Trace-imposed stretch correction in Kirchhoff prestack-time migration

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Right Running Head: Kirchhoff PSTM

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ABSTRACT

Kirchhoff prestack time migration (PSTM), which works trace-by-trace, remains appealing to academia and industry due to its robustness and efficiency. However, like the other prestack migration methods, Kirchhoff PSTM also suffers from the angle-dependent stretching effect, which narrows the amplitude spectra of seismic data. This effect gets more severe as the incident angle increases. In this paper, we propose a novel approach, which attaches a prediction shaping filter to the Kirchhoff PSTM, to mitigate the stretching effect. Our approach takes advantage on the trace-by-trace implementation of the PSTM algorithm, without the output of the angle-domain common-imaging gather (ADCIG). Also, our method can cascade with Q-compensation in PSTM. We examine our method with numerical examples and one field data.

Keywords: Prestack Kirchhoff time migration, Migration stretch, Shaping filter

1 INTRODUCTION

Seismic migration maps the subsurface information from the data domain to the image domain. Conventionally, the migration algorithm assumes the imaging point is an ideal scatter, generating an idealized impulse response. However, the seismic data, which is bandlimited, will spread out under the scatter assumption, giving rise to the wavelet stretch. The angle-dependent wavelet stretch is a well-known problem in prestack migration. Similar to the NMO (normal moveout) stretch ([Buchholtz 1972](#); [Dunkin and Levin 1973](#); [Tygel et al. 1994](#); [Perez and Marfurt 2007](#)), this stretch also lowers the imaging resolution and puzzles the amplitude-versus-angle (AVA) analysis ([Biondi and Symes 2004](#)). Given NMO stretch, this distortion is mainly caused by the nonstationary time shifts ([Barnes 1992](#)) or by the non-parallelism of the local traveltimes between seismic events ([Perroud and Tygel 2004](#); [Abedi and Riahi 2016](#)). Given migration stretch, the distortion is a consequence of the varying incident angle ([Tygel et al. 1994](#); [Roy et al. 2005](#)).

Many papers have presented effective methods to alleviate the NMO stretch ([Dunkin and Levin 1973](#); [Rupert and Chun 1975](#); [Barnes 1992](#); [Alkhalifah 1997](#); [Dong 1999](#); [Shatilo and Aminzadeh 2000](#); [Brouwer 2002](#); [Hilterman and Van Schuyver 2003](#); [Lazaratos and Finn 2004](#); [Hassan et al. 2010](#); [Kazemi and Siahkoobi 2012](#); [Zhang et al. 2013](#)). However,

conventional NMO methods cannot image complex subsurface structures well, and thus prestack migration stands out (Yilmaz 2001). Stretch correction in prestack migration only gets few solutions (Roy et al. 2005; Perez and Marfurt 2007; Zhu and McMechan 2013). Most of the existing methods are done post-migration. Roy et al. (2005) formulate that the migration stretch in layered media depends on the cosine of the reflection angle. They make a crucial skip from Lazaratos and Finn (2004) to a more straightforward stationary operator. Perez and Marfurt (2007) correct the stretch in binned ADCIGs of prestack Kirchhoff migration. Zhu and McMechan (2013) develop a stretch-free migration imaging condition containing a shrink-and-shift operation during reverse-time migration.

Despite simple assumption, Kirchhoff PSTM remains appealing because of its robustness and efficiency (Yilmaz 2001). Even with exciting results, the ADCIG based method in Perez and Marfurt (2007) is storage-demanding and depends on the quality of angle gathers. In this paper, rather than on ADCIGs, we propose a method which imposes the stretch-correction filter on the data traces. This way, our method does not need ADCIG. Moreover, our method closely follows one merit of Kirchhoff PSTM: trace-by-trace.

We arrange the paper as follows. First, we briefly review the cause of migration stretch and the conventional correction method. Then, by looking into Kirchhoff PSTM, we propose our method. Afterward, we discuss a stabilized division in shaping filter and a speeding-up trick for the phase-shift kernel. Finally, we exemplify our method on the synthetic data and the real data.

