure 3b) precludes the use of a simple low-cut filter. The aliasing prevents the use of modern f-k filtering. However, because the data were acquired in patches (Figure 2), we are able to modify a 3D structure-oriented filtering algorithm to model 3D dipping but coherent noise across the 3D channel number and shot number dimensions.

METHOD

Figure 4 summarizes our workflow. The seismic signal and noise are both broadband (12–85 and 10–50 Hz, respectively). 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 mute the data outside the ground-roll-contaminated zone using an average group velocity of 1000 m/s (Figure 5b), such that subsequent filters will not impact reflection events outside the ground-roll window. In the third step (Figure 5c), we apply an LMO correction using an average ground-roll phase velocity of $v = 1500$ m/s (5000 ft/s), thereby approximately flattening the shingled ground-roll events and misaligning the higher apparent velocity geologic reflections of interest. Note that the coherent ground-roll events in Figure 5c are not flat and will require a subsequent “residual” 3D dip analysis prior to forming a covariance matrix. In contrast, the weaker reflector events have been so overcorrected as to make them highly aliased and (within our dip search limits) incoherent. At this point, we have created a patch of data (Figure 2) that are amenable to 3D edge-preserving, structure-oriented filtering (Marfurt, 2006).

Following our edge-preserving, structure-oriented filtering prototype workflow, we compute the residual inline (Figure 6a) and crossline components of apparent dip and coherence (Figure 6b) within each and every three-channel by three-shot by 0.020 s analysis window. Each sample forms part of 9 spatial by 21 vertical (or 189) overlapping windows. Following Marfurt (2006), the most coherent Kuwahara et al. (1976) window (i.e., the one that best represents moderately dipping coherent ground roll) is used for subsequent analysis (Figure 7). If the window is sufficiently coherent ($c > 0.3$), we apply a KL filter to model the strongest event (the residual dip-corrected ground roll) at the current sample of interest. If the window is incoherent ($c < 0.2$), only a misaligned signal (or random noise) exists, and no filter is applied. We blend the modeled noise and signal for values of $0.2 < c < 0.3$.

We remove the residual dip correction and original LMO after applying the KL filter (Figure 6c) to obtain the modeled ground roll (Figure 8a). Finally, we subtract the modeled ground roll from the original data. A major advantage of KL filtering is that it is amplitude preserving (Marfurt, 2006), such that one simply subtracts the modeled noise from the original data (Figure 8b and 8c). In this workflow, the most important parameters are the high-cut frequency, LMO velocity, window size, residual dip search limits, and the threshold values of coherence. We obtain the high-cut frequency by applying band-pass filters to the gather to determine at which frequency band the ground roll is sufficiently low in amplitude. Because we know our data are dispersive and we will need to search for residual LMO, we only need an approximate phase velocity of ground roll. The size of the vertical analysis window used in the KL filter should be smaller than the dominant ground-roll period to avoid vertical mixing of events. Smaller windows will have a smaller signal-to-noise ratio. The larger windows will smear vertically adjacent events that may have a different waveform and move-out. 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 ground roll. Using all nine eigenvectors perfectly constructs the original data. Coherence (Figure 6b) is computed as the ratio of the energy represented by the first two eigenvectors to that of the original data. After LMO using the ground-roll group velocity, the strongly overcorrected and now aliased reflection events exhibit low coherence (black zones in Figure 6b). The residual dip search limits and coherence threshold are chosen by corendering Figure 5c plotted against a gray scale with Figure 6a and 6b plotted against polychromatic color bars.

VALIDATION WITH A SYNTHETIC PATCH

To validate our ground-roll-suppression workflow, we generated a flat layered elastic model with well-log P- and S-velocities and...
near-surface velocities from wave tests. We then used a commercial finite-different software package to generate a finely sampled elastic wave common-shot gather that can be considered as the impulse response (or Green’s function) for the model. We mimicked our acquisition by extracting the actual source and receiver locations from a patch of 15 shots fired into 360 live receivers (Figure 9a). The seismic trace for each source-receiver pair is the trace with equivalent offset from the synthetic impulse response. In Figure 9a,

Figure 8. A shot versus channel gather (a) with modeled ground roll with dominant frequency of 25–40 Hz, after reverse linear move on the gather shown in Figure 6c, and (b) after ground-roll suppression, subtraction of modeled ground roll (Figure 8a) from the original gather (Figure 3a). (c) Amplitude spectrum of the same shot gather before (in blue) and after (in red) ground-roll suppression. (d) After f-k filter is applied on the same gather.
application of our ground-roll-suppression workflow to the data shows that most of the dispersive ground roll was removed, whereas the reflections were preserved (Figure 9b and 9c). It is important to notice that the ground roll at near offsets appears to be an incoherent event and could not be removed by this technique.

**DISCUSSION**

Comparing the shot gathers before (Figure 3a) and after ground-roll suppression (Figure 8b) shows that we remove the highly aliased ground roll and preserve the reflection events of interest. This filter was significantly more effective than a more conventional $f-k$ filter (Figure 8d) applied to the offset-sorted gather shown in Figure 5a. When sorted to common midpoint super-gathers, the filtered data provide significantly improved velocity spectra. After ground-roll suppression (Figure 10a), we computed the coherence attribute (Figure 10b) on the seismic data and observed that the footprint is minimized and the geologic structures are enhanced.

We evaluated the computation cost (Table 1) of different steps involved in our workflow for highly aliased groundroll suppression on one patch of synthetic data displayed in Figure 9. If backscattered ground roll was a problem (Regone, 1997; 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.

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 versus channel gather for blue source (a) before ground-roll suppression, (b) after ground-roll suppression, and (c) removed coherent noise.
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Figure 10. After ground-roll suppression, (a) the vertical section of seismic amplitude and (b) time slice at \( t = 1.1 \) s at the level of Mississippian chert for coherence. Compare this figure with Figure 1 to see improvements after ground-roll suppression.

<table>
<thead>
<tr>
<th>Process</th>
<th>Run time per processors per patch (= 6480 traces)</th>
<th>Survey parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual dip search</td>
<td>135 s</td>
<td>Number of shots per patch</td>
</tr>
<tr>
<td>Coherence</td>
<td>120 s</td>
<td>Number of samples per trace</td>
</tr>
<tr>
<td>K-L filter</td>
<td>105 s</td>
<td>Total number of receivers for each shot</td>
</tr>
</tbody>
</table>

Table 1. Computation cost for the processes.

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

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REFERENCES


