Comparing the RTM and PSPI migrations to estimate the gradient using the fast waveform inversion

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Abstract

The gradient that optimize the model update in the full waveform routine is mainly obtained by a reverse-time migration of the residuals. However, if we can interpret the whole routine as a combination of seismic processing tools, we believe it is possible to obtain the gradient using any kind of depth migration. In this paper, we are comparing the use of RTM and PSPI migration to estimate the gradient, using the post-stack forward modeling-free approximations of the FWI, the FastWI. The inverted models using RTM and PSPI migrations have similar resolution in a simple velocity model, with the advantage of the PSPI been cheaper, but the RTM may lead to more continuous and high resolution models on more complex geologies.

Introduction and Theory

The objective function of the FWI method is:

$$C(\mathbf{m}) = ||\mathbf{d}_0 - \mathbf{d}(\mathbf{m})||^2 = ||\Delta\mathbf{d}(\mathbf{m})||^2 \tag{1}$$

The Fast waveform inversion (FastWI) is based on the gradient method of the FWI, which is a solution of equation 1:

$$\mathbf{m}_{n+1} = \mathbf{m}_n - \alpha_n \mathbf{g}_n \tag{2}$$

where g is the gradient, α is the step length and n is the iteration number. The gradient is obtained by migrating, stacking, and applying an impedance inversion over the residuals, which are seismic processing tools. Writing equation 2 in terms of the seismic processing operators:

$$\mathbf{m}_{n+1} = \mathbf{m}_n - \alpha_n I\left\{S\left[M\left(\mathbf{d}_0 - \mathbf{d}_n\right)\right]\right\} \tag{3}$$

On equation 3 the gradient is opened in terms of the migration operator M (the PSPI is used), the stacking operator S and the impedance inversion operator I. Assuming linearity of the seismic processing tools, we have:

$$\mathbf{m}_{n+1} = \mathbf{m}_n - \alpha_n\Big(I\left\{S\left[M\left(\mathbf{d}_0\right)\right]\right\} - \underbrace{I\left\{S\left[M\left(\mathbf{d}_n\right)\right]\right\}}_{\text{Current model}}\Big)$$
$$= \mathbf{m}_n + \alpha_n\left(I\left\{S\left[M\left(\mathbf{d}_0\right)\right]\right\} - \mathbf{m}_n\right) \tag{4}$$

The gradient can be obtained by simply processing the acquired data, and no forward modeling is required. By commuting the order of the migration and stacking operators, equation 4 becomes:

$$\mathbf{m}_{n+1} = \mathbf{m}_n + \alpha_n\left(I\left\{M\left[S\left(\mathbf{d}_0\right)\right]\right\} - \mathbf{m}_n\right) \tag{5}$$

