Forward modeling-free full waveform inversion with well calibration

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Abstract

Full waveform inversion (FWI) has the goal to find the Earth's model parameters that minimize the difference of acquired and synthetic shots. It is a powerful tool to automatize some complex processes. However, when we talk about seismic data, we are talking about huge datasets, and the FWI shows to be very hard to be applied in large scale, as it requires a large number of synthetic data and migrations at each iteration. In this work, We are proposing an approximation for the FWI that is forward modeling-free, requiring only the migration of the acquired data, which can be pre or post stack, and the optimization driven by a sonic log calibration. We tested the approximation for acoustic inversion in a synthetic 2D Marmousi survey. It is stable and leads to detailed inverted models with reduced computational costs.

Introduction and Theory

Full waveform inversion is a least squares minimization based algorithm. Its goal is to estimate the best model in which the computed synthetic data is equals to the acquired data. In other words, it minimizes the objective function:

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

The model is estimated iteratively and the gradient method is the one chosen for this work task:

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

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. Each one of these steps are very well known seismic processing tools. With that in mind, equation 2 can be written as a seismic processing work flow, and the update is intuitive:

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

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 that all the seismic processing tools on equation 3 are linear and it can be written as:

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

Equation 4 tells us that the gradient can be understood as a residual impedance between the impedance inversion of the migrated and stacked acquired data and the current model. No forward modeling is required during the gradient estimation. By commuting the order of the migration and stacking operators, equation 4 becomes:

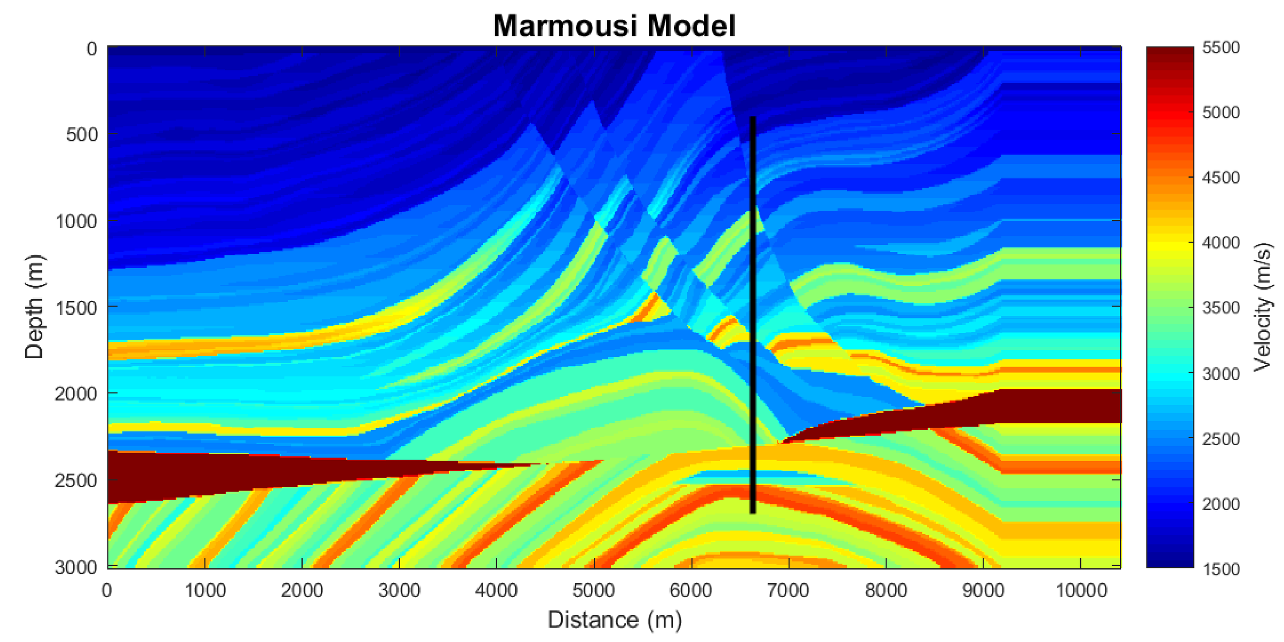
$$\mathbf{m}_{n+1} = \mathbf{m}_n + \alpha_n(I\left\{M\left[S\left(\mathbf{d}_0\right)\right]\right\} - \mathbf{m}_n) \tag{5}$$

