Influence of acquisition parameters for 2D acoustic frequency-domain full-waveform inversion.

C. Ravaut (1), M. Alerini (1), J. A. Haugen (2) and B. Arntsen (2)
(1) Seismic and Reservoir technology department, SINTEF Petroleum Research AS.
(2) StatoilHydro research centre, Trondheim, Norway

Abstract

In this paper, we studied and illustrated the influence of the acquisition parameters on the results of 2D acoustic frequency domain full-waveform inversion. We considered two synthetic geological models: a tilted layered blocks model and a complex salt dome model. In the first case, the inverse problem is quite linear up to 5Hz frequency and full-waveform inversion gives well constrained models for more industrial seismic acquisitions. In the salt dome context, the inverse problem is strongly non linear and very low frequencies and large offsets are necessary for full-waveform inversion to reconstruct properly the true velocity model. In this very complex case, dedicated acquisitions, like wide-offsets and low frequency sources, need to be designed to ensure the success of the method

Introduction

Over the last few years, full waveform inversion (FWI) has been used more and more to improve velocity model building in complex geological areas. Formulated in the frequency domain, this technique presents several advantages. Among others, it allows inverting for only a limited number of frequencies, due to the redundancy of information in the wavenumber (Sirgue and Pratt, 2004). In addition, progressively inverting from low to high frequency components helps to mitigate the non-linearity of the inverse problem. This approach has been successful on both synthetic and real datasets (Pratt, 2004). However, the success of the method was proven to be dependent from the initial model, the initial frequency inverted for and the range of recorded offsets.

In this paper, we study and illustrate in more details the influence of these parameters on the results of 2D acoustic frequency domain FWI. In this purpose, we carried out FWI on two very different synthetic cases: a relatively simple tilted layered blocks model representative of the North Sea structure (Stovas et al., 2006) and a more complex salt dome case where FWI was already proven to give encouraging results (Pratt and Brenders, 2004). The three main objectives of this study were: 1) analyze the non-linearity of the inverse problems with respect to the geometry of the acquisition and the inverted frequency, 2) evaluate the capability of FWI to reconstruct the true model using these acquisitions parameters, 3) design the acquisition parameters necessary to ensure the success of the method in those two cases.

By using the same FWI code and the same analysis process for both examples, we want to illustrate the difference between the two geological problems and show how the acquisition parameters need to be tuned to derive well defined images. Pratt (2004) showed the importance of the long offsets in the inversion. Also, in the following, we start performing inversion for long offsets acquisitions and progressively reduce the offset range toward more industrial seismic acquisition geometries. After a short description of the two synthetic velocity models and the FWI code used for this study, we describe the analysis of the FWI results obtained with different acquisition geometries and different initial frequencies in both examples.

Models and Method

For this study, we use two very different synthetic examples (Figure 1). The first one represents a tilted layered blocks model characterised by a large velocity inversion zone located in its upper part. It is quite representative of the North Sea area with low velocity gradient and maximum velocities around 3200 m/s. This model (Stovas et al., 2006) is 10km long by 4.5 km depth and is discretised on a regular square grid of 10 meters. The second synthetic model corresponds to a selected section of the 2004 BP benchmark model centred on the salt dome area which has been recognized as the most problematic part (Billette and Brandsberg-Dahl, 2005). It is characterised by a thick salt dome with vertical roots. This velocity model of 13.5 km long by 4.5 km depth was re-interpolated on a regular 15 meters square grid. For both models, we generated synthetic datasets with different acquisition geometries using sources and receivers spread every 100 meters. The source function is a Ricker wavelet with a frequency content ranging between 0 and 30 Hz and a dominant frequency of 10Hz.

We used here a 2D visco-acoustic FWI code formulated in the frequency domain (Operto et al., 2004; Ravaut et al., 2004). Only Vp velocities are inverted for.

