Using the Full Waveform Inversion to Improve the Depth Image from RTM

André Bulcão, Djalma Manoel Soares Filho, Gustavo Catão Alves, Túlio do Vale Moreira, CENPES/PETROBRAS, Brazil
Peter van den Berg, and Dries Gisolf. Delft University of Technology

This paper was prepared for presentation during the 12th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 15-18, 2011.

Abstract

This paper aims to estimate the effectiveness of the so called Full Waveform Inversion (FWI) as a tool to improve the accuracy of the velocity model employed by the Reverse Time Migration to produce depth images with the reflectors in correct lateral and depth positions.

Numerical results are presented and analyzed on a modified 2D slice of the 3D SEAM model. On the created model it is possible to investigate the image quality effect of a better definition of the top of salt body and how this affects the imaging on deeper targets.

Introduction

Part of the oil industry struggles for increasing the quality of depth images in complex geological areas, as in sub-salt plays, and several different techniques have been used together to improve these images. On the present work two of the most advanced schemes for this propose are employed sequentially, the so called Full Waveform Inversion (FWI) and Reverse Time Migration (RTM).

Methodology

The Full Waveform Inversion scheme employed on this work is the Finite Difference Contrast Source Inversion (FDCSI) proposed by Abubakar *et al* (2009). On this approach, using the acoustic wave equation in the frequency domain, a cost functional to be minimized is created considering basically the contrast (χ) and another term called the contrast source (w). This functional (F_n) at iteration n is defined as:

$$F_n(\chi, w_j) = \frac{\left\| d_j - \mathbf{M}^S \mathbf{H}_{\mathrm{b}}^{-1}(-k_b^2 w_j) \right\|^2}{\left\| d_j \right\|^2} + \frac{\left\| w_j - \chi u_j \right\|^2}{\left\| \chi_{n-1} u_j^{inc} \right\|^2}$$

Where:

χ - express a relation between the background velocity (v_b) and the correct velocity (v), $\chi = (v_b / v) - 1$;

$w \equiv \chi u$ - defined using the contrast and the wavefield;

K_b –wavenumber considering the background velocity;

M^S - projects the estimated wavefield along the observation surface;

H_b^{-1} - the inverse of the Helmholtz operator using the background velocity;

u and u^{inc} – the estimated total and incident wavefields, respectively;

j - subscript related to the seismic experiment (shot gather);

d_j – the measure wavefield.

The cost functional is minimized in each iteration by estimating the contrast and the contrast source in an alternating way, using the conjugated gradient method. The Helmholtz operator and the Fréchet derivatives are represented in a matrix form and approximated using finite differences (Abubakar *et al*, 2009).

The Reverse Time Migration applied in this work used the traditional cross-correlation image condition (McMechan, 1983 and Symes, 2007) and the wavefield extrapolations employed the acoustic two-way wave equation with constant density, but the implementation is done on Graphical Processing Unit (GPU) to address the computational issues related with this method.

Results

The velocity model employed in this work was created supported on a 2D section of the SEAM 3D model. The original model, based on complex geological features of the Gulf of Mexico, has compressional velocity and density fields (Brice, 2009).

In order to employ our Full Waveform Inversion at the current development stage, an equivalent model was made considering constant density in the entire model. To generate this equivalent velocity model, first a stiffness was calculated using the original values (velocity and density), then a new velocity model was obtained considering the density equal to 1.0 g/cm^3, and finally the velocity values were scaled to the same maximum and minimum values of the original one (respectively, 4800 and 1490 m/s).

The equivalent velocity model generated is shown in figure 1a. To investigate how the complex geology affects the dip-angles that could be correctly imaged, a sequence of rings or bubbles (figure 1b), with the velocity values decreased of 500 m/s, are placed inside the model (Stork & Diller, 2009).

The modeling to create the synthetic dataset, based on the acoustic two-way wave equation with constant density, was performed using the model presented in figure 1b. A smooth version (figure 2) of the equivalent model (figure 1a) was employed as the initial model for the inversion scheme and for the reference RTM.

