Sparsity-promoting joint microseismic source collocation and source-time function estimation

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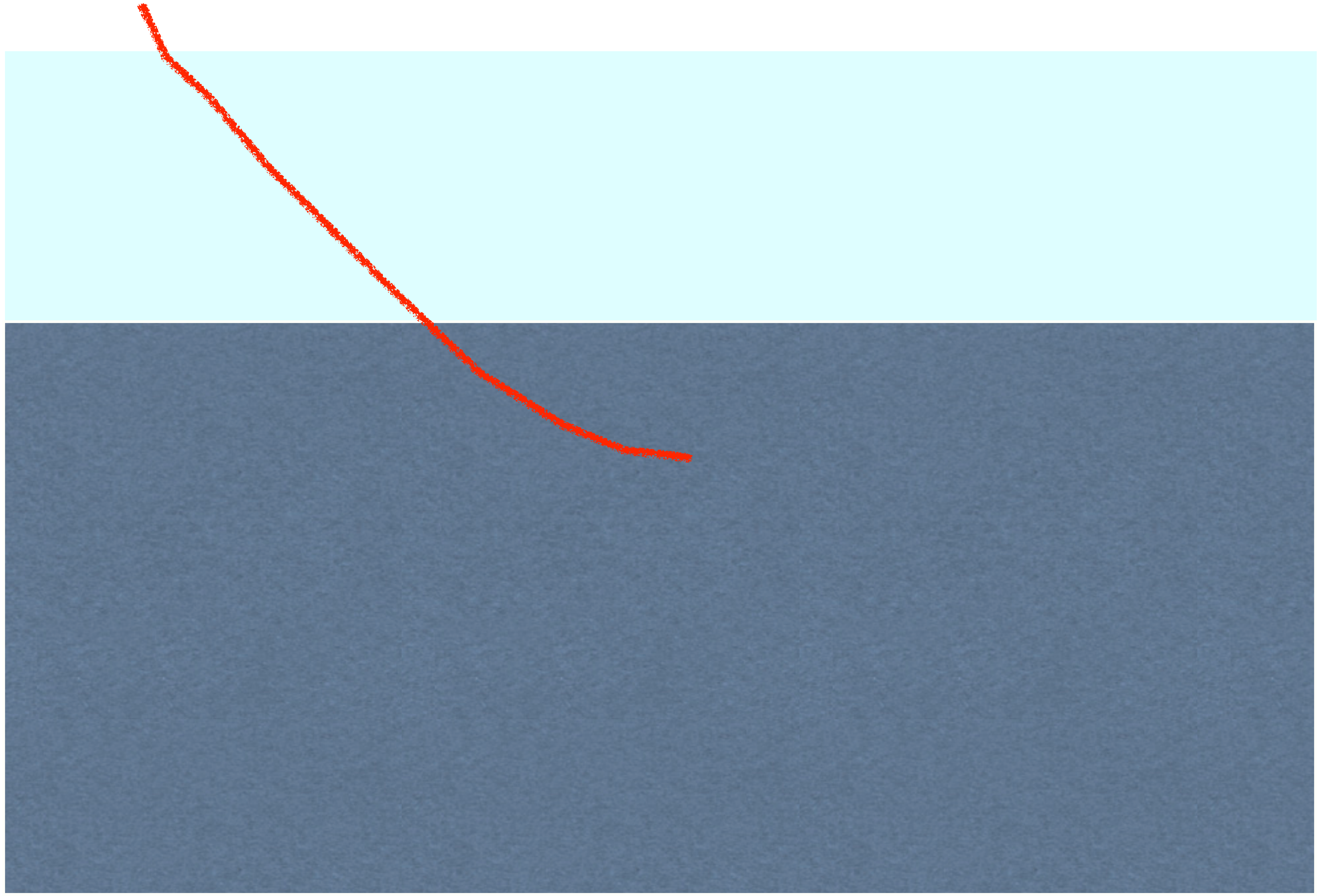
University of British Columbia

Motivation

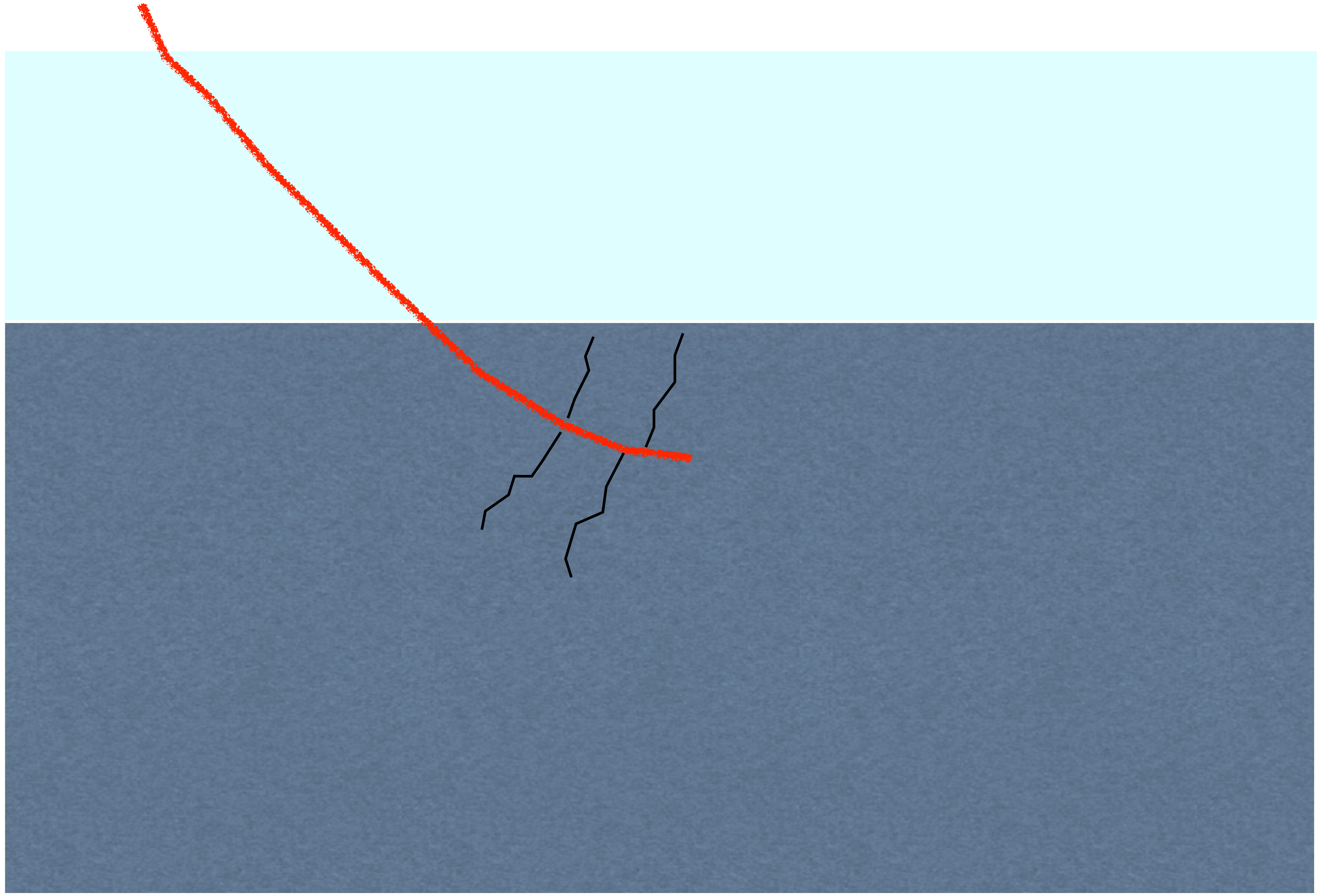
Unconventional Reservoir Schematic

Motivation



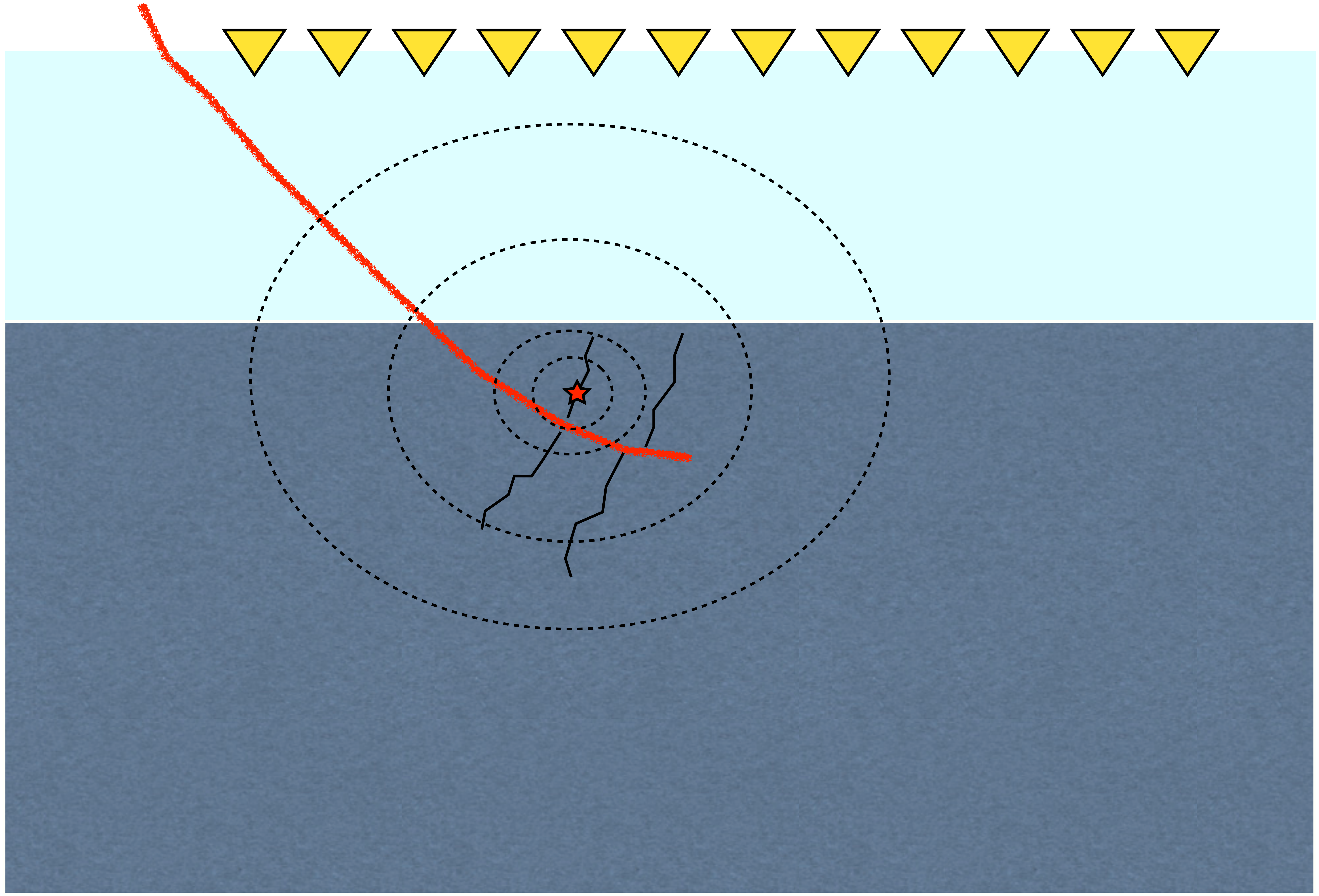
Unconventional
Reservoir Schematic

Motivation



Unconventional
Reservoir Schematic

Motivation



Unconventional
Reservoir Schematic

[Maxwell, ’14]

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Motivation behind microseismic imaging

Microseismic benefits

- Locating fracture at far distance from treatment well
- Tracer based and sonic log based method fails at far distances

Hazard prevention

- Activation of pre-existing faults
- Interference of fractures with wells

[Maxwell, ’14; Eaton,’14]

Motivation behind microseismic imaging

Reservoir evaluation

Source attribute estimation

- Moment tensor orientation
- Origin time
- Spectral properties of sources

Objectives

Super-resolution via sparsity promotion and "lifting"

Simultaneous estimation of the location of microseismic events and their source time functions

[Thurber, ’00; Waldhauser,’00]

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Pre-existing methods

Based on travel-time picking:

- estimate the origin time
- estimate the location
- time consuming
- no source time function

[Rentsch et al., ’07; McMechan, ’10; Gajewski et al., ’05; Sun et al.,’15; Nakata et al.,’16]

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Pre-existing methods

Imaging based

- estimates origin time
- estimates the location

Geometric-mean RTM

- based on cross-correlation imaging condition
- wave equation solve for each receiver

[Sun et al.,'15; Nakata et al.,'16]

Pre-existing methods

Hybrid imaging condition

- Computationally less intensive
- Requires grouping of neighboring receivers
- Lower resolution
- Receiver group length determination not trivial

[Sjögreen et al.,'14; Kaderli et al.,'15]

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FWI based method

$$\underset{\mathbf{f}\in\mathbb{R}^{n_x},\,\mathbf{w}\in\mathbb{R}^{n_t}}{\text{minimize}} \quad \|\mathcal{F}[\mathbf{m}](\mathbf{f}\mathbf{w}^T) - \mathbf{d}\|$$

*where $\mathcal{F}[\mathbf{m}] = \mathcal{P}\mathcal{A}[\mathbf{m}]^{-1}$ is the forward modelling operator

$\mathbf{f}$ and $\mathbf{w}$ are the spatial and temporal component of source

Merits:

- alternating estimation approach
- good estimation when either spatial or temporal components are known

[Sjögreen et al.,'14; Kaderli et al.,'15]

FWI based method

$$\underset{\mathbf{f}\in\mathbb{R}^{n_x},\, \mathbf{w}\in\mathbb{R}^{n_t}}{\text{minimize}} \quad \|\mathcal{F}[\mathbf{m}](\mathbf{f}\mathbf{w}^T) - \mathbf{d}\|$$

*where $\mathcal{F}[\mathbf{m}] = \mathcal{P}\mathcal{A}[\mathbf{m}]^{-1}$ is the forward modelling operator

$\mathbf{f}$ and $\mathbf{w}$ are the spatial and temporal component of source

Limitations:

- poor estimation when both source location & source time function unknown
- assumes prior knowledge on number of sources

Our method w/ sparsity promotion

Estimates complete source wavefield

- space
- time

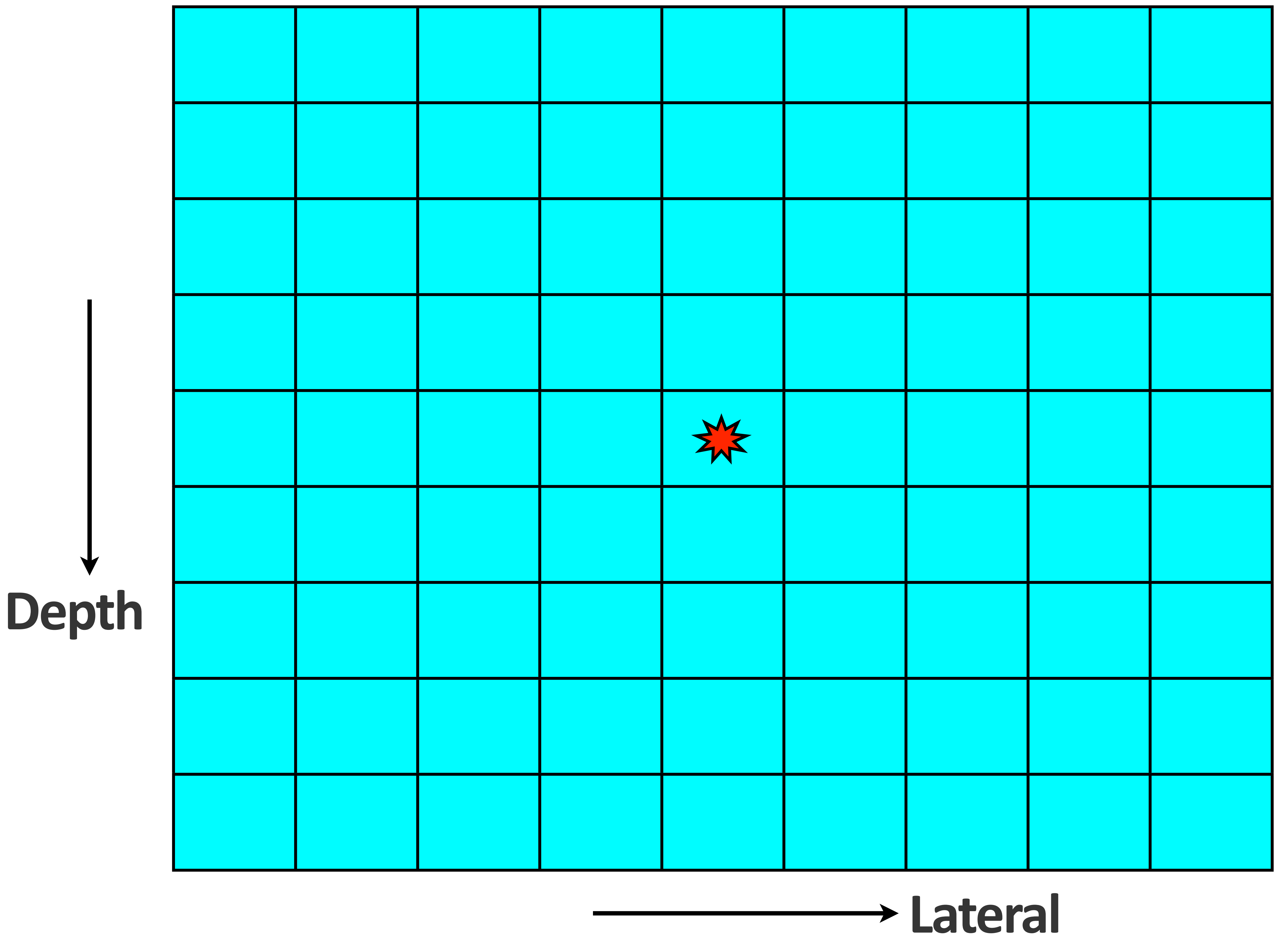
Simultaneous estimation

- source directivity pattern
- microseismic event location
- source time function
- source origin time

Our method w/ sparsity promotion

Assumptions:

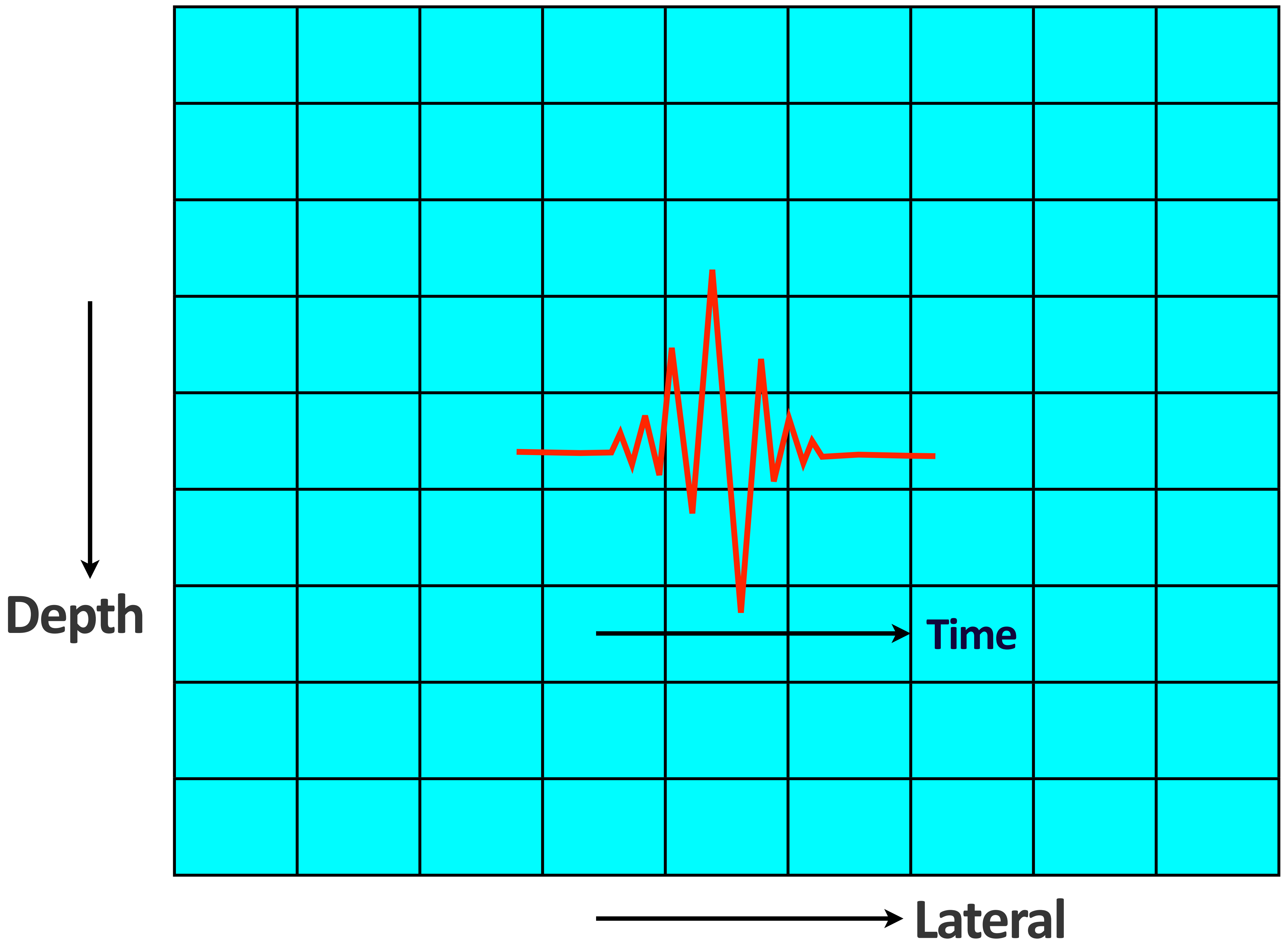
- localized in space



Our method w/ sparsity promotion

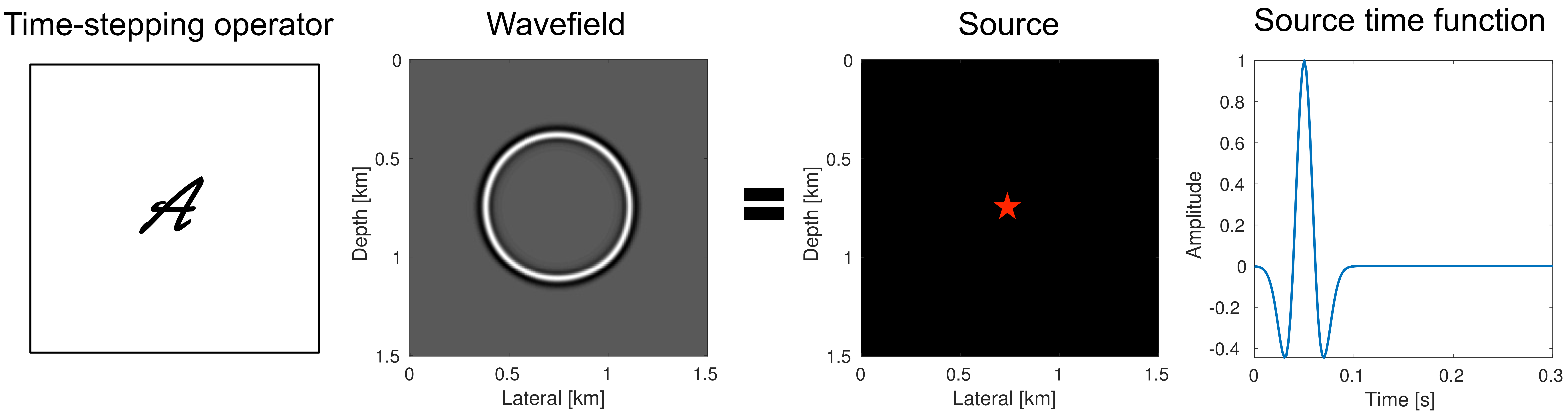
Assumptions:

- localized in space
- finite energy along time



[Kitić et al.,'16]

Co-sparsity property of wave equation



$$\mathcal{A}[\mathbf{m}](\mathbf{u}) = \mathbf{q}$$

Problem statement

$$\begin{aligned} \underset{\mathbf{u}}{\text{minimize}} \quad & \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1} \\ \text{subject to} \quad & \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon \end{aligned}$$

Problem statement

Time stepping operator

$$\underset{\mathbf{u}}{\text{minimize}} \;\; \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1}$$

$$\text{subject to} \;\; \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon$$

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Problem statement

Time stepping operator

Slowness square

$$\underset{\mathbf{u}}{\text{minimize}} \quad \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1}$$

$$\text{subject to } \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon$$

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Problem statement

Time stepping operator

Slowness square

Time domain wavefield

$$\underset{\mathbf{u}}{\text{minimize}} \;\; \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1}$$

$$\text{subject to } \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon$$

Problem statement

Time stepping operator

Slowness square

Time domain wavefield

$$\underset{\mathbf{u}}{\text{minimize}} \quad \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1}$$

$$\text{subject to } \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon$$

Receiver restriction operator

Problem statement

Slowness square

Time stepping operator

Time domain wavefield

$$\underset{\mathbf{u}}{\text{minimize}} \; \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1}$$

$$\text{subject to} \; \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon$$

Receiver restriction operator

Observed data

Problem statement

Time stepping operator

Slowness square

Time domain wavefield

$$\underset{\mathbf{u}}{\text{minimize}} \quad \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1}$$

$$\text{subject to} \ \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon$$

Receiver restriction operator

Observed data

Data residual

Our method w/ sparsity promotion

$$\underset{\mathbf{u}}{\text{minimize}} \quad \|\mathcal{A}[\mathbf{m}](\mathbf{u})\|_{2,1}$$
$$\text{subject to} \quad \|\mathcal{P}(\mathbf{u}) - \mathbf{d}\|_2^2 \leq \epsilon$$

- ✓ Does not require separable structure of source term into spatial & temporal components
- ✓ Does not require prior information on number of sources
- ✓ Simultaneously estimates location/directivity pattern & source origin/source time function

[Van Den Berg et al.,'08]

Method

Made more tractable by change of variable $\mathcal{A}[\mathbf{m}](\mathbf{u}) = \mathbf{Q}$

So we have

$$\begin{aligned} \underset{\mathbf{Q}}{\text{minimize}} \quad & \|\mathbf{Q}\|_{2,1} \\ \text{subject to} \quad & \|\mathcal{F}[\mathbf{m}](\mathbf{Q}) - \mathbf{d}\|_2^2 \leq \epsilon \end{aligned}$$

Similar to classic Basis Pursuit Denoising (BPDN) Problem!

[Lorentz et al.,'14; Herrmann et al.,'15]

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Modified Linearized Bregman

$$\underset{\mathbf{Q}}{\text{minimize}} \ \ \lambda\|\mathbf{Q}\|_{2,1} + \frac{1}{2}\|\mathbf{Q}\|_F^2$$

$$\text{subject to } \|\mathcal{F}[\mathbf{m}](\mathbf{Q}) - \mathbf{d}\|_2^2 \leq \epsilon$$

*where $\|.\|_F$ is the Frobenius norm

- Recent successful application
- Three-step algorithm simple to implement
- Solves slightly relaxed version of original Basis Pursuit Denoising problem

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Modified Linearized Bregman

$$\underset{\mathbf{Q}}{\text{minimize}} \;\; \lambda\|\mathbf{Q}\|_{2,1} + \frac{1}{2}\|\mathbf{Q}\|_F^2$$

$$\text{subject to } \|\mathcal{F}[\mathbf{m}](\mathbf{Q}) - \mathbf{d}\|_2^2 \leq \epsilon$$

*where $\|.\|_F$ is the Frobenius norm

- Choice of λ controls trade off between sparsity & Frobenius norm
- $\lambda \uparrow \infty$ corresponds to solving original BPDN problem

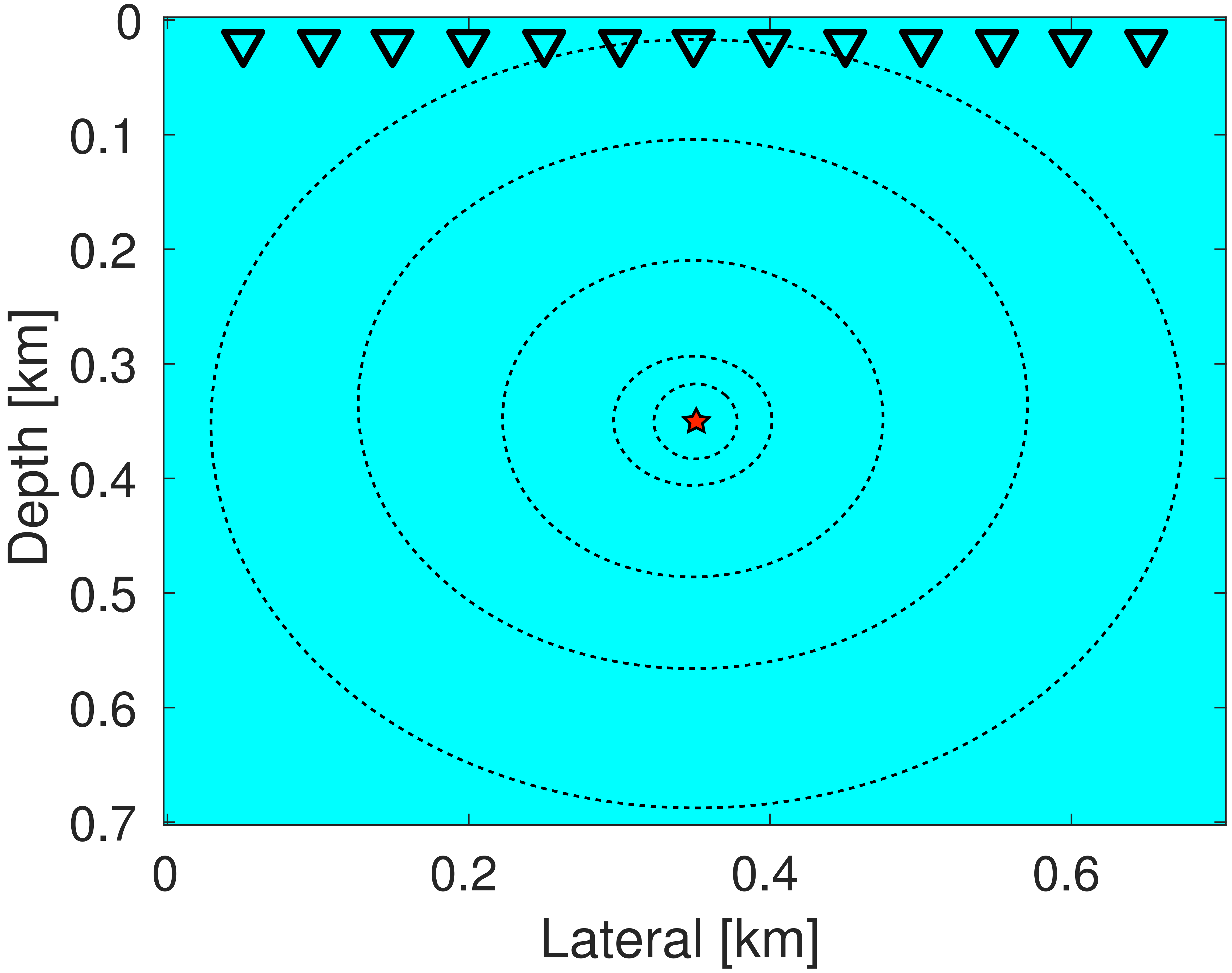
Algorithm

1. **for** $k = 0, 1, \cdots$
2. $\quad \mathbf{V}_k = \mathcal{F}^T[\mathbf{m}](\Pi_\epsilon(\mathcal{F}[\mathbf{m}](\mathbf{Q}_k) - \mathbf{d}))$ //adjoint solve
3. $\quad \mathbf{Z}_{k+1} = \mathbf{Z}_k - t_k \mathbf{V}_k$ //auxiliary variable update
4. $\quad \mathbf{Q}_{k+1} = \mathrm{Prox}_{\lambda\|.\|_{2,1}}(\mathbf{Z}_{k+1})$ //sparsity promotion
5. **end**

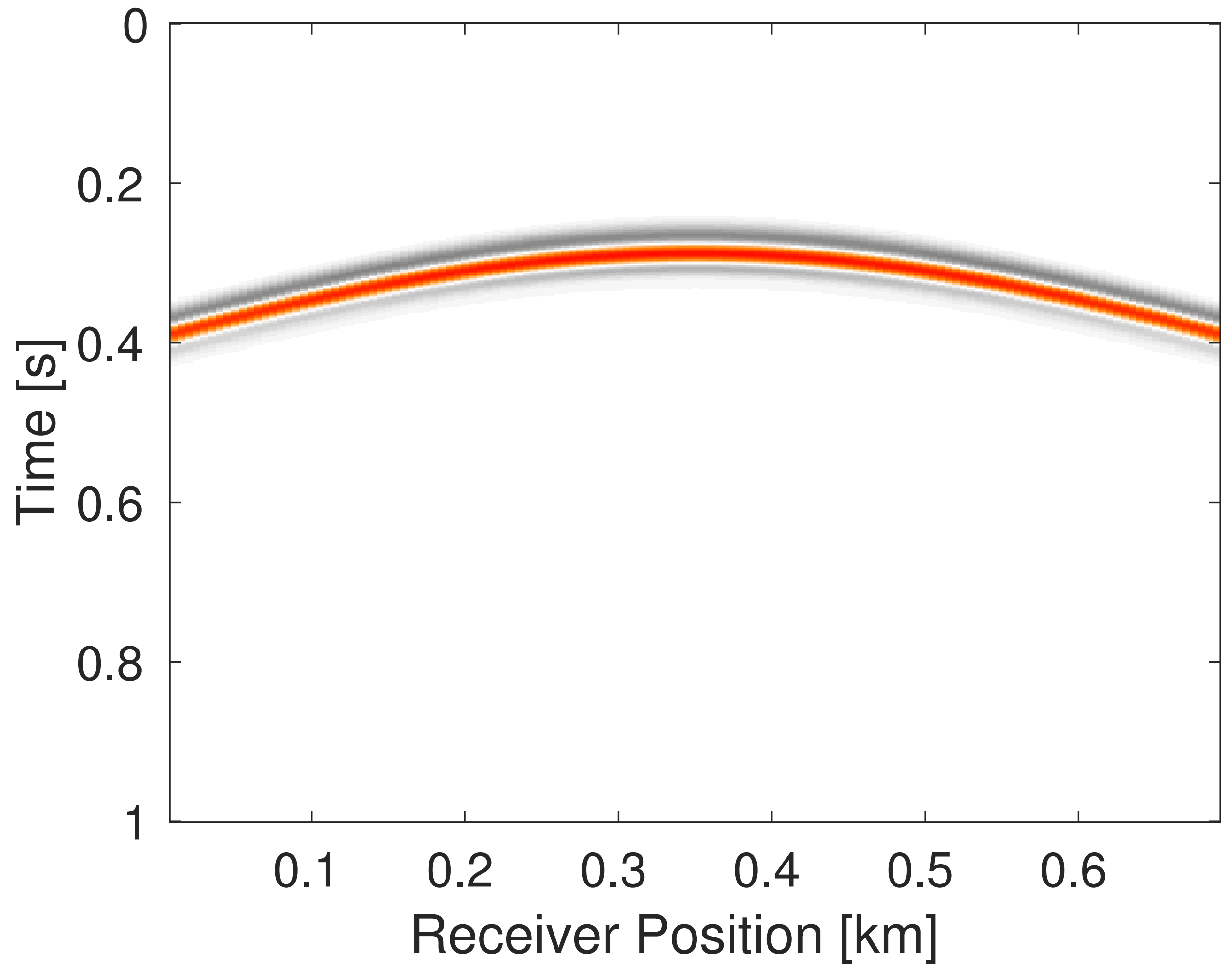
*where $t_k = \frac{\|\mathcal{F}(\mathbf{m})\mathbf{Q}_k - \mathbf{d}\|^2}{\|\mathcal{F}(\mathbf{m})^T(\mathcal{F}(\mathbf{m})\mathbf{Q}_k - \mathbf{d})\|^2}$ is the dynamic step length

