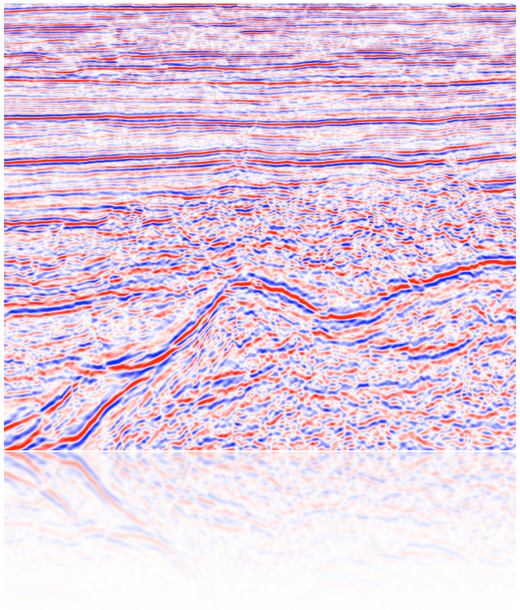
Groundroll prediction by interferometry & separation by curvelet-domain filtering



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Motivation

- Improve groundroll separation
  - preserve reflection, increase groundroll separation
- Develop data-driven workflow for groundroll separation
  - using data itself as prediction operator for groundroll
- Adapt tools for primary-multiple separation to reflection-groundroll separation

Strategy

- Use inteferometry to predict groundroll

  Xue & Schuster ‘07, Halliday et al ’07, Vasconcelos & Snieder ’08

- Adaptively match the prediction by Fourier and Curvelet domain matching technique

  Verschuur ’97, Herrmann ’08

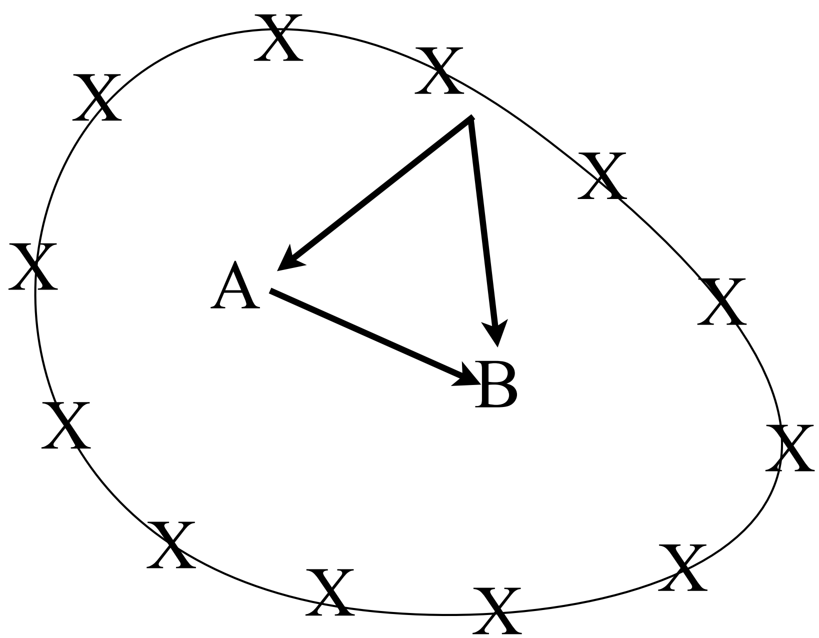
- Separate by sparsity promotion and Bayesian separation algorithm

  Wang, Saab, Yilmaz & Herrmann ‘08

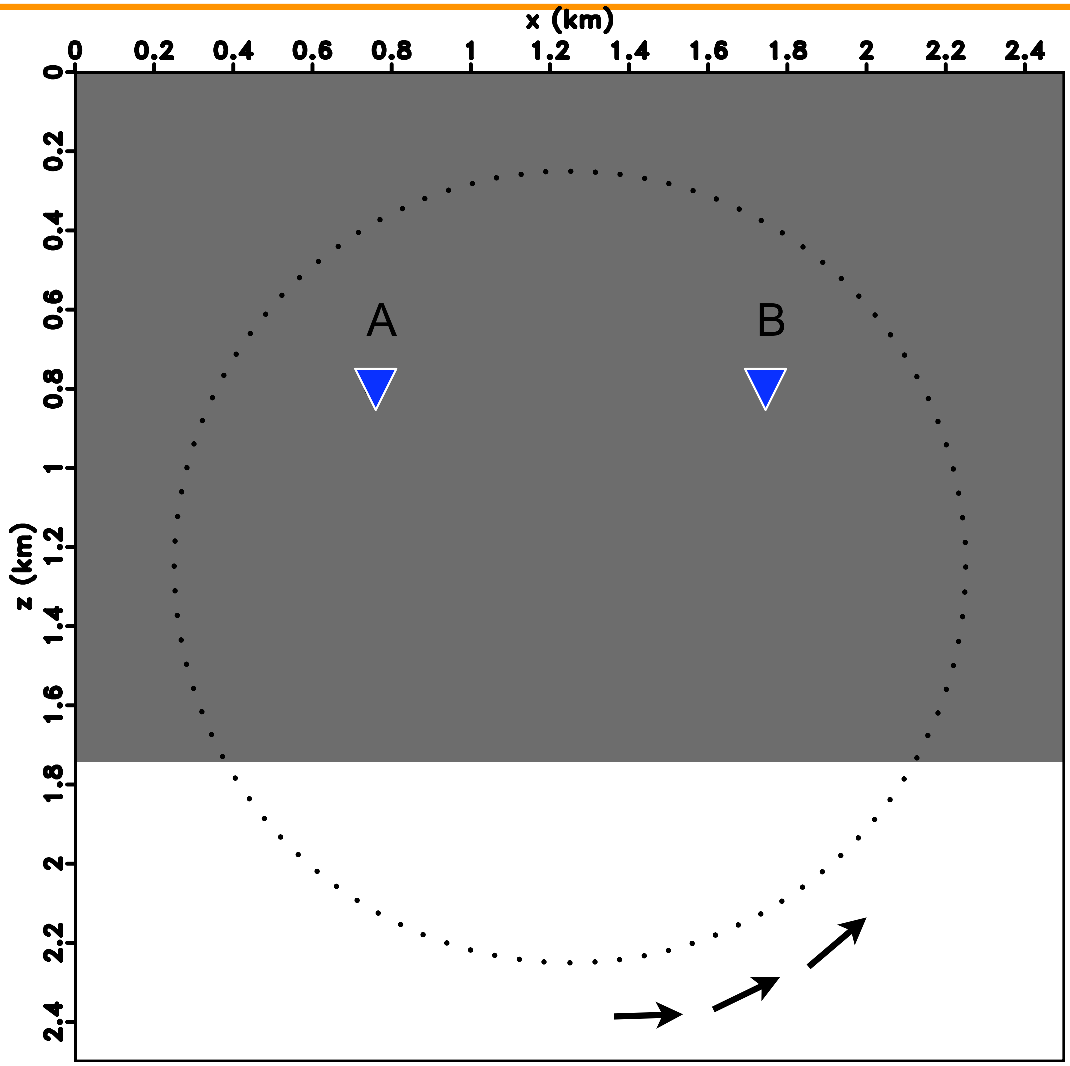
Interferometry

$$\mathbf{G}^*(x_B, x_A, \omega) + \mathbf{G}(x_B, x_A, \omega)$$
$$\approx \frac{2}{\rho c} \oint_{\partial V} \mathbf{G}(x_A, x, \omega)\mathbf{G}^*(x_B, x, \omega) d^2x$$

