Quantifying parameter resolution for elastic and anisotropic FWI with multi-parameter Hessian probing

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Objective

- ◇ Full-waveform inversion (FWI) methods are heading for recovering elastic and anisotropic properties for reservoir characterization;
- ◇ Complex physics of subsurface medium makes the inverse problems much more challenging;
- ◇ Parameter resolution issue arising from inverting multiple physical parameters;
- ◇ Quantifying the resolving abilities of different parameterizations lies at the heart of multi-parameter FWI;
- ◇ Most of traditional parameter resolution studies are based on ”scattering” or ”radiation” patterns following Tarantola (1986);
- ◇ Evaluate the parameter resolution via probing the multi-parameter Hessian;

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Outline

- Review the basic theory of full-waveform inversion (FWI)
- Parameter resolution issue in multi-parameter FWI
- Quantifying parameter resolution via probing multi-parameter Hessian
- Numerical Examples
- Conclusions

1. Review basic theory of full-waveform inversion (FWI)

Basic Theory of FWI

Search direction $\Delta \mathrm{m}$ is the solution of the Newton system:

$$\mathbf{H}_k \Delta \mathbf{m}_k = -\mathbf{g}_k \quad \rightarrow \quad \Delta \mathbf{m}_k = -\mathbf{H}_k^{-1} \mathbf{g}_k$$

Hessian matrix is an extremely large and dense matrix.

It is unaffordble to calculate, store and invert it explicitly for large-scale inverse problem.

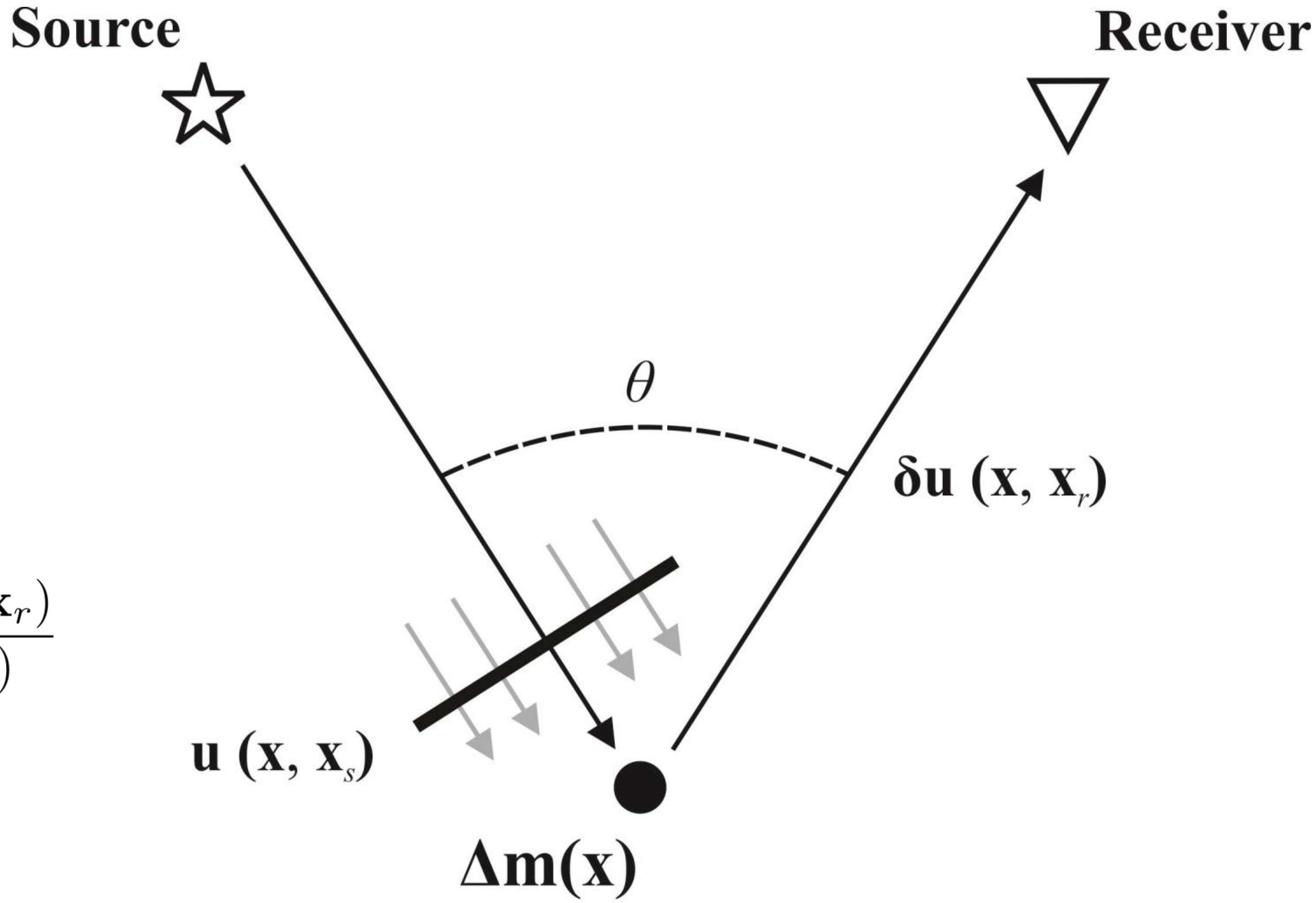
Different optimization methods have different approximations of the inverse Hessian H^{-1}.

The matrix multiplication can be written as an integral formulation:

$$\mathbf{g} = -\int\int H\left(\mathbf{x}, \mathbf{x}'\right) \Delta m\left(\mathbf{x}'\right) d\mathbf{x}' d\mathbf{x}$$

2. Parameter Resolution Issue in Multi-parameter FWI

Parameter resolution analysis based on scattering patterns



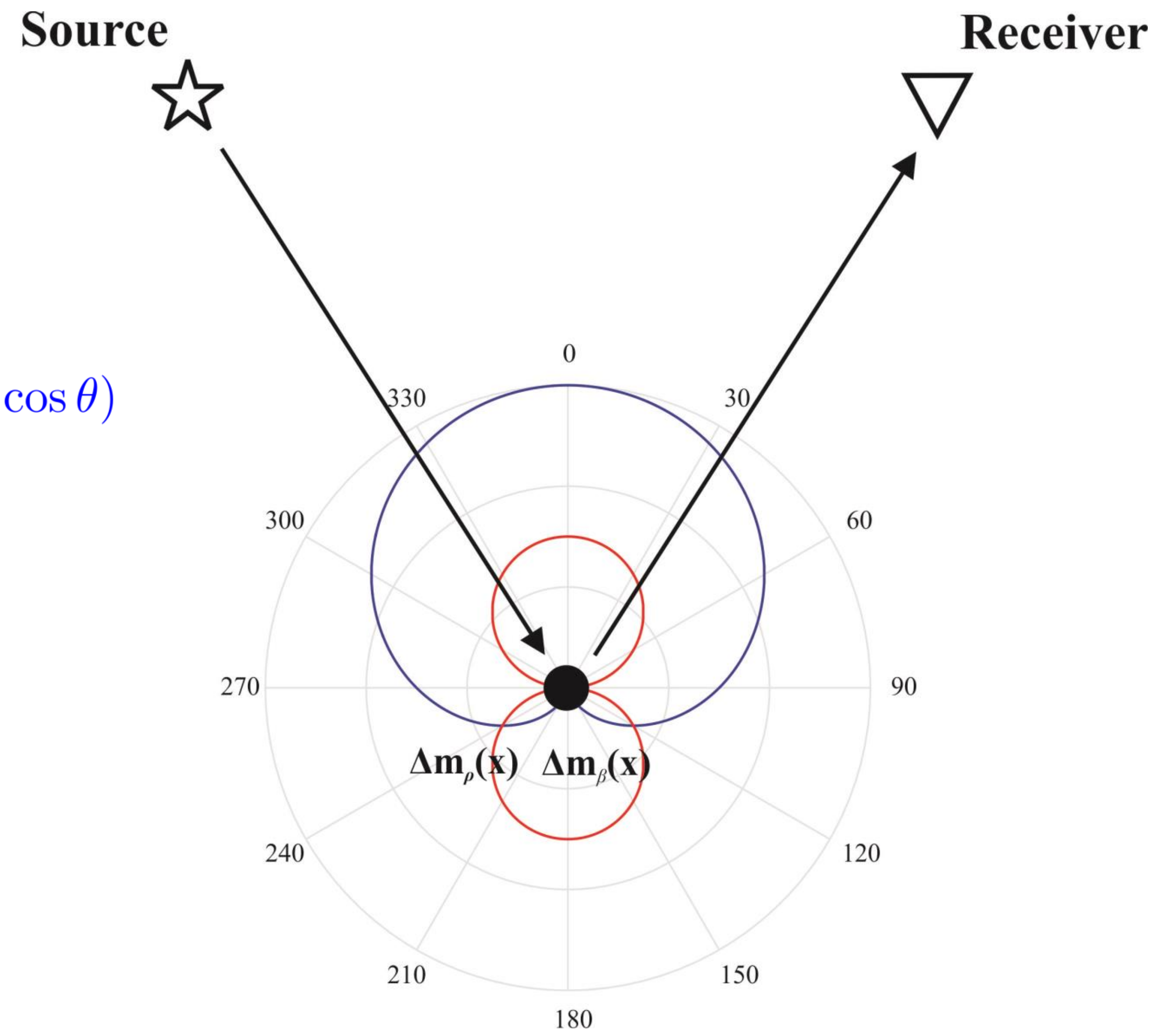
$$\frac{\partial \mathbf{u}\left(\mathbf{x}_s, \mathbf{x}_r\right)}{\partial \mathbf{m}\left(\mathbf{x}\right)}$$

Isotropic and Homogeneous

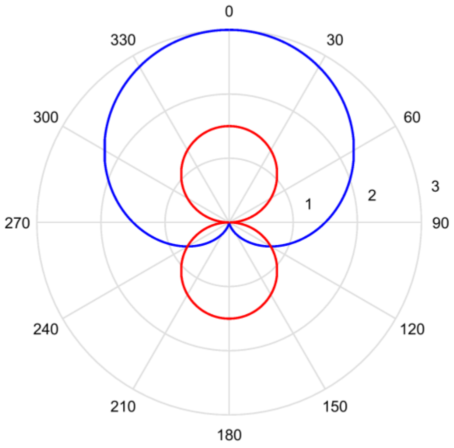
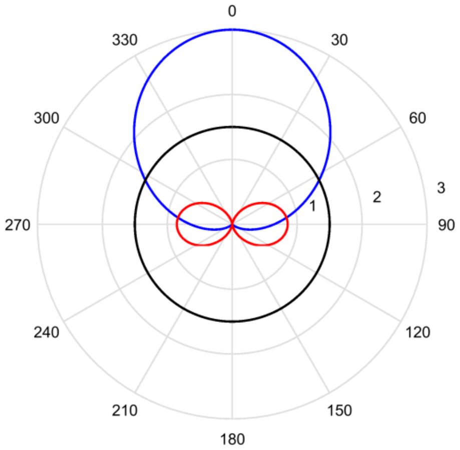
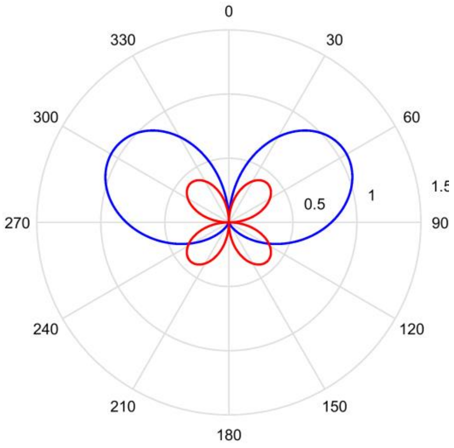
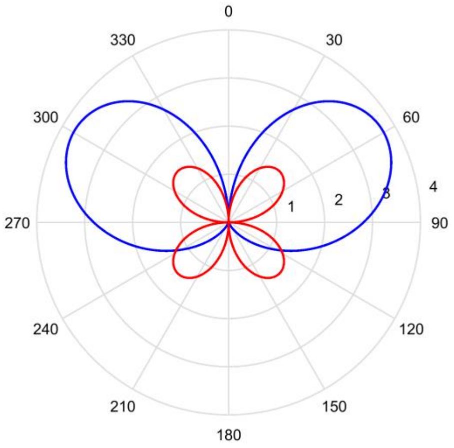
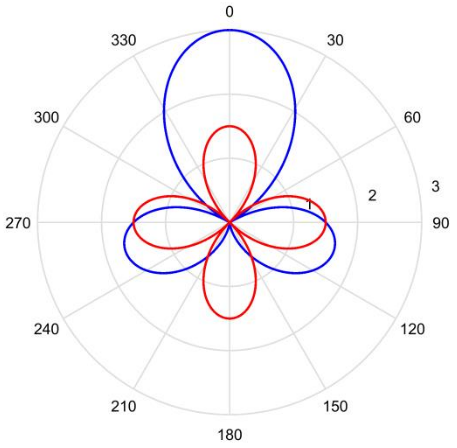
Parameter resolution analysis based on scattering patterns

$$\mathbb{A}^{\rho}_{SHSH} = \rho_0 \left(1 + \cos\theta\right)$$

$$\mathbb{A}^{\beta}_{SHSH} = \rho_0 \cos\theta$$



Parameter resolution analysis based on scattering patterns

$\mathbf{SH \rightarrow SH}$	$\mathbf{P \rightarrow P}$	$\mathbf{P \rightarrow SV}$	$\mathbf{SV \rightarrow P}$	$\mathbf{SV \rightarrow SV}$
				
$\mathbb{A}^{\rho}_{SHSH}$	$\mathbb{A}^{\rho}_{PP}$	$\mathbb{A}^{\rho}_{PSV}$	$\mathbb{A}^{\rho}_{SVP}$	$\mathbb{A}^{\rho}_{SVSV}$
$\mathbb{A}^{\beta}_{SHSH}$	$\mathbb{A}^{\beta}_{PP}$	$\mathbb{A}^{\beta}_{PSV}$	$\mathbb{A}^{\beta}_{SVP}$	$\mathbb{A}^{\beta}_{SVSV}$
	$\mathbb{A}^{\alpha}_{PP}$			

Parameter resolution analysis based on scattering patterns

Disadvantages

◇ **Isotropic and homogeneous background assumption:**

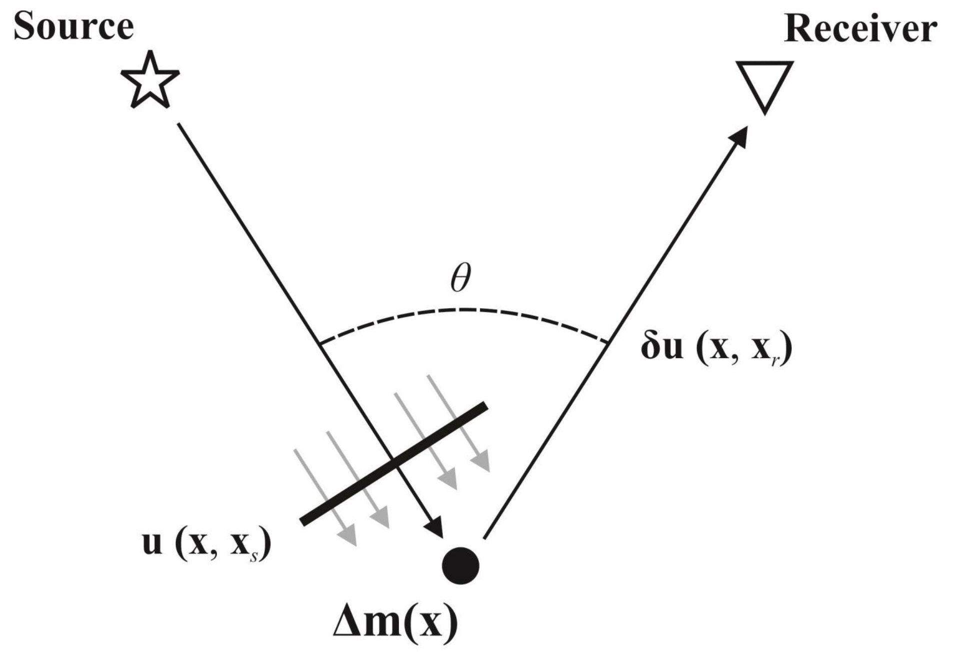
- Ignore more complex model (anisotropy);
- Ignore complex geological structure;

◇ **Incident plane wave with far-field assumption:**

- Ignore geometrical spreading;
- Ignore travel time contribution;

◇ **Overlapping the scattering patterns for analysis:**

- Only consider amplitudes and ignore the contributions of phase;
- Only consider the parameter trade-offs at the same location;
- Ignore the parameter trade-offs at adjacent locations;
- Equivalent to the diagonal elements of off-diagonal blocks in multi-parameter Gauss-Newton Hessian;



Isotropic and Homogeneous

3. Quantify the parameter resolution via probing multi-parameter Hessian

Parameter Crosstalk Difficulty

For a multi-parameter inverse problem, the Newton equation becomes:

$$\begin{bmatrix} \mathbf{H}_{\alpha\alpha} & \mathbf{H}_{\alpha\beta} & \mathbf{H}_{\alpha\rho} \\ \mathbf{H}_{\beta\alpha} & \mathbf{H}_{\beta\beta} & \mathbf{H}_{\beta\rho} \\ \mathbf{H}_{\rho\alpha} & \mathbf{H}_{\rho\beta} & \mathbf{H}_{\rho\rho} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{m}_{\alpha} \\ \Delta\mathbf{m}_{\beta} \\ \Delta\mathbf{m}_{\rho} \end{bmatrix} = - \begin{bmatrix} \mathbf{g}_{\alpha} \\ \mathbf{g}_{\beta} \\ \mathbf{g}_{\rho} \end{bmatrix}$$

α is P-wave velocity, β is S-wave velocity, ρ is density

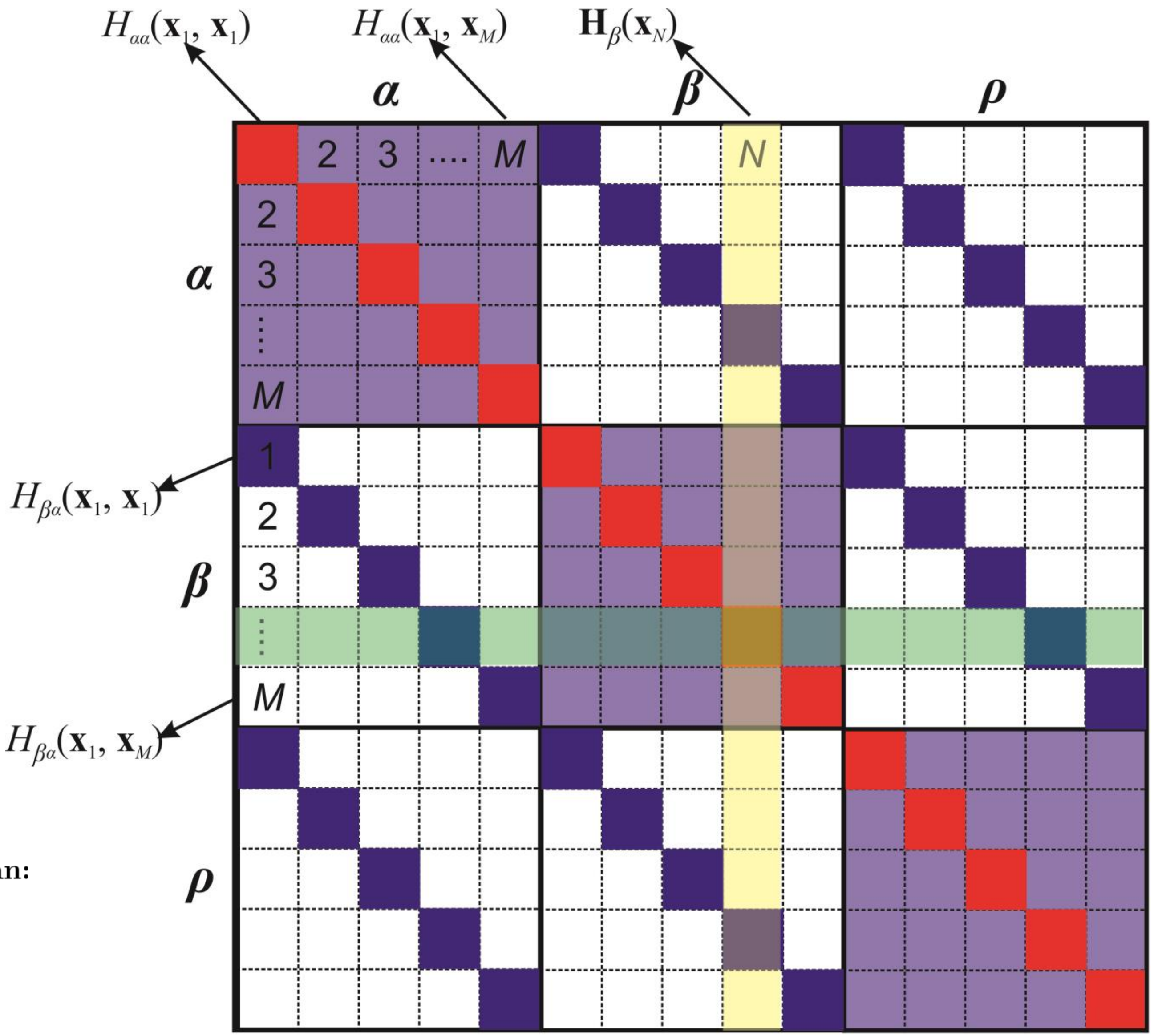
Multi-parameter Hessian has a block structure with 3 diagonal blocks and 6 off-diagonal blocks.

