Domain-Specific Abstractions for Full-Waveform Inversion

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A Unified 2D/3D Software Environment for Large Scale Nonlinear Inverse Problems

Curt Da Silva & Felix J. Herrmann

Available for download at

https://github.com/slimgroup/WAVEFORM

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Inverse Problems

Try to measure an unknown parameter from indirect measurements of a system

Many applications in science, engineering

- geophysics, medical imaging, radar, etc.

Challenges

Large amount of data in realistic problems

- $\mathcal{O}(10^9)$ model points, $\mathcal{O}(10^{15})$ data points
- $\mathcal{O}(10^6)$ sources

PDE system is large, sparse, indefinite

- can't even afford to store coefficients
- difficult for Krylov solvers without preconditioning
  - preconditioners are often difficult to program, exploit parallelism

Adjoint state/reduced formulation

Eliminate field variables $u_i = H(m)^{-1} q_i$ to obtain

$$\min_m \frac{1}{2} \sum_i \| P_r H(m)^{-1} q_i - d_i \|_2^2$$

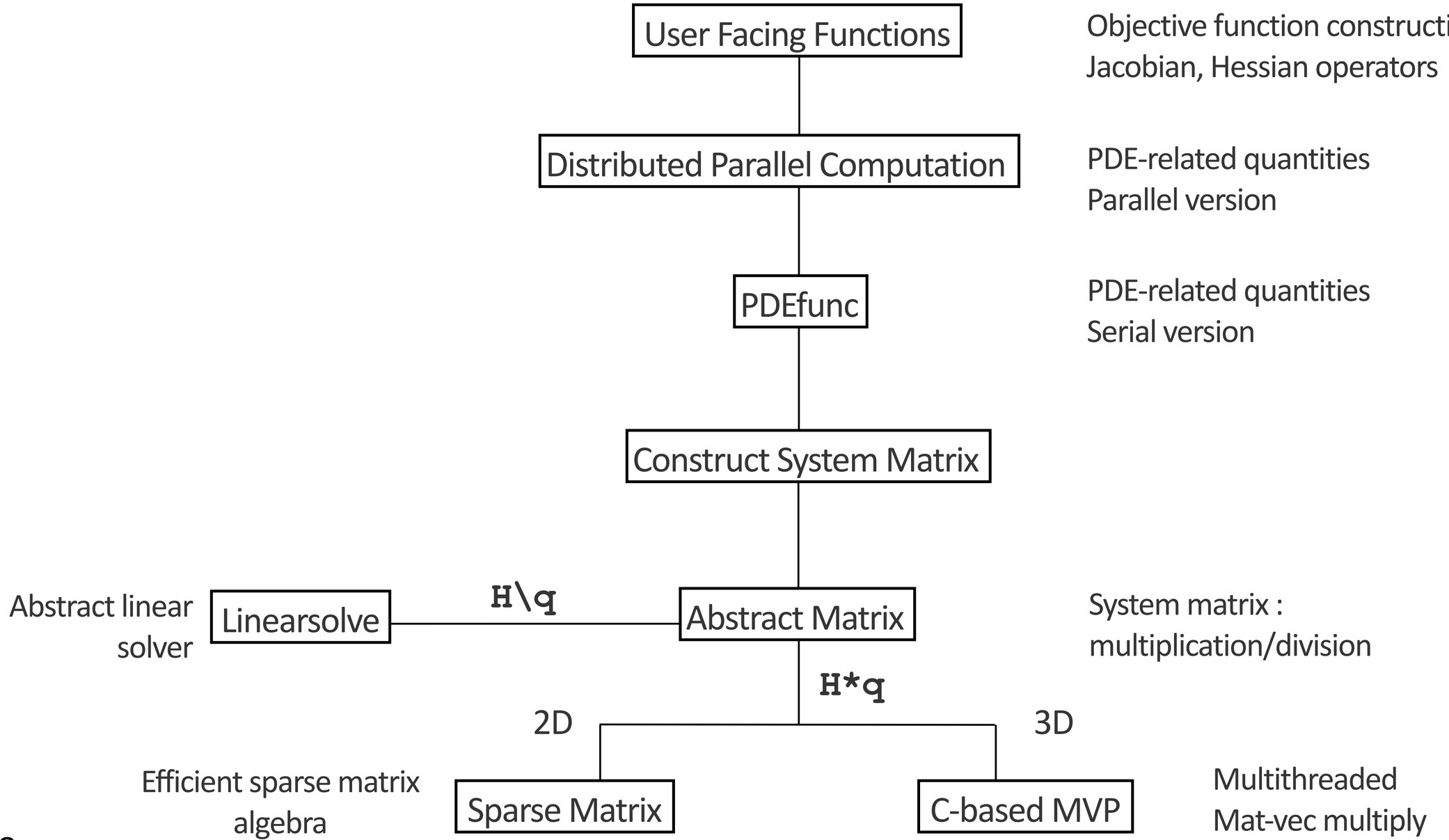
Software organization

Software hierarchy manages complexity

- we don’t have to sacrifice performance
  - lowest level operations implemented in C w/multithreading

- hiding irrelevant details at each level
  - higher level functions don’t have any idea about low level languages

Software Design



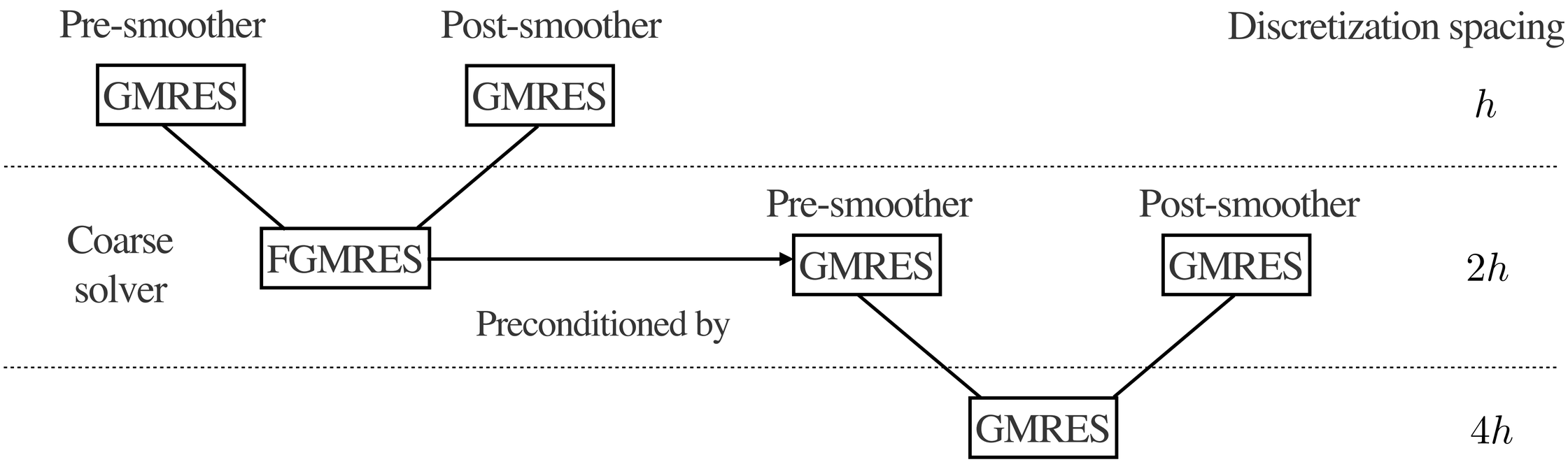
Parallel distribution

$$f_I(m) = \frac{1}{2|I|} \sum_{i \in I} \|P_r H(m)^{-1} q_i - d_i\|_2^2$$
$$= \frac{1}{2|I|} \sum_{i \in I} f_i(m)$$

