SINBAD CONSORTIUM 2011

Only dither: efficient marine acquisition "without" simultaneous sourcing

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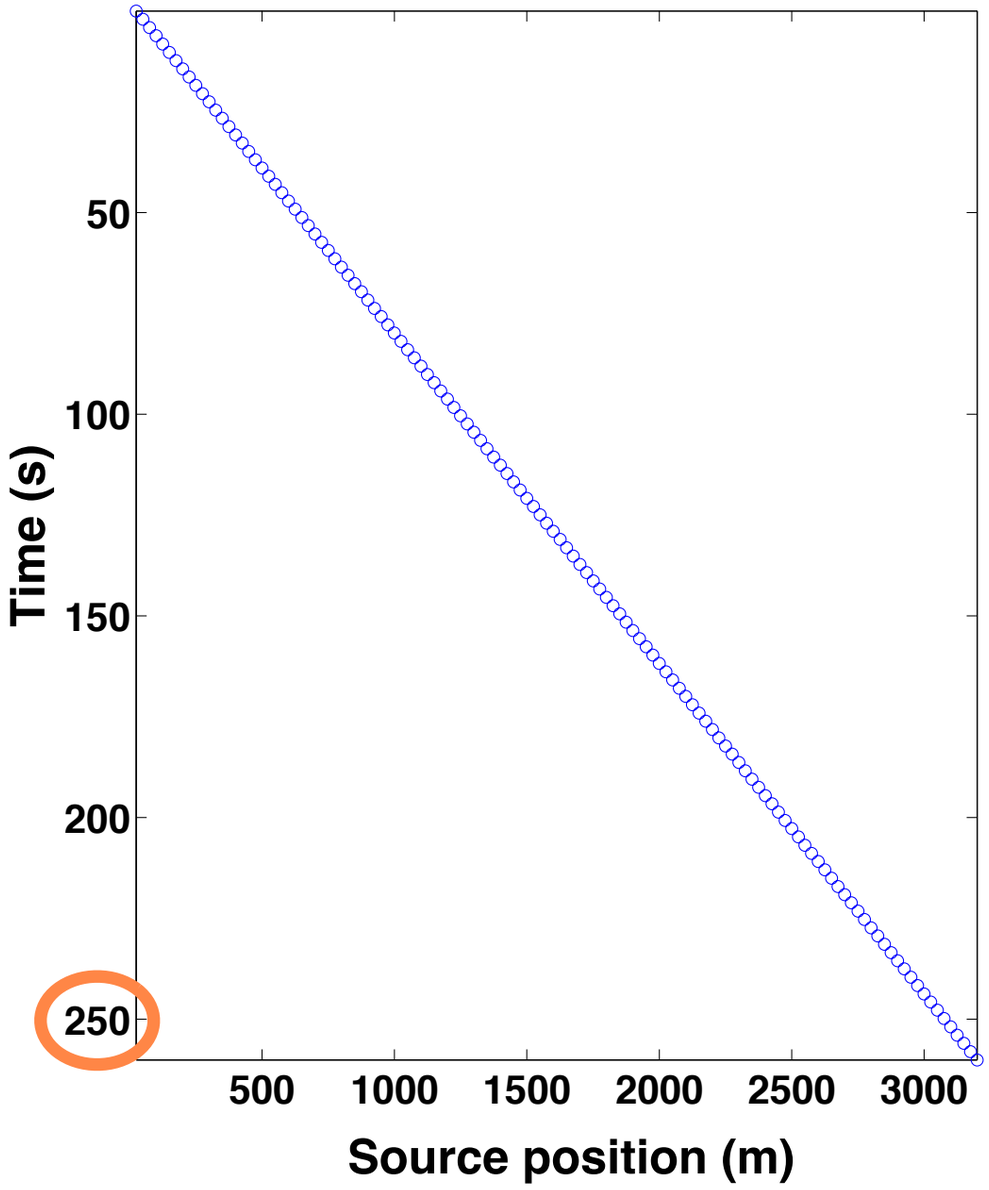
Joint work with Hassan Mansour, and Tim T. Y. Lin