* $\mathrm{Prox}_{\lambda\|.\|_{2,1}}(c) := \arg\min_b \lambda\|b\|_{2,1} + \frac{1}{2}\|c-b\|_F^2$ is the proximal mapping of the ℓ_{21} norm

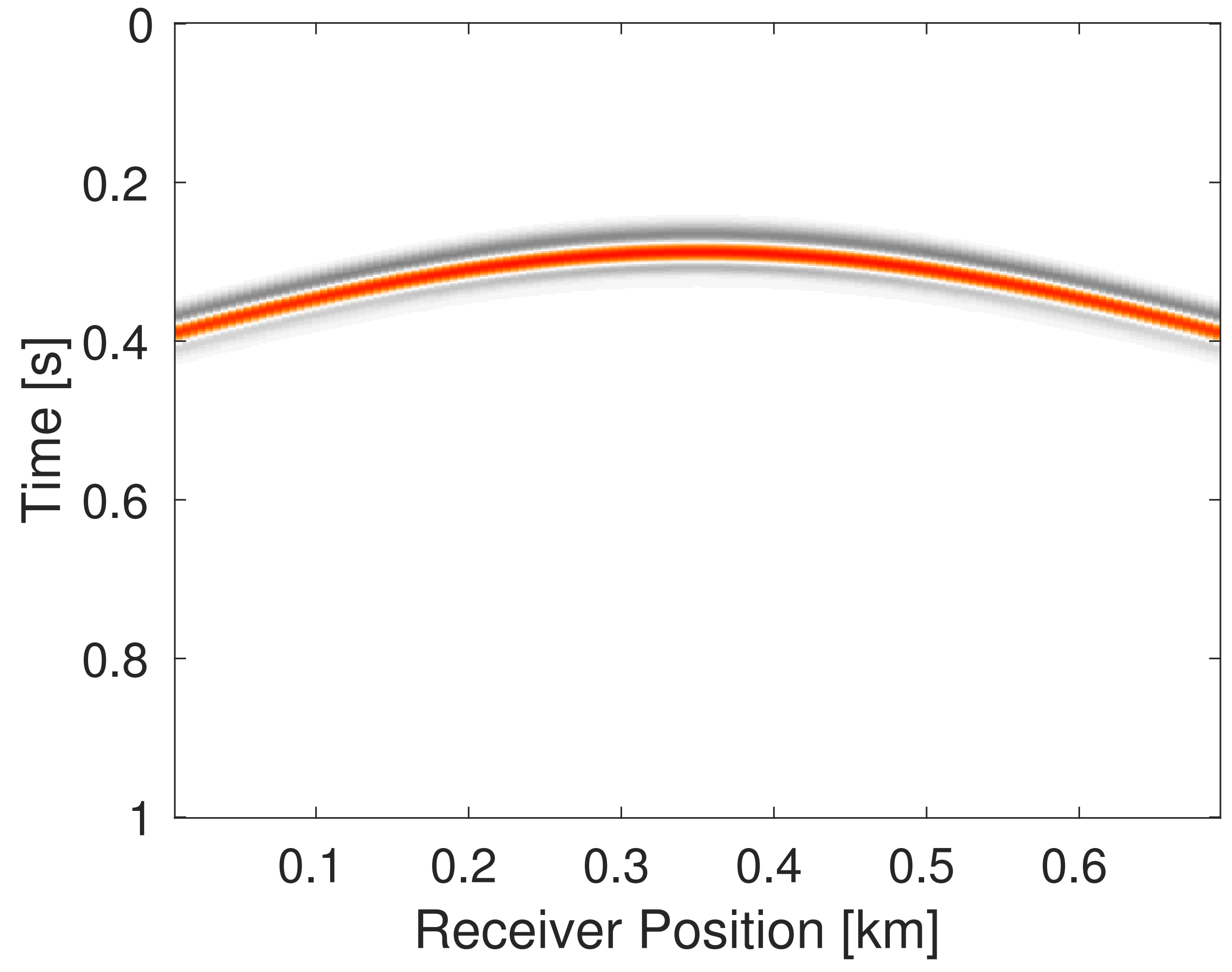
* $\Pi_\epsilon(\mathbf{x}) = \max\{0, 1 - \frac{\epsilon}{\|\mathbf{x}\|}\}.(\mathbf{x})$ the projection on to ℓ_2 norm ball



0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Depth [km]
0
0.2
0.4
0.6
Lateral [km]

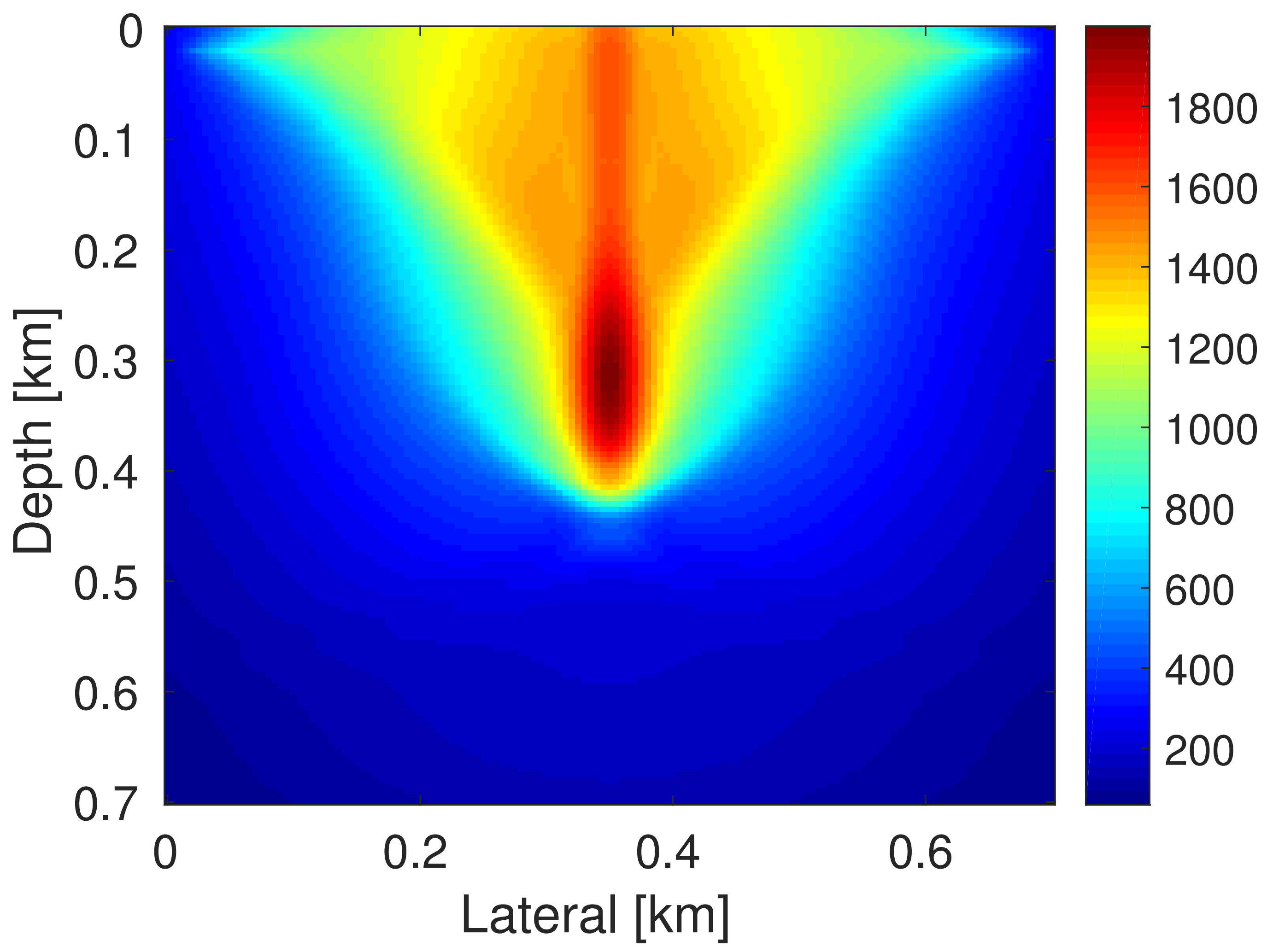


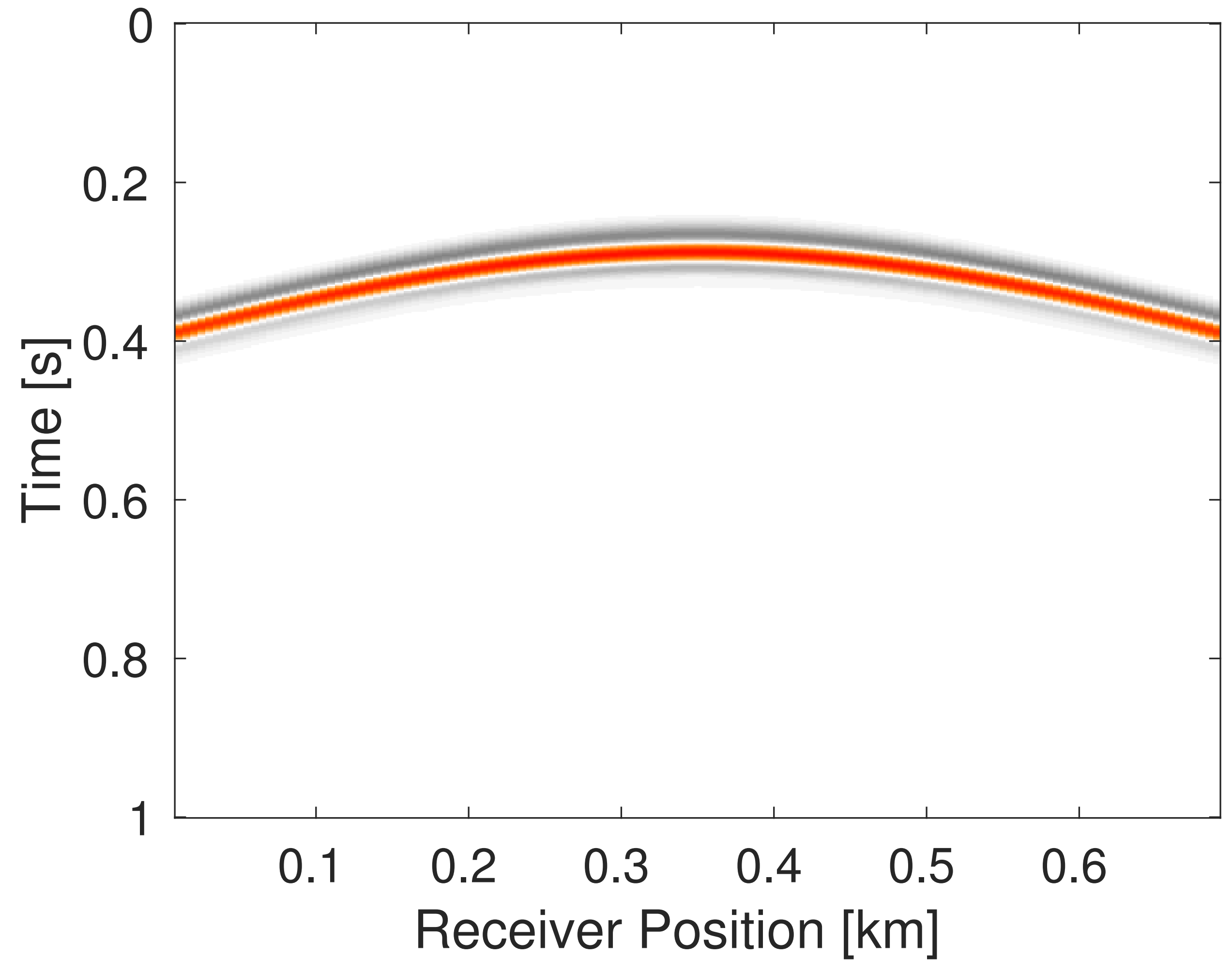
0
0.2
0.4
0.6
0.8
1
Time [s]
0.1
0.2
0.3
0.4
0.5
0.6
Receiver Position [km]



$$\mathbf{V}_1 = \mathcal{F}^T[\mathbf{m}](\Pi_\epsilon(\mathcal{F}(\mathbf{Q}_0) - \mathbf{d}))$$

Adjoint solve





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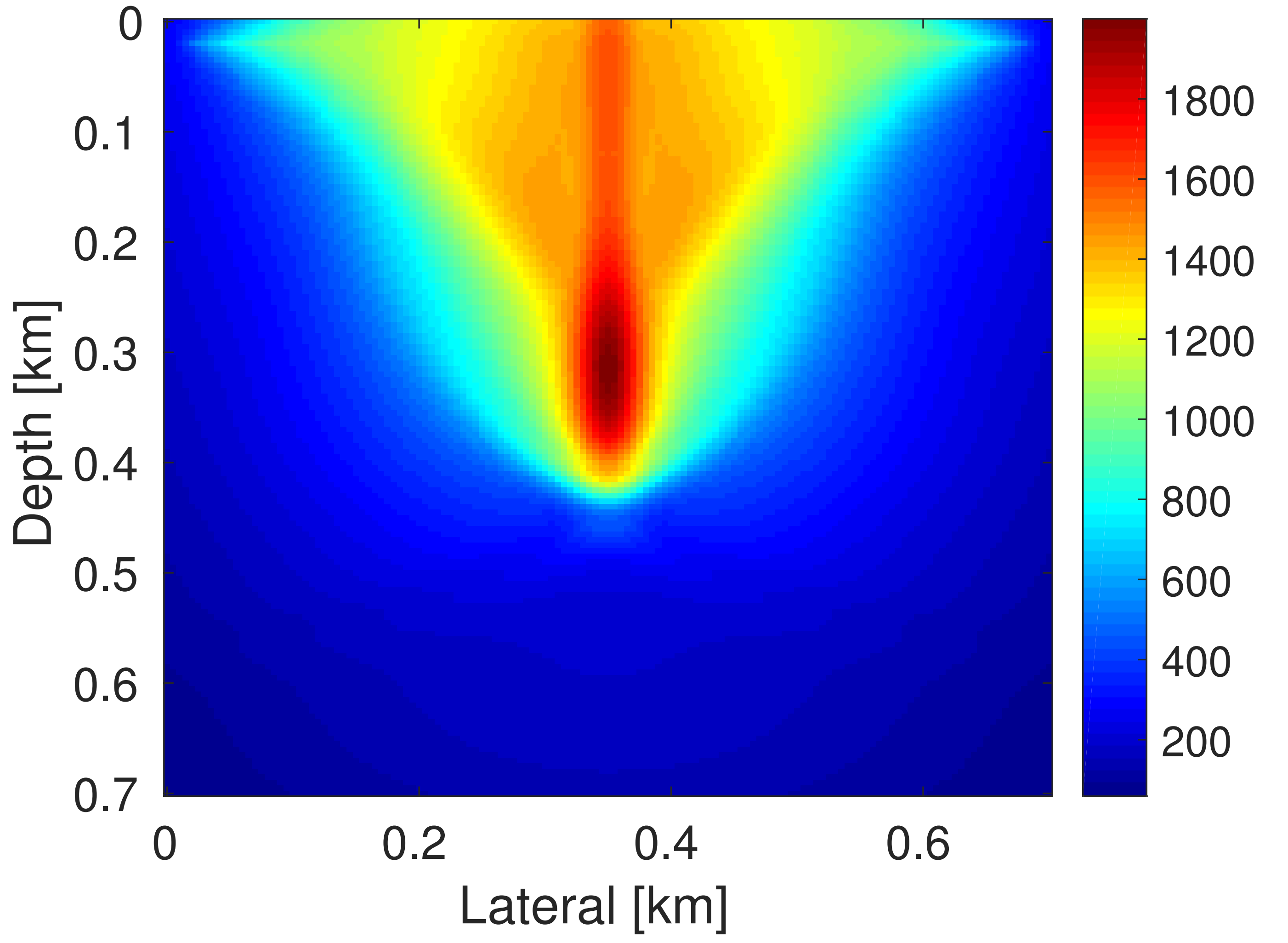
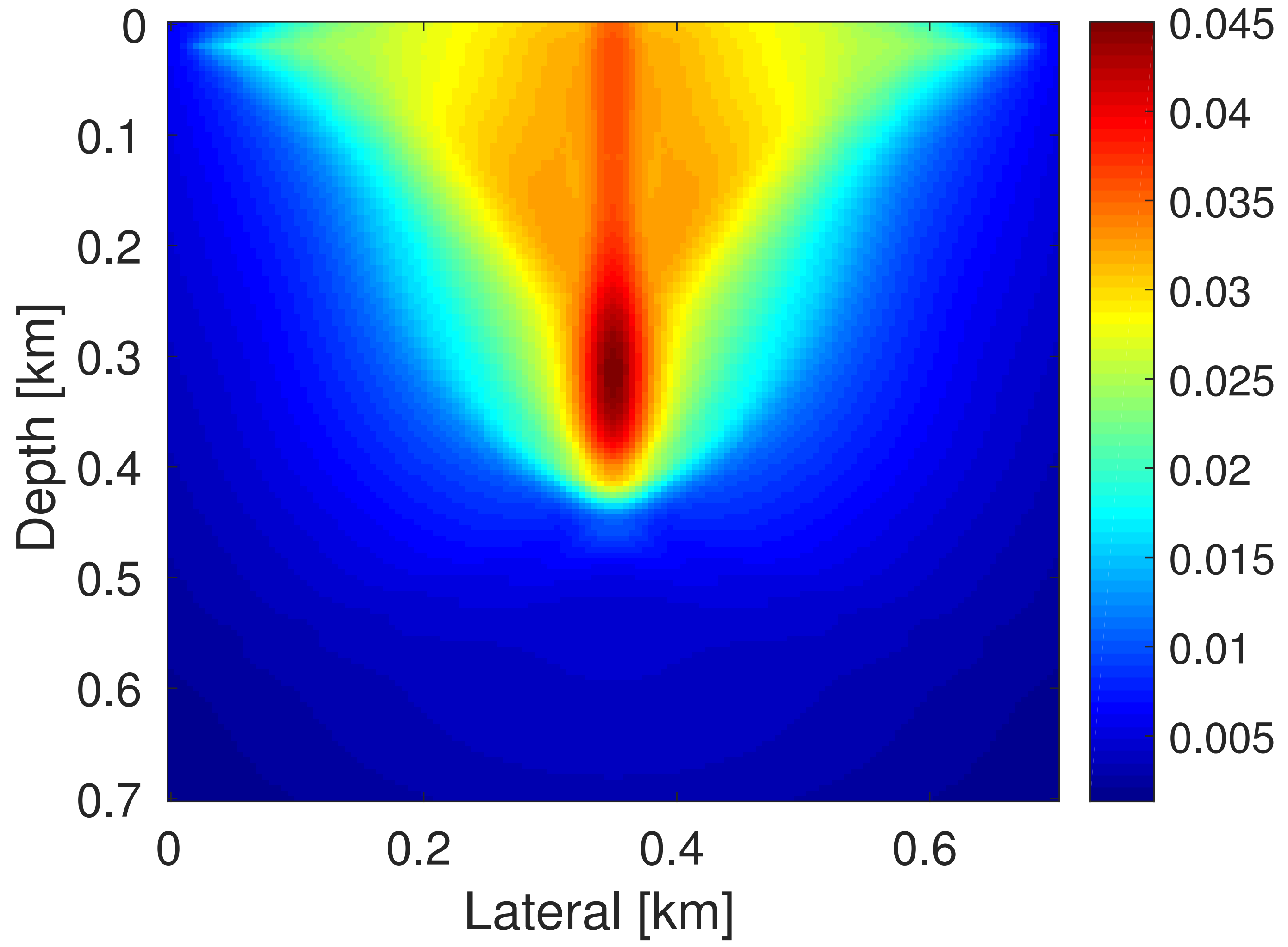
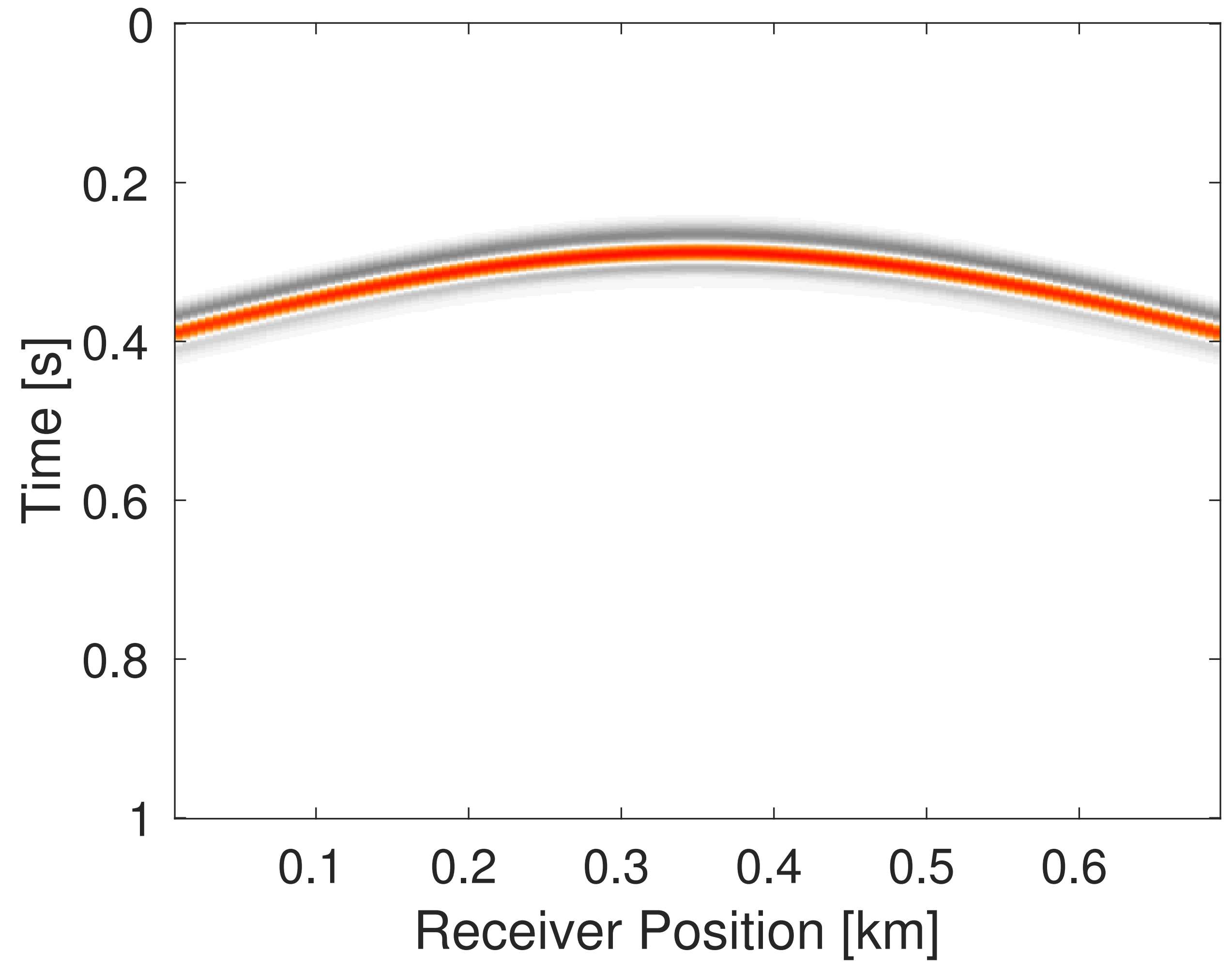


Auxiliary variable update

$$\mathbf{Z}_1 = \mathbf{Z}_0 - t_1\mathbf{V}_1$$





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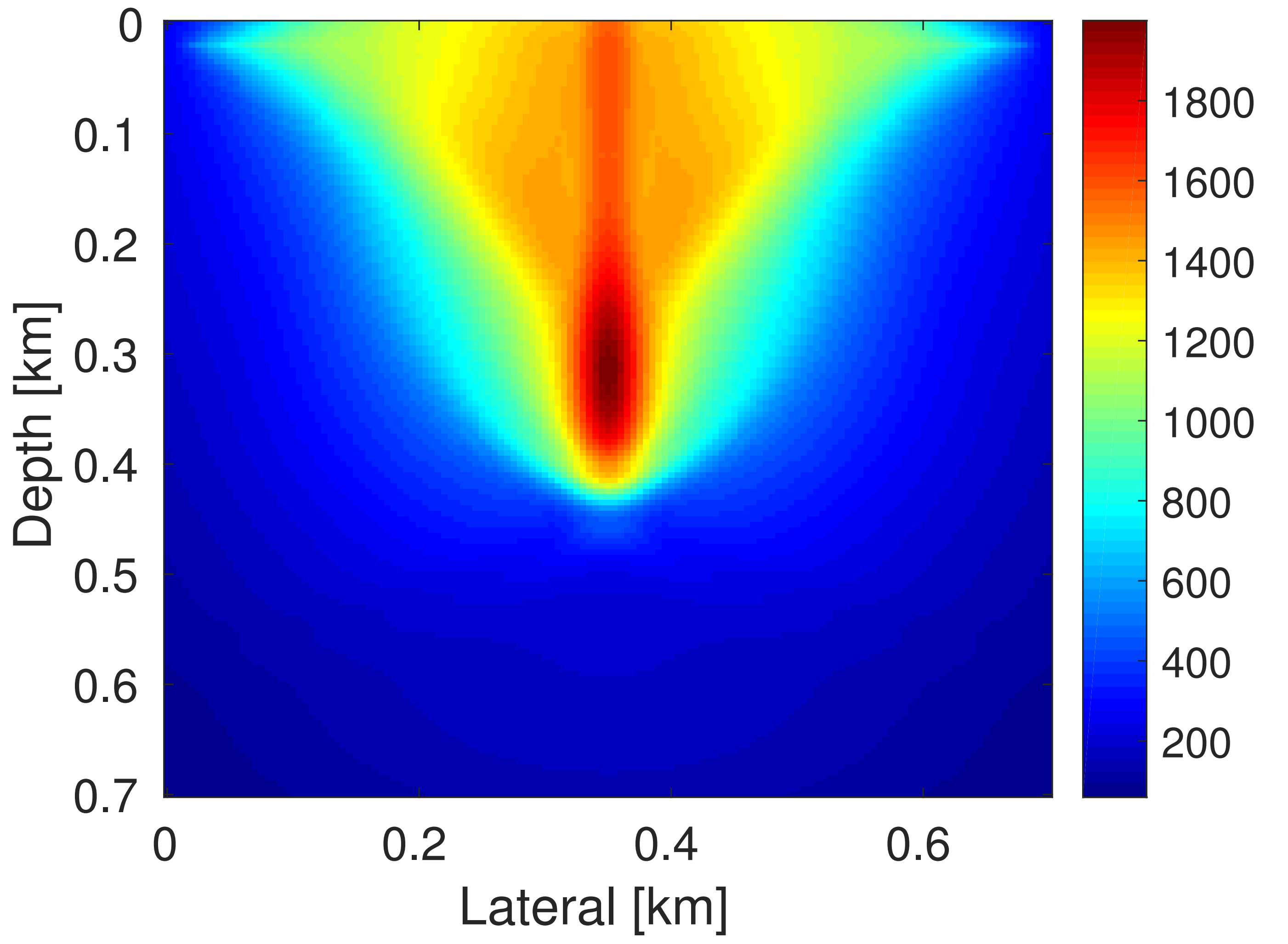

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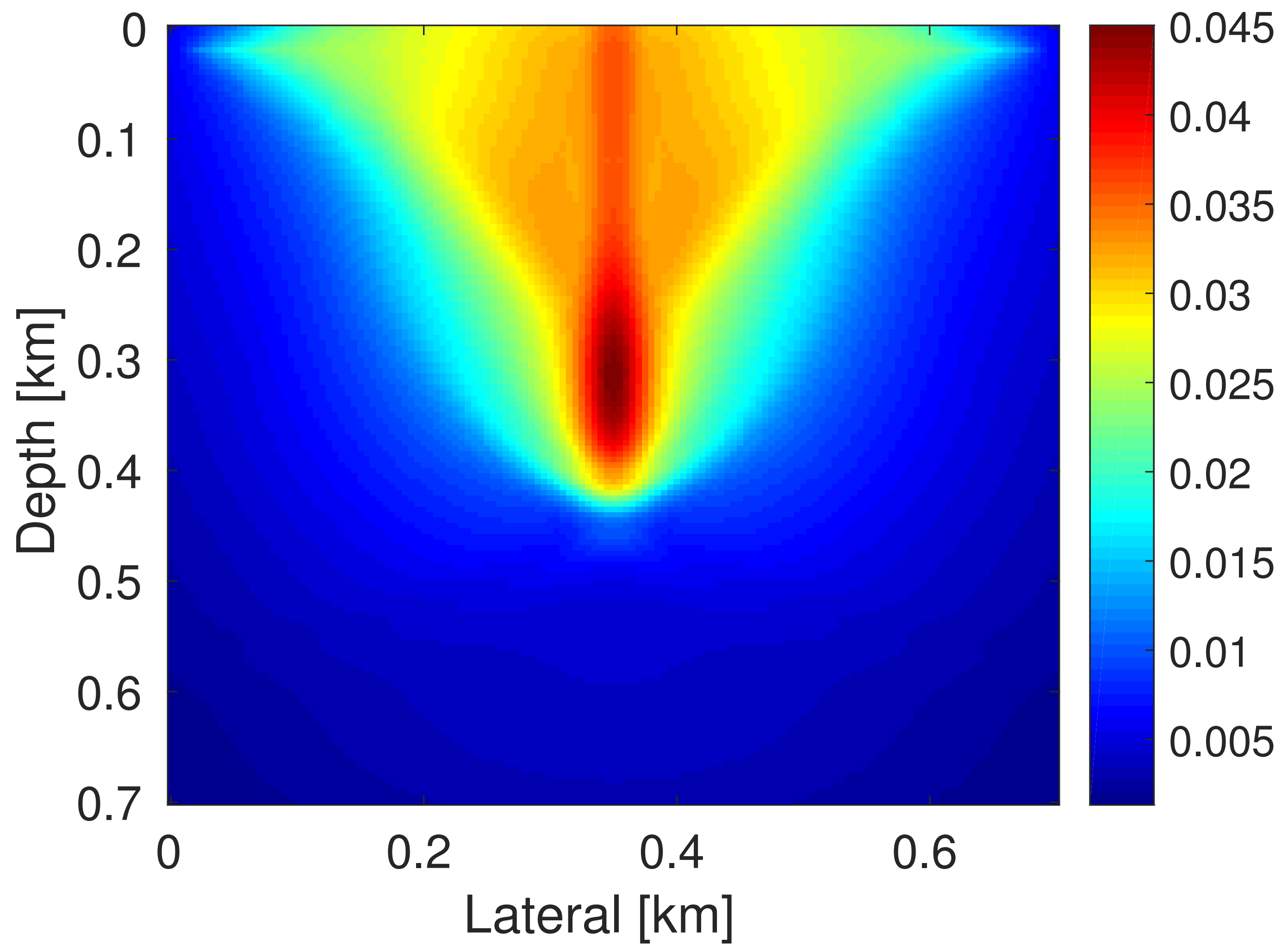
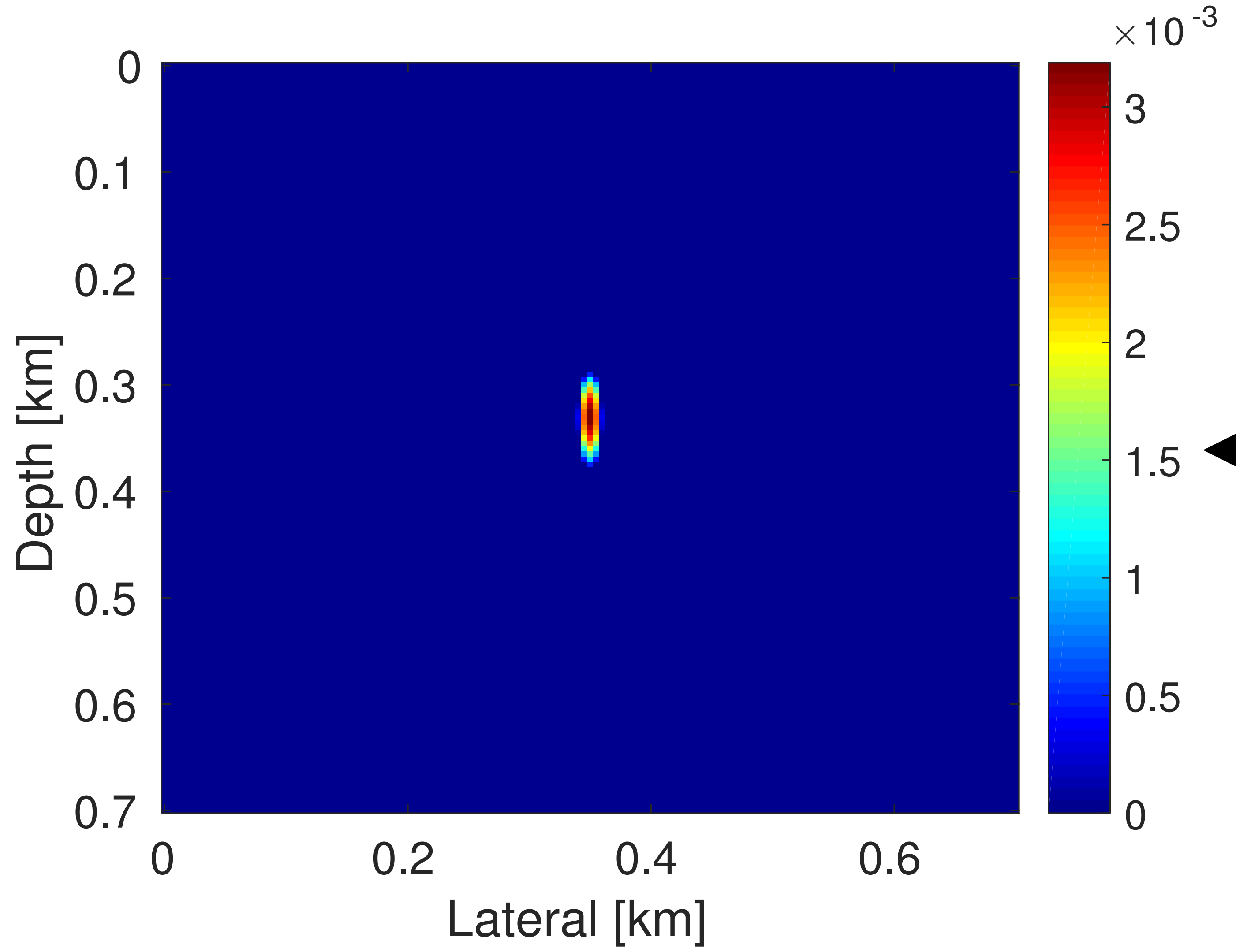
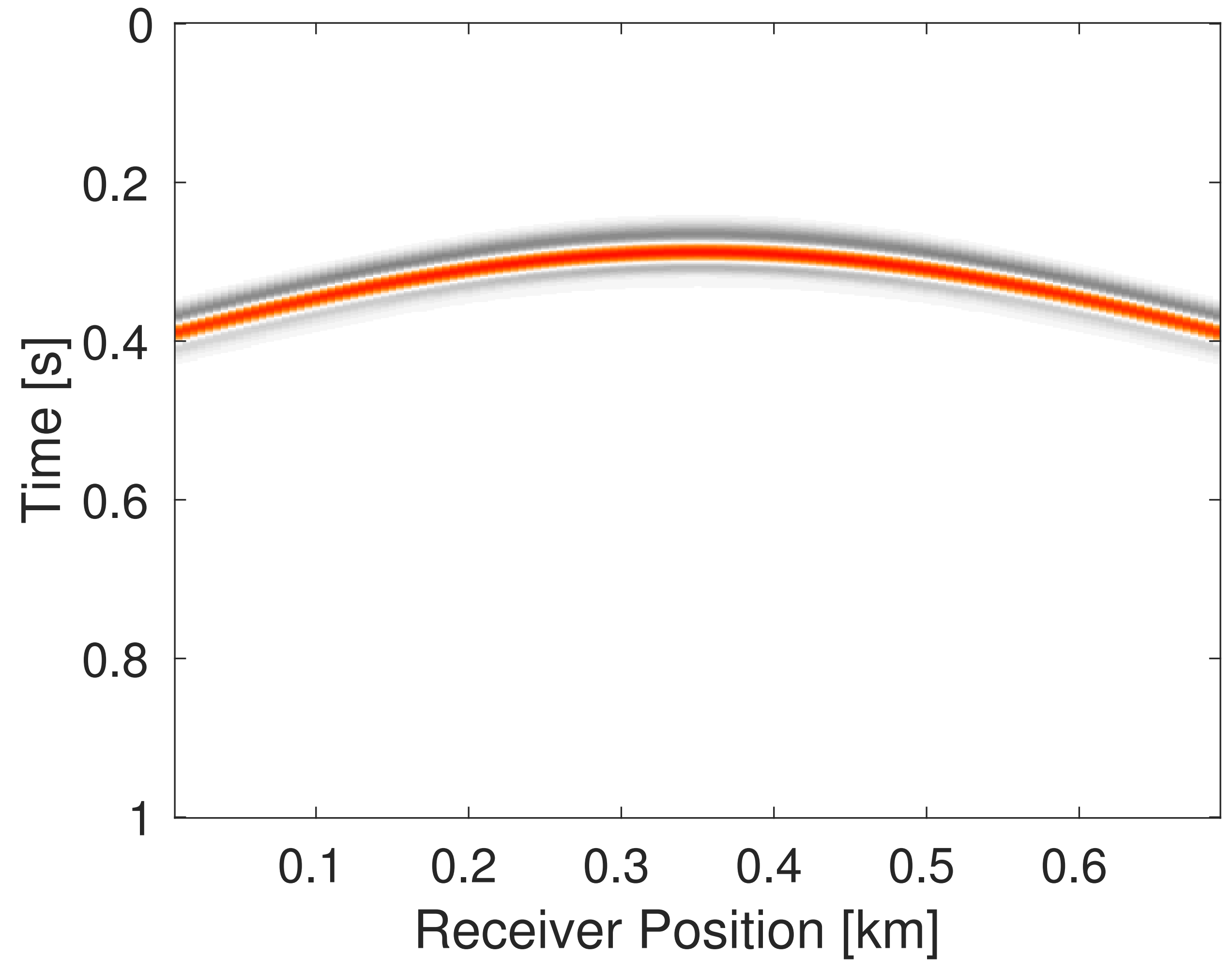
$$\mathbf{Z}_1 = \mathbf{Z}_0 - t_1\mathbf{V}_1$$