Hessian (or Resolution) matrix is extremely large and difficult to be constructed explicitly.

Physical Interpretations of Multi-parameter Hessian

- ◇ The elements of multi-parameter Hessian are classified into 4 types;
  1. Diagonal elements of the diagonal blocks: $H_{\alpha\alpha}(\mathbf{x}_1, \mathbf{x}_1)$
  2. Off-diagonal elements of the diagonal blocks: $H_{\alpha\alpha}(\mathbf{x}_1, \mathbf{x}_M)$
  3. Diagonal elements of the off-diagonal blocks: $H_{\beta\alpha}(\mathbf{x}_1, \mathbf{x}_1)$
  4. Off-diagonal elements of the off-diagonal blocks: $H_{\beta\alpha}(\mathbf{x}_1, \mathbf{x}_M)$
- ◇ Diagonal blocks measure spatial resolution;
- ◇ Off-diagonal blocks measure spatial plus parameter resolution;
- ◇ Columns and rows have different physical interpretations:
  - ◇ Rows are blurring kernels;
  - ◇ Columns are multi-parameter point-spread functions;
- ◇ Overlapping the scattering patterns is partial multi-parameter Hessian:

$$H_{\beta\alpha}^{GN}(\mathbf{x}_1, \mathbf{x}_1) = \frac{\partial \mathbf{u}^{\dagger}(\mathbf{x}_s, \mathbf{x}_r)}{\partial \mathbf{m}_\beta(\mathbf{x}_1)} \frac{\partial \mathbf{u}^{*}(\mathbf{x}_s, \mathbf{x}_r)}{\partial \mathbf{m}_\beta(\mathbf{x}_1)}$$



Parameter Crosstalk Difficulty

Newton equation system can be written in an integral formulation:

$$\mathbf{g}_\alpha = -\int\int H_{\alpha\alpha}(\mathbf{x},\mathbf{x}')\,\Delta m_\alpha(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\alpha\beta}(\mathbf{x},\mathbf{x}')\,\Delta m_\beta(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\alpha\rho}(\mathbf{x},\mathbf{x}')\,\Delta m_\rho(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x}$$

- ◇ **Model perturbations of S-wave velcotiy and denisty are mapped into gradient vector of P-wave velocity;**
- ◇ **Inter-parameter mappings are described by the off-diagonal blocks of multi-parameter Hessian;**

Vice versa, we have:

$$\mathbf{g}_\beta = -\int\int H_{\beta\alpha}(\mathbf{x},\mathbf{x}')\,\Delta m_\alpha(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\beta\beta}(\mathbf{x},\mathbf{x}')\,\Delta m_\beta(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\beta\rho}(\mathbf{x},\mathbf{x}')\,\Delta m_\rho(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x}$$

$$\mathbf{g}_\rho = -\int\int H_{\rho\alpha}(\mathbf{x},\mathbf{x}')\,\Delta m_\alpha(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\rho\beta}(\mathbf{x},\mathbf{x}')\,\Delta m_\beta(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\rho\rho}(\mathbf{x},\mathbf{x}')\,\Delta m_\rho(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x}$$

- ◇ **The strength, phase, and spread width of the inter-parameter mappings differ significantly;**

Spike Probing of Multi-parameter Hessian

Considering a point perturbation of P-wave velocity $\Delta\mathbf{m}_\alpha(\tilde{\mathbf{x}})$:

$$\Delta\mathbf{m}_\alpha = \delta(\mathbf{x}-\tilde{\mathbf{x}}), \qquad \Delta\mathbf{m}_\beta = 0, \qquad \Delta\mathbf{m}_\rho = 0$$

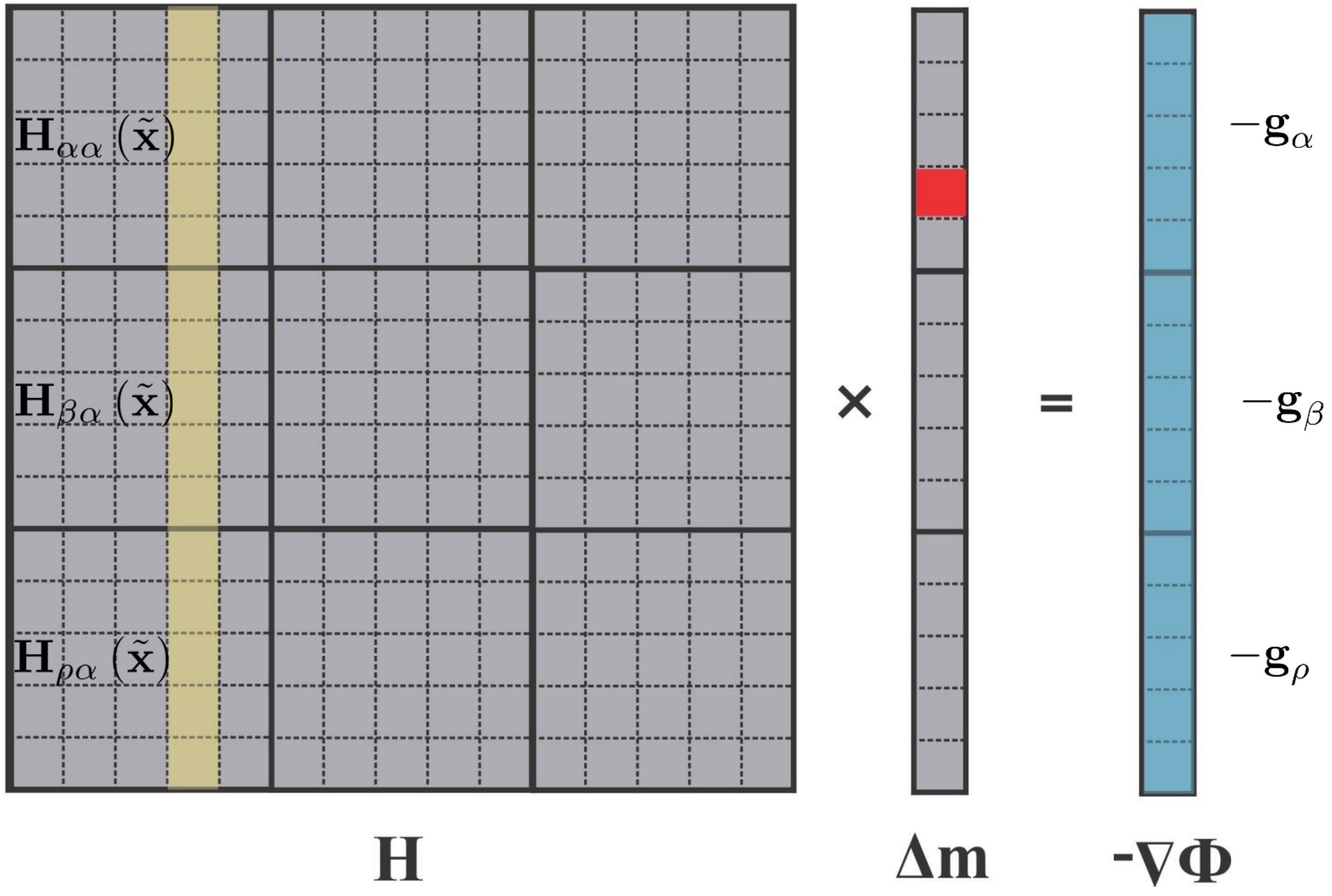
$$\begin{aligned}\mathbf{g}_\alpha &= -\int\int H_{\alpha\alpha}(\mathbf{x},\mathbf{x}')\,\Delta m_\alpha(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\alpha\beta}(\mathbf{x},\mathbf{x}')\,\Delta m_\beta(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} - \int\int H_{\alpha\rho}(\mathbf{x},\mathbf{x}')\,\Delta m_\rho(\mathbf{x}')\,d\mathbf{x}'d\mathbf{x} \\ &= -\int\int H_{\alpha\alpha}(\mathbf{x},\mathbf{x}')\,\delta(\mathbf{x}'-\tilde{\mathbf{x}})\,d\mathbf{x}'d\mathbf{x} - 0 - 0 \\ &= -\mathbf{H}_{\alpha\alpha}(\tilde{\mathbf{x}})\end{aligned}$$

$\mathbf{g}_\beta = -\mathbf{H}_{\beta\alpha}(\tilde{\mathbf{x}})$ The coupling of P-wave velocity at position $\tilde{\mathrm{x}}$ with S-wave velocity at adjacent positions.

$\mathbf{g}_\rho = -\mathbf{H}_{\rho\alpha}(\tilde{\mathbf{x}})$ The coupling of P-wave velocity at position $\tilde{\mathrm{x}}$ with density at adjacent positions.

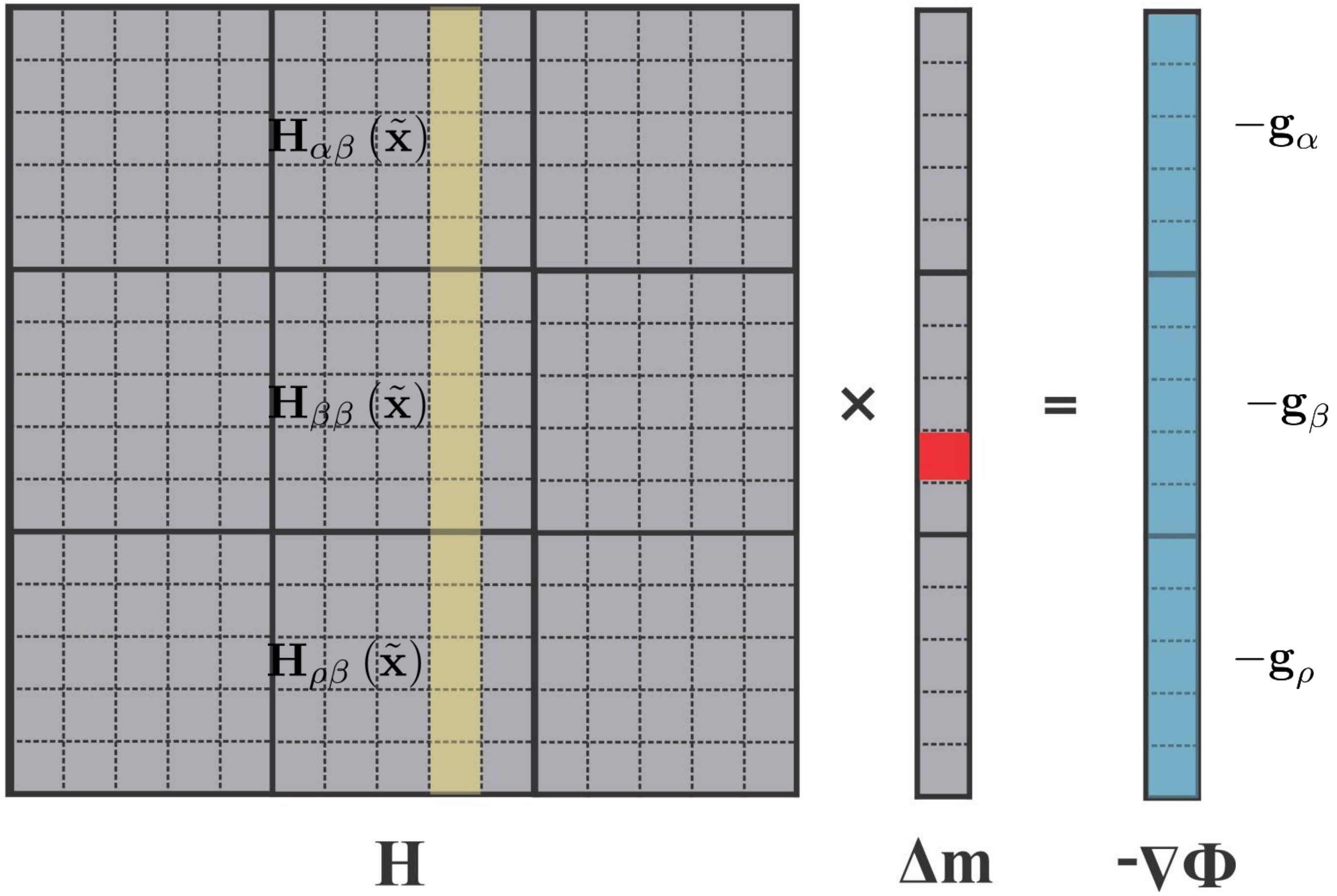
Spike Probing of Multi-parameter Hessian

$$\mathbf{g}_{\alpha} = -\mathbf{H}_{\alpha\alpha}\left(\tilde{\mathbf{x}}\right), \quad \mathbf{g}_{\beta} = -\mathbf{H}_{\beta\alpha}\left(\tilde{\mathbf{x}}\right), \quad \mathbf{g}_{\rho} = -\mathbf{H}_{\rho\alpha}\left(\tilde{\mathbf{x}}\right)$$



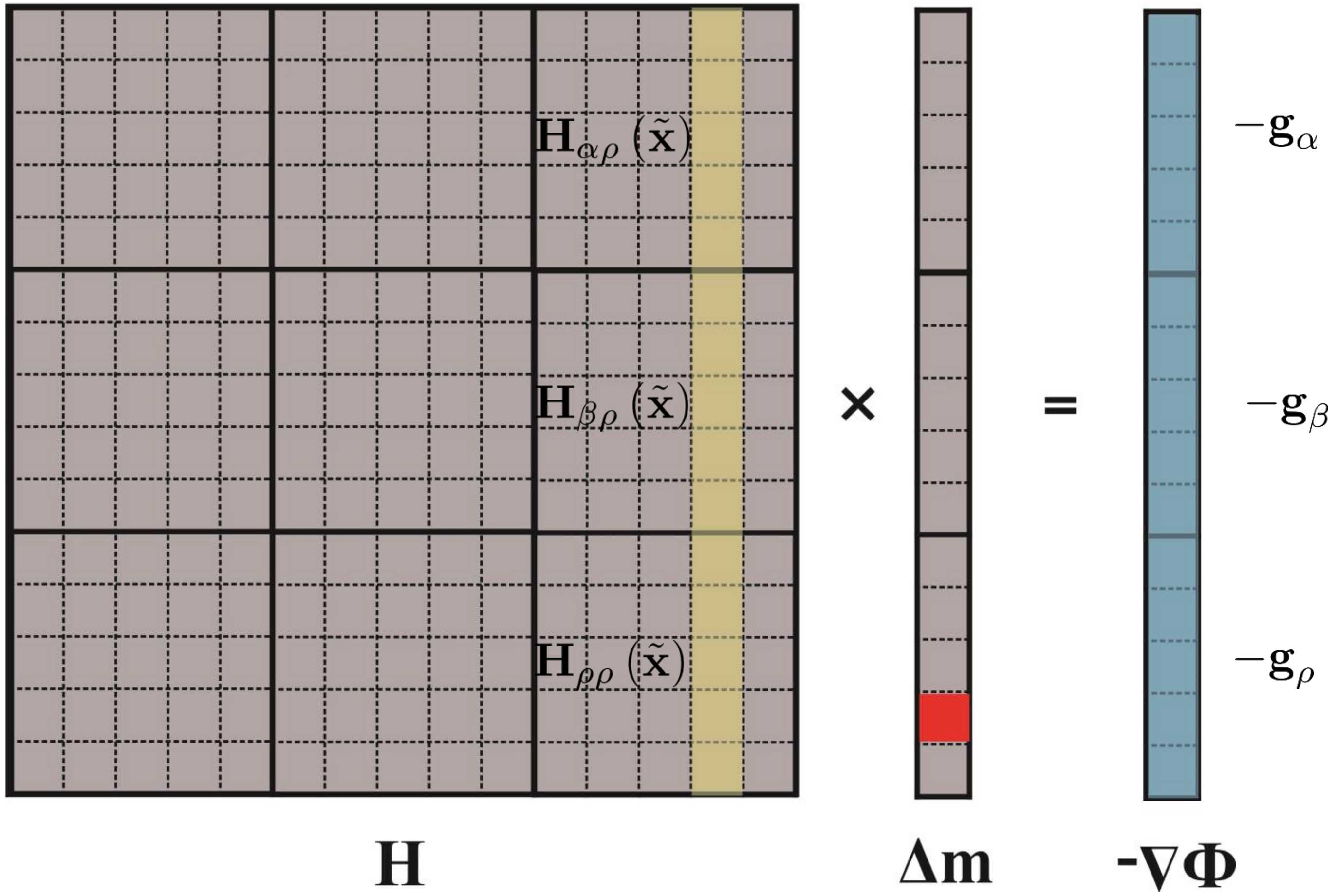
Spike Probing of Multi-parameter Hessian

$$\mathbf{g}_\alpha = -\mathbf{H}_{\alpha\beta}\left(\tilde{\mathbf{x}}\right), \quad \mathbf{g}_\beta = -\mathbf{H}_{\beta\beta}\left(\tilde{\mathbf{x}}\right), \quad \mathbf{g}_\rho = -\mathbf{H}_{\rho\beta}\left(\tilde{\mathbf{x}}\right)$$



