Full Waveform Inversion with Blended Seismic Data

André Bulcão, Djalma Manoel Soares Filho, Gustavo Catão Alves, Luiz Alberto Santos, Túlio do Valle Moreira (PETROBRAS), Peter van den Berg, and Dries Gisolf. (Delft University of Technology)

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Abstract

Full waveform inversion has the potential of playing the central role in seismic imaging in the near future. In fact, its power of providing higher seismic resolution compared to pre-stack depth migration may contribute to seismic interpretation in areas which present highly complex geology.

However, for complex geological models the success of seismic imaging depends on the design of the seismic experiment. In fact, besides the necessity of a broad band of frequencies, it is required to properly record the scattering wavefields associated with geological targets. Otherwise, the imaging and inversion schemes shall not be effective.

Acquiring the scattering wavefields as a 3D field may be unfeasible by using conventional schemes, where consecutive shot records don't have record time superposition. In this work, we abandon this condition, and extend the inversion scheme called Contrast Source Inversion (CSI) to handle data in which shots are superposed randomly (Blended data). On the proposed method, the deblending phase (separation of the interference between shots) is not necessary.

Numerical results applied on Marmousi model show how efficient, accurate and stable this method is when compared to results obtained with traditional acquisition approaches. Even in very low signal to noise ratio cases, except for small artifacts, it was possible to recover all features present in the original model.

Introduction

Seismic Migration has played a major role in data processing and interpreters have succeeded using migrated sections to find gas and oil fields, although it has been mainly based on the Born approximation. However, as exploration moves into more complex areas, those tasks become far more difficult to accomplish using conventional imaging approaches than they used to be. The development of subsalt fields in offshore Brazil is a good example (Beltrão *et al.*, 2009). Therefore, it is time to develop processing tools which go beyond the first iteration of the seismic inverse problem. In this sense, full waveform inversion is a promising candidate.

However, proper record of the scattering wavefields associated with the target zones is necessary for any kind of full waveform inversion scheme. In fact, without the fulfillment of this condition it is naturally impossible to succeed in solving the inverse problem. Therefore, as new discoveries are considered in areas associated with highly complex geology (which means wide spread scattering wavefields), wide azimuth acquisition surveys with high density of receivers and shots become a necessity. However, the costs involved in this kind of survey are not always acceptable, and full waveform inversion methods are many times applied to data which contain only a small part of the scattering wavefield connected to the target zones.

Having in mind the need to decrease the costs of this kind of data, Berkhout *et al.* (2008) introduced the concept of blended acquisition, which aims to increase the efficiency of densely sampled and wide-azimuth source distributions surveys, abandoning the condition of non temporal superposition of shot records. Therefore, it is believed that the space aliasing problem provoked by missing shot records is much harder to manage than the interference problem that arises as the result of randomly overlapping shot records.

In this work, this assumption for full wave-form inversion is verified. Specifically, the method of Finite Difference Contrast Source Inversion (FDCSI) proposed by Abubakar *et al.* (2009) is extended to handle data from blended acquisition surveys, and present applications on the Marmousi model in order to demonstrate the accuracy, stability and efficiency of the method. It is worth to mention that the Blended Data Finite Difference Contrast Source Inversion method succeeded even when starting from frequencies that are truly present in real cases, and using initial models obtained by severe smoothing of the target zone.

Contrast Source Inversion with Blended Data

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

$$\mathbf{P}(z_0, z_0) = \mathbf{D}(z_0)\mathbf{X_0}(z_0, z_0)\mathbf{S}^{+}(z_0) \text{ ,}$$

where $\mathbf{D}(z_0)$, $\mathbf{X_0}(z_0, z_0)$ and $\mathbf{S}^{+}(z_0)$ represent the impulsive response of the receiver arrays, the multidimensional transfer function of the subsurface $(z > z_0)$, and the source arrays, respectively. The *0* subscript refers to surface coordinates. The concept of blending in the source domain is introduced by:

$$S_{bl}^{+}(z_0) = \mathbf{S}^{+}(z_0)\Gamma_{bl}(z_0) ,$$

where $\Gamma_{bl}(z_0)$ is the matrix representation of the blending operator,

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

where t_n are random time delays.