2 METHODS

2.1 Review of migration stretch

Tygel et al. (1994) formulate an analytic equation for the local stretching factor in the prestack depth migration as

$$\frac{\partial z}{\partial t} = \frac{v}{2 \cos \beta \cos \theta}, \quad (1)$$

where v denotes the migration velocity, β denotes the local dip angle, θ denotes the opening angle (or the incident angle). Equation (1) describes the migration stretching as a derivative of the depth z concerning the two-way traveltime t . Although equation (1) is mathematically derived in the content of prestack Kirchhoff migration, Levin (1998) notes that the stretching effect exists commonly in prestack imaging and is independent of migration algorithm. Levin (1998) also shows that the stretching factor concerning reflector dip is due to the conventional plotting of seismic traces along the vertical direction. If we do not honor the convention of plotting but take the direction normal to the reflector dip as a reference, as suggested by Levin (1998), we can rewrite equation (1) as

$$\frac{\partial r}{\partial t} = \frac{v}{2 \cos \theta}, \quad (2)$$

where r denotes the new direction normal to the reflector dip. However, as suggested by equation (2), we need some prior information about local dips or estimate the local dips then correct the dip stretching factor after post-migration. In this paper, we focus on the stretch correction caused by the cosine of the incident angle θ without concerning about the graphical displaying. The term v in equation (2) accounts for the time-to-depth conversion between r and t . Similar to the suggested formulas on layered velocity without dip factor in Roy et al. (2005), only the $\cos \theta$ term enters the research scope of this paper, because the assumption of layered or weak layered velocity remains valid in PSTM.

2.2 Conventional correction method for migration stretch

According to Tygel et al. (1994) and Roy et al. (2005), the amount of migration stretch is stationary in the binned ADCIG. For simplicity, we formulate the seismic traces as the convolution between the reflection coefficient model with the source wavelet. The source wavelet can be estimated for the observed data (Gunning and Glinsky 2005). In the frequency domain, we have the angle-dependent imaged data $m(f, \theta)$ as

$$m(f, \theta) = R(f, \theta)W(f), \quad (3)$$

where $R(f, \theta)$ and $W(f)$ are the angle-dependent reflection coefficient model and the zero-phased source wavelet, respectively. In the time domain, the stretched wavelet during migration is given by

$$W_\theta(t) = W(t \cos \theta), \quad (4)$$

or in the frequency domain as

$$W_\theta(f) = \frac{1}{\cos \theta} W\left(\frac{f}{\cos \theta}\right), \quad (5)$$

where W_θ is the stretched wavelet concerning the incident angle θ . Similar formulations can be found in [Dunkin and Levin \(1973\)](#), [Barnes \(1992\)](#), [Lazaratos and Finn \(2004\)](#). Also, [equation \(5\)](#) accounts for the presence of low-wavenumber components in seismic migration, which is preferable in seismic inversion ([Virieux and Operto 2009](#)) but unwelcomed in seismic imaging ([Zhang and Sun 2009](#)). [Fig. 1](#) is a schematic diagram of a simple reflection experiment defining the incident angle θ . [Fig. 2](#) is an illustration of the wavelet stretch, from which we notice that the migration stretch broadens the wavelet in the time domain, as suggested by [equations \(4\) and \(5\)](#).

Conventionally, we correct the stretching effects in the binned ADCIG ([Roy et al. 2005](#); [Perez and Marfurt 2007](#)) as

$$m(f, \theta) = m(f, \theta) \frac{W(f)}{W_\theta(f)}, \quad (6)$$

where $m(f, \theta)$ are the corrected traces in the binned ADCIG, $W(f)/W_\theta(f)$ is an angle-dependent stationary spectral filter applied over all the ADCIG traces. Note that we can ignore the angle-dependent AVA behaviors of $m(f, \theta)$ in [equation \(6\)](#). The stacked uncorrected seismic imaging traces are $m(f) = \sum_\theta m(f, \theta)$ while the corrected traces are $m(f) = \sum_\theta m(f, \theta)$. To obtain $m(f, \theta)$, one needs to output and store the binned ADCIG

traces according to the incident angle between the source-to-image and receiver-to-image rays.