Spike Probing of Multi-parameter Hessian

$$\mathbf{g}_\alpha = -\mathbf{H}_{\alpha\rho}(\tilde{\mathbf{x}}), \quad \mathbf{g}_\beta = -\mathbf{H}_{\beta\rho}(\tilde{\mathbf{x}}), \quad \mathbf{g}_\rho = -\mathbf{H}_{\rho\rho}(\tilde{\mathbf{x}})$$



Stochastic Probing of Multi-parameter Hessian

Random vector: $\Delta\mathbf{m}_r$

Hessian-vector product: $\mathbf{H}\Delta\mathbf{m}_r$

Compute the product of the Hessian-vector with the random vector:

$$\Delta\mathbf{m}_r^{\dagger}\mathbf{H}\Delta\mathbf{m}_r$$

Apply expectation operator with a series of ranomd vector realizations:

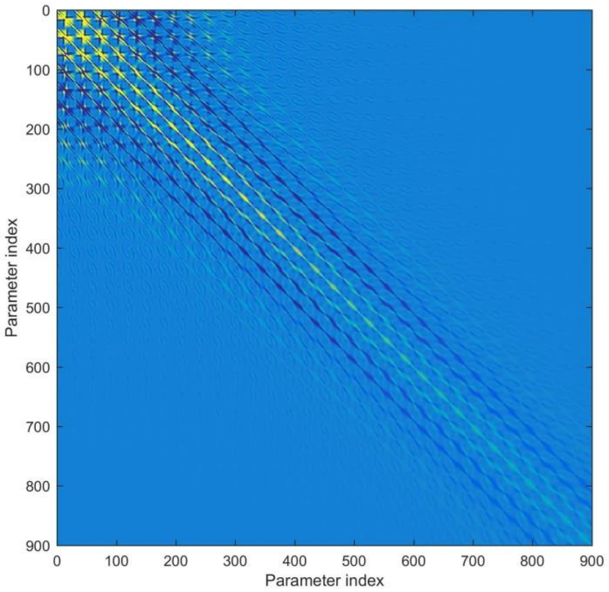
$$\sum_{r=1}^{NR}\mathbb{E}\left(\Delta\mathbf{m}_r^{\dagger}\mathbf{H}\Delta\mathbf{m}_r\right)/NR \approx \mathbf{H}_{\mathrm{diag}}$$

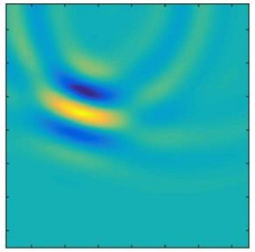
With different random vectors ensemble:

$$\sum_{r=1}^{NR}\mathbb{E}\left(\Delta\tilde{\mathbf{m}}_r^{\dagger}\mathbf{H}\Delta\mathbf{m}_r\right)/NR \approx \mathbf{H}_{\mathrm{diag}}^{\rho\beta}$$

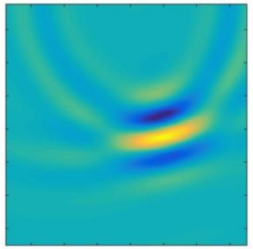
Stochastic Probing of Multi-parameter Hessian

$\mathbf{H}$



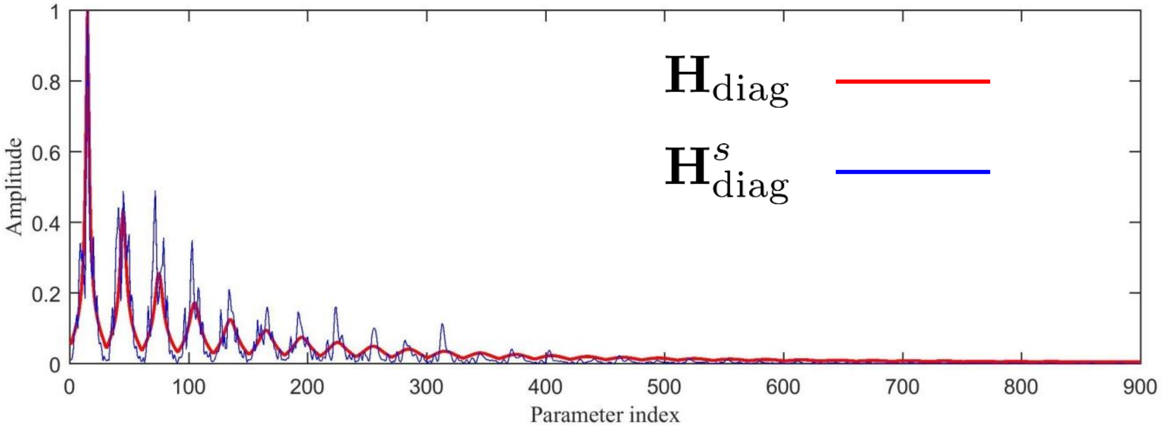


$\mathbf{H}\left(\mathbf{x}_1\right)$

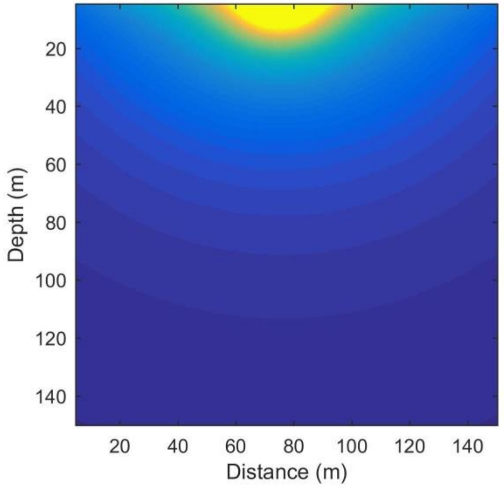


$\mathbf{H}\left(\mathbf{x}_2\right)$

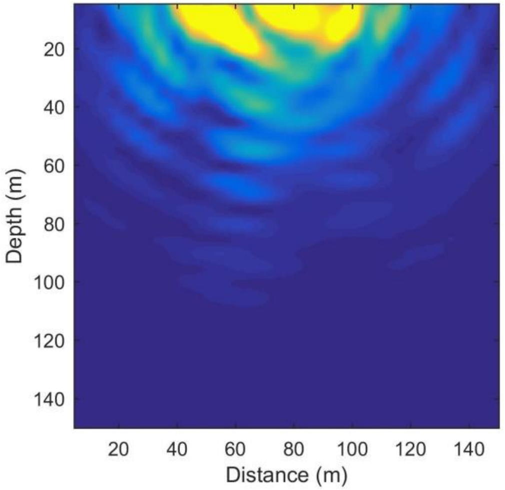
$$\sum_{r=1}^{NR} \mathbb{E}\left(\Delta \mathbf{m}_r^{\dagger} \mathbf{H} \Delta \mathbf{m}_r\right) / NR \approx \mathbf{H}_{\text{diag}}$$



$\mathbf{H}_{\text{diag}}$



$\mathbf{H}^{s}_{\text{diag}}$



Benefits of Probing Multi-parameter Hessian

Spike probing method:

- ◇ finite-frequency effects.
- ◇ Evaluate the strength, polarity and spread width of the inter-parameter mappings.
- ◇ Evaluate the coupling effects of different physical parameters at different locations.
- ◇ geometrical spreading, complex model and complex geological structure.
- ◇ local limitation.

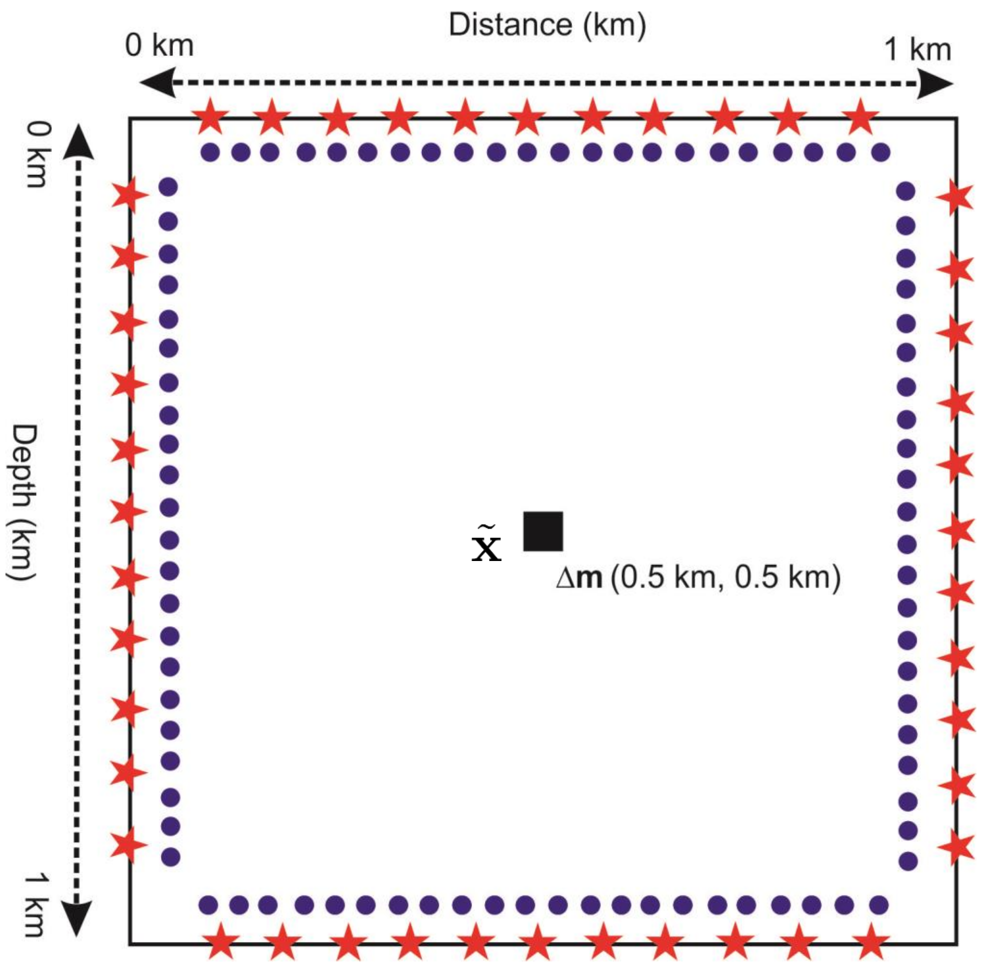
Stochastic probing method:

- ◇ travel time.
- ◇ whole volume.

4. Numerical Examples

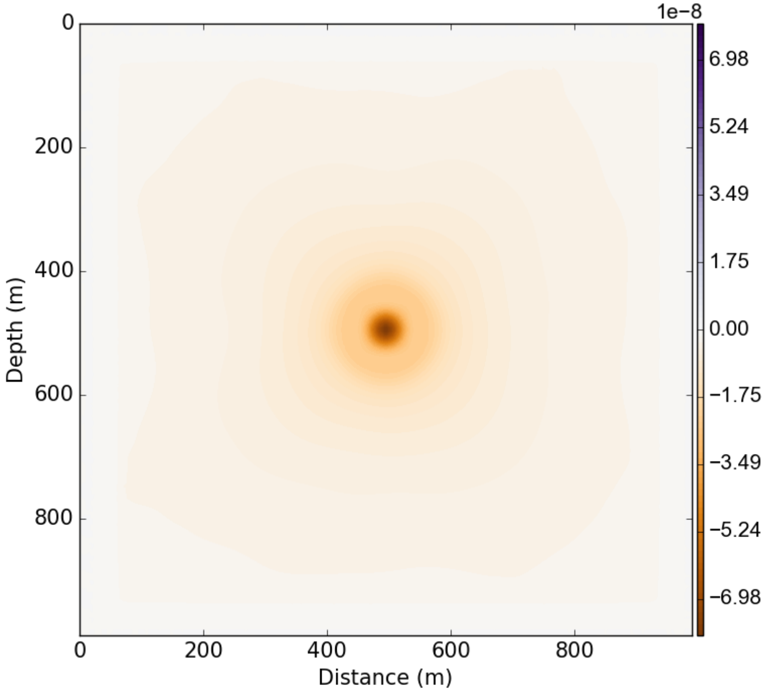
4.1 Isotropic and Elastic Examples

2D Elastic Example with Perfect Acquisition Geometry

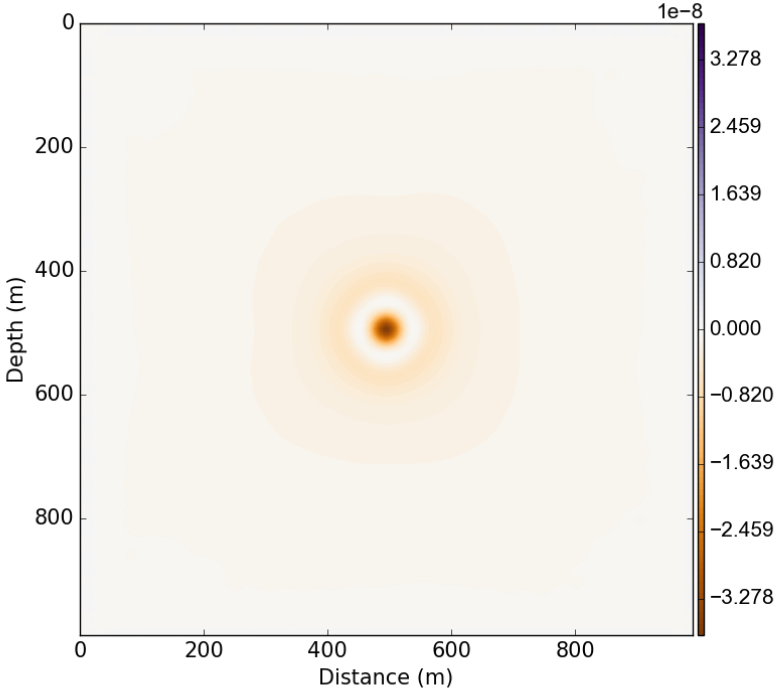


Multi-parameter Point Spread Function: SH Example

$\beta \rightarrow \rho$



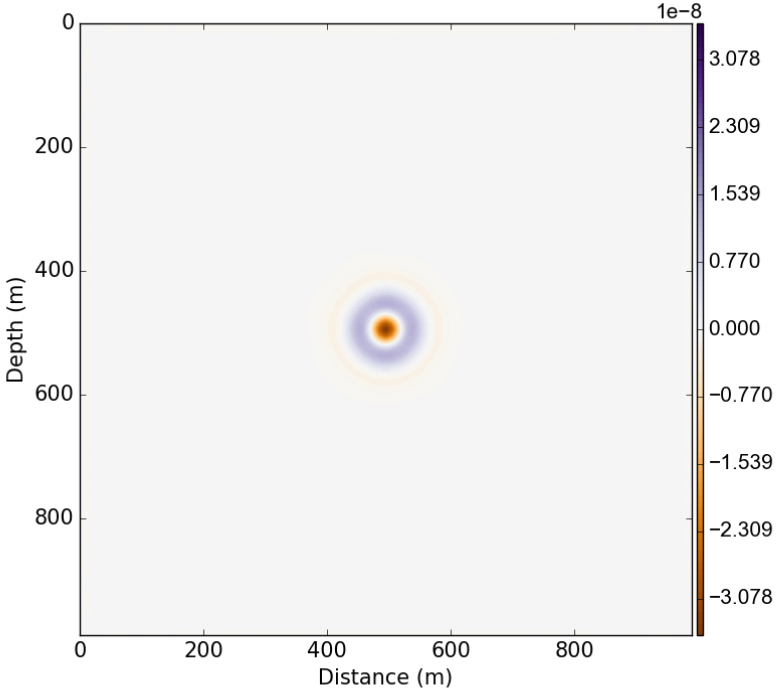
$-\mathbf{H}_{\beta\beta}\left(\tilde{\mathbf{x}}\right)$



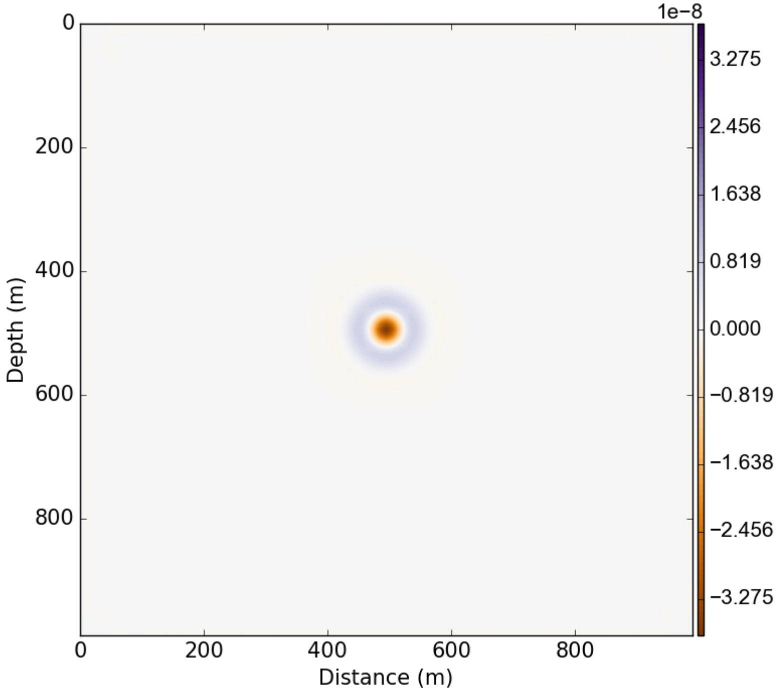
$-\mathbf{H}_{\rho\beta}\left(\tilde{\mathbf{x}}\right)$