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:

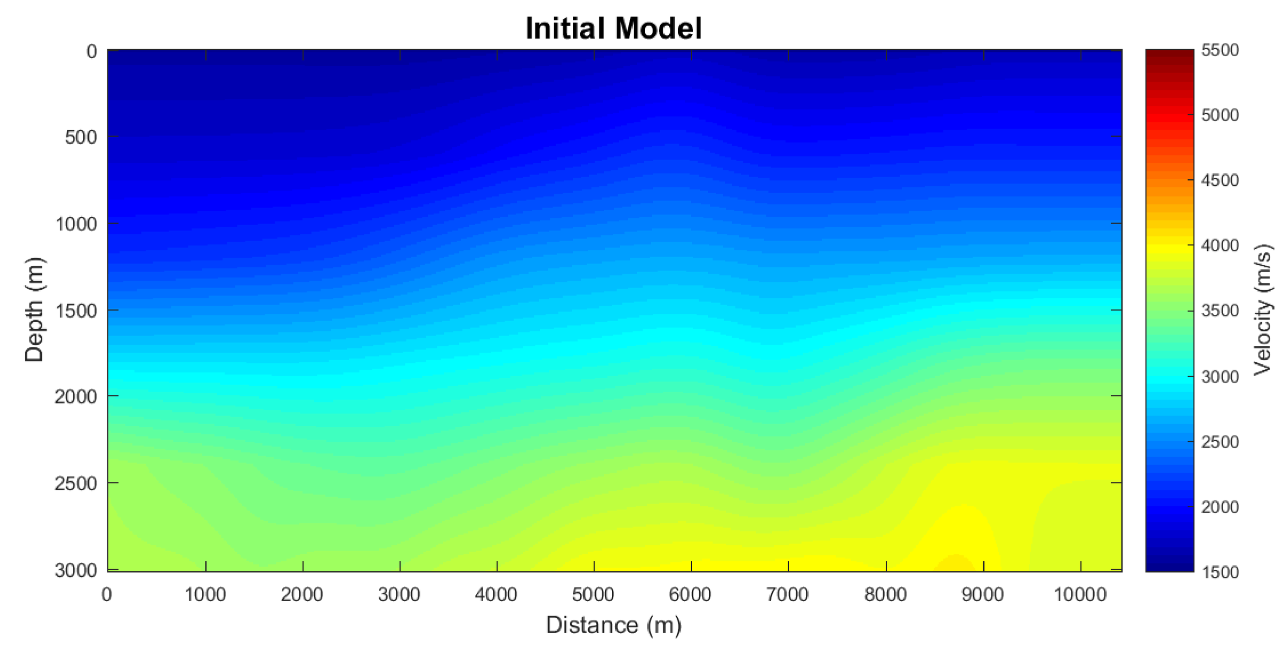
$$\alpha = \frac{S_{well}^T S_{grad}}{S_{grad}^T S_{grad}} \tag{6}$$

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.