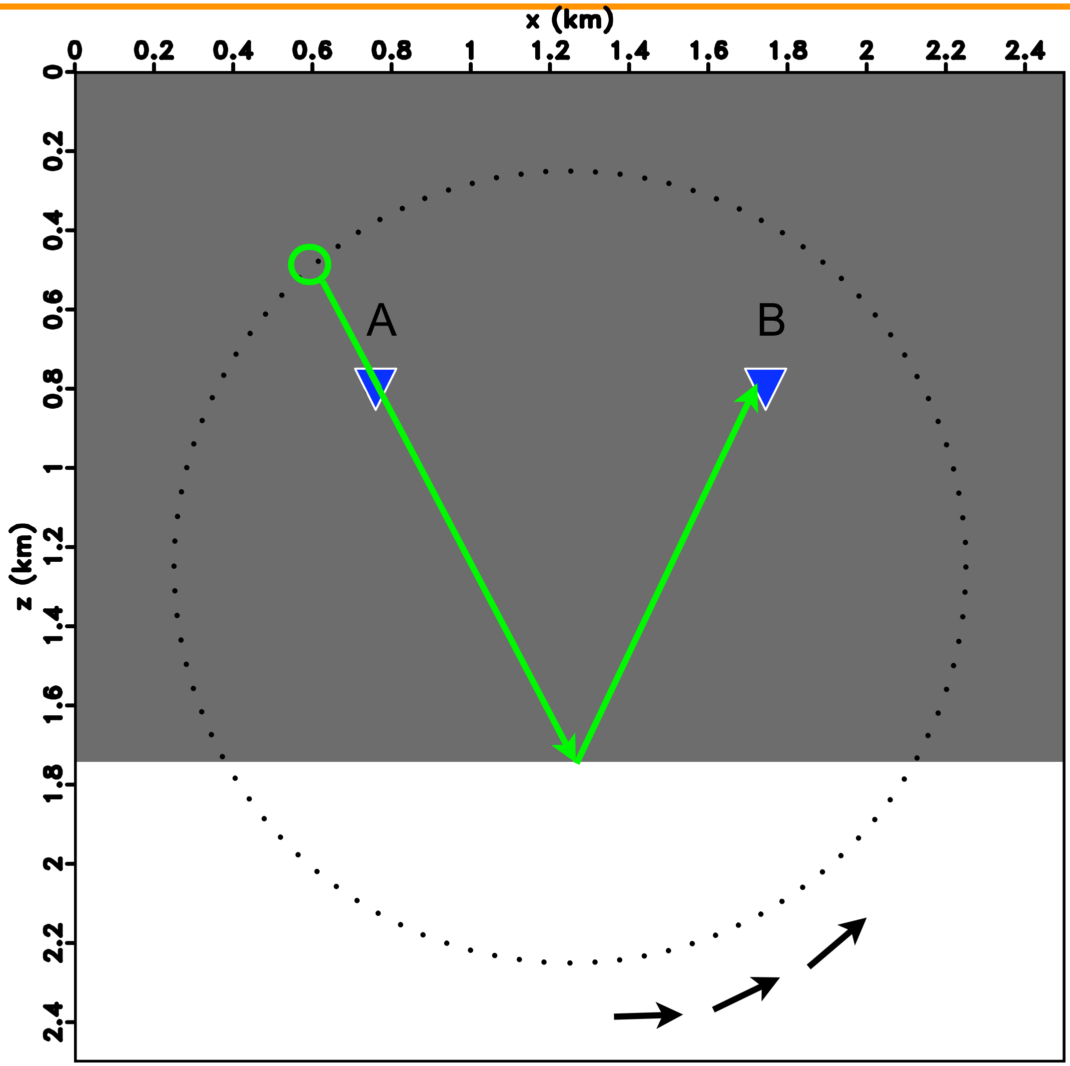
Wapenaar '04



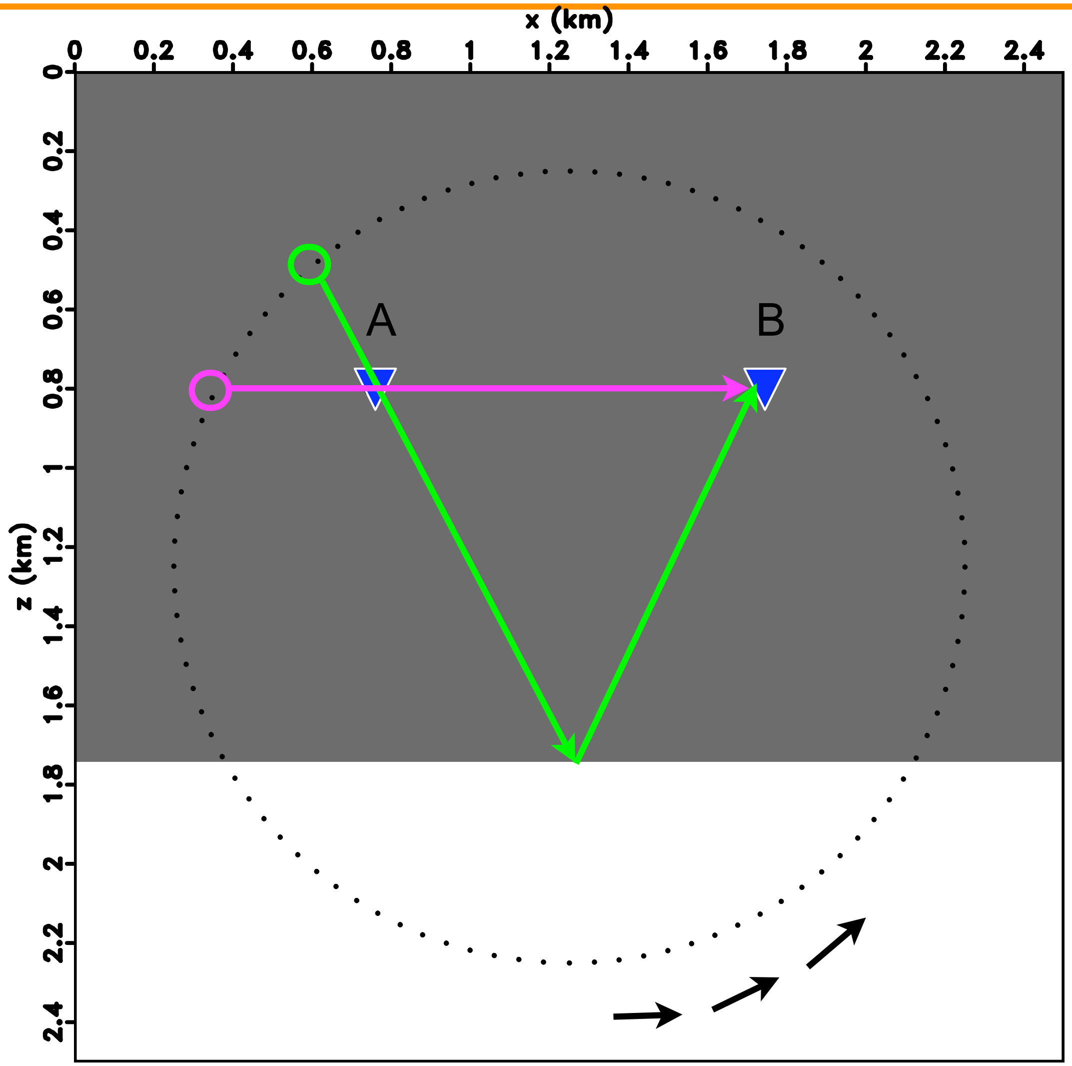
Interferometry: a simple example



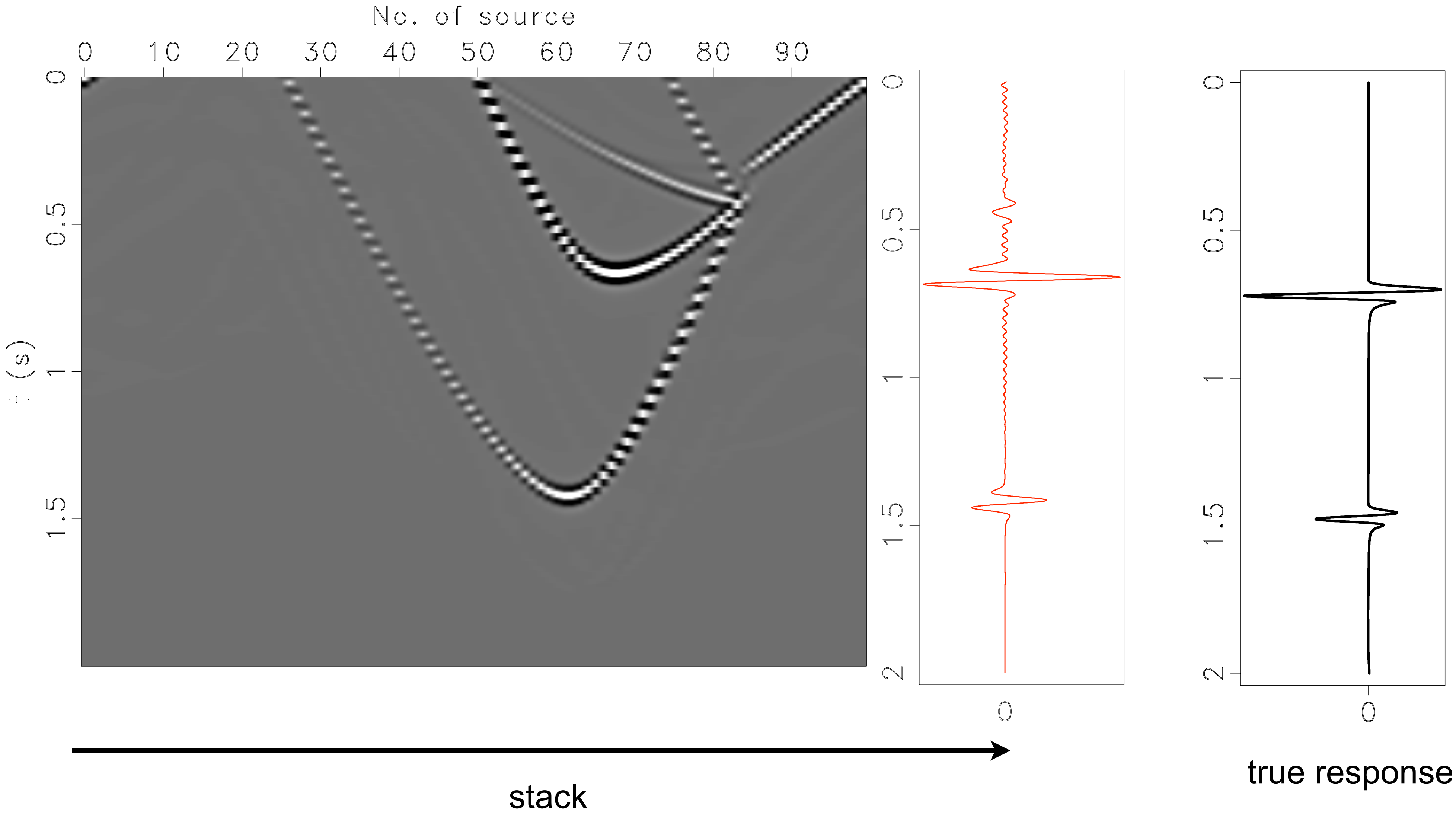
Interferometry: a simple example



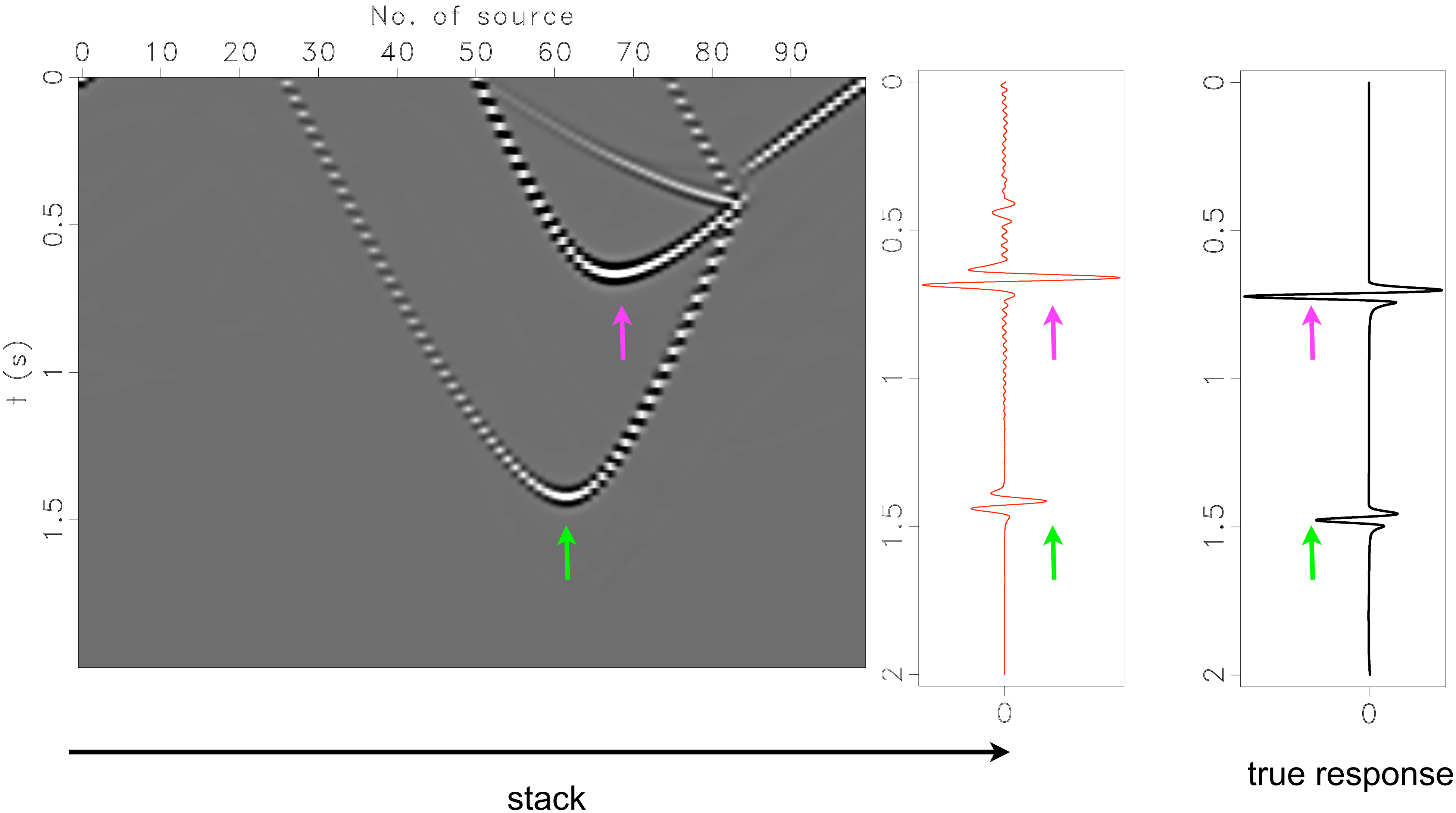
Interferometry: a simple example



Interferometry



Interferometry



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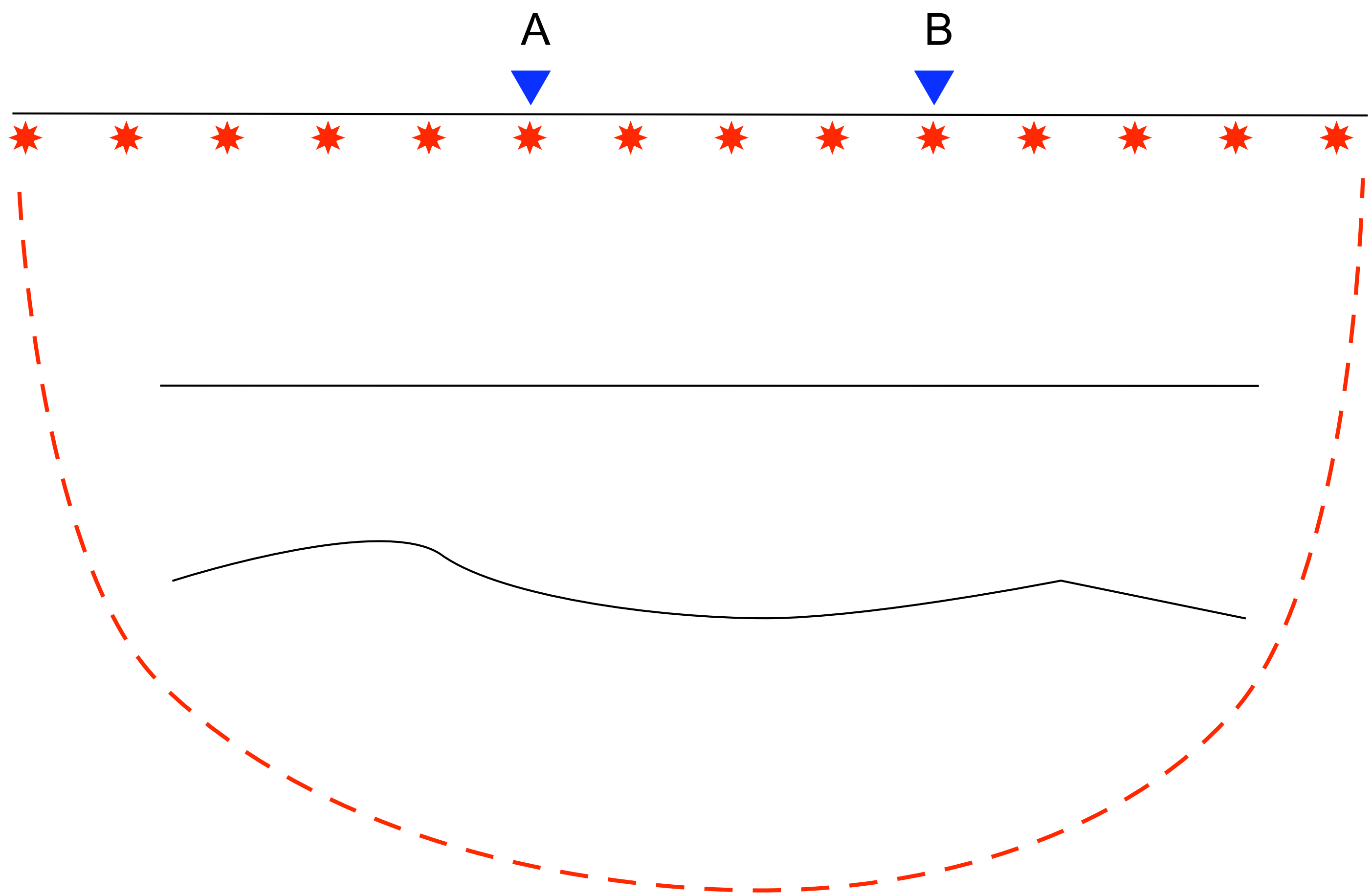
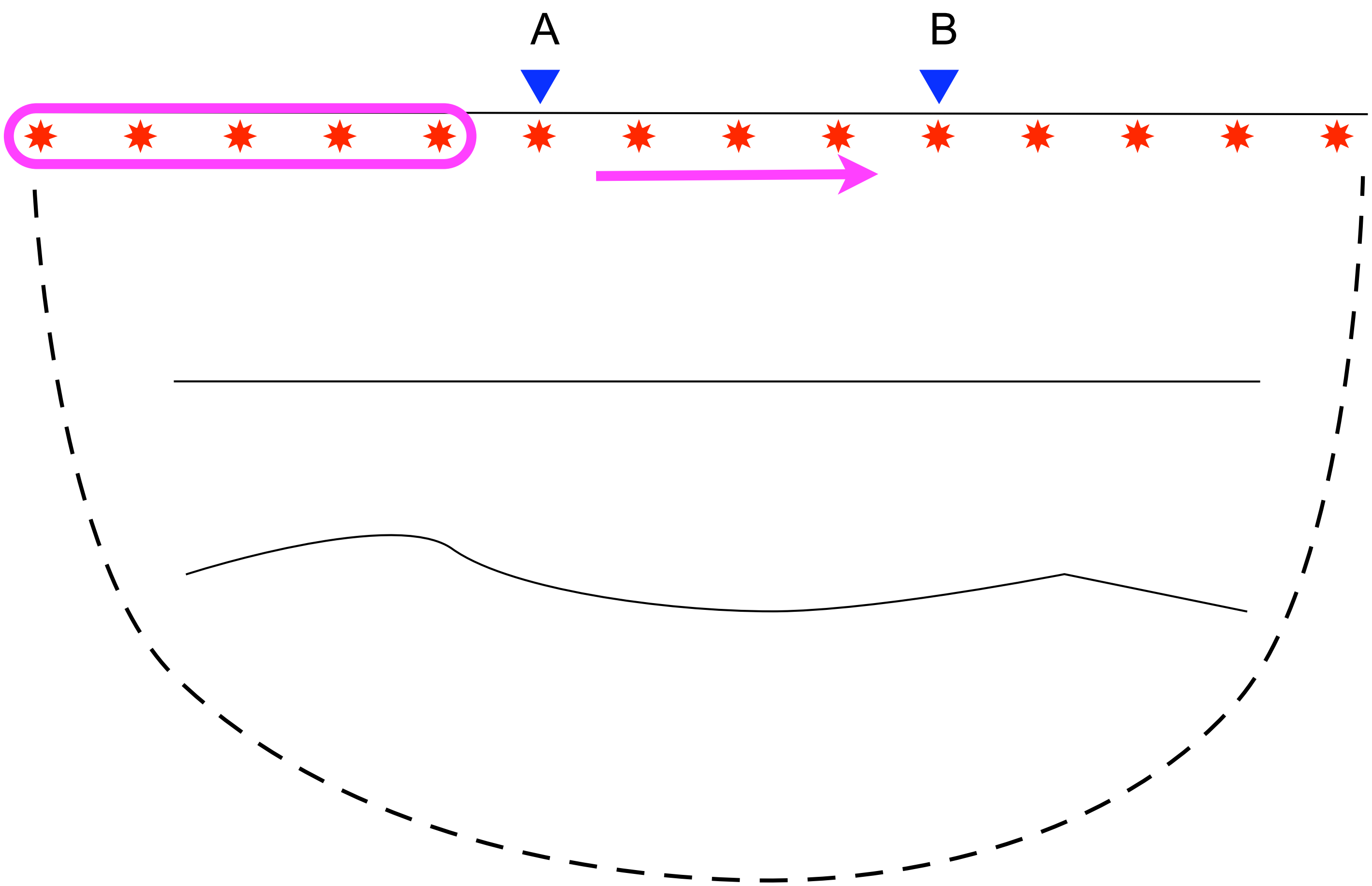
Interferometry of seismic data

