# Full Waveform Inversion: Investigating resolution on a Santos Basin model

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### Abstract

One very important point in Full Waveform Inversion is to know how far it goes in terms of resolution. In other words, up to which point can it fill the gap between low and high wavelengths as well as go beyond the limits established by the more traditional schemes, such as traveltime tomography and reverse time migration.

In this work, we investigate how well we can perform by using both reflected and refracted wavemodes in numerical simulations performed on a complex pre-salt model based on Santos Basin, offshore Brazil. We analyze the effects of maximum offsets, frequency content, and initial models in the convergence to the global solution.

### Introduction

Full waveform inversion remains one of the most promising techniques in imaging and inversion of seismic properties. In fact, results of applying it in determining velocities fields for depth migration, over the last few years, exhibits a resolution rarely seen in traditional inversion methods. The velocity field proper is becoming an interpretation tool, besides seismic volumes and impedances. The reason for its success lies on the fact that FWI, as the name implies, deals with the wave field in all its aspects, i.e. the left hand side in the *d=Gm* equation presents not only travel times and primary reflections, but also many other wave modes made manifest by the elastodynamic equation, such as primary reflections e multiples of any order, diffractions, refractions, reverberations and converted waves. It is a matter of an inversion process which explores the seismic data bank in a much broader way, in relation to traditional methods (Lailly 1983 & Tarantola 1984) However, FWI is a considerably non-linear optimization process. The model space is packed with local minima serving as traps to the search by gradient-based optimization processes.

The inversion methods exploring model space as a whole still involve a computational cost way above current capabilities. This way, the careful choosing of an initial guess in the vicinity of global minima is paramount for success. Such is the point in which resides the question brought by this work. What is, in practice, a good starting model? More to the point, in the context of the models of interest, which would be the bands of low, mid and high frequencies exposed by Claerbout (1985) that would define the resolution in seismic method?

On another front, Jennane et al. (1989) bluntly affirm the seismic method is incapable of obtaining wavelengths around 60 to 300 meters, the so called intermediate waves. Beyond the 300 meters mark, the more traditional methods of inversion of the velocity field – migration velocity analyses and travel time tomography, to name two – are very efficient. From 20 to 60 meters, PSDM gives good results (in reflectivity). However, despite the importance of that work, it catered to a very specific context. They considered exclusively reflected waves, registered in acquisitions with short offset; the inversion was made in time domain, with the classic $L_2$−norm objective function. They have not gone multi-scale (Bunks et al., 1995 & Hicks & Pratt, 2001), a strategy known for mitigating non-linearity. Would it be that, with the achievements of recent years in FWI, we would be able to bridge the mid wavelength gap, with a more effective use of reflected waves? We believe so.

This work raises the question and presents partial results of a study in resolution, in the light of the multiscale strategy. We performed two numerical experiments using as a model one which represents the typical reality of the Santos Basin. The first tackles the influence of large offsets while the second presents the result of inversion in face of disturbances of different resolutions.

### FWI

In general terms, FWI strategies are defined by the following choices: (1) domain (whether time or frequency); (2) wave modes included (usually refracted waves and diving waves); (3) type of objective function; (4) method for obtaining calculated data; (5) method for obtaining the Frechét derivatives; (6) mathematical model (acoustic, pseudo-elastic, isotropic elastic, anisotropic, viscoelastic); (7) strategy for obtaining the initial model (the result of a PSDM migration, for instance); (8) how the models (velocity, impedance, density) are represented. The most common way are values spread over an even grid, but there are many alternative choices, one good example being the Image-guided sparse-model FWI, proposed by Yong Ma (2012); (9) strategy for obtaining gradient and Hessian (commonly, the adjoint method) and optimization method (gradient, conjugate gradient, quasi-Newton, Newton); (10) pre-processing of data and QC methods applied along the optimization process.

