Full Waveform Inversion: Confronting Conventional and Blended Acquisition

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Abstract

This work compares the possible impact and improvement of the blended acquisition in the context of the full waveform inversion (FWI) in comparison with the conventional acquisition.

In the blended acquisition scheme, the possibility of overlapping shot-records allows acquiring densely sampled data within the same acquisition time. In this configuration it also becomes more feasible the recording of longer offset data and with a wider range of azimuths. This data is crucial for outlining dipping structures and flanks of salt domes in inversion algorithms.

The extra data originated from the blended acquisition is important for the stability of the FWI, when compared with severely under-sampled and noisy data. Also, the blended data is convenient in the proposed FWI methodology since the deblending procedure of the data (i. e., separation of the interference between shots) in not necessary.

The presented numerical results on the Marmousi model show how the blended acquisition data aids the convergence of the inversion algorithm, specially with a low signal to noise ratio data.

Introduction

The need of the oil industry to explore areas with complex geology pushes the development of geophysical imaging and inversion techniques. The ones that are data driven and that take into account the full effects of propagation of the seismic wave are the most likely to stay as the industry standard in the next years, since they should reduce the laborious human intervention in some critical processing stages while profiting from the full range of geophysical events present in the seismic data.

Amongst this class of techniques, the FWI (Lailly, 1983 and Tarantola, 1984) appears as a proposal to extract geophysical properties information by data-fitting the modeled full wave-field with the registered seismograms. Such bold and computationally intensive program faces great challenges, since the local optimization schemes are doomed to converge to local minima. This happens, among other reasons, due to the presence of noise and data incompleteness.

In this vein, the concept of silmultaneous source or blended acquisition as proposed by Beasley et al. (1998) and Berkhout (2008) may come as a solution for some of these issues. By allowing temporal superposition of shot records, the inversion scheme benefits from the densely sampled and wide-offset/azimuth source distributions survey. Thus, blended acquisition may imply better stability and quality data for FWI, while maintaining the acquisition costs affordable.

Motivated by the proposal of Bulcão et al. (2012) of extending the Finite Difference Contrast Source Inversion (FDCSI) to handle data from blended acquisition, it is proposed to investigate an analogous extension in the context of FWI. This methodology is applied to the Marmousi model, where the efficiency and stability improvement of this methodology are evaluated when compared with the traditional acquisition.

Full Waveform Inversion with Blended Data

Following the formulation of Berkhout (2008), the wave-field measured along the observation surface $\mathbf{P}(z_0,z_0)$, may be written in the frequency domain with matrix notation as:

$$\mathbf{P}(z_0,z_0) = \mathbf{D}(z_0,z_0)\mathbf{X_0}(z_0,z_0)\mathbf{S}(z_0), \tag{1}$$

where $\mathbf{D}(z_0,z_0)$, $\mathbf{X_0}(z_0,z_0)$, and $\mathbf{S}(z_0)$ represent the impulsive response of the detector arrays, the multidimensional transfer function of the subsurface $(z > z_0)$, and the source arrays, respectively. The concept of blending in the source domain may be formulated as:

$$\mathbf{S}_{bl}(z_0) = \mathbf{S}(z_0)\Gamma_{bl}(z_0), \tag{2}$$

where the operator $\Gamma_{bl}(z_0)$ comprises the random time delays, t_n. In matrix form, $\Gamma_{bl}(z_0)$ is cast as:

$$\Gamma_{bl}(z_0) = \left[e^{-i\omega t_1}\ e^{-i\omega t_2}\ \cdots\ e^{-i\omega t_N}\right]^T. \tag{3}$$

Accordingly, the modeling of blended seismic data is obtained by

$$\mathbf{P}_{bl}(z_0) = \mathbf{P}(z_0)\Gamma_{bl}(z_0). \tag{4}$$

Having defined the shot-blending formulation, the FWI may be conceived as the problem of minimizing with respect to the geophysical parameter, m (in this work, the square of the p-slowness) the L_2-norm misfit of the observed blended data, d_{bl}, and modeled blended data $\mathbf{P}_{bl}\,(m)$:

$$J_D(m) = \frac{1}{2}\left\|\mathbf{P}_{bl}(m) - d_{bl}\right\|^2 . \tag{5}$$

In this proposal, it is evident that there is no need for a deblending procedure (i. e., separation of the interference between shots), since the modeling is apropriate to handle blended data.

