



Robust time-domain migration velocity analysis methods for initial-model building in a full waveform tomography workflow

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Abstract

Full-waveform tomography (FWT) is notorious for its strong dependence on the initial model. We present a workflow for the construction of initial velocity-models for FWT methods consisting of automatic time-migration velocity analysis by means of double multi-stack migration, followed by time-to-depth conversion by image-ray wavefront propagation. Evaluation of the converted velocity model as an initial velocity model in an acoustic FWT process indicates the potential of using a combination of these methods to achieve a fully automatic tool for initial-model building in an FWT workflow. Our tests on a modified version of the Marmousi-2 model have shown that correct background velocity information can be successfully extracted from automatic time-domain migration velocity analysis even in media where time-migration cannot provide satisfactory seismic images.

Introduction

In 1984, Tarantola presented the basic idea of acoustic full waveform inversion (FWI) as a local optimization method that aims to minimize the least-squares misfit between observed and modeled seismograms. In other words, the aim of FWI is to find a subsurface model which explains the recorded seismic data (Symes, 2008). Toward the end of the 80's, Mora (1987a,b) and Tarantola (1986) extended the theory to the elastic case. Shortly after, Pratt and Worthington (1990) and Pratt (1990) introduced the frequency-domain version of full waveform inversion. While its high computational cost retarded its adoption for almost two decades, the advance of computing technology allowed to develop multiscale inversion, which became an area of very busy and active research, and it provided a hierarchical framework for robust inversion (Yang et al., 2015).

FWI proved to be an efficient tool for the determination of high-resolution details in multi-parameter models of complex subsurface structures, and it has been applied in different geophysical problem scales, ranging from ultrasonic data (Pratt, 1999) to seismological imaging (Fichtner et al., 2009).

However, being a highly nonlinear problem, FWI techniques face other drawbacks than their elevated computational cost. They are notorious for depending

strongly on the choice of a good starting model for convergence at a geologically meaningful result. Particularly, the long-wavelength components are crucial in this respect. Analyzing this dependence, Mora (1989) recognized that FWI has a migration component and a tomographic component. To ensure convergence of the tomographic component, a possible strategy is to start the inversion processing from the low frequencies, but this does not avoid the need of accurate initial velocity models (Biondi and Almomin, 2014).

For this reason, quite some effort has been made to come up with initial models for FWI. Traveltime tomography, Laplace-domain inversion, and migration-based velocity analysis (MVA) are some examples of seismic techniques that have been investigated for this purpose (Prioux et al., 2012).

In this paper, we investigate another possible strategy with potential to help the construction of initial velocity models for full-waveform tomography (FWT). We apply the double multi-stack technique of Schleicher and Costa (2009) to perform a time-domain MVA. This is a fully automatic tool that is useful to obtain a time migrated image and its corresponding migration velocity model in a computationally effective way. We then convert the background part of the time-migration velocity model to the depth domain by means of the time-to-depth conversion strategy based on image-wavefront propagation (Valente, 2013; Valente et al., 2014; Santos et al., 2015). We evaluate the converted velocity model as an initial velocity model in an acoustic FWT process (Kurzmann et al., 2013). For comparison, we carry out the same FWT using a smoothed version of the true velocity model.

Methodology

Our workflow (Figure 1) for initial-velocity model building and FWT is built upon the following techniques.

MVA by double multi-stack migration

The workflow starts with the double multipath time migration-velocity analysis of Schleicher and Costa (2009). This MVA technique is based on the multipath-summation imaging process of Landa et al. (2006). The fundamental idea of the latter is to stack the migration results for "all possible" velocities, or at least as many models as practically reasonable. Since only "good" models yield flat events in common-image gathers, these will prevail in the overall stacked image, which thus will show the geologic structure without the need for a migration-velocity model. A weighted double stack allows to determine the associated velocity values. Below, we will refer to this technique as multi-stack migration.

