Data normalization strategies for full-waveform inversion

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Introduction

Full-waveform inversion (FWI) relies on accurate estimation of signal amplitudes. Approximations made during the inversion process, as well as unknown information, cause amplitude mismatch effects at various levels: shot gather absolute magnitude, trace-by-trace scaling and time-varying relative amplitudes. Rewriting the problem in an amplitude free formulation mitigates the amplitude ambiguity and improve convergence. We present strategies to eliminate amplitude uncertainty; we derive update directions, compare and analyze the effect of each of the normalization schemes.

Aim

- Mitigate amplitude unknown in the source
- Introduce normalized formulations
- Derive the gradient for the formulations

Method

$$\mathbf{d}_s = \mathbf{P}_r \mathbf{A}(\mathbf{m})^{-1} \mathbf{P}_s^T \mathbf{q}$$

$$\mathbf{d}_0 : \text{Observed data}$$

- Normalized objective function

$$\underset{\mathbf{m}}{\text{minimize}}\, \Phi(\mathbf{m}) = \frac{1}{2} \left\| \frac{\mathbf{d}_s}{\|\mathbf{d}_s\|_2} - \frac{\mathbf{d}_0}{\|\mathbf{d}_0\|_2} \right\|_2^2$$

$$\nabla_m \Phi(\mathbf{m}) = \mathbf{J}^T \mathbf{r} = -(\frac{\mathrm{d}^2 \mathbf{u}}{\mathrm{dt}^2})^T \mathbf{A}(\mathbf{m})^{-T} \mathbf{P}_r^T \mathbf{r}.$$

$$\mathbf{r} = \frac{1}{\|\mathbf{d}_s\|_2} (\frac{\mathbf{d}_s}{\|\mathbf{d}_s\|_2} \frac{\mathbf{d}_s^T \mathbf{d}_0}{\|\mathbf{d}_s\|_2 \|\mathbf{d}_0\|_2} - \frac{\mathbf{d}_0}{\|\mathbf{d}_0\|_2})$$

- Normalized adjoint source

$$\underset{\mathbf{m}}{\text{minimize}}\, \Phi(\mathbf{m}) = \|\mathbf{d}_s\|_2 - \frac{\mathbf{d}_s^T \mathbf{d_0}}{\|\mathbf{d}_0\|_2}$$

$$r = \frac{\mathbf{d}_s}{\|\mathbf{d}_s\|_2} - \frac{\mathbf{d}_0}{\|\mathbf{d}_0\|_2}$$

$$\nabla_m \Phi(\mathbf{m}) = \mathbf{J}^T \mathbf{r}.$$

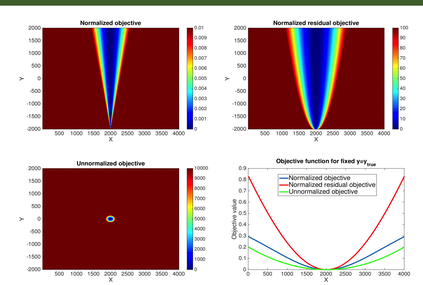
- Removes ambiguity on the source amplitude for a known source time signature.