$$\mathbf{Q}_1 = \mathrm{Prox}_{\lambda\|.\|_{2,1}}(\mathbf{Z}_1)$$

Sparsity promotion





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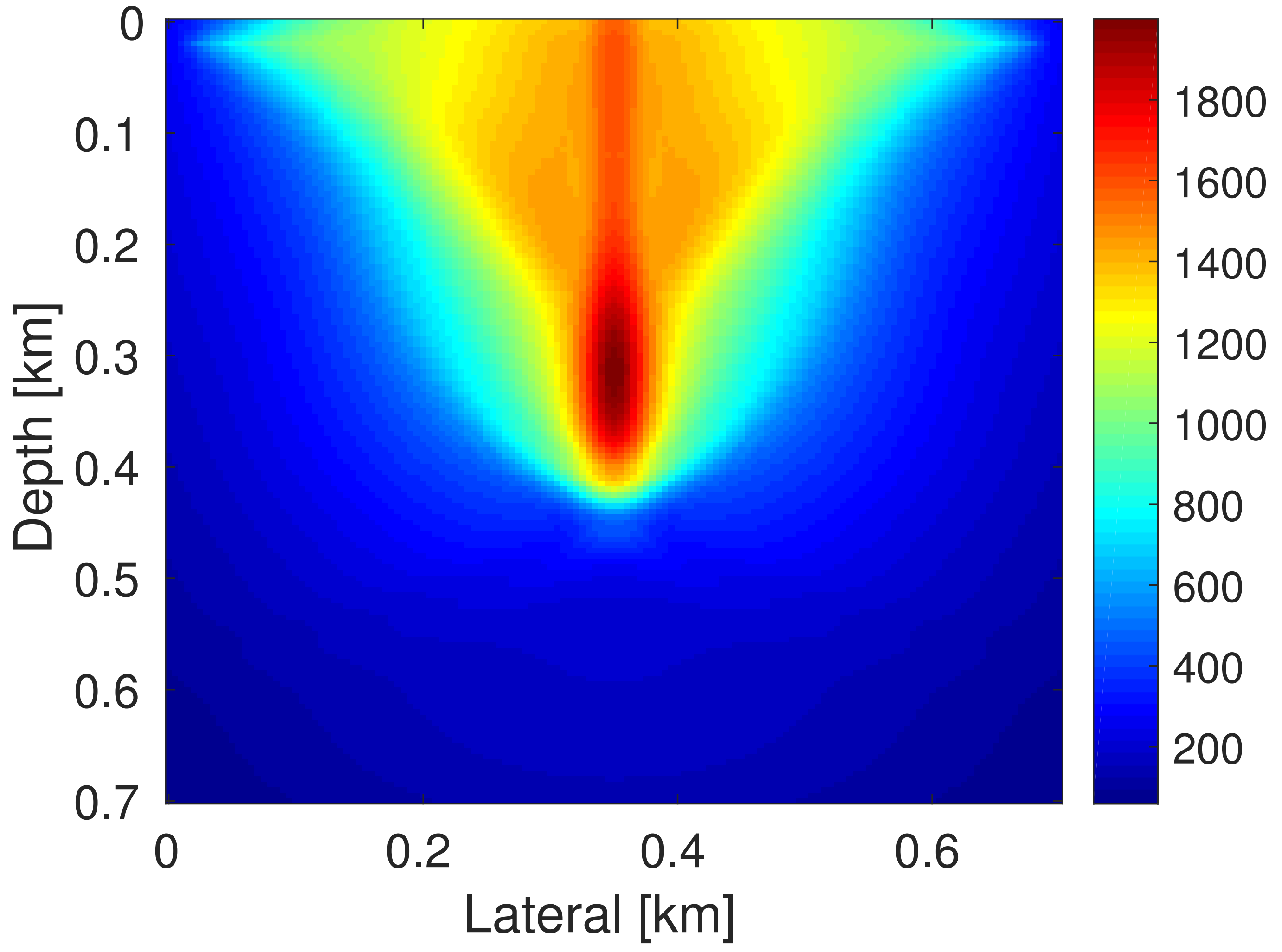
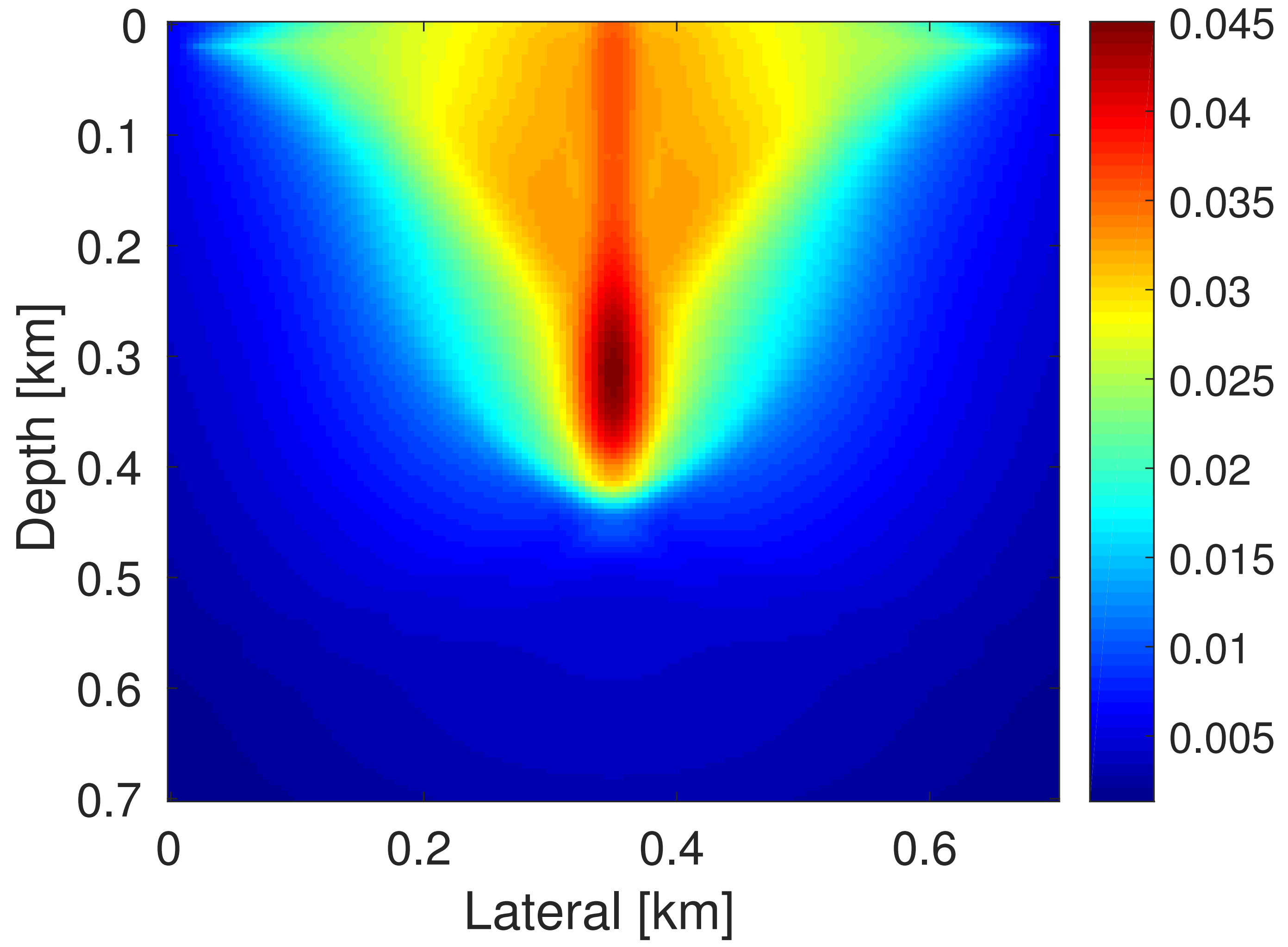
Adjoint solve



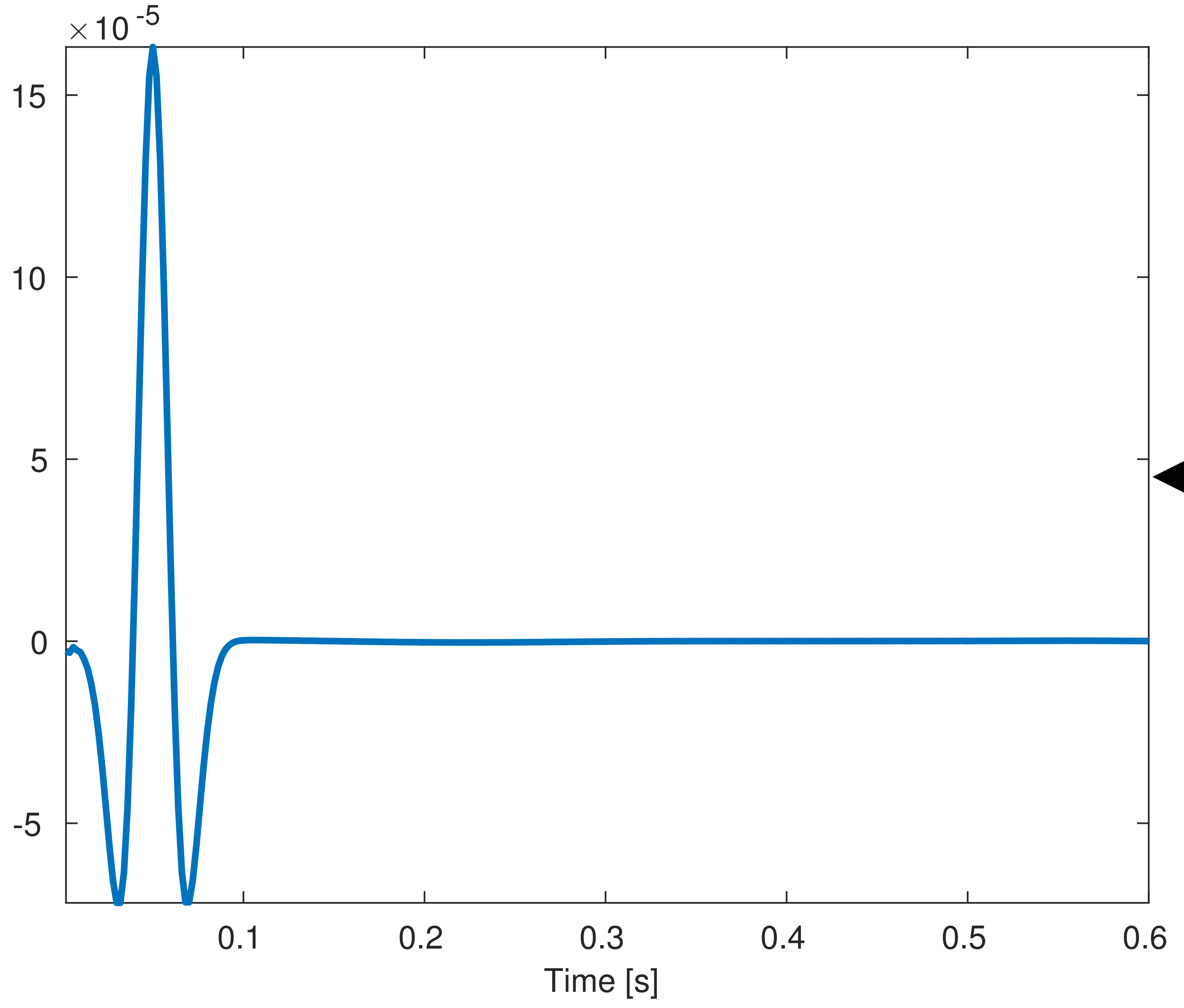
Auxiliary variable update

$$\mathbf{Z}_1 = \mathbf{Z}_0 - t_1 \mathbf{V}_1$$



$$\mathbf{Q}_1 = \mathrm{Prox}_{\lambda\|.\|_{2,1}}(\mathbf{Z}_1)$$

Sparsity promotion



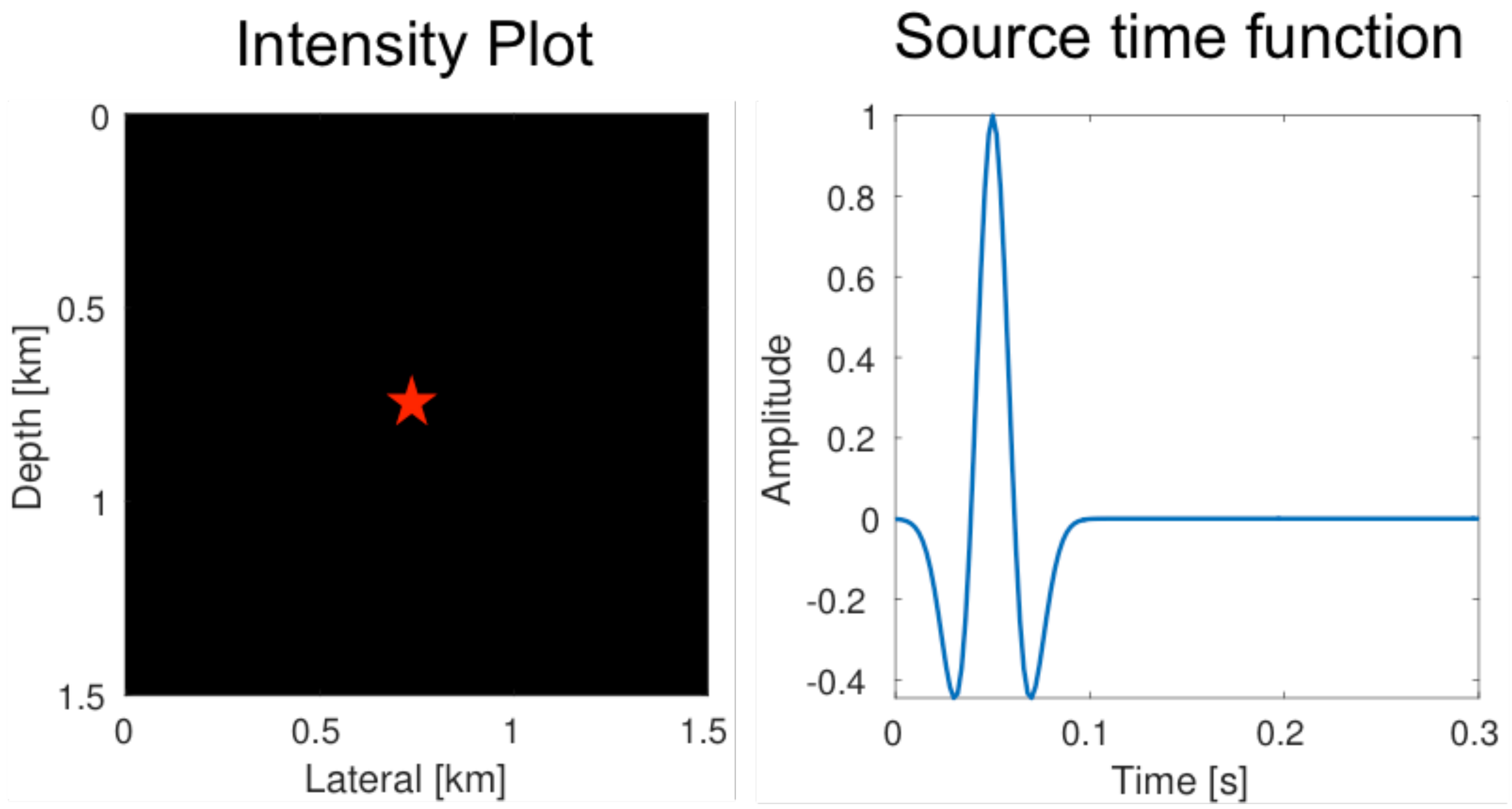
Location and source time function estimation

Source location: estimated as outlier in intensity plot

$$I(\mathbf{x}) = \sum_t |\ \mathbf{Q}(\mathbf{x}, t)\ |$$

Source time function: temporal variation of wavefield at estimated source location

Source location & source time function



Schematic showing source location as outlier and corresponding source time function

Case study

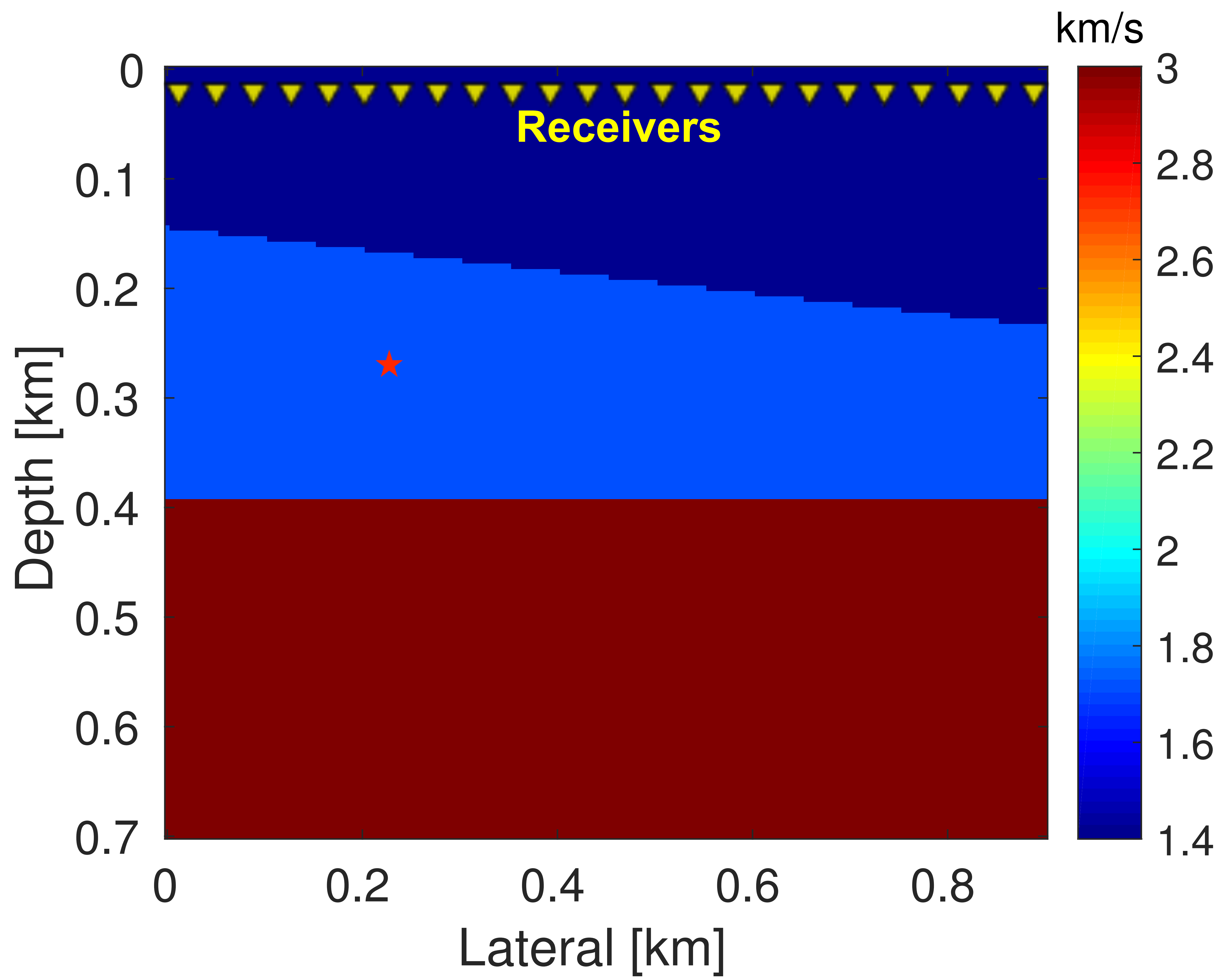
Case study 1: True velocity experiment

Assumptions:

- access to true velocity model
- noise-free data

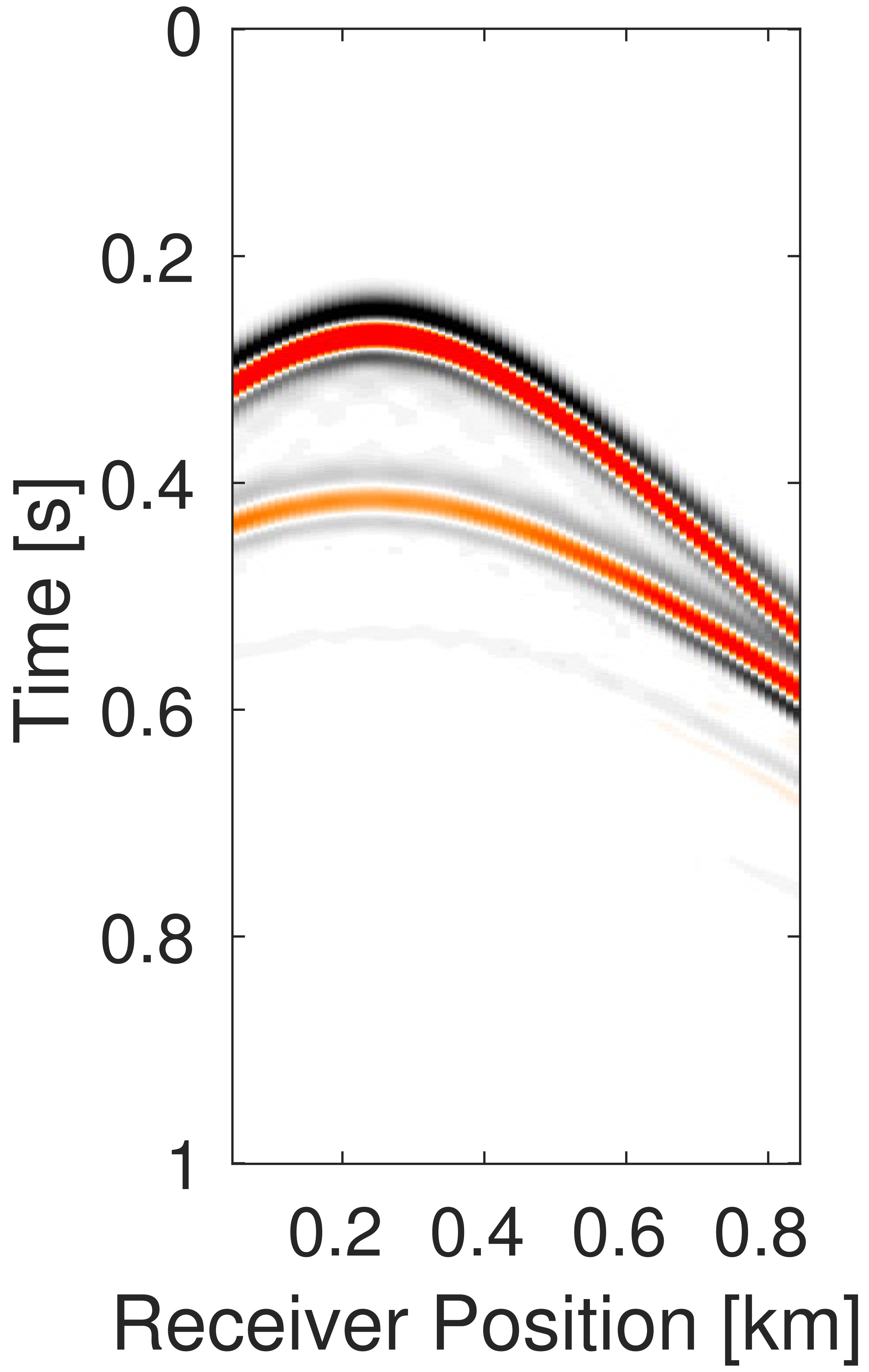
Both can be relaxed...

Experimental setup



Modeling information:

Model size: 0.9 km x 0.7 km
Grid spacing: 10m
Receiver spacing: 10m
Source depth: 0.27 km
Source lateral position: 0.25 km
Wavelet: Ricker wavelet
Receiver depth: 20m
Fixed spread: 0.88km
Sampling interval: 1 ms
Recording length: 1s
Peak frequency : 20 Hz