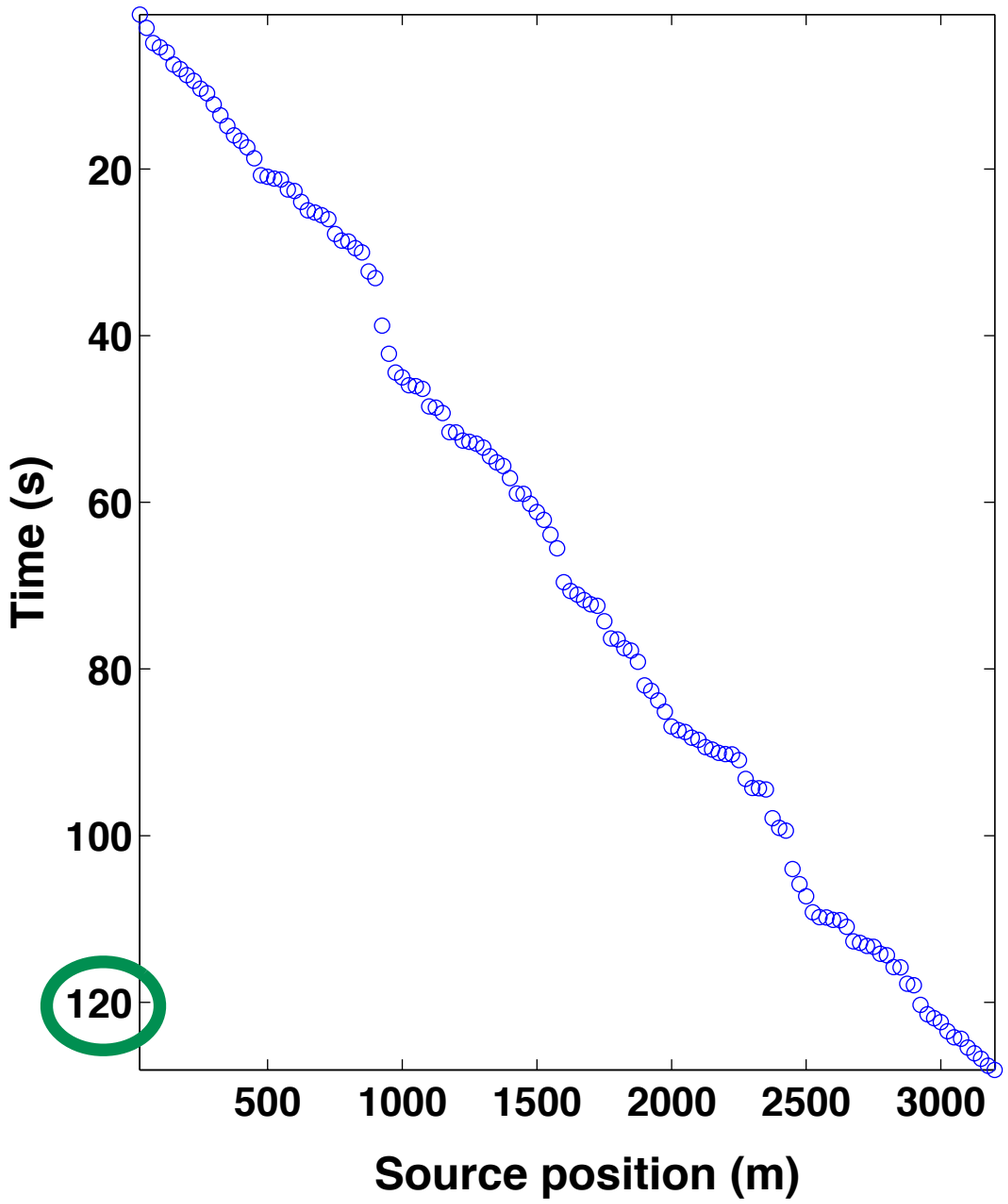
SLIM
University of British Columbia

Only dither

Conventional sequential acquisition

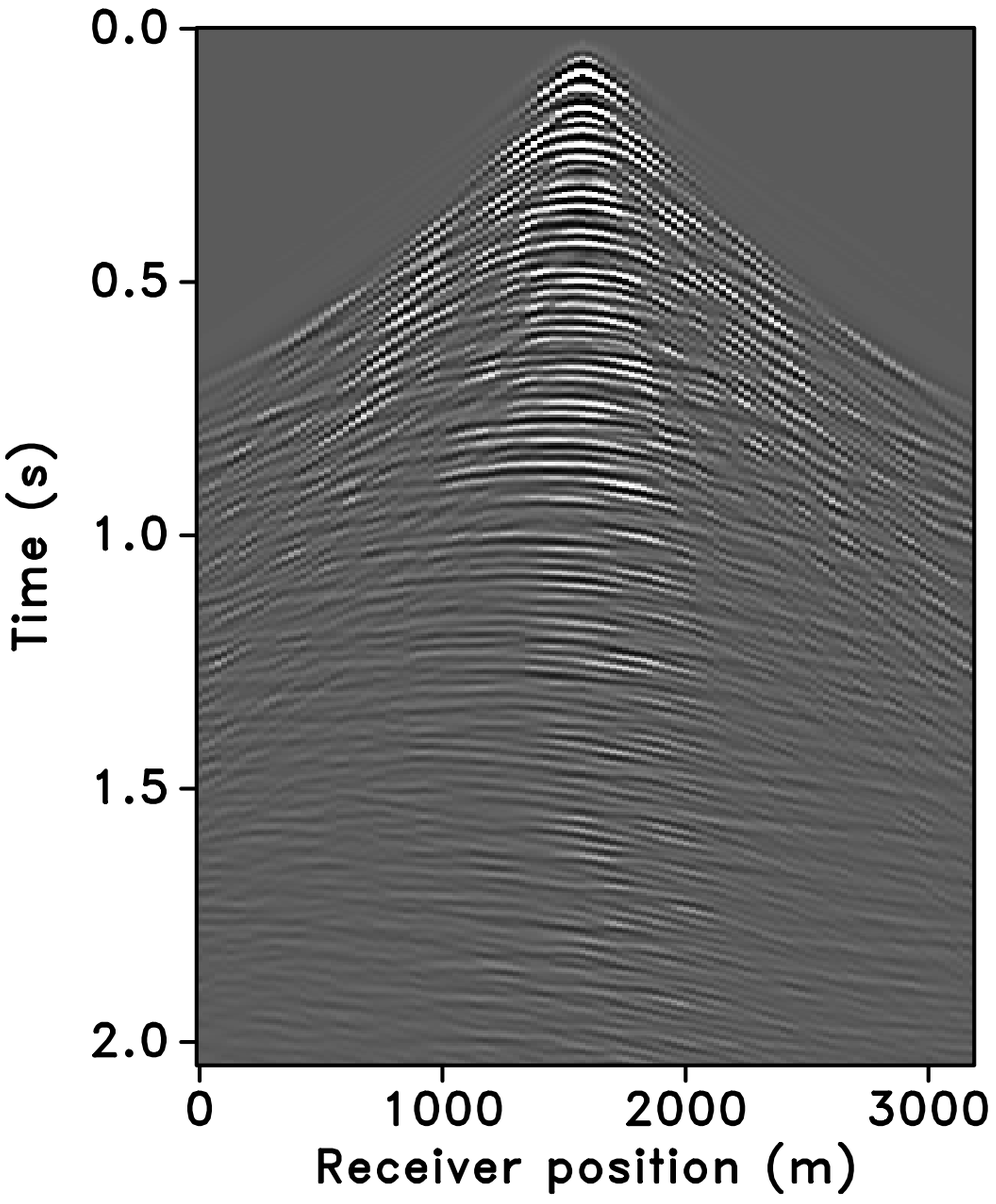


Random time-dithering



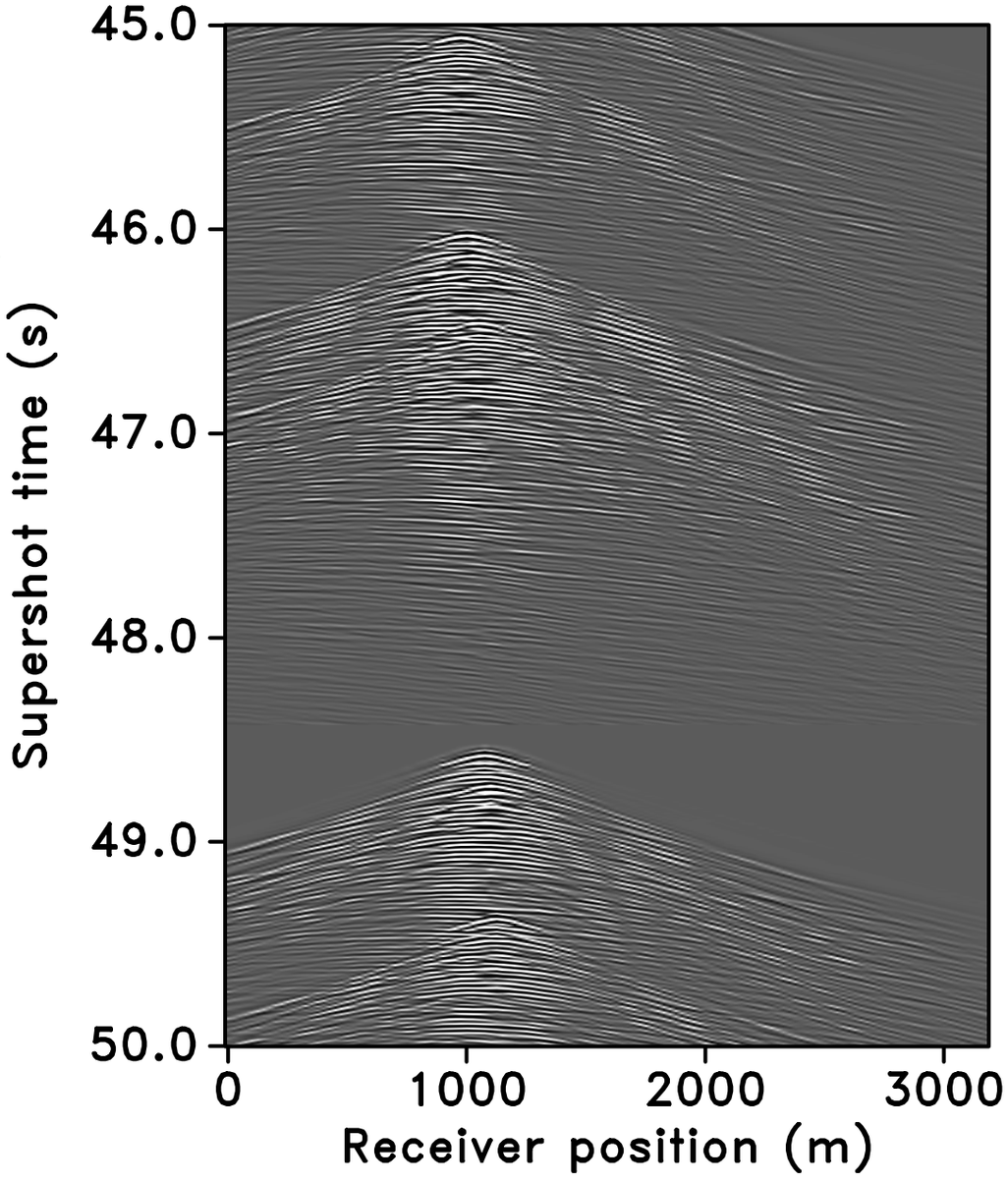
Only dither

Conventional sequential acquisition

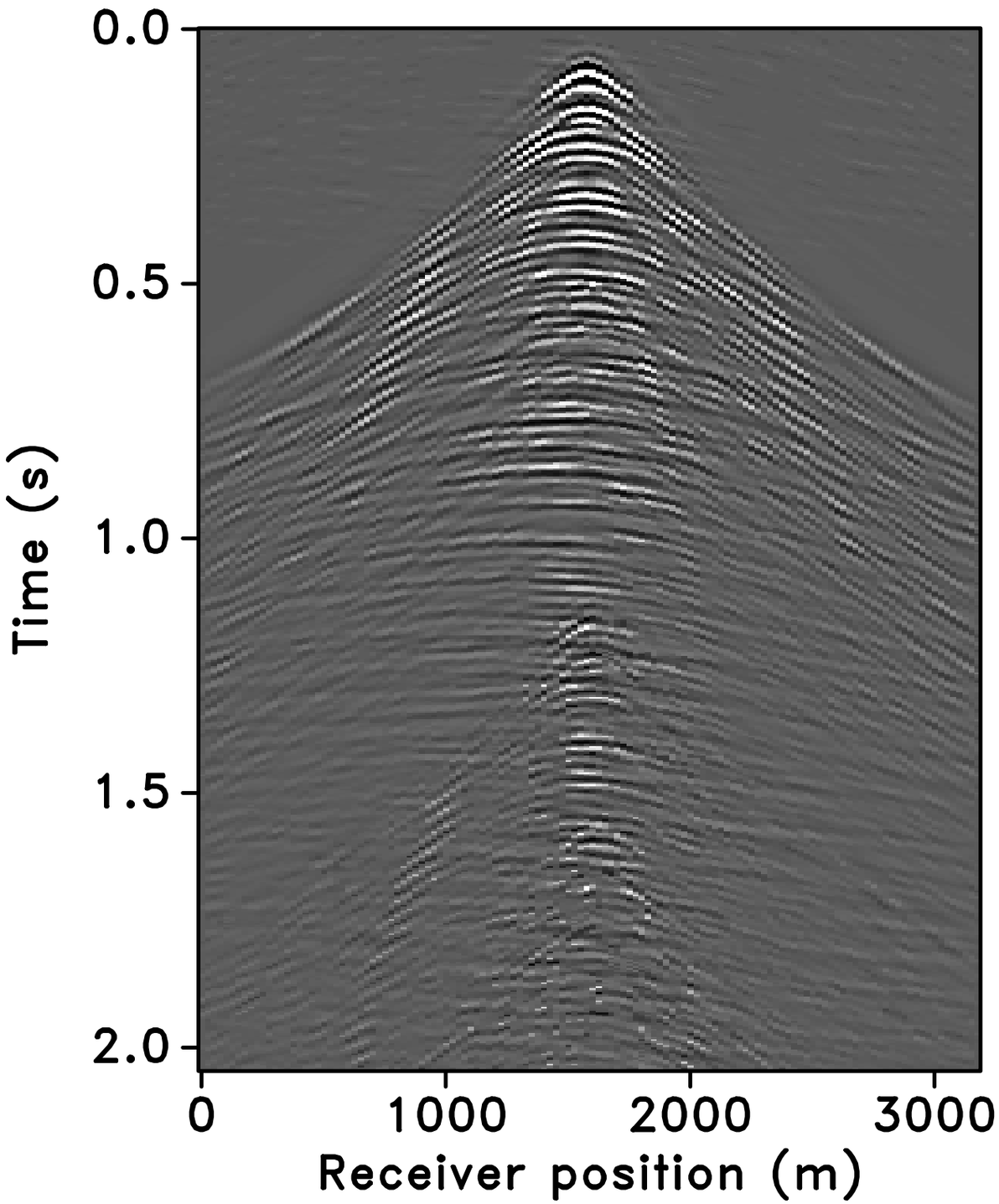


RECOVER

Random time-dithering

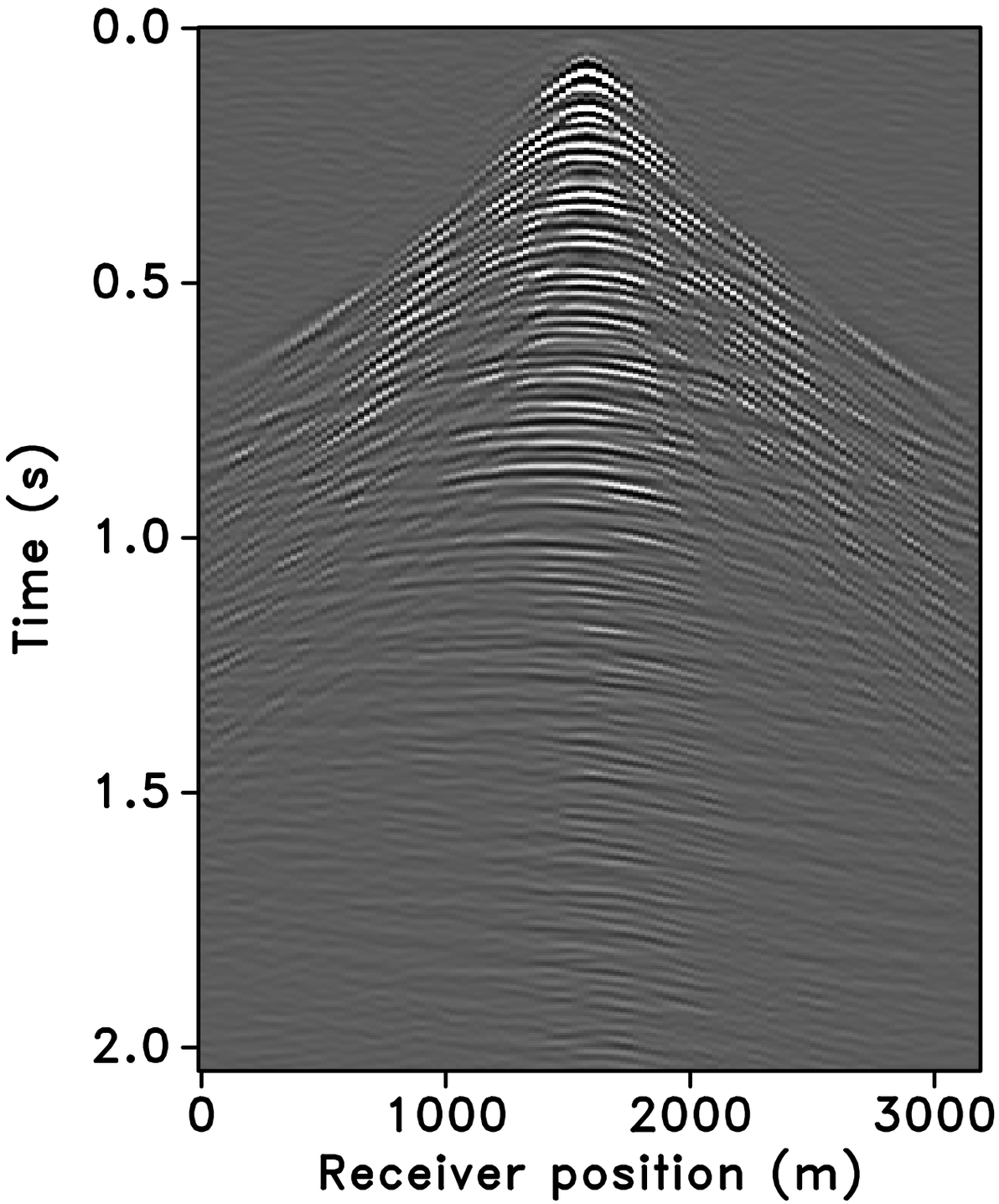


Conventional recovery



SNR = 3.92 dB