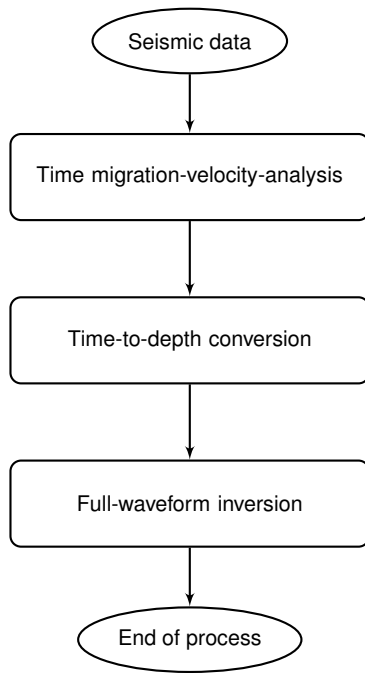


Figure 1: Velocity model building flowchart.

Time-to-depth conversion and velocity estimation

With this procedure, we can automatically construct a time-migration velocity model. However, FWI requires an initial model in depth. Therefore, we need to convert the multi-stack model to depth. For this objective, we chose the time-to-depth conversion of Valente (2013). First performance tests of that conversion procedure were reported by Valente et al. (2014).

The time-to-depth conversion of Valente (2013) is based on the algorithm of the level-set method. It pursues the construction of wavefronts instead of individual image rays. This strategy has the advantage of directly obtaining the velocity field $v(\mathbf{x})$ and the traveltime $\tau(\mathbf{x})$, avoiding to calculate the auxiliary functions $p(\mathbf{x})$ and $q(\mathbf{x})$ like in concurrent schemes (Cameron et al., 2007, 2008; Iversen and Tygel, 2008). By means of a modified fast-marching conversion algorithm, it directly determines the matrix $\gamma(\mathbf{x})$ of image-ray emergence points from the already known values of $v(\mathbf{x})$ and $\tau(\mathbf{x})$. For further details, see Valente (2013).

Acoustic full waveform tomography

To test whether the so-obtained depth model has sufficient quality for FWI, we used a modified version of the 2D acoustic time-domain FWT code initially implemented by Kurzmann et al. (2013). Here we briefly summarize the underlying concepts.

Forward modeling

The FWT implementation of Kurzmann et al. (2013) solves the homogeneous acoustic wave equation in the time domain by means of a time-domain finite-difference time-stepping method (Alford et al., 1974) with perfectly matched

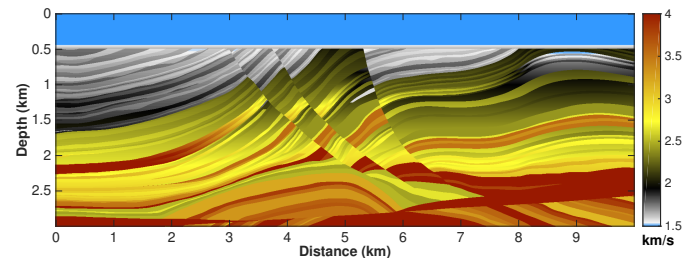


Figure 2: True velocity of the modified Marmousi-2 model.

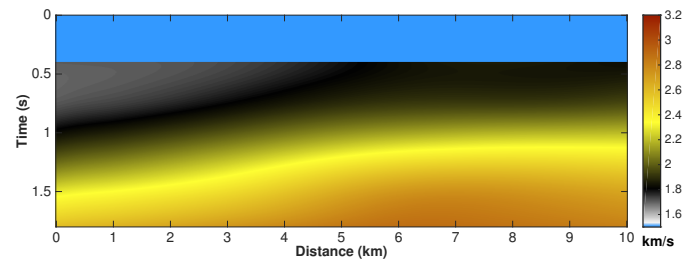


Figure 3: Time-migration velocity model obtained by the multi-stack MVA with strong regularization.

layer (PML) boundary condition (Berenger, 1994) and massive parallelization comprising domain decomposition (Bohlen, 2002) and shot parallelization (Kurzmann et al., 2009). The distribution of shots on different computers provides a reduction of network traffic and consequently a speedup of the inversion algorithm.

Inversion

The objective of the code is the reconstruction of an acoustic velocity model. For simplicity, the density is considered constant and not a subject of the inversion. The solution of the inverse problem is based on the time-domain FWT of Tarantola (1984) and Mora (1987a). It comprises the adjoint method and the conjugate gradient method using a least-squares misfit function. For further details, please refer to Kurzmann et al. (2013).