True and Initial Models

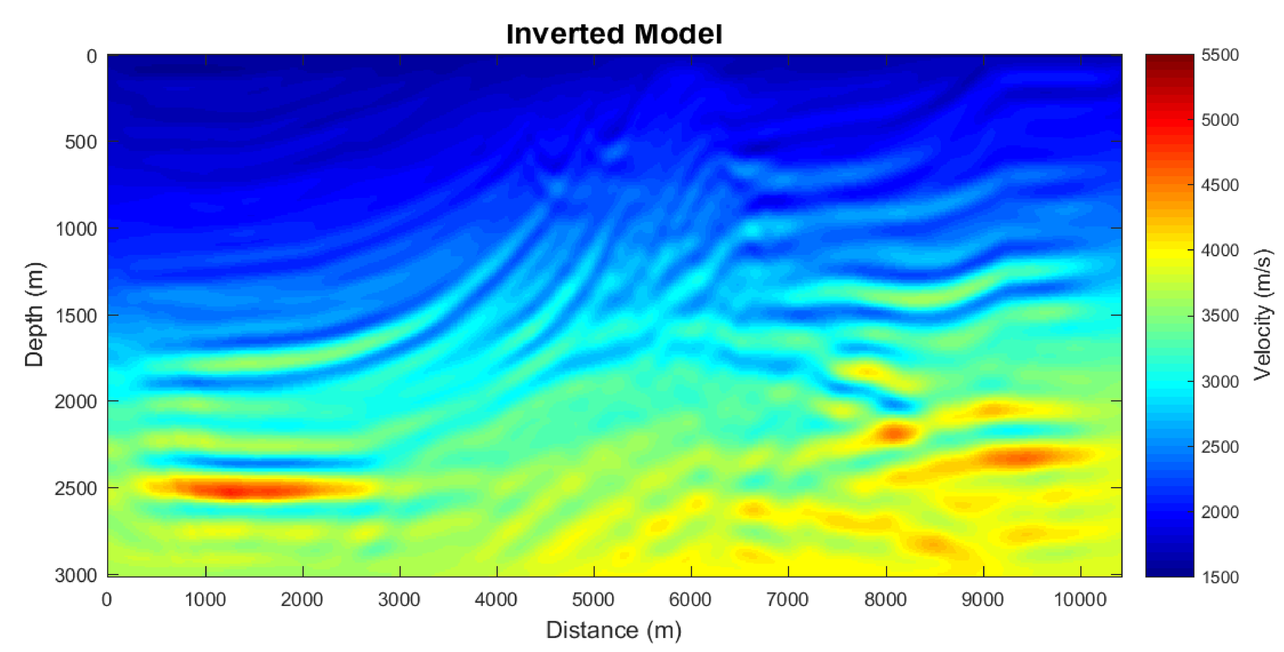


True Marmousi model. The black line is the sonic log simulation for the well calibration. The match filter obtained at this location is applied at the whole model.



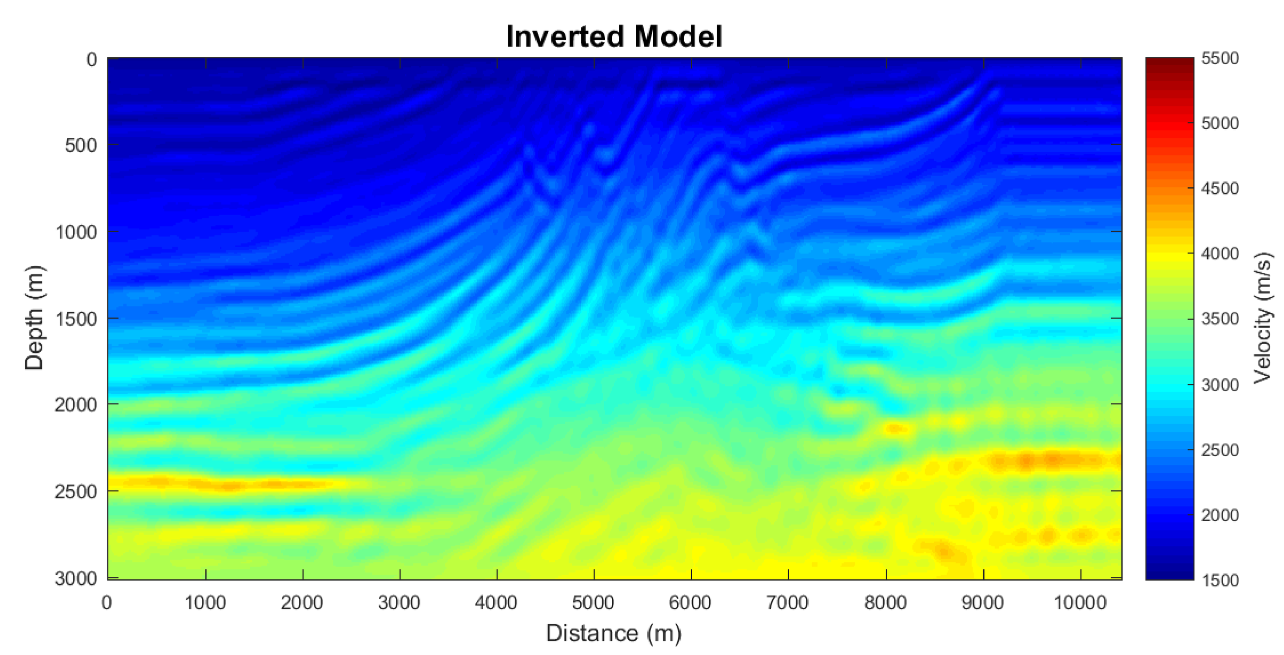
The initial model is the output of a velocity analysis process.