Equation (6) provides an effective way to correct the migration stretch. However, this method works on binned ADCIG, which is storage-consuming and subject to the quality of angle gathers. Given an incomplete receiver coverage, the quality of ADCIG is usually not so good. Even with a complete receiver coverage, we still need to interpolate the unevenly-sampled ADCIG to make it evenly-sampled under the least-squares solution (Sava and Fomel 2003).

2.3 Stretch correction during PSTM

We build the migration image using the Kirchhoff approach. Looping over seismic traces and stacking them yields the migrated result. The PSTM is computed as

$$m(t_i, \theta) = \sum_{s,g} a(s, g, t_i) \frac{\partial}{\partial t} d_{s,g}(t_{gi} + t_{si}, \theta), \quad (7)$$

where m is the migrated image, t_i the imaging time and θ the opening angle; $d_{s,g}$ is the seismic trace of receiver g and source s , t_{gi} is the one-way traveltime from the receiver g to imaging point i , t_{si} the one-way traveltime from the source s to imaging point i ; $a(s, g, t_i)$ is a composite amplitude correction term considering of the effects of obliquity factor, data and migration aliasing, visco-attenuation and so on. We define the traveltime vector along the lateral and vertical directions as

$$\mathbf{t}_{gi} = \left(\frac{l_{gi}}{v}, \frac{t_i}{2} \right), \quad \mathbf{t}_{si} = \left(\frac{l_{si}}{v}, \frac{t_i}{2} \right), \quad (8)$$

where l_{gi} and l_{si} are the lateral distances of the receiver-image and source-image points, respectively; $t_{gi} = \|\mathbf{t}_{gi}\|_2$, $t_{si} = \|\mathbf{t}_{si}\|_2$. For the angle binning, we calculate the opening angle between two rays by the following arccosine operation:

$$\theta = \arccos\left(\frac{\mathbf{t}_{gi} \cdot \mathbf{t}_{si}}{t_{gi} t_{si}}\right). \quad (9)$$

Conventionally, we output ADCIGs by equations (7) (8) and (9), and then correct the migration stretch by equation (6).

As a compromise in practice, the Kirchhoff PSTM can be implemented in the manner of phase-shift migration (Gazdag 1978; Yilmaz 2001):

$$m(t_i, \theta) = \sum_{s,g} a(s, g, t_i) \int j\omega D_{s,g}(\omega) \exp[j\omega(t_{gi} + t_{si})] d\omega, \quad (10)$$

Equation (10) is the frequency-domain form of equation (7), in which $D_{s,g}(\omega)$ denotes the frequency-domain seismic trace of receiver g and source s . By looking into equations (8) and (9), we find that the determination of θ by rays can go ahead of the migrating of seismic traces. That means, it is possible to design a prediction filter against the stretch effect before imaging. We thus add an angle-dependent prediction shaping filter $F_{s,g}(f, \theta)$ into equation (10)

$$m(t_i, \theta) = \sum_{s,g} a(s, g, t_i) \int j\omega D_{s,g}(\omega) F_{s,g}(f, \theta) \exp[j\omega(t_{gi} + t_{si})] d\omega, \quad (11)$$

in which j denotes the imaginary part, ω the angular frequency, f the frequency, and $\omega = 2\pi f$. Unlike the shaping filter in equation (6), $F_{s,g}(f, \theta)$ here reads

$$F_{s,g}(f, \theta) = \frac{W_\theta(f)}{W(f)}, \quad (12)$$

with $W_\theta(f) = \cos \theta W(f \cos \theta)$. The two filters in equations (5) and (12) are ordered upside-down due to their different targets: the first one performs on the ADCIG while the second one on the data traces. The seismic events in ADCIG have been stretched, while the

seismic events in data traces will be stretched. To avoid the stretching effect, we squeeze the seismic events by [equation \(12\)](#) in advance.

Note that $F_{s,g}(f, \theta)$ only performs on the amplitude spectra of the data, unlike Q-compensation on both the amplitude and phase spectra ([Bickel and Natarajan 1985](#); [Hargreaves and Calvert 1991](#); [Wang 2002](#); [Zhang and Wu 2013](#)). It is worth mentioning that our method can work together with Q-PSTM if we cascade the anti-stretch filter with the Q-compensation filter in PSTM. Our method is expected to improve the imaging resolution of Q-PSTM furthermore. This way, our method works trace-by-trace, honoring the convention of Kirchhoff PSTM, without the requirement to output ADCIG.

