Viscoacoustic compensation in RTM using the pseudo-analytical extrapolator

Jaime Ramos-Martínez, Alejandro A. Valenciano, Sean Crawley and Mikhail Orlovich, PGS*

Summary

We present a reverse-time migration algorithm whose extrapolator is based on an extension of the Pseudo-Analytical (PA) method, to compensate for amplitude loss and dispersion due to propagation in viscoacoustic media. The PA method has the advantage of allowing coarse computational grids and large time stepping without loss of accuracy even after long propagations in time and space. In the extrapolator described here, we account for spatial variations in attenuation by using a series expansion approximation of the viscoacoustic equations for the homogeneous case. We demonstrate the accuracy of the approach using synthetic examples, and apply it to a dual-sensor dataset from the North Sea using the inverse scattering imaging condition. We show how the resolution of the images is clearly improved after compensating for attenuation

Introduction

It is well-known that neglecting the viscoacoustic effects during migration may lead to amplitude-loss and phase-distortion of the reflected events which can deteriorate the resolution of the images. Thus, in order to build more accurate images, it is important to account for these effects during the extrapolation. Migration algorithms based on extrapolators applied in the frequency domain, such as those that solve the one-way wave-equation seem to be more suitable to account for such effects (*e.g.*, Valenciano *et al*., 2011). In this case, attenuation is simulated by turning the phase velocity into a complex quantity. During the implementation in this domain, phase-distortion and amplitude-loss effects can be separated more naturally as is desirable in any inversion/migration application.

Reverse-time migration algorithms require solving the two-way wave-equation in time domain. This implies a more elaborate implementation if the effects mentioned above need to be split during the extrapolation. In addition, it is challenging to find a good compromise between efficiency in the computations and accuracy of the constant-*Q* behavior within the seismic frequency bandwidth. For example, approaches based on the exact constant-*Q* model proposed by Kjartansson (1979) depend upon the calculation of fractional time derivatives that arise in the derivation of the wave-equation. Computing the fractional time derivative of a variable requires storing the history of time of such variable, implying the need for large memory resources. This is overcome by translating this time derivative into the Laplacian which can be easily computed in the Fourier domain (*e.g.*, Chen and Holm, 2004; Carcione, 2010). Based on the theoretical framework, Zhu and Harris (2014) derived a wave equation splitting phase-distortion and amplitude-loss in two operators. This equation was solved by Zhu *et al*. (2014) for the implementation of an RTM algorithm with *Q*-compensation using the pseudo-spectral method.

In this work, we describe an RTM algorithm that compensates for the viscoacoustic effects during propagation by the pseudo-analytical extrapolator (Etgen and Brandsberg-Dahl, 2009). To compute the fractional Laplacians arising in the wave equation, we use the concept of normalized pseudo-Laplacian within the context of the pseudo-analytical method introduced by Chiu and Stoffa (2011) We also introduce an approximation of the dispersive term of the equation proposed by Zhu *et al*. (2014) that accurately simulates the viscoacoustic propagation in heterogeneous media. Thus, we end up with an efficient algorithm that allows for the use of coarse spatial grids and large time steps without compromising the accuracy of the wavefield propagation. We show synthetic examples that validate our approach. We also successfully apply this new scheme to field data from the North Sea, using the inverse scattering imaging condition. Resolution of the images is boosted after compensating for attenuation.

Pseudo-analytical method for viscoacoustic media

We depart from the two-way wave-equation derived by Zhu and Harris (2014) assuming the constant-*Q* dispersion relation introduced by Kjartansson (1979). In the resulting wave-equation, operators driving the phase distortion and the amplitude-loss are split, so these effects can be isolated during the extrapolation. This makes implementation of the RTM algorithm very easy. Zhu and Harris (2014) phase-dispersion term, contains a fractional derivative which depends upon the spatially varying quality factor *Q*. Computation of this derivative in the wavenumber domain may lead to some inaccuracies since only a representative value (*e.g*., the average) of attenuation is used in the application of this operator in the Fourier domain. We overcome this problem with a series expansion of the operator that allows a better approximation for propagation in heterogeneous media. Details of the derivation of this operator can be found in Ramos-Martínez *et al*. (2015).