Sparsity-promoting recovery

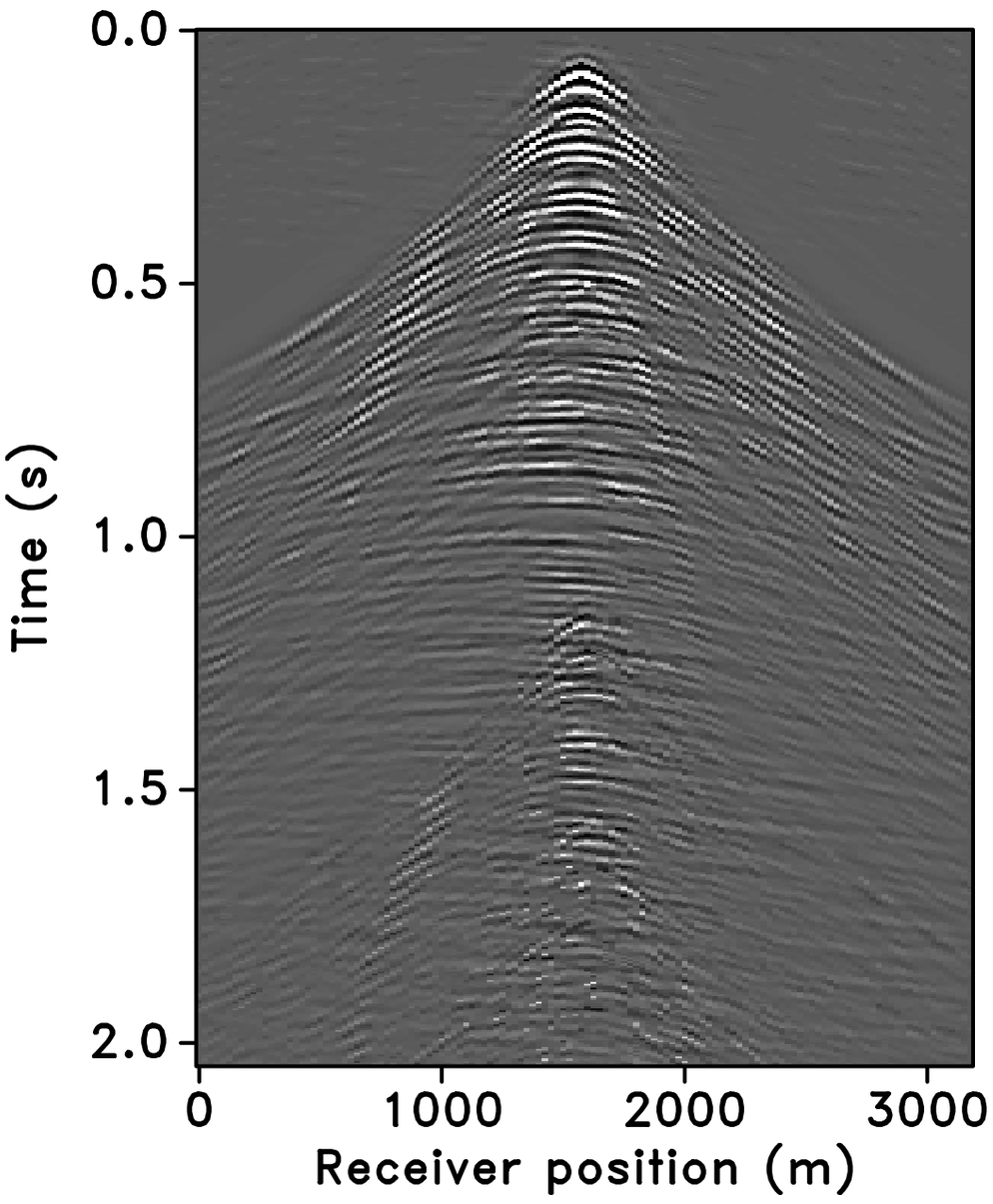


SNR = 8.06 dB

Motivation

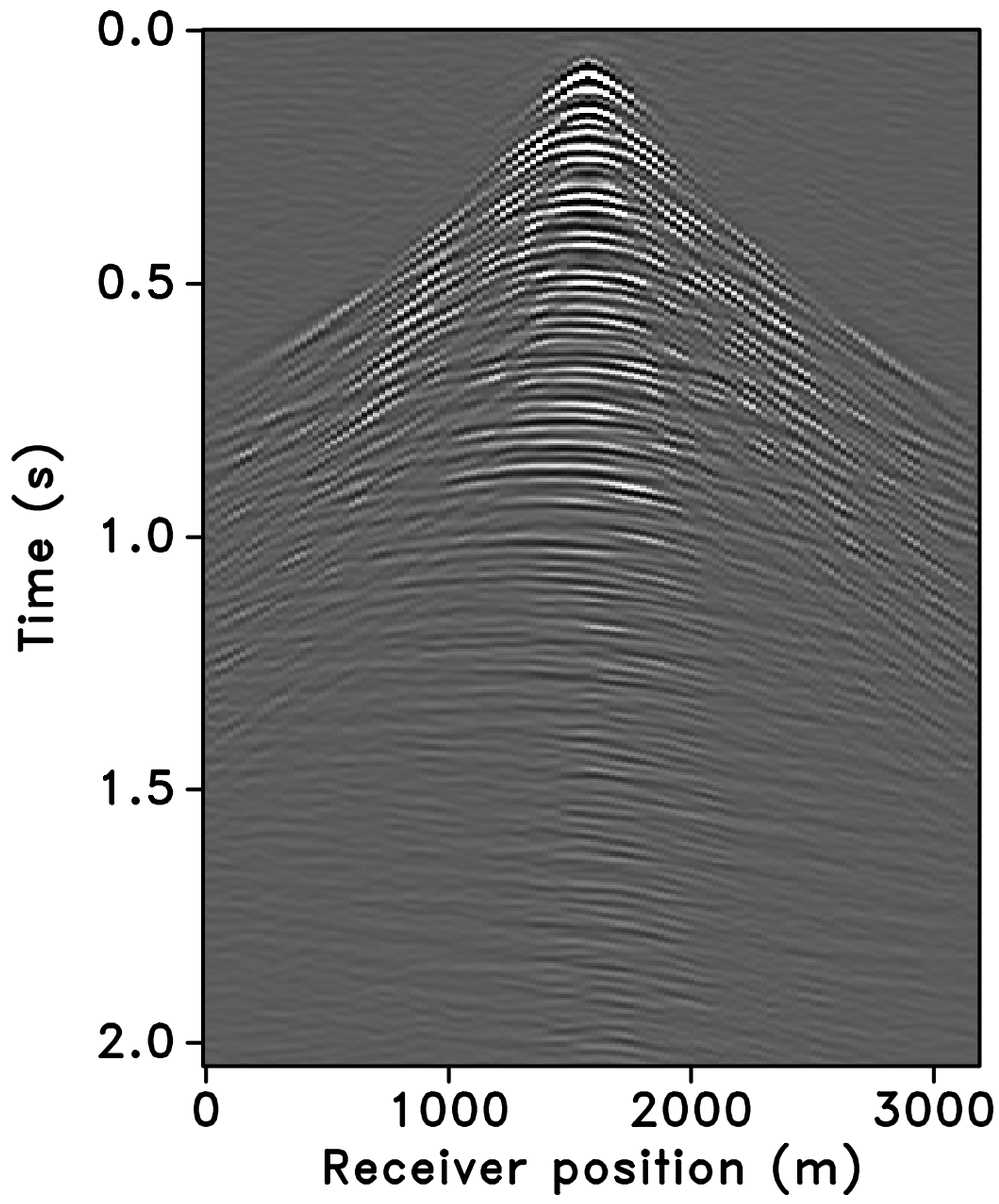
✗ Conventional recovery

SNR = 3.92 dB



✓ Sparsity-promoting recovery

SNR = 8.06 dB



Motivation

- Opportunity to rethink marine acquisition

- Concentrate on efficient acquisition "without" simultaneous sourcing

- Marine acquisition with ocean-bottom nodes

Outline

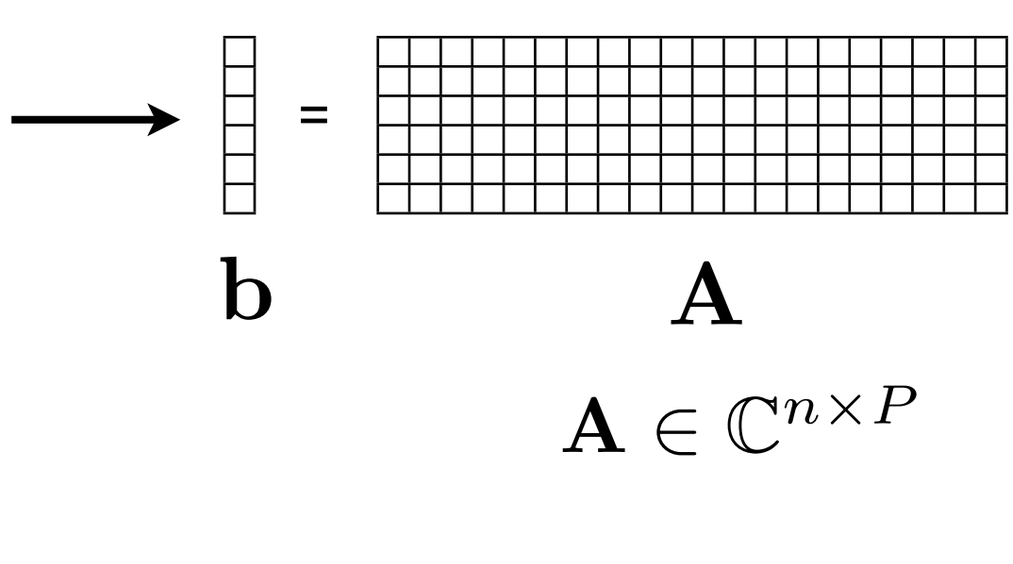