Multi-parameter Point Spread Function: SH Example

$$\rho \rightarrow \beta$$

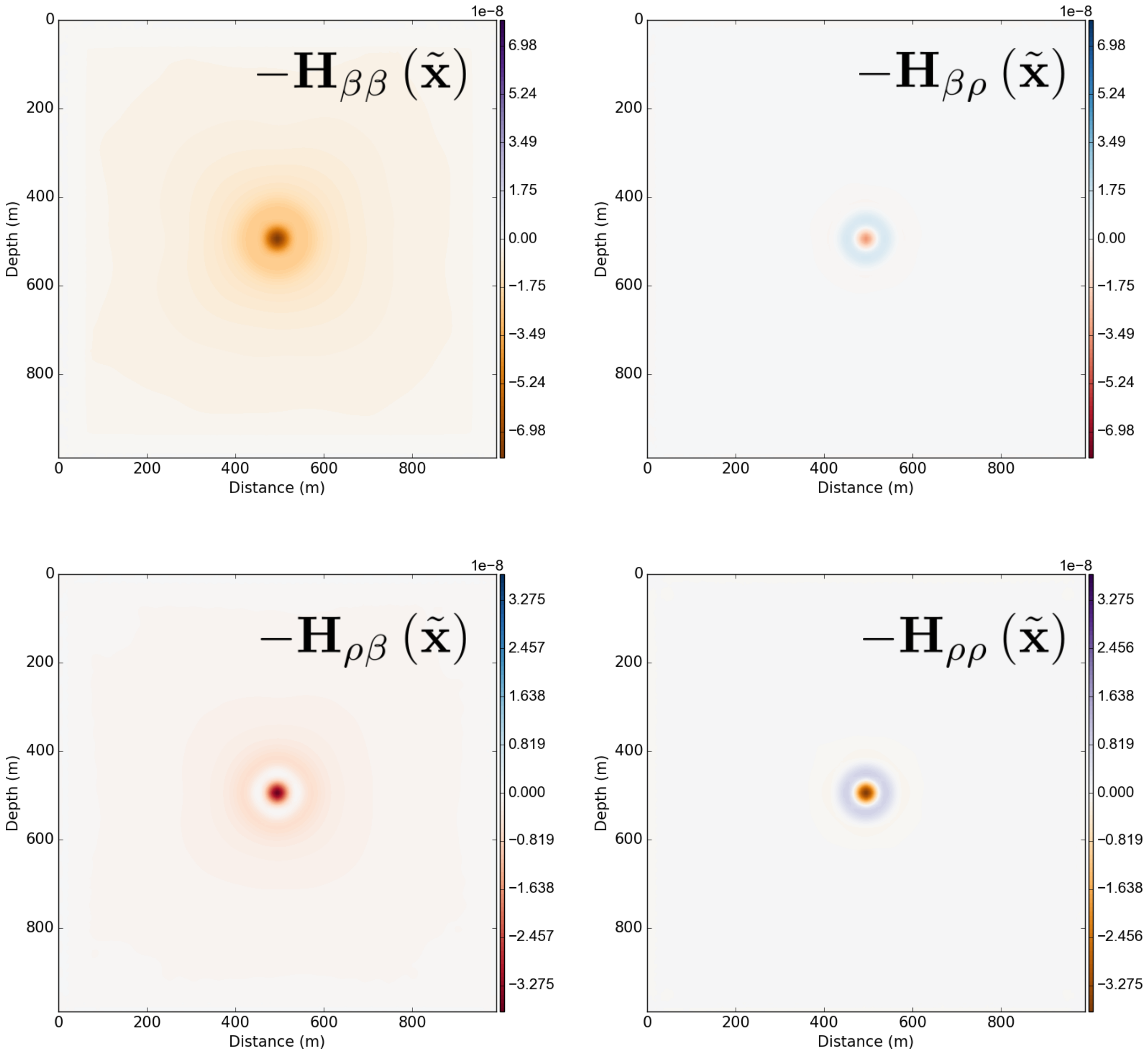


$$-\mathbf{H}_{\beta\rho}\left(\tilde{\mathbf{x}}\right)$$

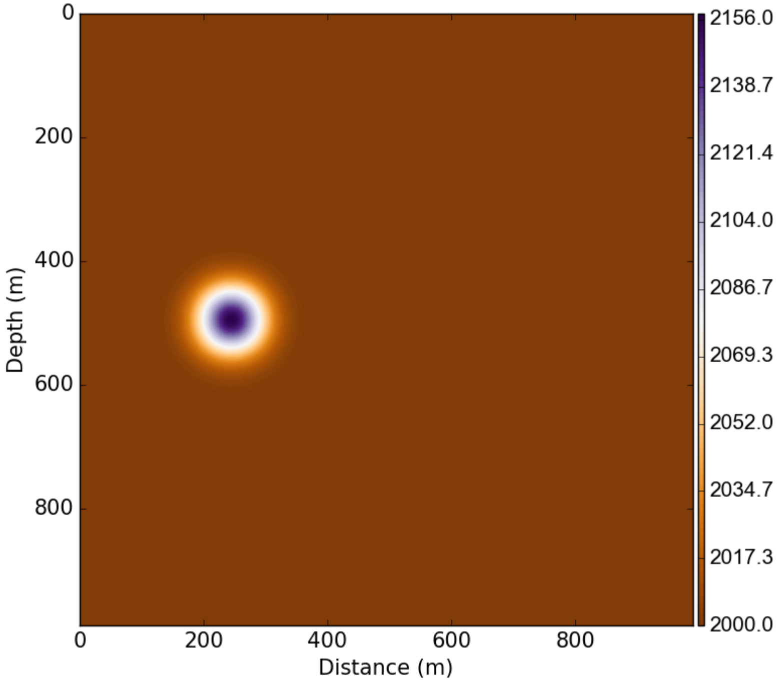


$$-\mathbf{H}_{\rho\rho}\left(\tilde{\mathbf{x}}\right)$$

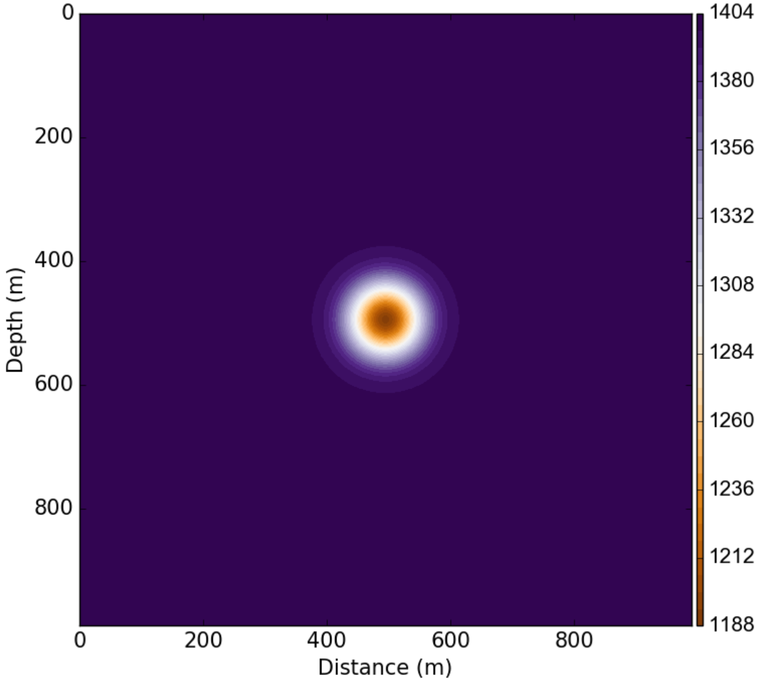
Multi-parameter Point Spread Function: SH Example



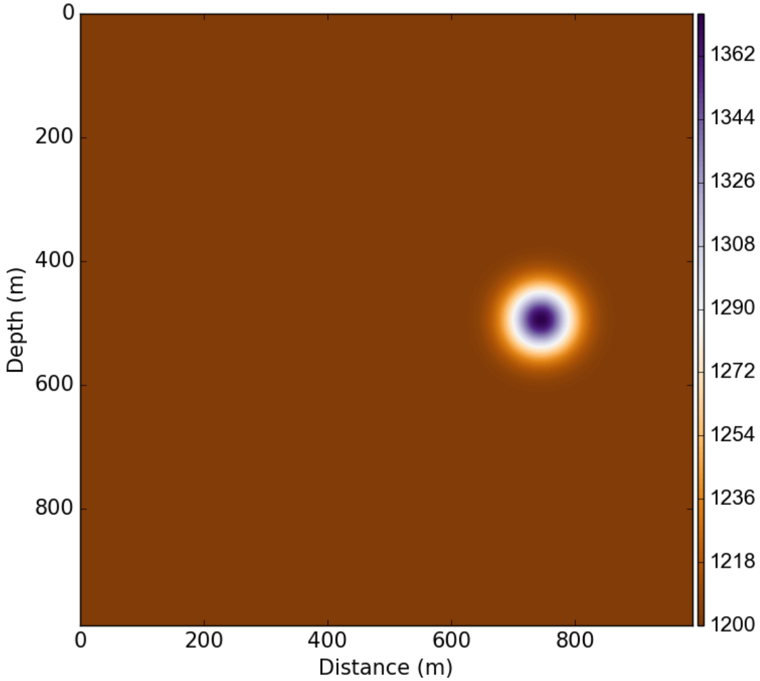
True Models



True P-wave Velocity: α



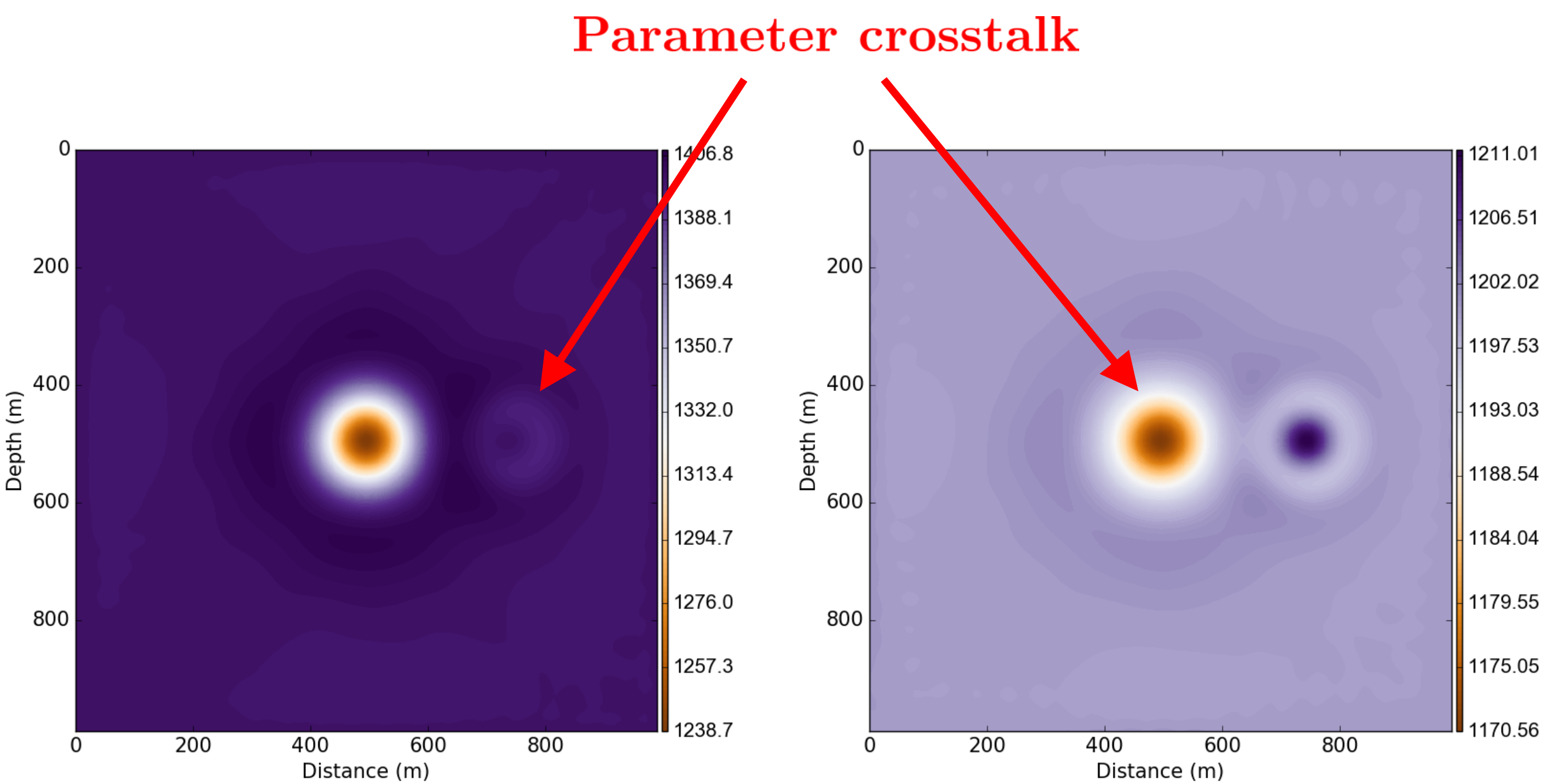
True S-wave Velocity: β



True Density: ρ

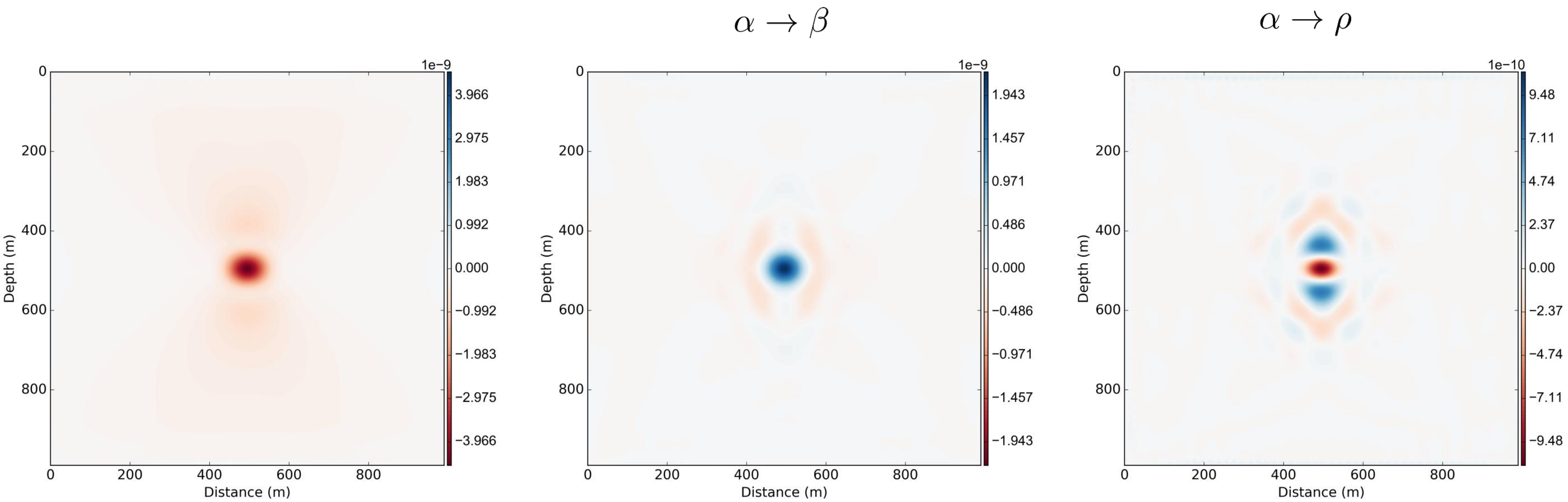
Initial Models are homogeneous.

Inverted Models



Inverted S-wave Velocity: β **Inverted Density:** ρ

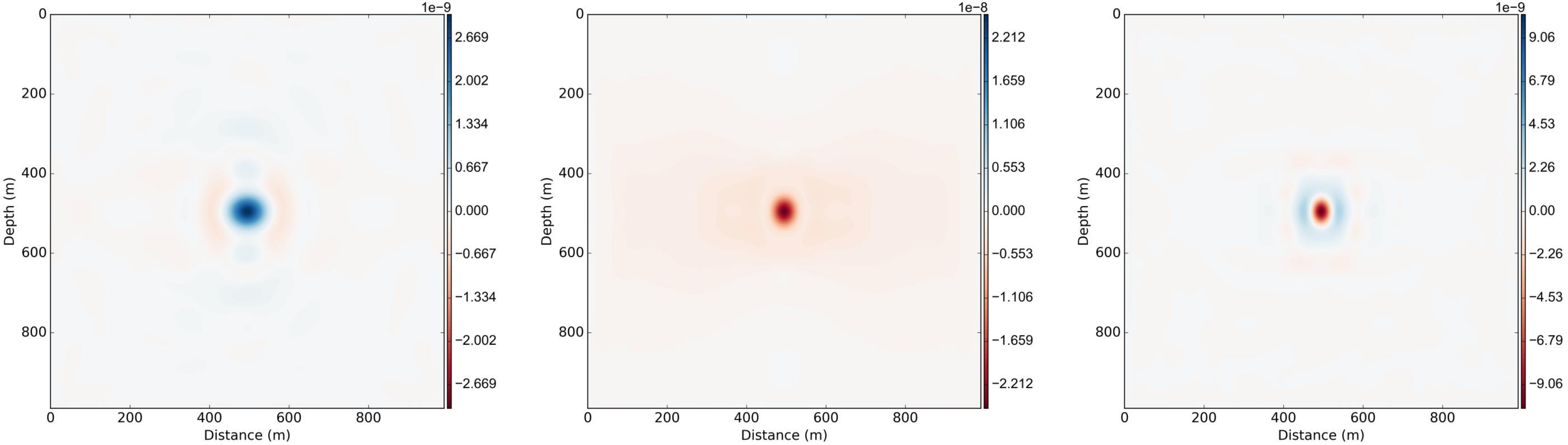
Multi-parameter Point Spread Function: P-SV Example



$-\mathbf{H}_{\alpha\alpha}\left(\tilde{\mathbf{x}}\right)$ $-\mathbf{H}_{\beta\alpha}\left(\tilde{\mathbf{x}}\right)$ $-\mathbf{H}_{\rho\alpha}\left(\tilde{\mathbf{x}}\right)$

Multi-parameter Point Spread Function: P-SV Example

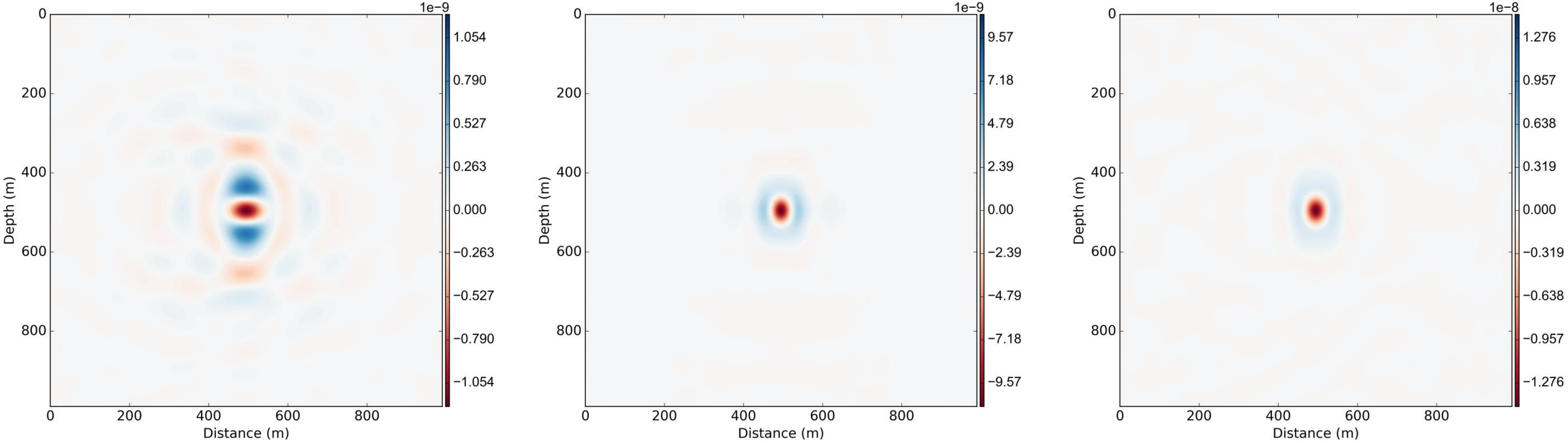
$\beta \rightarrow \alpha$ $\beta \rightarrow \rho$