On the other hand, several studies (*e.g*., Etgen and Brandsberg-Dahl, 2009; Crawley *et al*. 2010) have shown that the pseudo-analytic approach is able to compute accurate wavefields, even after long propagation in time and space, using coarse time and space discretization. This

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motivates us to extend the pseudo-analytical method to consider the viscoacoustic case adapting the viscoacoustic wave equation. In its discretized pseudo-analytic form, the viscoacoustic wave equation can be written as (Ramos-Martinez *et al.*, 2015)

$$\sigma^{n+1} = 2\sigma^{n} - \sigma^{n-1} + \Delta t^2 c_o^2(\mathbf{x})\eta(\mathbf{x}) FT^{-1}\left\{\tilde{f}(\mathbf{k})\sigma^{n}(\mathbf{k},t)\right\} + \Delta t^2 c_o^2(\mathbf{x})\eta(\mathbf{x})\gamma(\mathbf{x}) FT^{-1}\left\{\left[\tilde{f}(\mathbf{k})\log\left(\tilde{f}(\mathbf{k})\right)\right]\sigma^{n}(\mathbf{k},t)\right\} + \Delta t^2 c_o^2(\mathbf{x})\tau(\mathbf{x})\left[FT^{-1}\left\{\left(\tilde{f}(\mathbf{k})\right)^{\gamma+1/2}\sigma^{n}(\mathbf{k},t)\right\} - FT^{-1}\left\{\left(\tilde{f}(\mathbf{k})\right)^{\gamma+1/2}\sigma^{n-1}(\mathbf{k},t)\right\}\right] \quad (1)$$

where σ is pressure, n and Δt are the time stepping index and size, respectively, $\mathbf{k}$ is the wavenumber, and the coefficients as a function of space **(x)**, are defined as

$$\eta(\mathbf{x}) = -c_0^{2\gamma(\mathbf{x})}\omega_0^{-2\gamma(\mathbf{x})}\cos(\pi\gamma(\mathbf{x})), \quad (2)$$

$$\tau(\mathbf{x}) = -c_0^{2\gamma(\mathbf{x})-1}\omega_0^{-2\gamma(\mathbf{x})}\sin(\pi\gamma(\mathbf{x})), \quad (3)$$

$$\gamma(\mathbf{x}) = \pi^{-1}\tan^{-1}(1/Q(\mathbf{x})). \quad (4)$$

Q is the quality factor, and c_0 and ω_0 are the reference velocity and frequency, respectively. FT^{-1} stands for the inverse Fourier Transform and the normalized pseudo-analytic Laplacian (Chiu and Stoffa, 2011) is defined as

$$\tilde{f}(\mathbf{k}) = \frac{2\cos\left(c_0\Delta t|\mathbf{k}|\right) - 2}{-c_0^2\Delta t^2|\mathbf{k}|^2}$$

The third and fourth terms in the right-hand part of eq. (1) correspond to the dispersive operators resulting from the approximation to handle the spatial variation of *Q*, whereas the fifth term corresponds to the amplitude-loss term. As observed, there is no variability of the normalized pseudo-Laplacian operator as in Zhu and Harris (2014). Instead, γ adjust the fourth term in the space domain to account for heterogeneity in attenuation.

RTM implementation with Q-compensation

Zhu *et al*. (2014) discussed with some detail the modifications that must be performed in the computation of the source forward- and receiver backward-propagation to achieve a correct *Q*-compensation, using the cross-correlation imaging condition as a framework. As pointed out by these authors, one of the advantages of viscoacoustic wave equations in the form shown in eq. (1), is that the same algorithm can be used during the forward modeling and RTM extrapolation with only a change of sign in the amplitude-loss term. Following the same premises of Zhu *et al*. (2014), we implement our RTM algorithm using the inverse scattering imaging condition, to minimize the backscattering correlation noise and thus improve the quality of the images (Whitmore and Crawley, 2012).

Synthetic examples

We show synthetic examples that illustrate the effects of Q in the wave propagation and the consequences of neglecting them during migration. Figure 1 summarizes propagation in four different homogeneous media having the same background velocity and Q=10 (Zhu and Harris, 2104). Each quadrant corresponds to a snapshot of the wavefront captured at the same time, propagating in (a) acoustic, (b) amplitude-loss only, (c) dispersion only and (d) both amplitude-loss and dispersion media. For illustration purposes, we selected a reference frequency much higher than the seismic data frequency bandwidth. Figure 1d shows the superposition of viscoacoustic effects. In addition to the amplitude decay, the wavefront has propagated within a shorter distance at the same propagation time, because it is traveling with a velocity slower than the background velocity. This example also demonstrates the practicality of operators shown in eq. (1) to isolate each effect of attenuation.