- Compressed sensing (CS) overview
  - design
  - recovery
- *Design* of *efficient* marine acquisition
- Experimental results of *sparsity*-promoting processing

Problem statement

Solve an *underdetermined* system of *linear* equations:

data
(measurements
/observations)

$\mathbf{b} \in \mathbb{C}^n$



$\mathbf{b}$ = $\mathbf{A}$ $\mathbf{x_0}$

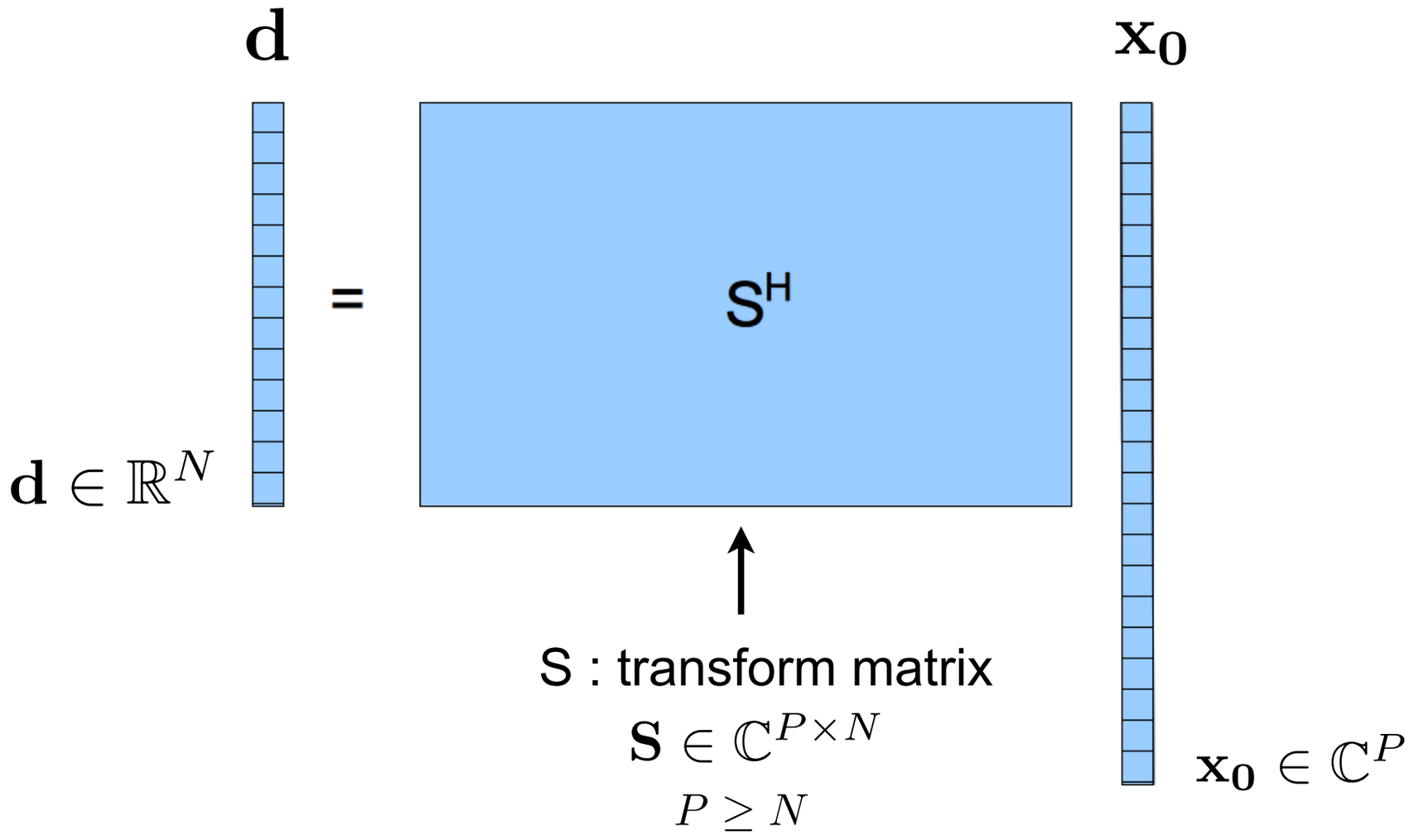
$\mathbf{A} \in \mathbb{C}^{n \times P}$