$-\mathbf{H}_{\alpha\beta}\left(\tilde{\mathbf{x}}\right)$ $-\mathbf{H}_{\beta\beta}\left(\tilde{\mathbf{x}}\right)$ $-\mathbf{H}_{\rho\beta}\left(\tilde{\mathbf{x}}\right)$

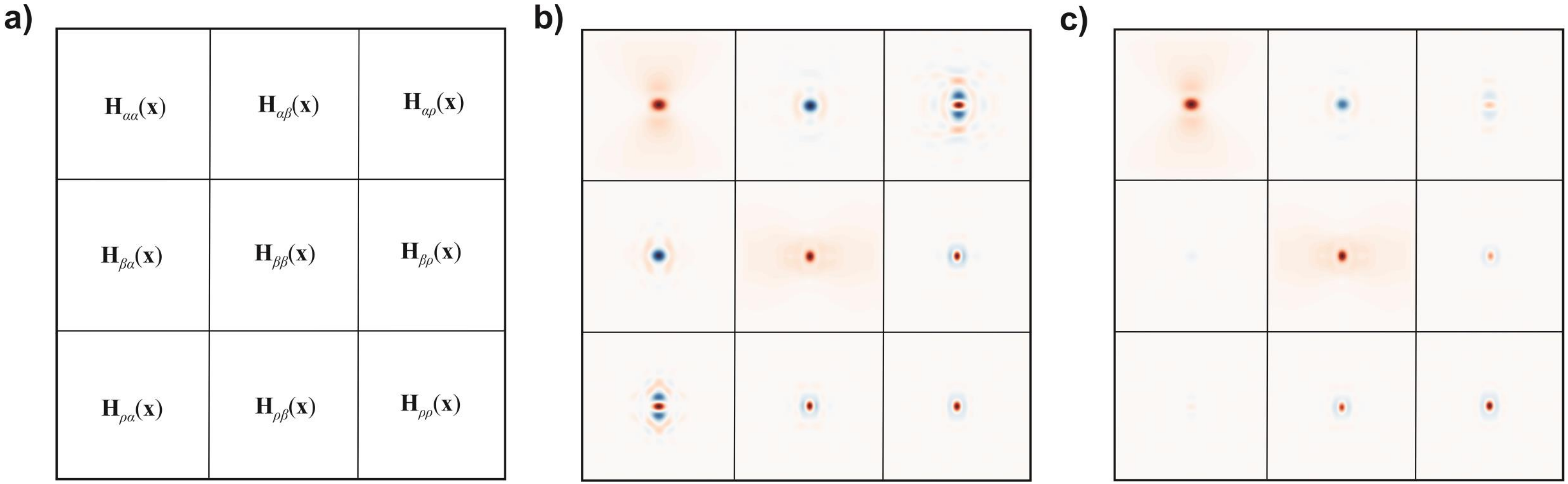
Multi-parameter Point Spread Function: P-SV Example

$\rho \rightarrow \alpha$ $\qquad$ $\rho \rightarrow \beta$



$-\mathbf{H}_{\alpha\rho}(\tilde{\mathbf{x}})$ $\qquad$ $-\mathbf{H}_{\beta\rho}(\tilde{\mathbf{x}})$ $\qquad$ $-\mathbf{H}_{\rho\rho}(\tilde{\mathbf{x}})$

Multi-parameter Point Spread Function: P-SV Example

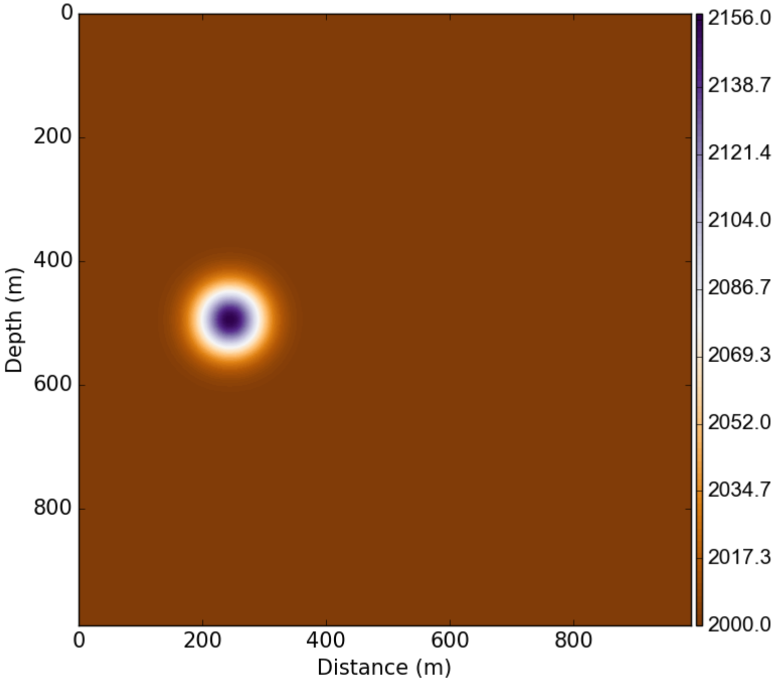


The mappings from P-wave to S-wave and density will be weak;

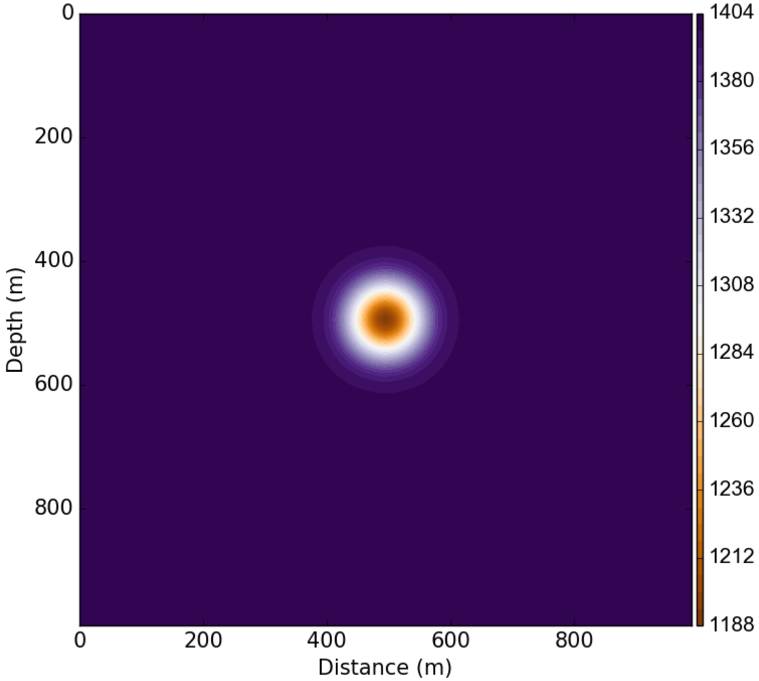
The mapping of positive S-wave velocity perturbation to P-wave velocity is negative and vice versa;

The mappings from S-wave velocity to P-wave velocity and density are stronger;