The objective function is *separable* over shots/frequencies

- distribute indices to parallel workers

Multilevel-GMRES



Results

3D FWI

Schmidt, et. al., “Optimizing Costly Functions with Simple Constraints: A Limited-Memory Projected Quasi-Newton Algorithm”, 2009

$$m_k = \arg\min_m \frac{1}{|I_k|} \sum_{i \in I_k} f_i(m)$$

$$\text{s.t.} \quad m_L \leq m \leq m_U$$

At the kth iteration, randomly draw a subset of sources $I_k \subset \{1, \ldots, N_s\}$ with $|I_k| = p$

Approximately solve the above problem with constrained LBFGS or spectral projected gradient

Repeat for T iterations

3D FWI Example

Overthrust model

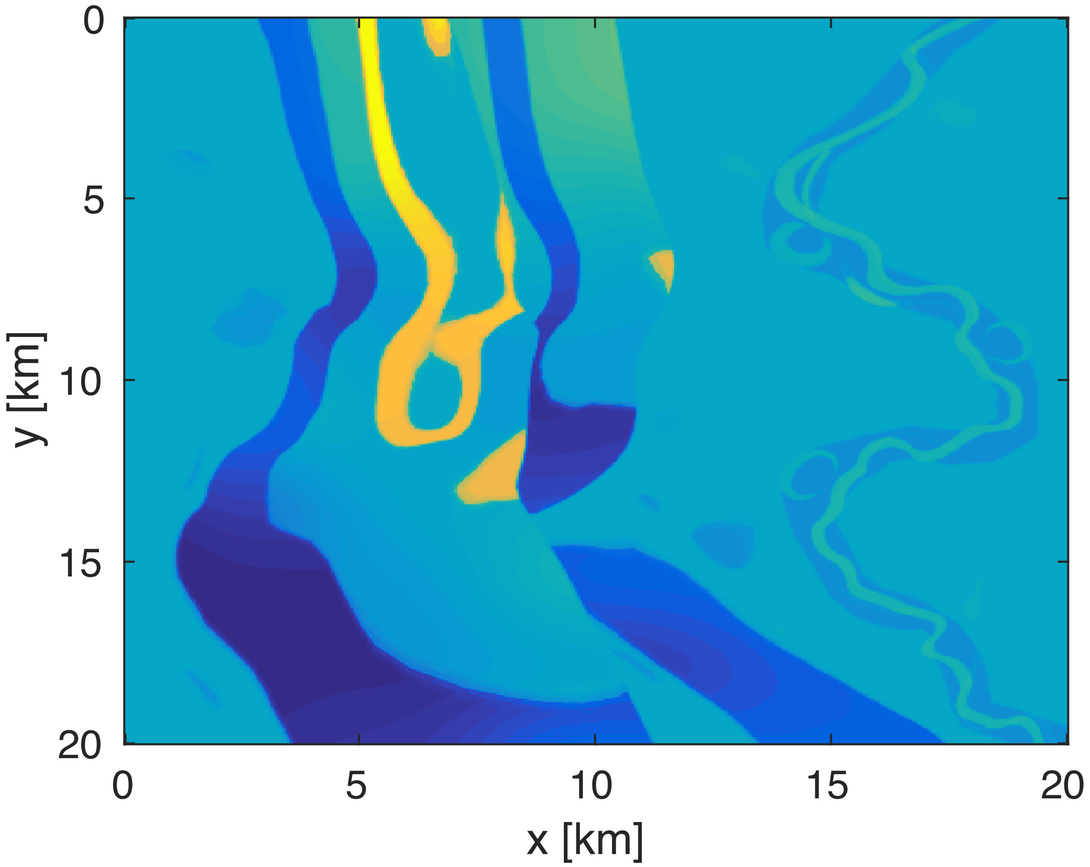
- 20 km x 20 km x 4.6 km - 50 m spacing, 500m water layer
- 50 x 50 sources, 200m spacing - 2500 shots
- 401 x 401 receivers, 50m spacing
- 3, 3.25, …, 5.5Hz frequency range, single freq. inverted at a time

Computational Environment

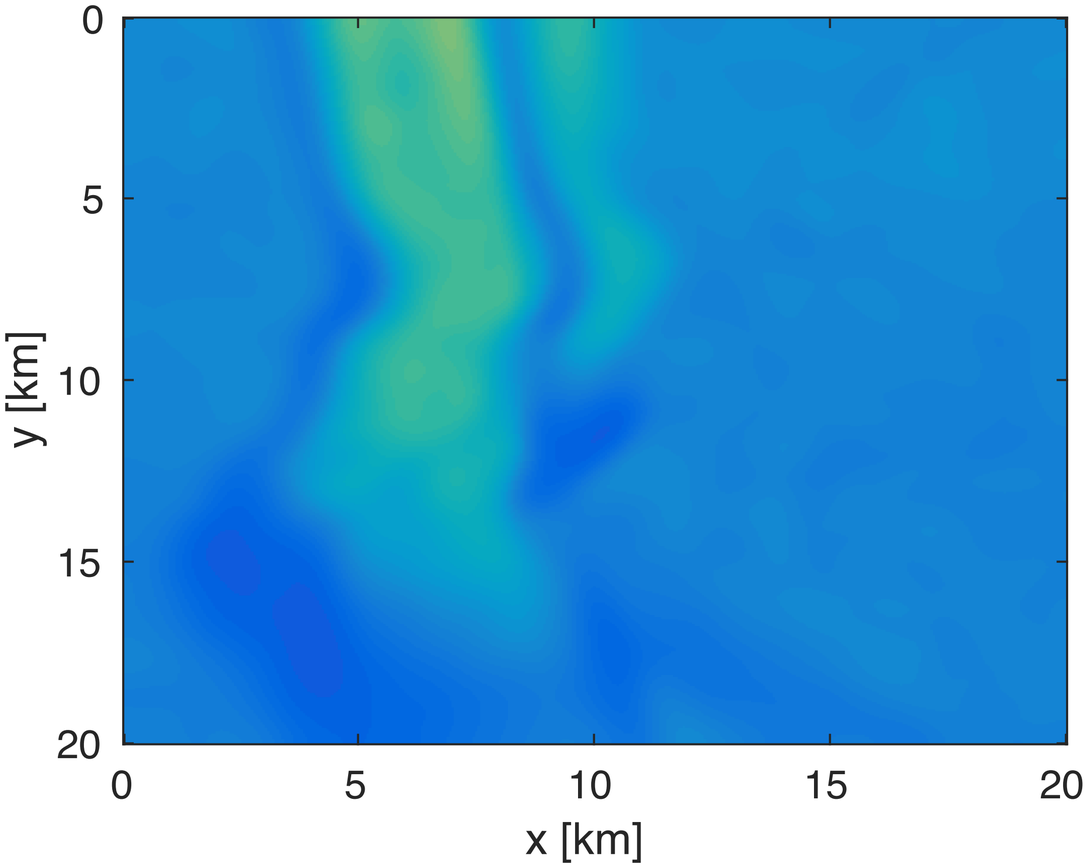
SENAI Yemoja cluster

- 100 nodes, 128 GB RAM each, 20-core processors - 2000 cores
- 400 Parallel Matlab workers (4 per node), Helmholtz MVP uses 5 threads - full core utilization