Numerical Example

To test our initial-model construction, we apply it to a modified version of the 2D Marmousi model similar to the one of Kurzmann et al. (2013).

We modified a section of the Marmousi-2 model (Figure 2) based on Versteeg (1994) and Martin et al. (2002). The velocities are clipped to the range of 1500 to 4000 m/s to reduce computational efforts. The acquisition geometry simulates a marine streamer geometry with a length of 5980 m, consisting of 187 shots and a maximum number of 300 receivers per source. Receiver spacing was 20 m and the nearest offset was 45 m. The source time function is a Ricker wavelet with peak frequency $f_{peak} = 9$ Hz. The model size is 3 km \times 10 km which, using a grid spacing of 5 m, resulting in a grid size of 600 \times 2000 grid points. We set a perfectly matched layer (PML) of 150 m width to avoid artificial boundary reflections in finite-difference modeling. The recording time of the seismic data was 5.6 s with a time

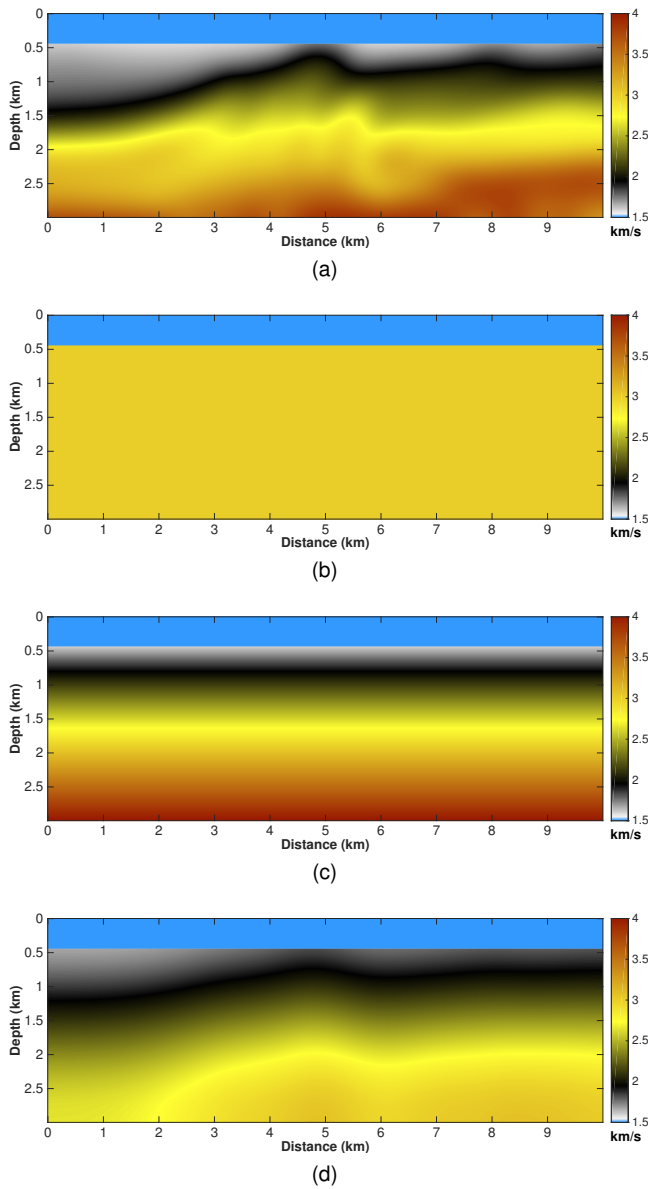


Figure 4: Initial models: (a) smoothed version obtained after low-pass filtering of the true model (Figure 2); (b) homogeneous velocity model ($v = 3 \text{ km/s}$); (c) constant vertical gradient; (d) velocity model obtained by the double multi-stack MVA converted from time-to-depth using the image-wavefront propagation.

discretization of $7 \cdot 10^{-4} \text{ s}$. We chose these parameters to make the conditions for the FWT nearly ideal.

