The role of FWI Imaging in compensating for transmission loss

J. Cooper[1], A. Ratcliffe[1]

[1] CGG

Summary

Seismic wavefields traveling through the subsurface lose energy due to various phenomena, such as geometric divergence and intrinsic attenuation. Imaging algorithms that account for these effects are well established. However, an often overlooked aspect of seismic imaging is transmission loss, which occurs due to propagating wavefields losing energy to back-scattered reflections. In this study, we examine the impact of transmission loss on various imaging algorithms and argue that it is not compensated for in standard applications of RTM and LS-RTM. Moreover, we find that transmission loss is naturally corrected for in the high-resolution reflectivity models derived from FWI Imaging, in which the effect is automatically encoded via sharp contrasts in velocity or density added to the earth model by the inversion. We assess the significance of transmission loss in different geological scenarios and evaluate the relative importance of this effect compared to other mechanisms that dissipate energy in the subsurface.

The role of FWI Imaging in compensating for transmission loss

Introduction

Seismic wavefields traveling through the subsurface lose energy due to various phenomena, such as geometric divergence and intrinsic attenuation (Q). Imaging algorithms that can account for these kind of illumination effects are well established and form an essential part of what defines a true-amplitude migration. However, an often-overlooked aspect of seismic imaging is transmission loss, which occurs due to the propagating wavefield losing energy to back-scattered reflections and, hence, becoming weaker than expected (from other illumination effects) as it travels through the Earth. We examine the impact of transmission loss and confirm that it is not compensated by standard applications of reverse time migration (RTM). Moreover, we discuss and demonstrate that transmission loss is naturally corrected in the high-resolution reflectivity models derived from full-waveform inversion (FWI).

Theory

At any boundary in the subsurface, the pressure reflection coefficient for downgoing normal incidence is given by $R_r = (Z_2 - Z_1)/(Z_2 + Z_1)$, where Z_1 and Z_2 are the acoustic impedances immediately above and below the boundary, respectively. The transmission loss associated with this boundary is given by the two-way transmission coefficient, $T_r = 1 - R_r^2$ for normal incidence (see, for example, Robinson and Treitel, 1980). Transmission loss will occur as a cumulative effect, as the wavefield traverses the numerous boundaries present in the subsurface. Reflection coefficients are typically sufficiently small that transmission loss is not significant; however, anomalies in reflectivity may give rise to some localized transmission loss in the recorded data.

RTM is an accurate method for the purposes of both structural and true-amplitude imaging in complex media (Xu et al., 2011). That said, standard implementations of RTM do not naturally account for transmission loss and any resulting variability in the recorded data will be embedded in the resulting image. Various forms of transmission loss compensation in RTM have been proposed, for example, by Deng and McMechan (2007) or Du et al. (2013), but they are not widely used as they typically require an estimate of angle-dependent reflectivity and involve two passes of imaging.

Inversion-based algorithms for reflectivity, such as least-squares RTM (LS-RTM) are well-known to compensate for a number of illumination issues and can significantly improve imaging under structures in complex areas (Nemeth et al., 1999; Wang et al., 2016). However, as noted by Zhang et al. (2023), LS-RTM does not fully account for transmission loss, due to single-scattering, Born modelling, assumptions. FWI Imaging (Zhang et al., 2020) is an alternative inversion-based approach, where intermediate model updates can include sharp contrasts at reflecting boundaries, meaning subsequent iterations can encode the transmission loss effect in the forward problem, such that it is then automatically corrected in the inverted result.

Results

We illustrate the impact of transmission loss with a simple synthetic example. Figure 1 compares an RTM image with an FWI Image for an earth model comprising two reflecting boundaries. As shown in Figure 1a, the true reflection coefficient of the upper boundary laterally oscillates between $R_r = 0.00$ and $R_r = 0.33$. The true reflection coefficient of the lower boundary is $R_r = 0.20$ everywhere. The shot domain data used for both RTM and FWI Imaging tests is obtained by conventional wavefield propagation through the true model, namely a constant velocity of 2000 m/s with reflections generated by density contrasts. We used FWI to invert for relative acoustic density, before converting to zero-angle reflectivity, whereas RTM outputs reflectivity directly. Both the RTM and FWI results utilise the true velocity model. The 80 Hz RTM and 80 Hz FWI results are shown in Figures 1b and 1c, respectively. Figure 1d compares amplitudes extracted at the lower reflector from the images in Figures 1a-c. Figure 1b illustrates that RTM gives an image of the upper boundary accurately, but the image of the lower boundary exhibits small spatial variations in amplitude, correlated with the locations of the higher reflectivity values in the upper boundary. This effect is subtle when examining the image itself but is illustrated more clearly by the extracted amplitudes in Figure 1d. The RTM contains an analytic geometrical spreading correction, and there is no intrinsic attenuation in this example; hence the observed variations in amplitude can be connected to the transmission loss at the upper reflector. By contrast, the 80 Hz FWI Image in Figure 1c images the reflectivity of the lower boundary accurately, with no effects of transmission loss observed.