$\mathbf{x_0}$ ← unknown

$\mathbf{x_0} \in \mathbb{C}^P$

Compressed sensing

- acquisition paradigm for sparse signals
- in some transform domain



Compressed sensing

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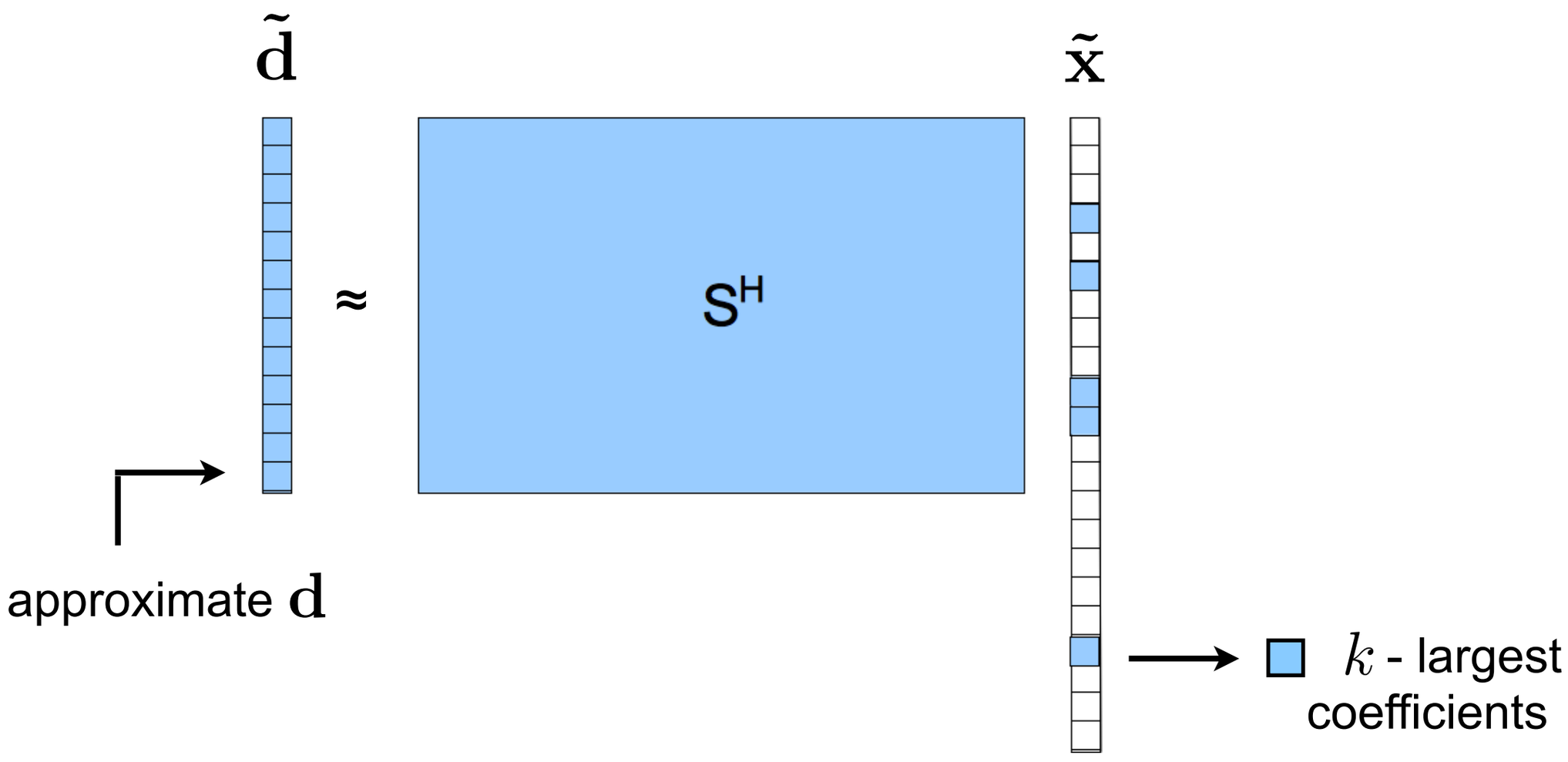
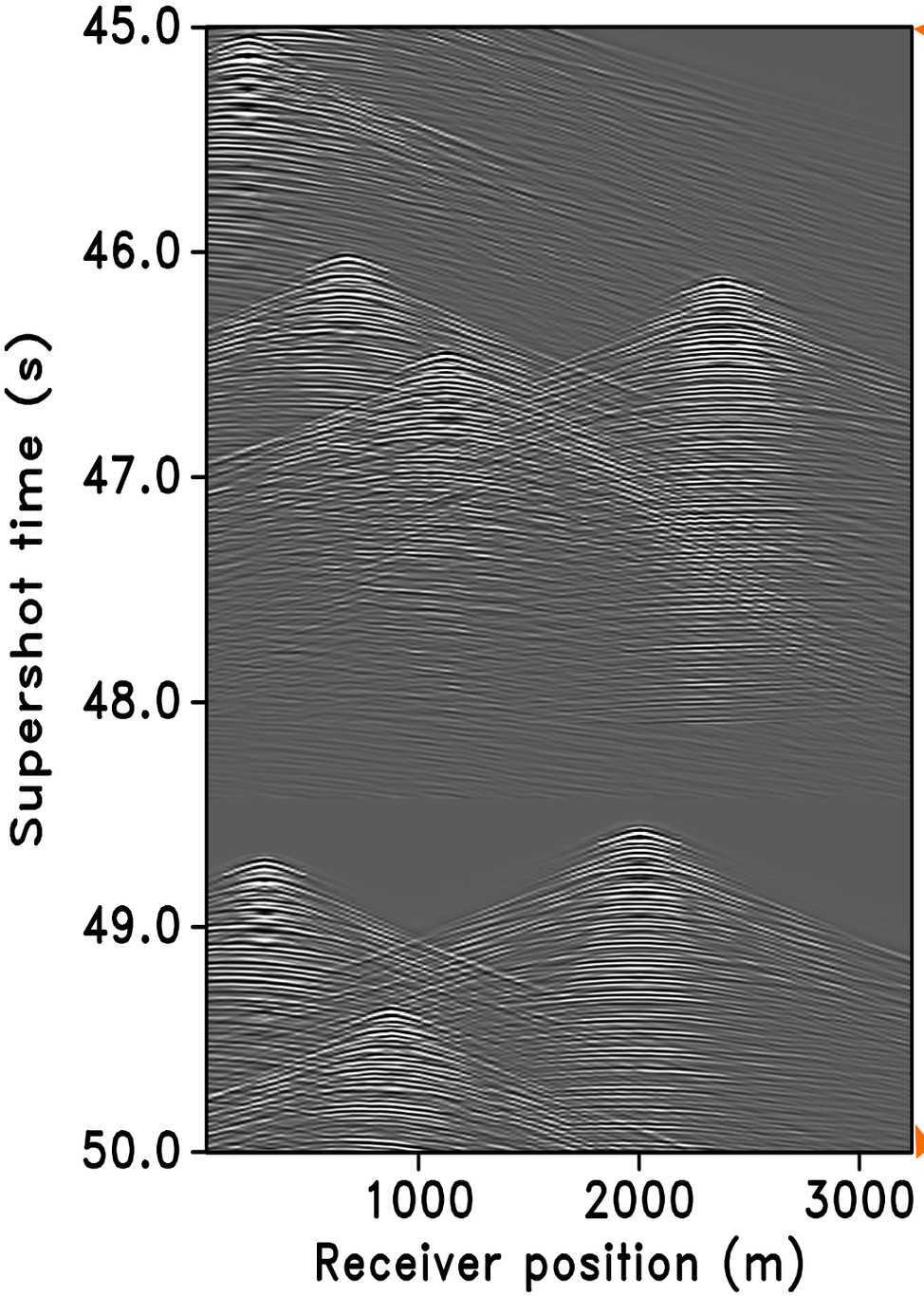
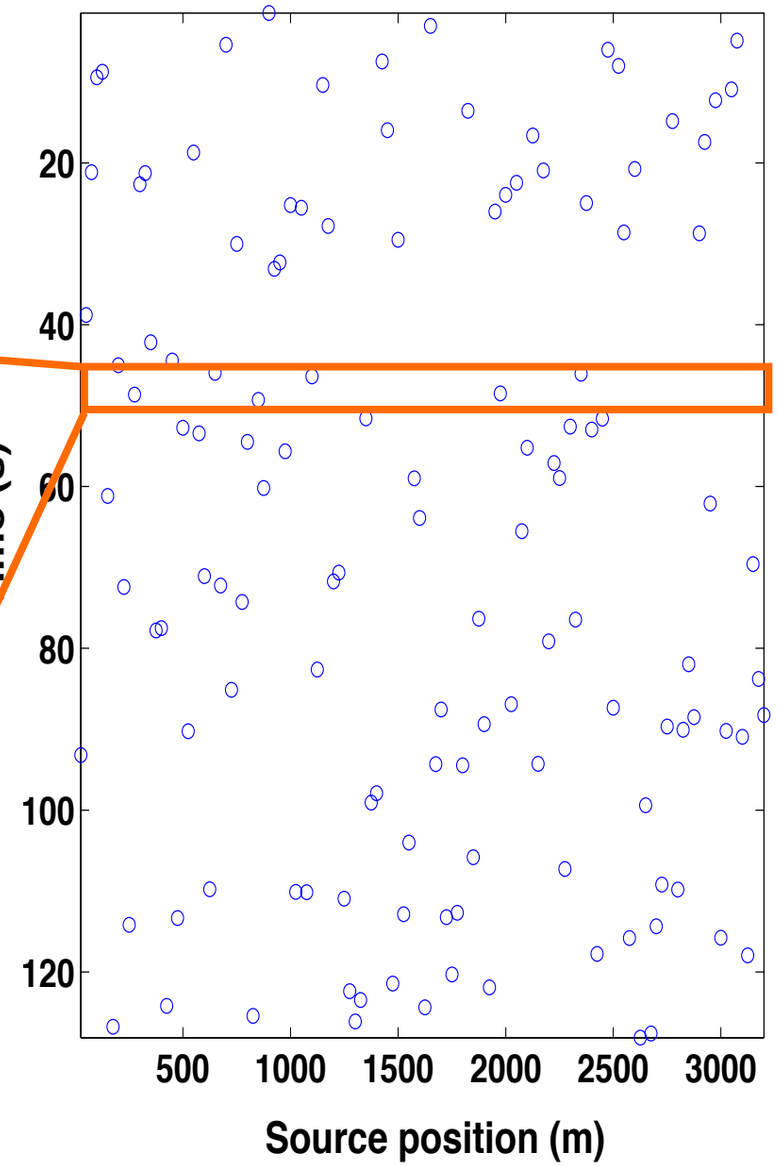