z=1000m slice

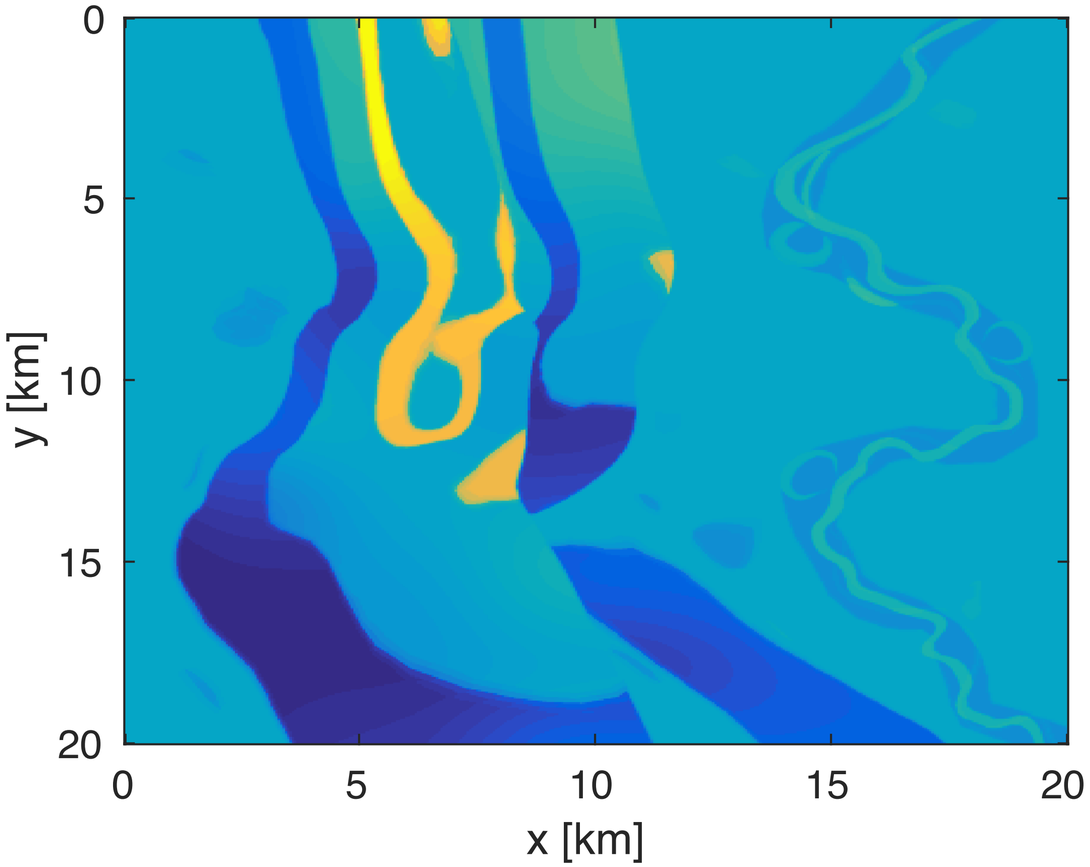


True model

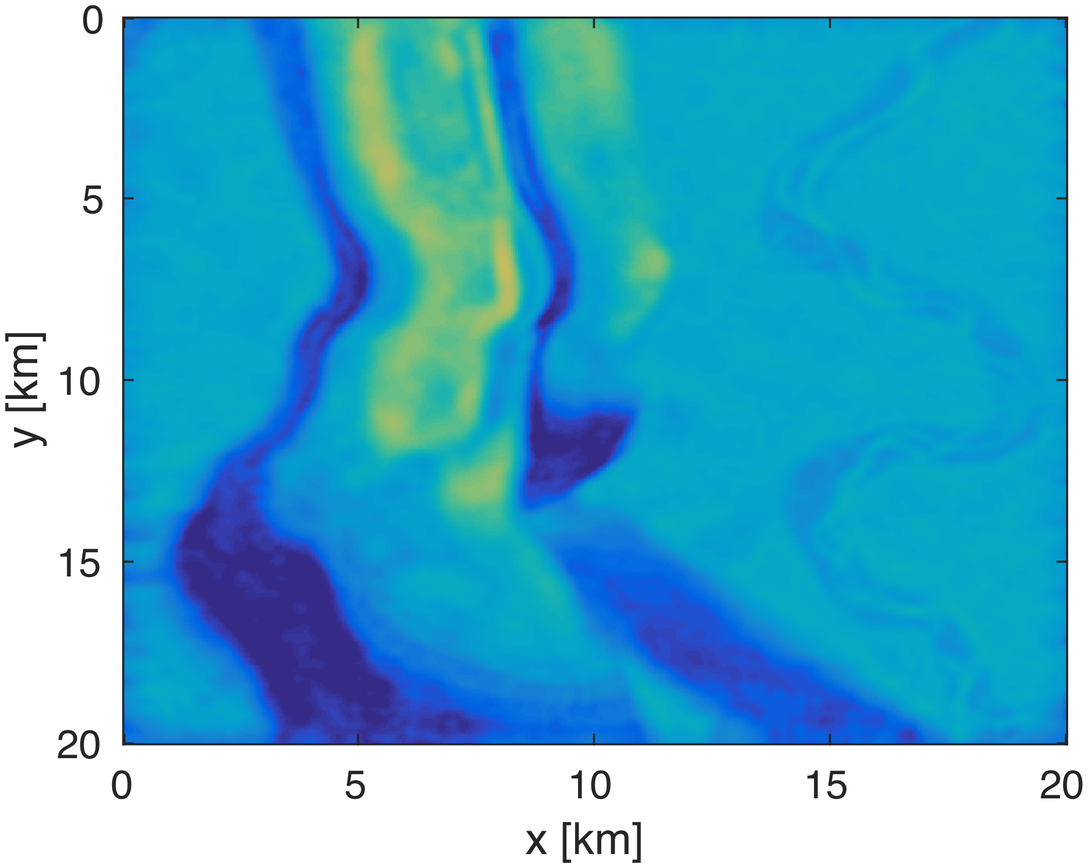


Initial model

z=1000m slice

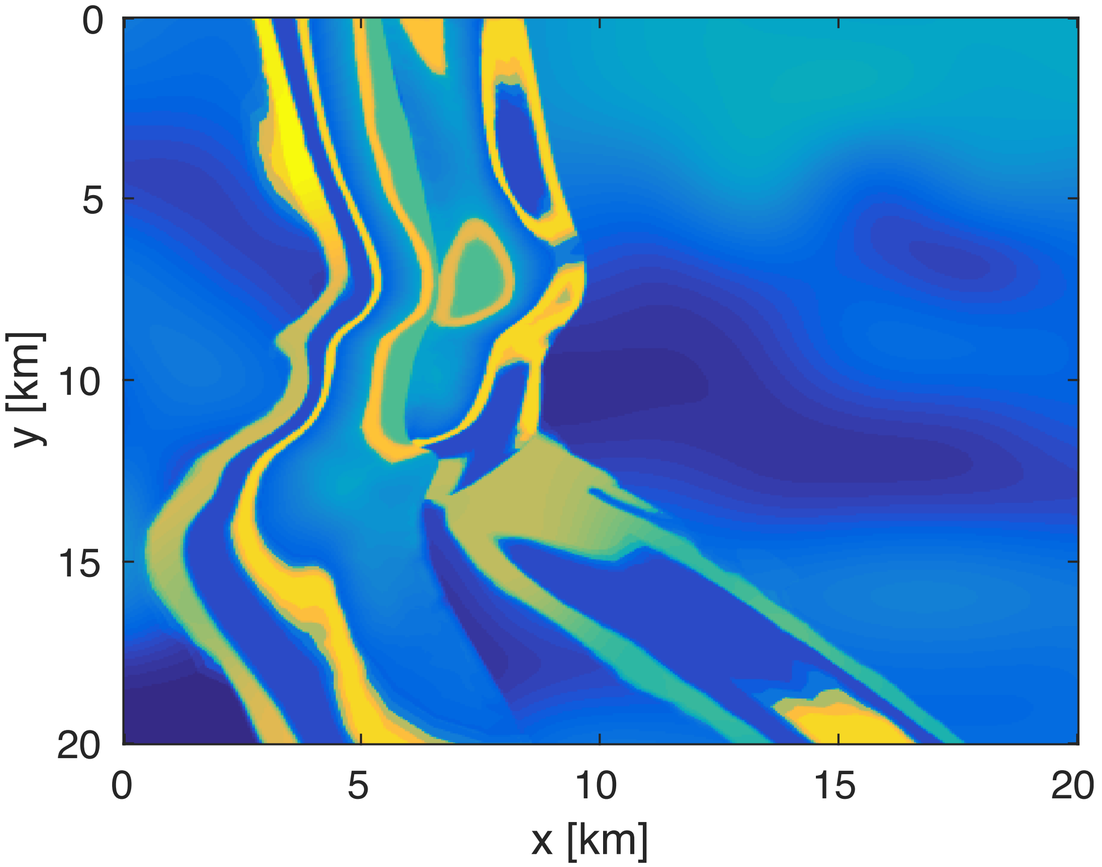