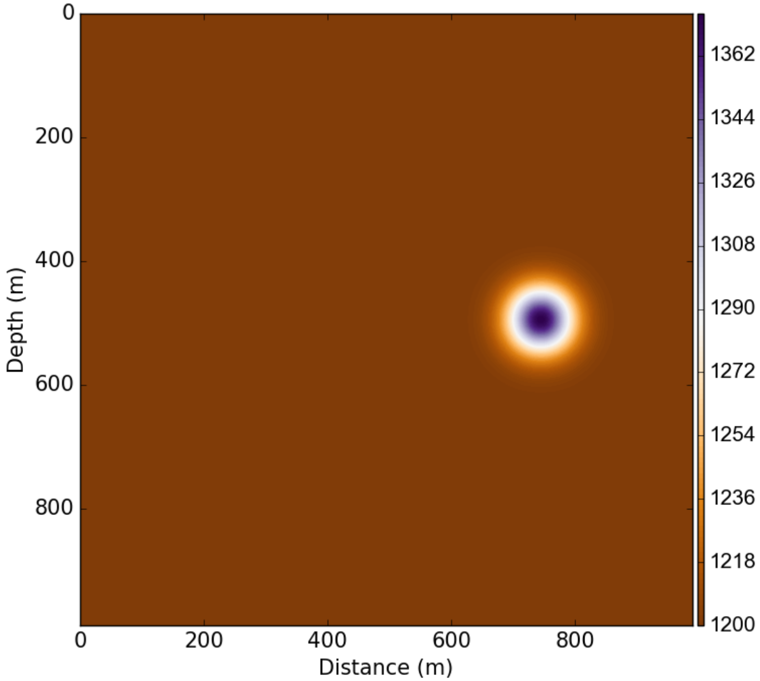
True Models



True P-wave Velocity: α

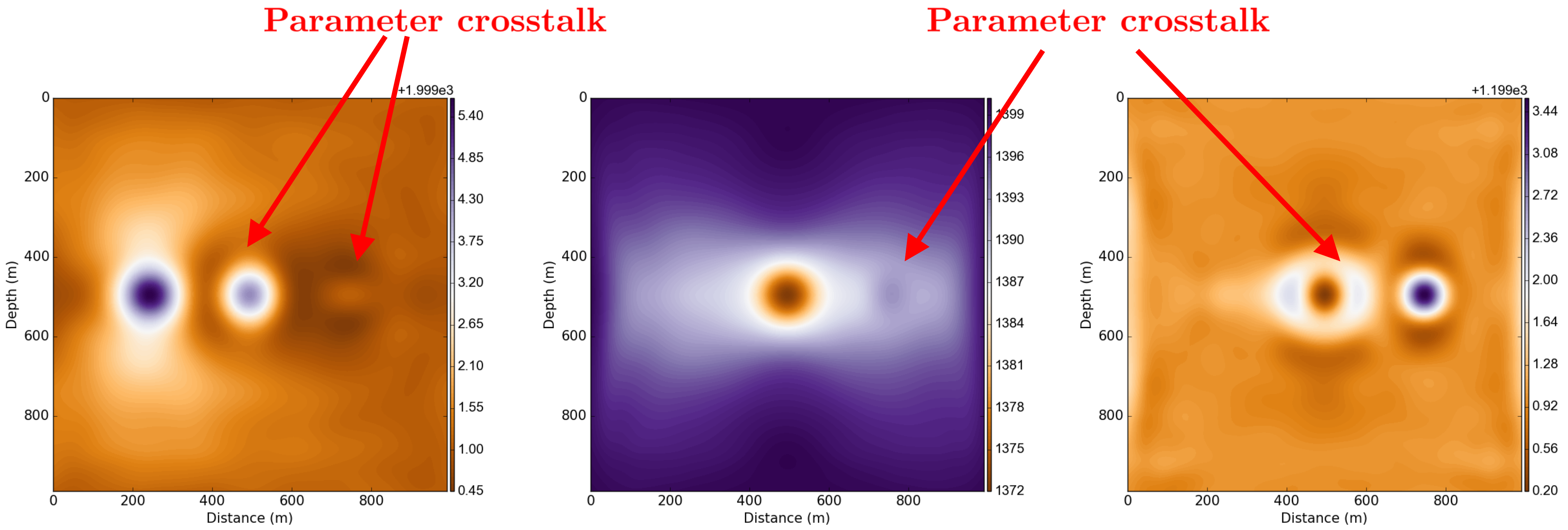


True S-wave Velocity: β



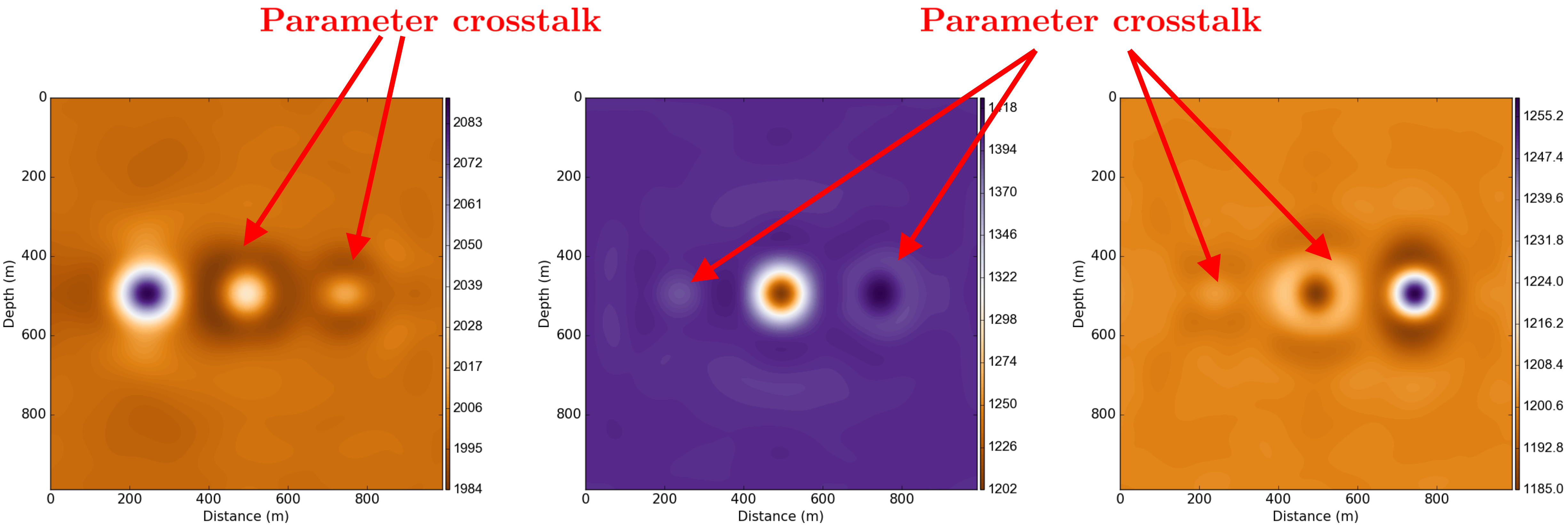
True Density: ρ

Inverted Models: P-SV Example 1st Iteration



Inverted P-wave Velocity: α Inverted S-wave Velocity: β Inverted Density: ρ

Inverted Models: P-SV Example 6th Iteration

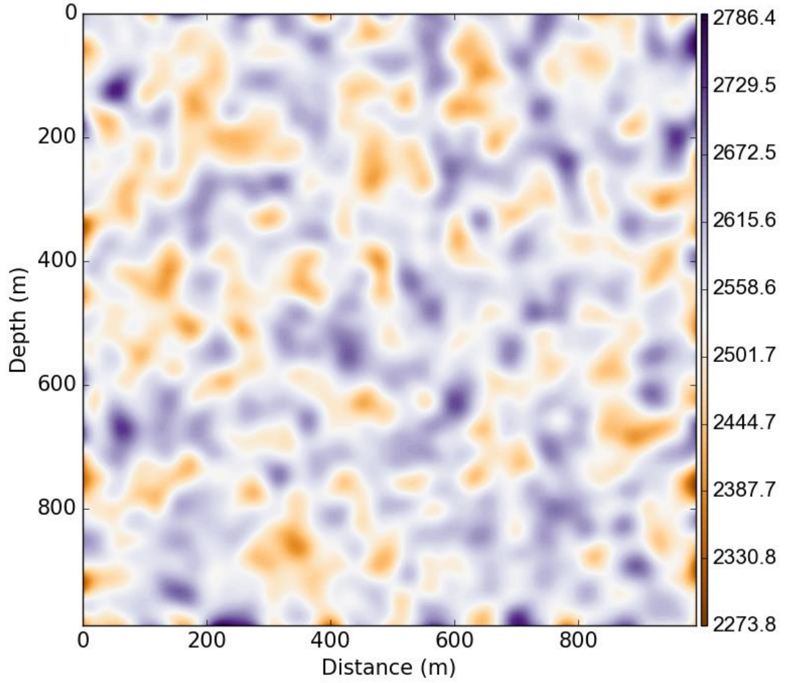


Inverted P-wave Velocity: α

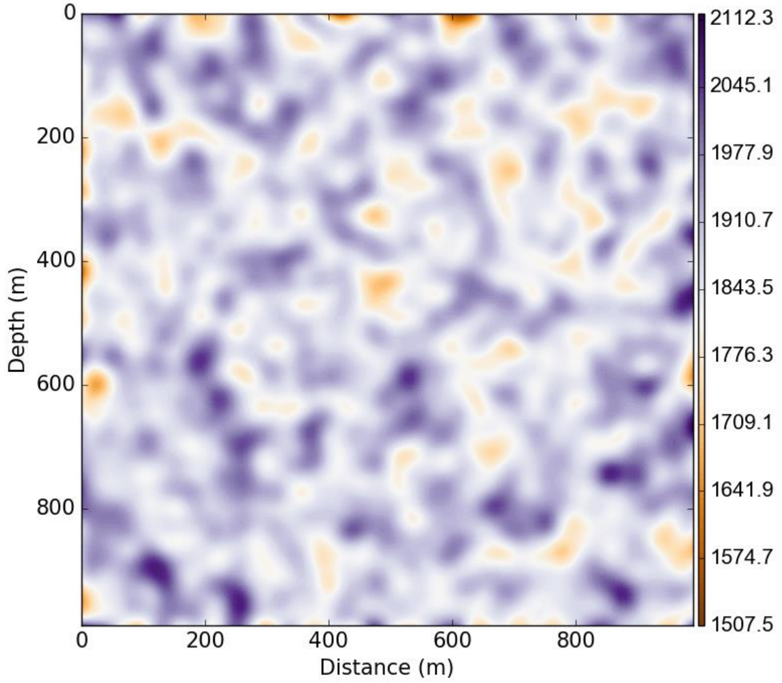
Inverted S-wave Velocity: β

Inverted Density: ρ

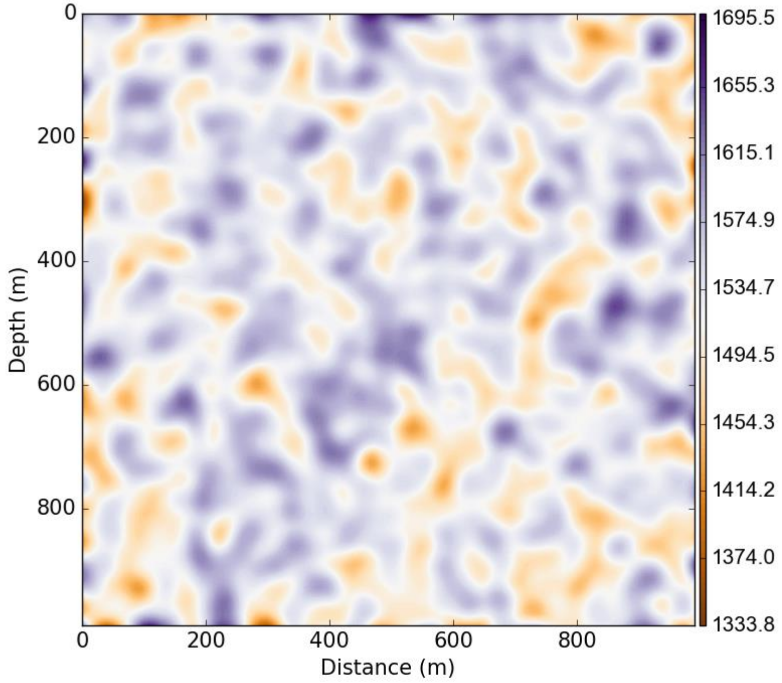
True Models: Random Media Example



True P-wave Velocity: α

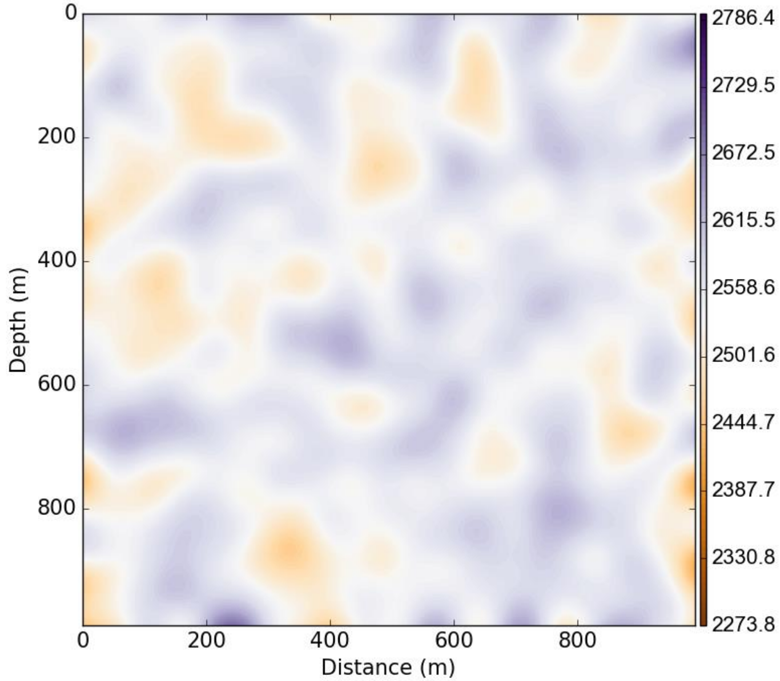


True S-wave Velocity: β

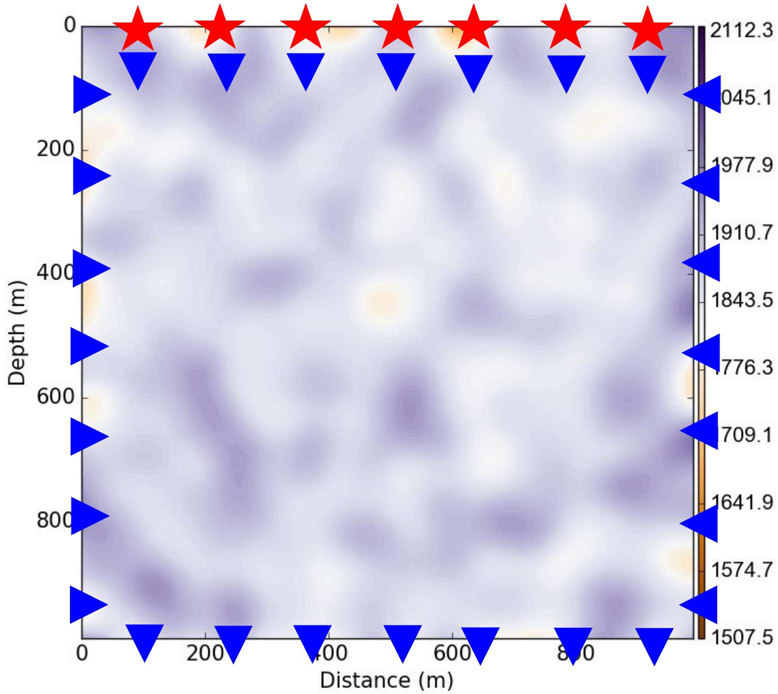


True Density: ρ

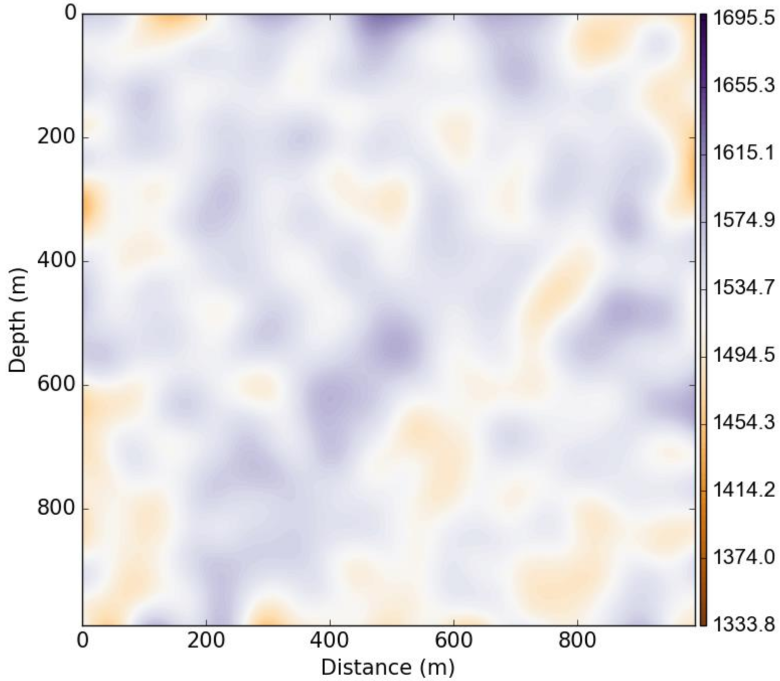
Initial Models



Initial P-wave Velocity: α

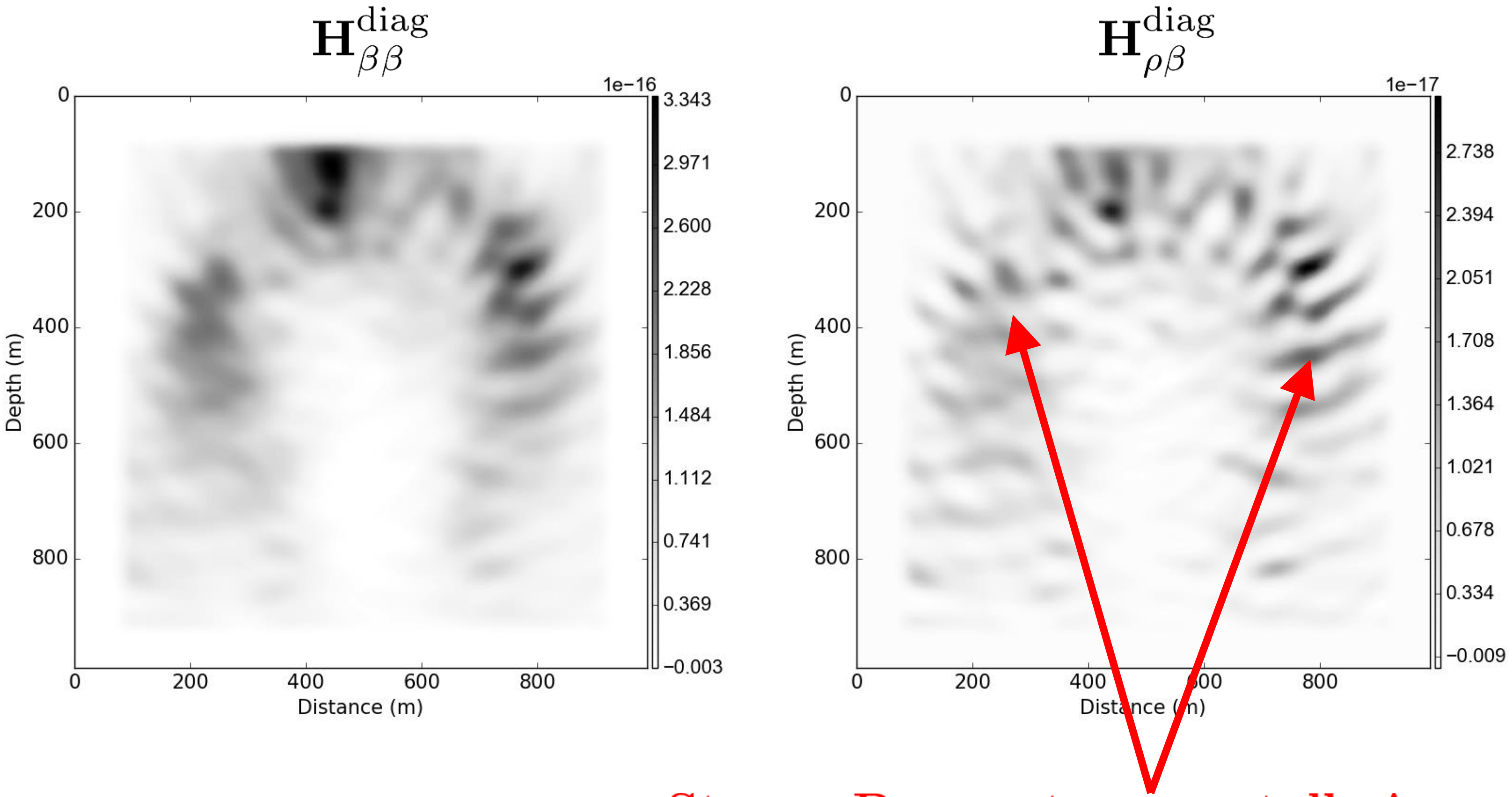


Initial S-wave Velocity: β