Initial velocity models

To decrease the computation time for the migration velocity analysis, and to work under more realistic conditions, we resampled the seismic data to 4 ms and windowed the offsets processing only half of them. From these data, we extracted a time-migration velocity model using the double multi-stack MVA with velocities between 1400 m/s and 4200 m/s at every 100 m/s. In order to avoid the presence of possible artifacts created during the conversion step, we used strong regularization and smoothed the time-domain

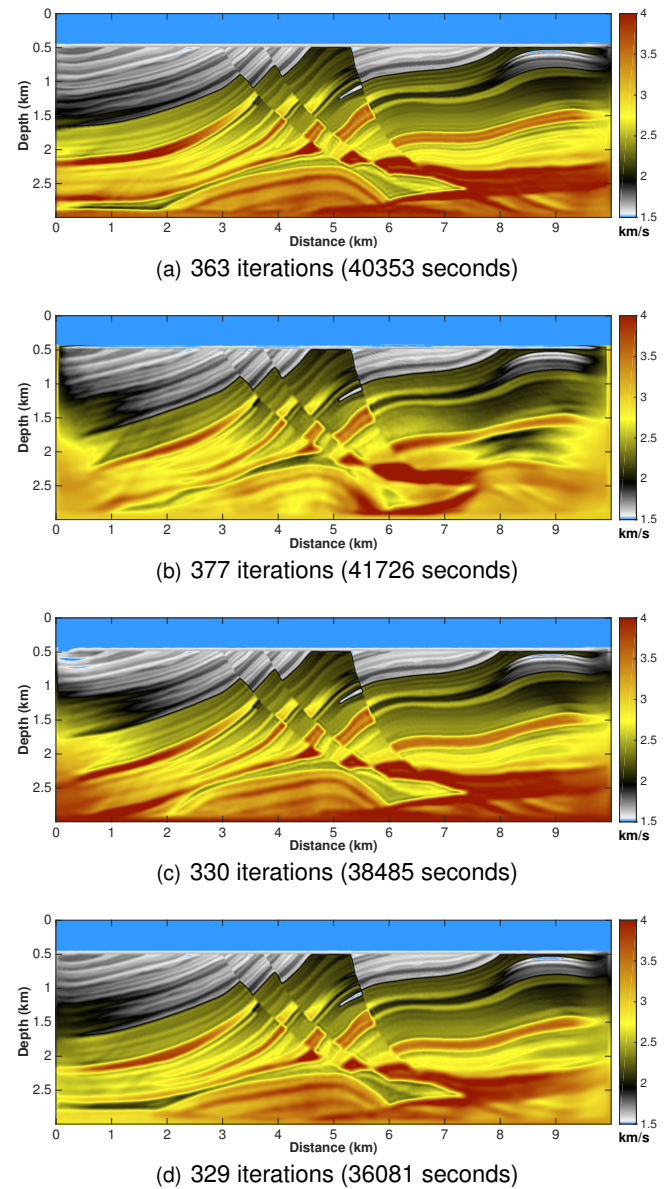


Figure 5: Recovered velocity models from the initial models in Figure 4. The individual amount of required iterations differs from each other.

model by one pass of a moving average with a $500 \text{ m} \times 500 \text{ m}$ (100 by 100 points) window. The resulting model is depicted in Figure 3. Less smoothed models resulted in worse FWT results. We then converted this model to depth using image-ray wavefronts as described above (Figure 4(d)).

For our evaluation, we compare the results of FWT with different initial velocity models. Figure 4(a) depicts a smooth initial velocity model, generated by application of a 2D Gaussian filter (size $1250 \text{ m} \times 1250 \text{ m}$, $\sigma=51$) to the sub-seafloor area of the true velocity model (Figure 2). This same P-wave velocity model was used by Kurzmann et al. (2013) in their sensitivity analysis of attenuation. Our other FWT tests used a constant velocity (Figure 4(b)) or a constant gradient below the see floor (Figure 4(c)).