Shot-by-Shot vs Trace-by-trace

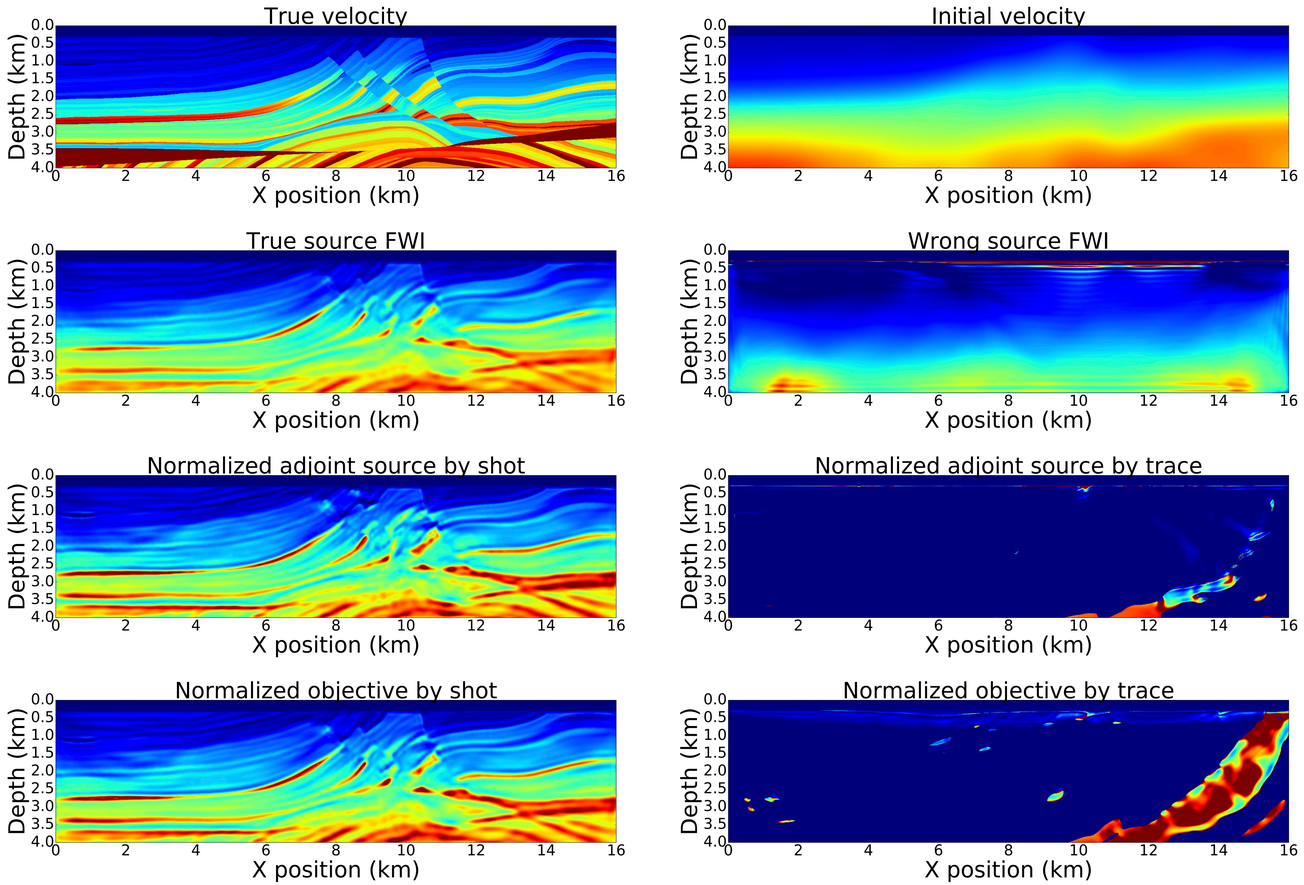
- Shot-by-shot conserves amplitude decay
- Shot-by-shot acts as crude source estimation
- Trace-by-trace improves large offset data influence on the update
- Trace-by-trace improves the illumination balance
- Trace-by-trace increase the chance to fall in a local minima as the large offset traces, more likely to be cycle skipped, have more influence

Objective functions shapes for a simple two variables setup.

Normalized formulations accept all solutions alignec with the true solution



Results on the Marmousi model



Conclusions

We showed that data normalization provides an automatic way to mitigate amplitude uncertainties and improves the inversion results compared to a naive FWI implementation when there are errors in the absolute source magnitude. Our results suggest that trace normalization is less reliable than shot normalization even though a normalized adjoint source formulation is more robust to large offset mismatches. Secondly, we showed that shot-by-shot normalization strategies are well suited for amplitude mismatch correction in seismic inversion. Even though this methods require a known source time signature, one could combine it with a source estimation method and guarantee that any amplitude ambiguity in the source estimation would be cancelled out.

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