True model

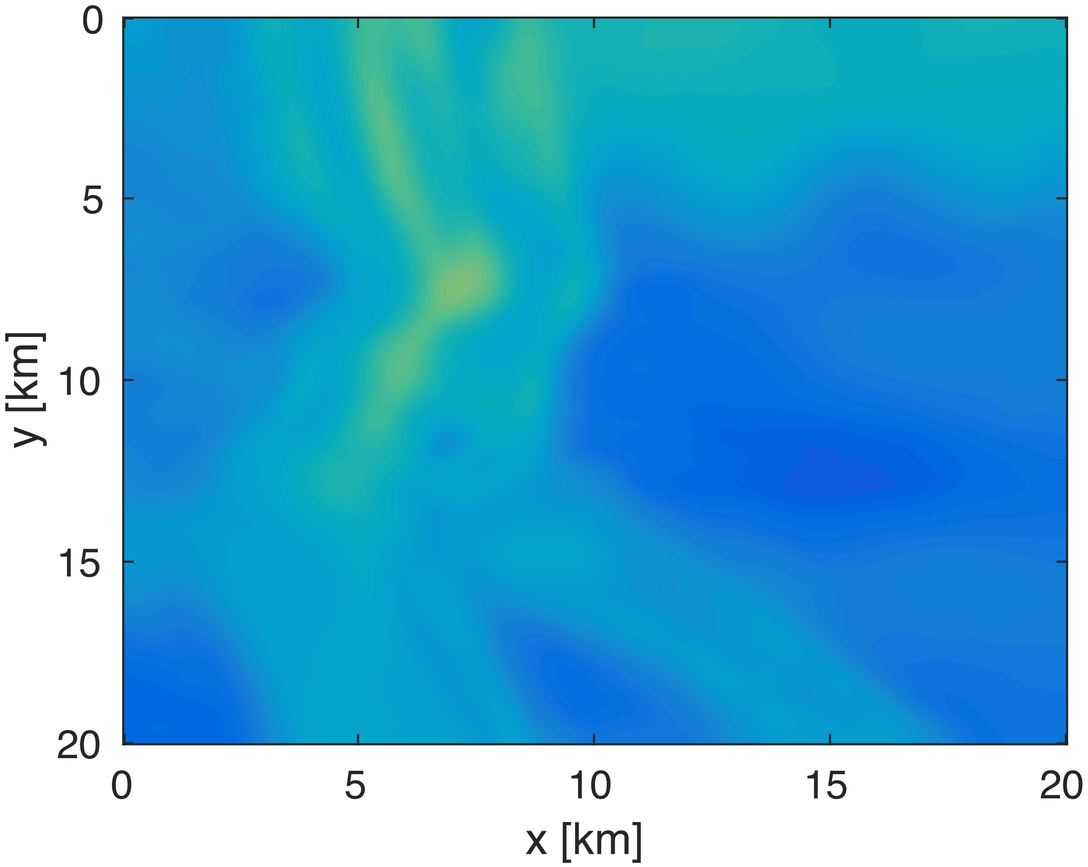


Stochastic LBFGS

z=2000m slice

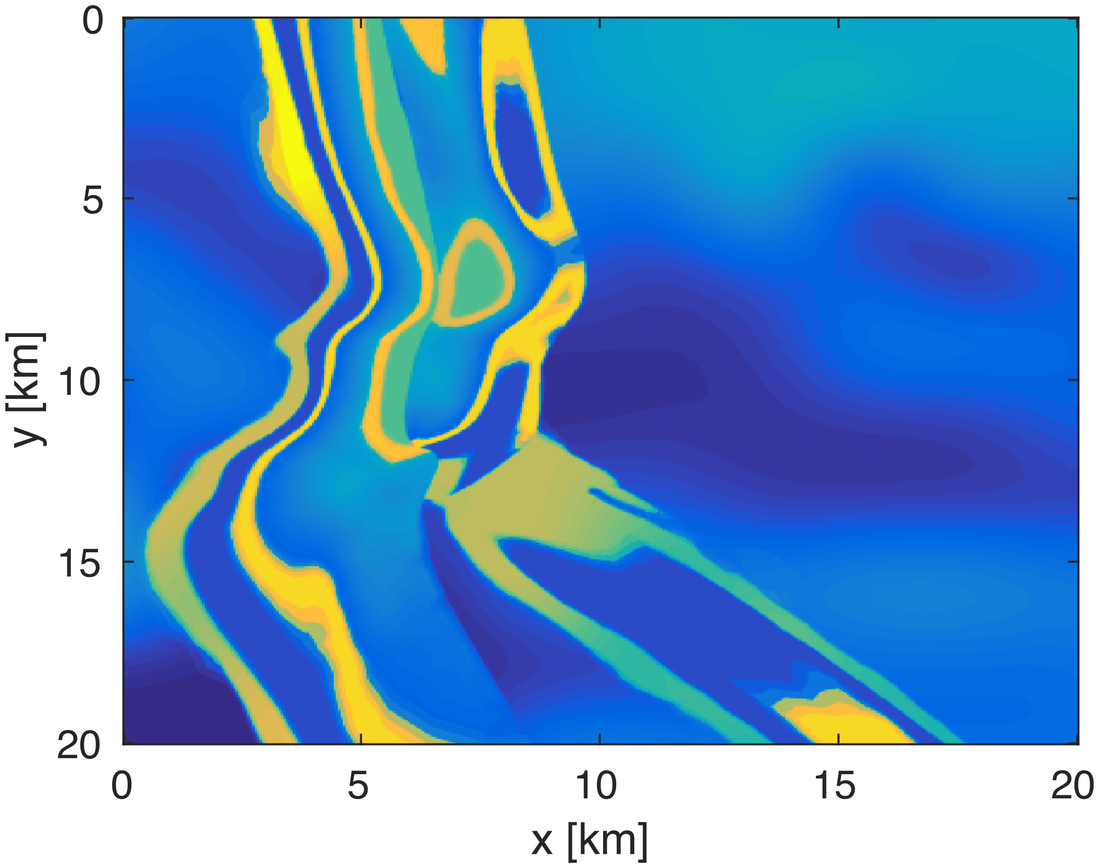


True model



Initial model

z=2000m slice