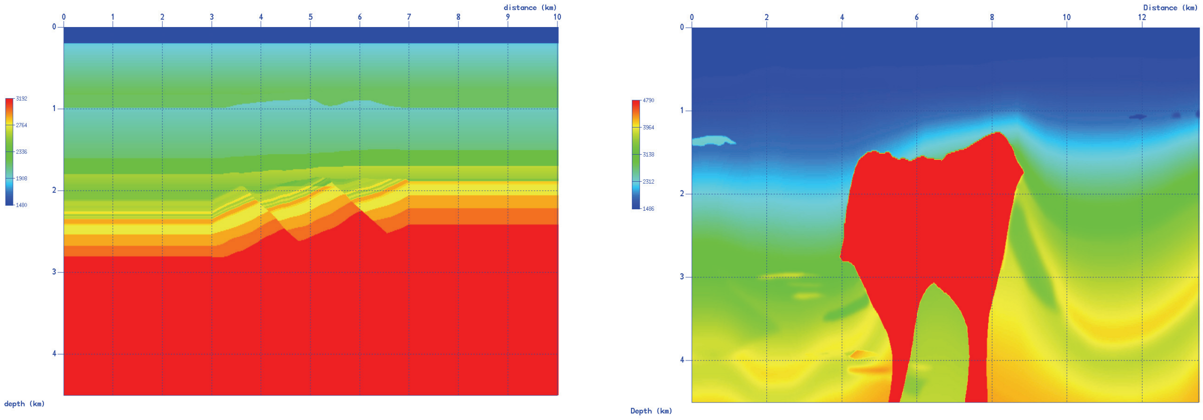

Figure 1: True velocity models. Left) Tilted blocks velocity model, Right) Salt velocity model.

Influence of the acquisition parameters: acquisition geometry and initial frequency

We first analyzed the non-linearity of the inverse problem with respect to the geometry of the acquisition and the inverted frequency. For each case, we considered three different acquisitions and different frequencies. To perform this analysis, we followed the approach presented by Sirgue (2006) where the normalised residuals are represented as a function of the smoothing of the true model (Figures 2 and 3). To evaluate the capability of FWI to reconstruct the true model using these acquisition parameters, we applied the inversion using these different acquisitions and one initial frequency (5Hz in the first case and 1Hz for the second one) (Figures 2 and 3). The starting models used for the inversions were derived by smoothing the true model. Finally, to illustrate the influence of the offset range on the reconstruction obtained by FWI, we represented one wavepath (Pratt et al., 1996) computed in the true model for each acquisition's geometry in the tilted block model (Figure 2).

Case 1: For the tilted blocks model, we considered acquisition geometries of 0-10, 0-6 and 0-2 km and frequencies of 1, 3 and 5Hz. In this case, the inverse problem is relatively linear for 3 and 1Hz frequencies and is slightly more non linear for 5Hz especially for the 0-2 km acquisition (Figure 2). Note that in general, the inverse problem is more non-linear for this acquisition than for the larger offset ones, although the opposite trend is observed when a single range of offset is extracted (Sirgue, 2006). 0-6km and 0-10km curves behave in the same way for all the frequencies. Both acquisitions allow reconstructing the true model using an initial frequency of 5Hz, although a better estimation of the velocity perturbations is obtained when using 0-10 km offsets (Figure 2). More difficulties are encountered when using 0-2km acquisition with an initial frequency of 3Hz as only velocity contrasts at the location of the interfaces are mainly retrieved (amplitude of the velocity perturbations are in this case not well reconstructed). This can be understood by looking at the wavepaths computed in the true model for the different acquisitions (Figure 2 g, h, i). For the same frequency, large offsets acquisition generates wider first Fresnel zone leading to a "tomographic-like" reconstruction (Pratt et al., 1996) of the model in a deeper and wider area. This gives better velocity estimation in these areas. For short offsets, the model is imaged mainly in a "migration-like" mode (higher order Fresnel zones) especially its deeper part.

Case 2: For the salt dome case, we considered three relatively large acquisition geometries: 0-19.5; 0-13.5 and 0-6 km and 3 different frequencies: 1, 3 and 5Hz. In this example, the inverse problem appears to be strongly non linear for every acquisition for frequencies 3 and 5Hz whereas it is slightly more linear for 1 Hz (Figure 3). Large offsets acquisition 0-19.5 km leads to stronger non linear problem at 3 and