Also, to ensure the continuity of the velocity model as an *a priori* information, it is possible to modify the misfit function by a multiplicative regularization term (van den Berg et al. 2003), (Abubakar et al. 2004) and (Ramírez and Lewis 2010):

$$J(m) = J_D(m)\,R(m), \tag{6}$$

A suitable choice for the $R(m)$ is the weighted L_2-norm, which ensures continuity of the velocity model with possible sharp model parameter contrast:

$$R_{WL_2}(m) = \frac{\int\left[|\nabla m|^2 + \gamma_{k-1}\right] d\Omega}{\int\left[|\nabla m_{k-1}|^2 + \gamma_{k-1}\right] d\Omega}, \tag{7}$$

with $\gamma_{k-1} = J_D(m_{k-1})\,\delta/\Delta V$ and δ a parameter defined by the user to control the regularization strength.

Given these considerations the update of the square of the p-slowness may be done by the steepest descent method,

$$m_k = m_{k-1} - \alpha \nabla J(m), \tag{8}$$

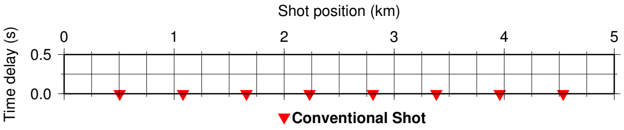
or a conjugate gradient method. The value of α is found using some type of line-search technique.

Results for the Marmousi Model

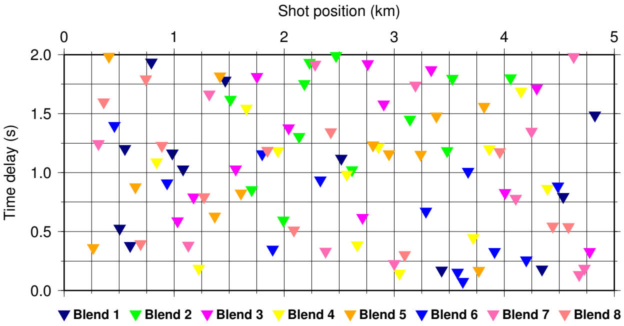
The results for the proposed methodology are applied to the Marmousi model (Bourgeois et al., 1991), shown in Fig. 4a. Four datasets were used. The first simulates a conventional acquisition procedure, where each shot gather registers only one shot, without time overlapping. The shot positions for the conventional survey are shown in Fig. 1a. The second dataset simulates the blended acquisition procedure (c.f. Eq. 4) where it is registered the wave-field originated from several sources with random time delays between them. The blended shot positions used in this work are shown in Fig. 1b. Also, for each dataset, two others were created with 20% additive random noise (in relation to the maximum amplitude of the dataset). A representative seismogram for each of these datasets is presented on Fig. 2.

The datasets were modeled in the frequency domain considering a fixed-spread acquisition geometry with 384 receivers along the surface. For the conventional acquisition were simulated 8 seismograms for equally spaced individual sources. In the blended case, 8 seismograms with 12 randomly distributed sources were modeled with less than 2s ramdom time-delay. The other modeling and inversion parameters are given in Table 1:

The inversion process was also carried out in the frequency domain. Only ten frequencies were used in the inversion scheme: starting from 5.37 up to 23.43 Hz with intervals of 1.95 Hz. On a multiscale fashion, the velocity model generated for a lower frequency inversion became the input velocity model for the next frequency. For each frequency, 25 iterative steps were used. Also, three loops over these frequencies were performed. The initial velocity model used for the inversion is represented on the Fig. 4b.