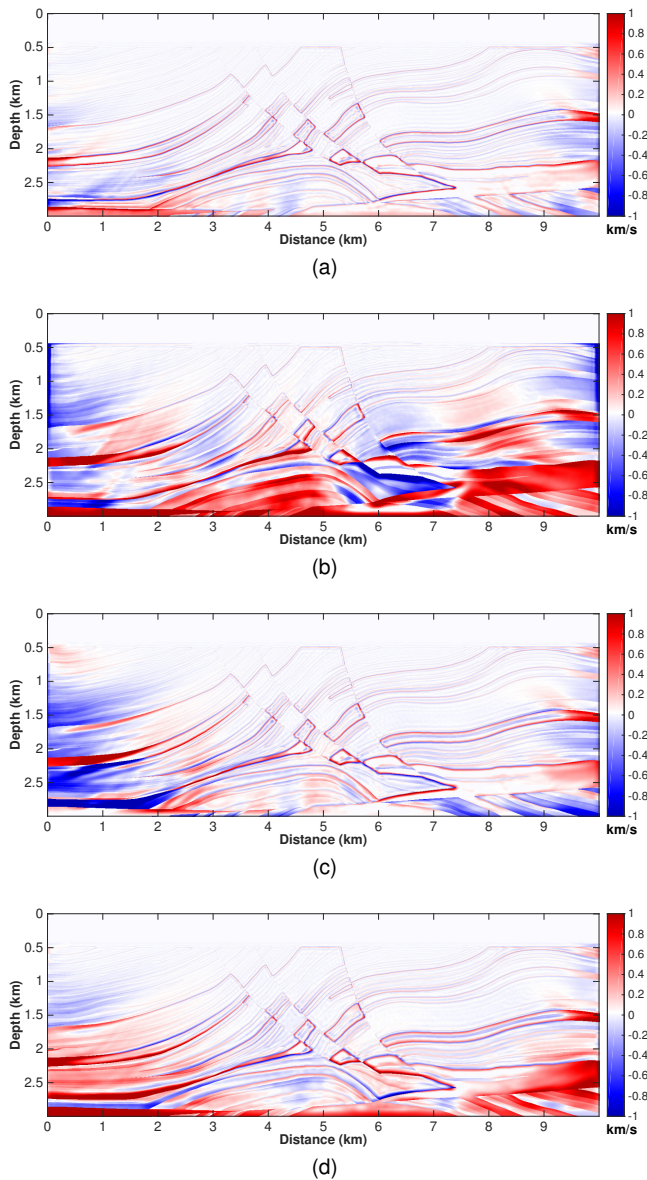


Figure 6: Differences of the results in Figure 5 to the true model in Figure 2.

FWT results

We then executed the FWT code on the original undecimated (i.e., almost ideal) data using the starting models of Figure 4. The final inverted models, after the FWT code reached convergence at the end of the workflow, are shown in Figure 5 and their differences to the true one in Figure 6.

We see that the results using the depth-converted multi-stack model (Figure 5(a)) are comparable in quality to the ones obtained with the smoothed model (Figure 5(b)) or the true vertical gradient (Figure 5(c)) and clearly superior to the ones obtained with the constant starting model (Figure 5(d)). Except for the boundary region, where the data are insufficient, the model inverted when starting at the converted time model is, at some places, even superior to the one obtained from the true vertical gradient and

reaches the same quality as the one obtained from the smoothed model (compare difference images in Figure 6).

Conclusion

In this work, we have presented a workflow for the construction of initial velocity-models for FWT methods. In an attempt to aid the search for more efficient model-building tools, we investigate the applicability of a recent automatic time MVA method. This method stacks twice over migrated images for many models with different weights in order to extract stationary migration velocities from the ratio of the images. Thus, it is able to generate a velocity model and a time-migrated image without a priori information.

For the use of such a velocity model in FWT methods, the result needs to be converted from time to depth. For this purpose, we chose a strategy based only on image-ray wavefront propagation. The results confirmed the method's efficiency in very complex geology structures, i.e., models with strong velocity variations.

Our first numerical results indicate the potential of using a combination of these methods to achieve a fully automatic tool for initial-model building in an FWT workflow. In our tests, the method was able to produce a sufficiently accurate initial model for an FWT under nearly ideal conditions converges to a model of comparable quality as when starting at a smoothed version of the true model. This indicates that correct background velocity information can be successfully extracted from automatic time-domain migration velocity analysis even in media where time-migration cannot provide satisfactory seismic images.

Future investigations will have to show whether some model detail can be already introduced in the time domain or added in an additional depth-domain MVA step in order to reduce the number of necessary FWT iterations and if the inversion can still be successful from such initial models if the data are less than ideal.

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