5Hz than the other ones. 0-13.5km and 0-6km curves behave in the same way for all the frequencies. At 1Hz, all the acquisition shows the same linearity for their inverse problems. 0-13.5 km and 0-6 km acquisitions allow reconstructing the true velocity model down to about 3.5km (Figure 3 b and c) whereas 0-19.5 km images better the model down to 4km. With 0-19.5 km acquisition, it is possible to get an image of the vertical roots of the salt (Figure 3a). In this salt dome case, large offsets are necessary to image below the salt but they are also the more non linear to handle. To be able to converge to the true solution very low frequencies are necessary. In this example we managed to retrieve a good estimation of the true velocity model with initial frequencies up to 2Hz (Figure 3 g, h, i). Our conclusions are in agreement with the results of the blind test performed by Pratt and Brenders in 2004. Our synthetic study helped to further analyze the problems encountered in their blind test and to confirm the necessity of very low frequencies and large offsets to be able to reconstruct correctly the true velocity structure of this area.

Conclusions

We have studied and illustrated the influence of the acquisition parameters (initial frequency available for the inversion/geometry of the acquisition) for two very different geological contexts. In the tilted block case, the associated inverse problem is mainly linear for a realistic range of frequencies and FWI can converge to the true solution using a starting frequency of 5Hz. If an accurate starting model is available, very similar results can be obtained with 0-6km and 0-10 km acquisitions. In this case, FWI can be easy to apply to derive well defined velocity models and more industrial seismic acquisitions can be considered. In the salt dome case, the inverse problem is strongly non-linear and very low frequencies are necessary to ensure the success of FWI. Large offsets are also essential to image beneath the salt and to construct a well defined initial velocity model. In this case, dedicated acquisition need to be designed for applying FWI, for example wide-offset acquisitions should be preferred (OBS/OBN, wide-azimuth) with very low frequency sources.

Acknowledgements

The authors thank StatoilHydro for funding and allowing publication of the results on the tilted layered block model. The authors thank BP and Frederic Billette for the opportunity of using the 2004 BP benchmark model. This part of the work was sponsored by the Norwegian Research Council, grant 159117/I30.

References

Billette, F. J. and Bransberg-Dahl, S. 2005. The 2004 BP Velocity benchmark. 67th Annual Internat. Mtg, EAGE, Expanded Abstracts, B035.

Operto S., Ravaut C., Improta L., Virieux J., Herrero A. and Dell'Aversana P., (2004): Quantitative imaging of complex structures from multi-fold wide-aperture seismic data: a case of study. *Geophysical prospecting*, 52, 6, 625-651, November 2004

Pratt, 2004 Velocity models from frequency-domain waveform tomography: Past, Present and Future, Presented at the 66th Annual EAGE meeting, Paris.

Pratt R. G. and Brenders A. 2004: Frequency-Domain waveform tomography using refracted arrivals. 66th Annual EAGE meeting, Paris.

Pratt, R.G., Song, Z., and Warner, M. (1996). Two-dimensional velocity models from wide-angle seismic data by waveform inversion, *Geophysical Journal International*, 124, 323-340.

Ravaut, C., Operto, S., Improta, L., Virieux, J., Herrero, A. and Dell'Aversana, P., 2004. Multiscale imaging of complex structures from multifold wide-aperture seismic data by frequency-domain full-waveform tomography: application to a thrust belt. Geophysical Journal International 159, 1032-1056.

Sirgue L. and Pratt R.G. (2004). Efficient waveform inversion and imaging: a strategy for selecting temporal frequencies, *Geophysics*, 69, 231-248.

Sirgue L. 2006: The importance of low frequency and large offset in waveform inversion. 68th Annual EAGE meeting, Vienna.

Stovas et al., 2006: A sensitivity study based on 2D synthetic data from the Gullfaks Field, using PP and PS time-lapse stacks for fluid-pressure discrimination, *J. Geophys. Eng.* **3** 314-328 doi:10.1088/1742-2132/3/4/003