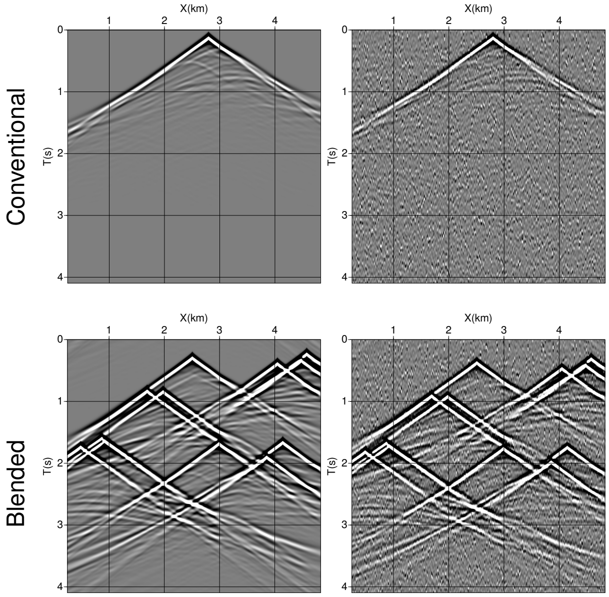


(a) Conventional shot positions



(b) Blended shot positions

Figure 1: Representation of the shot positions and time delays for the conventional acquisition (on the top) and blended acquisition (on the bottom).



Noise free data Noisy data

Figure 2: Seismograms used as input for the inversion scheme. On the top (bottom) is presented the data for conventional (blended) acquisition. The noise free data is on the left-side and the data with additive random noise is given in the right-side

Figure 4 contains the final results of the FWI and Fig.

Table 1: Modeling and inversion parameters

Grid point interval (h)	12 m
Time step	1 ms
Model dimension X and Z	384 x 120 grid points
Number of shot gathers	96
Number of receiver gathers	382
Shot interval (conventional)	576 m
Shot interval (blended)	48 m
Receiver interval	12 m

3 shows the relative objective functional for the first frequency inverted in the four proposed scenarios. By these results, one may see that:

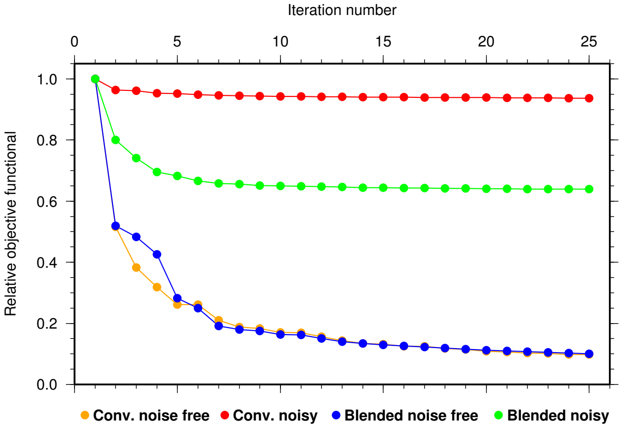


Figure 3: Graph of the relative objective functional for the inversion of the first frequency.

- In a noise-free scenario, the results for the conventional and blended datasets are very good and nearly equivalent (Figs. 4c and 4e) throughout the whole model. In fact, the fixed spread geometry of the receivers favors a good illumination of the subsurface, except on the borders and deeper region of the model. These results corroborate the robustness of the FWI algorithm that was used.

- The result of the inversion for conventional acquisition with noisy data is seriously innacurate (Fig. 4d). The low signal to noise ratio in this configuration inhibits a successful inversion, specially in the deeper region of the model.

- For the noisy data in the blended acquisition (Fig. 4f), the densely sampled dataset within the same noise configuration helps to stabilize the inversion problem. The Marmousi velocity model was greatly recovered, aside from small artifacts in the deeper region.

- The velocity profile presented in Fig. 4g shows that the conventional noise-free, blended noise-free and blended noisy-scenarios follow the true velocity model trend, while the conventional noisy data result gives wrong velocity measurements in several depth positions.

- All of these remarks are corroborated in Fig. 3, where the relative objective functional decreases faster for the conventional and blended noise-free scenarios, followed by the blended noisy and conventional noisy configurations.