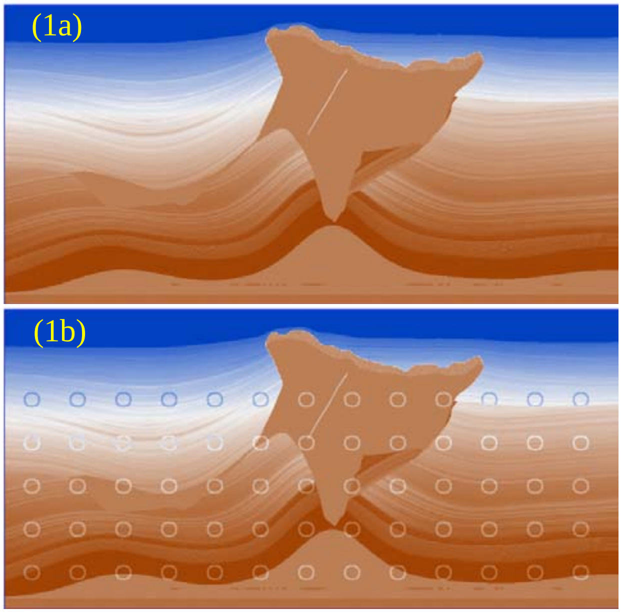

Figure 1 – Equivalent velocity model based on a 2D slice of the SEAM model (1a) and the circles or bubbles placed inside the model to investigate the dip-dependent illumination (1b).

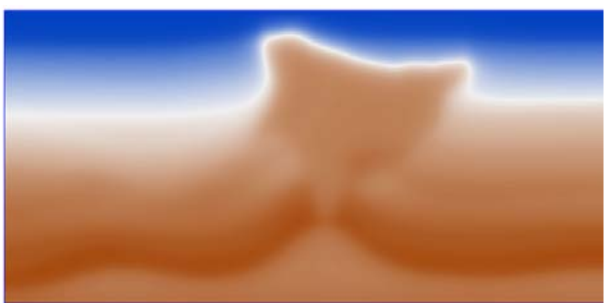

Figure 2 – Smooth velocity model used as input for inversion scheme and for reference RTM.

The inversion scheme uses the multi-scale approach in the frequency domain, where the initial inverted frequency serves as an input for the next inverted frequency (Virieux & Operto, 2009). The initial frequency was approximately 5.0 Hz, with steps of 1.0 Hz, up to 20.0 Hz, where each frequency iterates 251 times.

The final inverted velocity model is presented in figure 3. Comparing this figure with the velocity model used to generate the synthetic dataset (figure 1b), it is possible to observe a great improvement on the interface of the ocean bottom, features of the top of the salt body and the presence of the circles.

To investigate the influence of the velocity model on the depth migrated image, both the smoothed and the inverted model were employed by the RTM. This resulted in two final stacked migrated sections, considering 249 shot points evenly spaced at the surface.

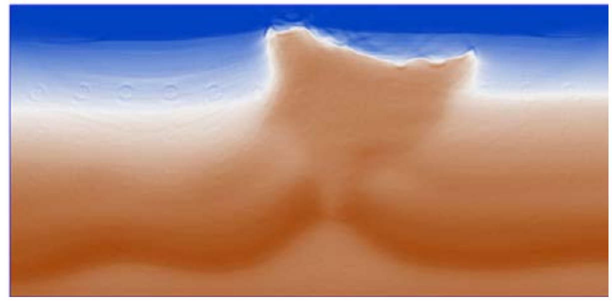

Figure 3 – Velocity model obtained from the Full Waveform Inversion, using sixteen different frequencies on multi-scale approach.

The parameters used to acquire the seismic data are important points to take into account in these types of approaches presented in this work, because there is no panacea. No matter what type of migration and inversion techniques are applied and how fancy and elaborate they are, they can not solve imaging problems caused by low illumination or poor seismic data. To diminish the influence of the acquisition parameters, on this work the receivers are placed along the entire surface at every grid point.

Another important aspect of the depth images results presented in this paper is that only a trapezoidal mute was applied before stacking the migrated images and an automatic gain control was used to enhance the reflectors. These simple processes leave opportunities to produce better stacked images.

To emphasize the difference between the depth images, figure 4 shows these images along with the correct velocity model (figure 1b) using another color scale that accentuates the interfaces. Figure 5 presents a zoom in some regions, presenting the same kind of analysis exposed in figure 4, but in addition, points were selected to highlight the difference in the reflector positions in each case.

