RTM noise attenuation and image enhancement using time-shift gathers
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Summary
Reverse time migration (RTM) has become a central tool in seismic imaging, especially in complex geologies where other migration methods fail. However, the way RTM is generally formulated introduces various types of artifacts, these include low-frequency noise in high velocity-contrast areas and shear-wave-like noise when anisotropy is included in the formulation. Using time-shift gathers from the extended imaging condition, we develop a method to effectively attenuate these artifacts and further enhance the final image by refocusing the migrated energy. We demonstrate the results of our method on both real and synthetic data sets.

Introduction
The RTM method has been developed more than twenty years ago (Baysal et al., 1983; McMechan, 1983; Whitmore, 1983); however, it hasn’t found its way into the mainstream industry until recently. This is not only due to its considerably higher cost when compared to other migration methods, but also due to the seismic industry’s historic inability to properly deal with the method’s intrinsic artifacts.

Perhaps, the most well-known RTM artifact is the generation of low frequency noise on top interfaces with a high velocity contrast. Obviously, this is the case for velocity models which include salt bodies, where the requirement for RTM is most evident. The reason for this is that in RTM we solve the full two-way wave equation where energy can be reflected upon velocity contrasts. This happens both on the source and receiver sides where the reflected energy correlates along the isochronal path of the main reflection event. This is demonstrated in Figure 1.

Many attempts have been made to attenuate this kind of artifact. Some of these methods are based on wave-field decomposition (Yoon and Marfurt, 2004; Liu et al., 2011), others are applied on the final stacked image (Zhang and Sun, 2008). In 2011, Kaelin, used pre-stack gathers from the time-shift imaging condition (Sava and Fomel, 2006) to suppress these artifacts. In our method, we tackle the problem with a similar approach; however, our formulation relies on the actual physics and dynamics of the problem making it more robust and easier to control.

Anisotropy essentially is an elastic phenomenon. When RTM is formulated to include Tilted Transverse Isotropy (TTI) or Vertical Transverse Isotropy (VTI), it suffers from shear-wave-like noise (Zhang et al., 2009). As our formulation employs the actual physics of the seismic imaging setup, we are able to extend the method to suppress these anisotropy artifacts.

Finally, we exploit the focusing nature of the time-shift imaging condition to further enhance the final stacked image and better refocus the migrated energy.

Theory
In Sava and Fomel (2006), the time-shift imaging condition is stated as
\[ I(x,t) = \int U_s(x,t - \tau) U_r(x,t + \tau) \, dt \] (1)
where \( x \) is the spatial coordinate vector, \( t \) is time, \( \tau \) is the time lag variable, \( U_s \) is the source wavefield and \( U_r \) is the receiver wavefield. The angle domain mapping function can be written as
\[ \frac{|k|^2}{\omega^2} = \frac{4}{c^2(x)} \cos^2(\theta) \] (2)
where \( k \) and \( \omega \) are the vector wave number and the angular frequency in the image domain. \( c(x) \) is the spatially variant medium velocity and \( \theta \) is the reflection angle.

Direct implementation of Equation 2 is not possible because of its non-stationary nature induced by the spatially variant velocity term. In Sava and Fomel (2006) it is applied using slant stacks in \( z - \tau \) slices where additional explicit dip information is required. Vyas et al. (2010) overcomes this limitation by slant stacking in the image wave-number domain, in the direction normal to the reflector.
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In our implementation, a much simpler and more efficient approach is developed. By a simple change of variables \( \tau \rightarrow \xi \) where

\[
\xi = \frac{\tau}{2} c(x)
\]

Equation 2 is transformed into

\[
\frac{|k|^2}{\psi^2} = \cos^2(\theta)
\]

where \( \psi \) is the Fourier transform variable of the new coordinate \( \xi \). Equation 4 can now be easily used to form the angle gathers \( I(x, \theta) \). For our purpose of noise removal and focusing enhancement, these angle gathers need not be formed explicitly.

As seen in Figure 1, the low-frequency artifacts are generated by reflections occurring at 90°, therefore, if we mute the energy in the image \( I(k, \psi) \) at these large angles, we get rid of these artifacts.

As it is impossible for any wave to have a reflection angle which has a cosine that is greater than one, all energy beyond this range is muted as well. In our case, the shear noise resulting from anisotropic acoustic propagation travels at velocities which are significantly different from the migration velocity; therefore, it is often mapped to the region where \( \cos(\theta) > 1 \).