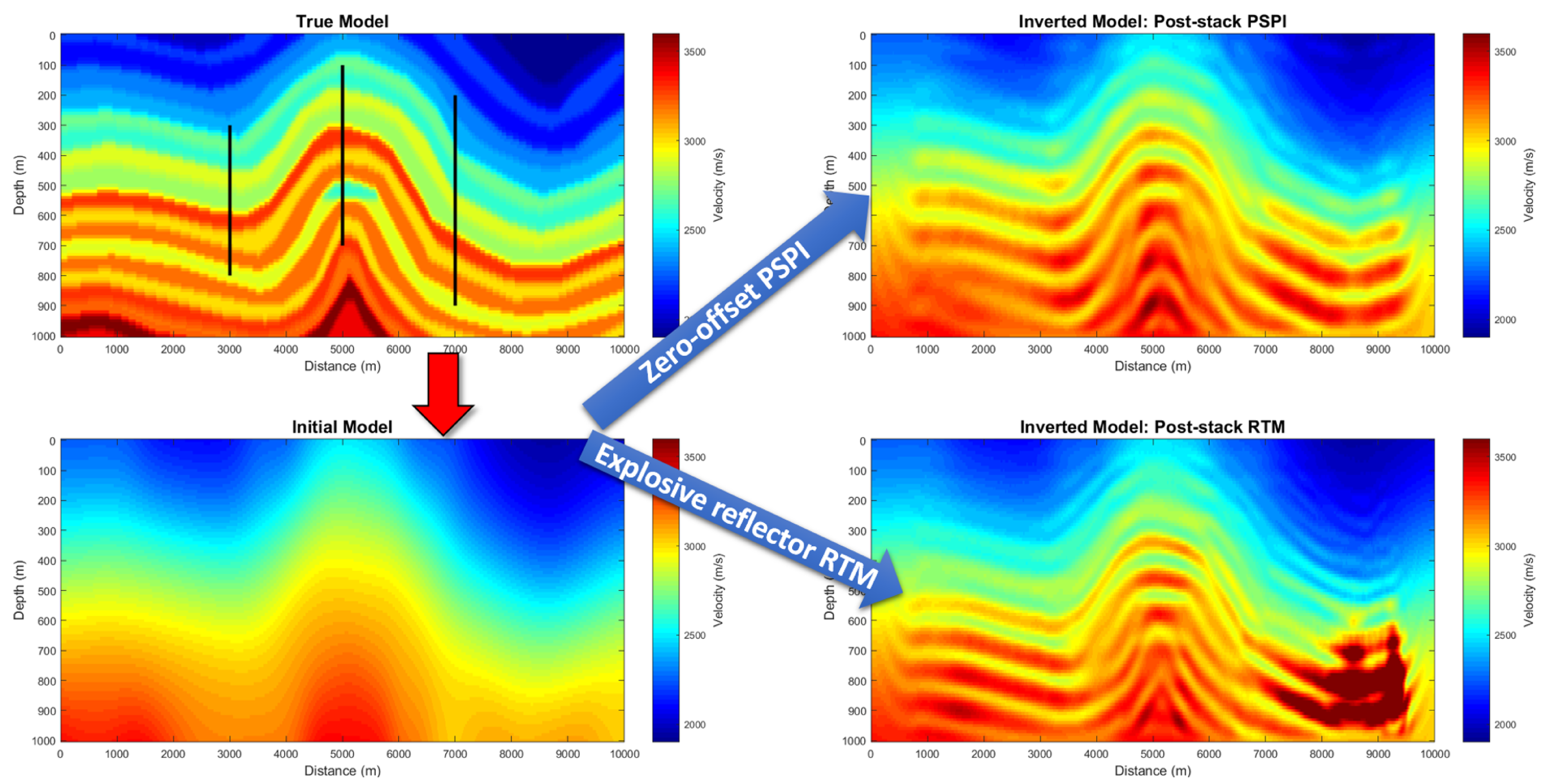
Estimating the gradient is reduced to a post-stack depth migration and impedance inversion of the acquired data. α_n is replaced by a well calibration, were the amplitude match is obtained by equation 6:

$$\alpha = \frac{S_{well}^T S_{grad}}{S_{grad}^T S_{grad}} \tag{6}$$

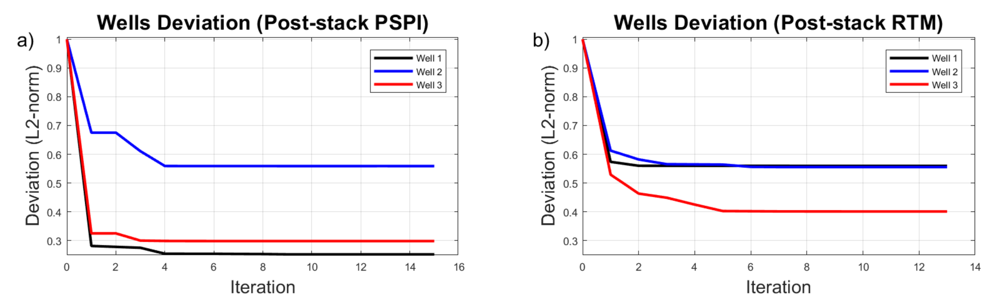
where S_{well} is the sonic log and S_{grad} is the a trace of the gradient at the matching location. The *Toolbox* code *constphase.m* finds the phase ϕ that matches the traces. By finding α and ϕ, a match filter is created and convolved with the gradient to calibrate it. The post stack approximation combined with the well calibration is what we call *Fast Waveform Inversion* (or FastWI).