Then, the blended seismic data are given by the data vector:

$$P_{bl}(z_0, z_0) = \mathbf{P}(z_0, z_0)\Gamma_{bl}(z_0).$$

On the other hand, considering that the observed blended wavefield is given by the sum of incident and scattering ones, $P_{bl}(z_0,z_0) = P_{bl}^{inc}(z_0,z_0) + P_{bl}^{sct}(z_0,z_0)$, the cost functional to be minimized is a generalization of the one proposed in van den Berg & Kleinman (1997), i.e.,

$$F(\chi, w_{bl,j}) = \sum_{j=1}^{N} \frac{\left\| P_{bl,j}^{sct} - M^S H_b^{-1}(k_b^2 w_{bl,j}) \right\|_S^2}{\left\| P_{bl,j}^{sct} \right\|_S^2} + \sum_{j=1}^{N} \frac{\left\| \chi P_{bl,j} - w_{bl,j} \right\|_D^2}{\left\| \chi P_{bl,j} \right\|_D^2},$$

in which, χ and w_{bl} denote the velocity contrast $(v_b^2/v^2 - 1)$ and the contrast-source function (χP_{bl}), respectively. H_b^{-1} stands for the inverse of the Helmholtz operator, i.e., $H_b P = \left(\nabla^2 + k_b^2\right)P$, and M^S projects the estimated blended wavefield along the observation surface S (see Figure 1). Finally, D is the domain where $\chi, w_{bl,j}$ are estimated. We minimize the above functional by estimating χ and $w_{bl,j}$ in an alternating way, using the conjugated gradient method, and the Helmholtz operator is represented in a matrix form by approximating the derivatives in the forward problem by finite differences (Abubakar et al, 2009).

Numerical Application

The current methodology was employed on two different datasets. The first one simulates a conventional acquisition procedure, where each shot gather records only one shot (without superposition between shots). The second dataset simulates the blended acquisition procedure where in the same shot gather (or experiment) several shots are fired and recorded within the same gather with random time delays between them. To generate these datasets, the Marmousi velocity model depicted in Figure 2 was used.

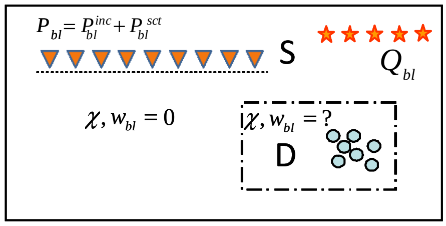

Figure 1: Schematic representation of the inverse problem.

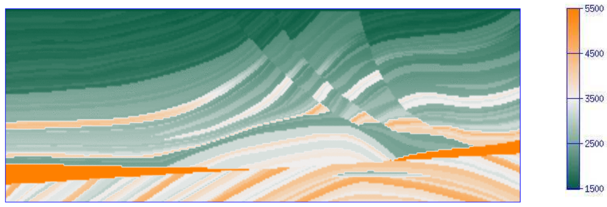

Figure 2: Marmousi velocity model. Velocities are in m/s.

Receiver locations were chosen along the entire surface of the velocity model. In addition to the conventional and blended datasets, two other datasets were created with 10% (with respect to the maximum amplitude of the datasets) of additive random noise. The parameters employed are presented on Table 1. In these examples, one experiment is considered as a single conventional (single source) common shot gather or a single blended (multiple sources) shot gather.

Table 1: Model parameters

Grid point interval (h)	12 m
Time step	1 ms
Model dimension for X and Z directions	384 x 122 (grid points)
Number of gathers (experiments)	8
Conventional data: shots per experiment	1
Blended data: shots per experiment	12
Blended data: maximum time delay	2.0 s

Figure 3 presents examples of the conventional and blended datasets (seismograms), as well as the datasets with added noise. Even though the inversion is performed in the Frequency Domain, the datasets shown in Figure 3 were converted to the time domain, making them easier to interpret.

Figure 4 depicts the initial velocity model employed, created with a moving average of 30 grid points on the Marmousi velocity model.

According to Table 1, eight experiments were generated for the conventional and blended cases. Figure 5 represents the time delay used in each experiment (indicated by the different colours). For the blended data, each shot gather has twelve shots with a random time delay between them.

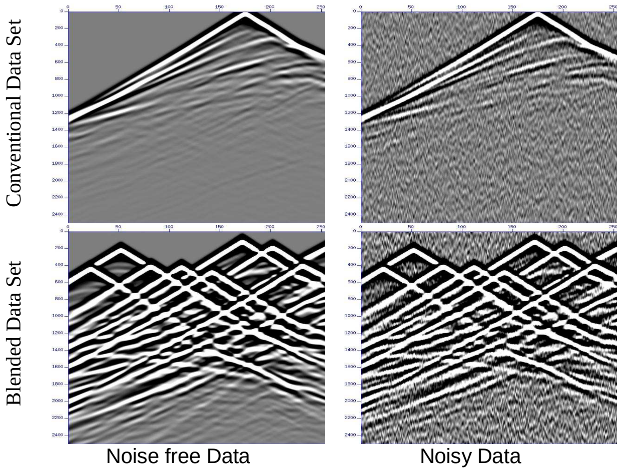

Figure 3: Seismograms used as input for the inversion scheme, for the conventional (top) and the blended (bottom) cases with (right) and without (left) additive random noise. Time is in ms and X coordinates in grid numbers.