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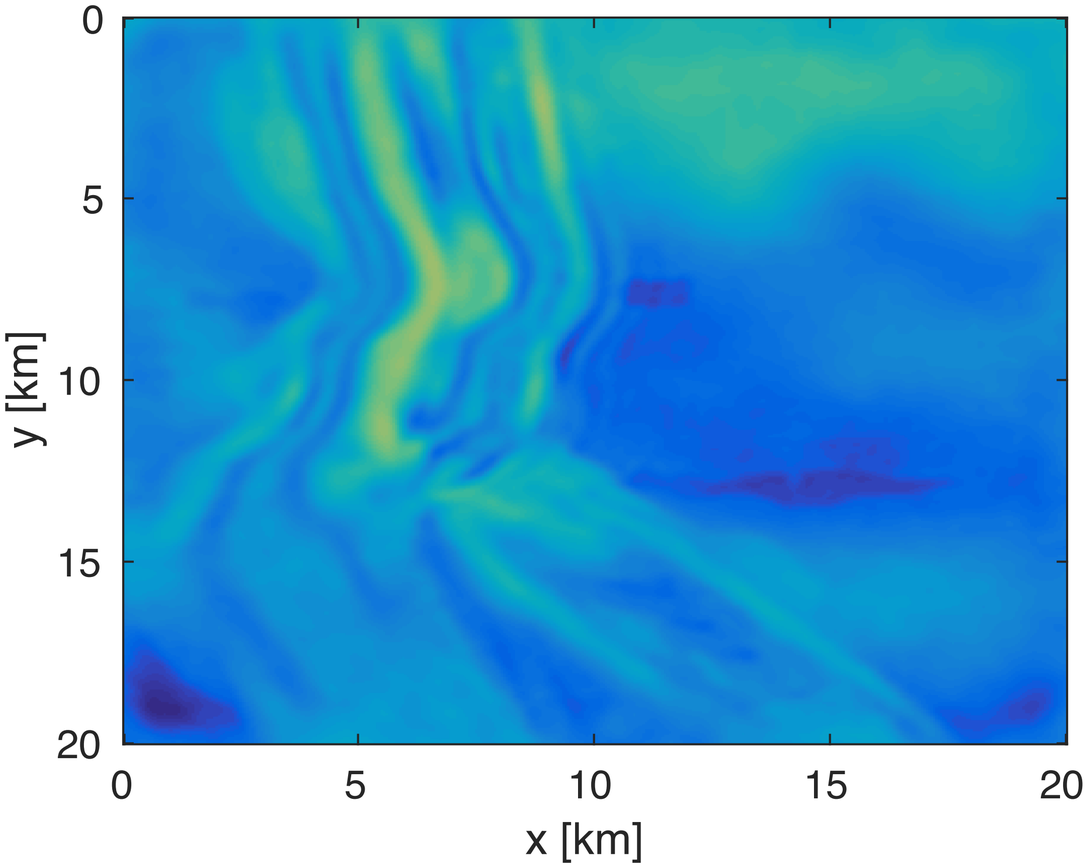
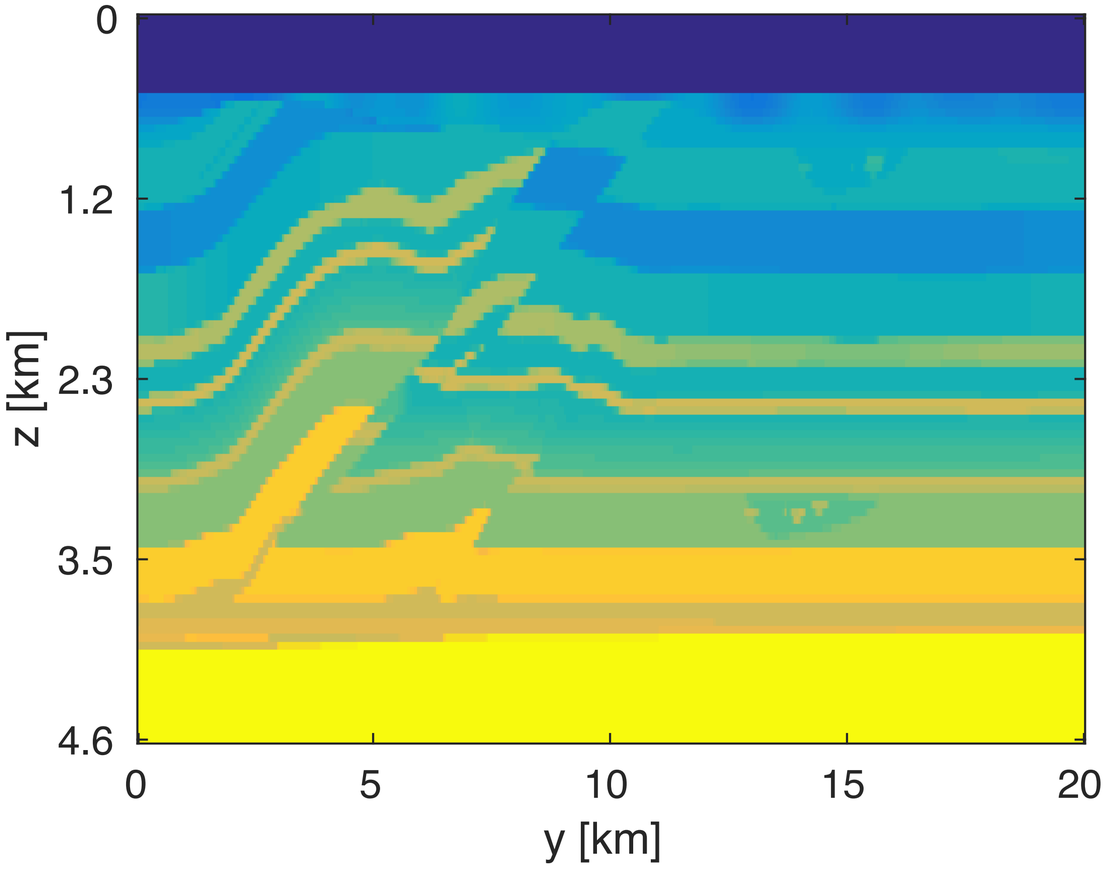
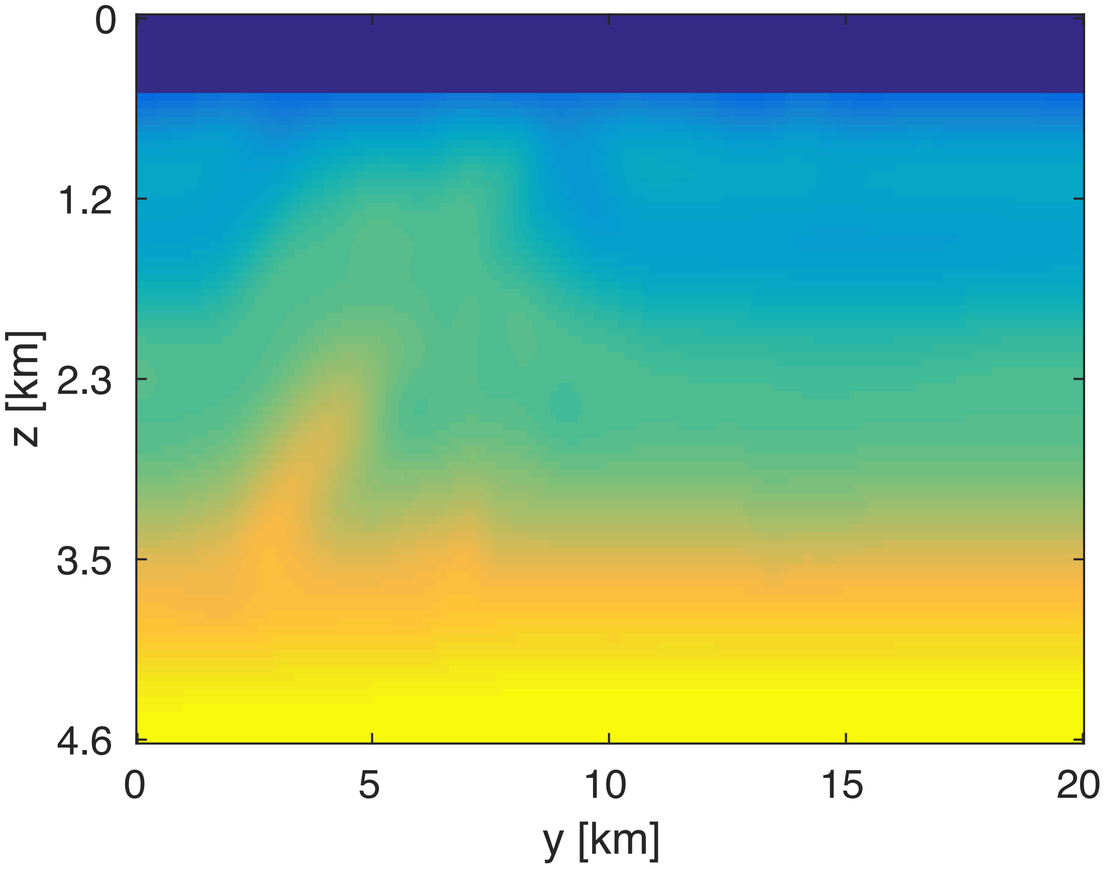