The migration performed using the FWI velocity model also enhanced the quality of the image for the salt top, as can be seen in figures 4 and 5. The reflector is at the right depth and details of the corrugated reflector are visible, which is not the case for the smoothed image.

In the case of figure 5, one selected point corresponds to the top of a circle for the correct velocity model and the FWI image, demonstrating that the migration corresponded to the original model, differently form the smoothed model, where the migration overestimated the velocity above the reflector, positioning the circle deeper than its correct depth.

Figure 5 also pinpoints a fault that is present in the correct model, underneath the top of the salt body. Here, the fault and the surrounding circles are still imaged for the FWI case. In the smoothed velocity case, these cannot be seen in the right places.

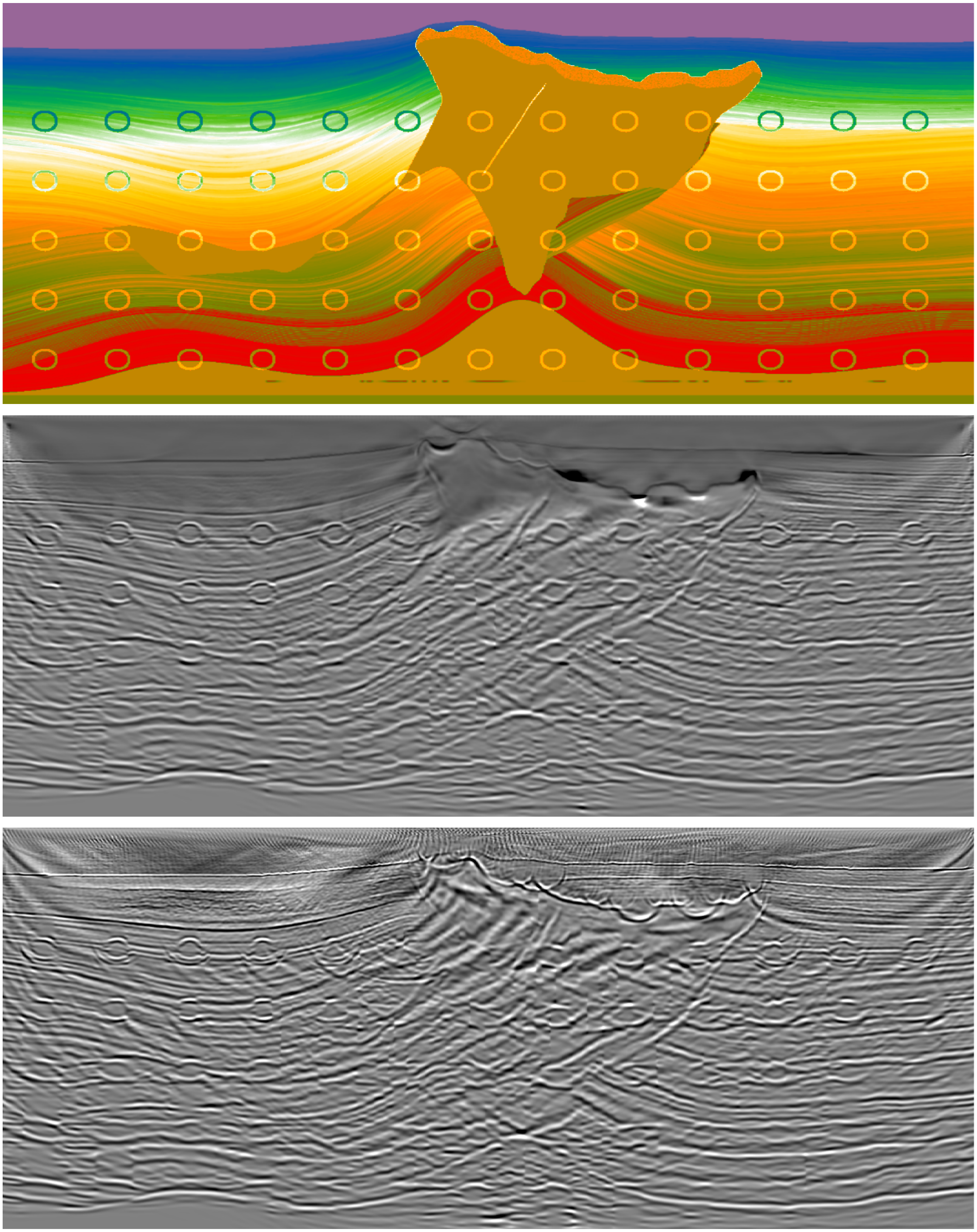

Figure 5 - Correct velocity model (top); RTM stacked depth image using velocity model obtained from FWI (middle); and RTM stacked depth image using a smoothed velocity model (down).