In this work, we opt for the multiscale, Full Waveform Inversion in time domain, i.e. from the original seismic dataset, subsets have been taken by means of progressively higher low-pass filtering (Bunks et al., 1995). Regarding the objective function, we choose the $L_2$−norm of the difference between observed and calculated data. Both calculated data and gradient, as well as approximations to the Hessian, are carried out in the finite differences method. The chosen mathematical model has been acoustic with variable density. Each iteration took the conjugate gradient method. The stopping criterion we chose was simple iteration count.

**Application**

In the first experiment, we have estimated the performance of the classical FWI applied to a typical Santos Basin model. (Figure 1). The specific objective was to verify the role of the lowest valued, yet valid frequency and the largest offset possible, based on current reality. We simulated two acquisitions with sources and receptors positioned at sea surface with max offsets of 8 and 16 kilometers. In the case of the 8Km cable, we considered 4Hz as the lowest possible valid frequency. In the other case we allow for 2Hz. Figures 2a and 2b present the corresponding common shot gathers. Notice the many refracted waves registered in the second case.

In the first case, just direct wave and reflections in the main horizons are promptly recognizable. In both cases, 50 common shot gathers were generated, with a spacing of 300m and receptors every 25m. The 12Hz cutoff Ricker wavelet acted as source signature. Figure 3 presents the initial model and figure 4 shows the results.

In the second experiment, we estimated the resolution in classical FWI as exposed by Jennane et al. (1989). However, instead of considering different unidimensional perturbations with different wavenumbers, we considered square-shaped disturbances of many sizes. These were implemented as a ±5% change over the original model, as depicted in figures 5a, 6a, 7a and 8a. Square sizes are 200m, 400m, 600m and 800m. We used the same parameters as the ones used in the second case of the first application. The results are exposed in figures 5b, 6b, 7b and 8b.

**Conclusions: Offsets, frequency, initial model and non-linearity**

In the first part of the first experiment, departing from an initial model that was is relatively distant from the target model, maximum offsets of 16Km and lowest viable frequency of 2Hz, we have obtained satisfactory results, with the exception of the unnatural numerical borders. Specifically, success has been obtained in recovering the velocity field in all post-salt, salt and pre-salt regions. However, in the 8Km−4Hz case, we could not resolve very well in the regions below the top of the salt layer.

In the second part of the first experiment, disturbances sized over 400m have been recovered well under the 16Km−2Hz assumption. This suggests features of this magnitude could very well be interpreted in the velocity model and certainly the presence of the same would considerably increase resolution in the final migrated image.

In the second application, the method was able to detect the 800m squares. However, initial model choice played a very important part. In both applications, the initial models had the intermediate frequencies in them. Had they not, there could be convergence to local minima and the results would be much less appealing. Another crucial aspect to this good behavior lies on the fact of the non-linearity that the virtual sources (scatterers) promote, critically so in improving the bottom model.

We must point out that in these experiments we have been very conservative in respect to the initial model, an extremely smoothed out version of the target model. In practice, usually, the model estimated by reflection tomography or migration velocity analysis techniques come relatively close to global minimum. On the other hand, we could have used more effective techniques, as the one proposed by Yong Ma (2012) and then start the inversion process from an initial 1D model, even if it bears little resemblance to the model to be recovered.

At last, we would like to emphasize that the success of the FWI method is intimately tied to the fact that it goes beyond the Born approximation. In general terms, the use of seismic illumination in regions of interest is promoted by the multitude of virtual sources, i.e. multiples of all types and orders are the key to achieve images of higher quality.

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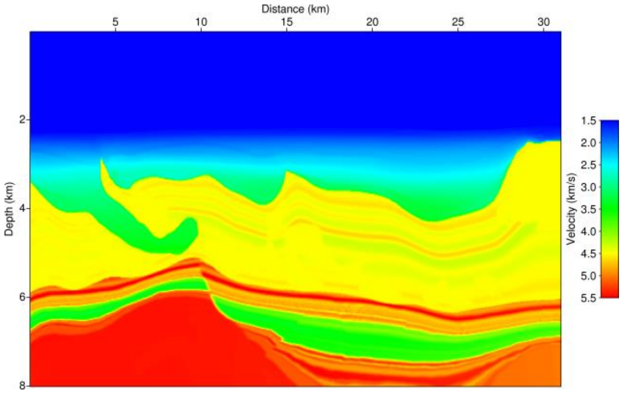


Figure 1: Target model, a typical reality in the pre-salt region in Santos basin.