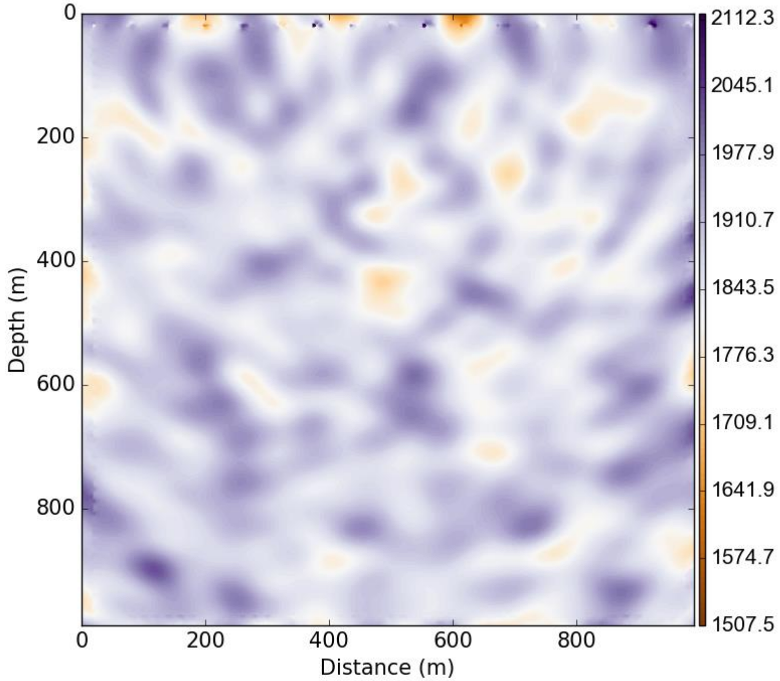
Initial Density: ρ

Stochastic Probing: SH Example

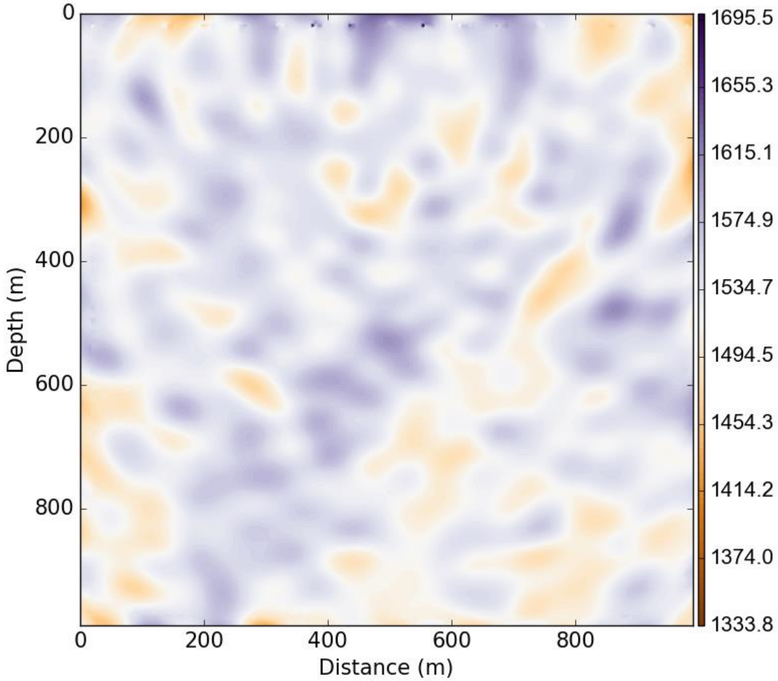


Strong Parameter crosstalk Area

Inverted Models: SH Example

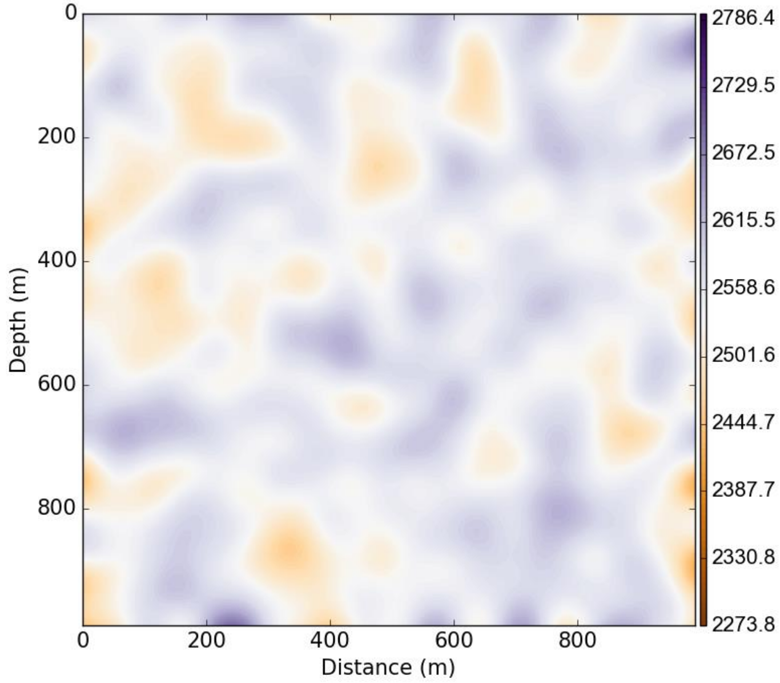


Inverted S-wave Velocity: β

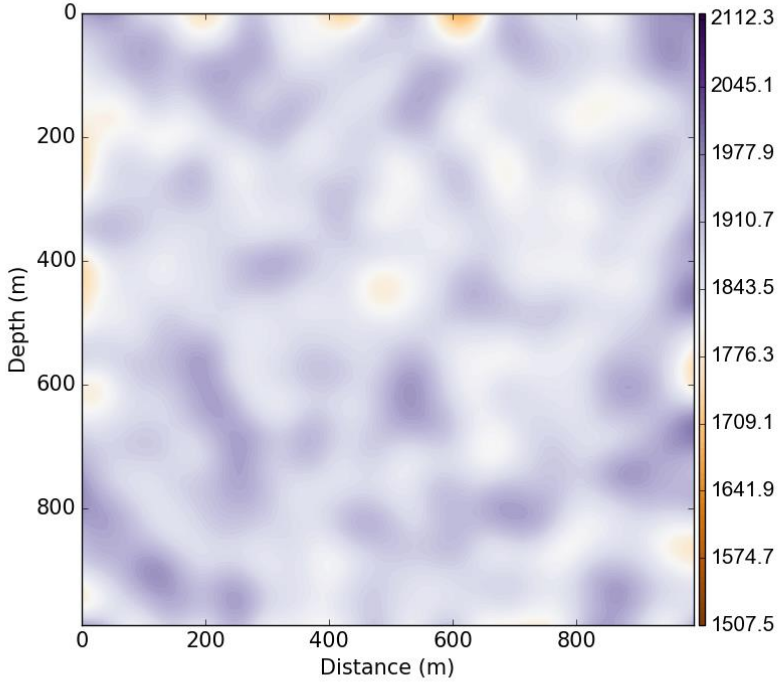


Inverted Density: ρ

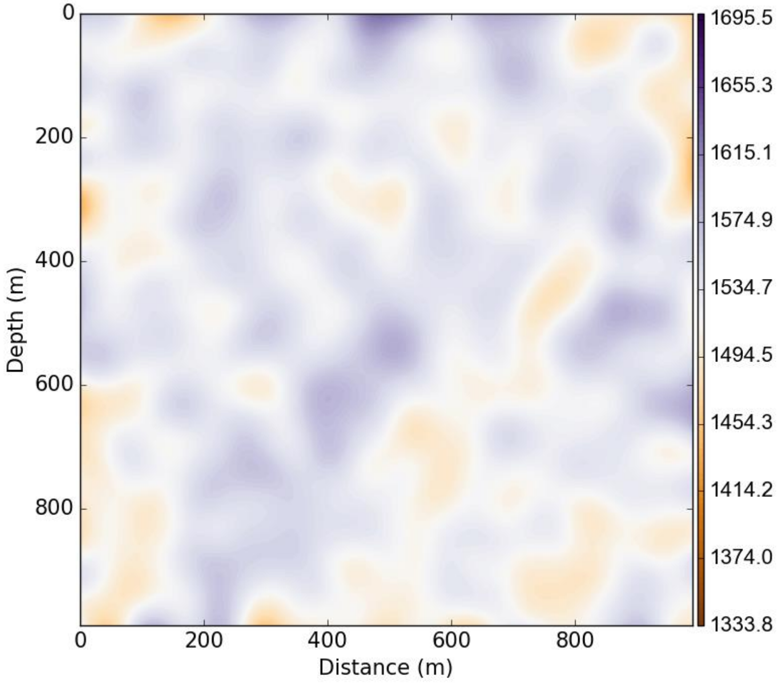
Initial Models



Initial P-wave Velocity: α

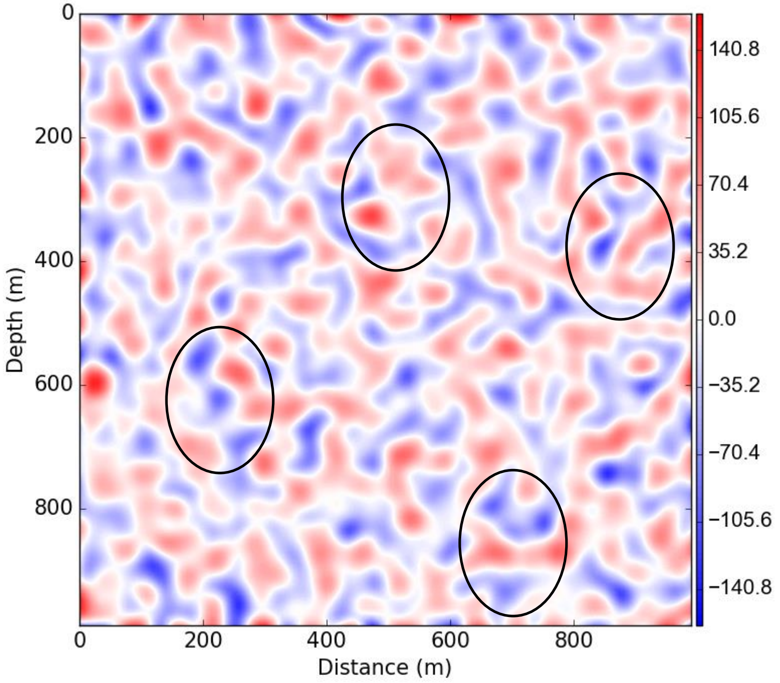


Initial S-wave Velocity: β

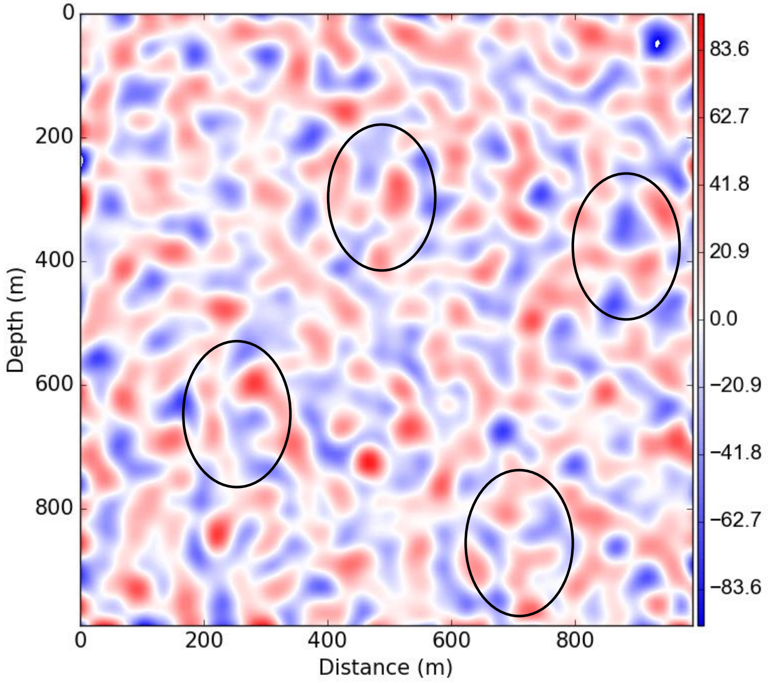


Initial Density: ρ

True Model Perturbations



True S-wave Velocity Perturbation

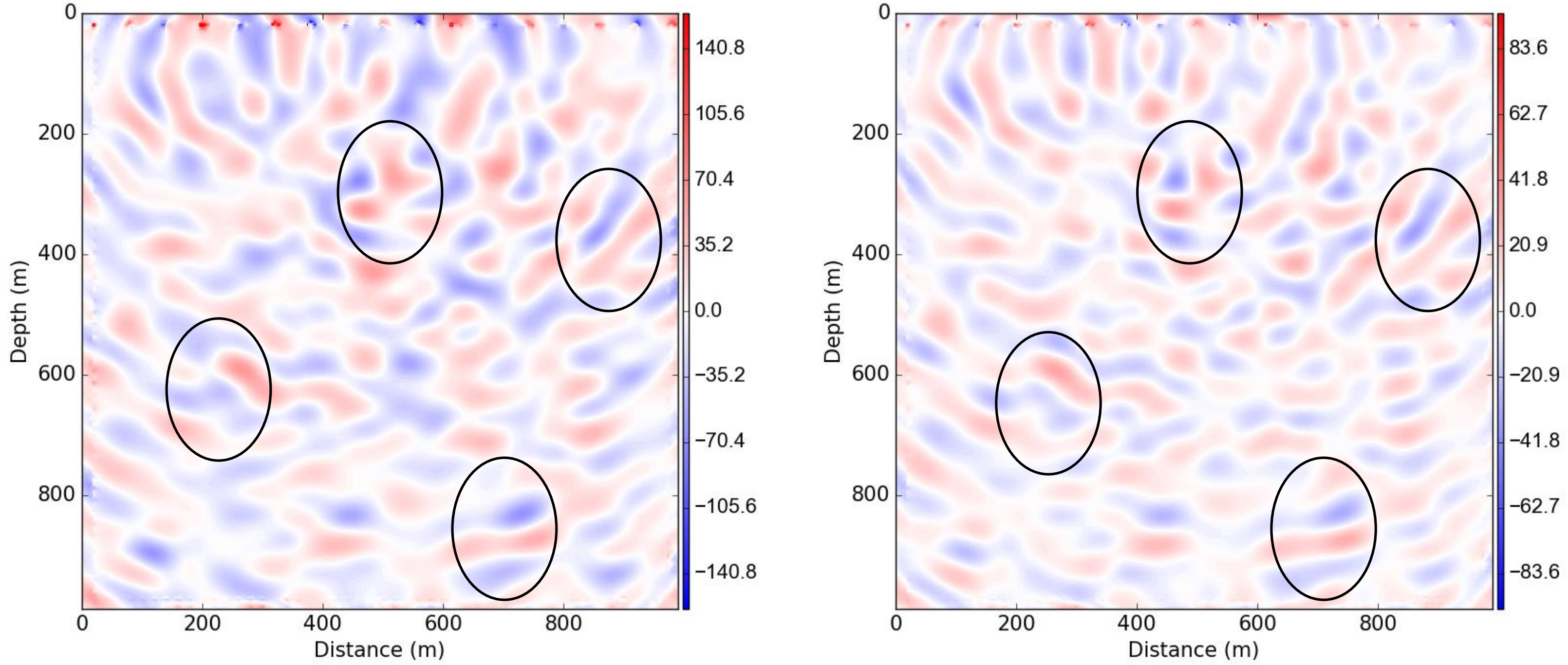


True Density Perturbation

Estimated Model Perturbations

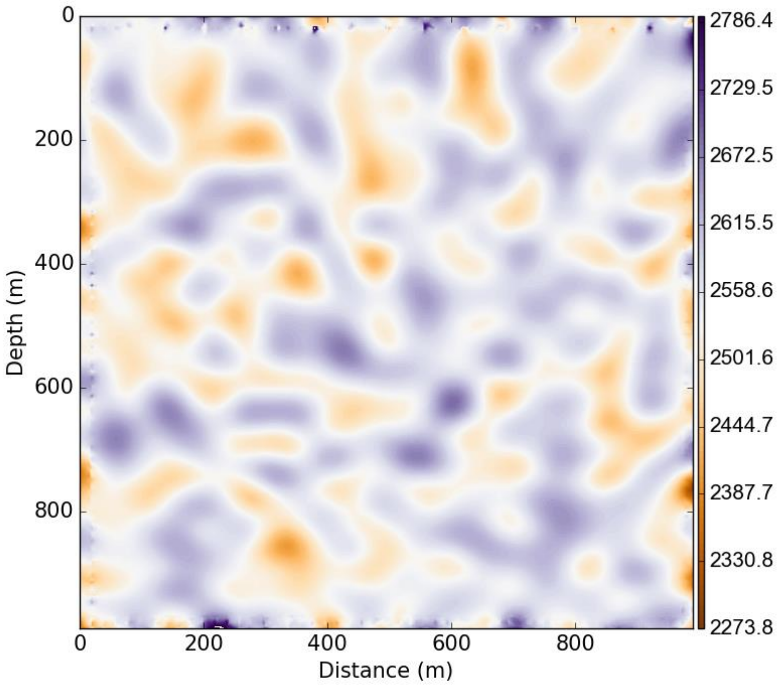
Inverted density perturbation is very similar to S-wave velocity perturbation.

Strong interparameter mapping from S-wave velocity makes density difficult to be inverted.