- Sources restricted to surface



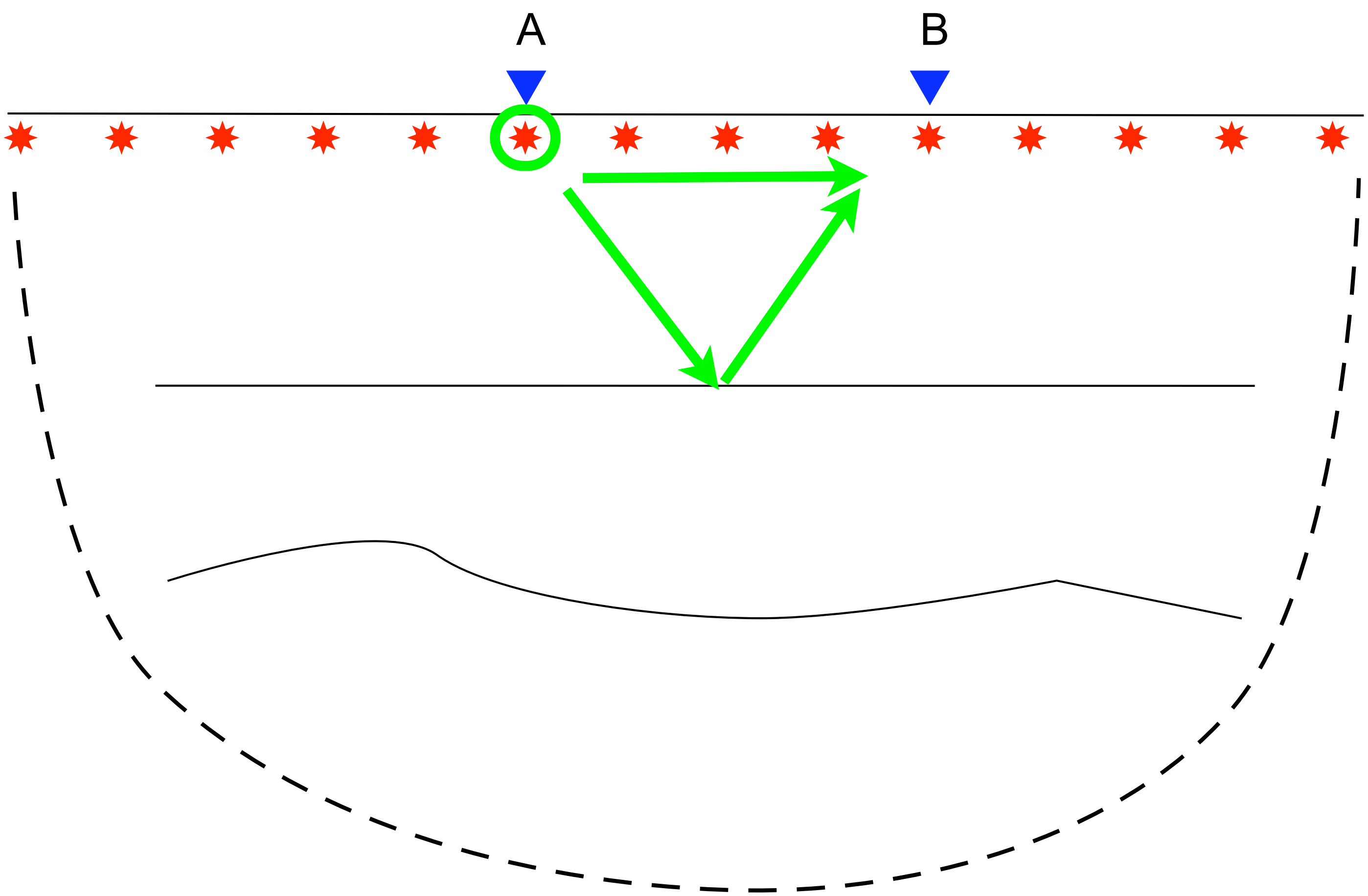
Interferometry of seismic data

- Sources contributing to surface waves



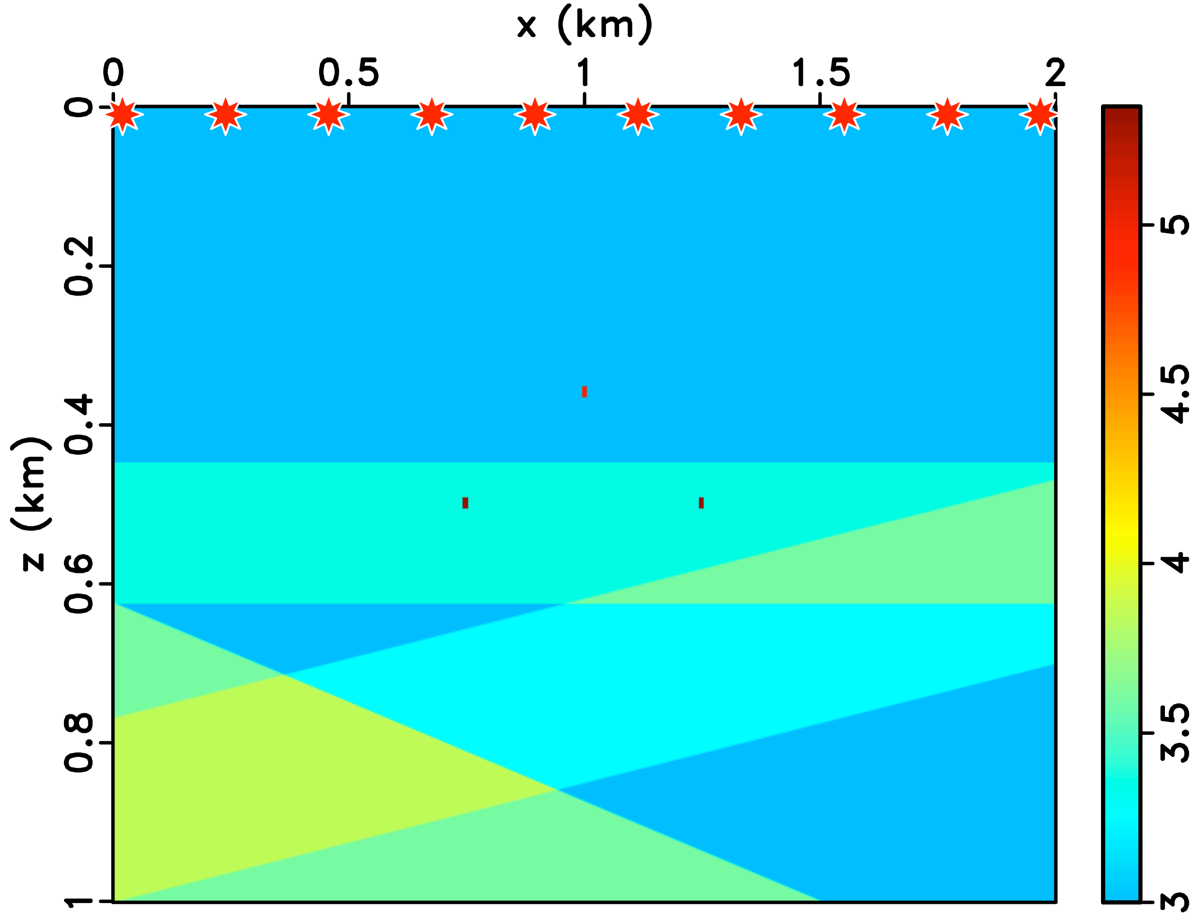
Interferometry of seismic data

- Sources contributing to surface waves and reflections



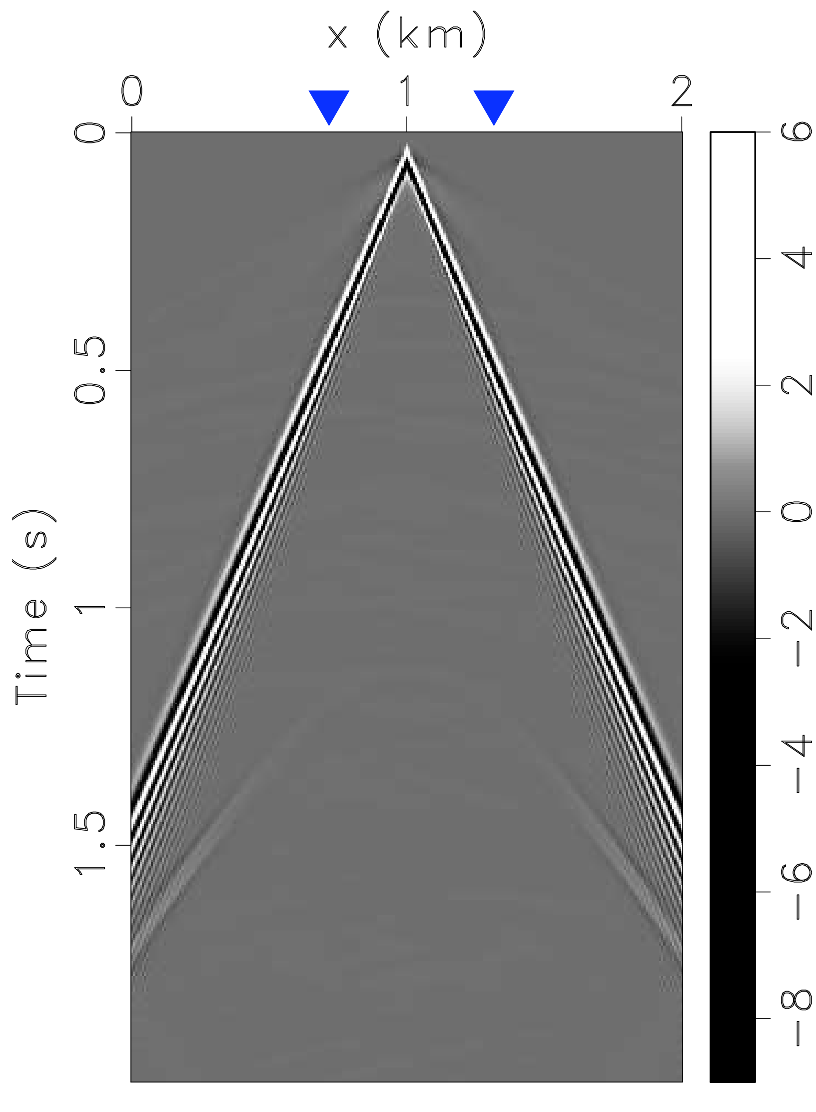
Synthetic example

- Elastic finite difference modeling: P wave velocity profile:
  - 250 active sources locate on surface

