Image-guided wavefield tomography for VTI media

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SUMMARY

Transversely isotropic (TI) models have become essential in generating accurate depth images from seismic data. Here, we develop image-domain tomography (IDT) for building acoustic VTI (TI with a vertical symmetry axis) models from P-wave reflection data. Based on a separable dispersion relation, the modeling operator extrapolates only P-wavefields without the shear-wave artifacts. The inversion algorithm includes least-squares reverse-time migration (LSRTM), which improves the quality of the extended images and accuracy of parameter estimation. Whereas the zero-dip NMO velocity (V_{nmo}) and anellipticity parameter η are updated by focusing energy in space-lag LSRTM gathers, the Thomsen parameter δ is constrained by image-guided interpolation between two or more boreholes. We also apply image-guided smoothing to the IDT gradients of V_{nmo} and η to steer the inversion towards geologically plausible models. To mitigate the trade-off between V_{nmo} and η , we adopt a multistage approach that gradually relaxes the constraints on the spatial η -variation. The robustness of the algorithm is demonstrated on the elastic VTI Marmousi-II model. We also present preliminary inversion results for a line from a 3D data set acquired in the Gulf of Mexico.

INTRODUCTION

Image-domain wavefield tomography (IDT), based on wave-equation migration, commonly operates in the extended domain (Sava and Vasconcelos, 2011) and employs energy-focusing criteria (Symes and Carazzone, 1991; Zhang and Shan, 2013). Despite being better suited for complex geologic structures than conventional reflection tomography, IDT applications remain limited, in part due to illumination- and aperture-induced defocusing in extended images (Mulder, 2014; Dafni and Symes, 2016). Such defocusing can be addressed in the penalty operator (Yang and Sava, 2015) or mitigated prior to velocity updating. The latter approach can be implemented either analytically by refining the imaging condition (Hou and Symes, 2015; Chauris and Cocher, 2017) or numerically through LSRTM as done in migration-based traveltime tomography (Clément et al., 2001) and reflection waveform inversion (Hicks and Pratt, 2001; Xu et al., 2012). The efficiency of LSRTM can be significantly enhanced with nonstationary matching filters applied to gradient preconditioning (Guitton, 2017).

P-wave kinematics in VTI media is controlled by the zero-dip normal-moveout velocity (V_{nmo}) and anisotropy parameters η and δ . VTI tomography needs to address two inherent properties of P-wave reflection moveout: its low sensitivity to δ and the trade-off between V_{nmo} and η . V. Li et al. (2017a) present

an IDT algorithm designed to update V_{nmo} , η , and δ in the extended domain starting from a purely isotropic model. Here, we modify their methodology by including nonstationary matching filters that substantially improve the quality of extended images. Also, we design a multistage inversion scheme that gradually relaxes constraints on the spatial variation of η . The algorithm is tested on the elastic Marmousi-II and offshore field data.

METHODOLOGY

We employ an integral wave-equation operator based on the dispersion relation described in Schleicher and Costa (2015). Parameter updating is carried out by implementing energy-focusing criteria in the extended domain. Application of least-squares RTM helps suppress illumination- and aperture-truncation artifacts that hamper the estimation of the parameter η . Following Guitton (2017), we apply nonstationary convolution filters to precondition the LSRTM gradient. As suggested by Shan et al. (2014) and Y. Li et al. (2014), the objective function combines the differential semblance optimization (DSO) and image-power (IP) (Zhang and Shan, 2013) criteria:

$$\mathcal{J} = \mathcal{J}_{\text{DSO}} + \alpha \mathcal{J}_{\text{IP}}, \quad (1)$$

where $\mathcal{J}_{\text{DSO}}$ and $\mathcal{J}_{\text{IP}}$ are the DSO and IP terms, respectively, and α is a model-dependent weighting factor. The adjoint-state gradients of both terms are derived by V. Li et al. (2017b). The image-power term helps reject unphysically large η -updates that satisfy the DSO criterion of small residuals at nonzero lags. Our three-stage inversion strategy is designed to address the following issues with VTI velocity analysis:

- parameter estimation may not be feasible if the initial vertical velocity (V_{P0}) or V_{nmo} is highly inaccurate.
- imaging results are less sensitive to η than to V_{nmo} , and there are trade-offs between these parameters.
- δ -estimation requires additional (e.g., borehole) information.
- accurate background velocity is needed to constrain high model-wavenumber components.

Based on the sensitivity analysis by Alkhalifah and Plessix (2014) and Alkhalifah (2016), we parameterize the VTI medium by $\{(V_{\text{nmo}}/V_{\text{nmo}}^{\text{init}})^2, 1 + 2\delta, 1 + 2\eta\}$, where $V_{\text{nmo}}^{\text{init}}$ is the initial V_{nmo} -field. All three initial parameters are equal to unity if the inversion starts with a purely isotropic model. Only the NMO velocity and η are estimated in the image domain, while δ is obtained by image-guided interpolation between boreholes (Hale, 2009a). The interpolation is performed with the LSRTM image generated at the current iteration.

Similarly to Wang and Tsvankin (2013) and Pattnaik et al. (2016), we update V_{nmo} and η sequentially to mitigate the dominant influence of V_{nmo} on reflection moveout and reduce the trade-offs between V_{nmo} and η . The first inversion stage is designed to update only V_{nmo} , whereas the second stage is limited to updating η using the refined V_{nmo} -field. Finally, V_{nmo} and η are updated simultaneously at the third stage. The weighting factor α in equation 1 is fixed for each stage and increases during the optimization to emphasize the IP term as the background model becomes more accurate. Image-guided smoothing (Hale, 2009b) is applied to the V_{nmo} - and η -gradients as part of applying the L-BFGS inversion algorithm.