Conclusions and Discussion

It has been shown that the usage of the blended data may be a good strategy in the context of FWI to stabilize the inversion process, when compared with a severely under-sampled conventional acquisition. Such alternative becomes more evident when noisy data is considered. Therefore, blended acquisition may be an important tool to reduce the impact of the ambient noise in the inversion of real data.

Also, the proposal for implementing the FWI algorithm for blended data is very efficient in the sense that there is no need for a deblending stage. The reason is that the interference between shots is modeled by the algorithm and inverted in the same way. This comes with no extra computational cost for the FWI algorithm.

Acknowledgments

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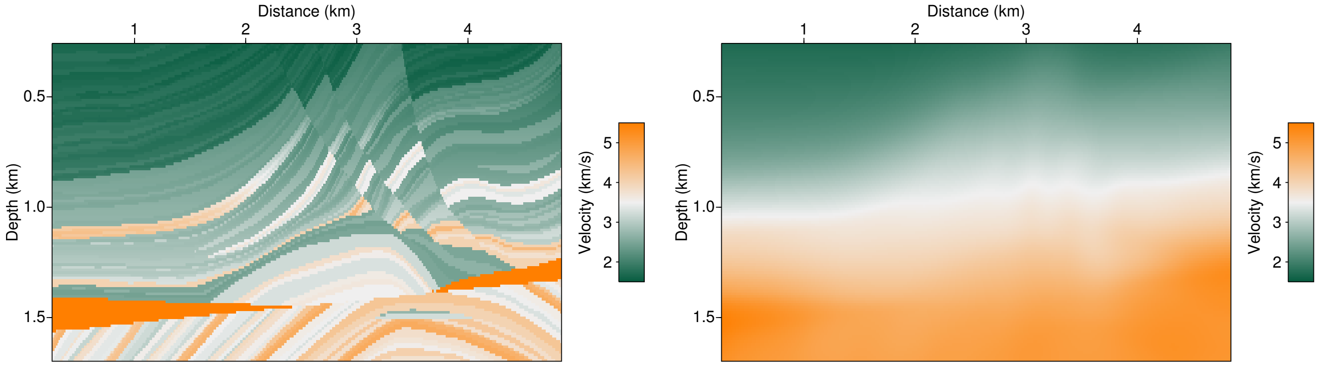
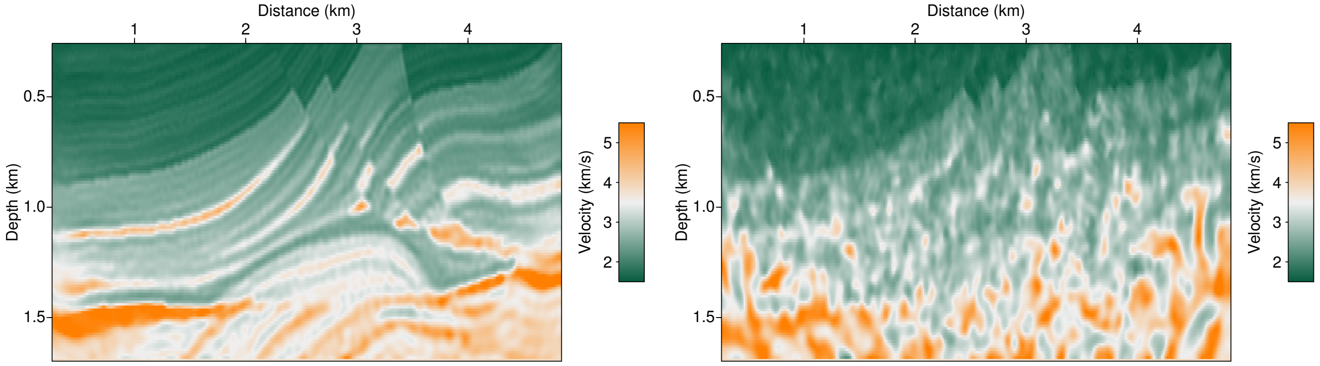
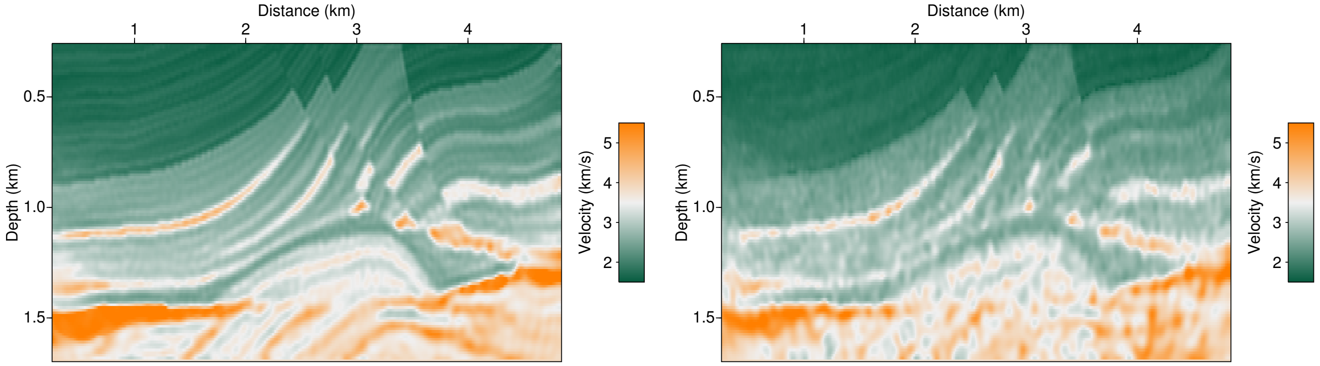