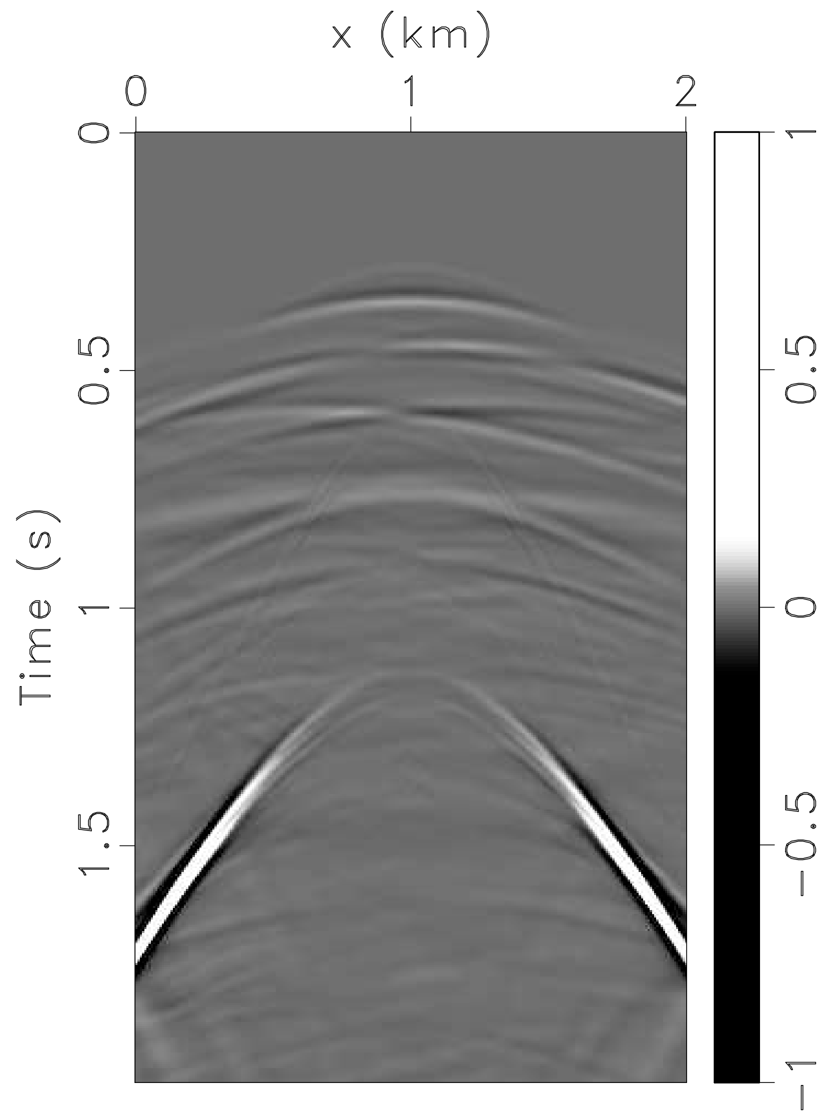


Thanks to Dr. Vasconcelos

Synthetic example



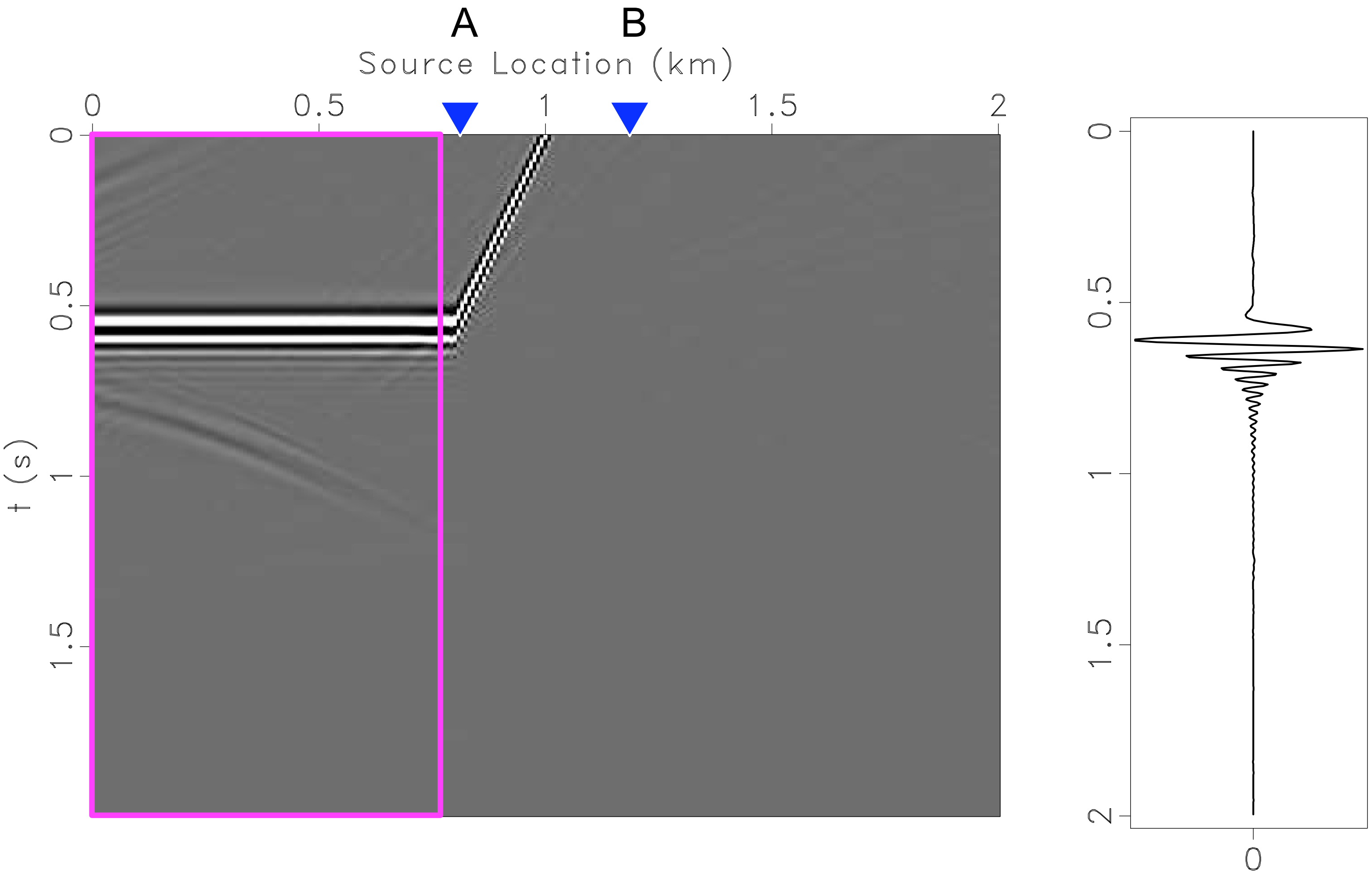
Total data



True reflections

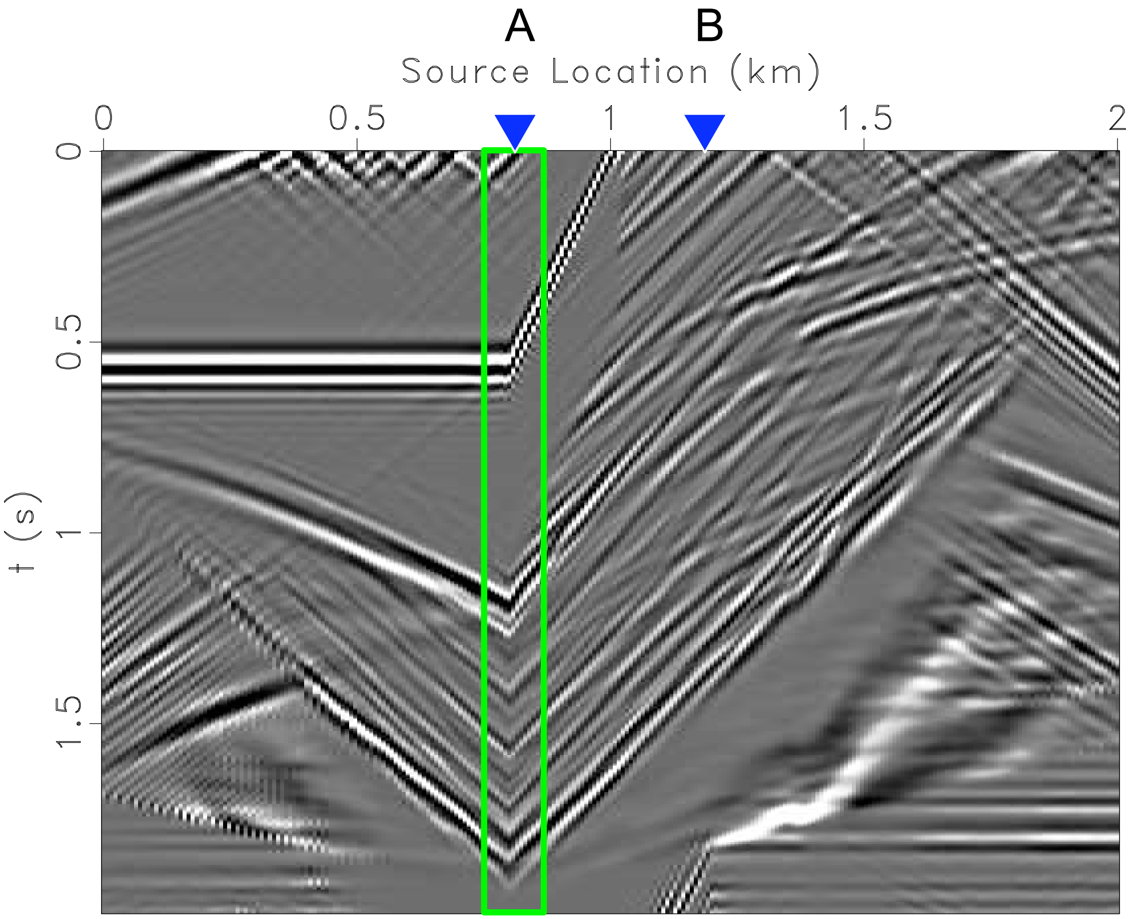
Synthetic example

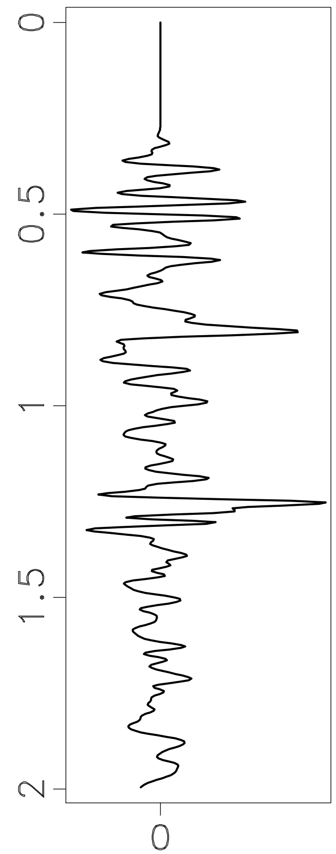
- Sources contributing to surface waves



Synthetic example

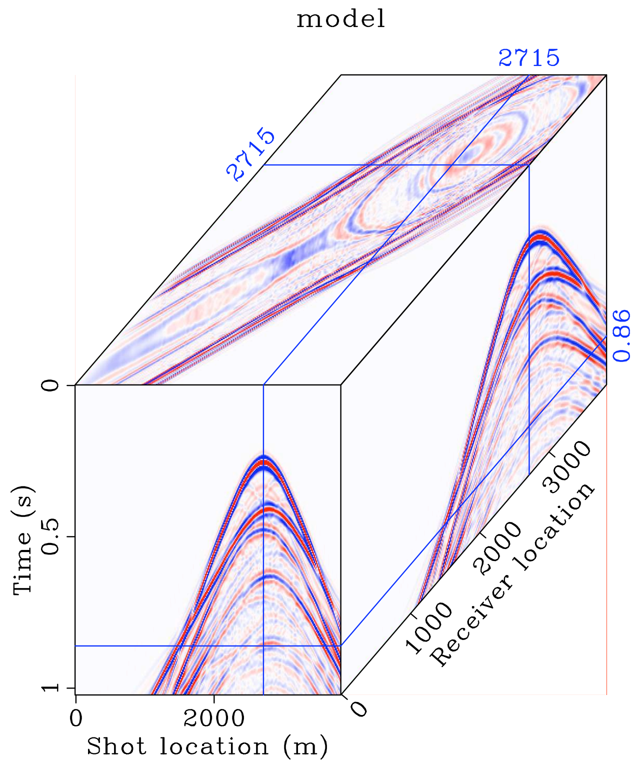
- Sources contributing to surface waves and reflections



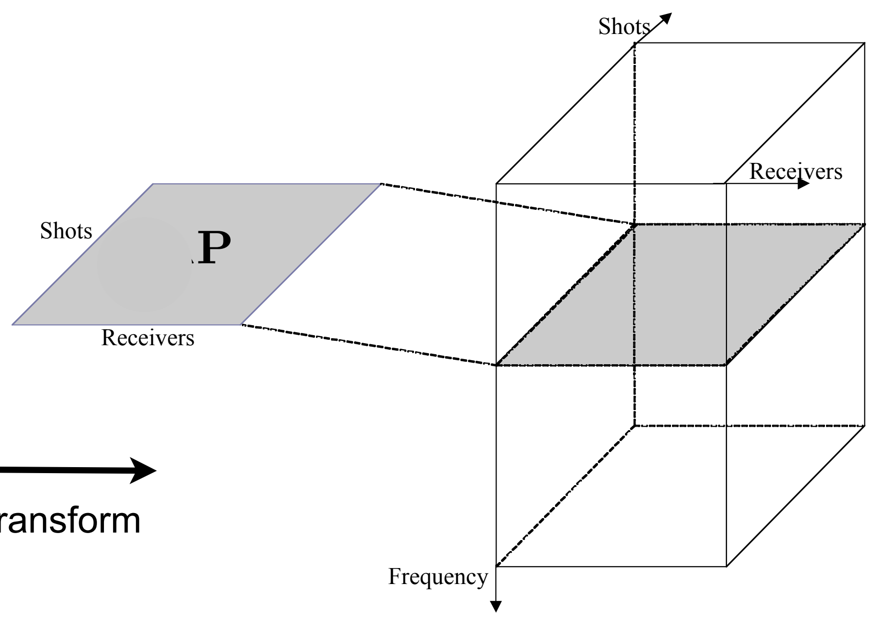


Prediction of groundroll

- Cross-correlation of 3D data cube equals to matrix multiple in frequency domain



Fourier transform



Frequency slice from data cube

Berkhout '97

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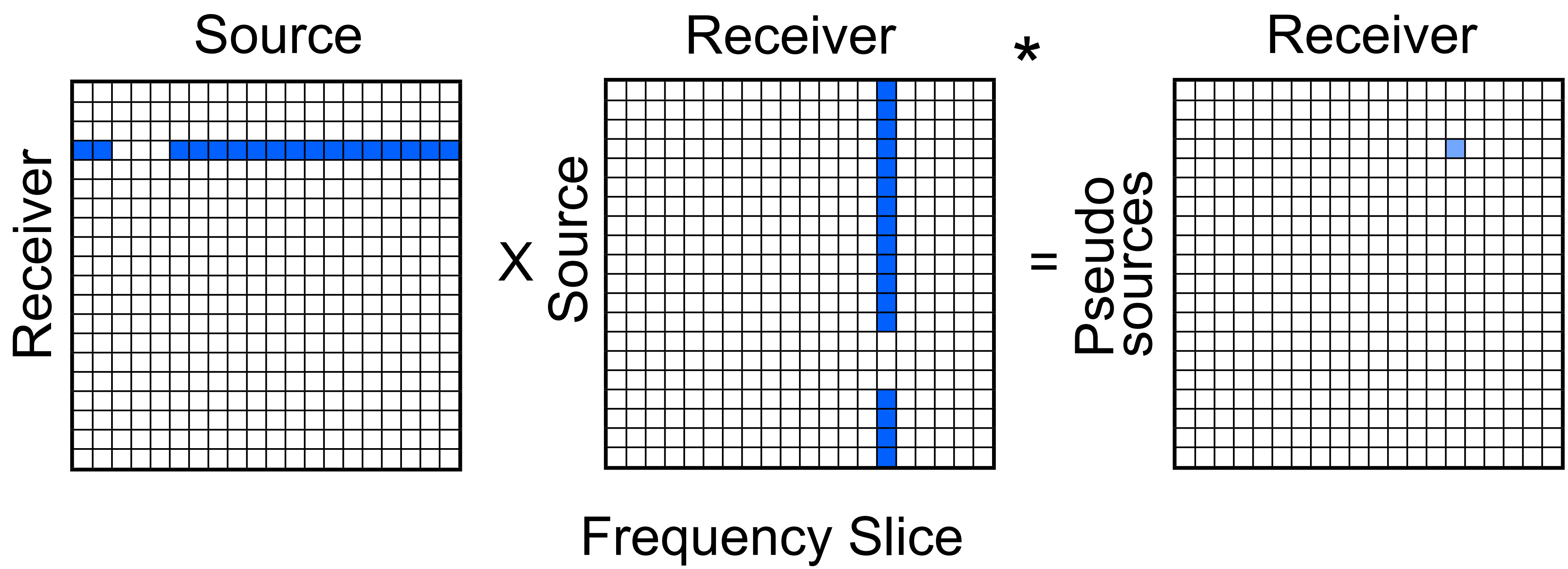
Prediction of groundroll