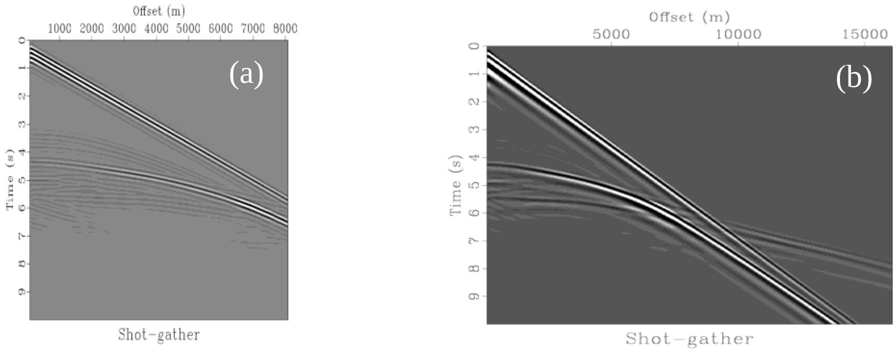


Figure 2: Common shot gathers: (a) Maximum offset of 8Km, lower viable frequency of 4Hz; (b) Maximum offset of 16Km, lower viable frequency of 2Hz.

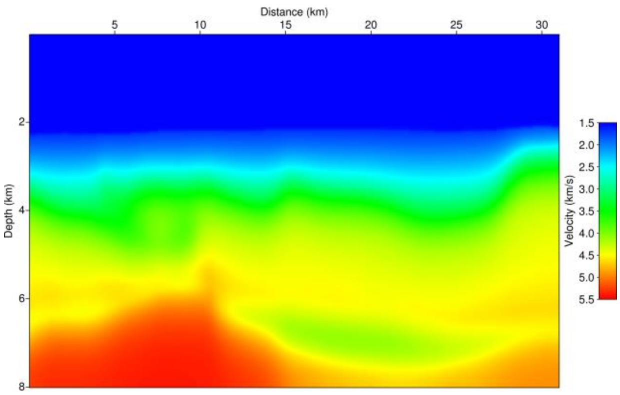


Figure 3: Initial model

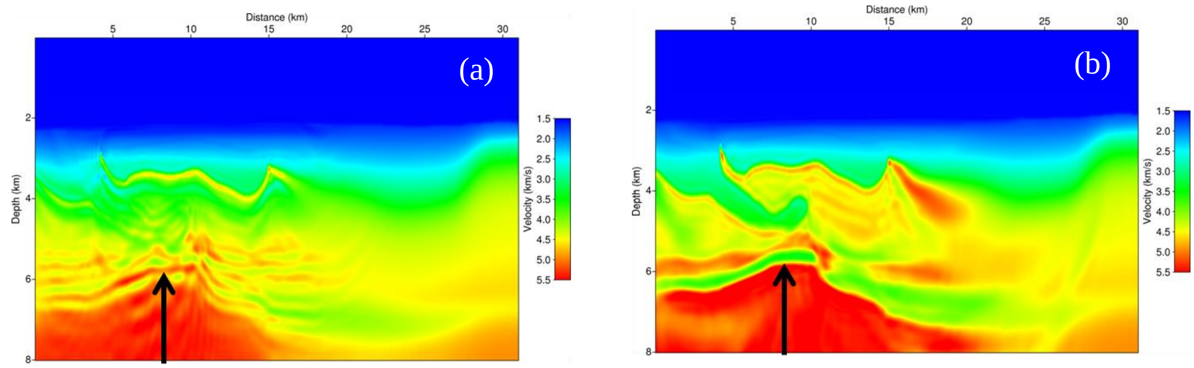


Figure 4: Results obtained with assumptions (a) 8Km−4Hz e (b) 16Km−2Hz.