MARMOUSI MODEL

The “observed” data for the VTI Marmousi-II model are computed with an elastic wavefield simulator and include 100 streamer arrays with the maximum offset of 6 km (Guitton and Alkhalifah, 2016). We assume that the vertical δ -profile is known at two “borehole” locations (Figure 1). The initial isotropic velocity model is obtained by applying strong smoothing to the actual V_{nmo} -field (Figure 1d), and IDT is performed using the three-stage approach described above. The inner loop of the algorithm includes two iterations of the preconditioned extended LSRTM. The IDT gradients of V_{nmo} and η are normalized by their smoothed envelopes to increase the contribution of weaker reflection events.

The initial model is not sufficiently accurate to allow for robust simultaneous updating of V_{nmo} and η . At the first inversion stage, we update only V_{nmo} and set the factor α in the objective function (equation 1) to 0.5, so that the gradient is mostly determined by the DSO term. At the second inversion stage, designed to update only η , we assign equal weights to both objective-function terms ($\alpha = 1$) and apply image-guided smoothing to the η -gradient. With the refined V_{nmo} - and η -fields, at the third stage the two parameters are updated simultaneously, and the factor α is set to two to emphasize the IP term. Also, we relax the smoothing constraints but still apply stronger image-guided smoothing to the η -gradient compared to that for V_{nmo} . Two more model updates add higher-contrast features to the V_{nmo} -field and slightly increase the resolution of η (Figure 2a-b). The δ -field (Figure 2c) is obtained using interpolation between the boreholes guided by the final LSRTM image (Figure 2d). Despite the relatively low resolution of the inverted η -field, the quality of the final image (Figure 2d) is satisfactory.

GULF OF MEXICO DATA SET

Here, we provide preliminary results for a line from a 3D ocean-bottom node (OBN) data set acquired in the Gulf of Mexico (GoM). Preprocessing includes data projection onto the line, debubbling, P-Z summation, and normalization with a smooth data envelope. The data normalization increases the amplitudes of reflections from the deeper layers. The elliptic ($\eta = 0$) initial model provided by Shell features a salt dome embedded in subhorizontal sediments (Figure 3). To increase the robustness

of imaging and eliminate diffractions, we smooth the edges of the original salt body. Given the relative sparseness of OBN data, we employ a mirror imaging technique (Figure 3a) to increase the illumination. Following Guitton (2017), the matching filters are used to precondition the first two LSRTM iterations. Figure 4 shows the results after 16 iterations, which reduce the initial data misfit by 40%.

Because the initial model produces relatively weak defocusing in extended gathers, we start the inversion with stage 2 designed to update only η ; the weighting factor α is set to unity. The sensitivity kernels of η mainly involve horizontal wavenumbers, so the summation of the η -gradients over individual shots mitigates the sparseness of the ocean-bottom nodes. Figure 5 shows the initial inversion gradients for η before (Figure 5a) and after (Figure 5b) preconditioning that includes image-guided smoothing and normalization with a smooth envelope. We also set η to zero in the water and salt body, as well as at depths below 4 km where this parameter cannot be reliably constrained within the available range of offsets.

CONCLUSIONS

We presented an acoustic IDT algorithm designed to reconstruct P-wave VTI velocity models using wave-equation imaging. Application of LSRTM plays a crucial role in suppressing aperture- and illumination-induced artifacts in the extended domain. Nonstationary matching filters facilitate the convergence of LSRTM, which significantly improves the efficiency of IDT. The three-stage inversion strategy mitigates the trade-off between the parameters V_{nmo} and η , and image-guided smoothing steers the algorithm towards geologically plausible solutions. The parameter δ is reconstructed from image-guided interpolation between available boreholes. The high computational cost of the inner-loop LSRTM is partly compensated by a small number of outer-loop iterations.

The algorithm was applied to the elastic VTI Marmousi-II model starting from a purely isotropic, substantially distorted velocity field. The updates in V_{nmo} , η , and δ obtained after six iterations of IDT significantly improved the LSRTM image. Preliminary inversion results for a line from the Gulf of Mexico suggest that the initial elliptic model can be improved with positive η -updates. The robustness of field-data applications can be increased by extending the algorithm to 3D which, however, remains prohibitively expensive. Ongoing work includes a modification of the method for tilted TI media.

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Figure 1: Parameters of the elastic VTI Marmousi-II model: (a) V_{nmo} , (b) η , and (c) δ . The vertical black lines on plot (a) mark the boreholes where δ -profiles are available. The data are recorded by 100 receiver arrays located between 0 and 16 km (one of them is marked by a yellow line) with a maximum offset of 6 km. The sources (one is marked by a red dot) are evenly spaced at the surface between 0 and 12 km. (d) The initial isotropic model obtained by smoothing the actual V_{nmo} -field.

Figure 2: Inverted parameters of the model from Figure 1: (a) V_{nmo} , (b) η , and (c) δ . (d) The LSRTM image obtained with the final model.

Figure 3: Initial elliptic ($\eta = 0$) model for the line from the Gulf of Mexico: (a) V_{nmo} (with mirror geometry used for imaging and tomography) and (b) $\epsilon = \delta$.

Figure 4: LSRTM output for the model from Figure 3. (a) The conventional image and (b-d) the space-lag gathers at the locations marked by the vertical blue lines. (e) The normalized LSRTM objective function.

Figure 5: IDT gradient for η (a) before and (b) after preconditioning.

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