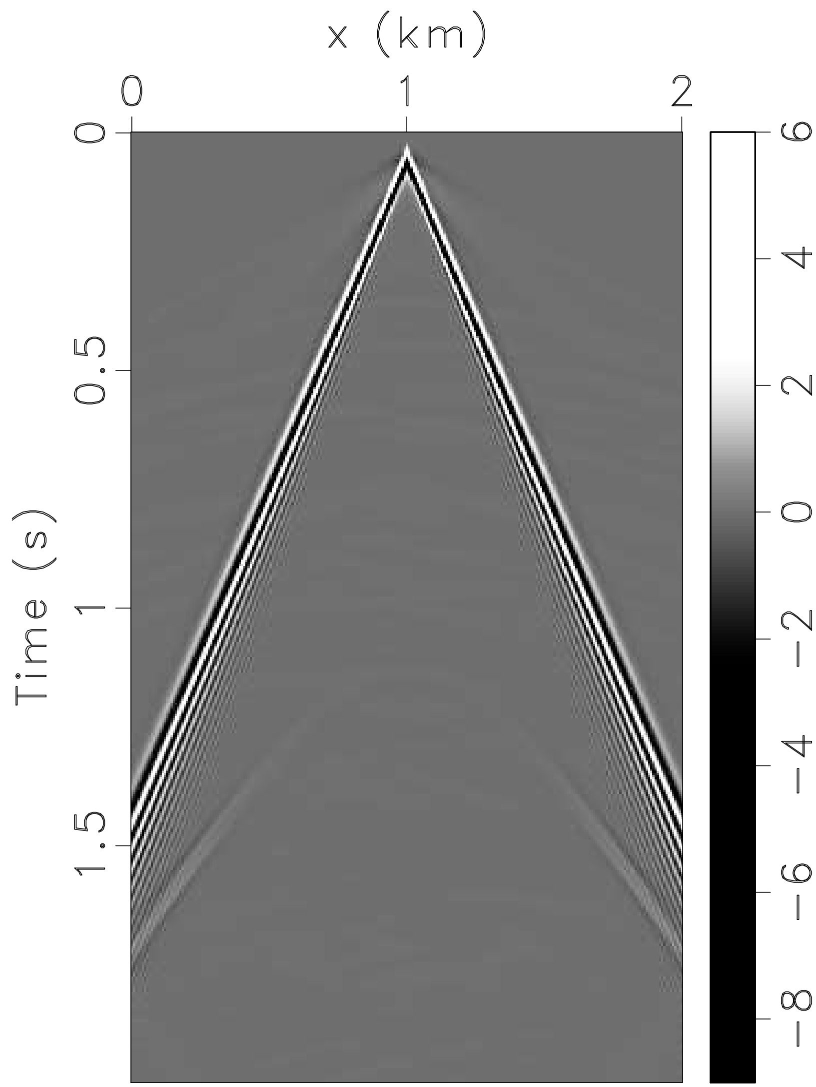


$$\mathbf{RPRP}^*$$

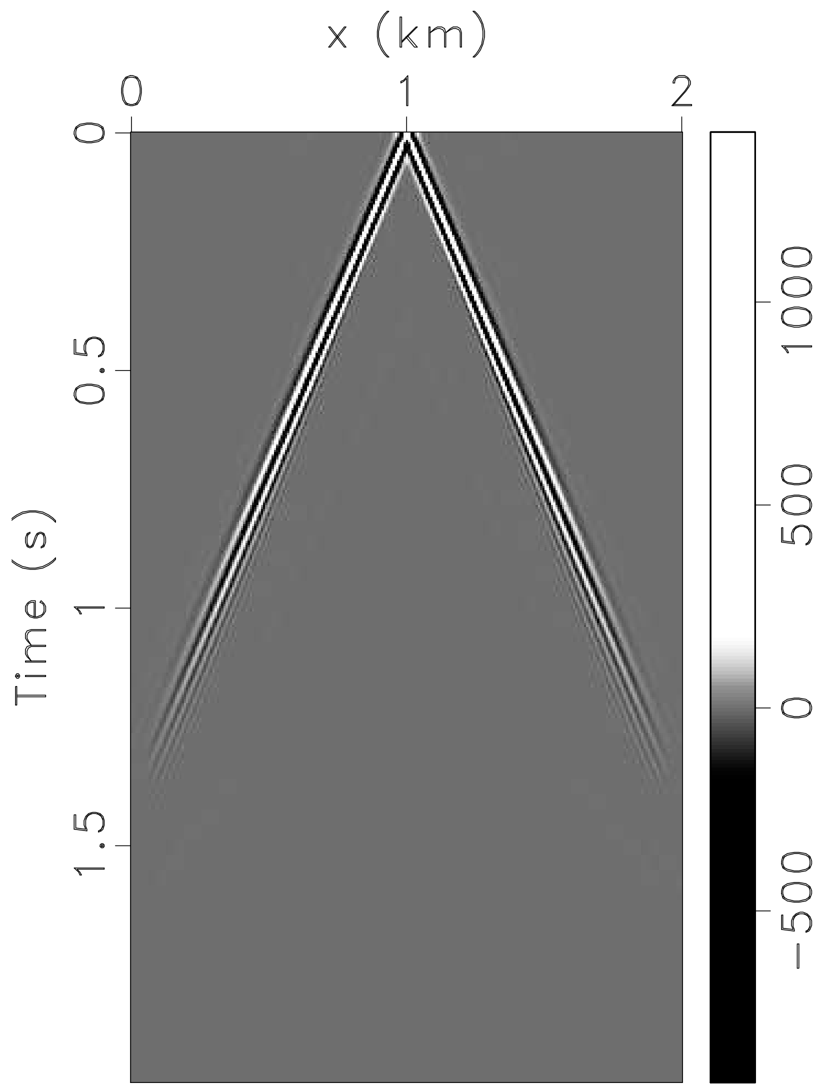
$\mathbf{P}$ frequency slice of data

$\mathbf{R}$ restriction matrix muting diagonal receivers

Synthetic Example



Original data



Groundroll prediction

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Problems with the prediction

- Unknown source wavelet

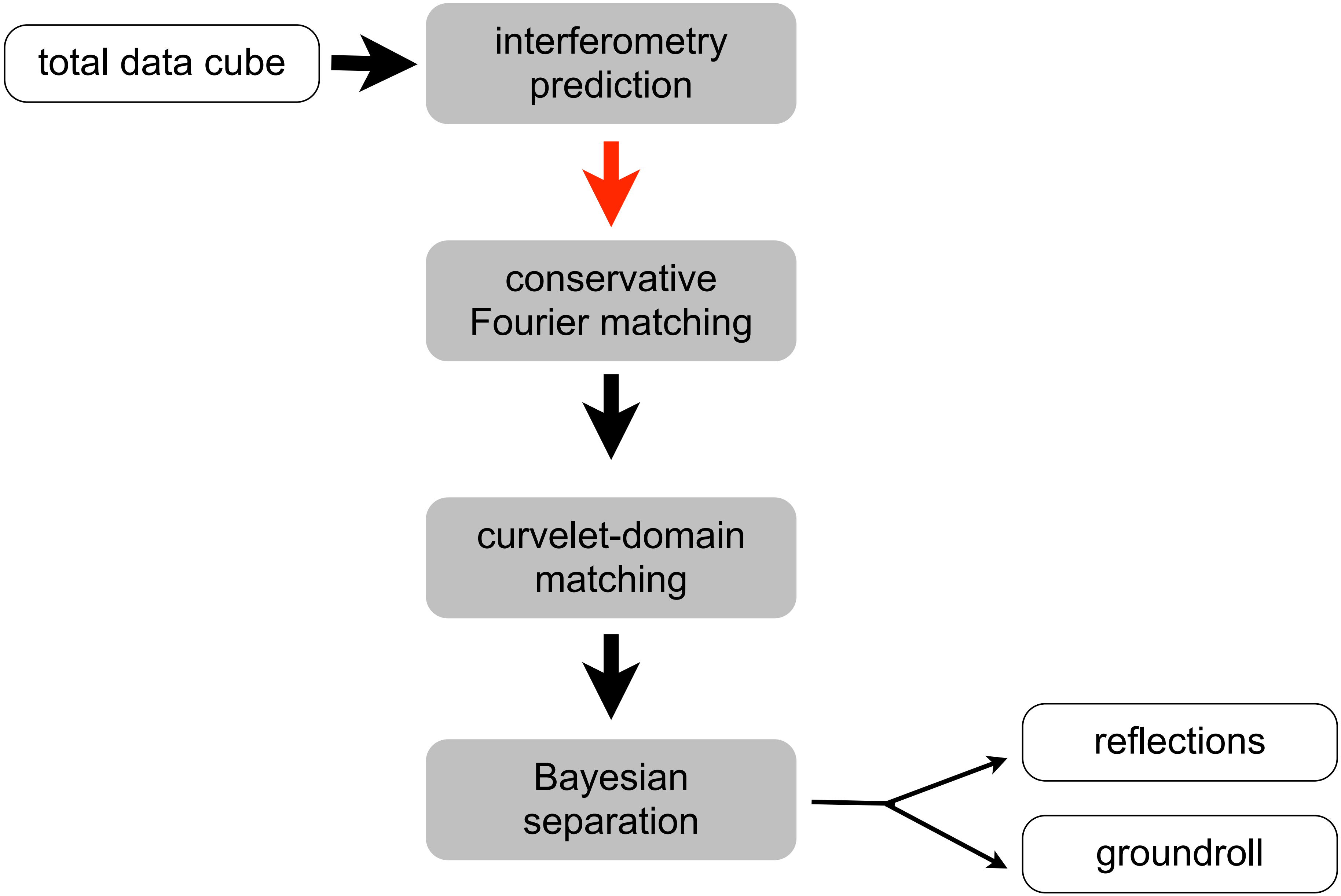
  ➡ Global prediction error in interferometry data

- Conditions to produce exact Green's function not met
  - finite aperture
  - attenuating media
  - usually only vertical sources available, etc.

  ➡ Prediction error depends on position and dip etc,

- Requires adaptive matching, similar to problems in SRME method (surface related multiples elimination)

Workflow


total data cube
interferometry prediction
conservative Fourier matching
curvelet-domain matching
Bayesian separation
reflections
groundroll

Adaptive matching methods

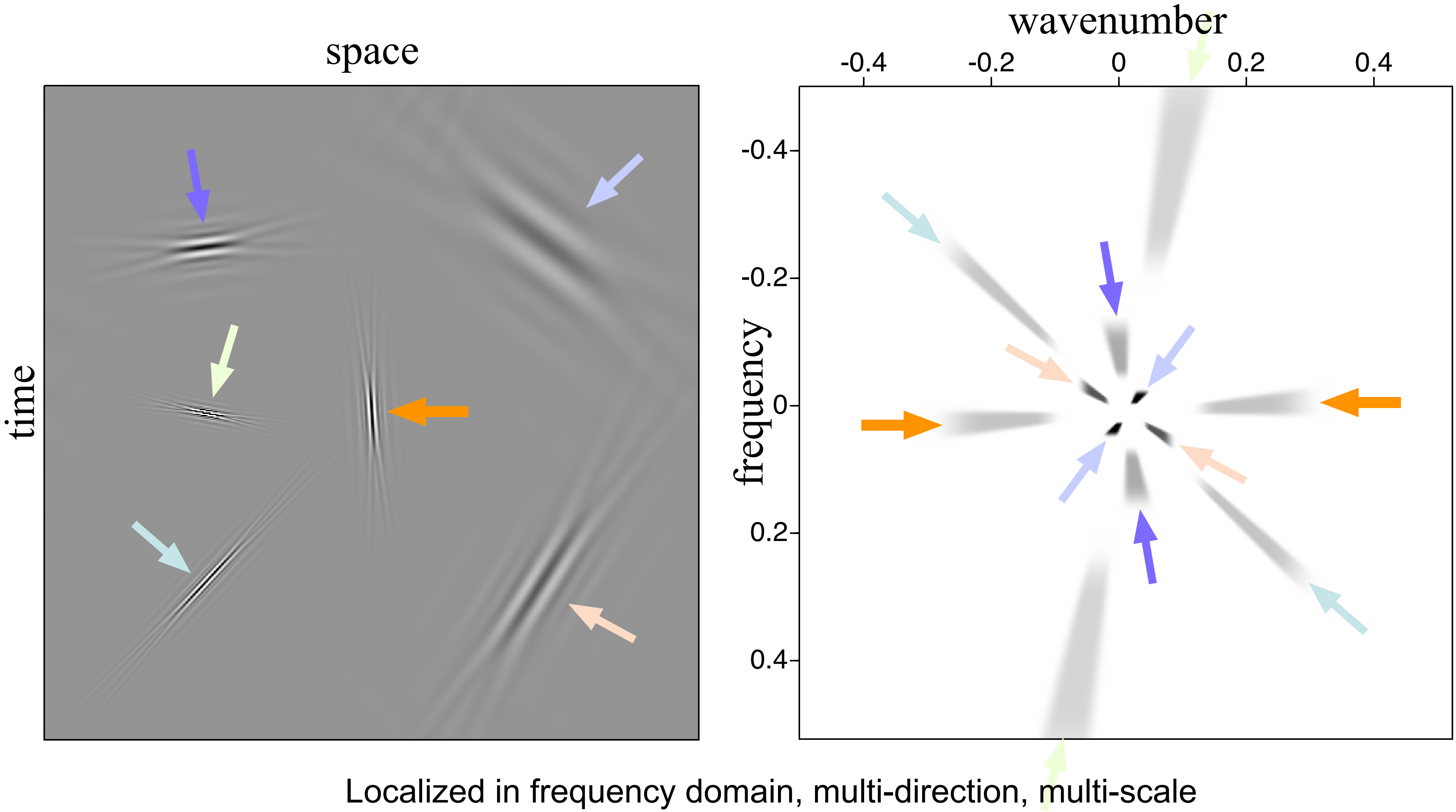
- *Transform-domain* matched-filtering forms the basis of
  - *adaptive* subtraction during surface-related multiple elimination [Verschuur ‘97]
  - *idem* during surface-wave removal with interferometry [Vasconcelos ’08, Wapenaar ‘08]

- *Fourier-based* matching
  - accounts for amplitude-spectra mismatches & global kinematic errors
  - fails for errors that vary spatially & as function of the local dip

- *Spatial & windowed Fourier* matching
  - run risk of over fitting (loss of primary energy) [Verschuur ‘97]

- *Curvelet-domain* matching in phase space
  - corrects for *amplitude* errors that vary *smoothly* as a function of position & dip
  - successful applications in multiple elimination [Herrmann ’08]

2D discrete curvelets



Localized in frequency domain, multi-direction, multi-scale

E. J. Candes, et al ‘05

Our two step matching method

- Step 1: global Fourier matching

$$\hat{\mathbf{f}} = \arg\min_{\hat{\mathbf{g}}} \frac{1}{2}\|\hat{\mathbf{d}} - \hat{\mathbf{g}}\hat{\mathbf{m}}_{\text{predicted}}\|_2^2 + \lambda\|\mathbf{L}_{\mathcal{F}}\hat{\mathbf{g}}\|_2^2$$

  - $\mathbf{L}_{\mathcal{F}}$ *Fourier-space* sharpening operator that promotes smoothness in Fourier domain, which means short in time

$$\tilde{\mathbf{m}}_{\text{matched}} = \mathcal{F}\hat{\mathbf{f}}\hat{\mathbf{m}}$$