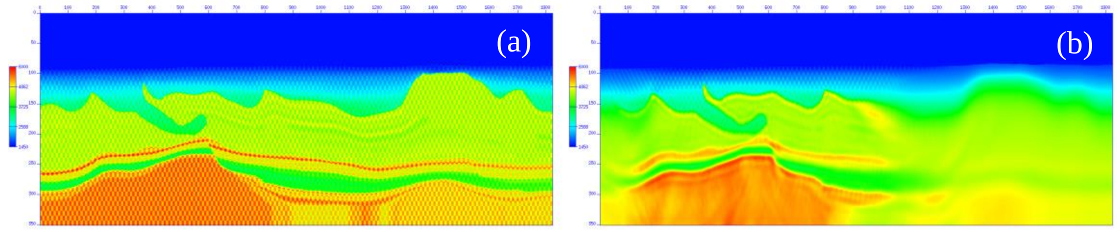


Figure 5: Experiment 2: (a) 5% disturbance 200m checkered grid; (b) FWI result

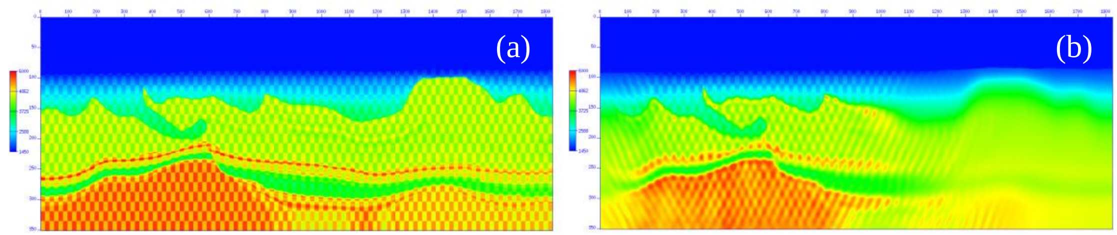


Figure 6: Experiment 2: (a) 5% disturbance 400m checkered grid; (b) FWI result

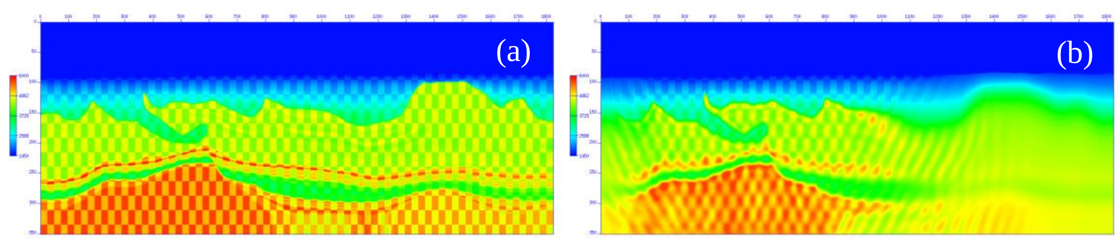


Figure 7: Experiment 2: (a) 5% disturbance 600m checkered grid; (b) FWI result

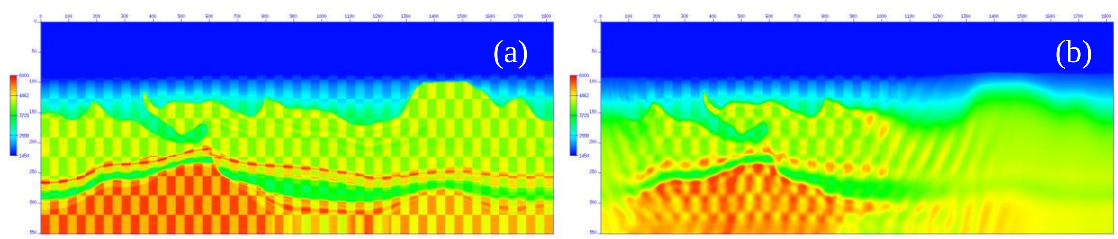


Figure 8: Experiment 2: (a) 5% disturbance 800m checkered grid; (b) FWI result