Stochastic LBFGS

x=12.5km slice

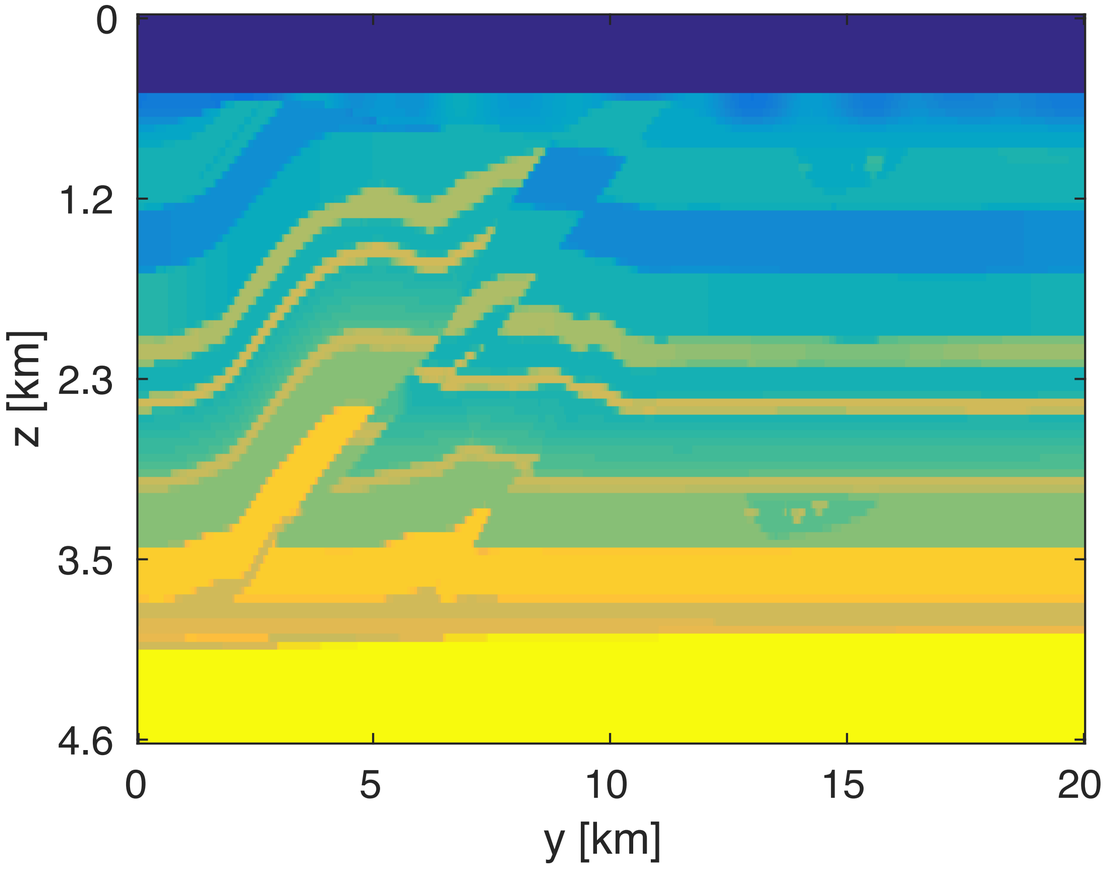


True model

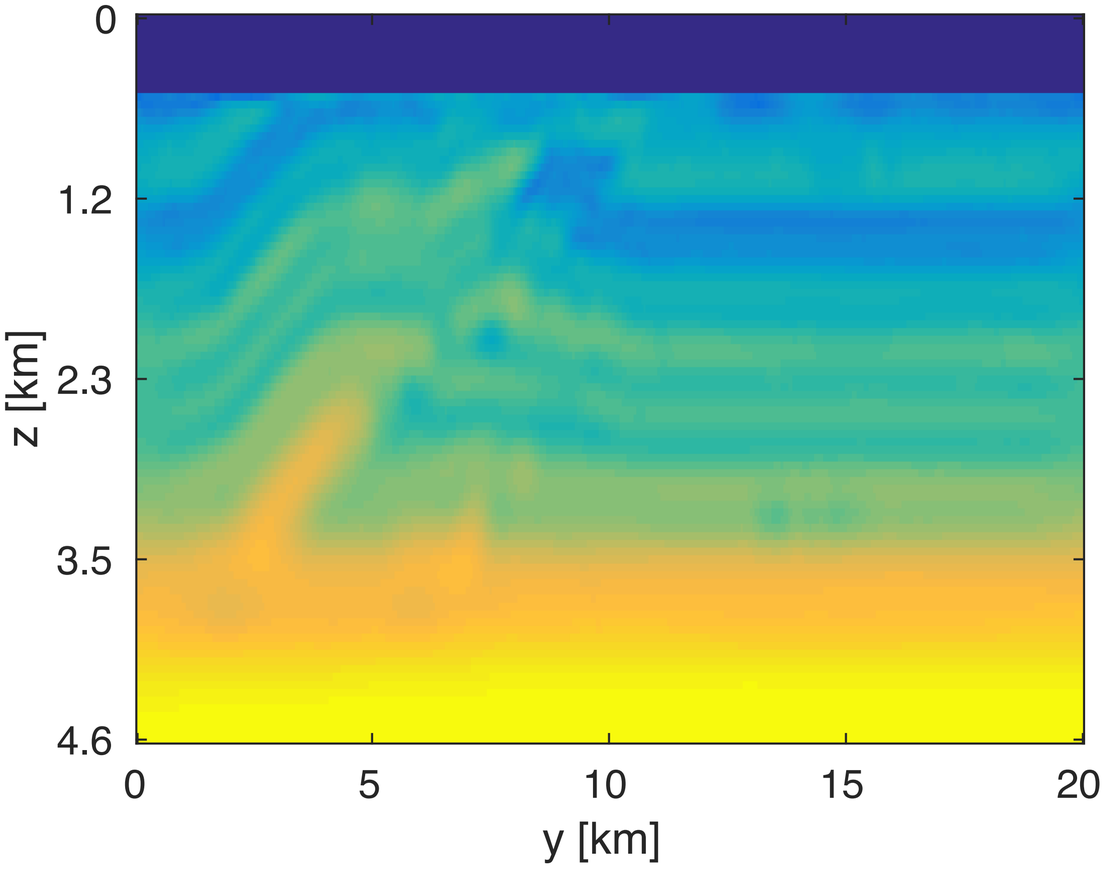


Initial model

x=12.5km slice

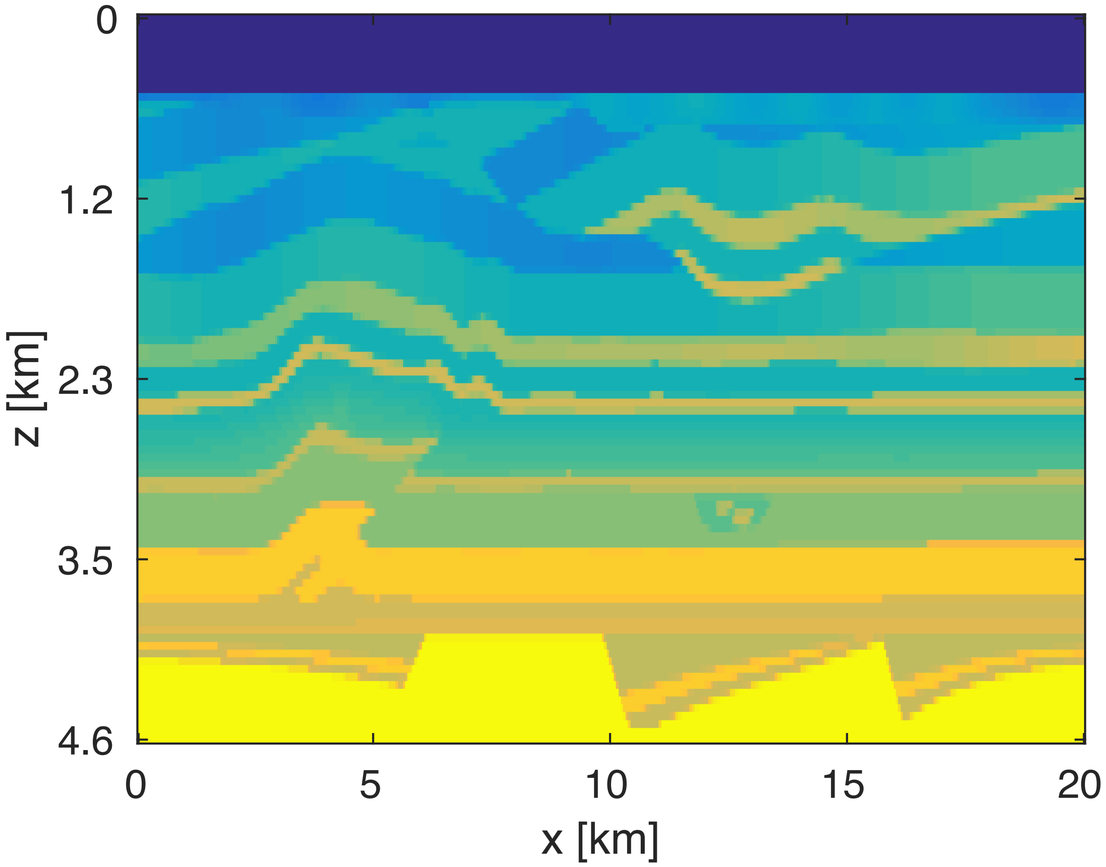


True model

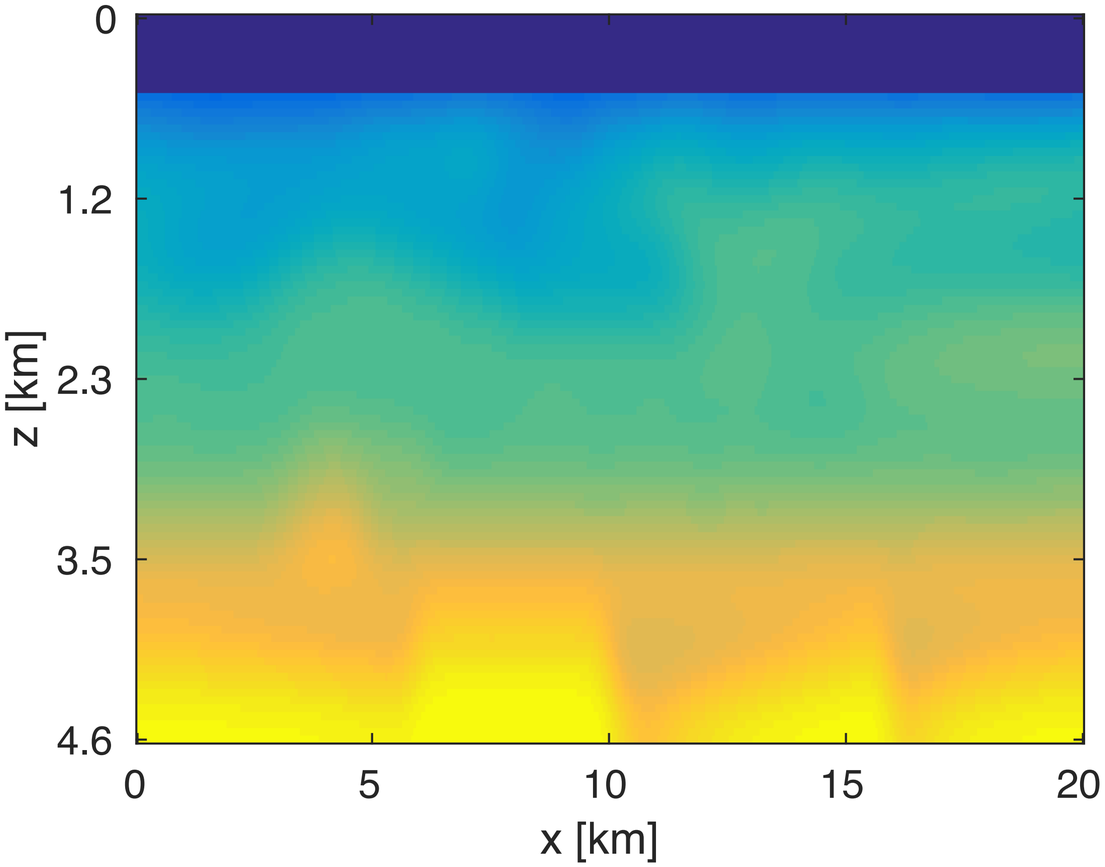


Stochastic LBFGS

y=10km slice

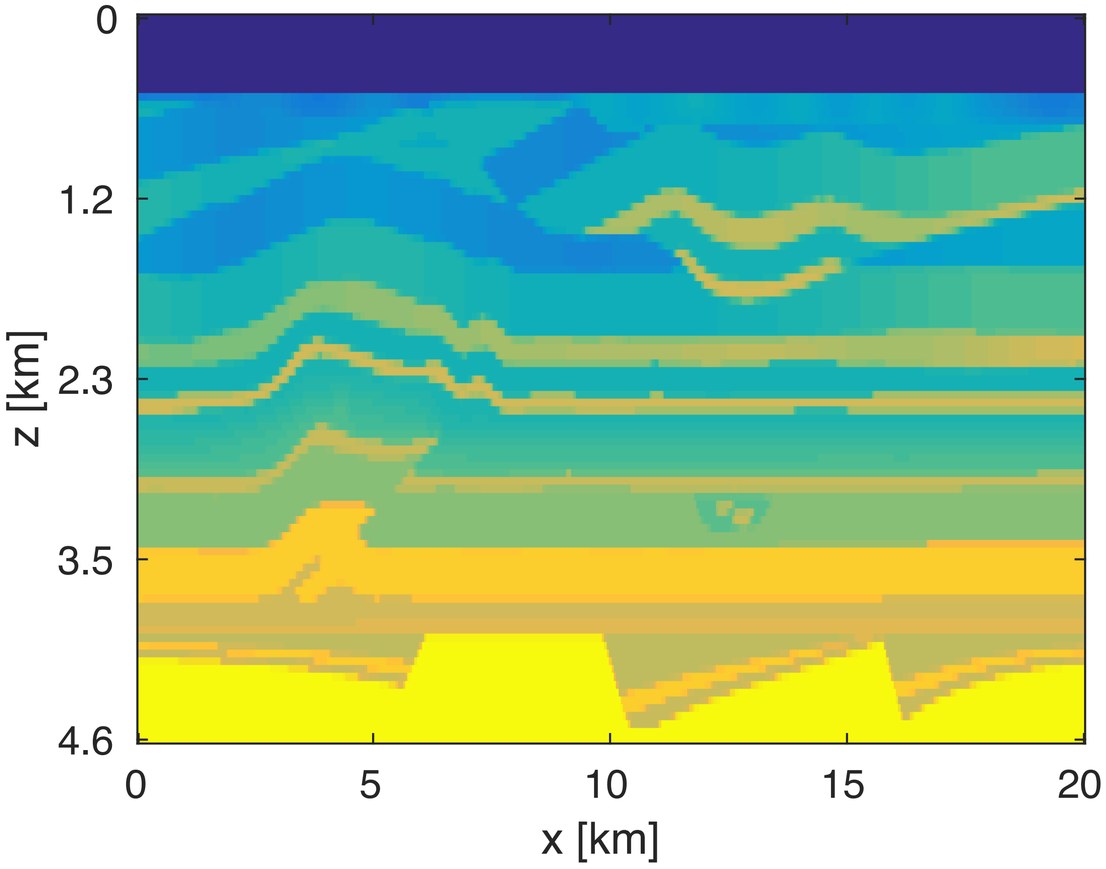


True model

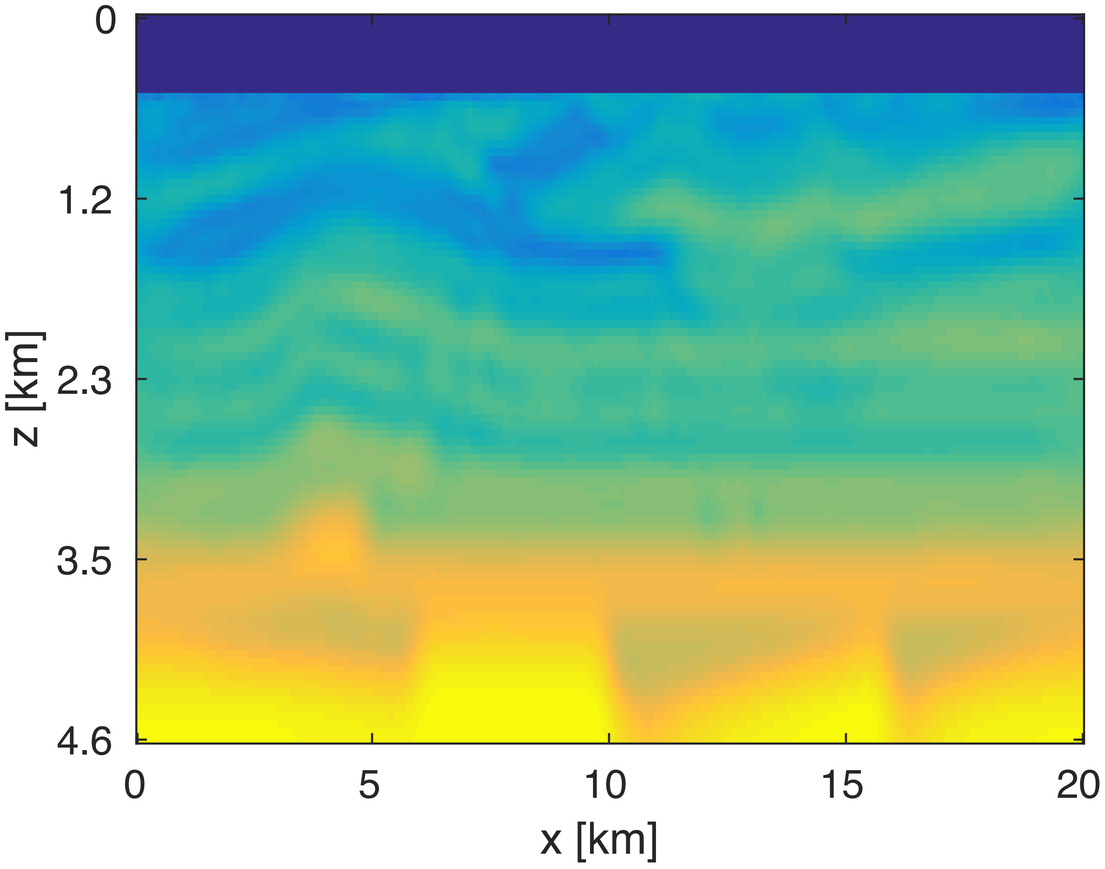


Initial model

y=10km slice



True model



Stochastic LBFGS

Summary

Performance and high-level abstractions don't have to be mutually exclusive

- Design software in a modular, hierarchical way yields benefits of both

Modularity -> flexibility

- Very easy to swap out modules (PDE discretizations, preconditioners) without changing code

Software

Available for download at

https://github.com/slimgroup/WAVEFORM

Paper

Paper submitted to ACM Transactions on Mathematical Software

"A Unified 2D/3D Software Environment for Large Scale Nonlinear Inverse Problems" Curt Da Silva and Felix J. Herrmann.

Look for a preprint soon at https://www.slim.eos.ubc.ca/

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Thank you for your attention