Building starting model for full waveform inversion from wide-aperture data by stereotomography

Vincent Prieux\(^1\), G. Lambaré\(^2\), S. Operto\(^1\) and Jean Virieux\(^3\)

\(^1\)Géosciences Azur - CNRS - UNSA, France; \(^2\)CGG Veritas, Massy, France; \(^3\)LGIT - UJF - CNRS, France

Abstract

Building a reliable starting model remains one of the most topical issues for successful application of full waveform inversion (FWI). In this study, we assess stereotomography as a tool to build a reliable starting model for frequency-domain FWI from long offset (i.e., wide-aperture) data. Stereotomography is a slope tomography method based on the use of traveltimes and slopes of locally-coherent events in the data cube. A key feature of stereotomography is that it can be coupled efficiently with semi-automatic picking, which partially frees one from the tedious and difficult interpretive travelt ime picking. We assessed a tomographic workflow based on stereotomography and frequency-domain FWI with the 2D acoustic synthetic Valhall case study. The Valhall model is mainly characterized by a large-scale low velocity zone associated with gas layers above the reservoir level. We first computed an acoustic full-wavefield dataset using a finite-difference time-domain modeling engine for a wide-aperture survey with a maximum offset of 16 km. The source bandwidth is between 10 and 45 Hz. Compared to the conventional application of stereotomography, we assess in this study the benefits provided by the joint inversion of refraction and reflection traveltimes from long-offset data. Use of refraction traveltimes is expected to stabilize and improve the reconstruction of the shallow part of the model. In a similar manner for frequency-domain FWI, we design a multiscale approach which proceeds hierarchically from the wide-aperture to the short-aperture angles to mitigate the non-linearity of the inversion. Starting models for FWI were built by stereotomography using two sets of picked events. For the first data set, the picking is limited to reflection traveltimes with a maximum offset of 4 km, while both refracted and reflected events were picked in the second case using the full range of offsets (± 16 km). We highlight the improvements of the FWI results obtained from the starting stereotomographic model built from the long-offset data set. The improvements are observed at the reservoir level below the gas layers but also in the upper part of the model where the joint use of refraction and reflection traveltimes is helpful to improve the ray illumination.
**Introduction**

Building a reliable starting model remains one of the most topical issues for successful application of full waveform inversion (FWI), in particular, when very low frequencies (\(< 2 \text{ Hz}\)) are not available in the data. Starting models for FWI are usually built by first-arrival traveltime tomography (FATT) or reflection traveltime tomography (RTT) (Woodward et al. (2008) for a review). Although FATT has been shown to be relevant in many case studies (e.g. Operto et al., 2004), it is not well suited in presence of low velocity zones, and can require a wide range of offsets for sufficient ray-path sampling of deep targets. Finite-frequency FATT based on full-wavefield sensitivity kernels can provide, however, a promising alternative to ray-based FATT to properly regularize the traveltime inversion (Effelsen, 2009).

RTT makes use of reflection traveltimes to build velocity macromodels of higher resolution but suffers from the difficult problem of interpretive travelt ime picking of coherent events. Alternative approaches based on the Laplace and Laplace-Fourier inversions, closely related to amplitude and first-arrival phase inversions, have been recently proposed but the sensitivity of these approaches to noise deserves further investigations (Shin and Cha, 2008; Shin and Ha, 2008). In this study, we assess stereotomography as a tool to build a reliable starting model for frequency-domain FWI from long offset (i.e., wide-aperture) data. Stereotomography is a slope tomography method where the velocity macromodel is estimated from locally coherent events (LCE) characterized by their slopes and their traveltimes in the pre-stack data cube (Lambaré (2008) for a review). A key feature of the stereotomography is that it can be advantageously coupled with semi-automatic picking of traveltimes and slopes of locally-coherent events, which partially frees one from the tedious and difficult interpretive travelt ime picking. While stereotomography was limited to the use of reflection traveltimes so far, we assess in this study the benefits provided by the joint use of refraction and reflection traveltimes in stereotomography. The benefit expected from the refraction traveltimes is to stabilize and improve the imaging of the shallow part of the target during the early stages of the tomography. In a similar manner for frequency-domain FWI, we design a multiscale approach which proceeds hierarchically from the wide-aperture to the short-aperture angles to mitigate the non-linearity of the inversion. In the following, we assess stereotomography as a tool to build a reliable velocity model for frequency-domain FWI with a realistic synthetic offshore case study corresponding to the Valhall model.

**Stereotomography**

In stereotomography, each LCE picked on a given seismogram associated with a stereotomographic data is parameterized by a source and receiver positions (S,R), a two-way traveltime $T_{SR}$, and two local slopes ($P_S = \frac{\partial T_{SR}}{\partial S}$, $P_R = \frac{\partial T_{SR}}{\partial R}$) (Billette and Lambaré, 1998). The stereotomographic data is interpreted as a primary reflection/diffraction data at some position $x$ in depth. The stereotomographic model $m$ is parameterized by the velocity model discretized with cardinal cubic B-splines $C_j$, and pairs of ray segments defined by the position $x$ of the diffracting points, two scattering angles ($\beta_S, \beta_R$) and two one-way traveltimes ($T_S, T_R$). These ray parameters allow one to compute synthetic stereotomographic data, which can be compared with the recorded data. Stereotomographic optimization aims at finding models (velocity and ray segment parameters) that minimize the misfit between recorded and computed stereotomographic data. The tomographic system, regularized by a damping operator, is solved by an iterative non-linear conjugate gradient scheme based on LSQR (Paige and Saunders, 1982).