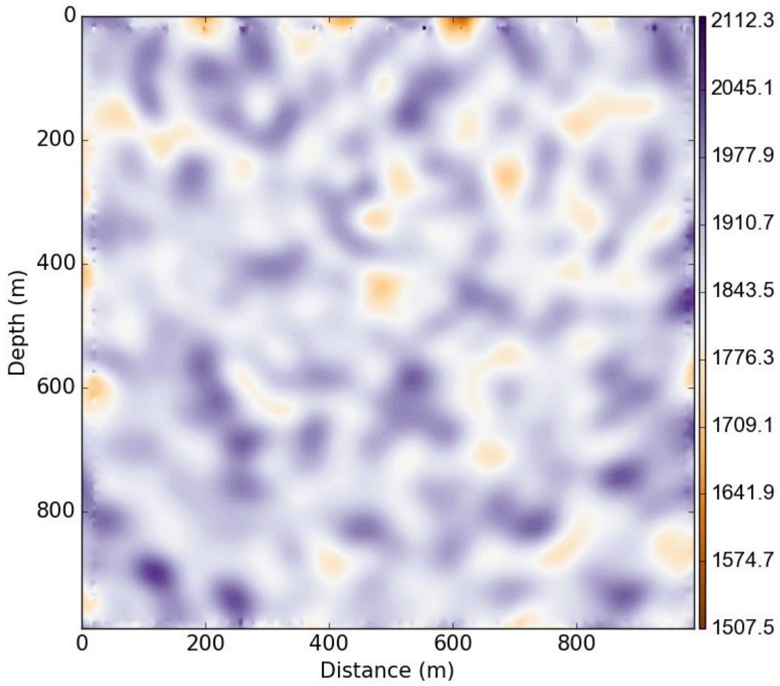


Inverted S-wave Velocity Perturbation **Inverted Density Perturbation**

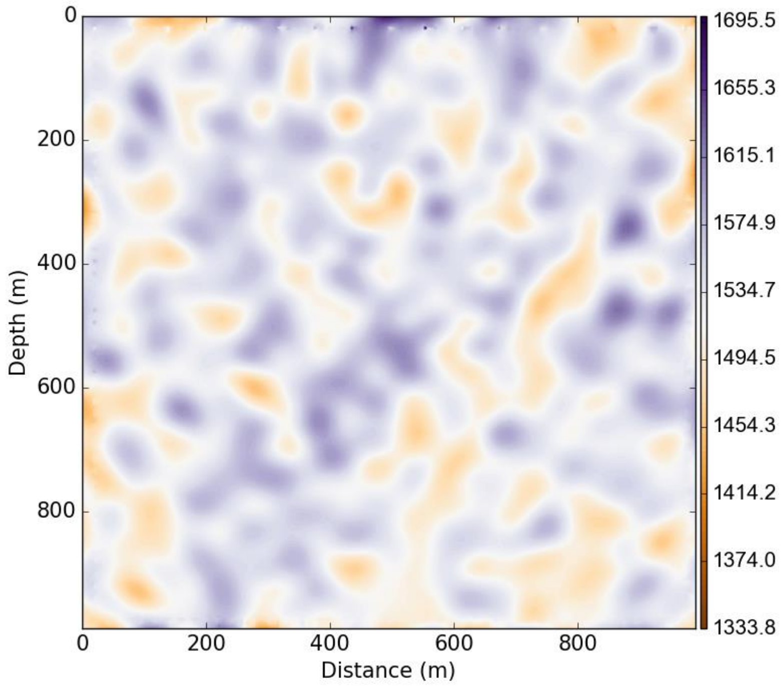
Inverted Models: P-SV Example



Inverted P-wave Velocity: α

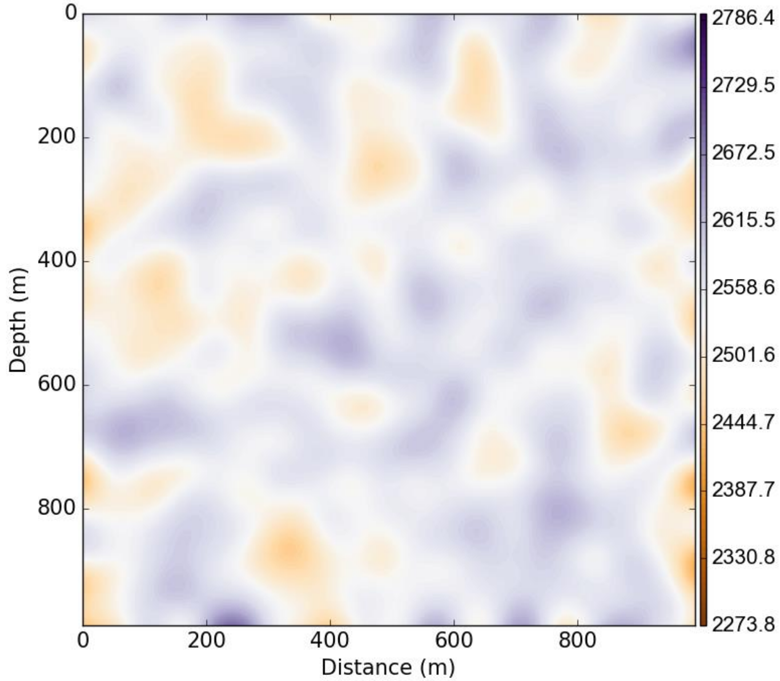


Inverted S-wave Velocity: β

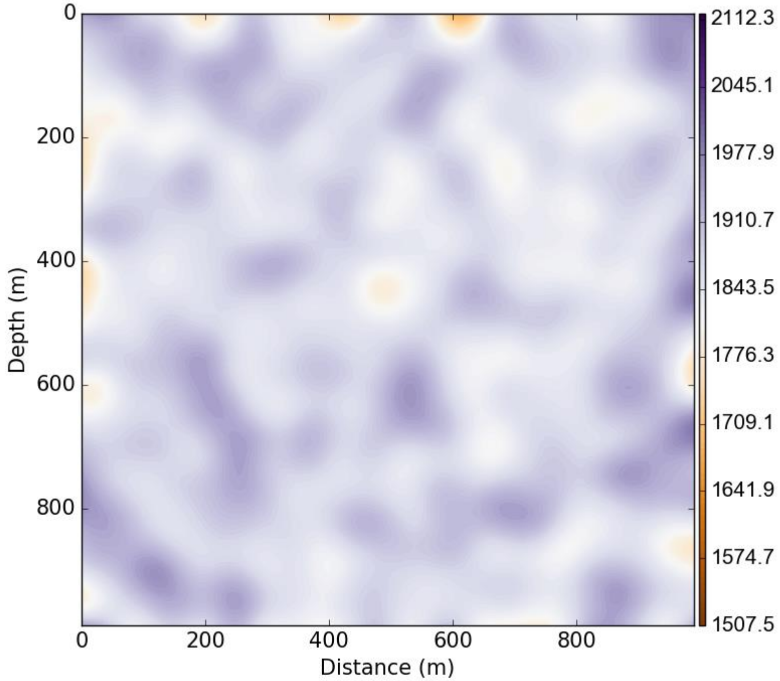


Inverted Density: ρ

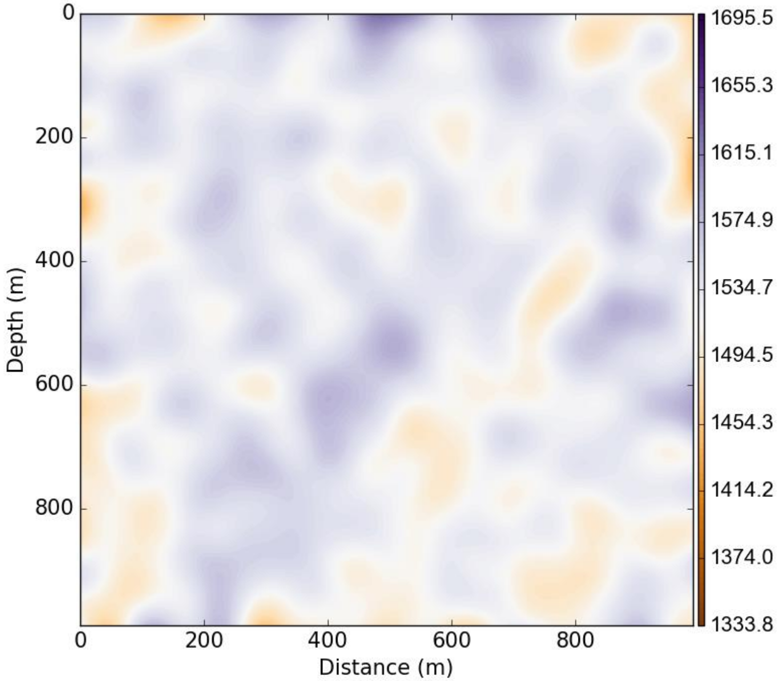
Initial Models



Initial P-wave Velocity: α

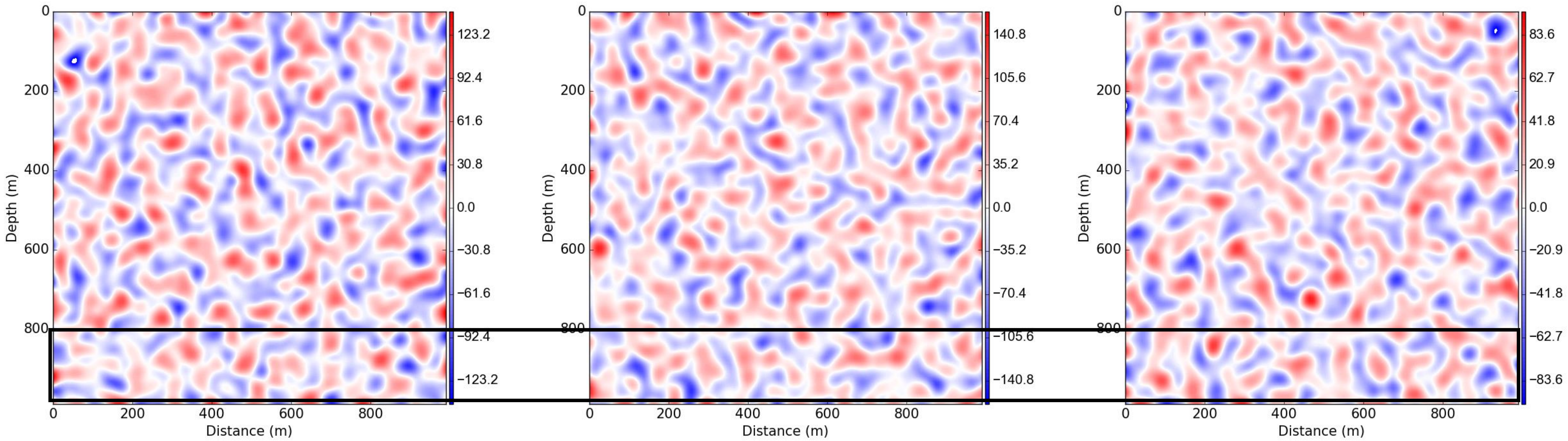


Initial S-wave Velocity: β



Initial Density: ρ

True Model Perturbations

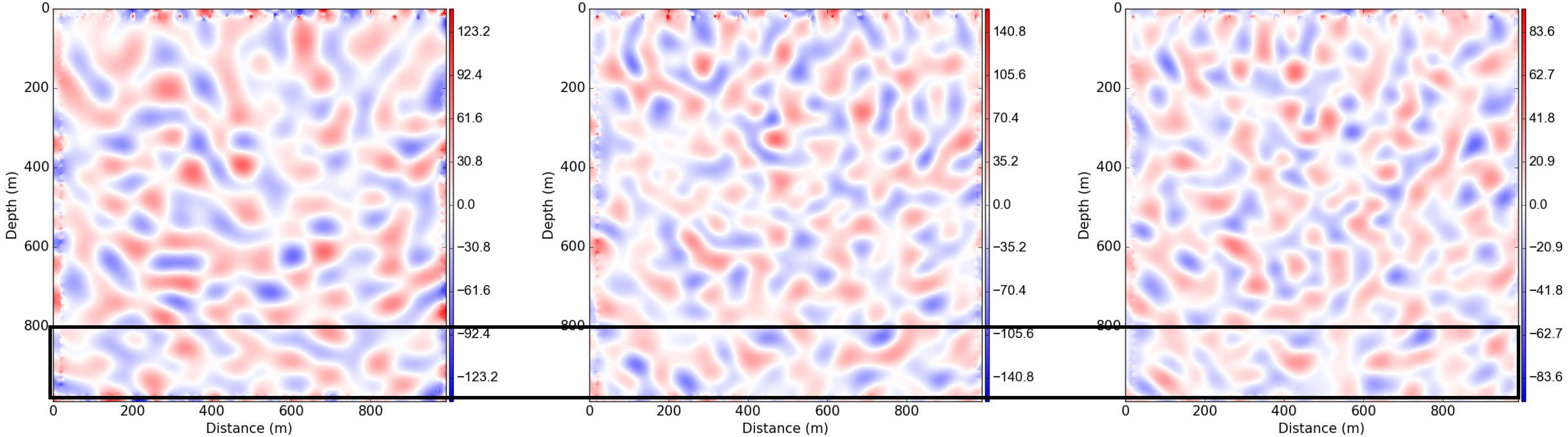


True α Perturbation

True β Perturbation

True ρ Perturbation

Inverted Model Perturbations



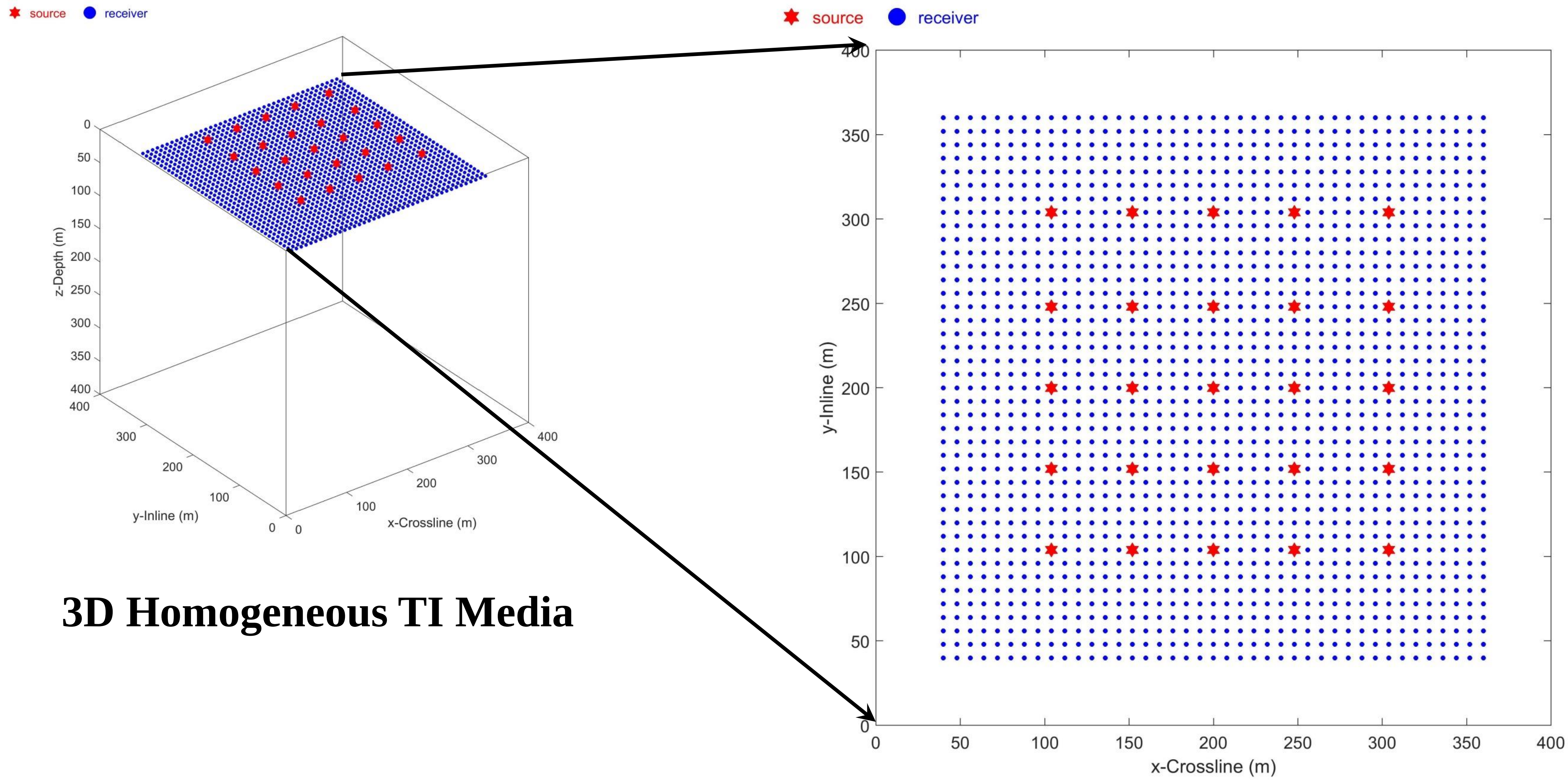
Inverted α Perturbation | Inverted β Perturbation | Inverted ρ Perturbation

S-wave velocity is best inverted;

P-wave velocity and density are contaminated by parameter crosstalk artifacts;

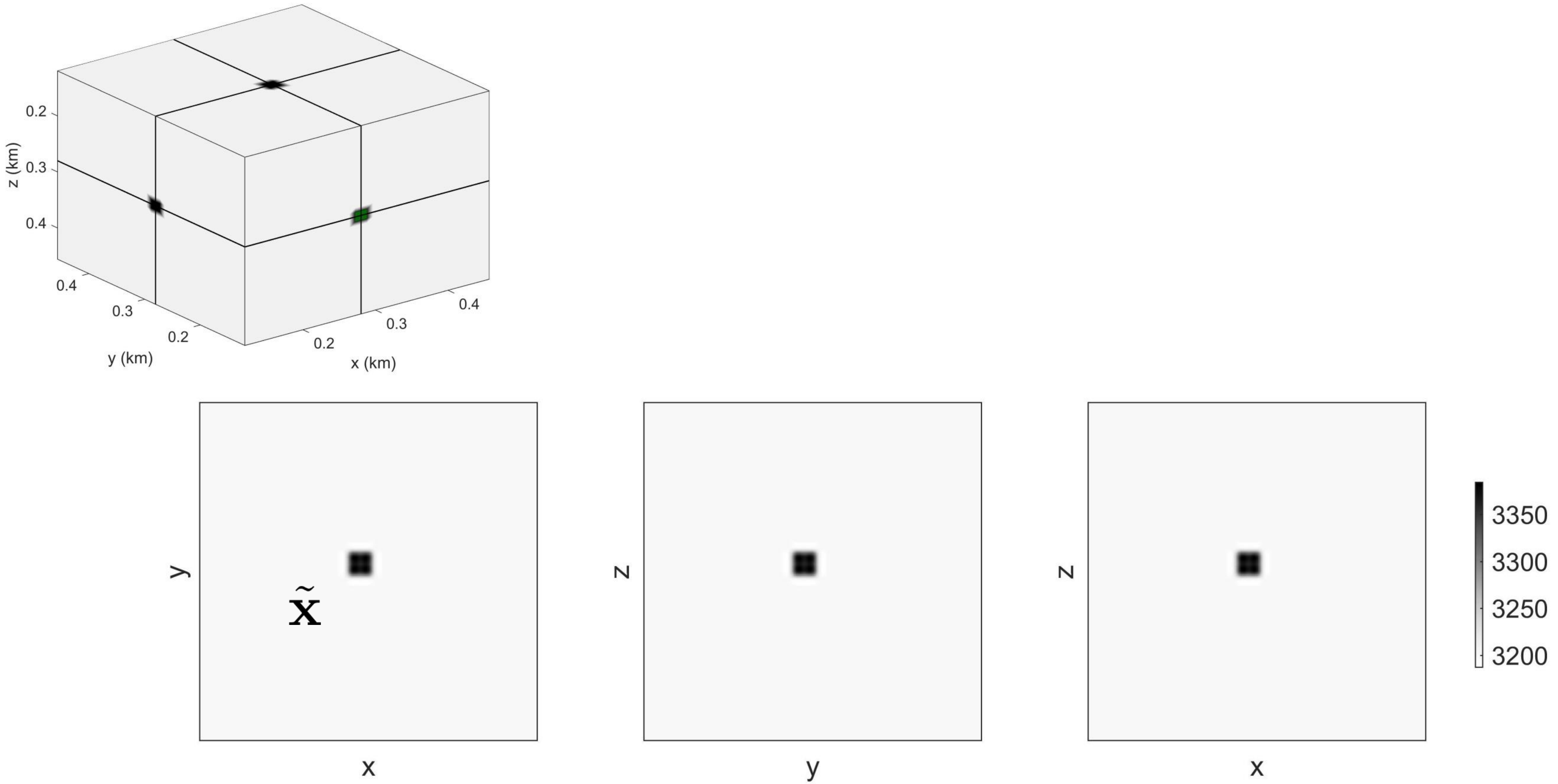
4.2 Anisotropic and Elastic Example

Multi-parameter Point Spread Function in Anisotropic Media

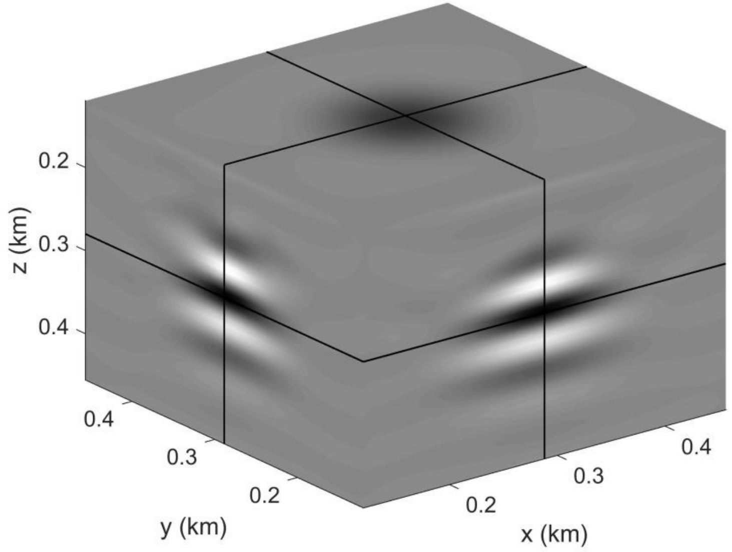


3D Homogeneous TI Media

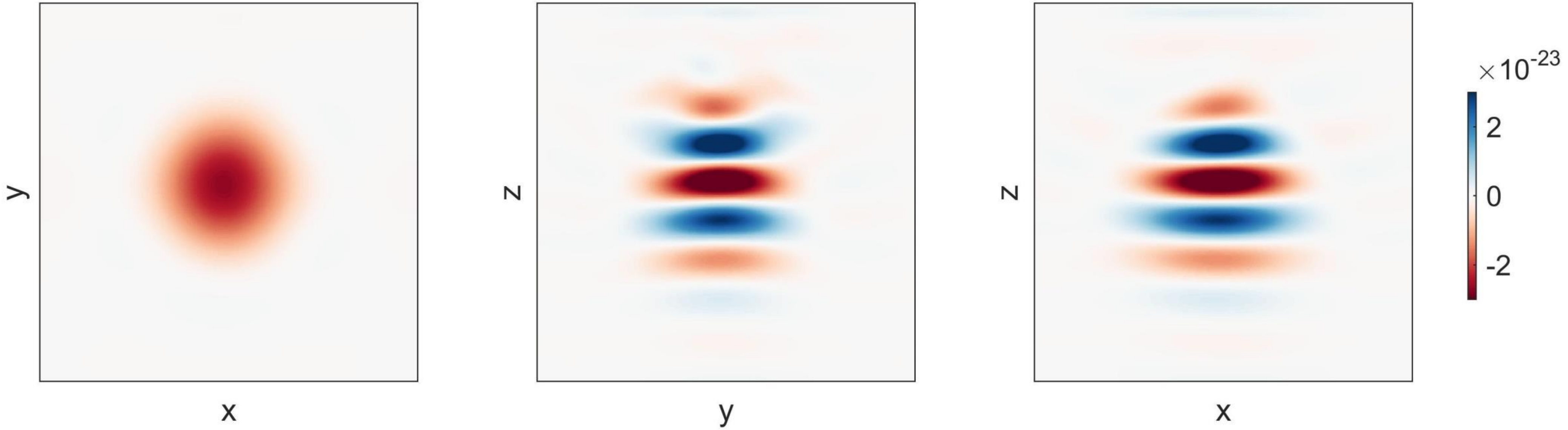
Numerical Examples



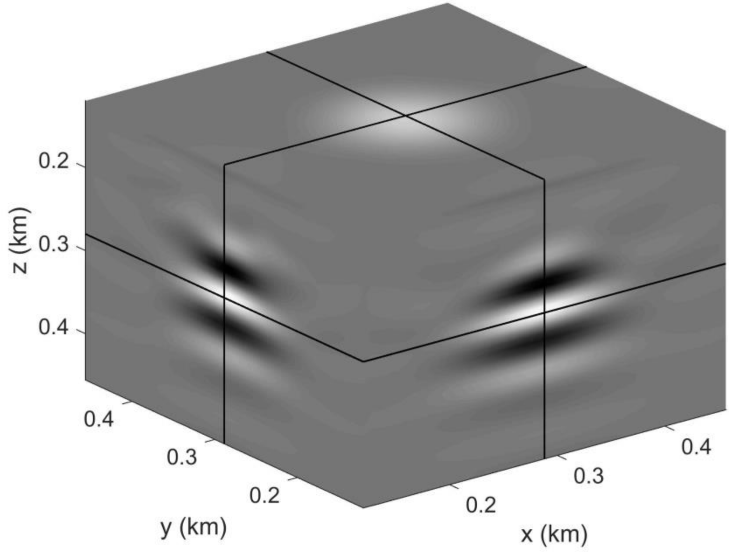
Multi-parameter Point Spread Function in Anisotropic Media



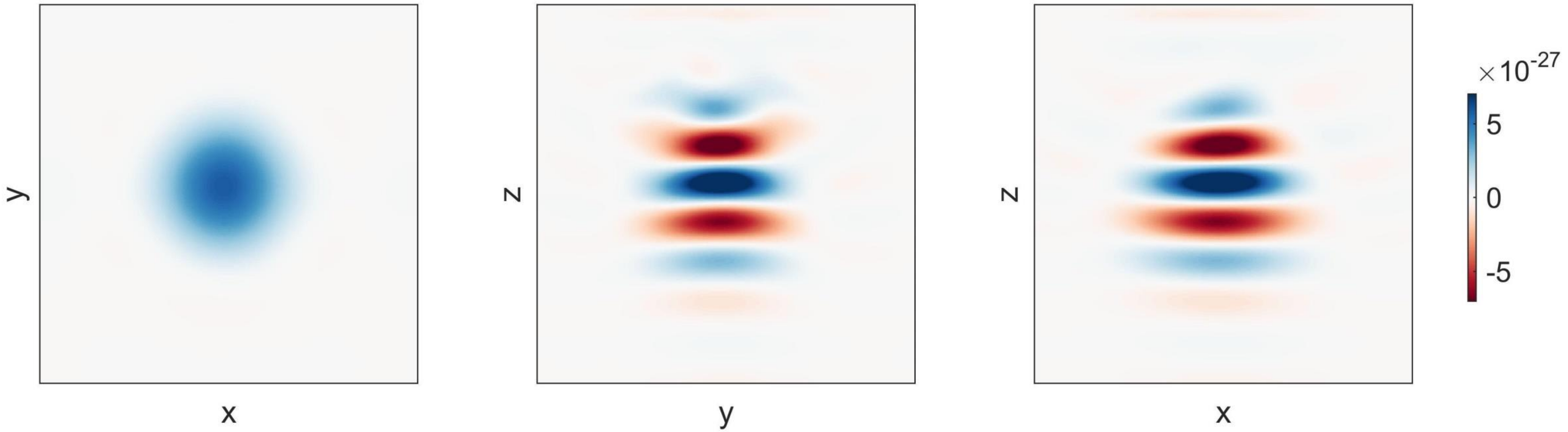
$$\mathbf{H}_{\alpha\alpha}\left(\tilde{\mathbf{x}}\right)$$



Multi-parameter Point Spread Function in Anisotropic Media



$$\mathbf{H}_{\beta\alpha}\left(\tilde{\mathbf{x}}\right)$$



Conclusions

1. Parameter resolution analysis based on scattering patterns should be improved;
2. Multi-parameter Hessian provides more complete measurements of parameter trade-offs;
3. Spike and stochast probing methods can be used to quantify the parameter resolution and uncertainties in multi-parameter FWI;
4. In elastic FWI, S-wave velocity suffers from limited parameter crosstalk from P-wave and density;
5. Strong trade-off from S-wave velocity make P-wave and density difficult to be inverted;
6. The travel time contribution may result in the difficulty of inverting density;

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- Eyes High International Doctoral Scholarship

Thanks!