Pre-stack Approximation



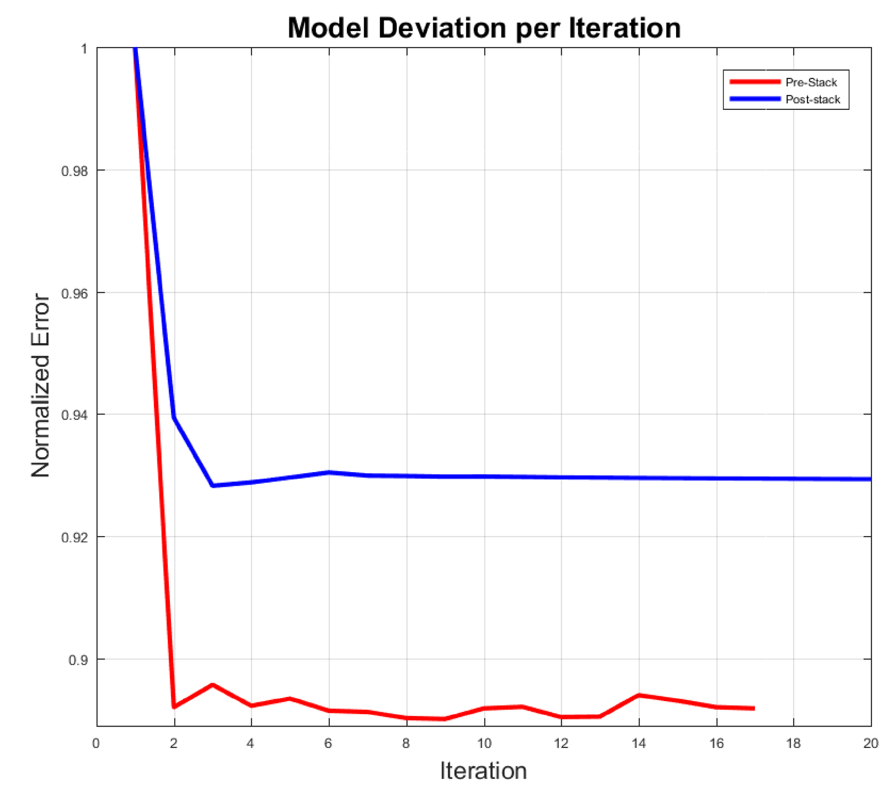
Inversion based on equation 4, the pre-stack approximation of the forward modeling-free FWI. Most of the main features of the true model are "recovered", even with a poor starting model.