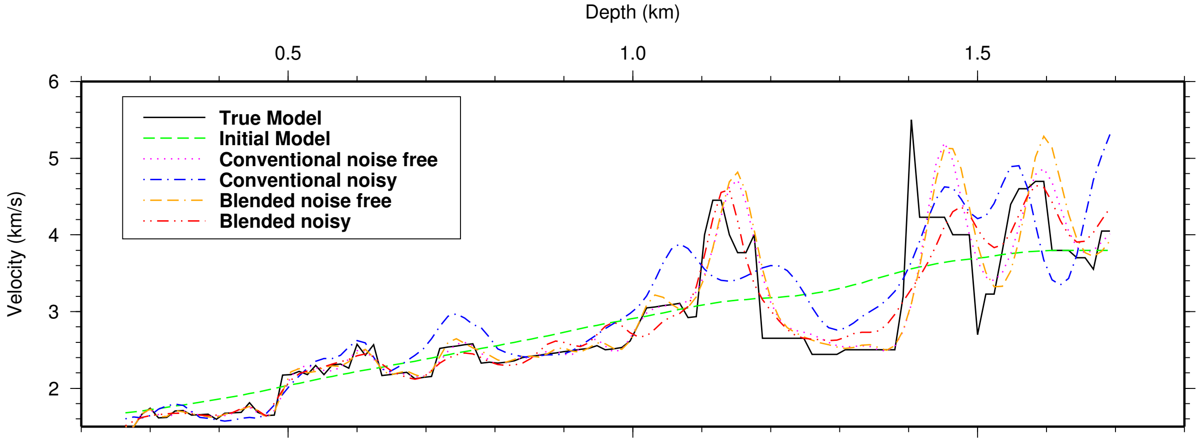
(a) True Marmousi velocity model (b) Initial velocity model



(c) Result for conventional noise-free data (d) Result for conventional noisy data



(e) Result for blended noise-free data (f) Result for blended noisy data



(g) Velocity profile at x=3.5 km

Figure 4: Results of the FWI the Marmousi velocity model. The true Marmousi velocity model is given on Fig. 4a. The initial model for the inversion is depicted on Fig. 4b. The inversion results for the conventional and blended datasets with and without noise are shown in the Figs. 4c-4f. Also, a velocity profile for the presented results at the position x=3.5 km is given in the Fig. 4g.