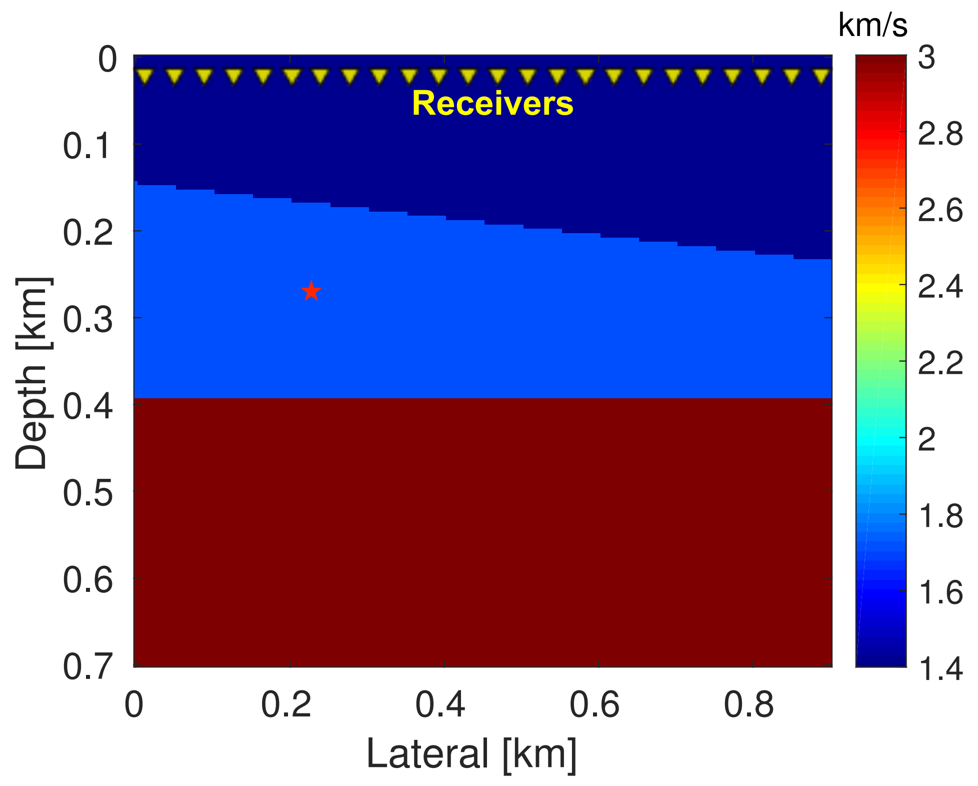


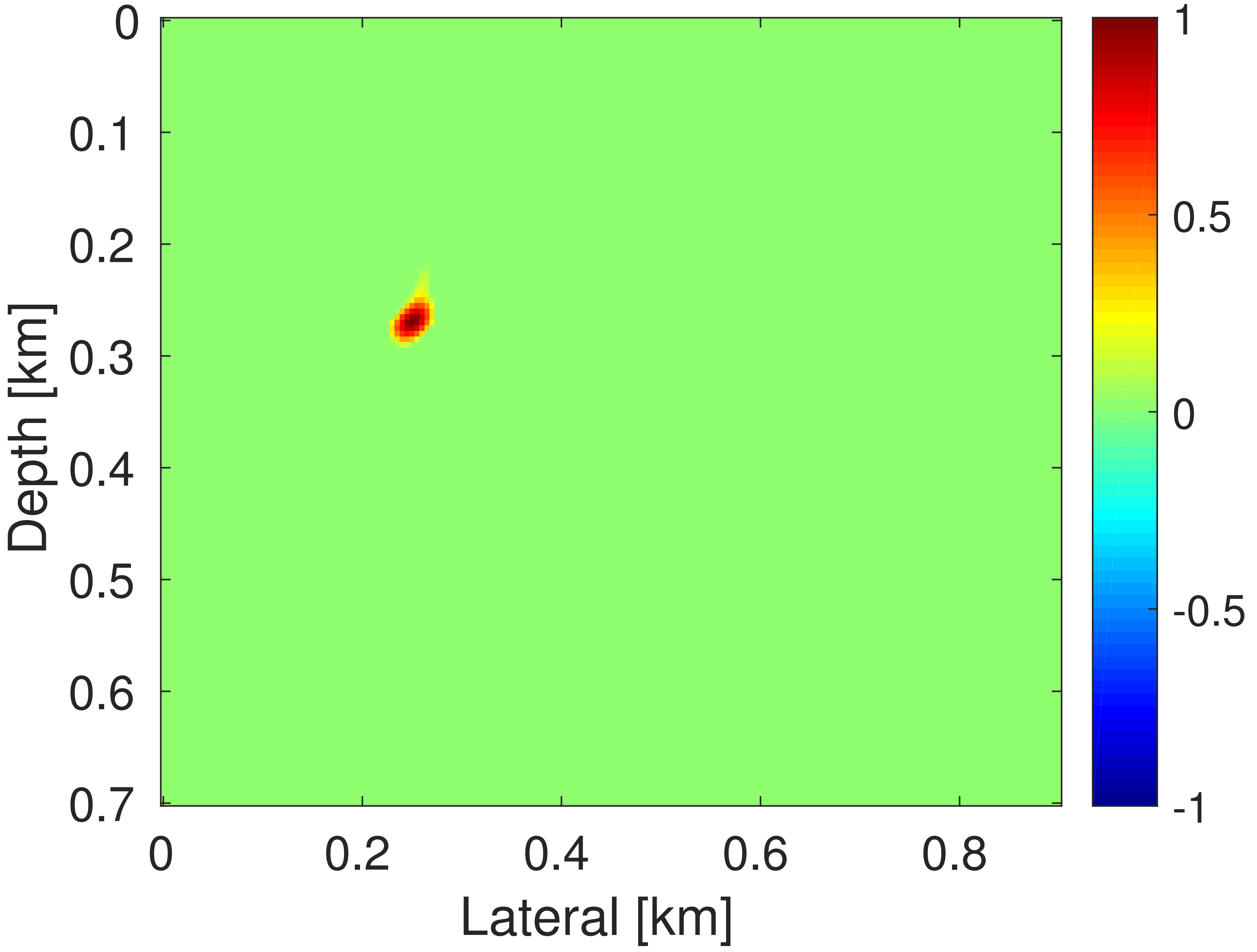
Synthetic microseismic data

Data is simulated using finite difference time stepping code

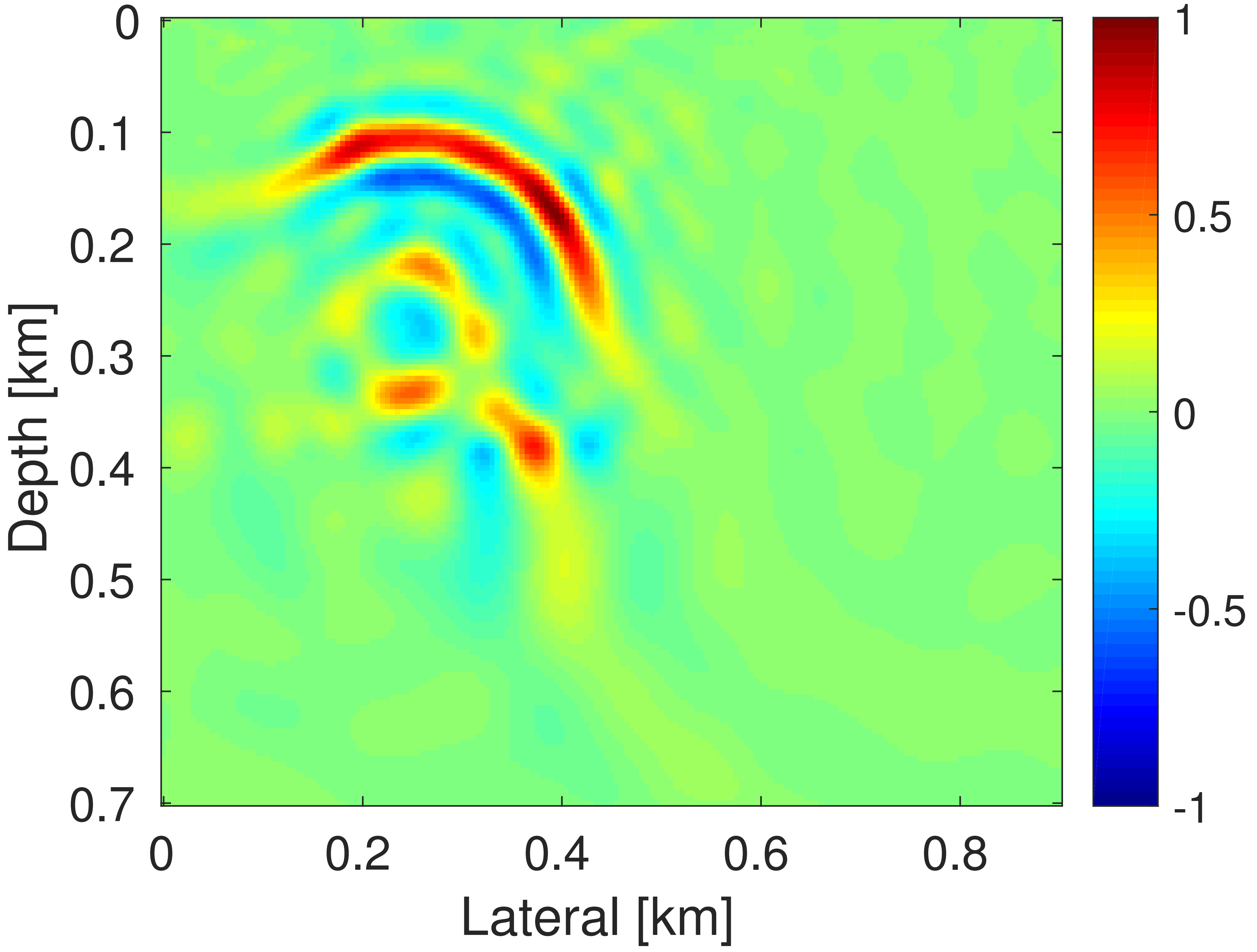
Kaderli et al.,'15

Estimated source location





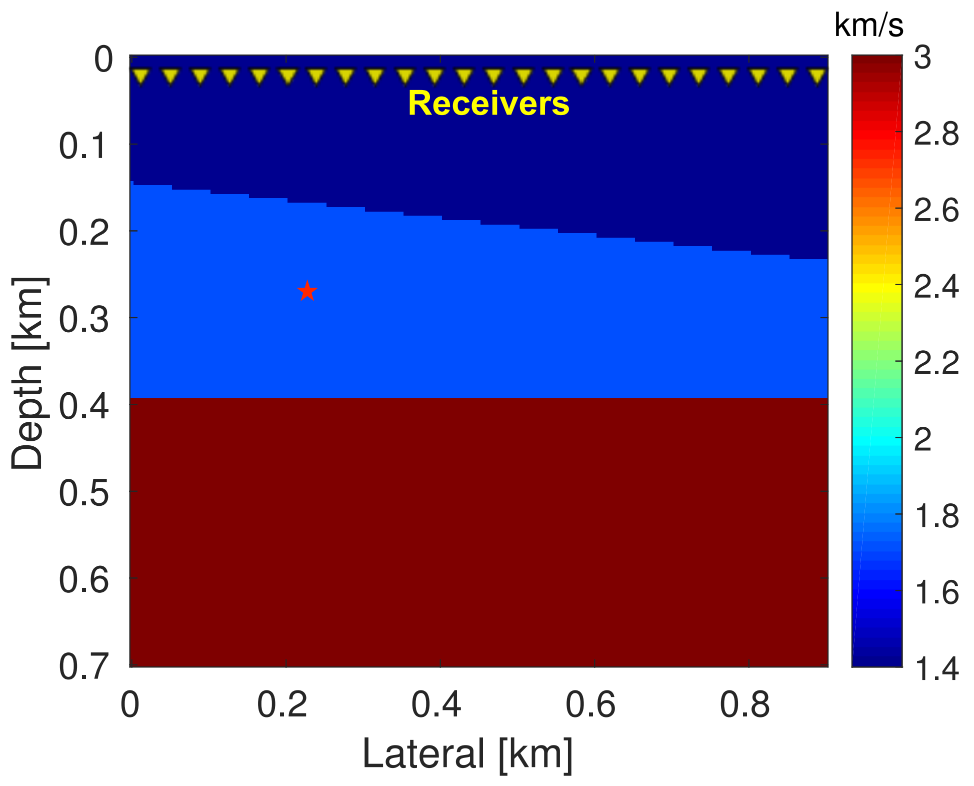
Sparsity-promoting method

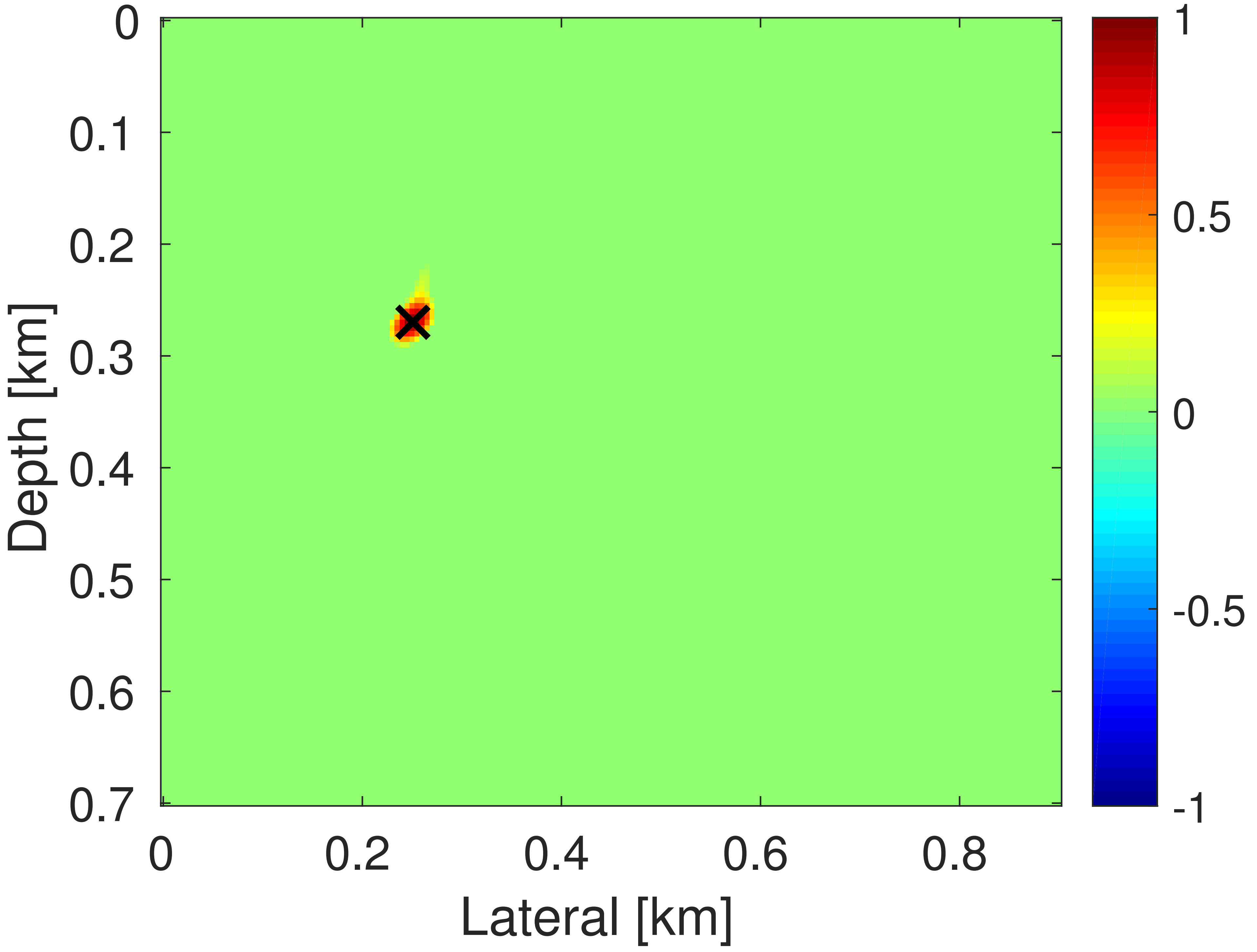


FWI

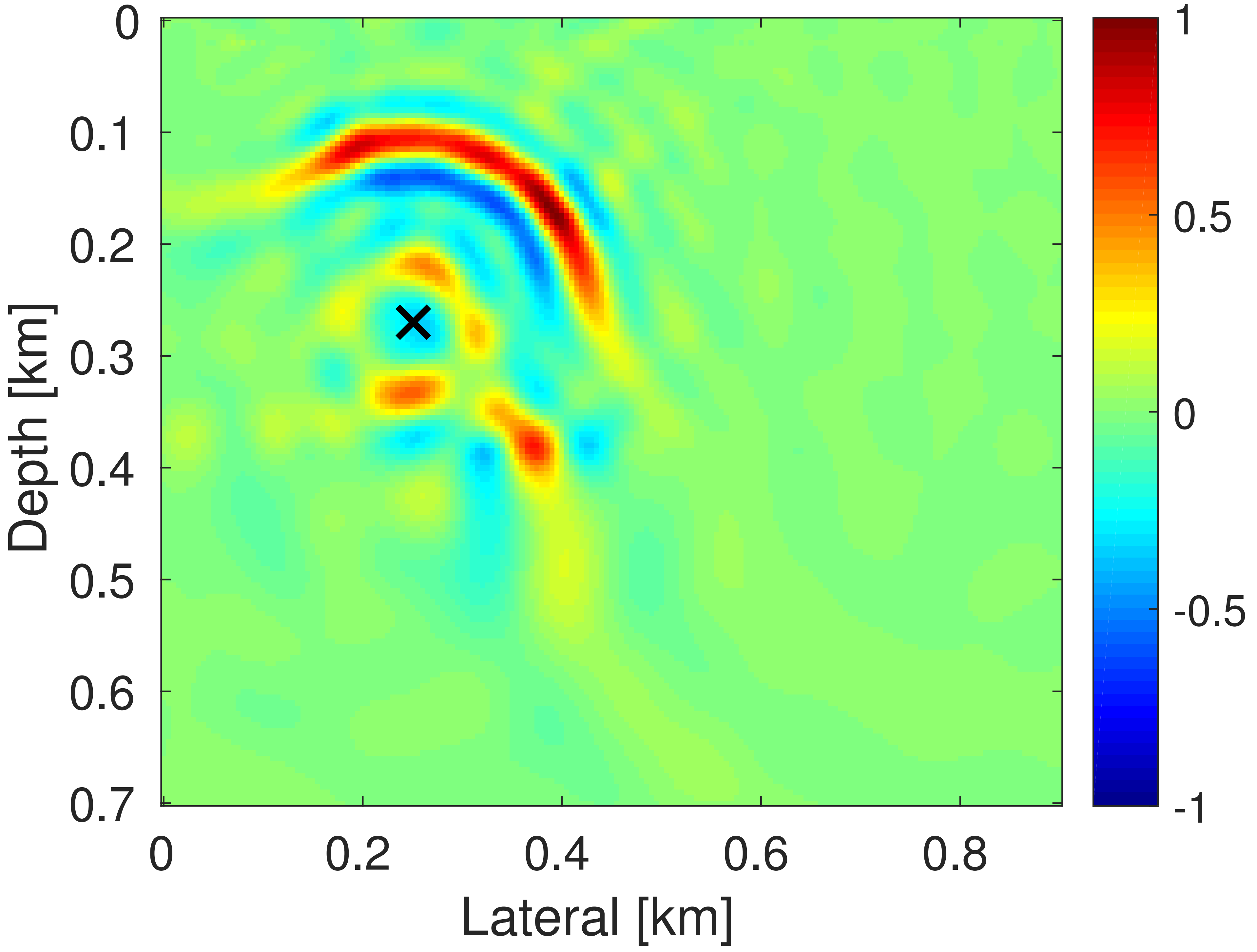
Kaderli et al.,'15

Estimated source location



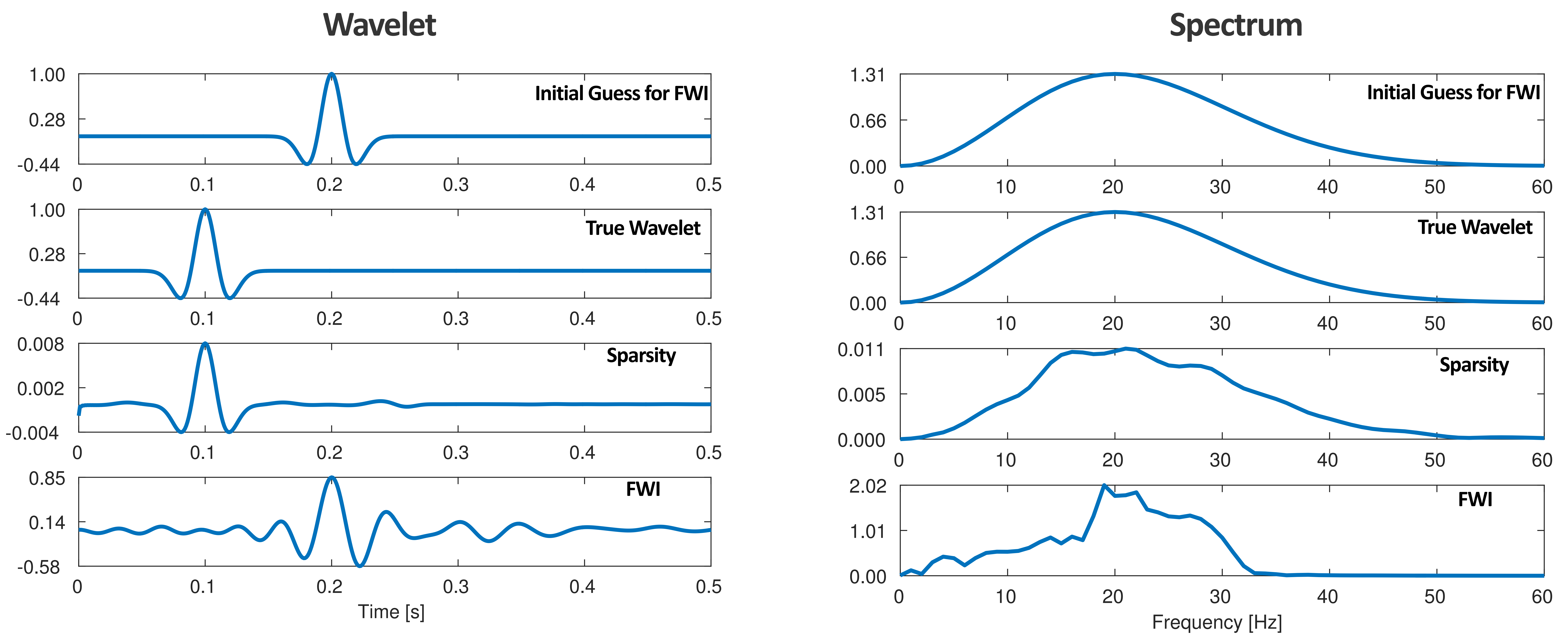


Sparsity-promoting method



FWI

Wavelet comparison



Case study 2: Multiple source experiment

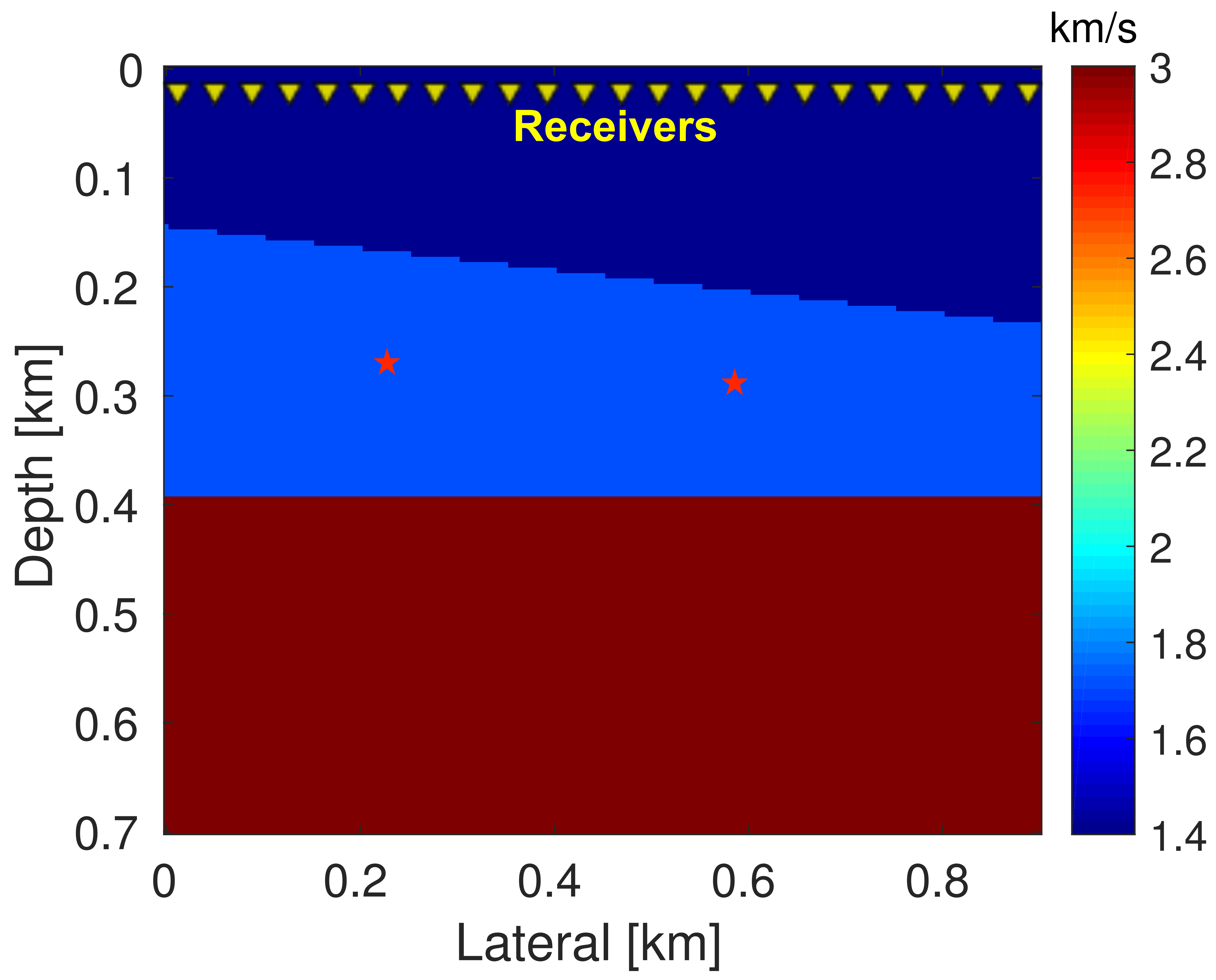
Assumptions:

- access to smooth background velocity model
- noisy data (bandwidth limited random noise up to 45 Hz)

Sources are activating at

- different source origin times
- different dominating frequencies

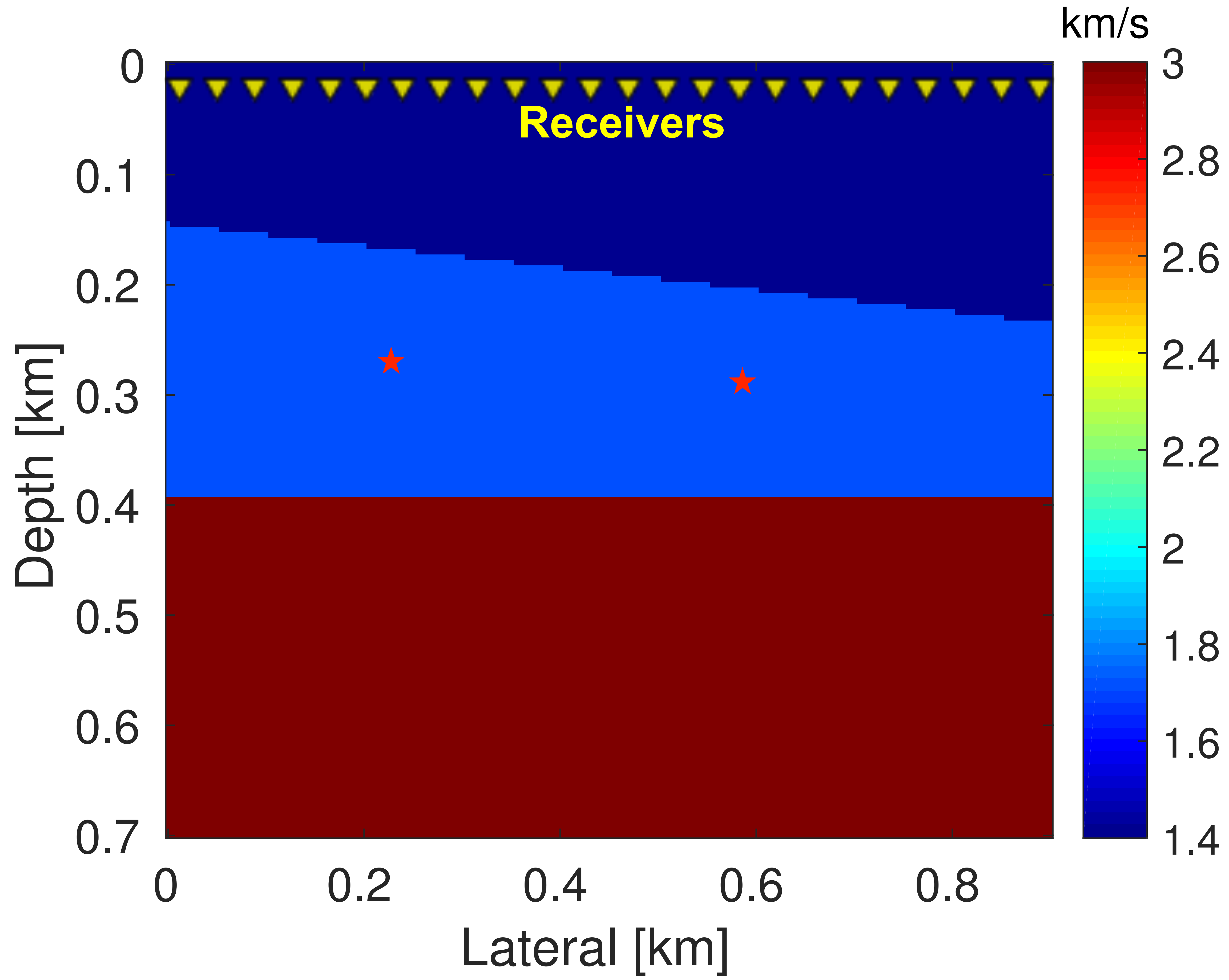
Experimental setup



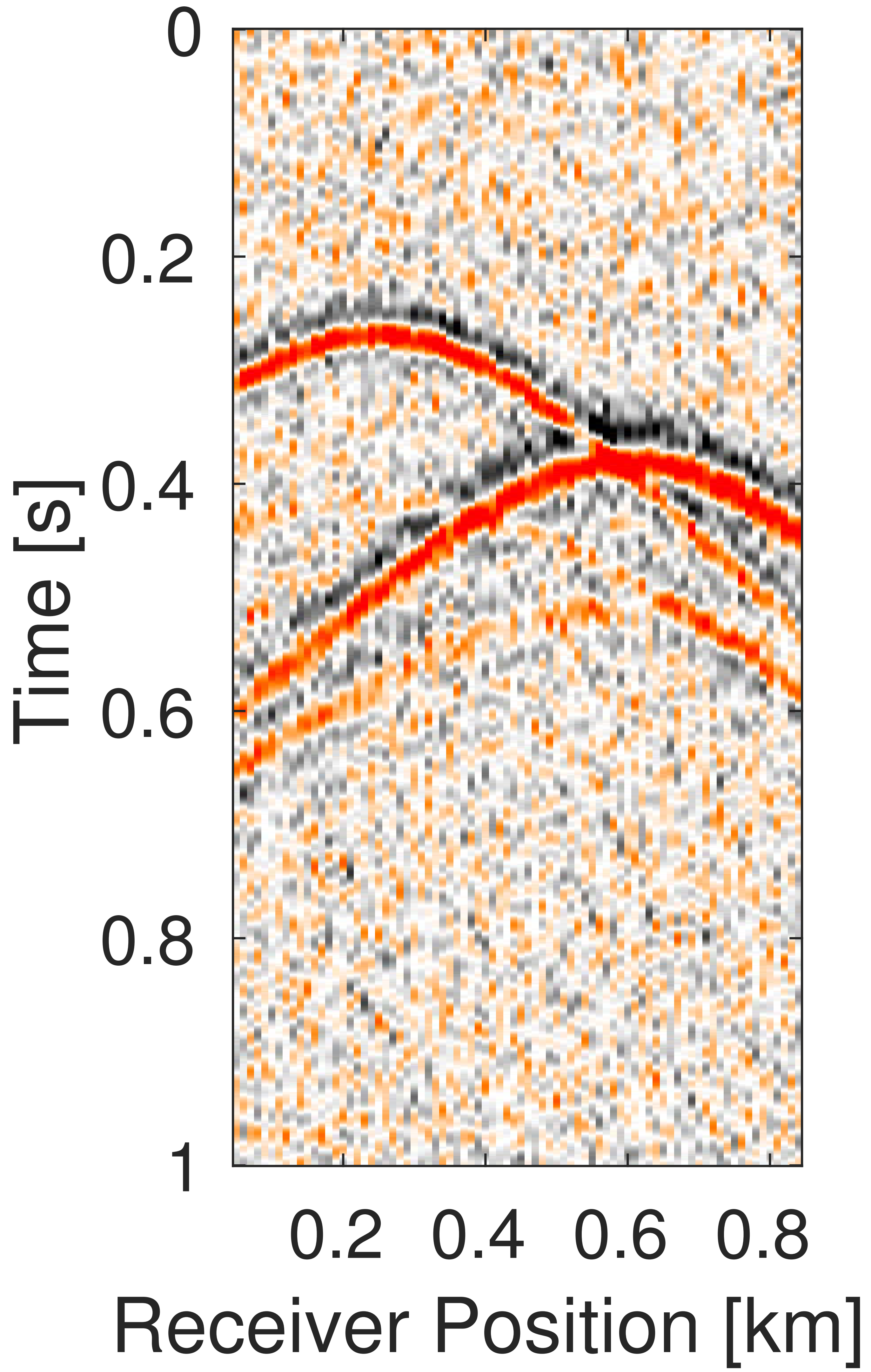
Modeling information:

Model size: 0.9 km x 0.7 km
Grid spacing: 10m
Receiver spacing: 10m
Source 1 depth: 0.27 km
Source 1 lateral position: 0.25 km
Source 2 depth: 0.60 km
Source 2 lateral position: 0.28 km
Receiver depth: 20m
Fixed spread: 0.88km
Sampling interval: 1 ms
Recording length: 1s
Source 1 Peak frequency : 20 Hz
Source 1 Peak frequency : 15 Hz

Experimental setup



Dominant wavelength: 113 m

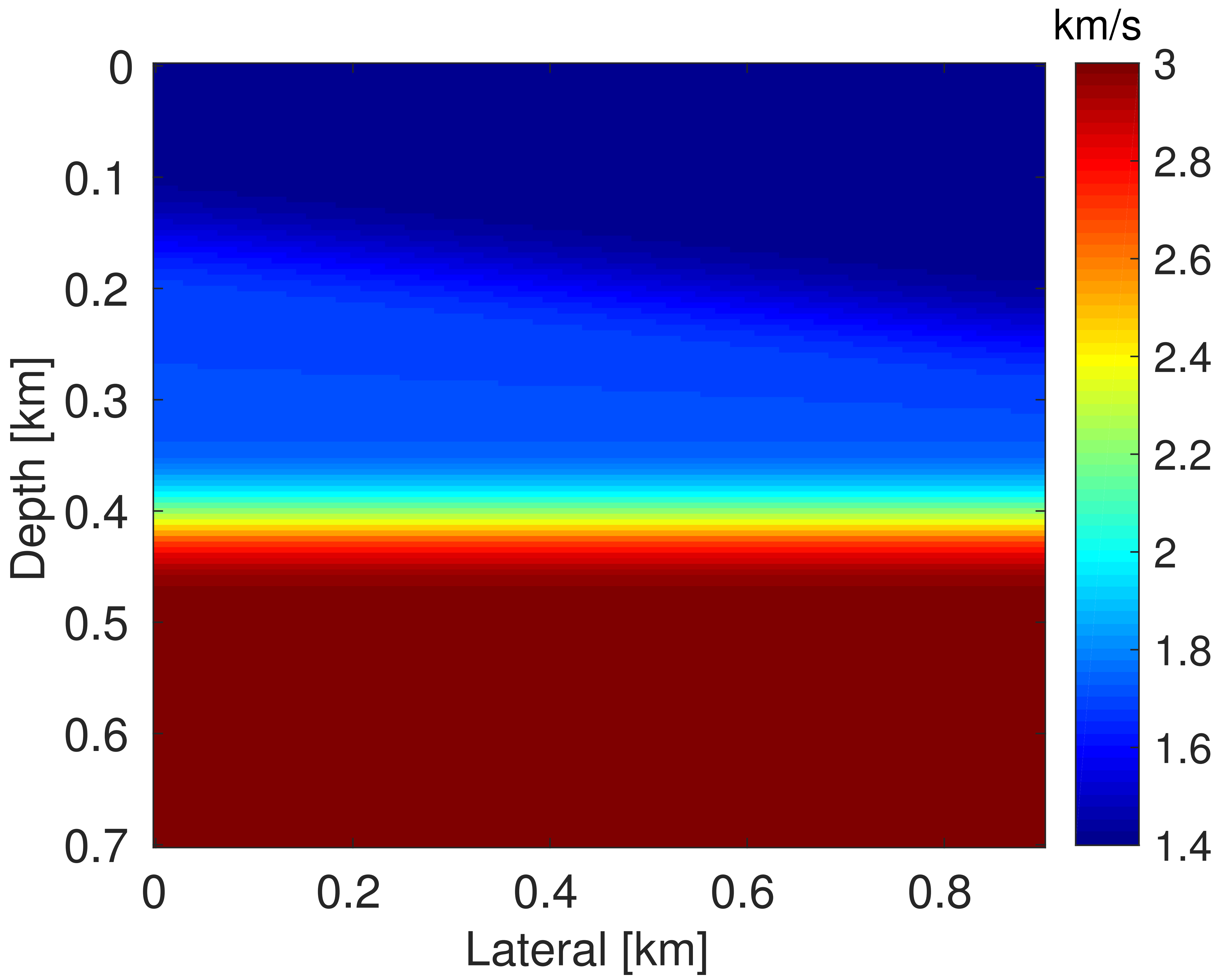


Observed microseismic data, SNR = 0.34

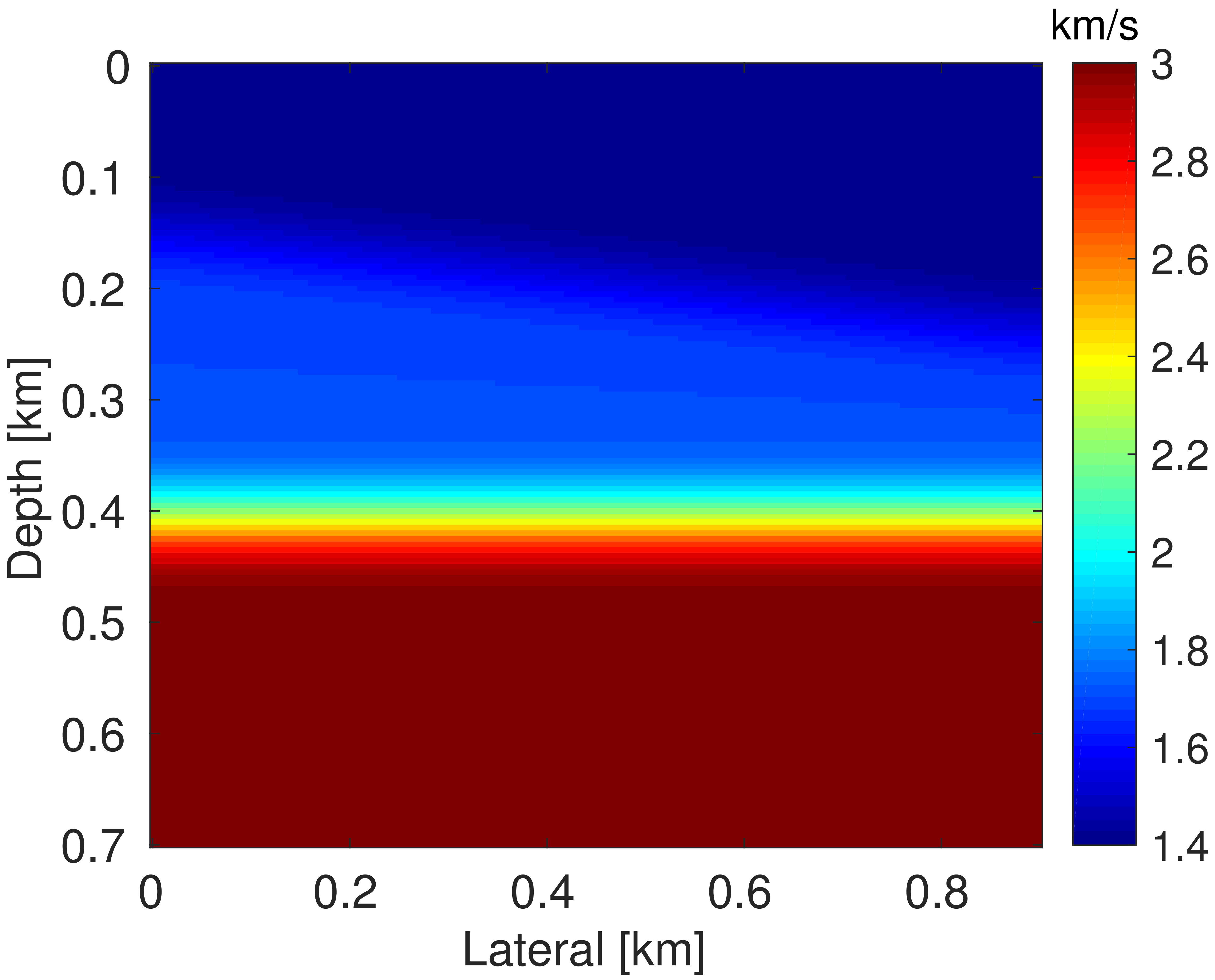
Data is simulated using finite difference time stepping code

Data is contaminated with low frequency random noise (up to 45 Hz)