Post-stack Approximation



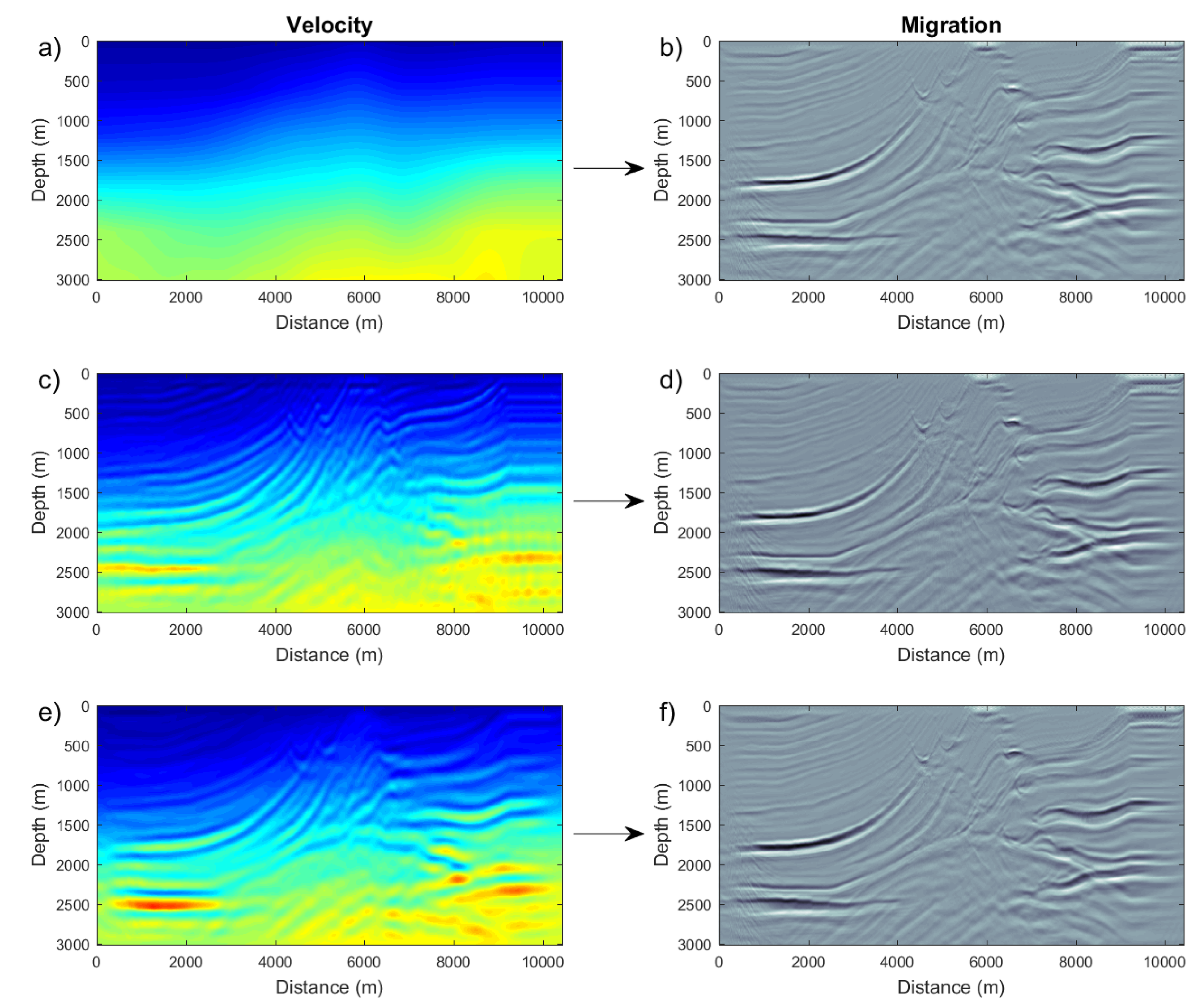
Inverted model based on the post-stack approximation of equation 5. This method is also named as *FastWI* (or fast waveform inversion). It is the cheapest and fastest version of our waveform inversion.

Model Deviation (L2-norm)



Normalized model deviation (L2-norm) of the pre (red line) and post (blue line approximations). The first one leads to an inverted model closer to the true model, but the second requires less computer power.

Migration Velocities



Initial, pre and post stack inversion models are used as migration velocity.

Conclusions

In this work we proposed a new approximation for the full waveform inversion that, assuming linearity of the seismic processing tools, allows us to obtain the gradient free of forward modeling, and combining it with the well calibration of the gradient, replacing the step length, we have a full waveform inversion that is 100% free of froward modeling and source estimation. We should consider that for an initial model that is far from the true model, both the pre and post stack approximations resulted on inverted models with high level of details, with reduced computing costs. In the future work, we will be extending the same approximation idea for a multi-parameter FWI (if possible) and for 3D seismic surveys.

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