- Step 2: Curvelet matching

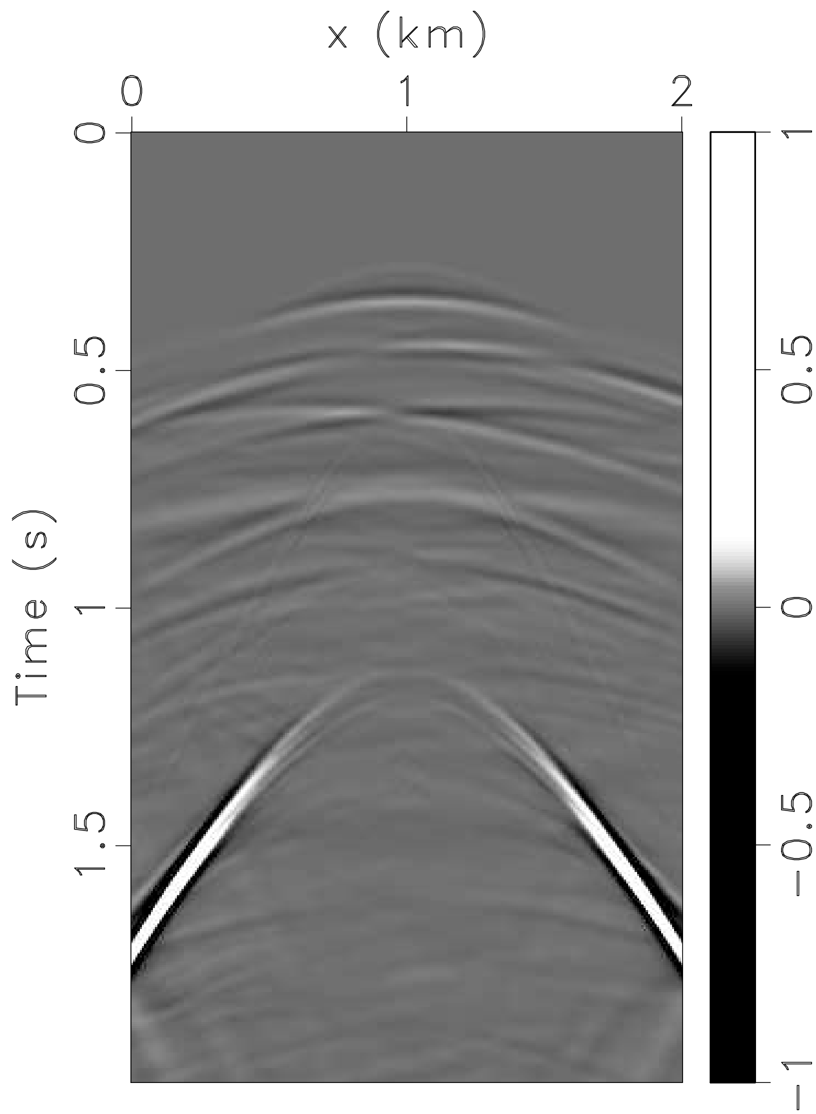
$$\tilde{\mathbf{b}} = \arg\min_{\mathbf{b}>0} \frac{1}{2}\|\mathbf{d} - \mathbf{C}^T \text{diag}\left(\mathbf{C}\mathbf{m}^0\right)\mathbf{b}\|_2^2 + \gamma\|\mathbf{L}_{\mathcal{C}}\mathbf{b}\|_2^2$$

  - $\mathbf{L}_{\mathcal{C}}$ *curvelet-domain* sharpening operator that promotes smoothness

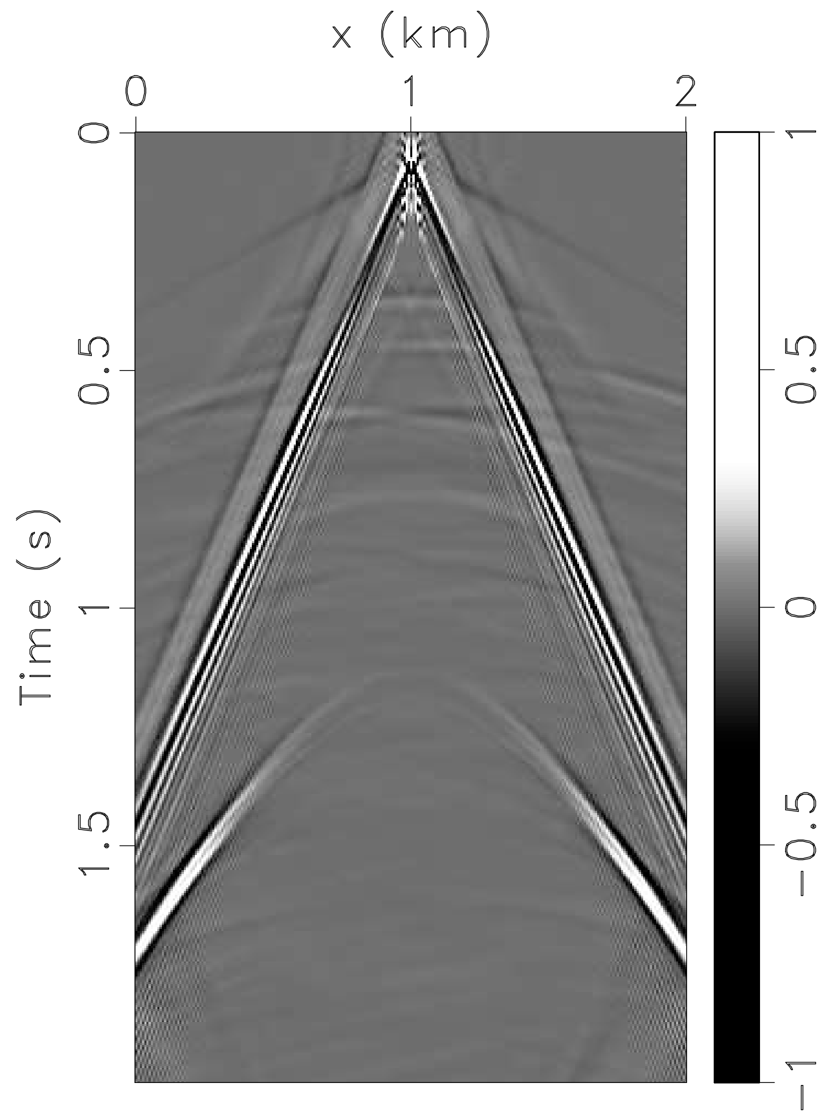
$$\mathbf{m}^0 = \tilde{\mathbf{m}}_{\text{matched}}$$