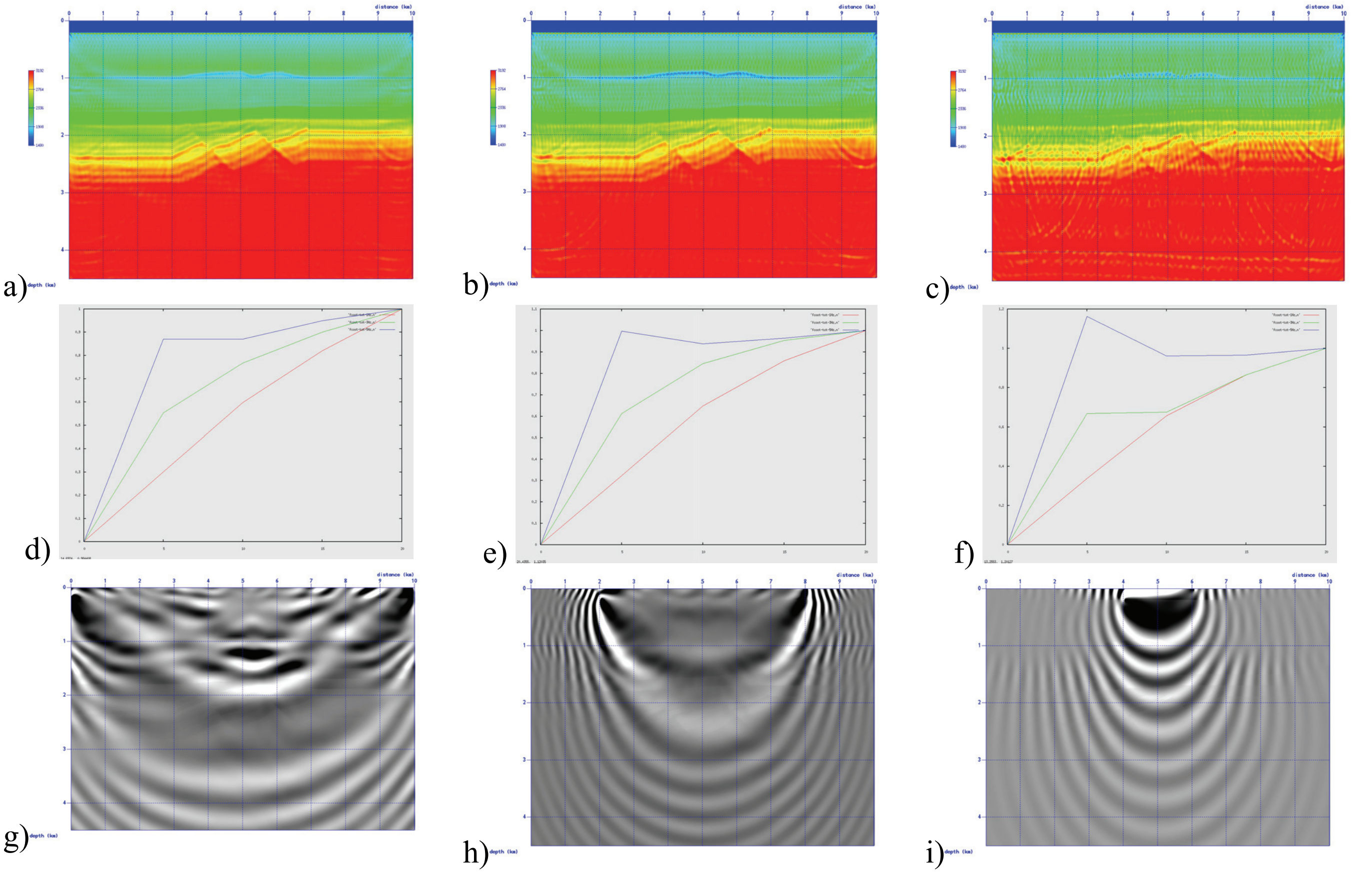

Figure 2: Reconstructed velocity models after inversion of 13Hz with an initial frequency 5Hz for acquisition a) 0-10km, b) 0-6km and initial c) 0-2km acquisition and 3Hz. Analysis of the non linearity of the inverse problem: normalised residuals (vertical axis) with respect to the smoothing factor of the true model (horizontal axis) and different frequencies for acquisition geometry d) 0-10km, e) 0-6km, f) 0-2km. The red, blue and green curves correspond respectively to 1Hz, 3Hz and 5Hz. Wavepath computed in the true model for the same conditions than g) figure a), h).figure b and i) figure c.

