Reverse time migration with frequency-dependent $Q$ compensation accelerated with GPU computing

Introduction

It is well known that the earth strata are far from perfectly elastic but demonstrate the properties of viscoelasticity, in which seismic waves suffer wavelet shape distortion and energy loss during propagation. Seismic attenuation is commonly characterized by the quality factor $Q$. The linear model of wave attenuation with frequency independent $Q$ is widely used in exploration seismology (Kjartansson, 1979). Based on this theory, different frequency components of seismic waves propagate in anelastic materials with a frequency-dependent phase velocity, while in elastic media all frequency components travel with the same phase velocity. In anelastic media the energy loss is approximately proportional to the frequency. In general, higher frequency components in seismic waves tend to travel faster than low frequency components, and their amplitudes decay more quickly. Seismic imaging without proper accounting of dispersion and amplitude loss produces images with distorted phases, dimmed amplitudes and reduced resolutions, especially for deeper horizons under low quality factor (low $Q$) strata, making it more difficult to do AVO interpretation analysis and to tie seismic horizons to well data.

In early efforts anelastic effects are removed from seismic traces prior to migration. Based on one-dimensional wave modeling, these attempts include phase-only inverse $Q$-filtering (e. g. Bickel and Natarajan, 1985; Bano, 1996) as well as full inverse $Q$-filtering that performs amplitude compensation and phase correction simultaneously prior to migration (Wang 2006). Since these methods are based on 1D earth model and they do not follow the actual wave path and do not account for the fact that velocity dispersion and energy loss occur along with wave propagation, they are not suitable for correcting the dissipation effects in data from complex geology areas. An ideal way is to apply $Q$-compensation in prestack depth migration methods based on wavefield simulations (Dai and West, 1994; Zhang et al., 2010; Zhu et al., 2014). Because of the frequency dependency of both velocity dispersion and energy attenuation in anelastic media, it is natural and straightforward to implement such migration in the frequency domain. Earlier work in this area includes an inverse $Q$ migration by Dai and West (1994) and a PSDM by wavefield extrapolation (Zhang and Wapenaar, 2002). However, some of these proposals did not thoroughly resolve the numerical instability problems caused by amplification operations in the wavefield extrapolation that is implemented to compensate the energy loss.

In this paper, we describe our implementation of $Q$-compensated RTM in the frequency domain. We simulate dispersion-only wavefields as well as viscoacoustic wavefields and extract frequency-dependent energy loss ratio from them in frequency domain. The proposed $Q$-RTM approach brings computational challenges since a lot of additional computations are required to accomplish the compensation. To be practically applicable, it has to be accelerated with GPU computing on the CPU-GPU heterogeneous systems (Cheng, 2014). This study presents our GPU implementation on the modern NVIDIA Tesla V100. The simulation results are very promising: a roughly 40 to 70-times speedup can be achieved, compared to the CPU implementation, and reduction of local disk storage from up to 1000Gb to a few GB via GPU compression.

Reverse time migration with frequency-dependent $Q$ amplitude compensation

In $Q$-compensated RTM, we propose another approach to avoid numerical amplification and instability. Instead of directly compensating energy decay in finite difference wave field extrapolation which will introduce numerical instability, we simulate two wavefield propagation, one with energy attenuation accounted and one without energy attenuation. These two wave field propagation simulations are both stable and suffer no numerical instability issue. By computing their amplitude spectrum ratios in frequency domain at each image point we obtained the amplitude compensation factors that are then used in the frequency domain imaging process of RTM to compensate energy loss for each individual frequency considered.
The wavefield propagation in viscoacoustic media can be described using following equation (Kjartansson 1979, Zhou and Harris 2014)

$$\frac{1}{c_0^2(x)} \frac{\partial^2 \sigma(x,t)}{\partial t^2} \eta(x) (-\nabla^2)^{-1/2} \sigma(x,t) + \tau(x) \frac{\partial}{\partial t} (-\nabla^2)^{-1/2} \sigma(x,t)$$

(1)

where, \( \eta(x) = -c_0^2(x) \omega_0^2 \gamma(x) \cos(\pi\gamma(x)) \), \( \tau(x) = -c_0^2(x) \omega_0^2 \gamma(x) \sin(\pi\gamma(x)) \), and \( \gamma = \pi^{-1} \tan^{-1}(1/Q) \). The introduction of spatial varying \( Q \) factor and therefore \( \gamma \) as well as \( \eta \) and \( \tau \) in above equation produces dispersion and energy attenuation along wave propagation. In this representation dispersion and attenuation are decoupled. The first term on the right hand side of Equation (1) is the dispersion term and the second term is the energy attenuation term. If we drop the second term Equation (1) becomes

$$\frac{1}{c_0^2(x)} \frac{\partial^2 \sigma(x,t)}{\partial t^2} = \eta(x) (-\nabla^2)^{-1/2} \sigma(x,t)$$

(2)

which simulates only dispersion effects without accounting for attenuation effects.