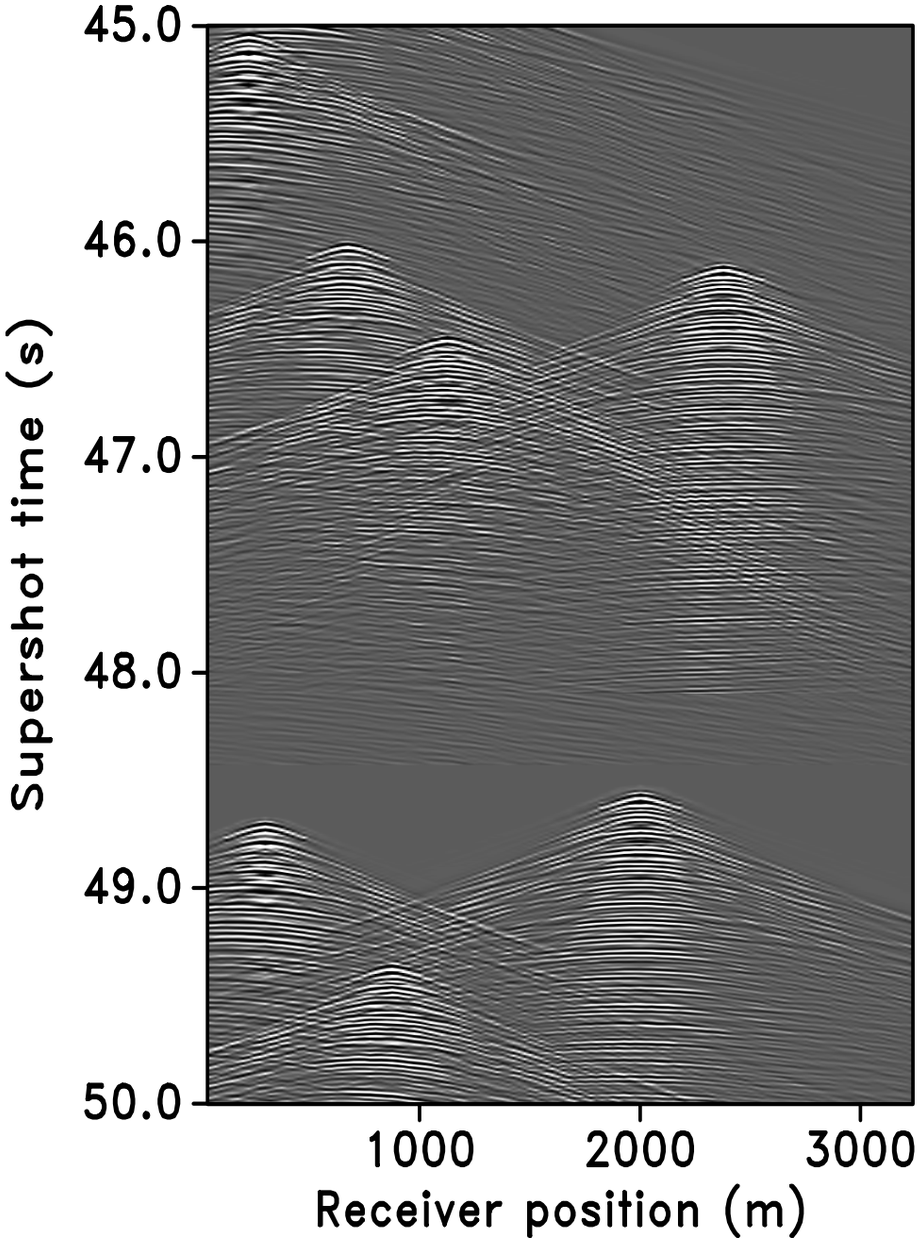
Bigger picture



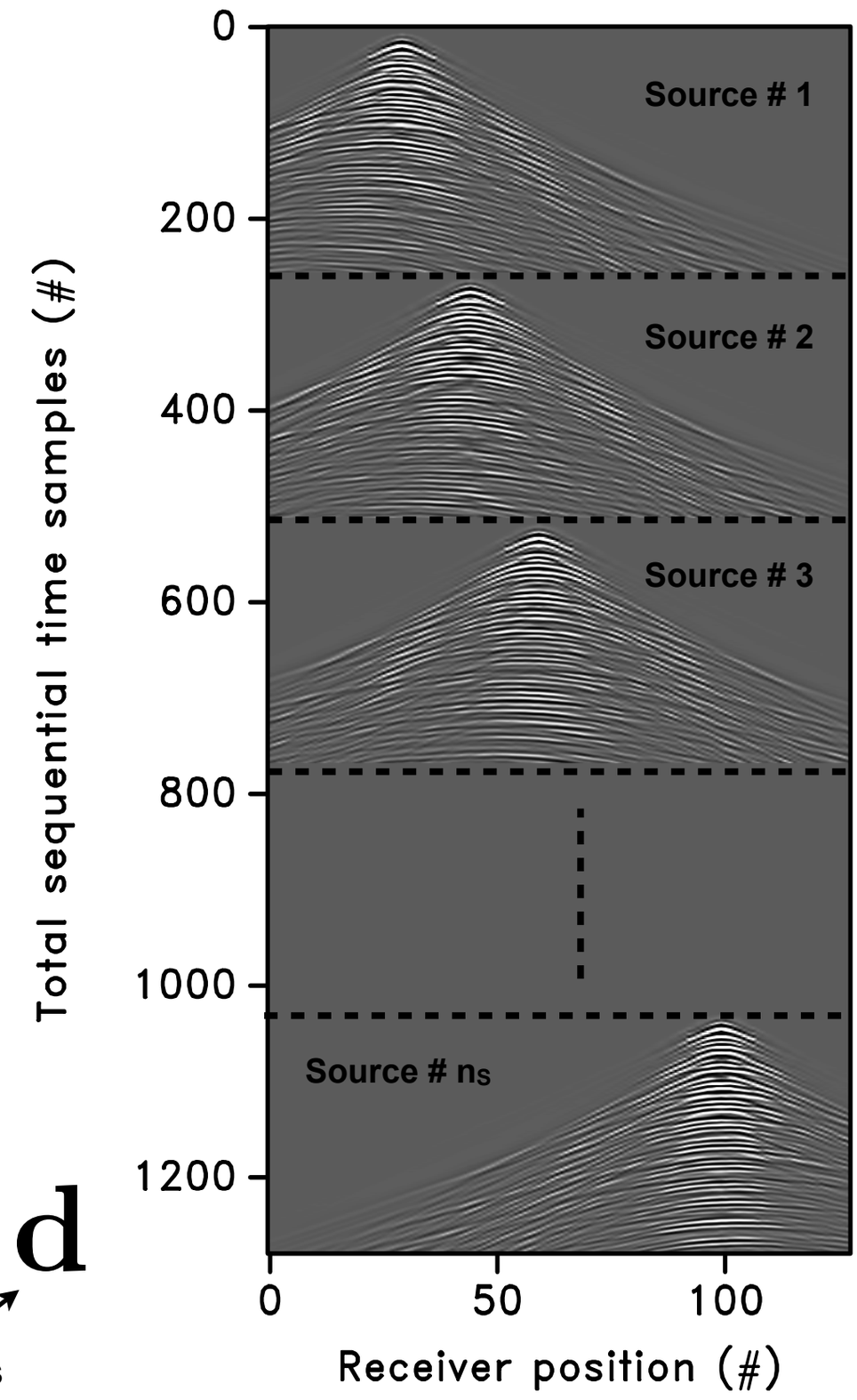


b SIMULTANEOUS MEASUREMENTS

Bigger picture



b

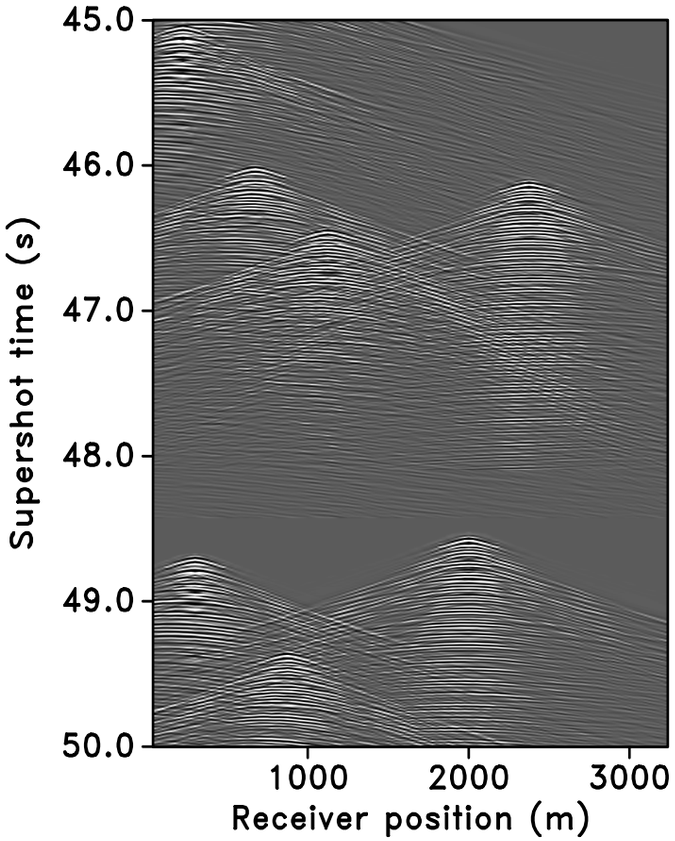


d

series of
sequential shots

Bigger picture

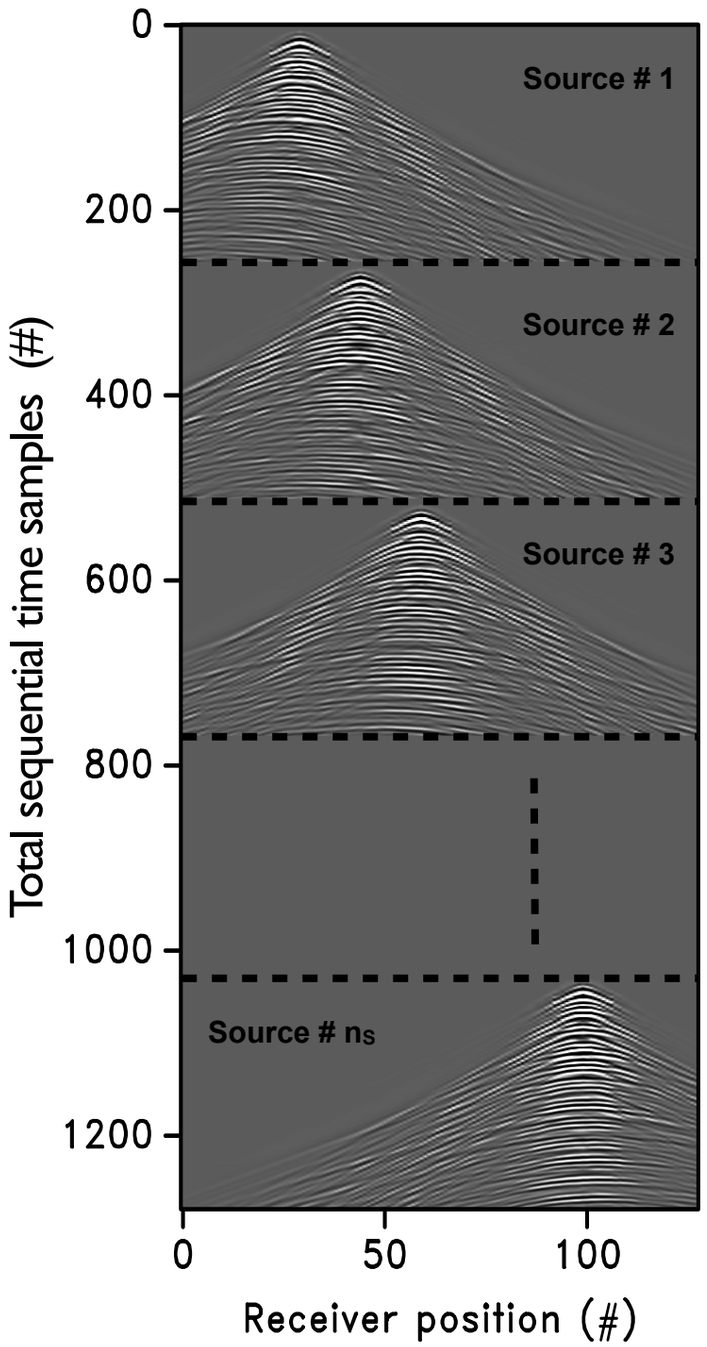
b



=

Simultaneous
measurement matrix

d



Bigger picture

$$\mathbf{b} = \boxed{\text{Simultaneous measurement matrix}} \times \mathbf{d}$$

$$\downarrow$$

$$\tilde{\mathbf{d}} \approx \mathbf{S}^{\mathbf{H}}\tilde{\mathbf{x}}$$

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$$\boxed{\text{Simultaneous measurement matrix}} \times \mathbf{S}^{\mathbf{H}}\tilde{\mathbf{x}}$$

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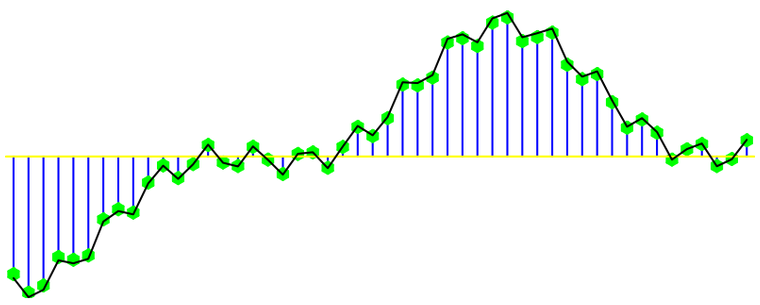
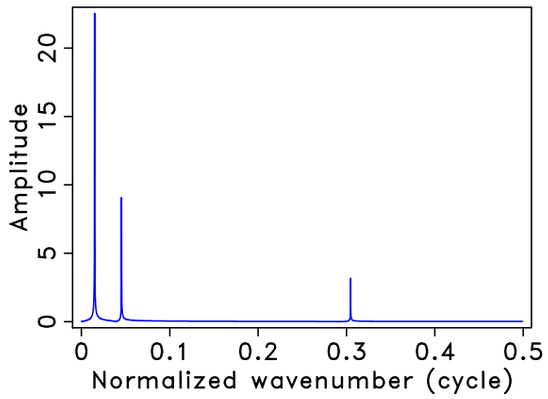
$$\downarrow$$

$$\underbrace{\text{Simultaneous measurement matrix} \quad \mathbf{S}^{\mathbf{H}}}_{\mathbf{A}}\ \tilde{\mathbf{x}}$$