Smooth velocity model

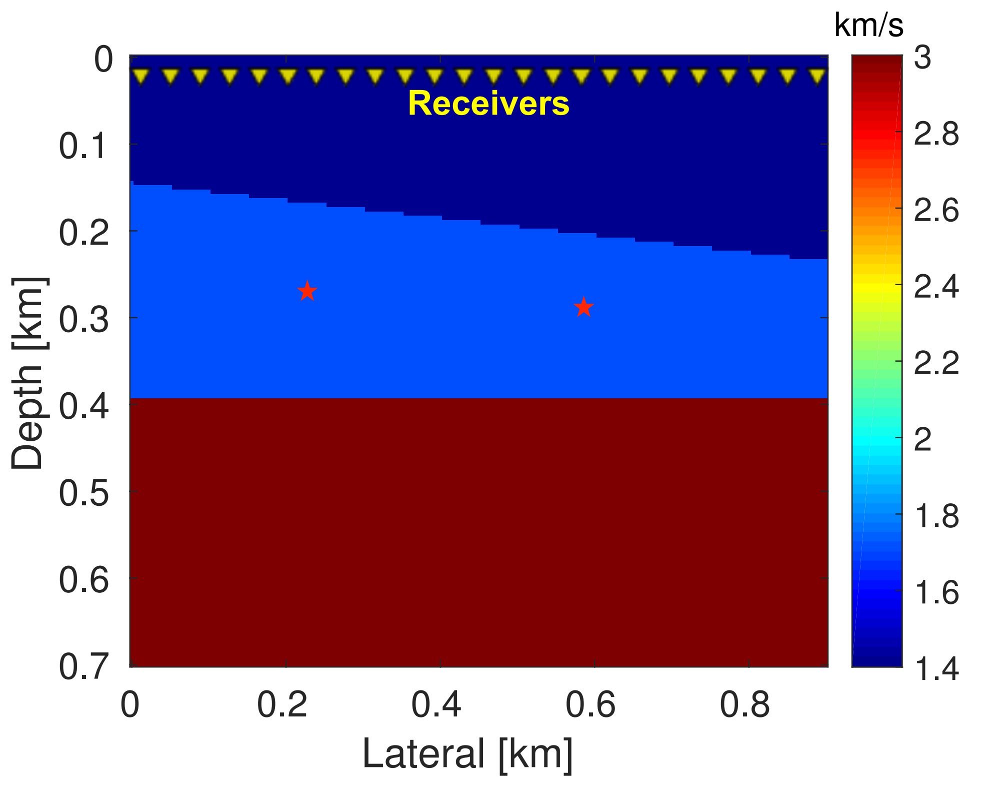


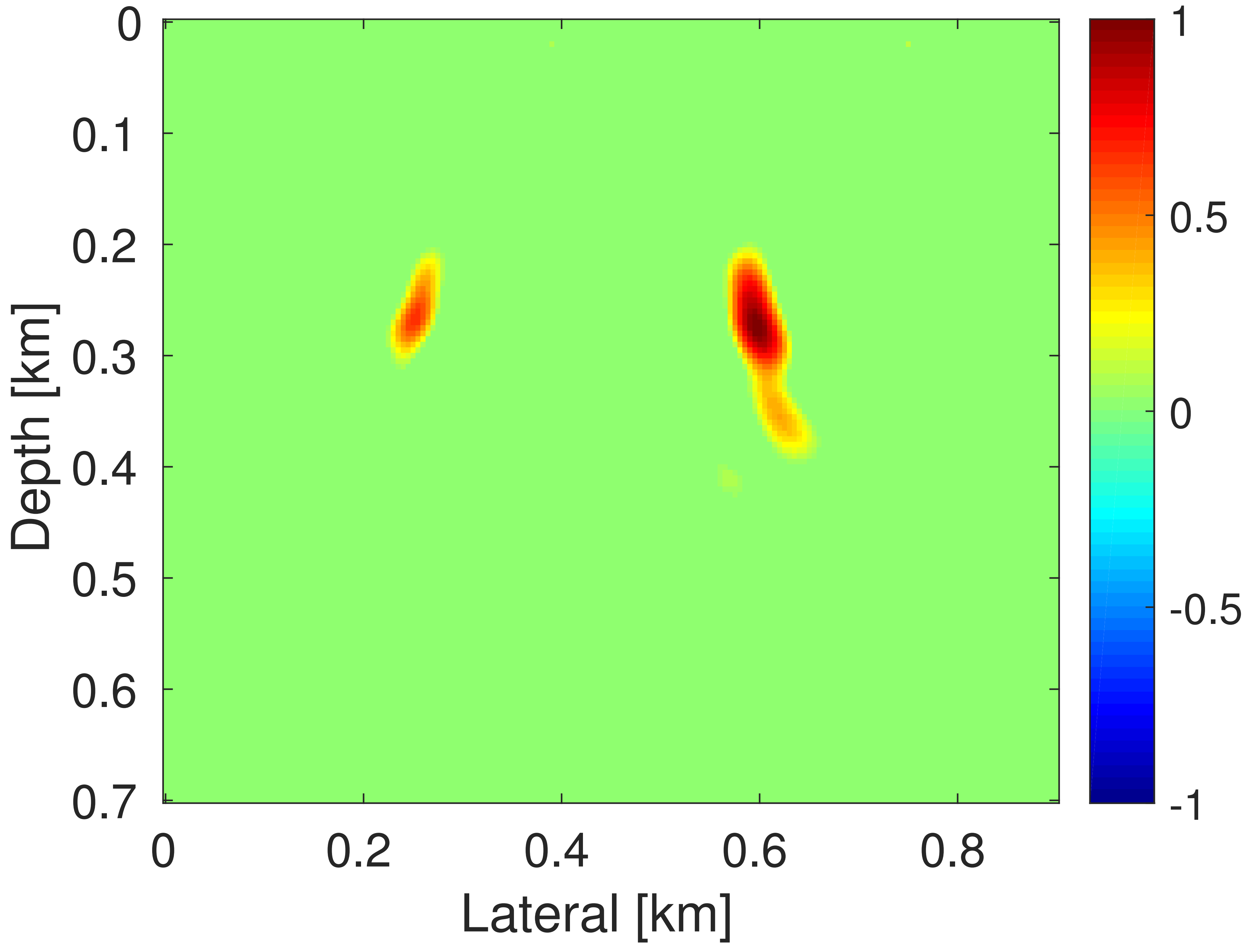
Smooth velocity model



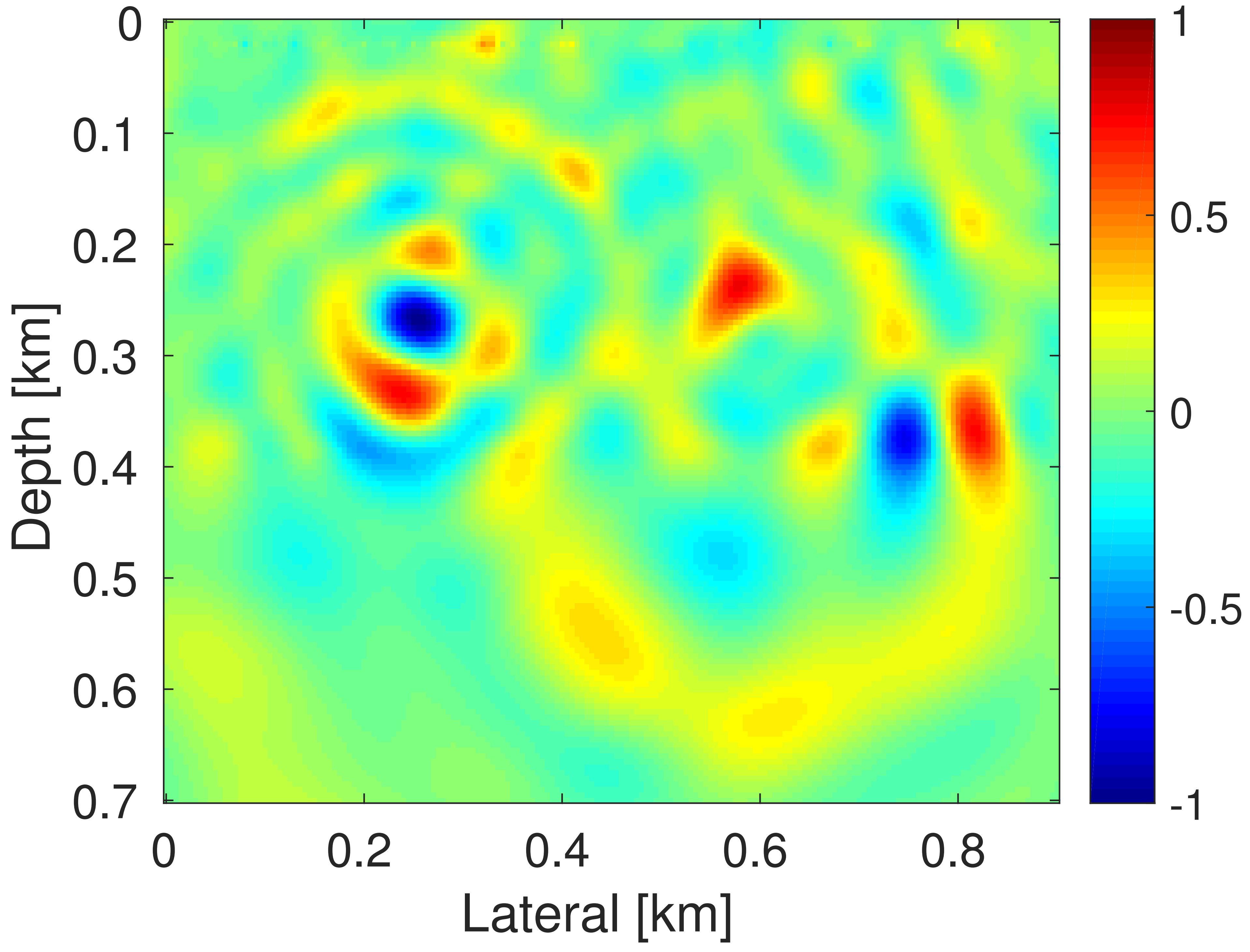
Used for joint microseismic source location & source time function estimation

Estimated source location



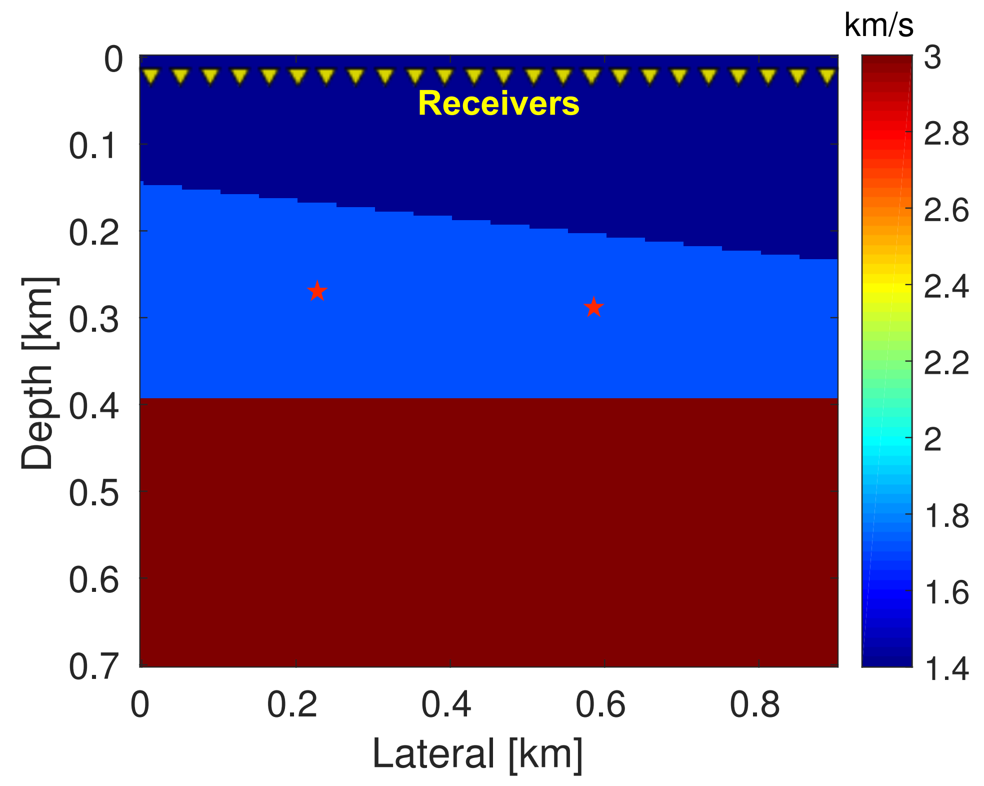


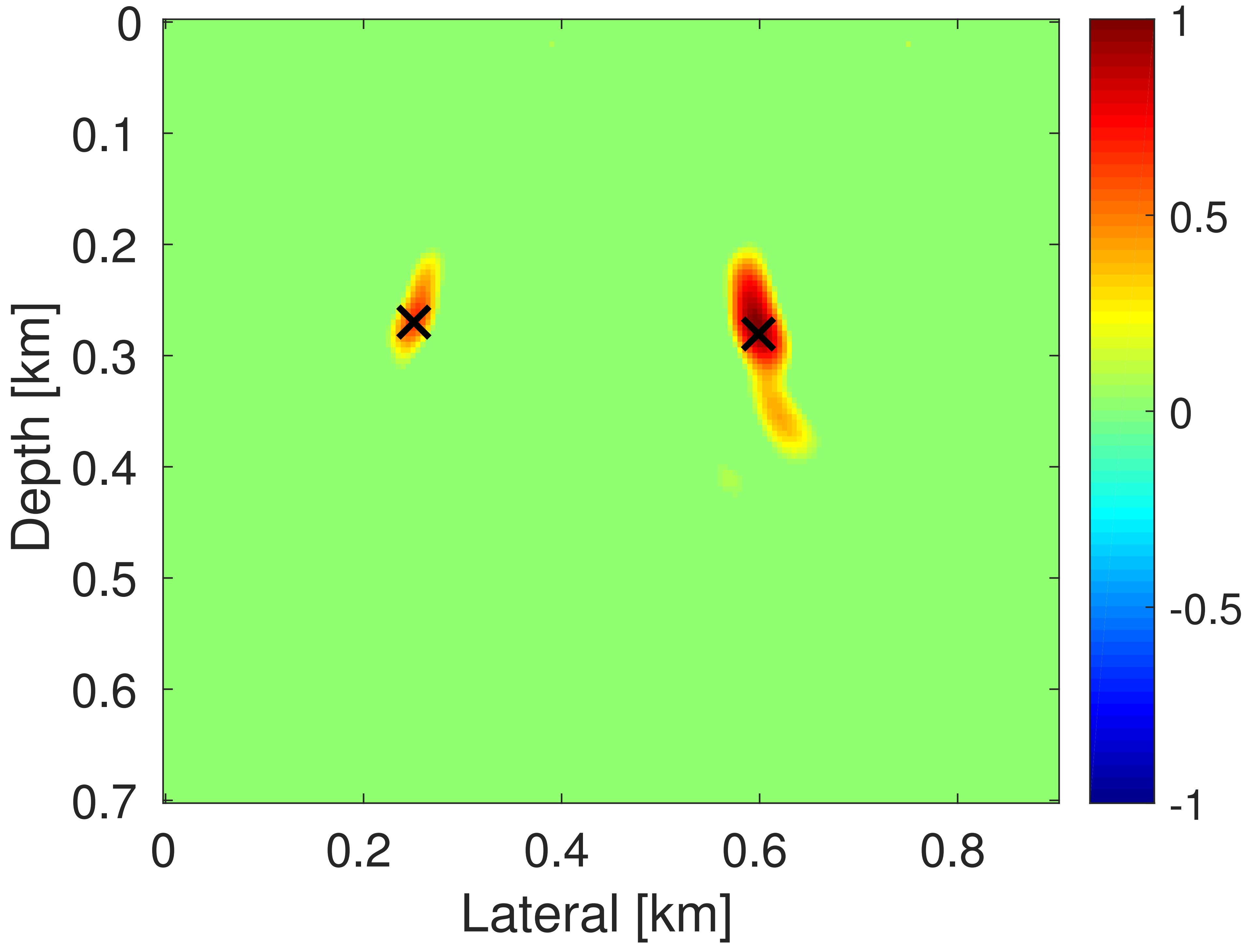
Sparsity-promoting method



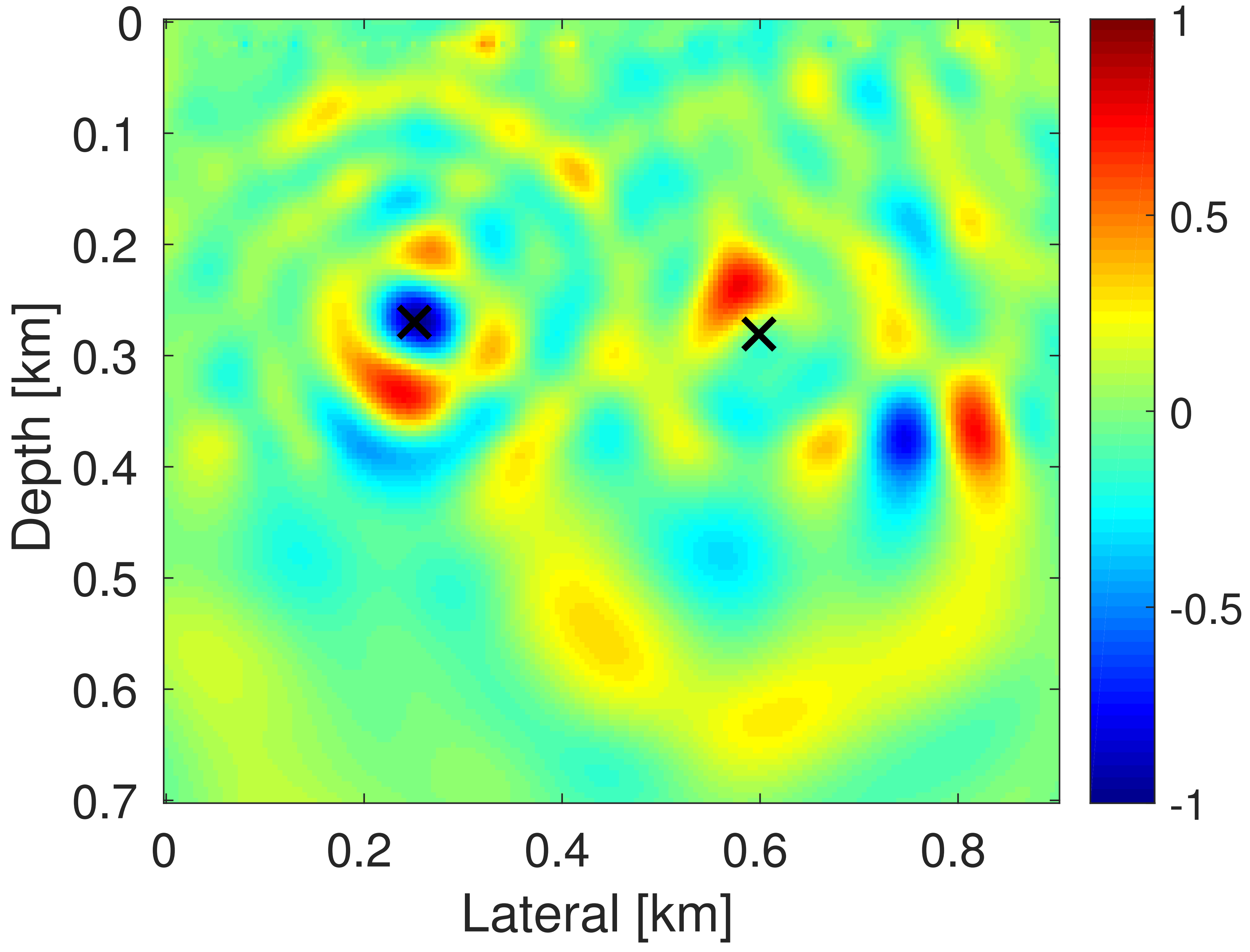
FWI

Estimated source location



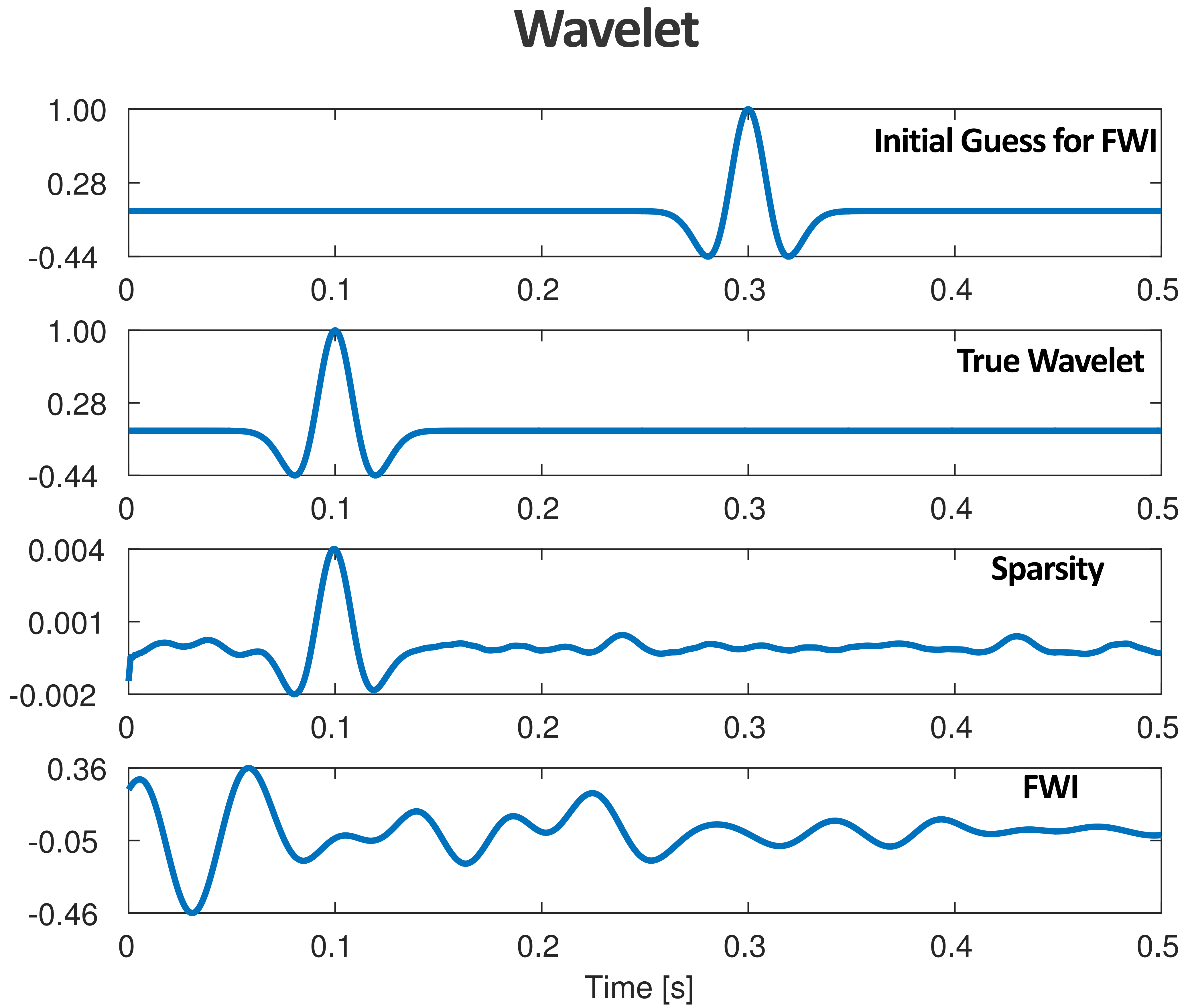


Sparsity-promoting method

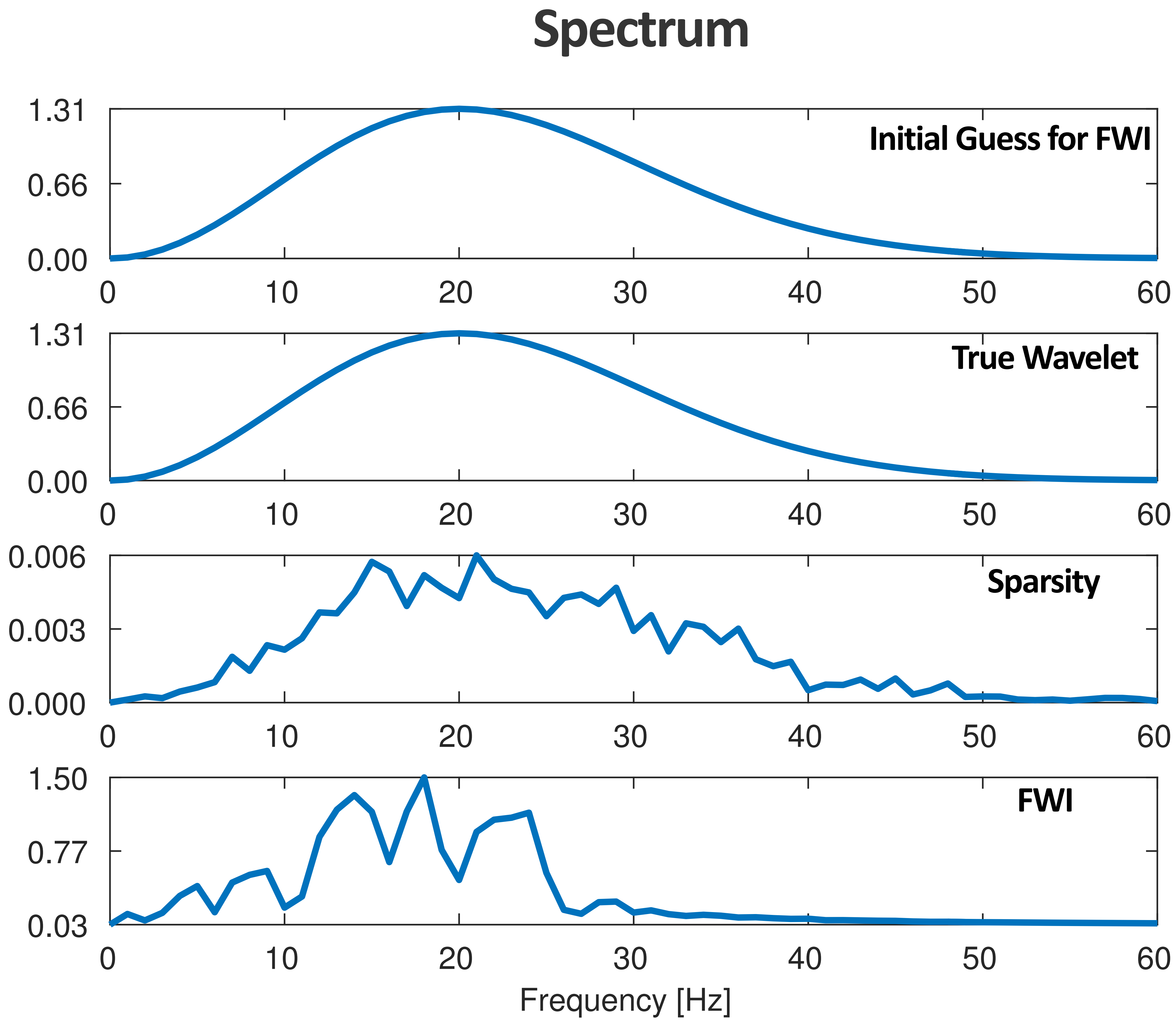


FWI

Location 1

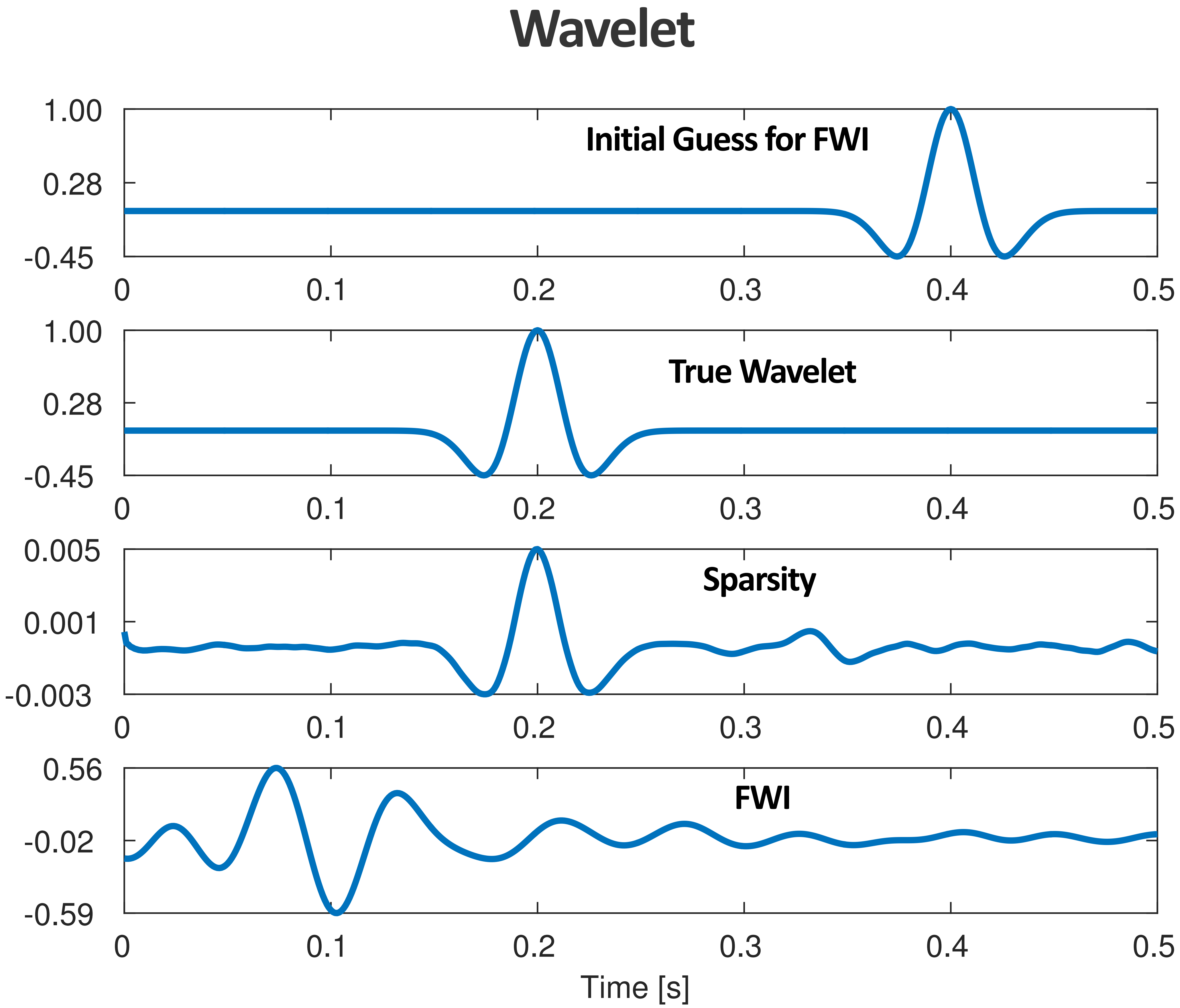


Wavelet
1.00
0.28
-0.44
Initial Guess for FWI
True Wavelet
0.004
0.001
-0.002
Sparsity
0.36
-0.05
-0.46
FWI
0
0.1
0.2
0.3
0.4
0.5
Time [s]

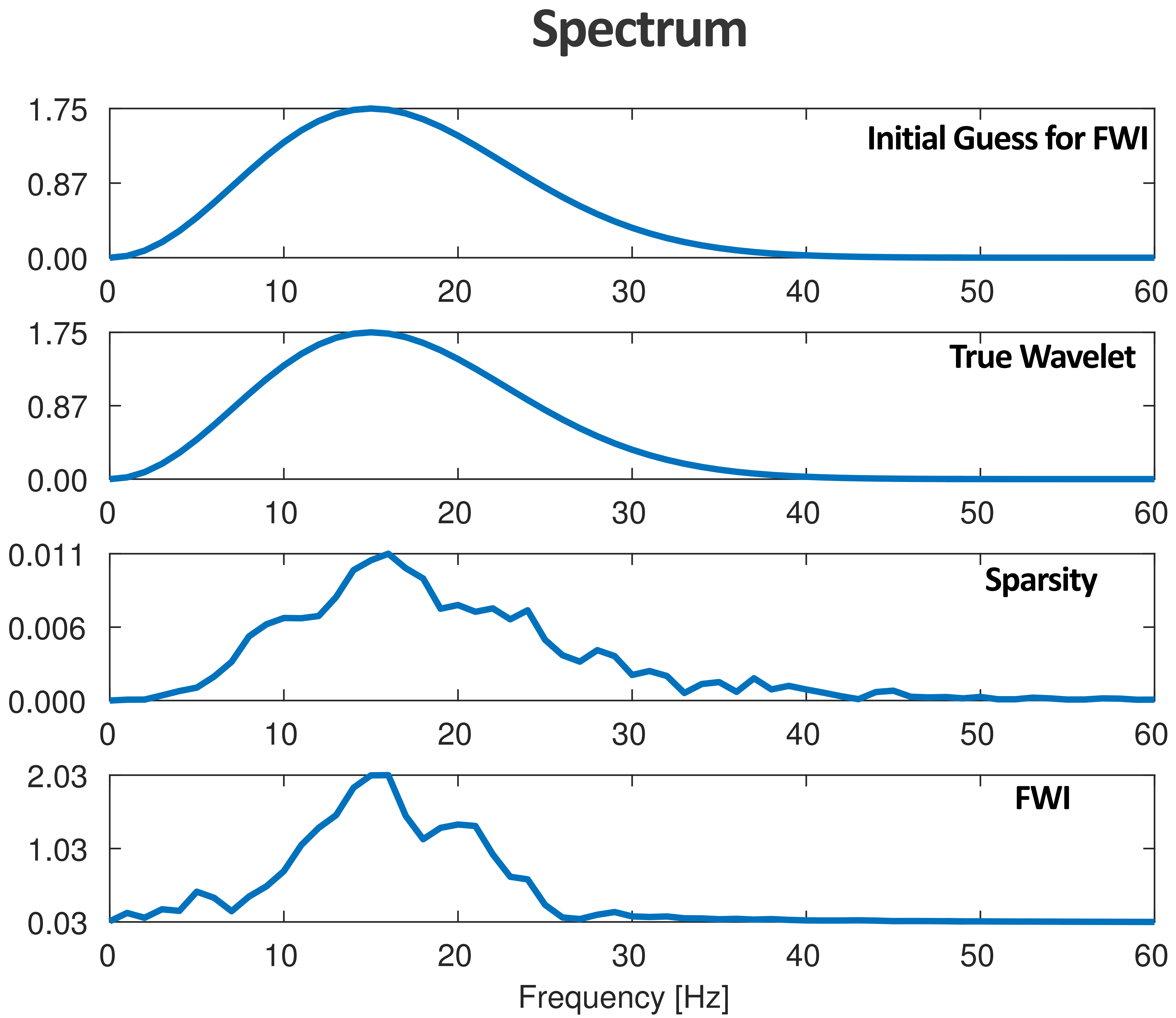


Spectrum
1.31
0.66
0.00
Initial Guess for FWI
True Wavelet
0.006
0.003
0.000
Sparsity
1.50
0.77
0.03
FWI
0
10
20
30
40
50
60
Frequency [Hz]

Location 2



Wavelet
Initial Guess for FWI
True Wavelet
Sparsity
FWI
1.00
0.28
-0.45
0.005
0.001
-0.003
0.56
-0.02
-0.59
0
0.1
0.2
0.3
0.4
0.5
Time [s]



Spectrum
Initial Guess for FWI
True Wavelet
Sparsity
FWI
1.75
0.87
0.00
0.011
0.006
0.000
2.03
1.03
0.03
0
10
20
30
40
50
60
Frequency [Hz]