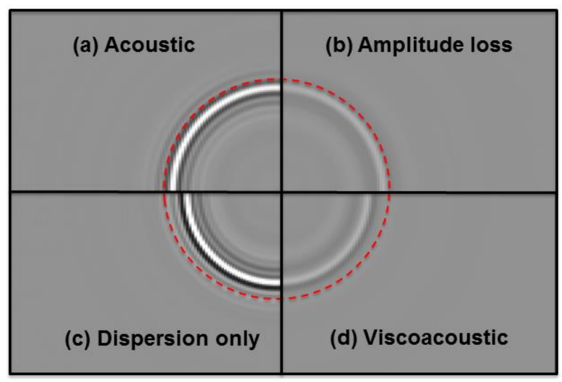

Figure 1. Snapshots in a vertical slice of a wavefront propagating in four different media having homogeneous background velocity and Q. Each quadrant corresponds to the wavefield captured at the same traveling time in (a) acoustic, (b) amplitude-loss only, (c) dispersion only and (d) a viscoacoustic (amplitude-loss + dispersion) media.

In a second example, we validate the consistency of the implementation of our RTM algorithm. Figures 2a and 2b show a layered velocity model and the corresponding *Q*–model used in this example, respectively. A low-*Q* velocity anomaly is embedded in the second layer. We generate shot gathers for the acoustic case, using the velocity model of Figure 2a and assuming constant infinite Q, and for the viscoacoustic case, from the models shown in Figure 2a and 2b. Then we use these shot gathers to compute the RTM images with and without *Q*-compensation. For

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modeling the data used here, we choose an arbitrarily reference frequency higher than the frequency bandwidth of the wavelet just for illustration purposes.

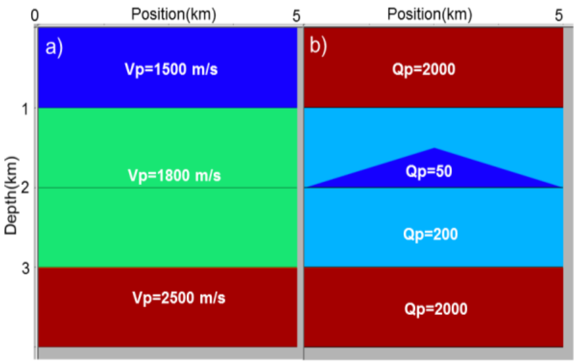

Figure 2. (a) Velocity and (b) Q models used for the computation of the synthetic shot gathers used in the RTM experiments shown in Figure 3.

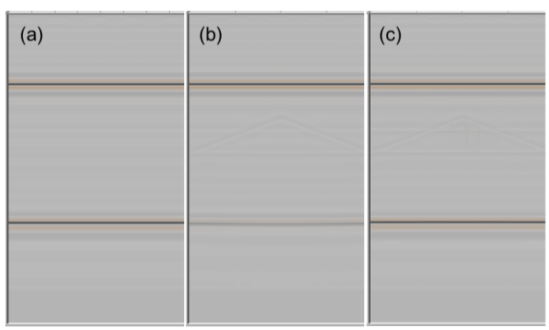

Figure 3. RTM images for the model (shown in Figure 2) corresponding to (a) acoustic migration from acoustic data; (b) acoustic migration from viscoacoustic data; and (c) viscoacoustic migration from viscoacoustic data. For the sake of comparison, the amplitude range is the same in all the images.

Figure 3a shows the image for the consistent acoustic experiment, *i.e.*, acoustic migration from acoustic data, which is used as a reference. Figure 3b shows the corresponding image for viscoacoustic data and migration without *Q*- compensation. As observed, the reflection of the second velocity interface shows strong phase distortion in addition to significant amplitude decay due to the accumulated effect of *Q* in the second layer and the low-*Q* anomaly. For the same dataset, when *Q*-compensation is considered during the RTM extrapolation (Figure 3c), we observe a similar quality of the event as displayed in the corresponding image of the consistent acoustic experiment. For the examples using viscoacoustic data, images also show slight reflections with the shape of the *Q*-anomaly. This is produced by the contrast in *Q* between the anomaly and the layer in which it is embedded (see *e.g.*, Ursin and Stovas, 2002). In addition, we observe that the waterbottom reflection remains unaltered in the cases using viscoacoustic data. This suggests that our approximation for handling heterogeneous *Q* media, performs well and does not affect the arrival times of the events that should not be affected by attenuation, as expected in propagation within the water.