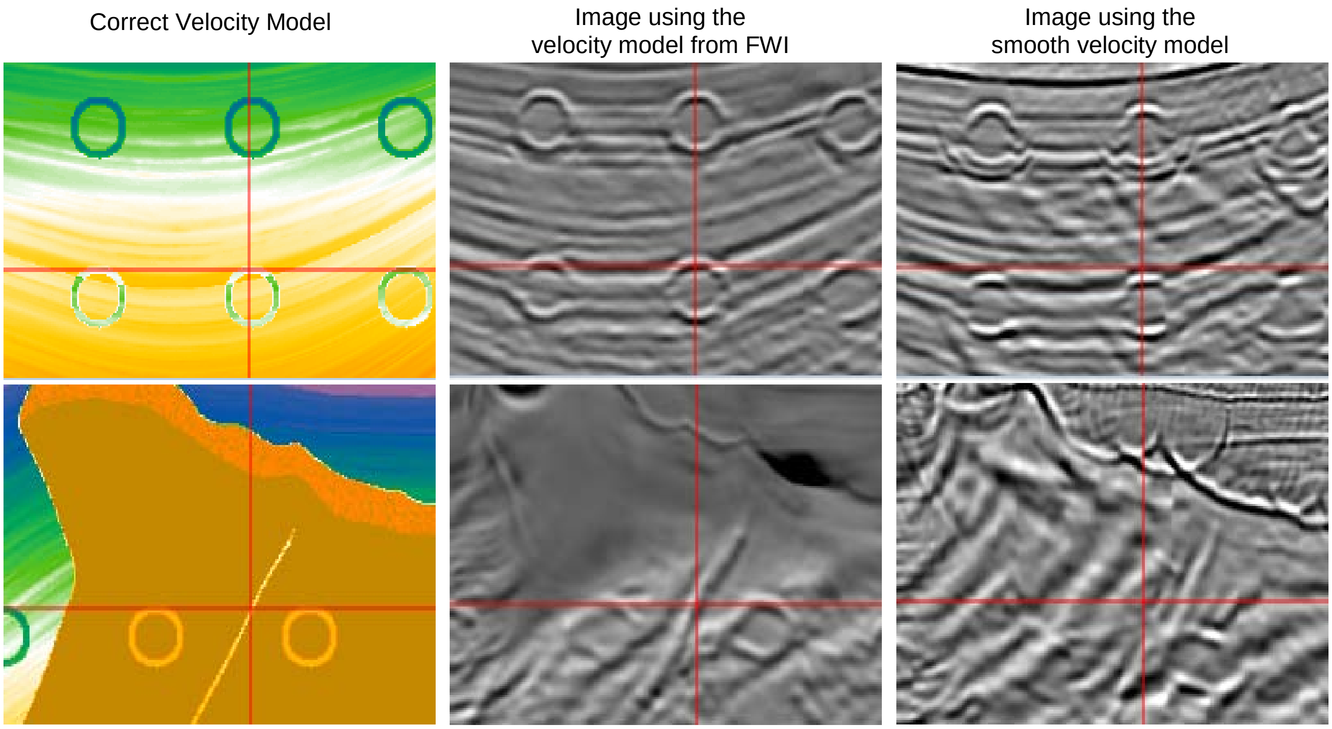

Figure 6 – Zoom in on the correct velocity model (left); RTM stacked depth image using velocity model obtained from FWI (center); and RTM stacked depth image using a smoothed velocity model (right).

Conclusions

The results presented confirm that the Full Waveform Inversion is a powerful tool to improve the velocity model, especially when employed in conjunct with Reverse Time Migration (RTM). Using this approach a great improvement was achieved on imaging targets associated with complex overburden, as presented in the case of the bubbles and the fault inside the salt body.

The results prove that, when a good velocity model is provided, the RTM is capable to produce images with excellent quality, despite the geological complexity, where the reflector are well focused at the correct position.

Acknowledgments

The authors would like to thank Petrobras for authorizing this publication.

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