Examining Equation 4 more carefully reveals an interesting property. It has the form of a dispersion relation. If we approximate \( \cos(\theta) \approx 1 \), the underlying wave equation has a solution in the form

\[
I(k, \xi) = I_o(k, \xi)e^{-i|k|}\]

If we apply the inverse phase shift term \( e^{-i|k|} \) to the image, in principle, this would be equivalent to removing propagation effects and thus, moving the solution to \( \xi = 0 \). This creates different realizations of the image at each \( \xi \) value. If all these realizations are now stacked, we obtain a cleaner and better focused version of the final stacked image.

The BP TTI data set

The first example we show is from the synthetic BP TTI data set. We used the exact velocity and anisotropy models in this test. In Figure 2, the final migrated stack before and after our artifact suppression method is shown. The figure shows that the low frequency noise is effectively removed. In this run, energies falling beyond a reflection angle of 60° have been muted.

The right side of this model has the strongest anisotropy. This is where we expect the shear noise to be most visible. Inside the blue circle, the shear-wave noise has also been removed. Figure 3 shows the impulse response generated at the blue circle location before and after we mute energies which have nonphysical angles.

The Sigsbee2a data set

This is an isotropic data set, so no shear wave noise is expected. For this test, we compromised the accuracy of the velocity model by significantly smoothing it and adding a velocity function that increases linearly with depth, thus simulating to some extent the uncertainty we face in real data sets. Figure 4 shows the exact and the perturbed velocity models. Note that the salt body has been kept unchanged.

Figure 5 shows an input time-shift gather and the output after every step in the proposed method. The central trace in these gathers represents the zero lag of the time-shift gathers, that is the conventional RTM output. Figure 5b shows the gather after the change of variables described in Equation 3. Most events now seem to have almost the same apparent velocity which confirms that we removed the non-stationary nature of the original input gather. Figure 5c shows the gather after a 70° mute where the vertical event corresponding to the low-frequency noise has been suppressed. Figure 5d is after applying the inverse phase shift term from Equation 5 and after limiting its range. Note that now all the events became horizontal, which suggests that we could stack them all together to get a cleaner and more focused final stack.

Figure 6 shows the RTM image after low frequency removal with and without applying the inverse phase shift term and stacking. This step considerably enhances the final image by cleaning it and by refocusing the migrated energy.

A real data set from the North Sea

The final example we show is from CGG’s data library. The data set was acquired in the North Sea region. We use a TTI model for imaging. Figure 7 shows an input time-shift gather, after the change of variables, and after applying the inverse phase shift. Similar observations can be made as in the Sigsbee2a data set. The change of variables removes the velocity effect making the image field stationary. The inverse phase shift flattens the gathers which enables us to stack them. Figure 8 shows a zoomed-in section of the final RTM migrated stack after noise removal with and without the extra focusing step. It's
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obvious that the extra focusing step significantly enhances the image and delineates some hidden features.

Conclusions

We have presented a method to effectively attenuate low frequency and shear wave artifacts in RTM. The method uses the underlying physics and dynamics of the problem which makes it easy to implement, control and tune. As an extension to the proposed method we formulated an approach to enhance the final migrated stack which significantly improves the final image. The method was verified on both real and synthetic data sets.

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Figure 2: The final stack for the BP TTI data set. (Top) raw RTM output showing both the low frequency noise and the shear wave noise. (Bottom) after the application of noise suppression. Energies falling beyond 60° as well as energies at nonphysical angle values have been muted.

Figure 3: The impulse response of the BP TTI data set at the location of strongest anisotropy. (Top) raw input (Bottom) after muting energies at nonphysical angle values.

Figure 4: The Sigsbee velocity model: (Left) exact velocity (Right) perturbed velocity. The salt body is kept unchanged.

Figure 5: An input time-shift gather and its output at various steps of the method for the Sigsbee2a data set. (a) input (b) after the change of variables (c) after muting energy falling beyond 60° (d) after applying the inverse phase shift.
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Figure 6: (Top) RTM output after low frequency noise removal (Bottom) after applying the inverse phase shift term and stacking.

Figure 7: An input time-shift gather and its output at various steps of the method for the North Sea data set. (Left) input (Middle) after the change of variables (Right) after applying the inverse phase shift.

Figure 8: RTM output stack for the North Sea data set after artifact suppression. (Top) without enhancement (Bottom) after enhancement by applying the inverse phase shift term and stacking.
EDITED REFERENCES
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REFERENCES