Extension to BG compass model

Objective

- to show the ability of our method in realistic geological setting

Extension to BG compass model

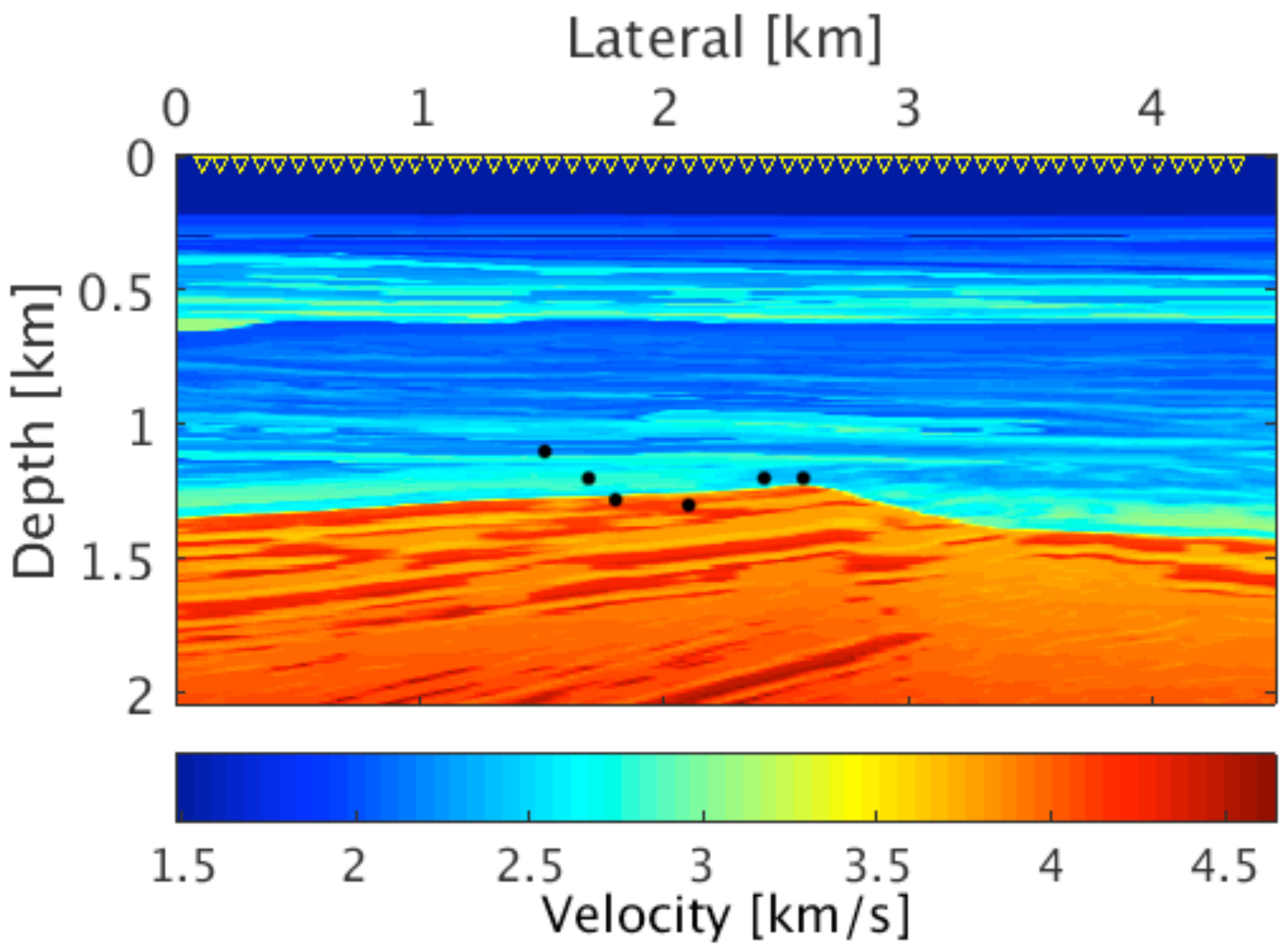
Objective

- to show the ability of our method in realistic geological setting

Assumptions

- access to smooth background velocity model
- noisy data (bandwidth limited random noise up to 45 Hz)

Experimental setup

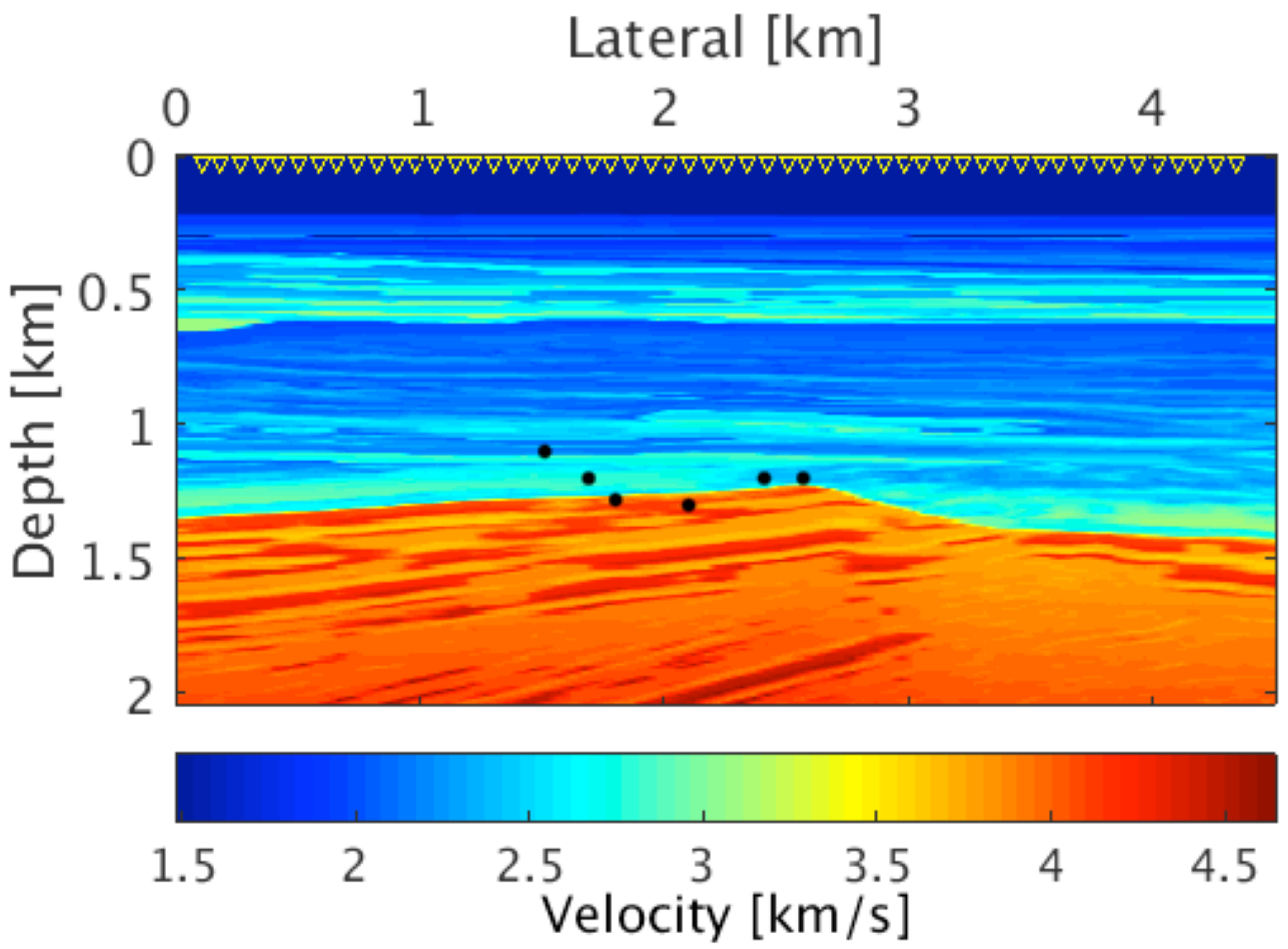


BG Compass velocity model

Modeling information:

Model size: 2.04 km x 4.50 km
Grid spacing: 10m
Total number of sources: 6
Receiver spacing: 20m
Receiver depth: 20m
Fixed spread: 4.30 km
Sampling interval: 1 ms
Recording length: 2.5 s
Peak frequency : 15 Hz & 10 Hz

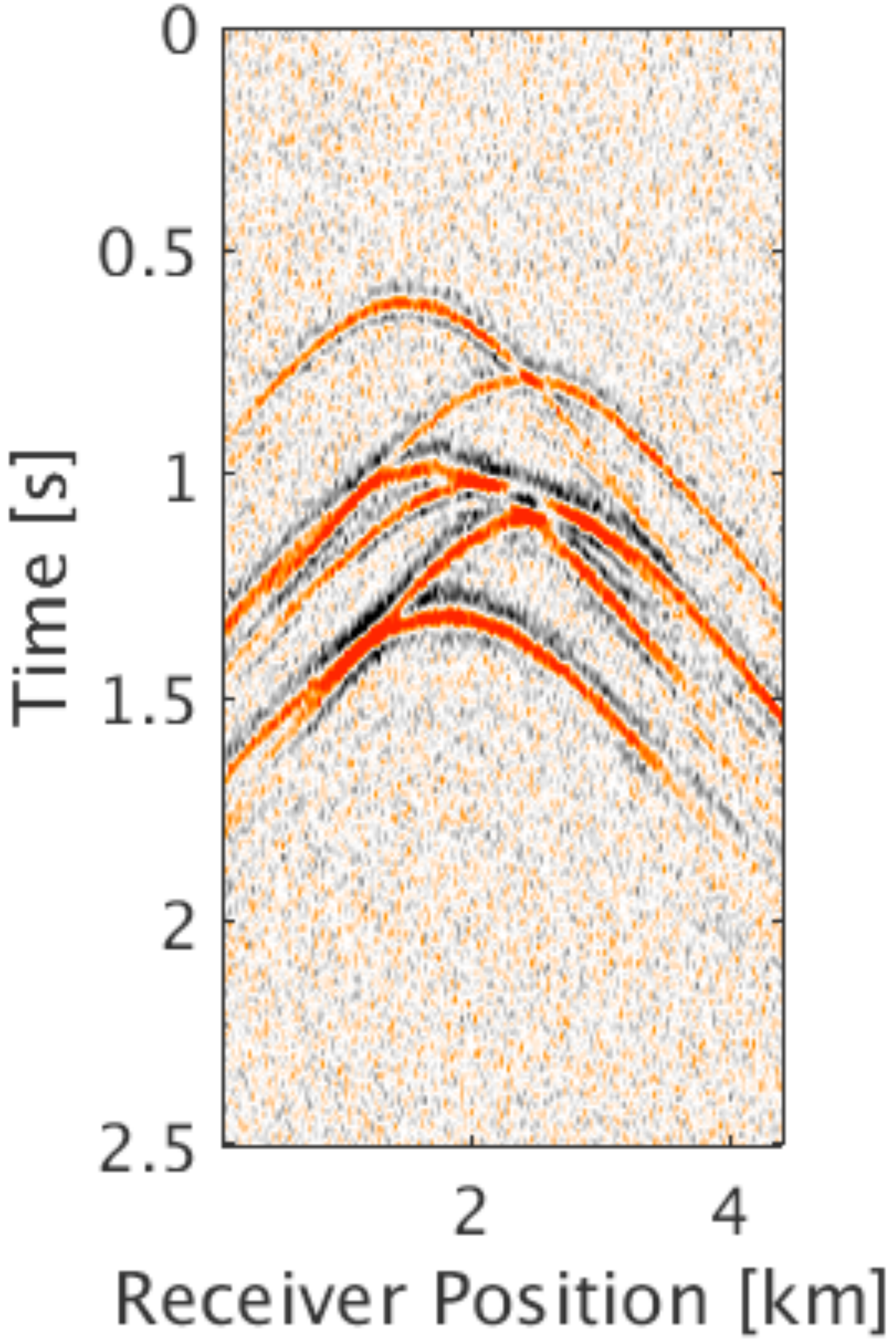
Experimental setup



BG Compass velocity model

Dominant wavelength: 420 m

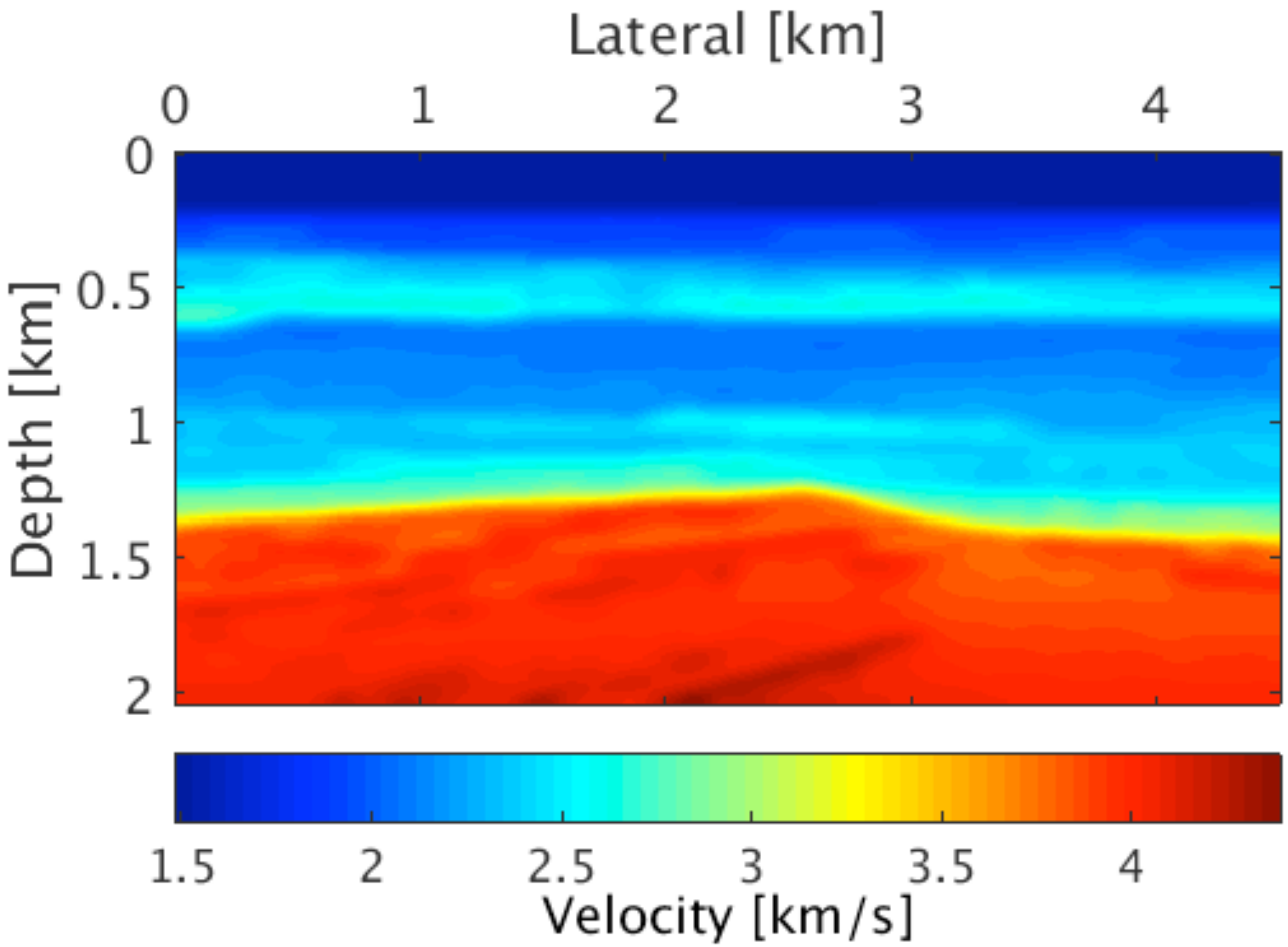
Observed microseismic data



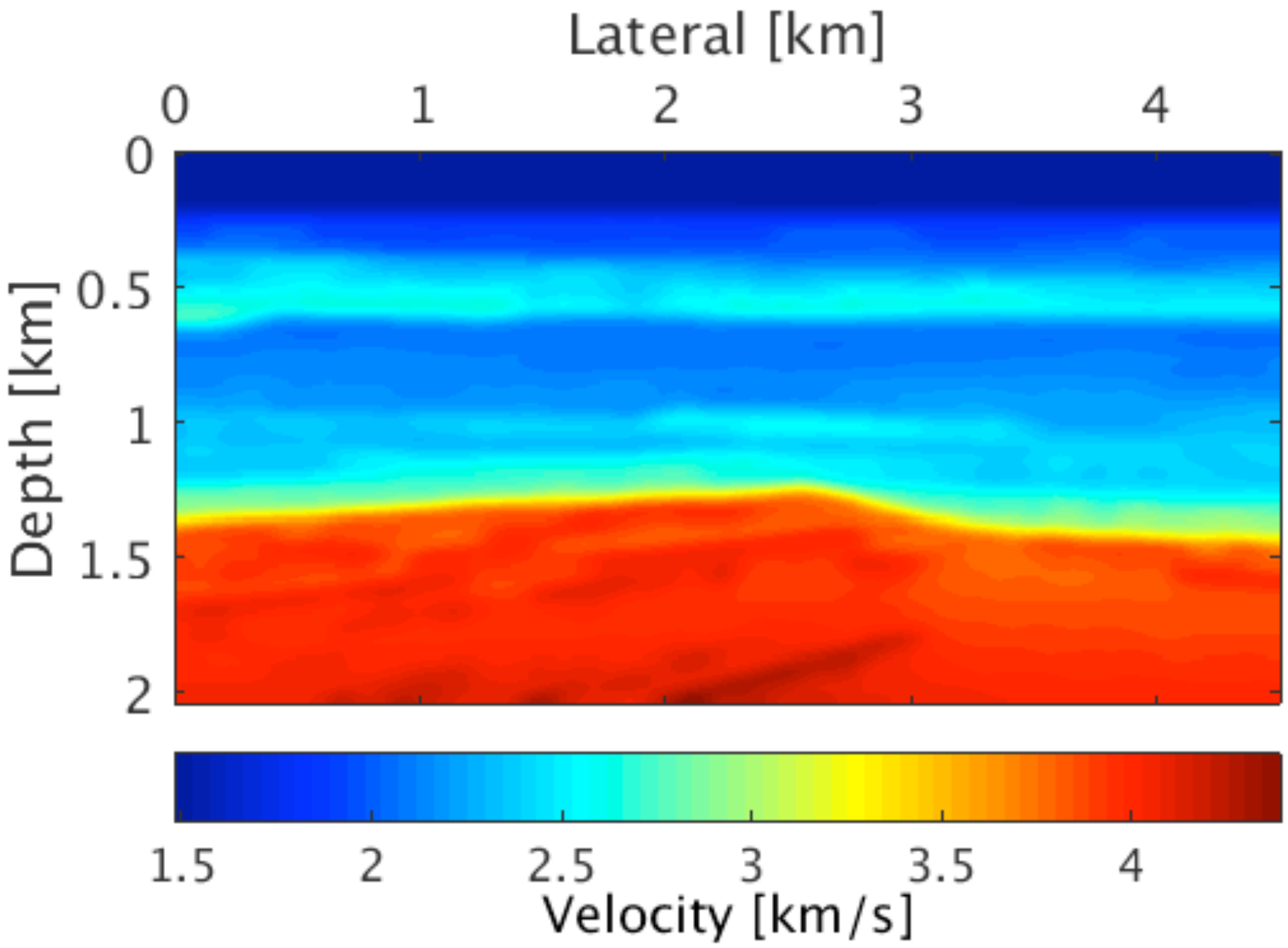
Noisy microseismic data, SNR = 2.83

Data is contaminated with low frequency random noise (up to 45 Hz)

Smooth velocity model

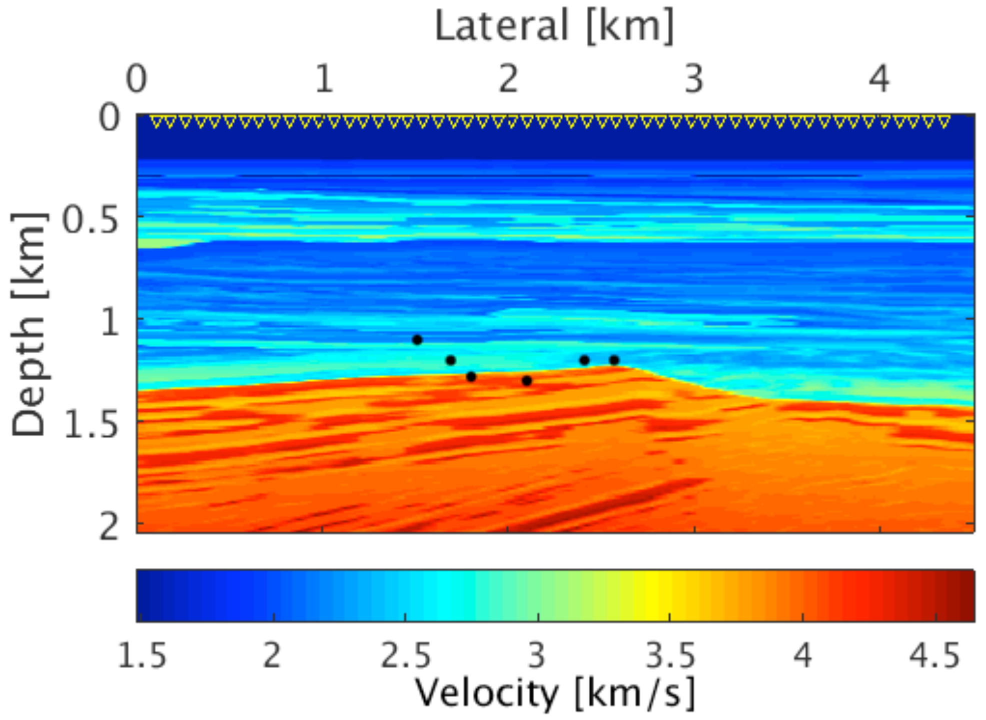


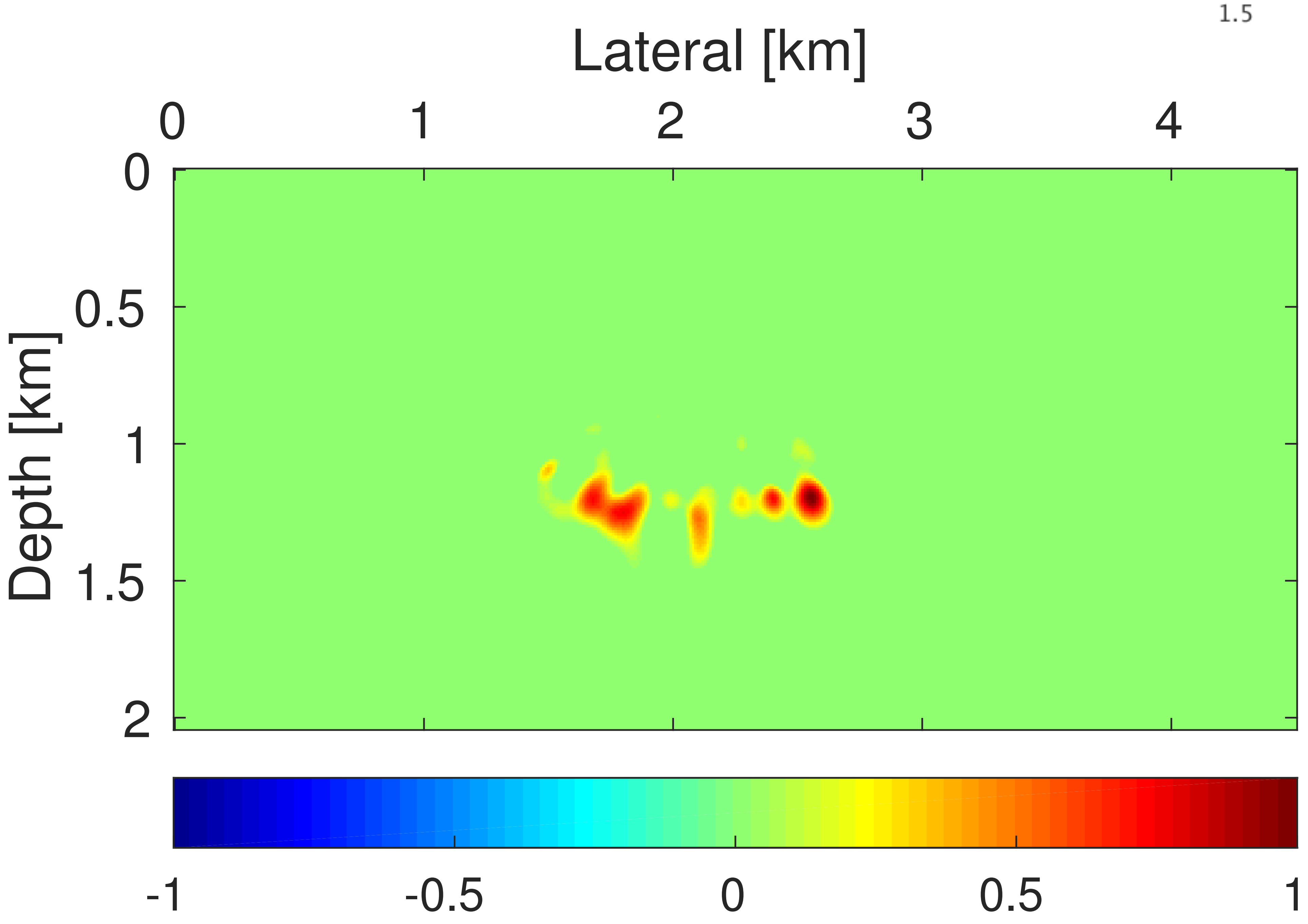
Smooth velocity model



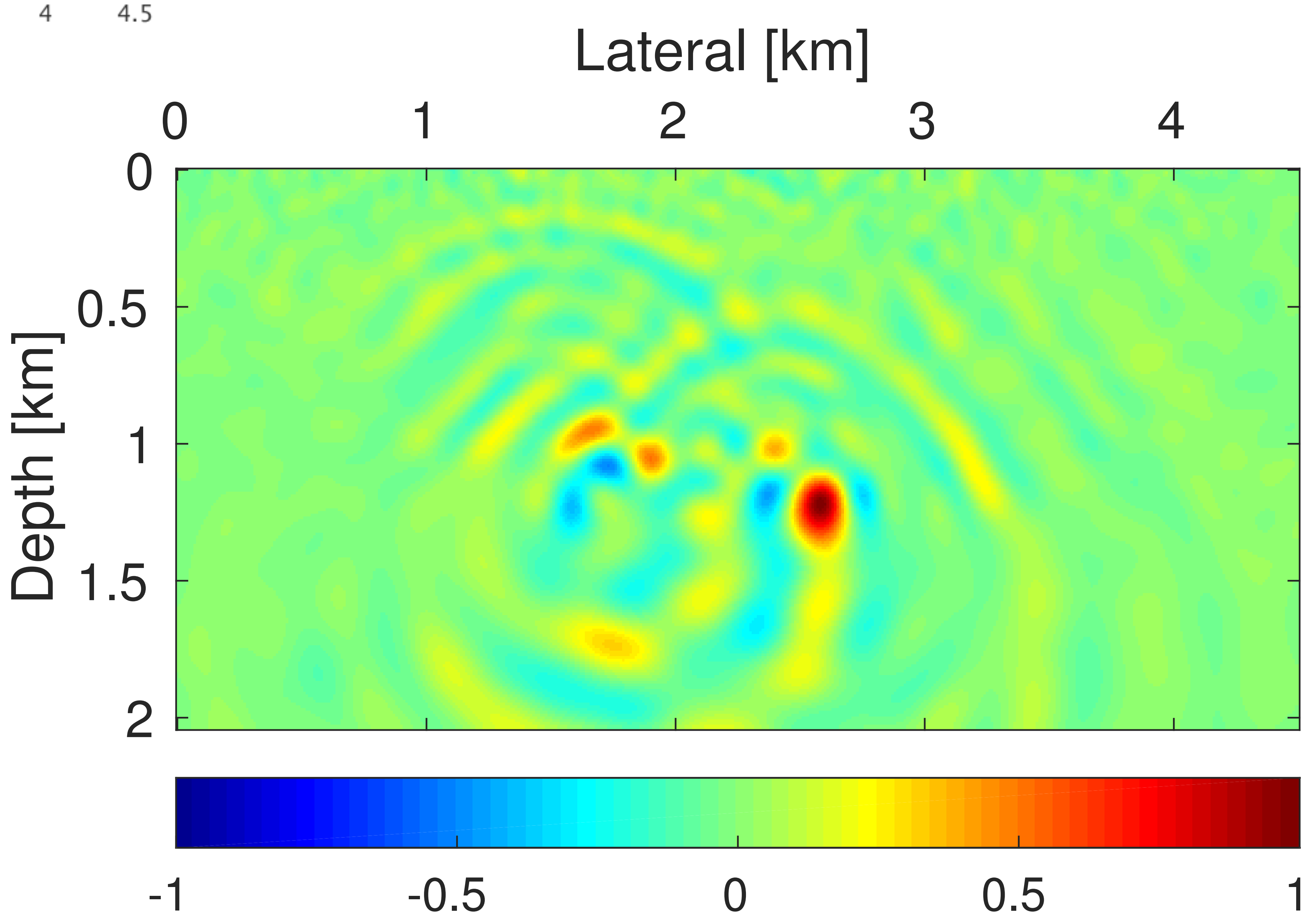
Used for joint microseismic source location and source time function estimation

Estimated Source location (From noisy data)



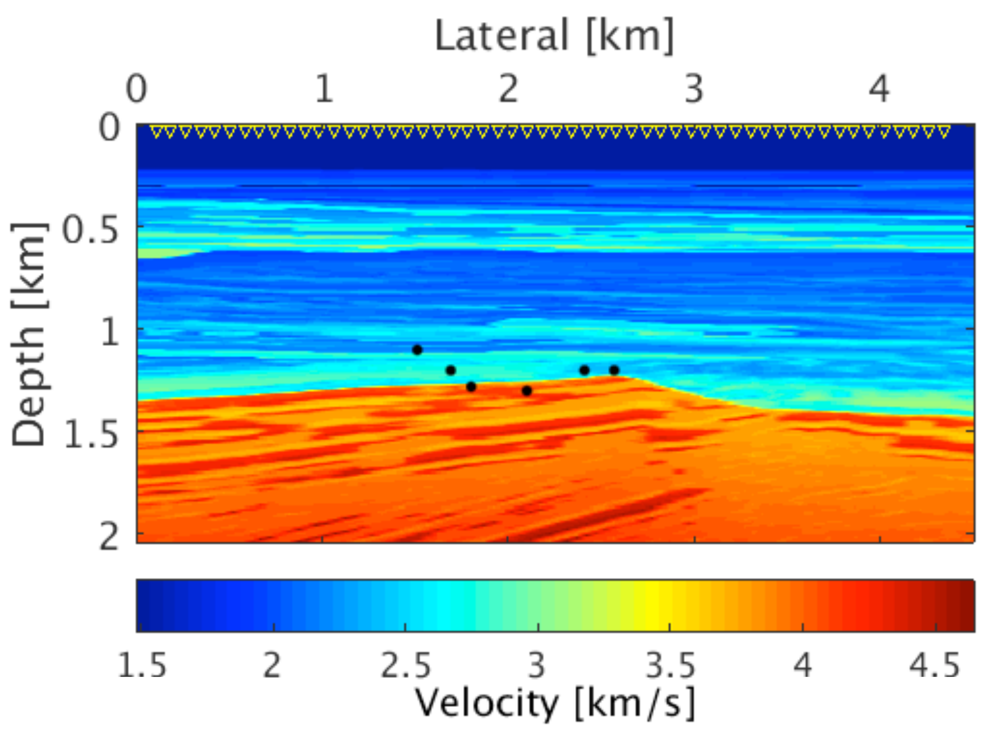


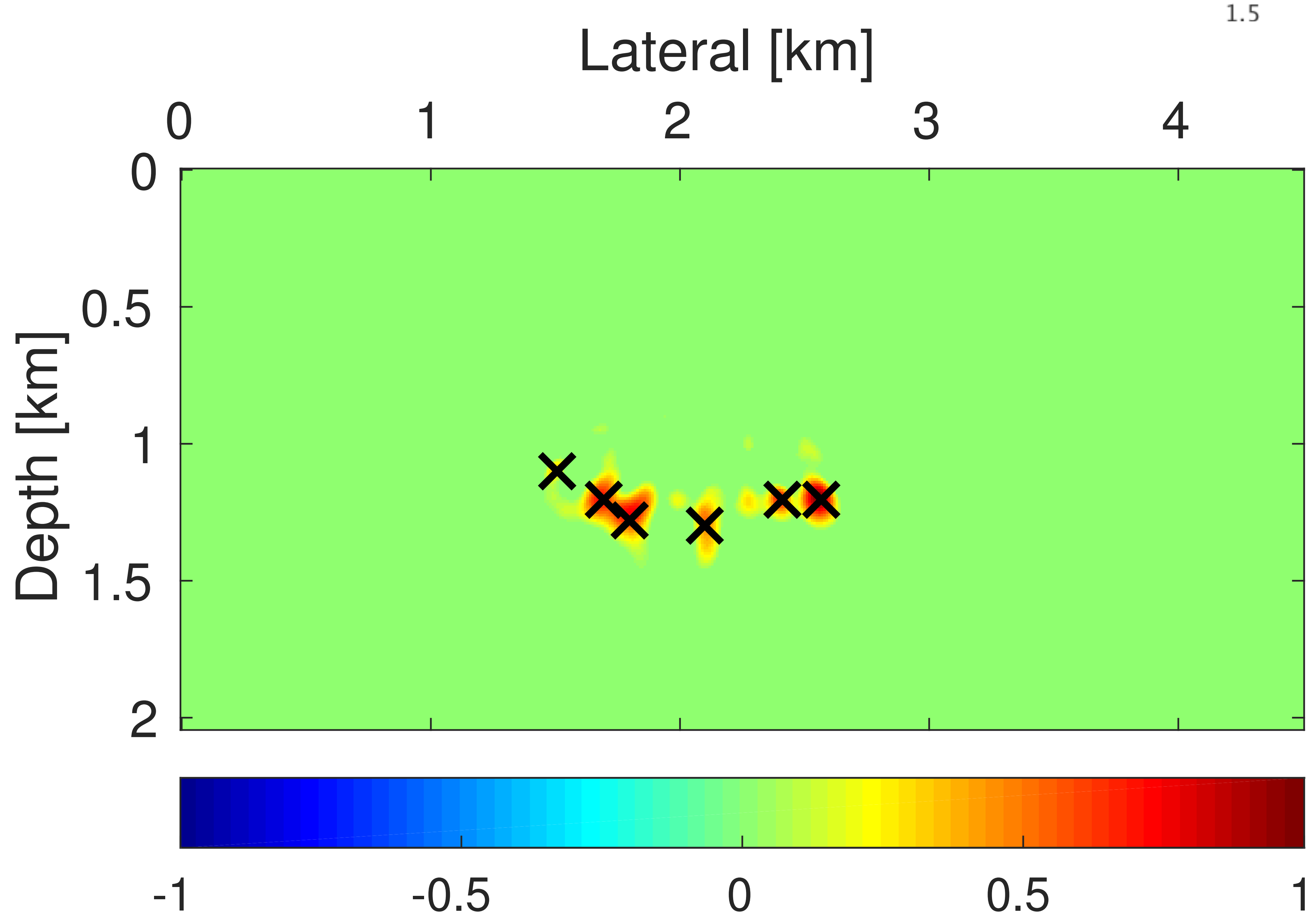
Sparsity-promoting method



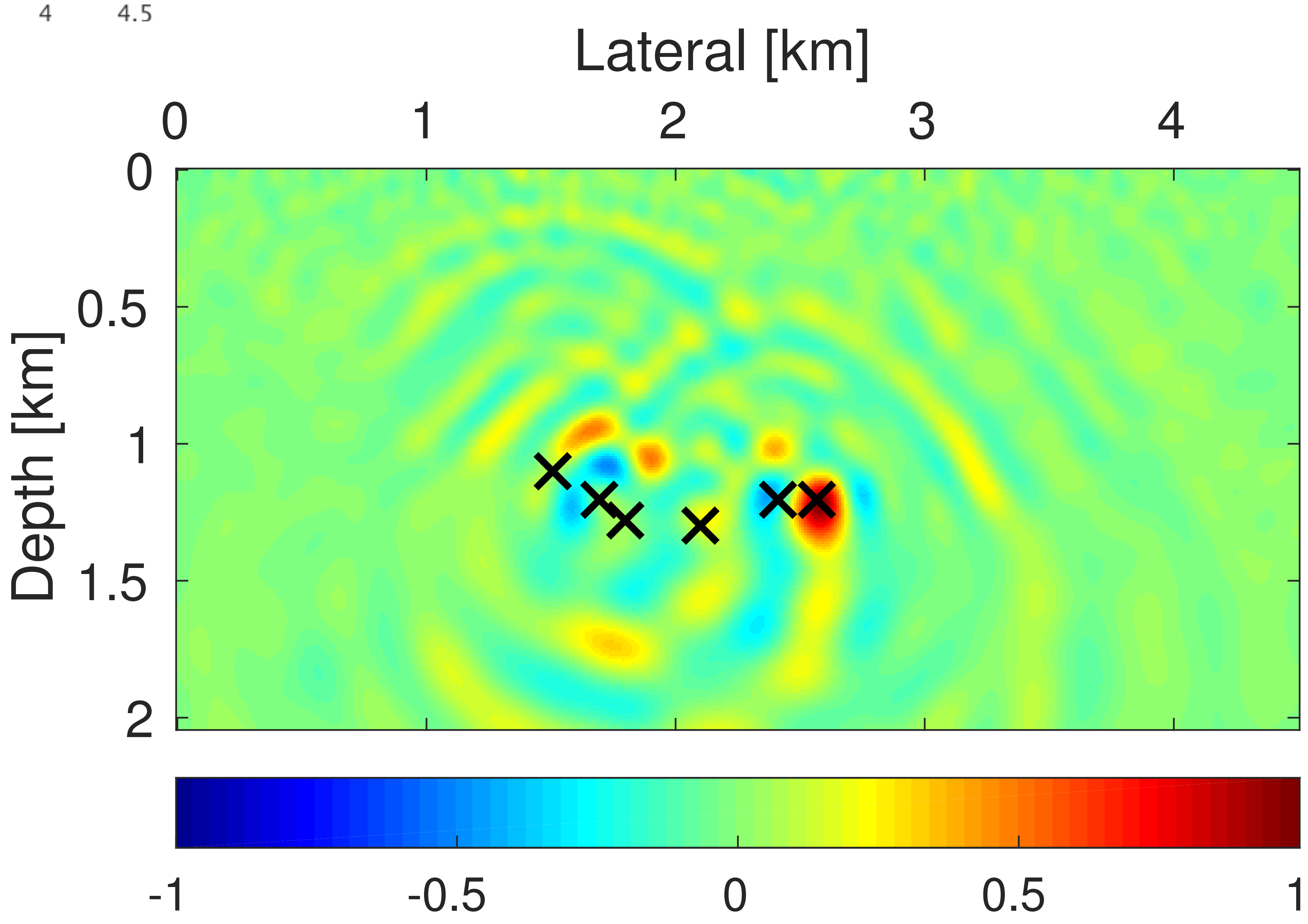
FWI

Estimated Source location (From noisy data)