Herrmann ’08

Synthetic Example

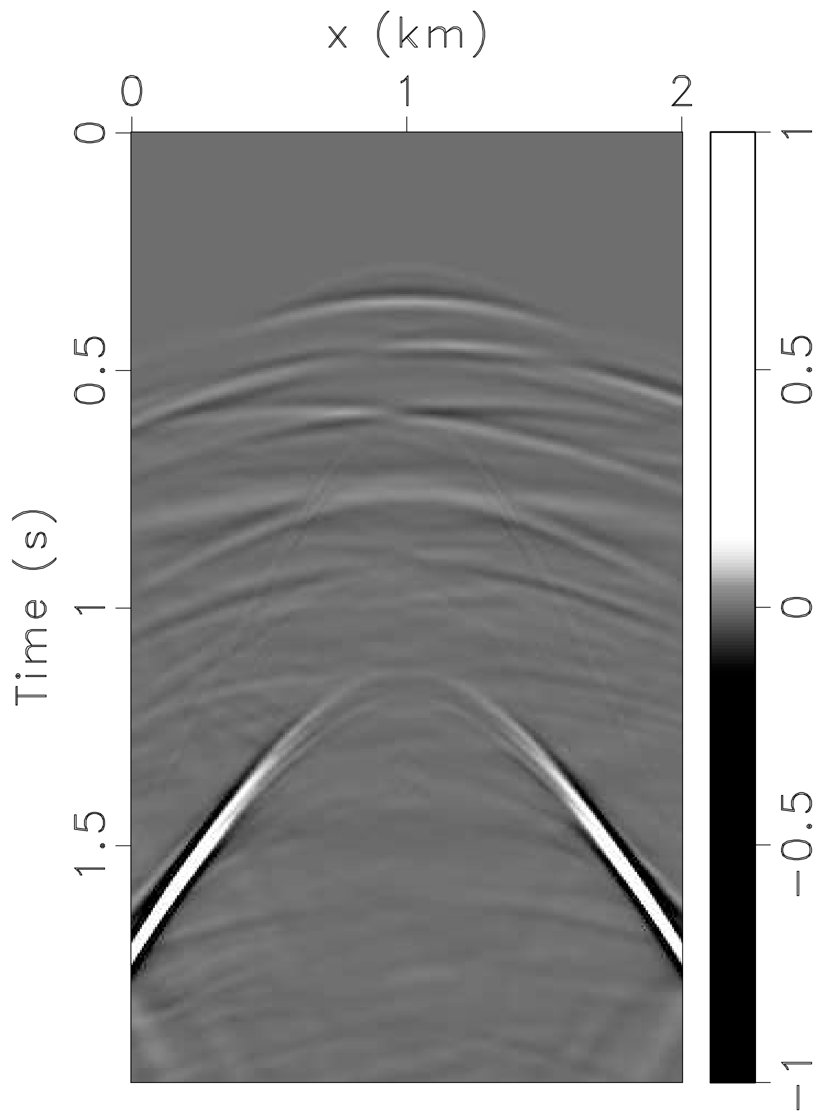


True reflection

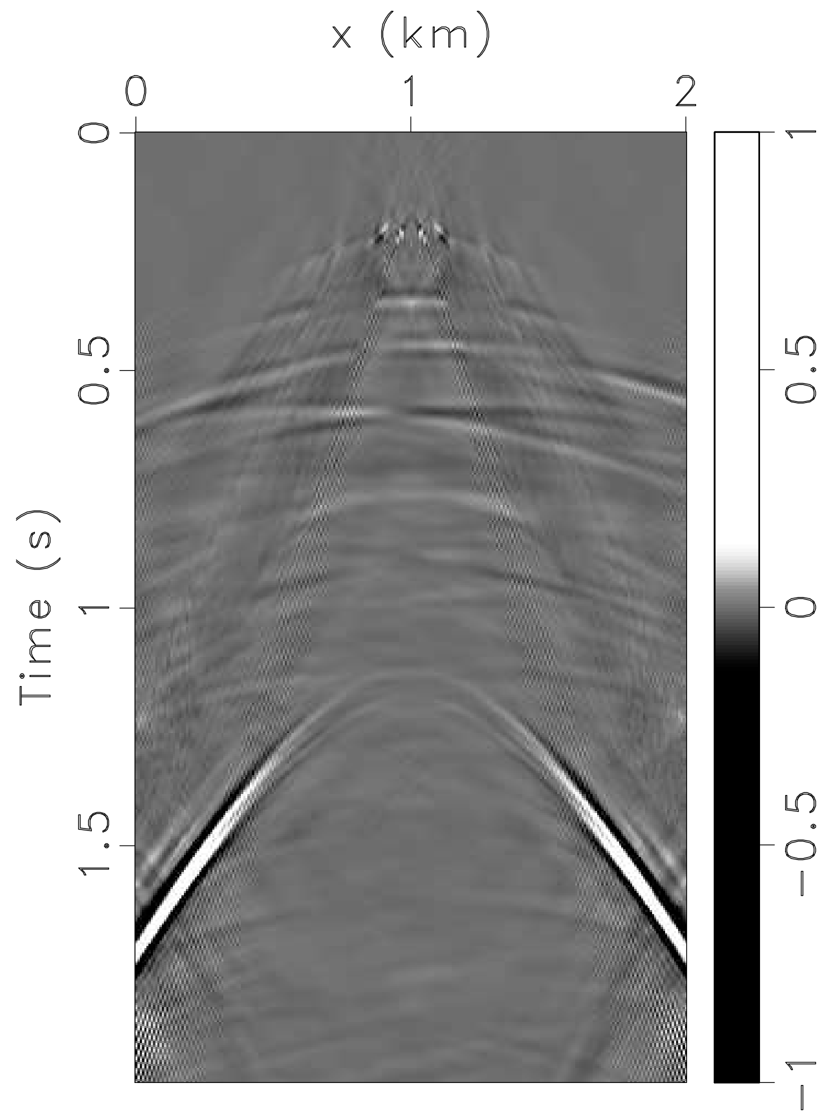


Subtraction after Fourier matching

Synthetic Example

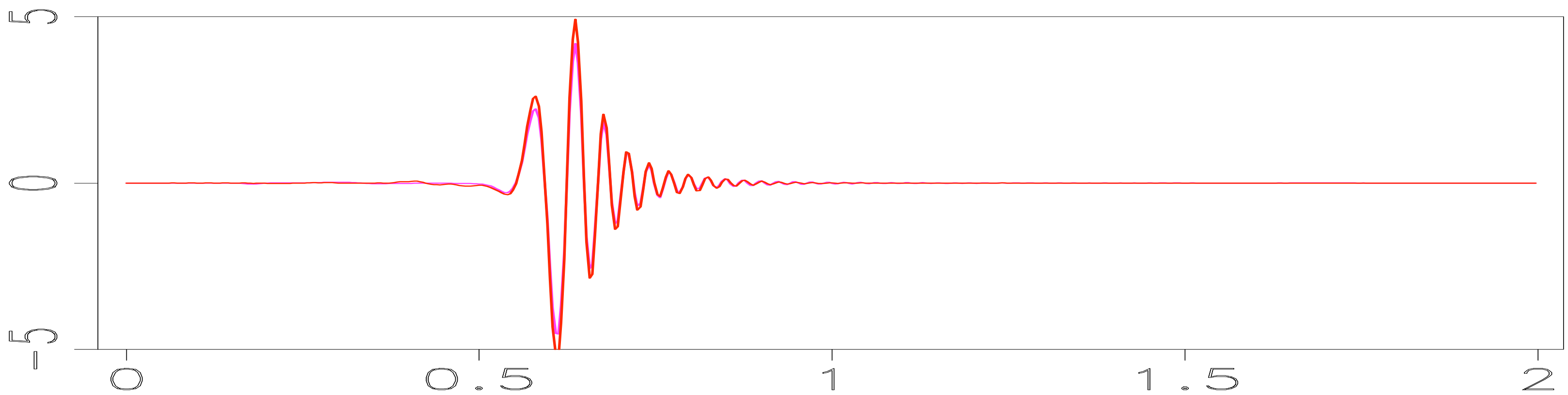


True reflection

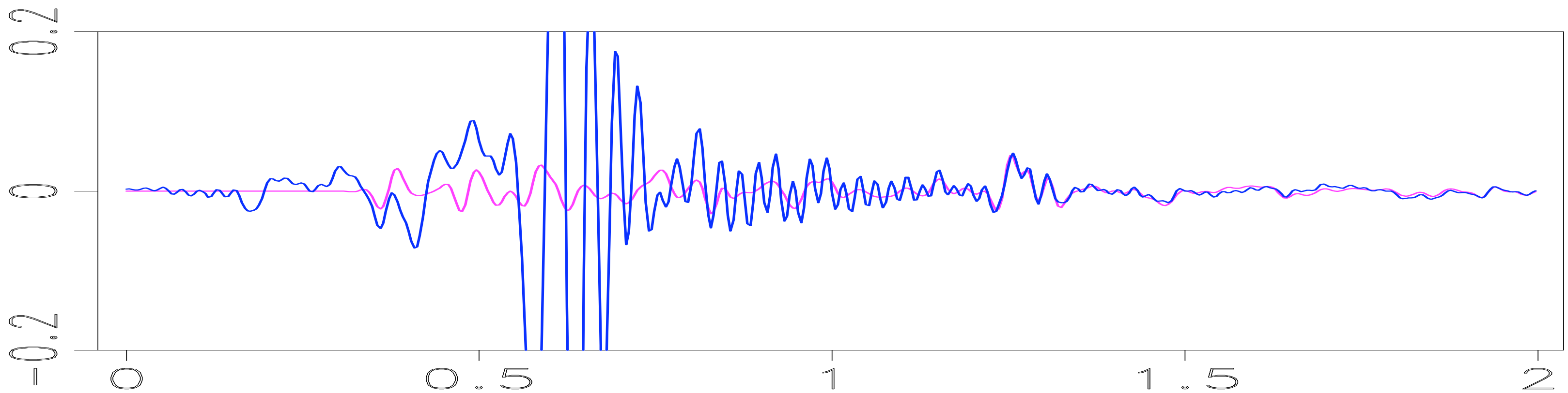


Subtraction after curvelet matching

Fourier matched trace

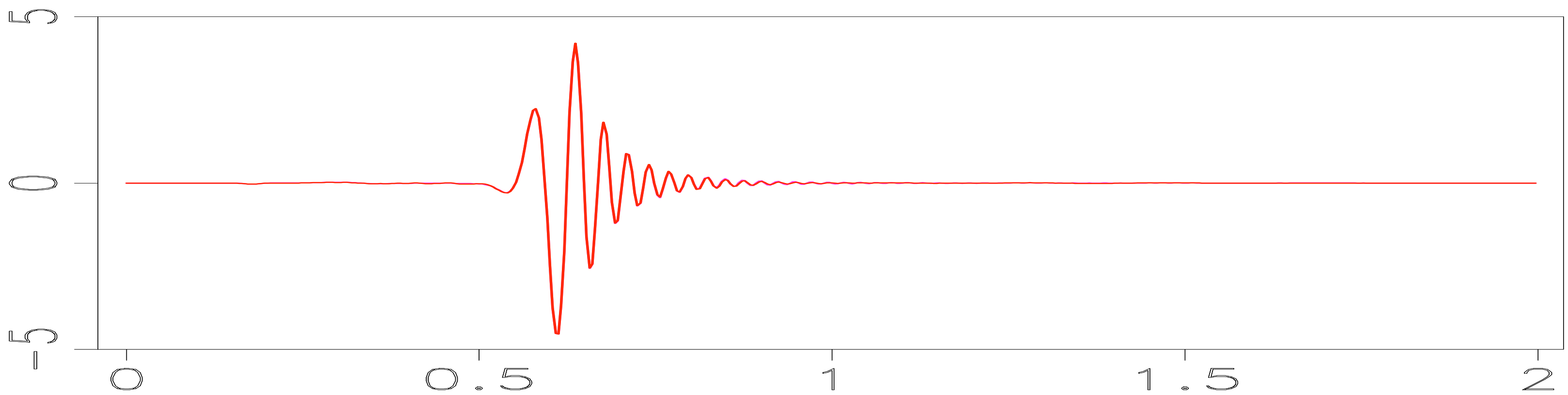


Comparison of groundroll at offset 0.4km

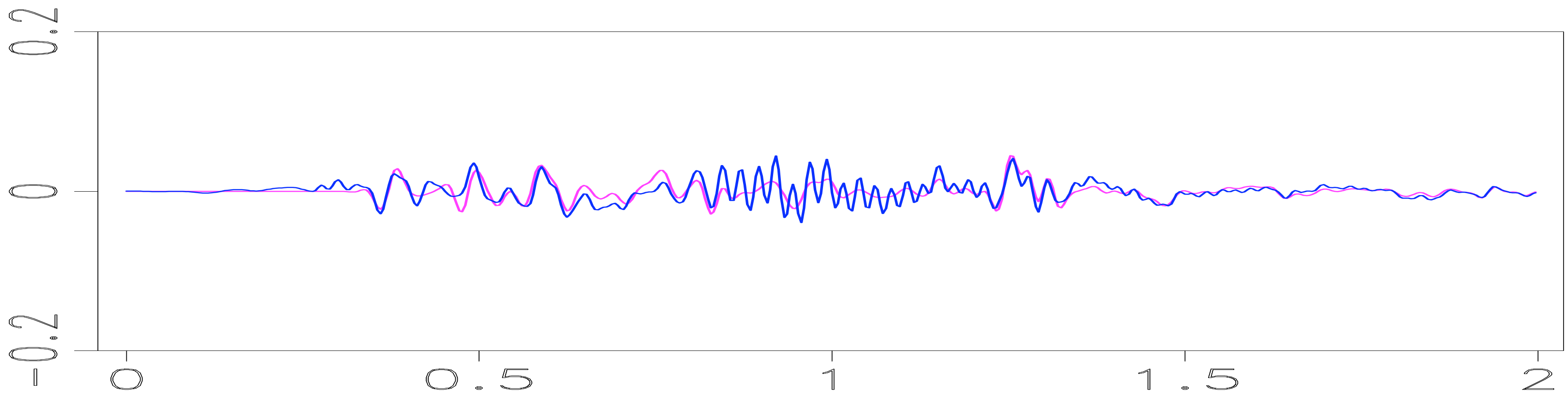


Comparison of reflection at offset 0.4km

Curvelet matched trace



Comparison of groundroll at offset 0.4km



Comparison of reflection at offset 0.4km

Curvelet-based Bayesian Separation

Instead of minus directly, solve the sparsity-promoting program:

$$f(\mathbf{x}_1,\,\mathbf{x}_2) = \lambda_1\|\mathbf{x}_1\|_{1,\mathbf{w}_1} + \lambda_2\|\mathbf{x}_2\|_{1,\mathbf{w}_2} + \|\mathbf{C}^{\mathbf{T}}\mathbf{x}_2 - \mathbf{b}_2\|_2^2 + \eta\|\mathbf{C}^{\mathbf{T}}(\mathbf{x}_1 + \mathbf{x}_2) - \mathbf{b}\|_2^2$$

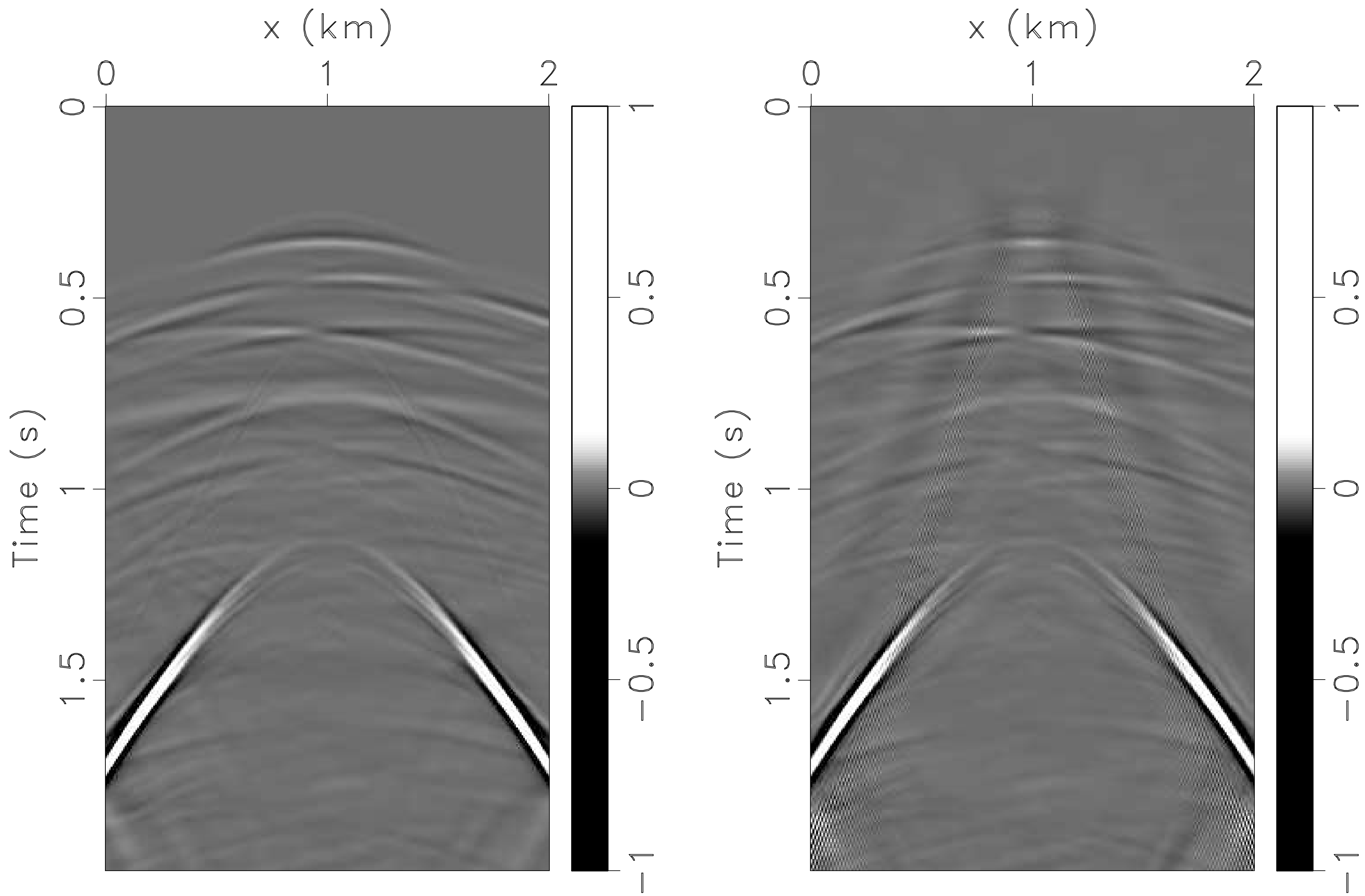
η	Prediction confidence parameter
λ_1	Expected reflector sparsity
λ_2	Expected groundroll sparsity

Can be solved by iterative soft thresholding.