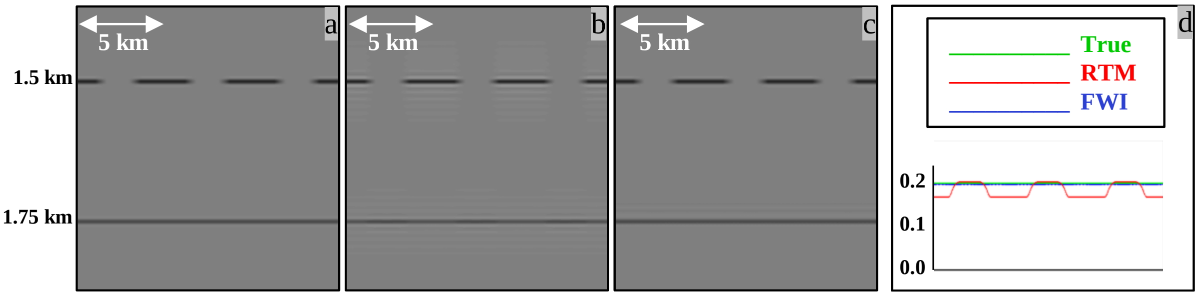

Figure 1 *(a) True reflectivity for a simple 2-layer earth model. Corresponding 80 Hz images from: (b) RTM and (c) FWI Imaging; (d) amplitudes extracted at the lower reflector in panels (a)-(c).*

In Figure 2, we show 80 Hz results from an LS-RTM algorithm, for the same input data used in Figure 1. Figure 2a shows an iterative application of LS-RTM, and Figure 2b shows a second iterative application wherein the number of iterations is increased by 50% over the first application. Figure 2c shows amplitudes extracted at the lower reflector for the two LS-RTM tests. We have confirmed that the LS-RTM results have compensated for geometrical spreading (as expected from Nemeth et al., 1999) as the measured relative amplitudes of the upper and lower reflectors are the same as in the RTM result shown in Figure 1b (which has an analytic correction for geometrical spreading). However, Figure 2c also highlights that both LS-RTM results still exhibit similar amplitude variations in the lower reflector to those seen in the earlier RTM example. The additional iterations in the second LS-RTM have only a very small effect on the results, confirming good convergence in the inversions. It should be emphasized that this example uses a constant velocity model plus density contrasts to highlight the impact of transmission loss alone; more generally, LS-RTM is well established to improve the imaging of poorly illuminated regions in complex geologies when compared to RTM (Wang et al., 2016).

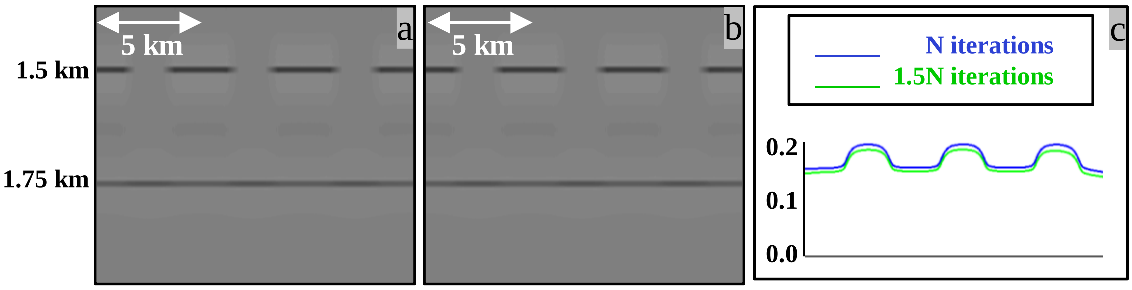

Figure 2 *80 Hz LS-RTM images for a simple 2-layer earth model. (a) Iterative LS-RTM, (b) iterative LS-RTM, increasing the number of iterations by 50%, and (c) amplitudes extracted at the lower reflector from (a)-(b).*

Conclusions

FWI Imaging automatically handles effects due to transmission loss by encoding it in the forward modelling of the inversion (via contrasts in the updated earth model). RTM and LS-RTM can account for various forms of illumination compensation, but do not naturally correct for transmission loss. Using a controlled synthetic example, we have demonstrated that the FWI Image avoids variations in the amplitudes due to transmission loss. On field data, the impact of transmission loss will depend on the strength and spatial variability of the reflectors in the subsurface and may often coincide with other effects resulting in amplitude loss in the recorded data, such as weak illumination and intrinsic attenuation. During the presentation, we will show field data examples to discuss and demonstrate the influence of transmission loss and other illumination issues.

Acknowledgements

The authors thank CGG for permission to publish this abstract, and Gordon Poole for helpful discussions.

References

Deng, F. and McMechan, G. A. [2007] True amplitude prestack depth migration. *Geophysics*, **72**(3), S155-S166.

Du, Q. Z., Fang, G., Gong, X. F., Zhang, M. Q. and Li., S. [2013] Wave Propagation Operators for True-amplitude Reverse Time Migration. *75th EAGE Conference & Exhibition*, Extended Abstracts, We P09 05.

Nemeth, T., Wu, C. and Schuster, G. T. [1999] Least-squares migration of incomplete reflection data. *Geophysics*, **64**(1), 208-221.

Robinson, E. A. and Treitel, S. [1980] Geophysical Signal Analysis, Prentice-Hall.

Wang, P., Gomes, A., Zhang, Z. and Wang, M. [2016] Least-squares RTM: Reality and possibilities for subsalt imaging. *86th Annual International Meeting, SEG*, Expanded Abstracts, 4204-4209.

Xu, S., Zhang, Y. and Tang, B. [2011] 3D angle gathers from reverse time migration. *Geophysics*, **76**(2), S77-S92.

Zhang, Z., Wu, Z., Wei, Z., Mei, J., Huang, R. and Wang, P. [2020] FWI Imaging: Full-wavefield imaging through full-waveform inversion. *90th Annual International Meeting, SEG*, Expanded Abstracts, 656-660.

Zhang, Z., Wu, Z., Wei, Z., Mei, J., Huang, R. and Wang, P. [2023] Enhancing salt model resolution and subsalt imaging with elastic FWI. *The Leading Edge*, **42**(3), 207-215.