Using the same interpretation that the FWI is a combination of seismic processing tools, we understand that any depth migration can be used to obtain the gradient. We will compare the difference between a zero-offset PSPI migration with an explosive reflector based RTM to obtain the gradient in the FastWI updates.

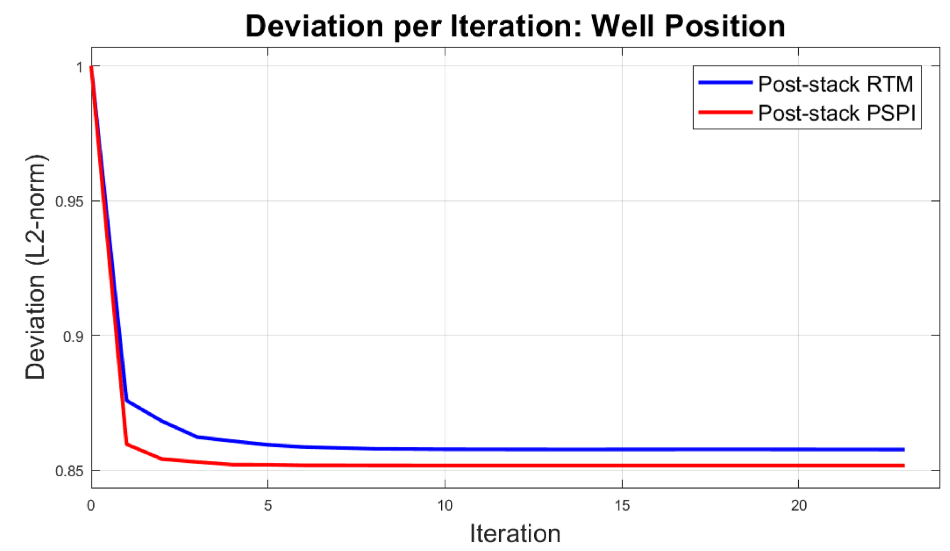
RTM vs PSPI

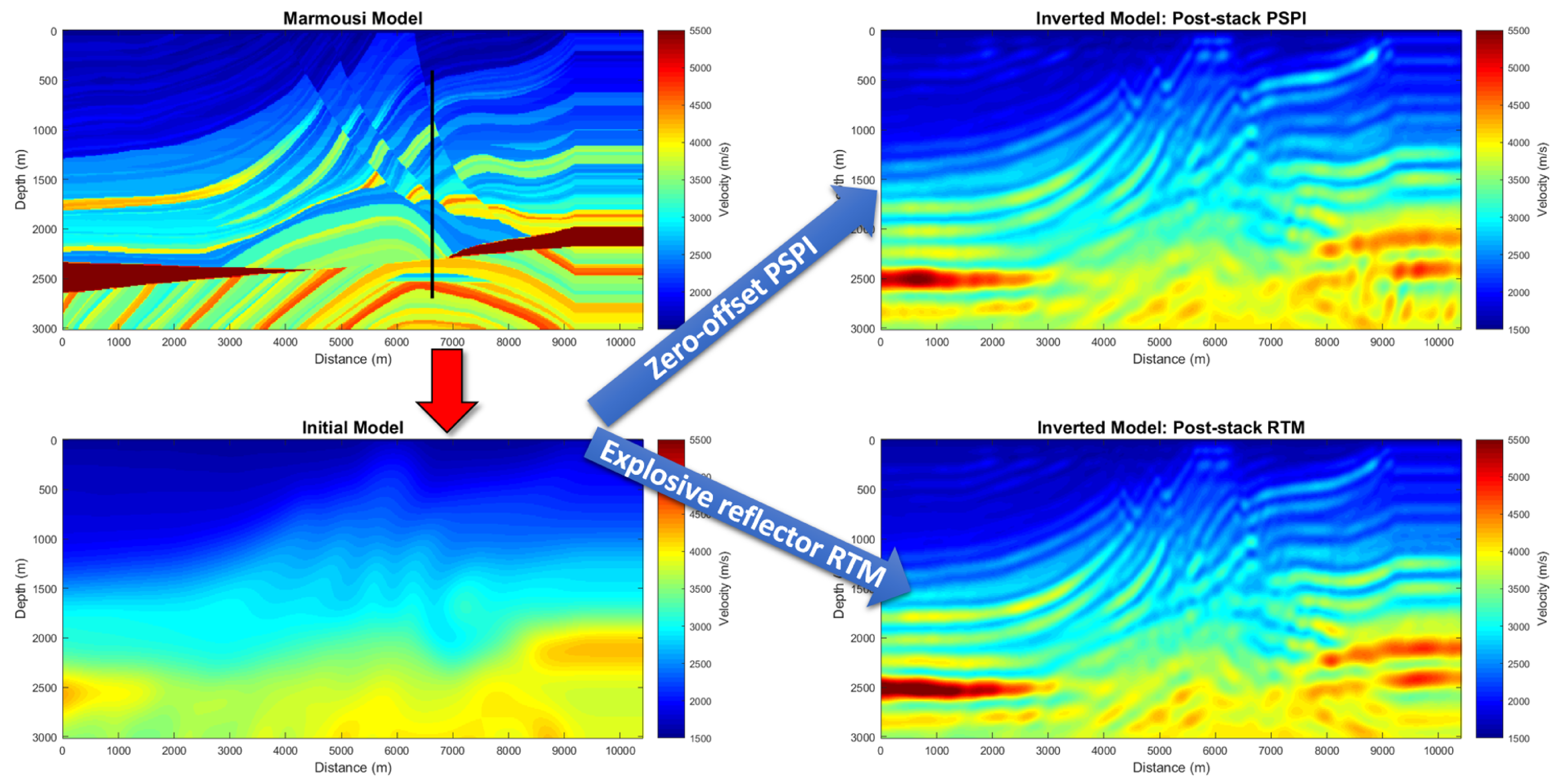


The initial model is obtained by convolving the true model with a 2D Gaussian window. As part of the FastWI, only the post stack approximation (equation 5) is used to estimate the gradient. Three sonic logs are used to calibrate the gradient for this simpler model. A match filter is obtained for each well and are interpolated for the whole model. The inversion using the PSPI migration leaded to a final model closer to the true model and with less artifacts, when compared to the RTM one.