**Valhall case study**

We applied combined stereotomography and frequency-domain FWI to the synthetic Valhall case study. The Valhall velocity model is shown in Figure 1. The low velocity zone created by the stack of gas layers makes difficult the imaging of the target by FATT. The target zone (Figure 1) was augmented laterally by 8 km on both sides, leading to a 32-km long model. A wide-aperture data set with a maximum offset of $\pm 16$ km was computed in the augmented Valhall model with a two-way wave equation finite-difference time-domain method. The CMP fold provided by this acquisition is shown in Figure 2a. Free surface multiples were not included in the modeling. The source and receiver spacing is 50 m. The source bandwidth is between 10 and 45 Hz (Figure 2b). Before picking, we applied to the data an automatic gain control as well as internal and external mutes to remove as much as possible internal multiples from...
the seismograms (Figure 3a).

Figure 1 Synthetic velocity model of Valhall.

Figure 2 a) Acquisition geometry of the entire survey represented in the CMP-offset domain. The target is the 16-km long model centred on the 32-km long survey. A maximum CMP fold of 320 is reached in the middle of the model. b) Amplitude spectrum of the data set.

Short-offset inversion
We perform a first application where the stereotomography inversion is limited to reflection traveltimes associated with a maximum offset of 4 km (Figure 3a). The horizontal spacing between B-spline nodes is 1 km. A multiscale inversion was subdivided in four hierarchical steps where the vertical spacing between B-spline nodes is progressively decreased from 0.5 to 0.125 km and the damping regularization is progressively relaxed. Starting from a simple vertical-gradient velocity model, a preliminary inversion of few iterations is first performed to remove outliers. The number of iterations during the four inversion steps were between 500 and 750. The final stereotomographic velocity model, centred on the 16-km-long target zone, with and without superimposed dip bars (or migrated facets) (Billette and Lambaré, 1998; Billette et al., 2003) is shown in Figure 4(a-b). This stereotomography model was used as a starting model for frequency-domain FWI. Seven frequencies ranging between 4 Hz and 15 Hz were successively inverted during frequency-domain FWI. The acquisition geometry for FWI is a 16-km-long wide-aperture survey centred on the target zone, with sources and receivers evenly deployed near the surface. The source and receiver spacings are 100 m and 50 m, respectively. The final FWI model is shown in Figure 4c. Vertical velocity profiles extracted from the true model, the stereotomography model and the FWI model in the middle of the target are compared in Figure 5(a-b). The results show inaccurate reconstruction of velocities at the reservoir level at 2.6-km depth below the gas layers.

Long-offset inversion
We performed a second application where the full range of offsets and aperture angles are involved in stereotomography to improve the reconstruction in depth of the velocity model. A multiscale inversion was designed to regularize the inversion of the long-offset data by proceeding successively on local events associated with decreasing scattering angles. Five ranges of scattering angles greater than 130°, 80°, 60°, 30° and 0°, respectively, were used during the inversion. The local events in a shot gather associated with each class of scattering angles are shown in Figure 3(b-d). Our motivation behind this hierarchical strategy is to proceed from the imaging of the long wavelengths from the wide-aperture components to the shorter wavelengths from the short-aperture components to mitigate the non-linearity of the inversion, just like in frequency-domain FWI (see Sirgue and Pratt (2004) for the relationship between scattering angles and spatial resolution of diffraction-based tomography). More inversion iterations (between 500 and 3000) were required for this application compared to the short-offset one to achieve convergence because of the larger amount of data involved in the inversion. This application required a more careful quality control of the semi-automatic picking. For example, events associated
Figure 3 Example of shot gather with superimposed picked data (red bars). (a) Picking is performed for a maximum offset of 4 km. (b-d) Picking of events associated with scattering angles greater than 130° (first-arrivals) (b), 80° (c) and 0° (full data set) (d).

with diffracting points below the gas layers and corresponding to frowning events in common image gathers were identified as multiples from the gas layers and, therefore, removed.

The final stereotomographic velocity model, centred on the 16-km-long target zone, is shown in Figure 3(d-e). The final FWI model inferred from this stereotomographic model used as a starting model is shown in Figure 3f. Vertical velocity profiles extracted from the true model, the stereotomography model and the FWI model are compared in Figure 5(c-d). The FWI model shows an improved reconstruction of velocities at the reservoir level at 2.6-km depth below the gas layers as well as more accurate velocities in the shallow part down to 1 km depth. In fact, the upper part of this FWI model is close to a FWI model that would have been derived from a starting model developed by FATT (Prieux et al., 2009). This strongly suggests that stereotomography successfully inverted the first-arrival traveltimes. We noticed some instabilities in the deep part of the stereotomography model near the lateral end of the model. These instabilities can result from a more limited fold near the ends of the model (Figure 2a). This assumption is being investigated using a 64-km long survey.

Conclusion
We have proposed to use stereotomography as a tool to build a starting model for frequency-domain FWI from long-offset data. The novel aspect is the joint inversion of refraction and reflection traveltimes in a multiscale stereotomography, which proceeds hierarchically from the wide scattering angles to the shorter ones. The Valhall model was successfully imaged by frequency-domain FWI using the stereotomography model as a starting model, where a maximum offset of 16 km was used for both stereotomography and FWI. Since the starting model for stereotomography is a simple vertical-gradient model, stereotomography combined with FWI can be seen as a promising tomographic workflow to build high-resolution velocity models from scratch.

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Figure 4 Short-offset inversion. Final stereotomographic model with (a) and without (b) superimposed dip bars. (c) Final FWI model obtained from the model (b) used as a starting model. (d-f) Same as (a-c) for the long-offset inversion.

Figure 5 Log extracted in the stereotomographic model from the test a) with 4 km offset and c) using aperture angles. b) and d) are the log in their associated FWI model. Red curve is the true model, the black one is the initial model used by stereotomography, and the green and blue curves are the log from the stereotomographic and the FWI model respectively.

References