Figure 4: Initial velocity model. Velocities are in m/s.

Only fifteen frequencies were selected to be inverted, from 7.32 up to 24.41 Hz with increments of 1.22 Hz, on a multi-scale fashion. On this procedure, the velocity model generated for a lower frequency is the input velocity model for the next frequency.

Figure 6 shows the final results for the inversion using the generated datasets for conventional and blended data, with and without random noise. These results lead to the following:

- Comparing the noise free results, the interferences between the shots in the blended case produce small artifacts in the final velocity model;
- For the noisy data sets, the greater illumination present in the blended case helps to stabilize the inversion problem;

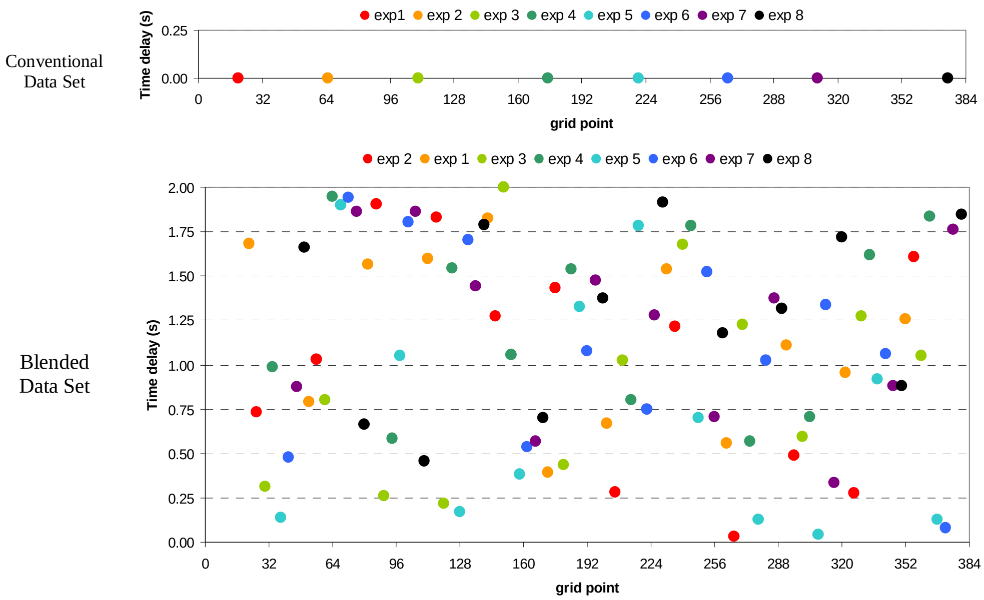

Figure 5: Representation of the time delay between gathers for conventional and blended cases.

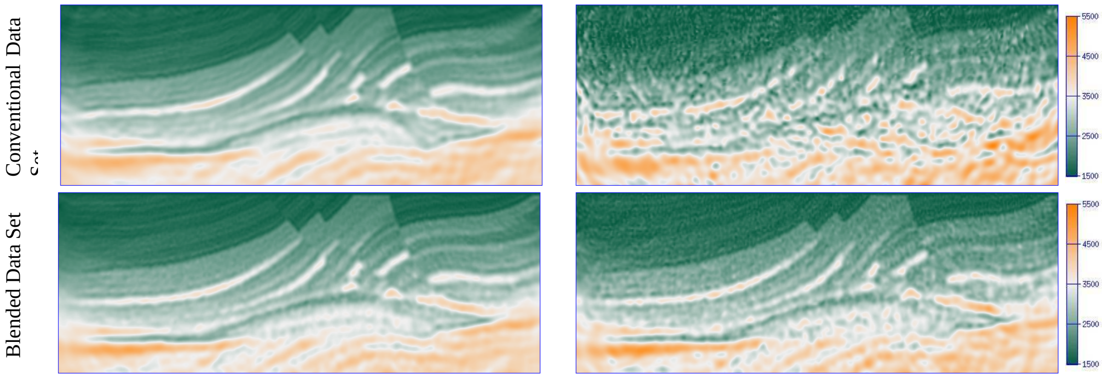

Figure 6: Finite difference contrast-source inversion results. Velocities are in m/s.

Conclusions

The extreme low number of experiments - only eight - was purposely selected to estimate the method´s stability considering the datasets with and without noise for this rough condition. Even though it was possible to achieve good results, recovering entirely the main features of the original velocity model, only with the conventional acquisition dataset with noise the inversion seems to have reached a local minimum. In this case, maybe including more information for the inversion algorithm (more common shot gathers) it would be possible to produce an output model with similar quality.

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