Coarse sampling schemes



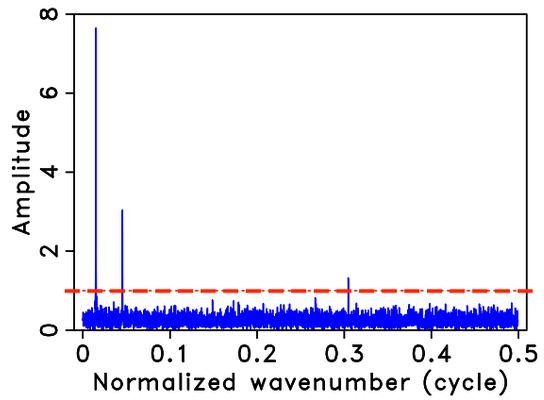
Fourier transform



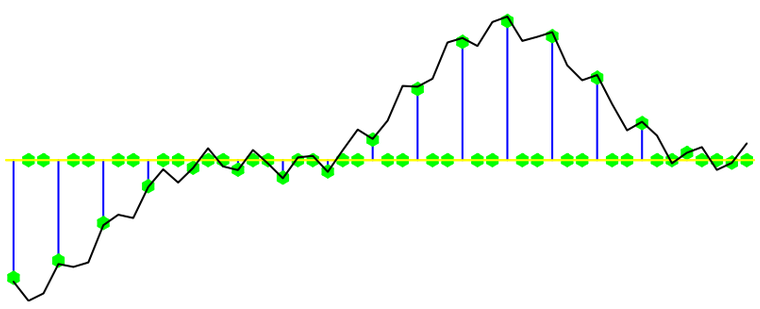
few significant coefficients

3-fold under-sampling

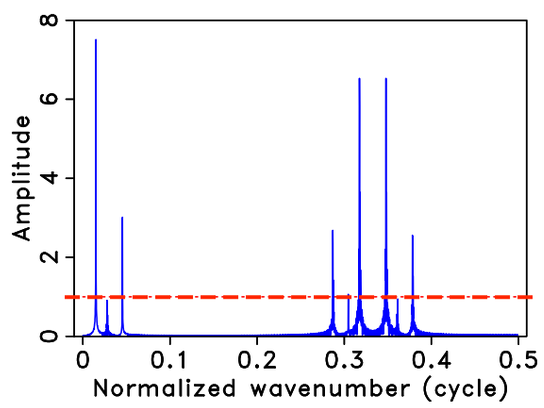
Fourier transform



✓ significant coefficients detected



Fourier transform



✗ ambiguity

[Hennenfent & Herrmann, ’08]

Mutual coherence

- measures the orthogonality of all columns of $\mathbf{A}$
- equal to the maximum off-diagonal element of the *Gram* matrix

Restricted isometry property (RIP)

- indicates whether every group of k columns of $\mathbf{A}$ are nearly orthogonal
- *restricted isometry constant* $0 < \delta_k < 1$ for which

$$(1 - \delta_k)\|\mathbf{x}\|_2^2 \leq \|\mathbf{A}\mathbf{x}\|_2^2 \leq (1 + \delta_k)\|\mathbf{x}\|_2^2$$

Sparse recovery

Solve the convex optimization problem (one-norm minimization):

$$\tilde{\mathbf{x}} = \underbrace{\arg\min_{\mathbf{x}} \|\mathbf{x}\|_1}_{\text{“sparsity”}} \quad \text{subject to} \quad \underbrace{\mathbf{A}\mathbf{x} = \mathbf{b}}_{\substack{\text{data-consistent} \\ \text{amplitude recovery}}}$$

Sparsity-promoting solver: $\mathbf{SPG}\ell_1$ [van den Berg and Friedlander, ‘08]

Recover single-source prestack data volume: $\tilde{\mathbf{d}} = \mathbf{S}^{\mathbf{H}}\tilde{\mathbf{x}}$

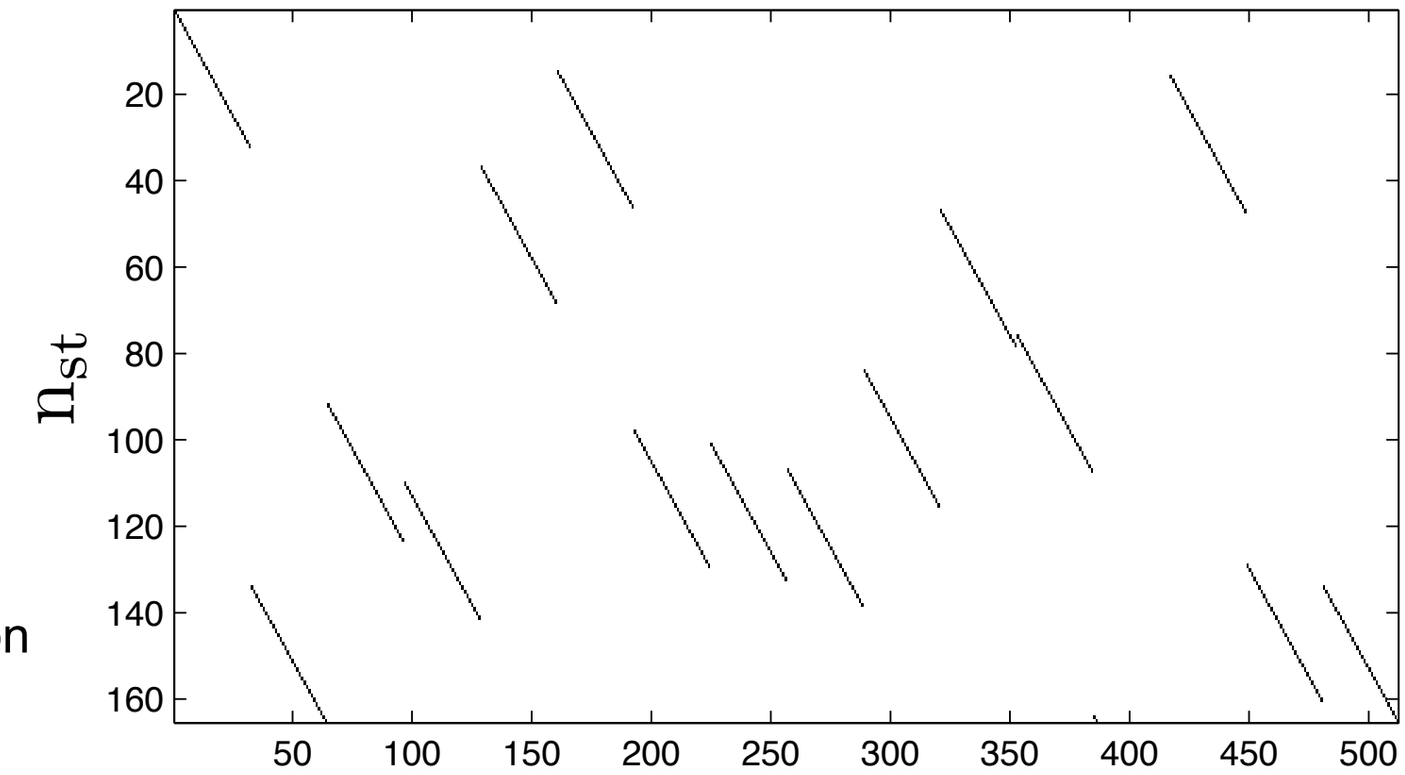
Outline

- Compressed sensing (CS) overview
  - design
  - recovery
- *Design* of *efficient* marine acquisition
- Experimental results of *sparsity*-promoting processing

“Ideal” simultaneous acquisition matrix

For a seismic line with N_s sources, N_r receivers, and N_t time samples, the sampling matrix is

$\mathbf{RM}$



samples recorded at each receiver during simultaneous acquisition

samples recorded at each receiver during sequential acquisition

[Mansour et.al., ‘11]

Bigger picture

$$\mathbf{b} = \boxed{\text{Simultaneous measurement matrix}} \times \mathbf{d}$$

$$\downarrow$$

$$\tilde{\mathbf{d}} \approx \mathbf{S}^{\mathbf{H}}\tilde{\mathbf{x}}$$

$$\downarrow$$

$$\boxed{\text{Simultaneous measurement matrix}} \times \mathbf{S}^{\mathbf{H}}\tilde{\mathbf{x}}$$