2.4 A practical stabilization

From a practical point of view, the shaping filter in [equation \(12\)](#) has to be stable and efficient because the filter works on every trace. Conventionally, a stabilized version of [equation \(12\)](#) reads

$$F_{s,g}(f, \theta) = \frac{W_{\theta}(f)}{W(f) + \varepsilon}, \quad (13)$$

where ε is a constant stabilizer. However, we cannot quantitatively control the upper limit of [equation \(13\)](#). To have better control of the stabilization, we insert the stabilizer as following

$$F_{s,g}(f, \theta) = \frac{1}{\frac{W(f)}{W_{\theta}(f)} + \varepsilon}. \quad (14)$$

Thus, the upper limit of $F_{s,g}(f, \theta)$ is $1/\varepsilon$. Sometimes we hope the stabilizer $\varepsilon(f)$ to vary against frequency, so [equation \(14\)](#) becomes

$$F_{s,g}(f, \theta) = \frac{1}{\frac{W(f)}{W_{\theta}(f)} + \varepsilon(f)}. \quad (15)$$

In [equation \(15\)](#), for example, if we have the most trust on $W(f)/W_\theta(f)$ at $f = f_1$, but the trust decreases as f approaches to f_2 gradually, with $f_1 < f_2$, we can define the stabilizer as $\varepsilon(f) = \alpha(f - f_1) + \varepsilon_1$, with $\alpha = (\varepsilon_2 - \varepsilon_1)/(f_2 - f_1)$. Consequently, $\varepsilon(f)$ varies within $[\varepsilon_1, \varepsilon_2]$ linearly regarding $[f_1, f_2]$. The selection of epsilon-1 and epsilon-2 depends on the SNR levels of the frequencies. For example, if the lower frequencies are less noisy than the upper ones, we may take a higher value for ε_1 , e.g., 500, and a smaller value for ε_2 , e.g., 100.

2.5 Speed up the phase-shift kernel

The phase-shift kernel in [equation \(11\)](#) is a bit computationally costly because it involves the calculation of $\exp[j\omega(t_{gi} + t_{si})] = \cos[\omega(t_{gi} + t_{si})] + j\sin[\omega(t_{gi} + t_{si})]$ over the band-limited frequencies of the seismic data. We notice that, generally, the addition/subtraction or multiplication operation only takes around one FLOP (floating point of operation) while the cosine/sine function takes 15 FLOPs. Calculating the trigonometrical functions for each frequency is unnecessary. Instead, for example, given the reference values of $\sin \varphi_1$, $\cos \varphi_1$, $\sin 2\pi t$, $\cos 2\pi t$ with $\varphi_1 = \omega t$ at imaging point t , one can recursively calculate the remaining cosine/sine values as following

$$\begin{aligned}
 \sin \varphi_2 &= \sin \varphi_1 \cos 2\pi t + \cos \varphi_1 \sin 2\pi t, \\
 \cos \varphi_2 &= \cos \varphi_1 \cos 2\pi t - \sin \varphi_1 \sin 2\pi t, \\
 \sin \varphi_3 &= \sin \varphi_2 \cos 2\pi t + \cos \varphi_2 \sin 2\pi t, \\
 \cos \varphi_3 &= \cos \varphi_2 \cos 2\pi t - \sin \varphi_2 \sin 2\pi t, \\
 &\dots \\
 \sin \varphi_{n+1} &= \sin \varphi_n \cos 2\pi t + \cos \varphi_n \sin 2\pi t, \\
 \cos \varphi_{n+1} &= \cos \varphi_n \cos 2\pi t - \sin \varphi_n \sin 2\pi t.
 \end{aligned} \tag{16}$$

in which only some basic addition/subtraction and multiplication operations get involved. Our numerical experiences suggest this trick could speed up the phase-shift kernel by four times.