Wang, Saab, Yilmaz & Herrmann ‘08

Yarham, C., and F. J. Herrmann, ‘08

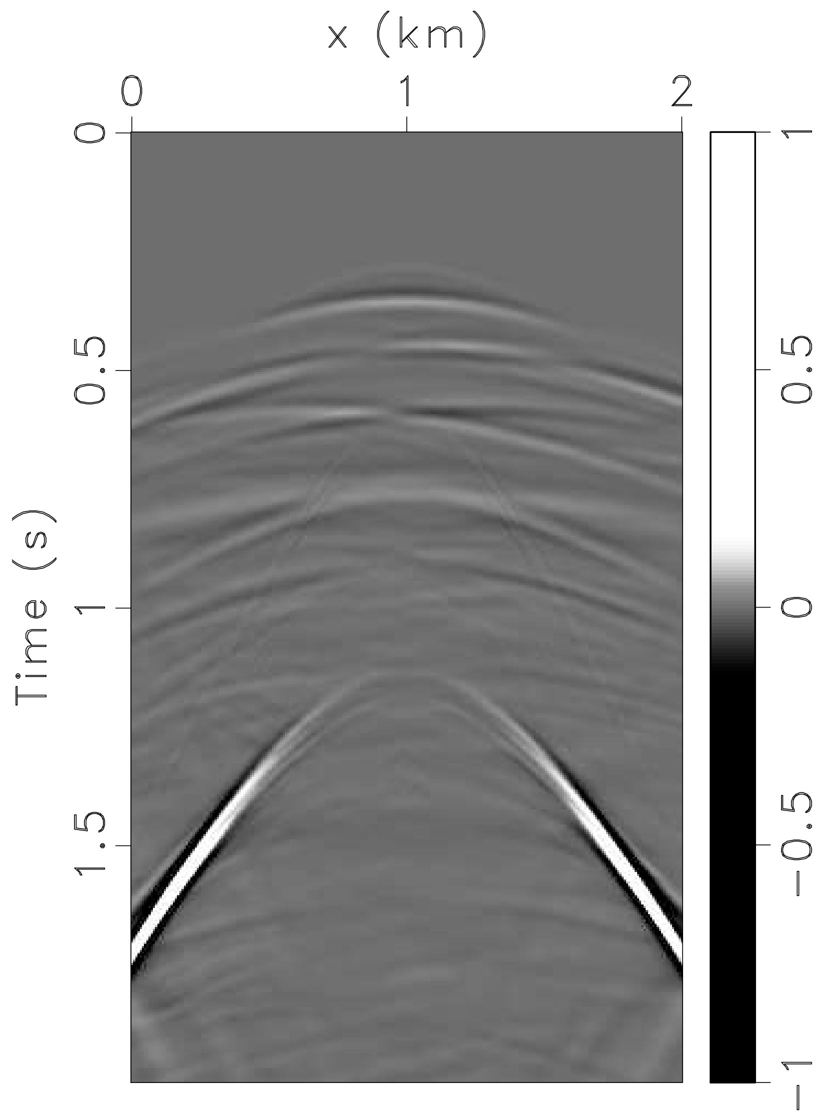
Synthetic Example



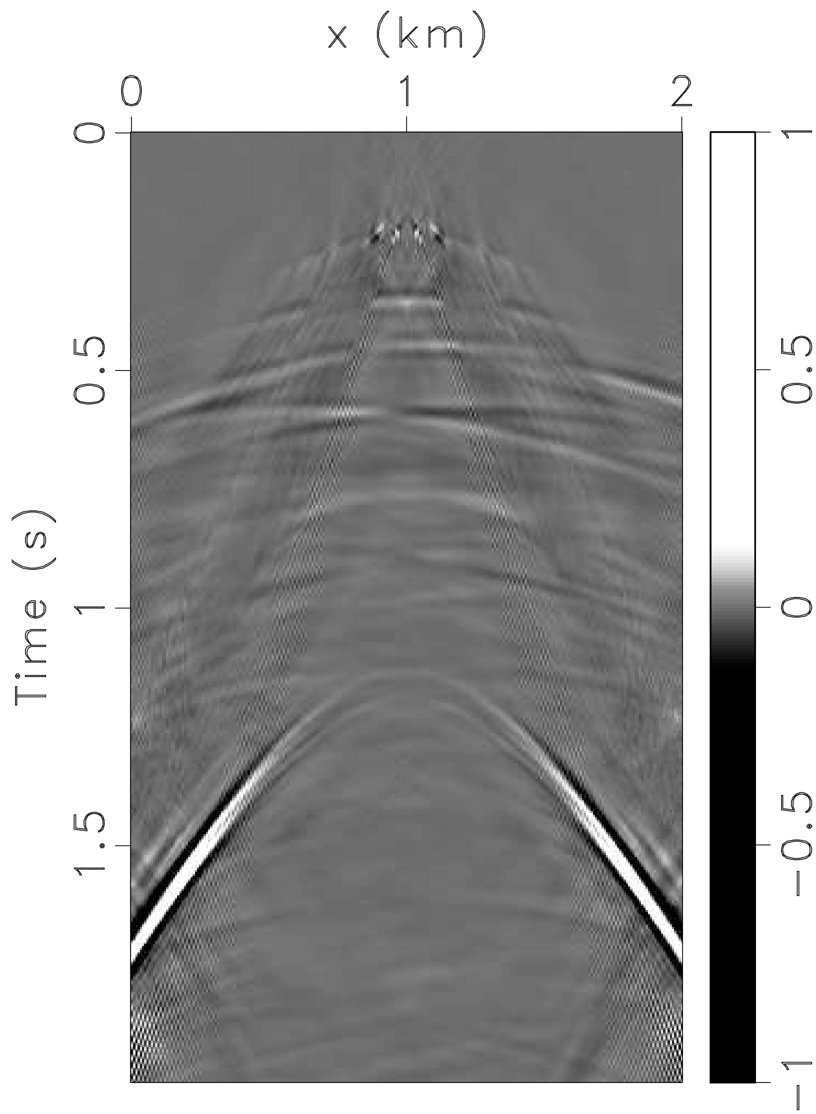
True reflection

Subtraction after Bayesian

Synthetic Example

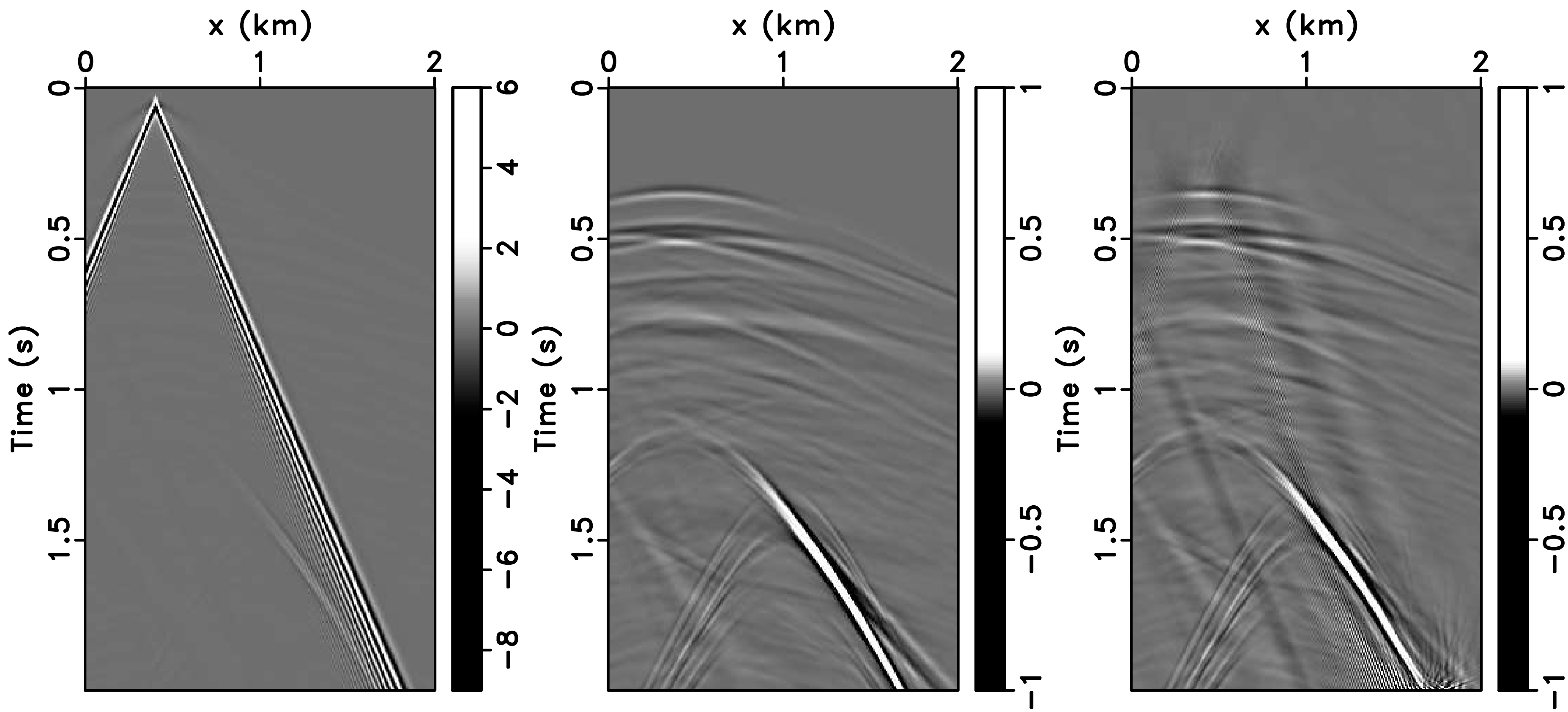


True reflection



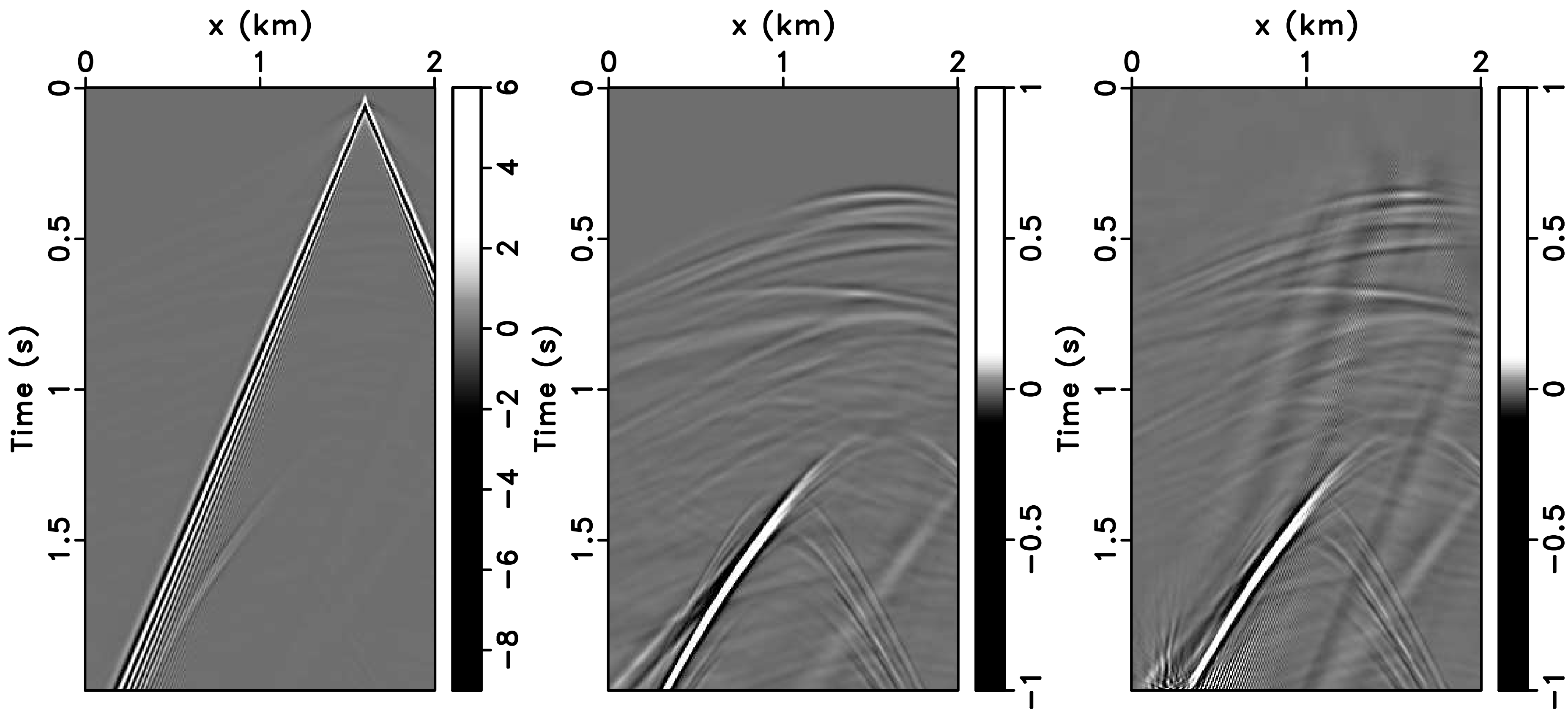
Subtraction after curvelet matching

Synthetic Example



Original data | True reflection | Our result

Synthetic Example



Original data True reflection Our result

Workflow

input data

↓

conservative Fourier matching

↓

curvelet-domain matching

↓

Bayesian separation

$$\mathbf{m}_{\text{predicted}} = \boxed{\mathbf{RPRP}^* \ \text{(multi-D correlation)}}$$

$$\mathbf{m}_0 = \mathbf{F}\mathbf{m}_{\text{predicted}} \text{ with } \mathbf{F} = \mathcal{F}^H \text{diag}\left(\hat{\mathbf{f}}\right)\mathcal{F}$$

$$\begin{aligned} \mathbf{b}_2 &= \mathbf{B}\mathbf{m}_0 \\ \text{with } \mathbf{B} &= \mathbf{C}^T \text{diag}\left(e^{\mathbf{z}}\right)\mathbf{C}\mathbf{m}_0 \\ &\approx \mathcal{F}^H b(x,k)\mathcal{F}\mathbf{m}_0 \end{aligned}$$

$$\mathbf{P}_{\mathbf{w}} : \begin{cases} \tilde{\mathbf{x}} = \arg\min_{\mathbf{x}} \lambda_1 \|\mathbf{x}_1\|_{1,\mathbf{w}_1} + \lambda_2 \|\mathbf{x}_2\|_{1,\mathbf{w}_2} + \\ \|\mathbf{A}\mathbf{x}_2 - \mathbf{b}_2\|_2^2 + \eta\|\mathbf{A}(\mathbf{x}_1 + \mathbf{x}_2) - \mathbf{b}\|_2^2 \\ \tilde{\mathbf{s}}_1 = \mathbf{A}\tilde{\mathbf{x}}_1 \quad \text{and} \quad \tilde{\mathbf{s}}_2 = \mathbf{A}\tilde{\mathbf{x}}_2. \end{cases}$$

Conclusions & future work

- Correlation interferometry can provide data-driven groundroll predictions
- Significant improvements in separation can be made by exploiting curvelet-domain adaptation and sparsity
- Similar workflow with SRME

- Real data example
- Deconvolution interferometry prediction

Acknowledgments

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- Demanet, Ying, Candes, Donoho for Curvelab
- S. Fomel, P. Sava, and the other developers of Madagascar
- SLIM group members
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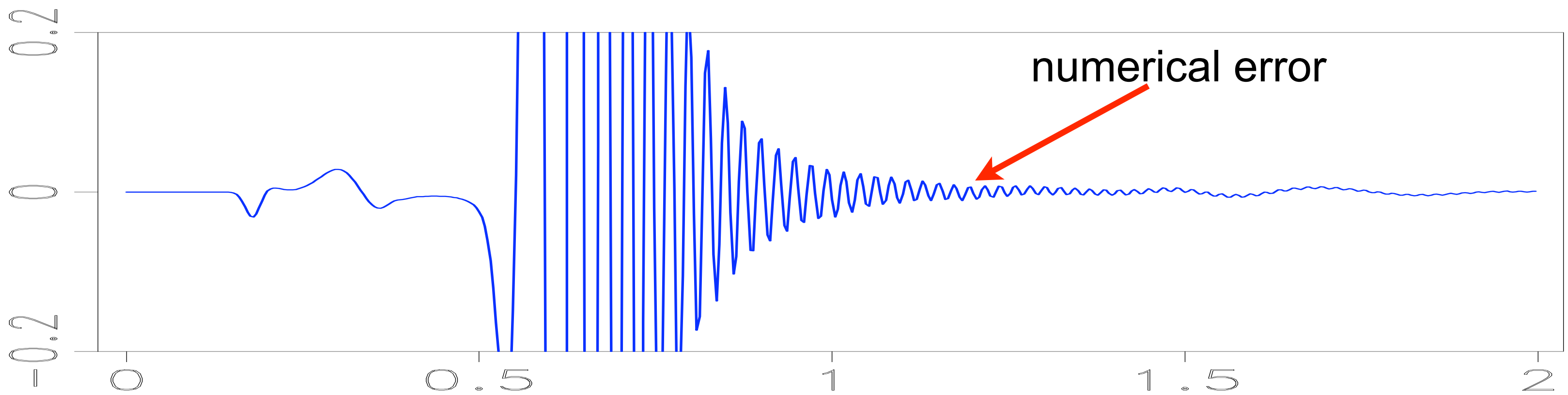
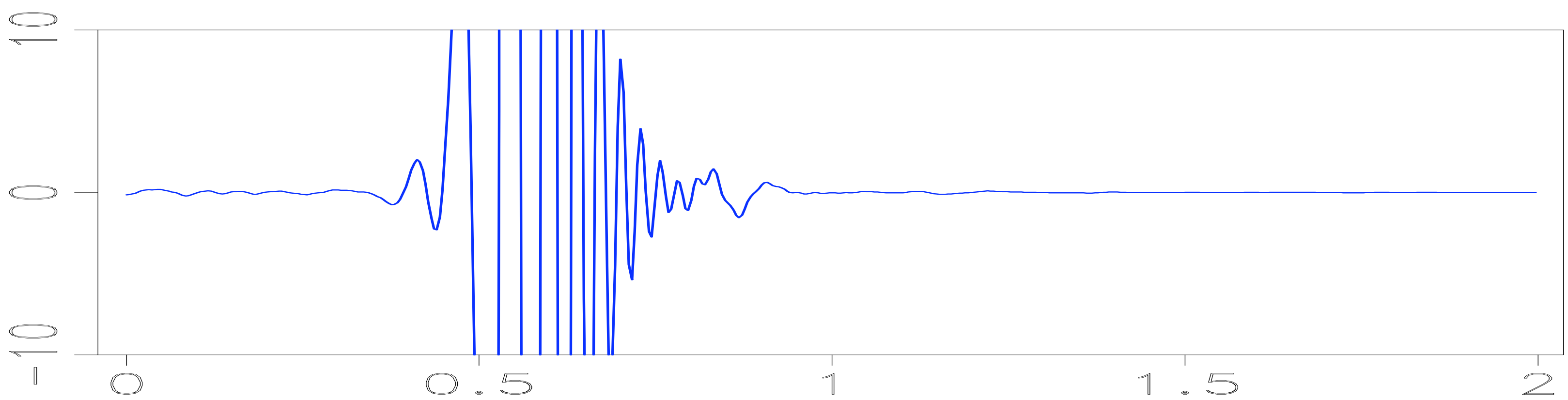
True groundroll and interferometry prediction



True groundroll at offset 0.4km



Prediction of groundroll at offset 0.4km

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