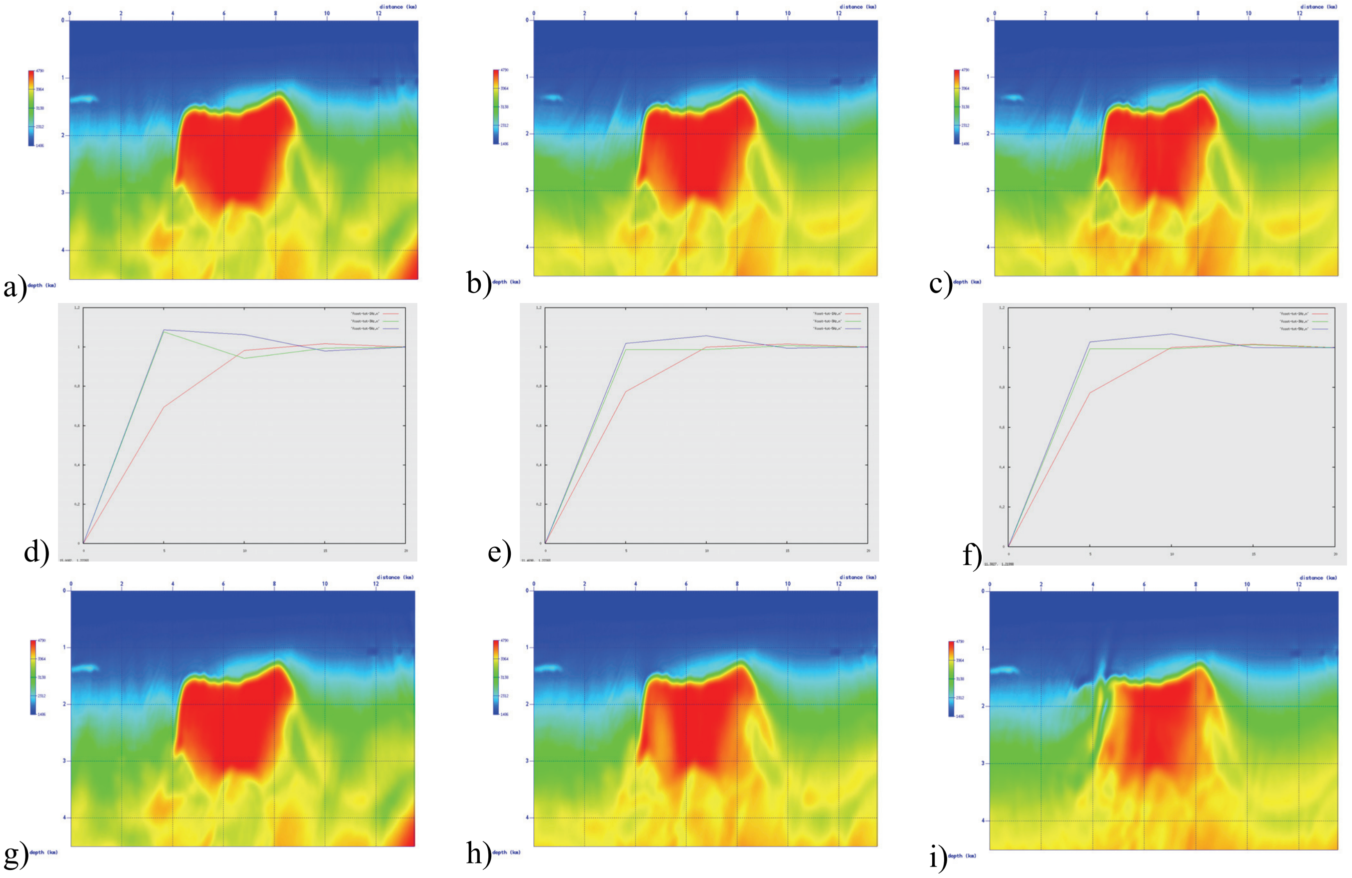

Figure 3: Reconstructed velocity models after inversion of 7 Hz with an initial inverted frequency of 1Hz and acquisition of a) 0-19.5km, b) 0-13.5km, c) 0-6km. Analysis of the non linearity of the inverse problem: normalised residuals (vertical axis) with respect to the smoothing factor of the true model (horizontal axis) and different frequencies for acquisition geometry d) 0-19.5km, e) 0-13.5km, f) 0-6km. Same curve colors than in Figure 2.Velocity models derived by FWI after inversion of frequency component 7Hz using 0-19.5 km acquisition and initial frequency g) 1Hz, h) 2Hz and i) 3Hz.