3. NUMERICAL EXAMPLES

In this part, we exemplify our method on one synthetic example and one real dataset.

3.1 Synthetic data

The first example is a simple layered model containing several reflectors in the background velocity 1500 m/s. The observed data shown in Fig. 3a is generated from the layered model using ray-tracing. Its offset extends up to 8 km, and its recording time is 9 s. The source is a Ricker wavelet with dominant frequency at 25 Hz. We do not aim to apply our method to all the data but only to those with incident angles less than 60 degrees. The migrated images in the offset and angle domains are shown in Figs. 3b and 3c, respectively. The observed data have two-way timing while the image has one-way timing. We observe that the stretching effects increase against the offset and the angle in Figs. 3b and 3c.

Conventionally, we implement the stretch corrector in equation (5) on the ADCIG in Fig. 3c, resulting in the corrected ADCIG in Figs. 4a and 4b. The difference between Figs. 4a and 4b are caused by the operation of evenly sampling (Sava and Fomel 2003). Fig. 4a is a straightforward result from Fig. 3c. while we preprocess the ADCIG in Fig. 3c before stretch correction to obtain Fig. 4b. This comparison suggests that it is necessary to evenly interpolate the ADCIGs (Sava and Fomel 2003) before the conventional stretch correction. Otherwise, we may get Fig. 4a because the uneven sampling of ADCIG is more likely to occur in the shallow and far-offset part. For comparison, we perform our method on the data in Fig. 3a. We calculate the incident angle and predict the shaping filter for stretch correction during ray-tracing. The output of the stretch-free image in Fig. 4d is straightforward. No binned ADCIG or the following interpolation is required. The stretch-free ADCIG in Fig. 4c is optional but just for demonstration. If we compare Figs. 4b and 4c carefully, we will find some small differences at the large incident-angle part. Our shaping filter, which directly acts on the data rather than on ADCIG, contributes to the superiority of Fig. 4b over Fig. 4c, because the seismic traces are usually well-sampled.

Let us consider an extreme case: randomly decimated data, which could occur in the regional geophysical surveys with missing traces. The decimated data is shown in Fig. 5a and the originally migrated offset-domain and angle-domain CIGs in Figs. 5b and 5c. We cannot handle the ADCIG in Fig. 5c by conventional method because it is bad-sampled. However, if implementing our method instead, we can get the stretch-free images in Fig. 6. This

example demonstrates that our method is not limited by the spatially sampling along the offset axis, because it works on seismic traces separately.

To test the stability of our method, we apply it to the noisy data shown in Fig. 7a with Gaussian noise at SNR (Signal-to-Noise-Ratio) 5. The original and corrected offset-domain CIG images are displayed in Figs. 7b and 7c, respectively. We notice that our method can correct the stretch effect even for the noisy data. Note that no ADCIG is required in our method such that we just show the offset-domain images. Also, our method can cascade with Q-compensation. Fig. 8a shows the original migration image with Q-attenuation of $Q = 100$ (the Q value in Sandstone IV), and Fig. 8b is its stretch-free version. The Q-compensation in Fig. 8a yields Fig. 3b. The Q-compensation and stretch correction on Fig. 8a produces Fig. 4d.

3.2 Field data

In this study, we furthermore test our method on real data from East China. This survey zone has been characterized as horizontal strata with sandstone reservoirs. The data available to us has been processed clean. A general source wavelet for the data has been provided. Conventionally, one firstly migrates the data by PSTM and then corrects for the migration stretch on the binned ADCIG. In our method, we can get the non-stretched image directly. No storage of ADCIG is required. We also incorporate our method into an existing Q-PSTM module (Wang 2002; Zhang and Wu 2013).

Figs. 9a, 9b, 9c, 9d display the results of PSTM, PSTM with stretch correction, Q-PSTM, Q-PSTM with stretch correction, respectively. We choose the shallow part of the seismic image for the demonstration because this part is rich in stretching effects. By comparing Figs. 9a and 9b, we observe that the imaging resolution is improved by our method, with more details revealed. By comparing Figs. 9c and 9d, we observe that even for Q-PSTM, the imaging resolution could be further improved. No additional noise arises. We also extract common-offset gathers at CDP=3315, as shown in Fig. 10, for detailed comparisons. Some unflattened events arise from the imperfection of the migration velocity, which stands outside of this study. From Fig. 10, we observe that our method shrinks the seismic events at far offsets. In Fig. 11, we compare the spectra of the traces from CDP=3315 in Fig. 9. We notice that no matter for PSTM or Q-PSTM, our stretch correction method can furthermore extend the spectra of their images.