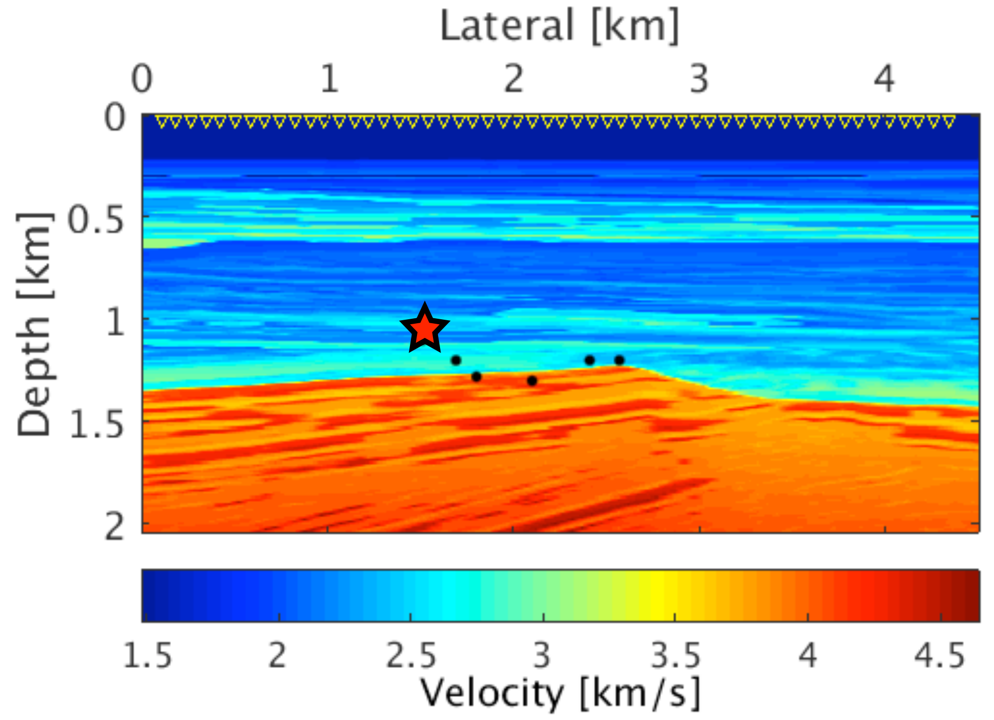


Sparsity-promoting method

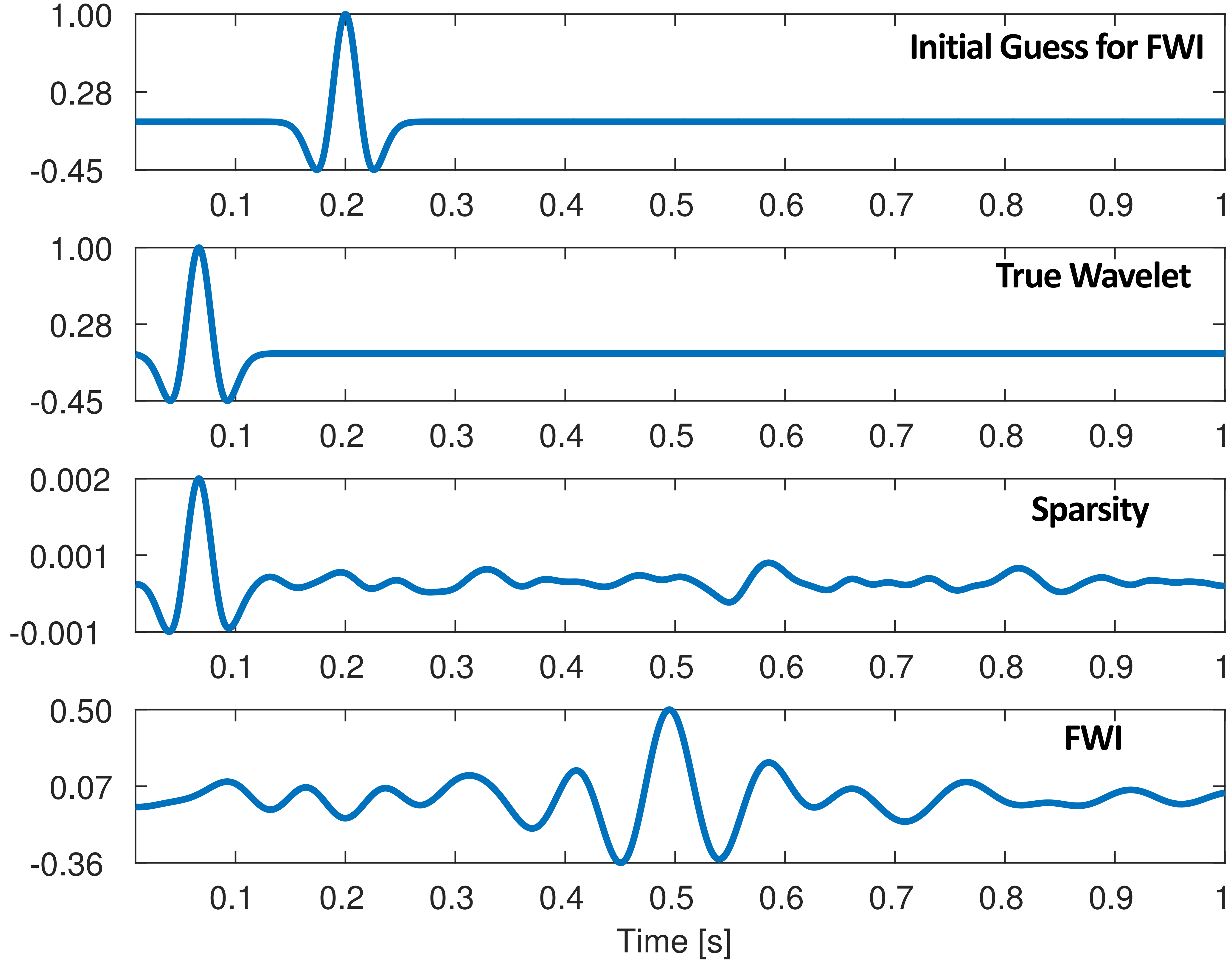


FWI

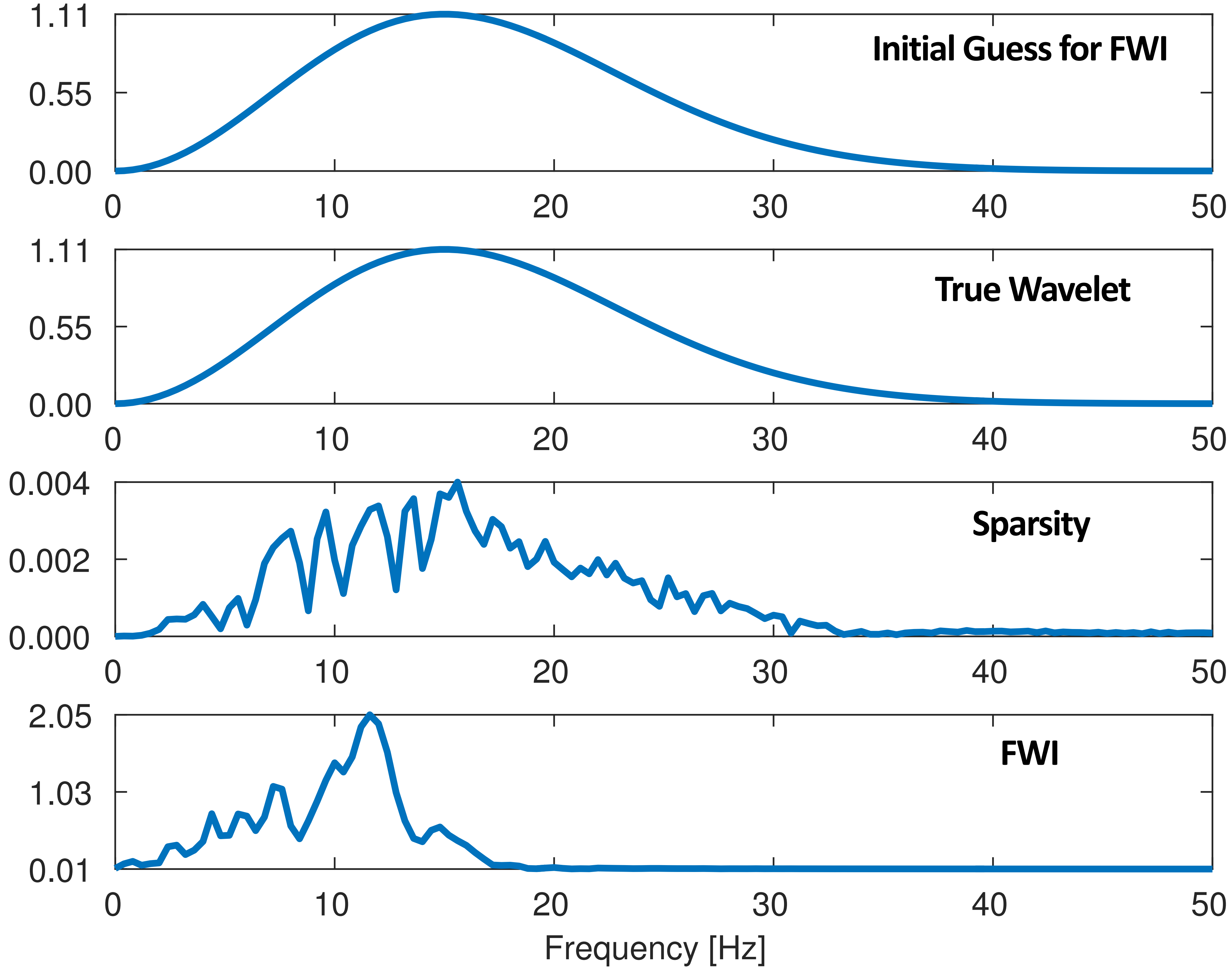
Location 1



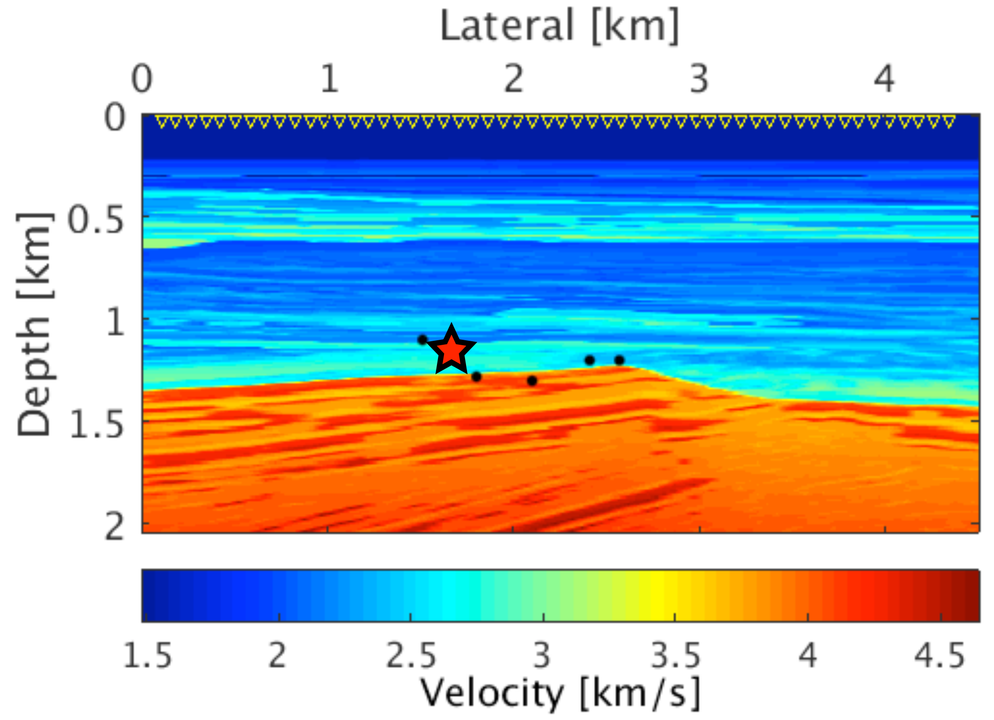
Wavelet



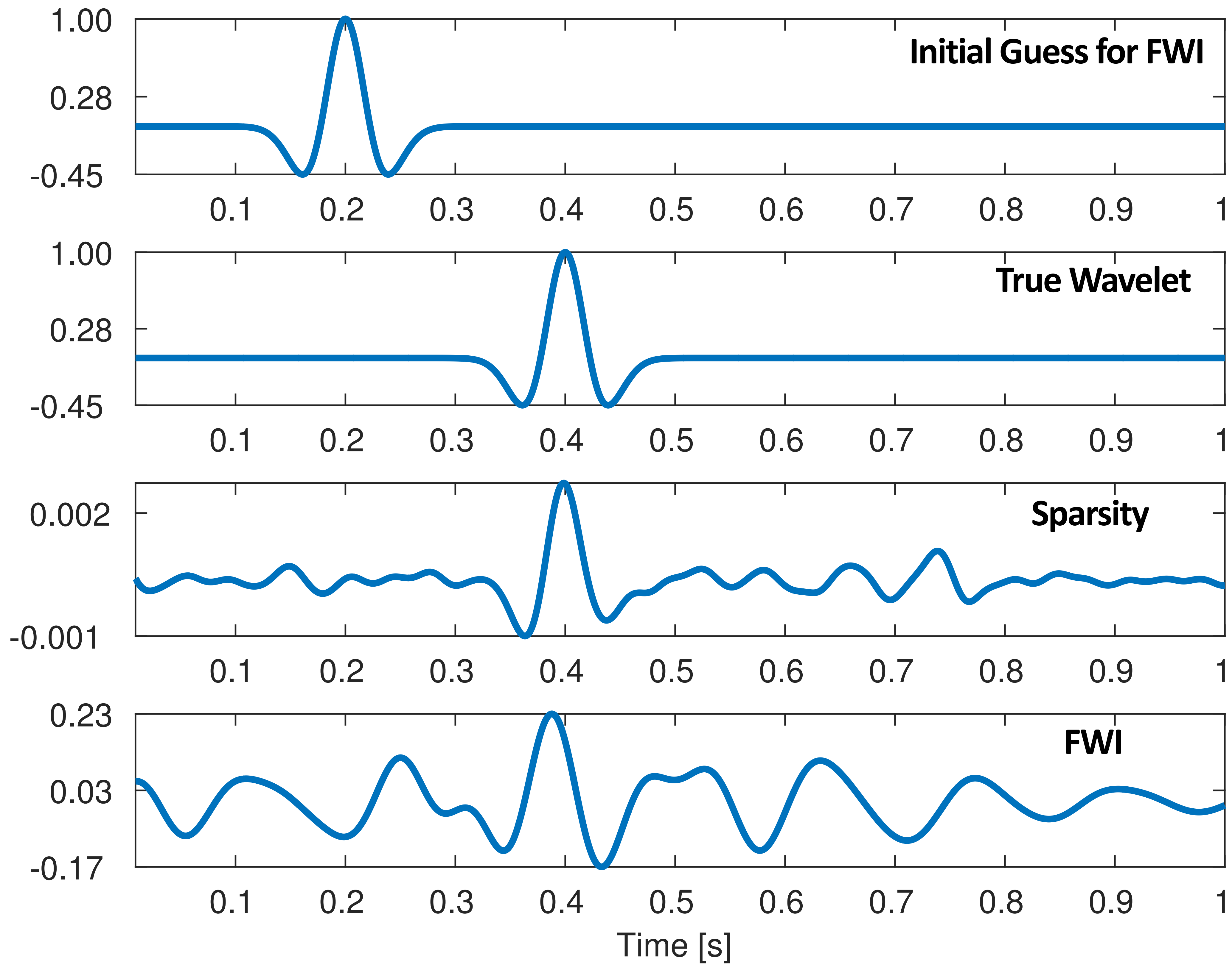
Spectrum



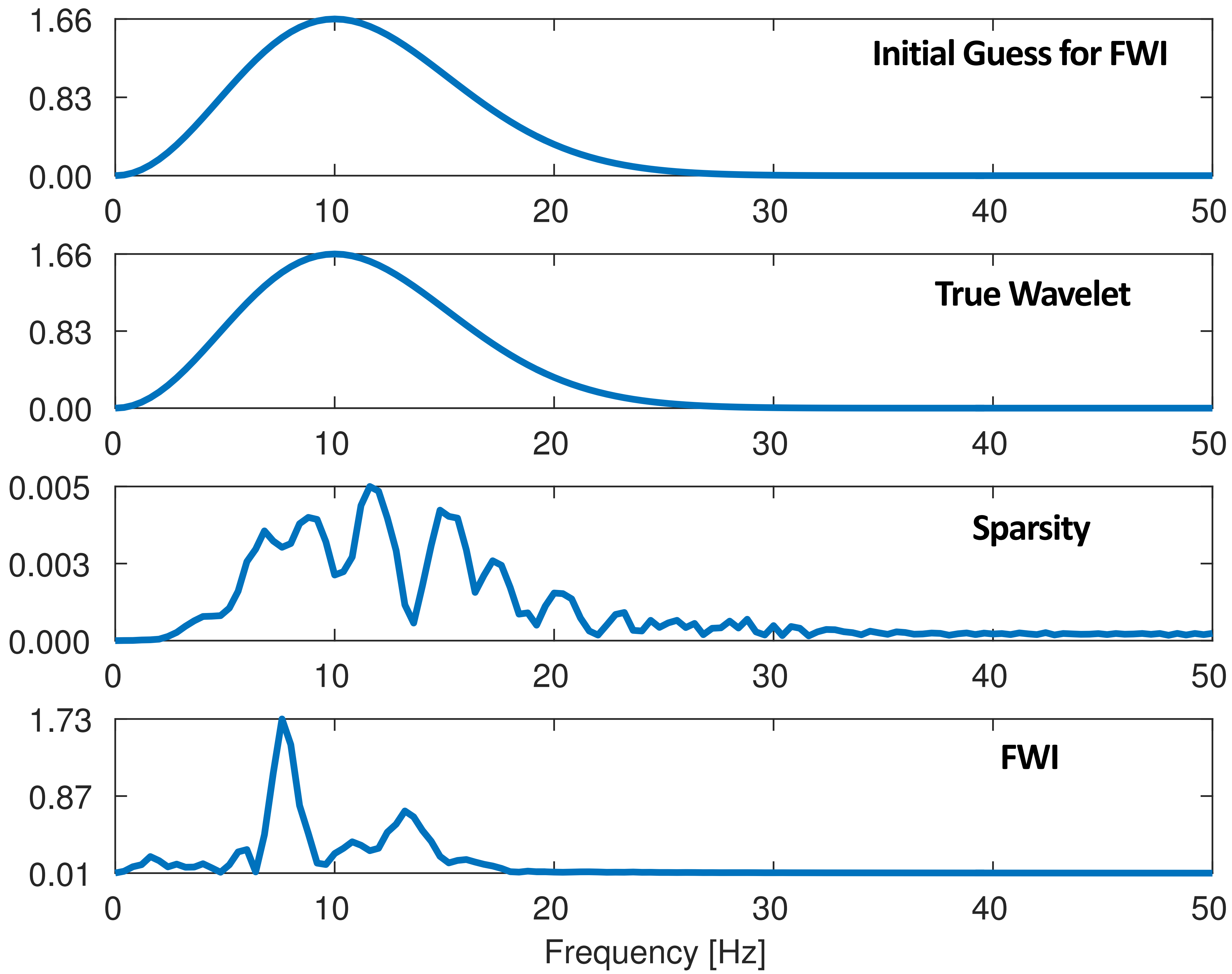
Location 2



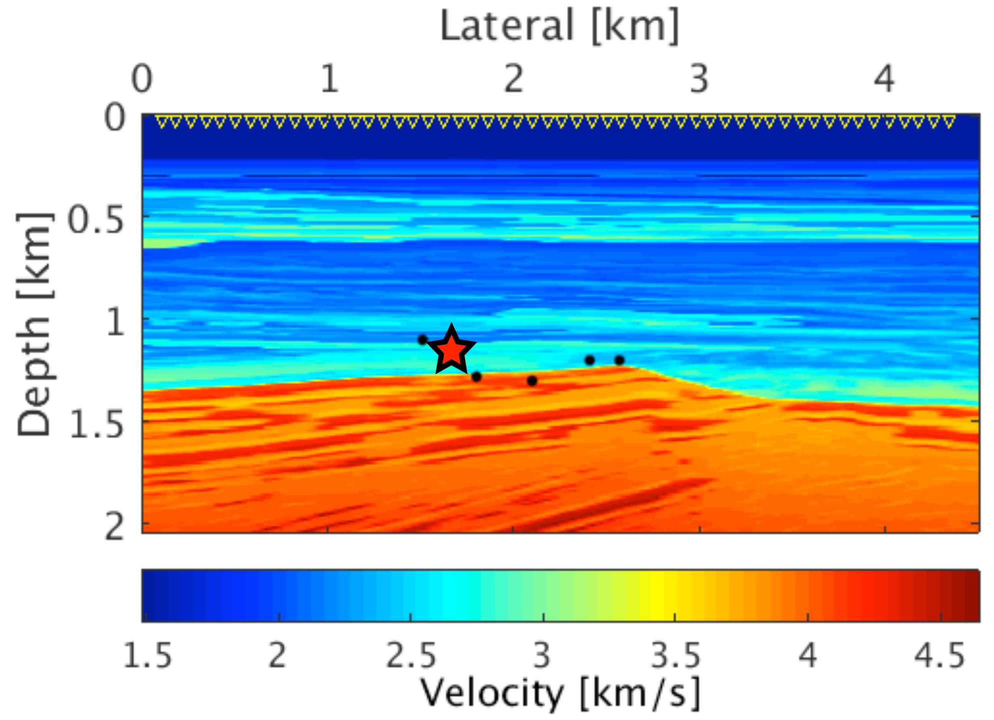
Wavelet



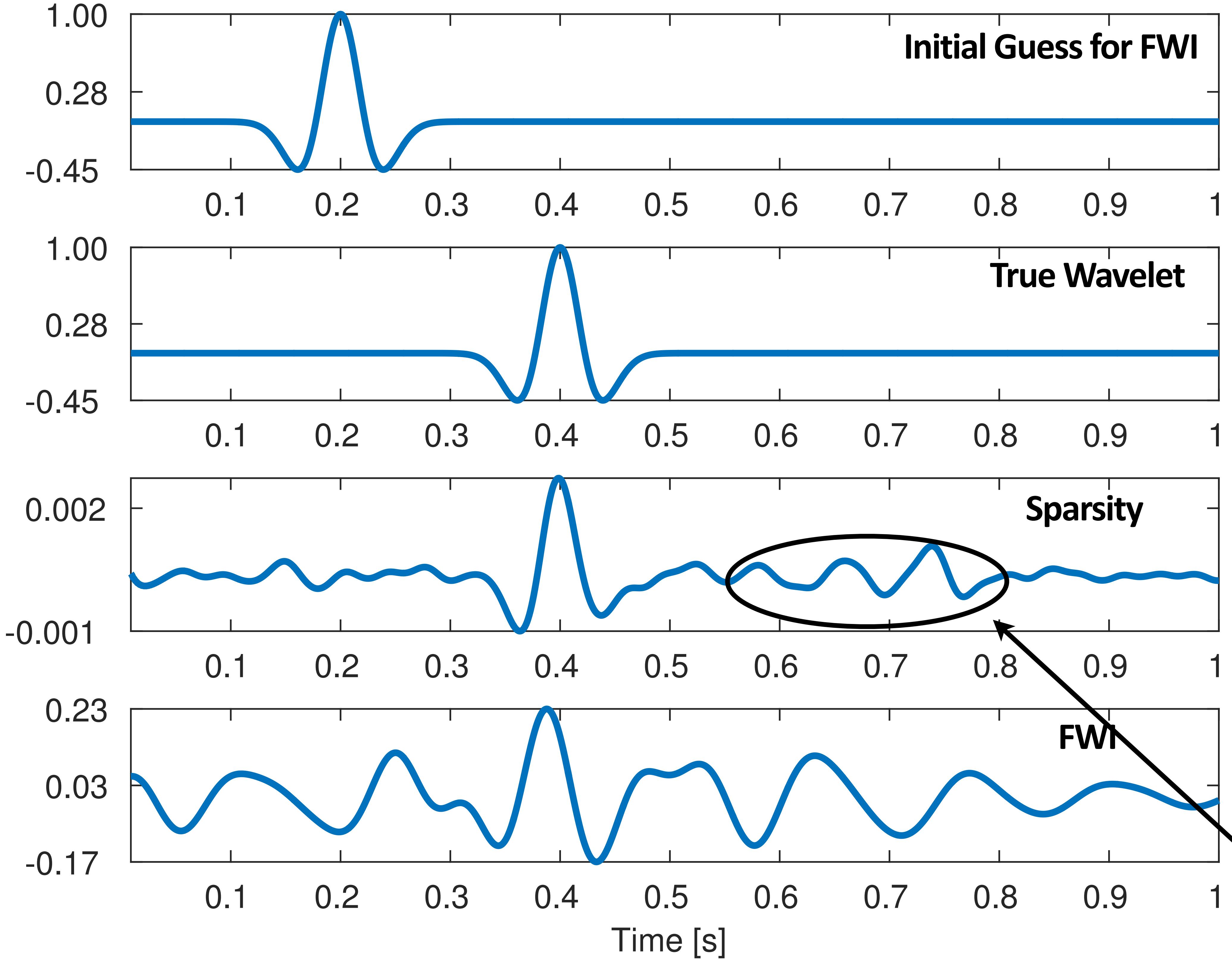
Spectrum



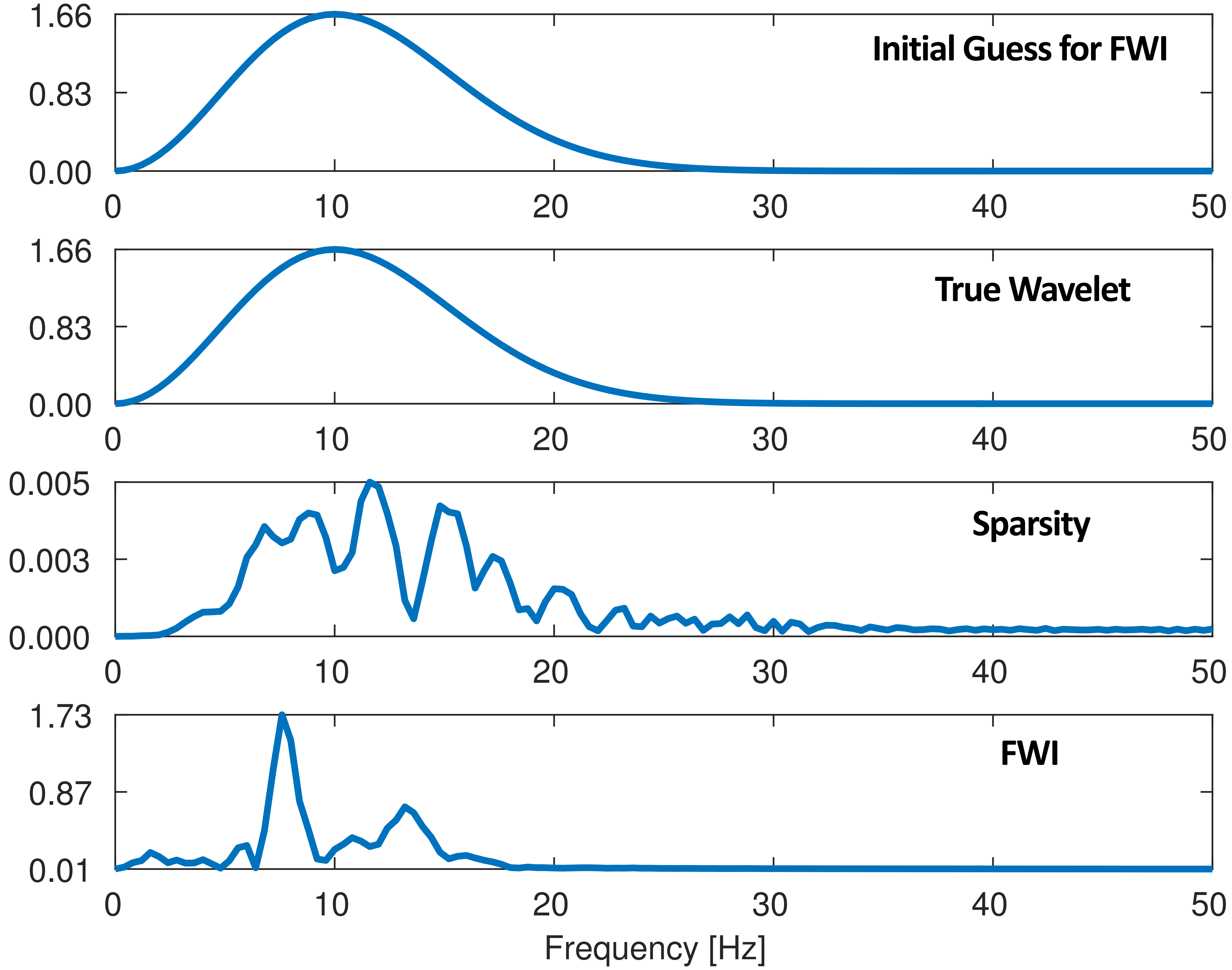
Location 2



Wavelet

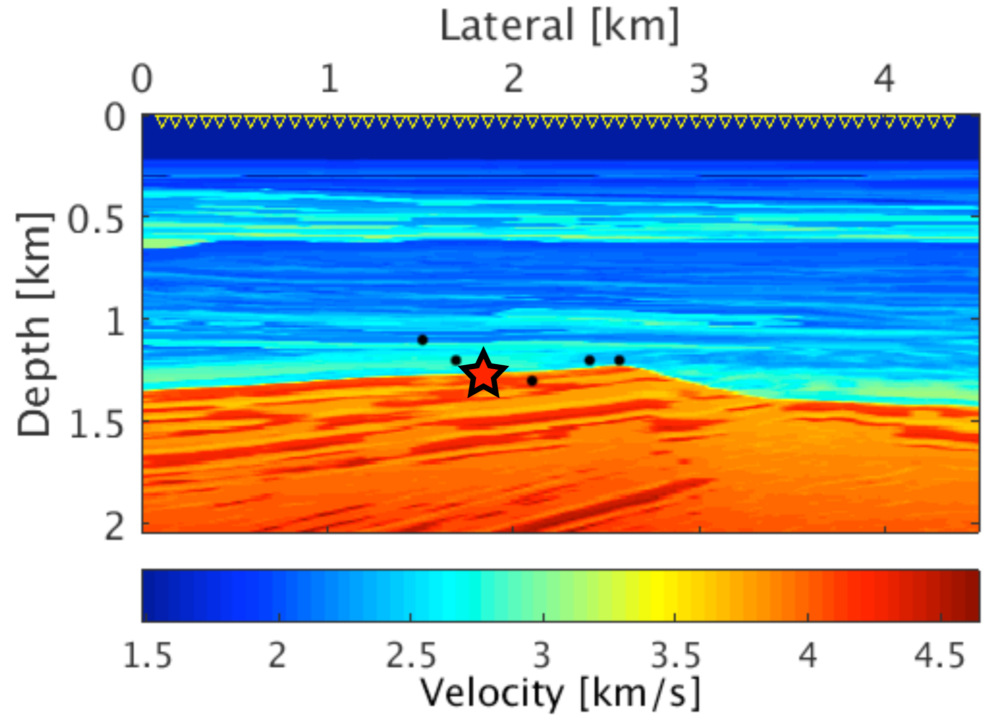


Spectrum

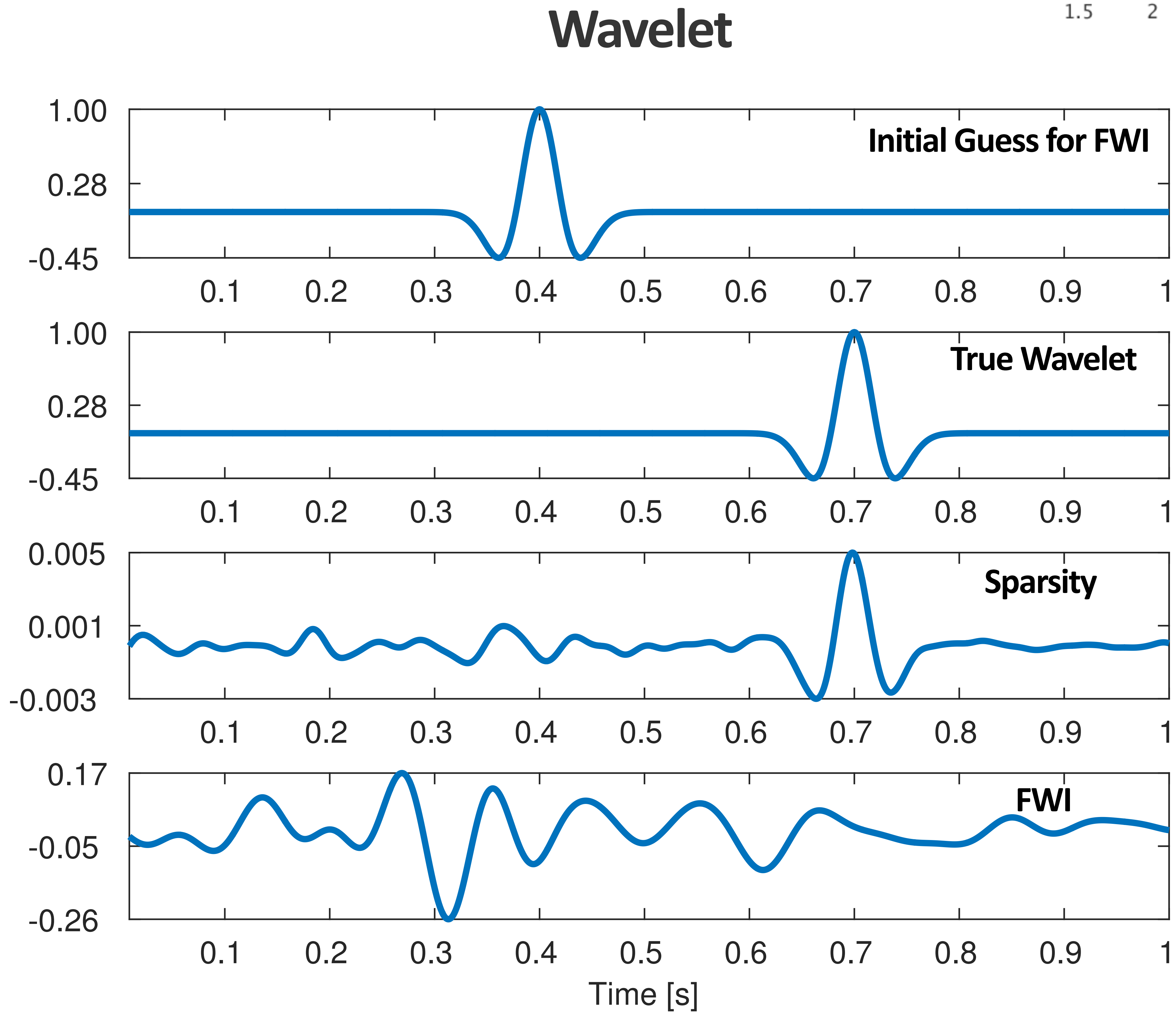


Sources within a wavelength

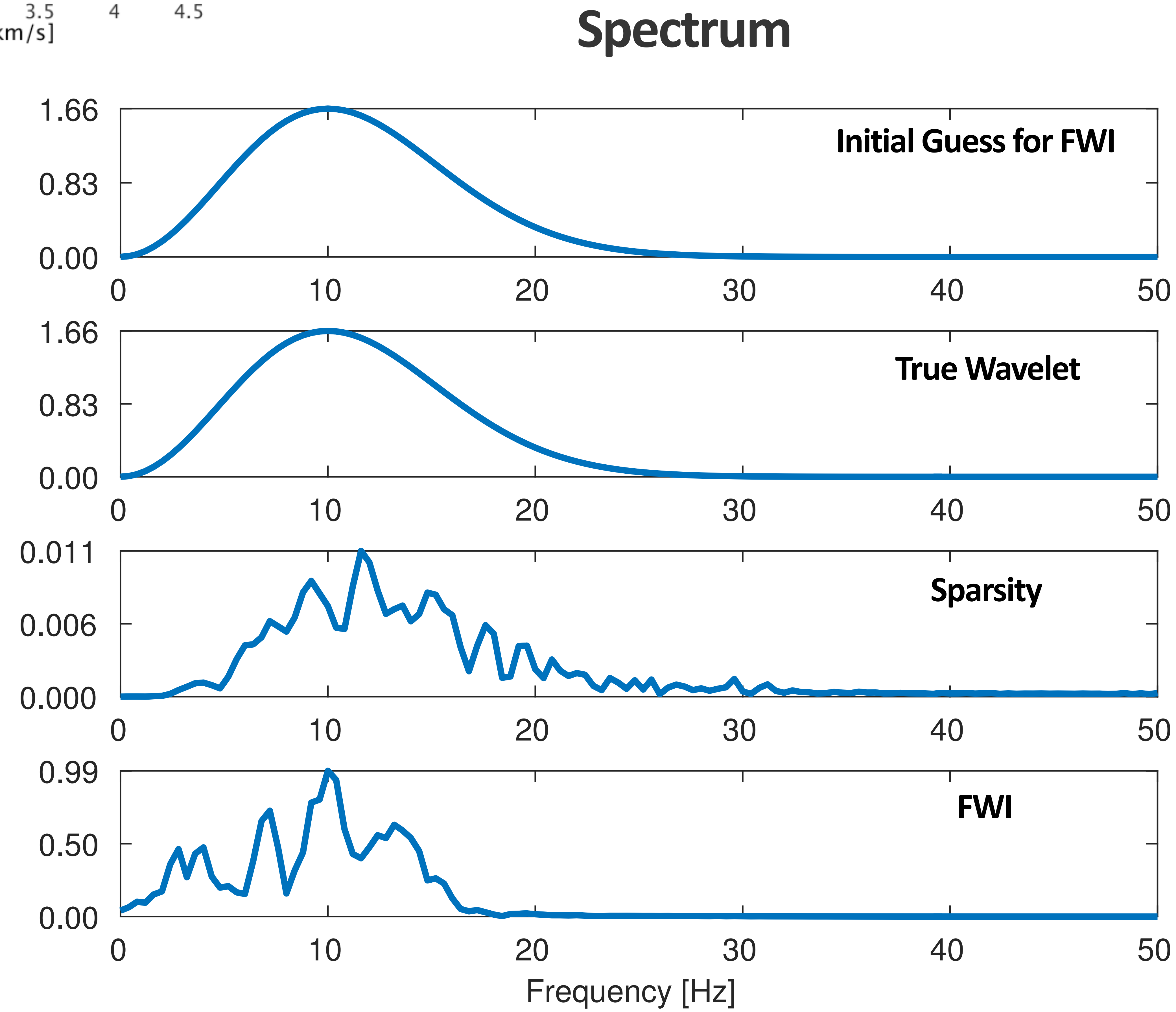
Location 3



Lateral [km]
0
1
2
3
4
Depth [km]
0
0.5
1
1.5
2
1.5
2
2.5
3
3.5
4
4.5
Velocity [km/s]

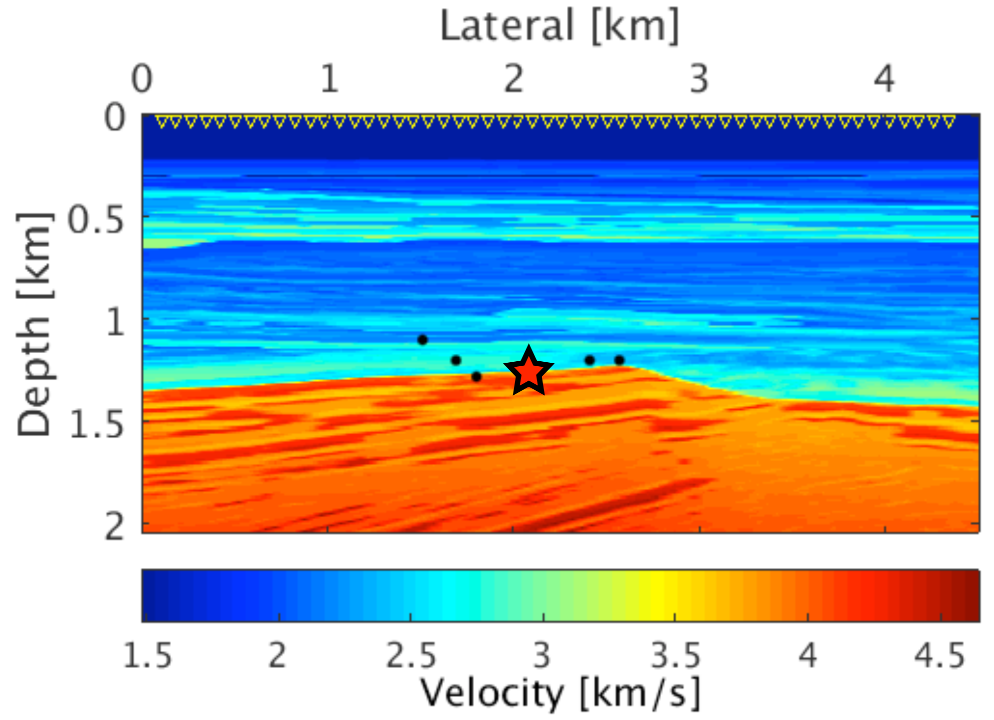


Wavelet
Initial Guess for FWI
True Wavelet
Sparsity
FWI
1.00
0.28
-0.45
0.005
0.001
-0.003
0.17
-0.05
-0.26
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time [s]