In our \( Q \)-RTM implementation, both forward and backward wavefields are simulated with (i.e., equation 1) and without (i.e. equation 2) energy attenuation. At each spatial image point, forward and backward wavefields with and without attenuation are obtained and their entire time history are stored in local disk. They are transformed into frequency domain to compute amplitude compensation ratios for both source and receiver sides. Migration image are obtained in the frequency domain by multiplying the forward wavefield with backward wavefield at this frequency, along with amplitude compensation factors for both forward and backward propagation. A summation over all frequencies yields a RTM image with dispersion accounted and attenuation compensated.

**Acceleration with GPU computing**

The proposed method needs to access four extrapolated wavefields within the entire time-marching history, which makes the method not only computational expensive, but also a huge volume of data storage capacity required. It is the common industrial practice to use a lossy compression method to avoid the later obstacle, and GPU computing can accelerate the performance greatly, a roughly 40 to 70-times speedup compared with CPU implementation, to make the method feasible and practical.

The overall workflow of the proposed method consists of four wave propagation phases plus the imaging phase. A typical profile of computation effort among them is 32.44% time spent in wave propagation in the dispersion-only wavefield, 61.95% in the viscoacoustic wavefield, and 5.61% in imaging phase. In a typical backward, 7.97% in the finite difference operator, 34.27% in the dispersion correction operator, 49.21% in the energy attenuation compensation operator. Clearly the performance of \( Q \)-RTM is dominated by the compensation computation. During wave propagation, we can span a parallel thread to do the data compression and file save to disk tasks to get nearly free computation, only 0.02% spent in threads waiting.

How to optimize 3D stencil kernel on GPU has been extensively studied, and the best way on V100 is the one-pass approach (Micikevicius, 2011). The average performance of our finite difference operator on V100 is about 34 GCell/ms or higher. The dispersion correction and the energy attenuation operators are implemented in the wavenumber domain, and the major computational burden is the huge amount of 3D FFT R2C and 3D FFT C2R transforms, which can be easily carried out with cuFFT library.

The imaging operator is implemented in the frequency domain. Since it is impossible to load all four wavefields into global memory, we divide each wavefield into blocks during the phase of data compression, and each block is a 4D data consisting all time-matching history for that given portion. The imaging is computed in a block-wise fashion: decompress the block, transpose the 4D data into
the time-fast arrangement with cuBlas, conduct many 1D FFT R2C transform with cuFFT, calculate the spectra ratios of the dispersion-only and viscoacoustic wavefields, and finally compute the image in the frequency domain.

**Numerical and Field Data Examples**

We created a 3D shot-gather of synthetic seismic data using a finite difference method based on a three-layer model with faults. The model is a viscoacoustic media with a constant $Q = 30$. In Figure 1, we show the images of 3D RTM results of the one-shot data. Figure 2 shows the zoom-in image of the central portion of the first horizon in Figure 1. Figure 1a and 2a are the same output of a standard RTM. The wavelets in these images are asymmetrical although the source wavelet used in the finite difference modeling is symmetrical. Figure 1b and 2b show the result of dispersion-only $Q$-compensated RTM. The wavelets in these images are now symmetrical and also positioned at the right depth, but their amplitudes are still dimmed. Figure 1c and 2c are images from the full $Q$-compensated RTM with dispersion accounted and energy loss compensated. The wavelets of this image are not only symmetrical, at the correct depth but also with much shorter time-duration hence uplifted resolution.

A real data example is shown in Figure 3. Figure 3a is the RTM image, while Figure 3b is the 3D full $Q$-compensated RTM image. Figure 3b shows more detailed interpretable seismic characteristics with slightly modified horizon depths and phases compared to the image in Figure 3a. The amplitude spectra of the images in Figure 3a and Figure 3b are shown in Figure 4 which clearly demonstrates the broader bandwidth of the image from the $Q$-compensated RTM.

![Figure 1](image1.png)  
*Figure 1. RTM image of 1 viscoacoustic shot gather, (a) by conventional RTM; (b) by the $Q$-compensated RTM with only the dispersion correction; (c) by the full $Q$-compensated RTM with dispersion accounted and attenuation compensated.*

![Figure 2](image2.png)  
*Figure 2. The zoom-in images of the central portion of the first horizon in Figure 1, (a) by conventional RTM; (b) by the $Q$-compensated RTM with only the dispersion correction; (c) by the full $Q$-compensated RTM with dispersion accounted and attenuation compensated.*

**Conclusions**

We presented a $Q$-compensation method implemented in the frequency domain for reverse time migration (RTM). The method corrects the phase distortion caused by the velocity dispersion in anelastic media by extrapolating wavefield with frequency-dependent velocity model. The energy lose due to anelasticity are compensated in the frequency domain in the imaging stage. Synthetic and real data examples demonstrate that the $Q$-compensation RTM not only produces images with horizons positioned at the right depths and with wavelets of corrected phases but also broadens the spectra of the images and uplifts the seismic resolution. The GPU acceleration makes the proposed approach applicable in real productions, with a very promising 40 to 70-times speedup, compared to the CPU implementation.
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