Field data example

We applied our approach to a 3D dual-sensor field dataset acquired in an oil field located in the North Sea. The overburden in the area does not show significant structural complexity, but is characterized by some gas clouds that degrade the image resolution at the reservoir depth. Valenciano and Chemingui (2013) derived a *Q*-model from a tomography approach that relates the *Q* model with the measured spectral ratios for the input data. They used this model in a flow to obtain images compensated for *Q* using a one-way wave-equation migration algorithm. In this work, we compute from the same model, the RTM images without (Figure 4a) and with *Q*-compensation (Figure 4b) for a maximum frequency of 50 Hz using the inverse scattering imaging condition. As observed, *Q*-compensation during RTM significantly improves the resolution of the images and the continuity of the events. Figure 5 shows the amplitude spectra corresponding to each case after being stretched to time. This corroborates the recovery of the high frequency content when *Q* is taken into account during the RTM extrapolation.

Conclusions

We describe a reverse-time migration algorithm with *Q*-compensation that uses a pseudo-analytical extrapolator in order to solve a viscoacoustic, two-way, wave equation. Our extrapolator includes an approximation of the dispersive term in the viscoacoustic equation. It allows for a better approximation of the wave propagation in heterogeneous attenuating media. The numerical solution enables efficient computation without jeopardizing the accuracy of the simulated wavefields, even for long propagations in time and space. Significant improvements in image resolution can be achieved by incorporating attenuation in the migration. This is demonstrated by the migration of a 3D dual-sensor, towed-streamer survey from the North Sea.

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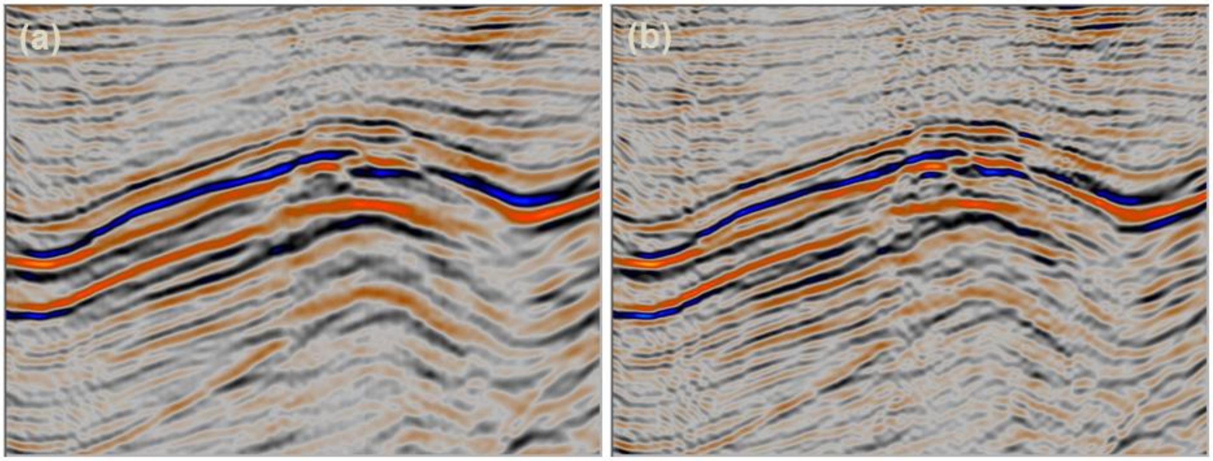

Figure 4. RTM images using the inverse scattering imaging condition (a) without and (b) with compensation for Q for a 3D dual-sensor dataset from the North Sea.

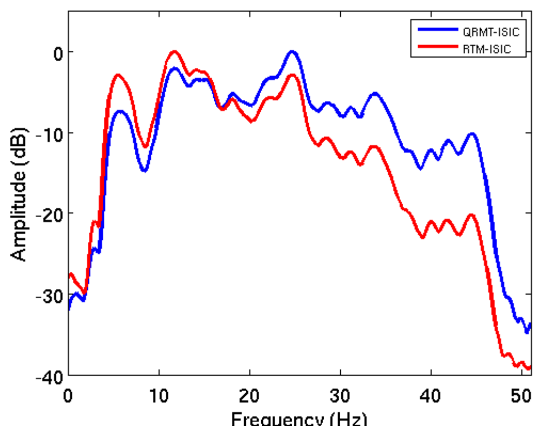

Figure 5. Amplitude spectra for the images displayed in Figure 4, after depth to time conversion, with (blue line) and without (red line) Q-Compensation.

EDITED REFERENCES

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