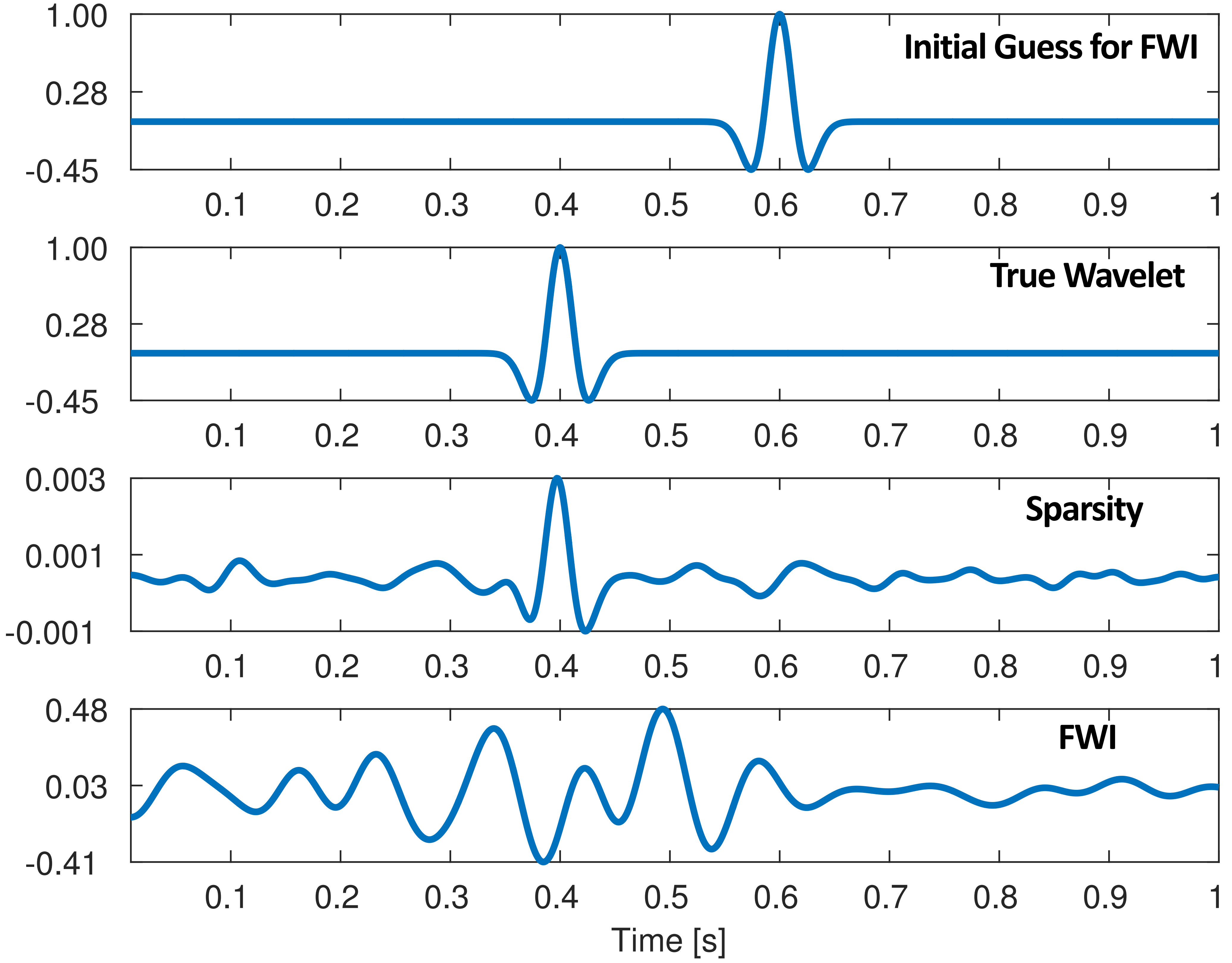


Spectrum
Initial Guess for FWI
True Wavelet
Sparsity
FWI
1.66
0.83
0.00
0.011
0.006
0.000
0.99
0.50
0
10
20
30
40
50
Frequency [Hz]

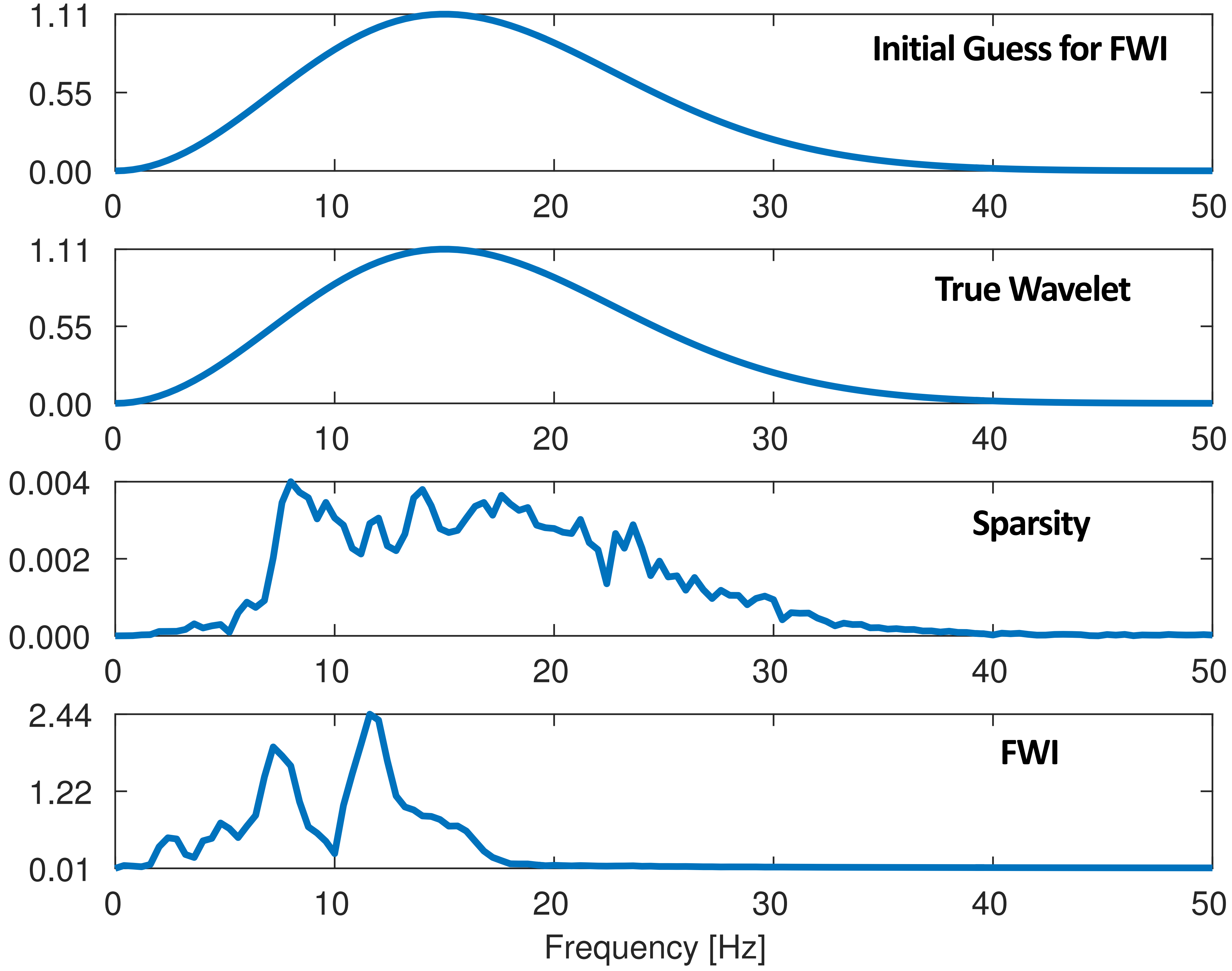
Location 4



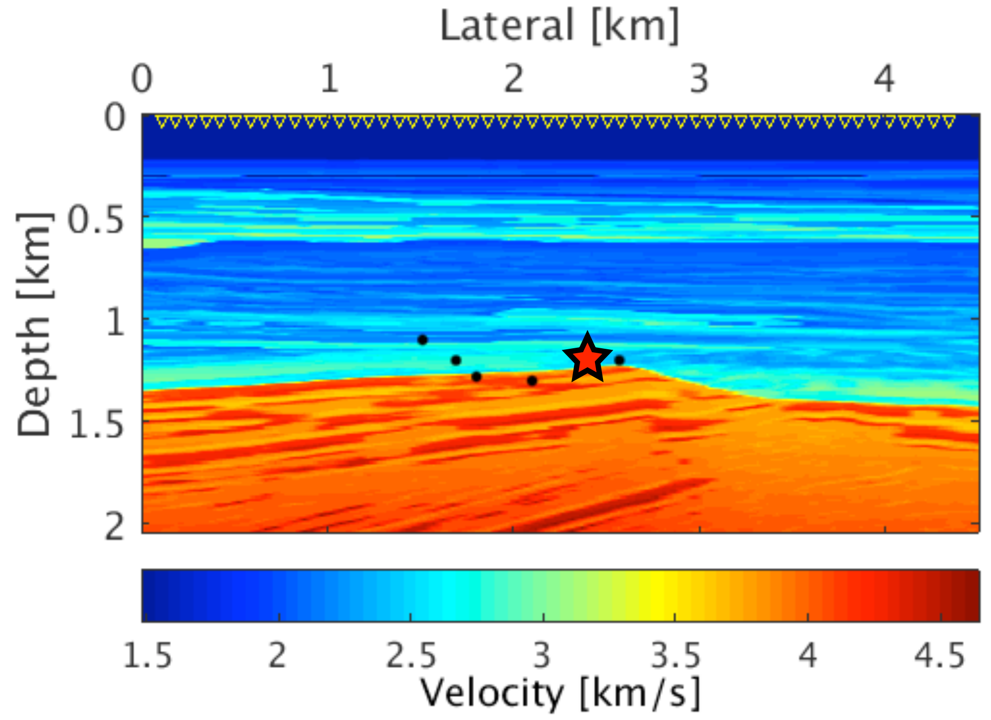
Wavelet



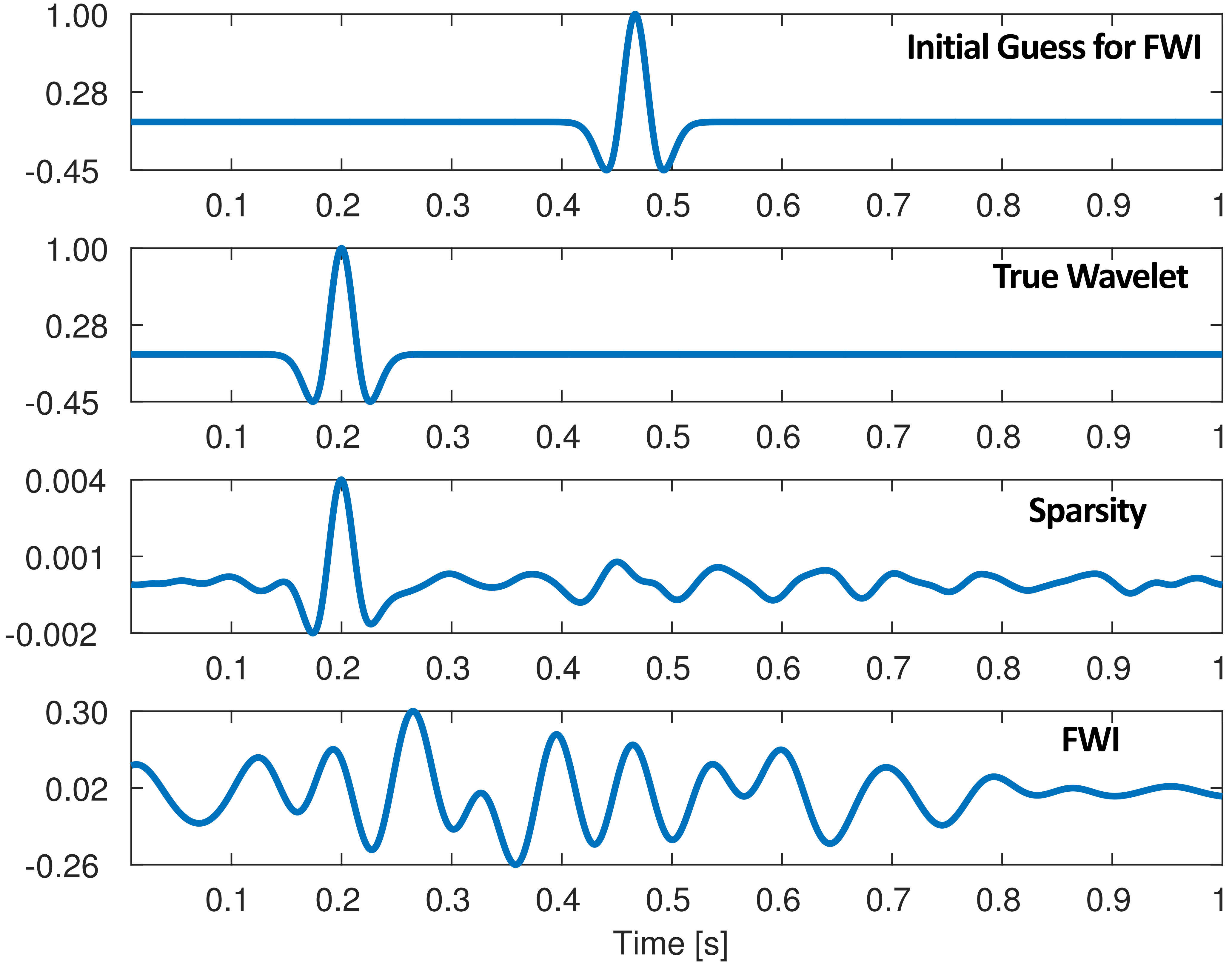
Spectrum



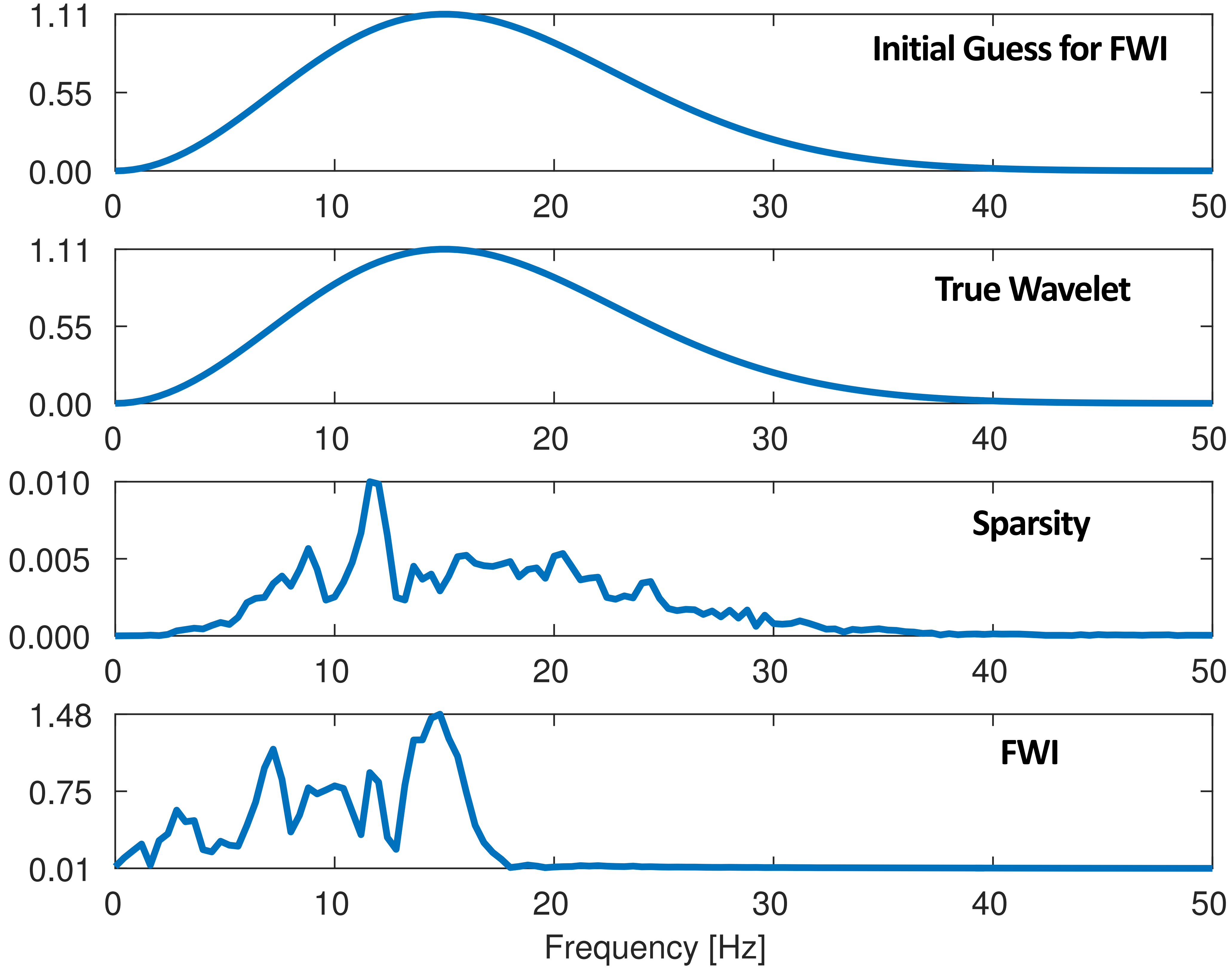
Location 5



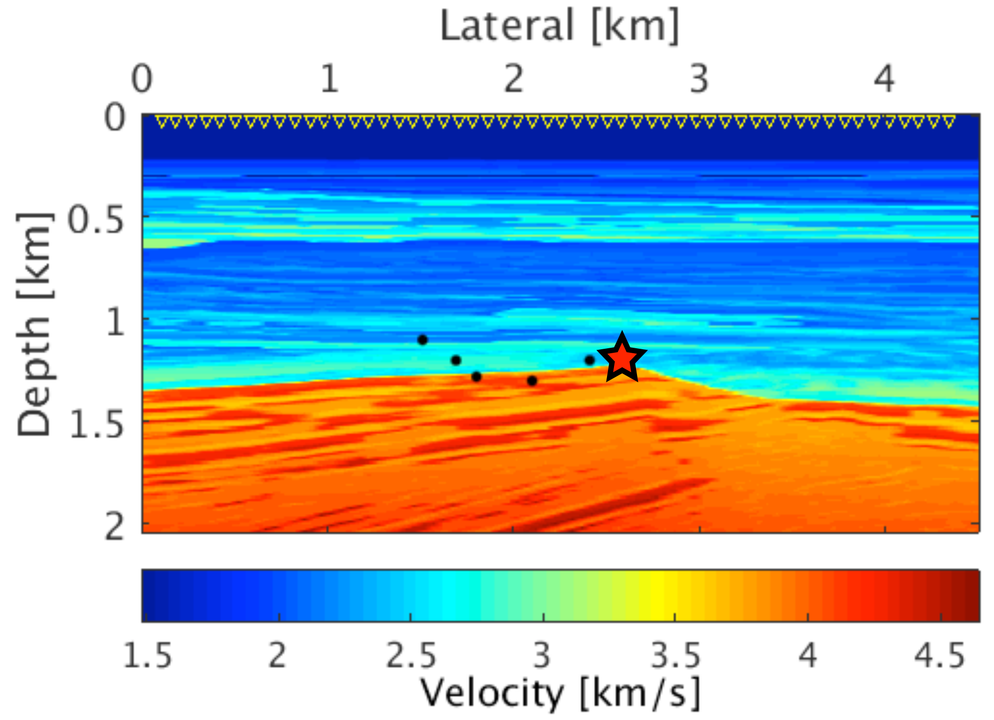
Wavelet



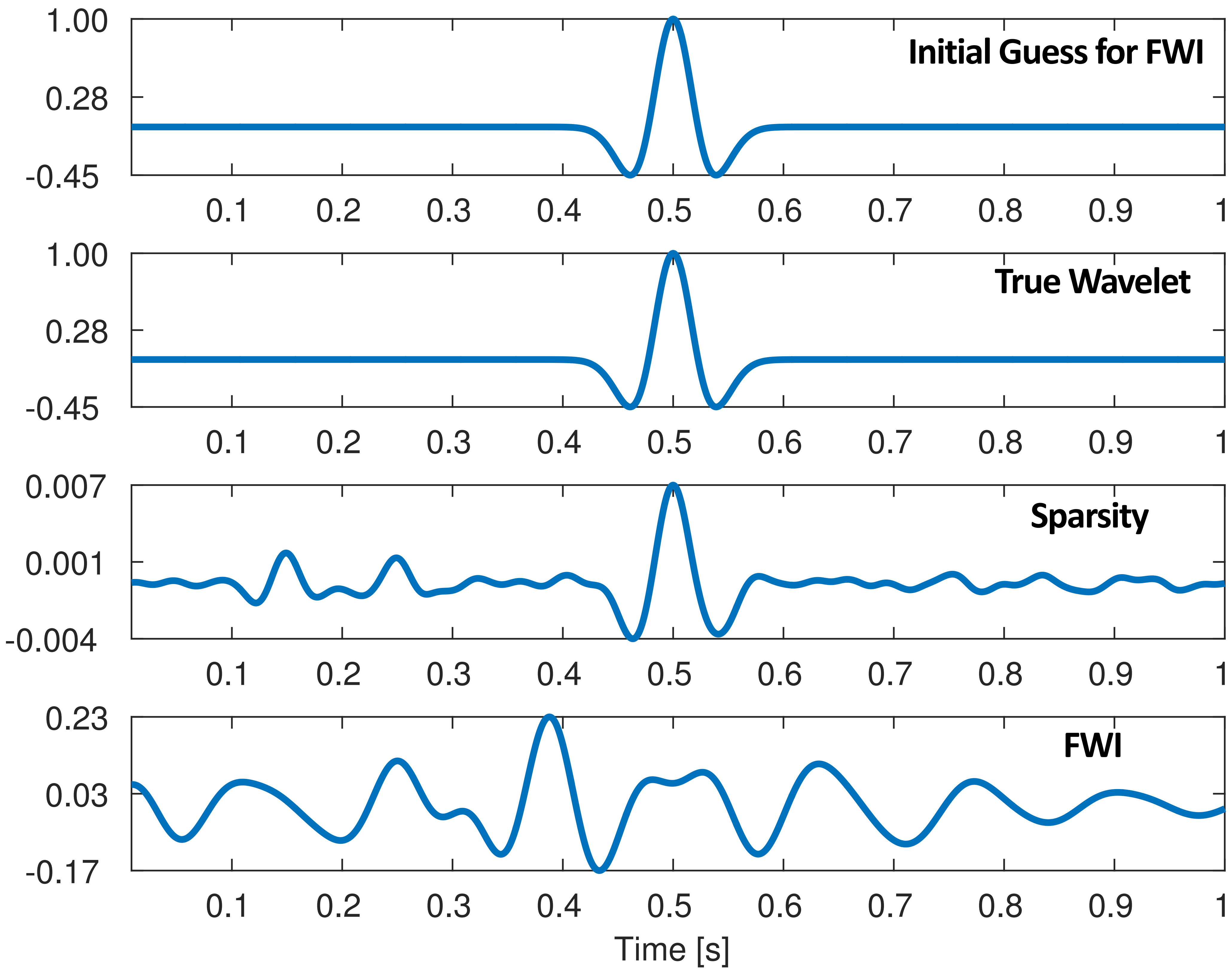
Spectrum



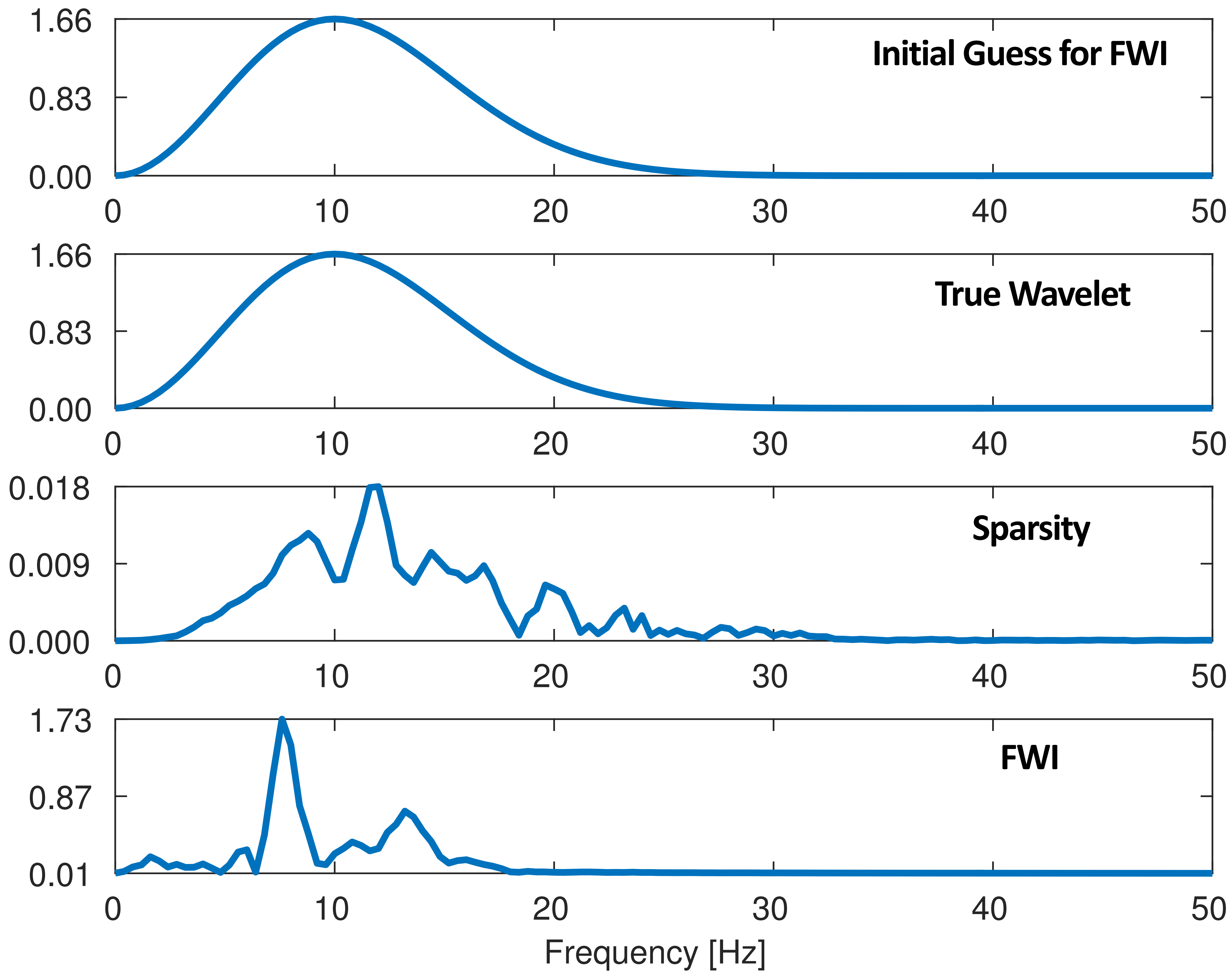
Location 6



Wavelet



Spectrum



Conclusions

A new methodology to simultaneously estimate

- source location
- source time function

Robust to noise

Conclusions

Works well with zero initial guess

Ability to work with realistic scenarios

- noisy data
- smooth background velocity model
- sources with different frequencies

Acknowledgements

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SINBAD