4 CONCLUSION

We have presented a method which corrects the stretching effect in Kirchhoff PSTM without ADCIG and its limitations. This method, which honors the trace-by-trace convention of Kirchhoff migration, performs on the data as a prediction shaping filter. To ensure the stability and efficiency of our method, we introduce a stabilized division in the shaping filtering and a speeding-up trick for the phase-shift kernel. We validate our method with synthetic data and real data. The stretch-free migrated images show that our method is easy and robust to implement for imaging or further geophysical applications.

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CONFLICT-OF-INTEREST STATEMENT

No conflict-of-interest exists in the submission of this manuscript.

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Figure 1 Schematic diagram of the acquisition system in a geophysical survey. S denotes the source and R the receiver. The incident angle is indicated by θ . The stretching factor in seismic migration is related to the cosine of θ .

Figure 2 A simple illustration about migration stretch. Given an incident angle of 60 degrees, the migration wavelet (dashed line) stretches twice as wide as the original wavelet (solid line).

Figure 3 (a) Synthetic seismic traces modeled by ray tracing, and migration results in the (b) offset-domain and (c) angle-domain CIGs. We can observe the wavelet-stretch effects in both (b) and (c). This stretching effect gets severer as the incident angle increases.

Figure 4 (a) Corrected ADCIG from Fig. 3c by equation (6) without evenly sampling. (b) Corrected ADCIG from Fig. 3c by equation (6) but after the evenly sampling. (c) Stretch-free angle-domain CIG by our method. (d) Stretch-free offset-domain CIG by our method. The artificial noise in (a) is a consequence of unevenly sampling, which is more likely to appear in the shallow and far-offset part. Note that (c) is as good as (b) when the incident angle is less than 50 degrees, and even better than (c) when the incident angle is higher than 50 degrees, as indicated by the arrows. From the arrow in (b), we can find some small artificial noises. The ADCIG in (c) is not necessary for our method but we here output it for demonstration.

Figure 5 (a) Randomly decimated data and its images in (b) offset-domain and (c) angle-domain CIGs. We cannot correct the migration stretch on (c) because it is poorly sampled.

Figure 6 Stretch-free images of the decimated data in Fig. 5a in (a) offset-domain and (b) angle-domain CIGs. Because our shaping filter directly acts on the data, it is not subject to the unevenly spatial sampling at all.

Figure 7 (a) Noisy seismic traces contaminated by Gaussian noises at SNR=5. (b) Conventional migration result. (c) Stretch-free migration result by our method. No ADCIG displays here because it is unnecessary in our method. From (c) we can see that our method can work well even with noisy data.

(b)

Figure 8 (a) Conventional and (b) stretch-free images with Q attenuation. The ADCIGs do not show up because they are unnecessary. When compensating the known Q-model to (a) and (b), we can get [Fig. 3b](#) and [Fig. 4d](#).

Figure 9 The stacked images by (a) PSTM, (b) stretch-free PSTM, (c) Q-PSTM, (d) stretch-free Q-PSTM, respectively. We select the shallow part for the show because this part is rich in imaging information with large incident angles. We notice that no matter for PSTM or Q-PSTM, our method can furthermore enhance the imaging resolution.

Figure 10 Four offset-domain CIGs (a), (b), (c), (d) from CDP = 3315 in [Figs. 9a, 9b, 9c, 9d](#), respectively. Our method exhibits the ability to correct the stretch effects at large offsets. The stretch correction is embedded in PSTM without ADCIG, so we do not output ADCIGs during the testing of our method on the real data.

Figure 11 The comparisons about the spectra of the migrated data in [Fig. 9](#). We observe that no matter for PSTM or Q-PSTM, our method can broaden their spectrum bands furthermore.