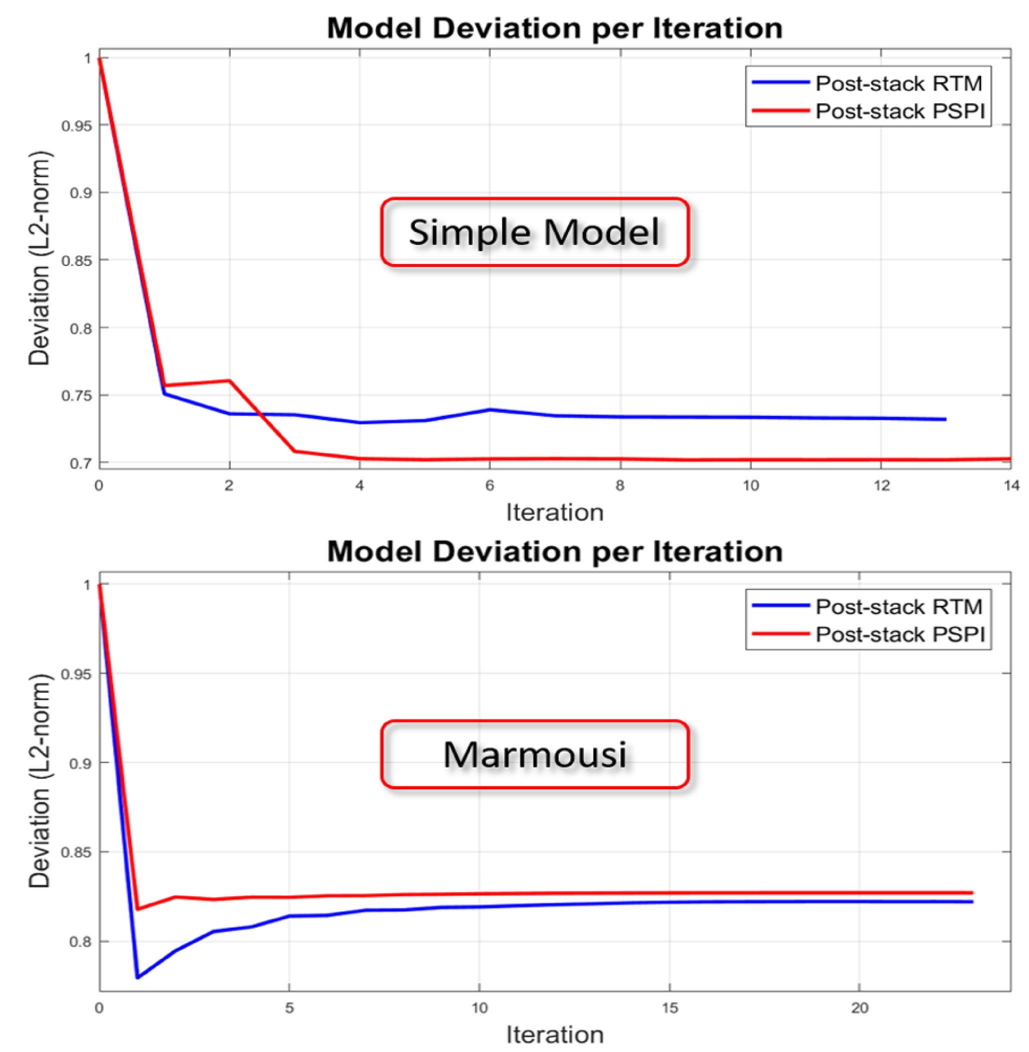


Only one sonic log is used during the Marmousi simulation. The match filter obtained at the well location is applied to the whole gradient. Both the RTM and PSPI migration ended with a final model closer to the true model. The RTM showed to work better on the deeper areas and to invert the high velocity bodies.





Model Deviation (L2-norm)



Normalized model deviation (L2-norm) of the PSPI (red line) and RTM (blue line) migrations. The choice of which migration to use will depend on the complexity of the geology and computational resources.

Conclusions

In this work we compared the use of two different depth migrations to obtain the gradient: the zero-offset PSPI and the explosive reflector based RTM. For the simpler model, the RTM shows to invert a model with higher resolution, but with more artifacts and over-corrected velocities, but the PSPI leaded to an inverted model that, in overall, is closer to the true model. However, the opposite happens when we do the comparison in the Marmousi model. As the geology gets more complex, the inversion using the RTM does a better job, mostly in the deeper area of the model. In the end of the day, which depth migration to select for the FastWI depends on the computational resources of the processor (with the advantage for the PSPI) and the complexity of the geology in the studying area (as it gets more complex, the advantage goes to the RTM). For our simulation, the PSPI migration shows to be, in the overall scenario (the gain in costs for the RTM does not represent a linear gain in quality), the best option.

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