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Bigger picture

$$\mathbf{b} = \boxed{\mathbf{RM}} \times \mathbf{d}$$

$$\downarrow$$

$$\tilde{\mathbf{d}} \approx \mathbf{S}^{\mathbf{H}}\tilde{\mathbf{x}}$$

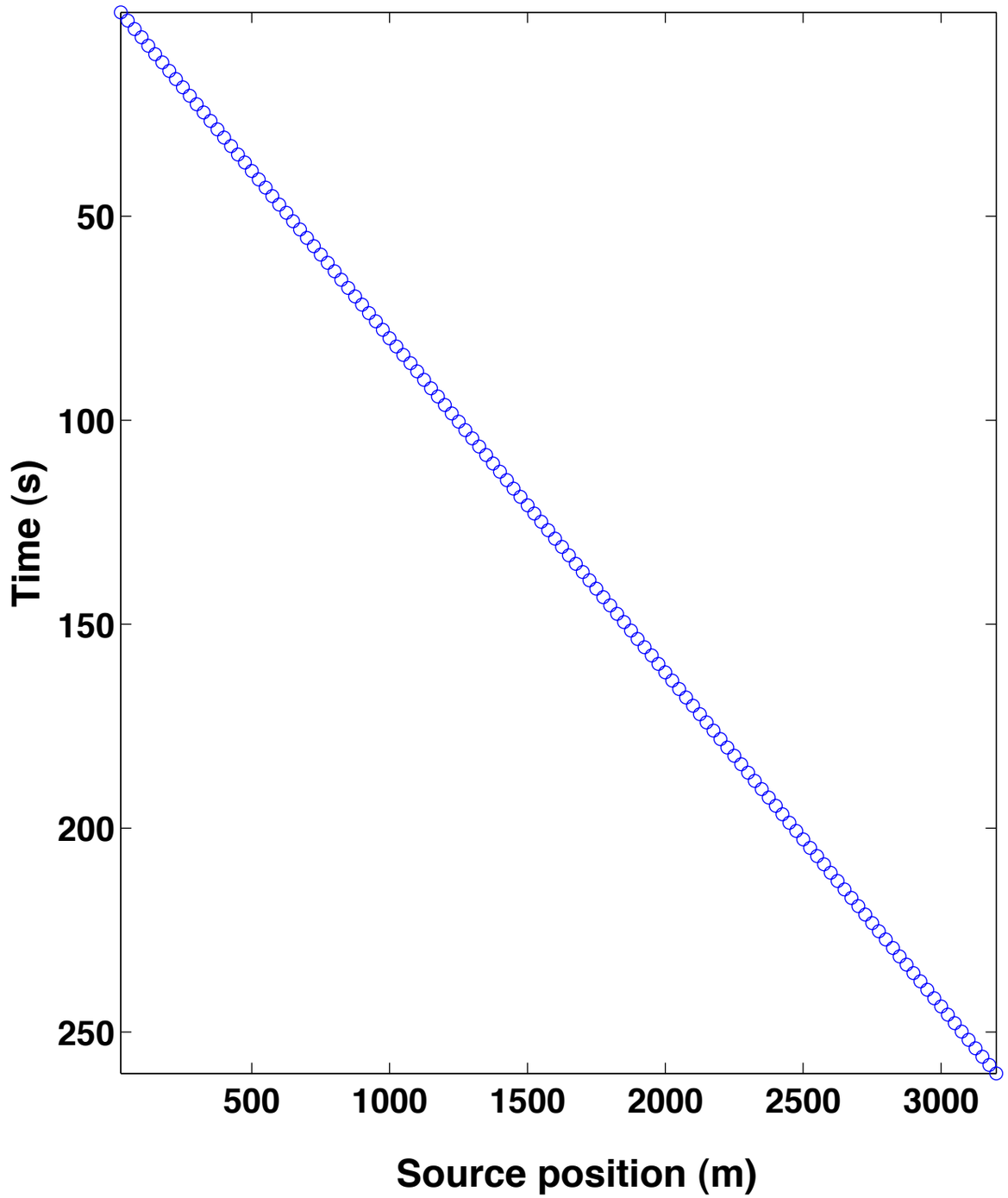
$$\downarrow$$

$$\boxed{\mathbf{RM}} \times \mathbf{S}^{\mathbf{H}}\tilde{\mathbf{x}}$$

$$\downarrow$$

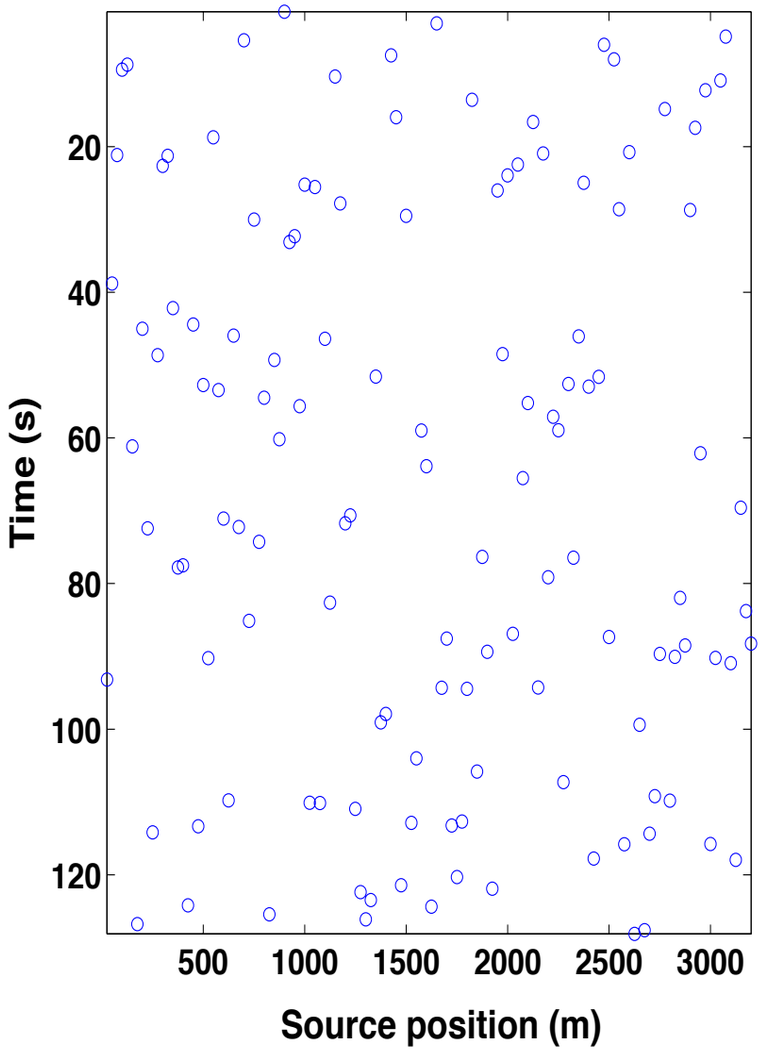
$$\underbrace{\boxed{\mathbf{A}}}_{\text{“Compressive sampling matrix”}} \leftarrow \tilde{\mathbf{x}}$$

Conventional sequential acquisition

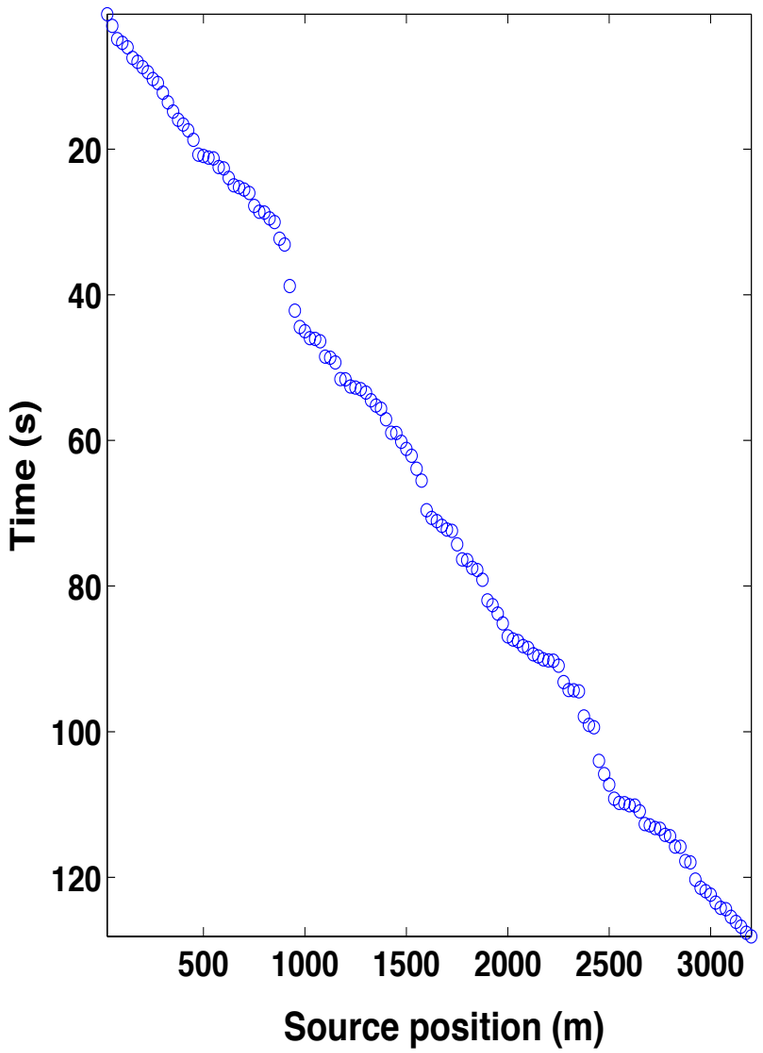


Sampling schemes

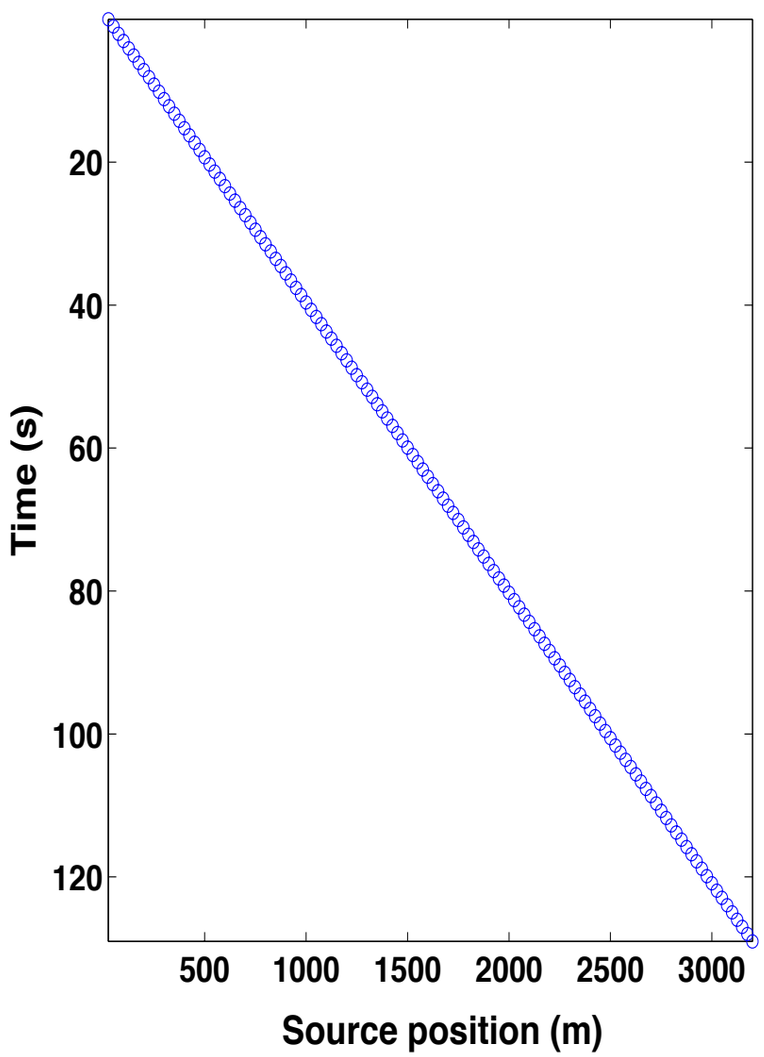
"Ideal" simultaneous acquisition



Random time-dithering

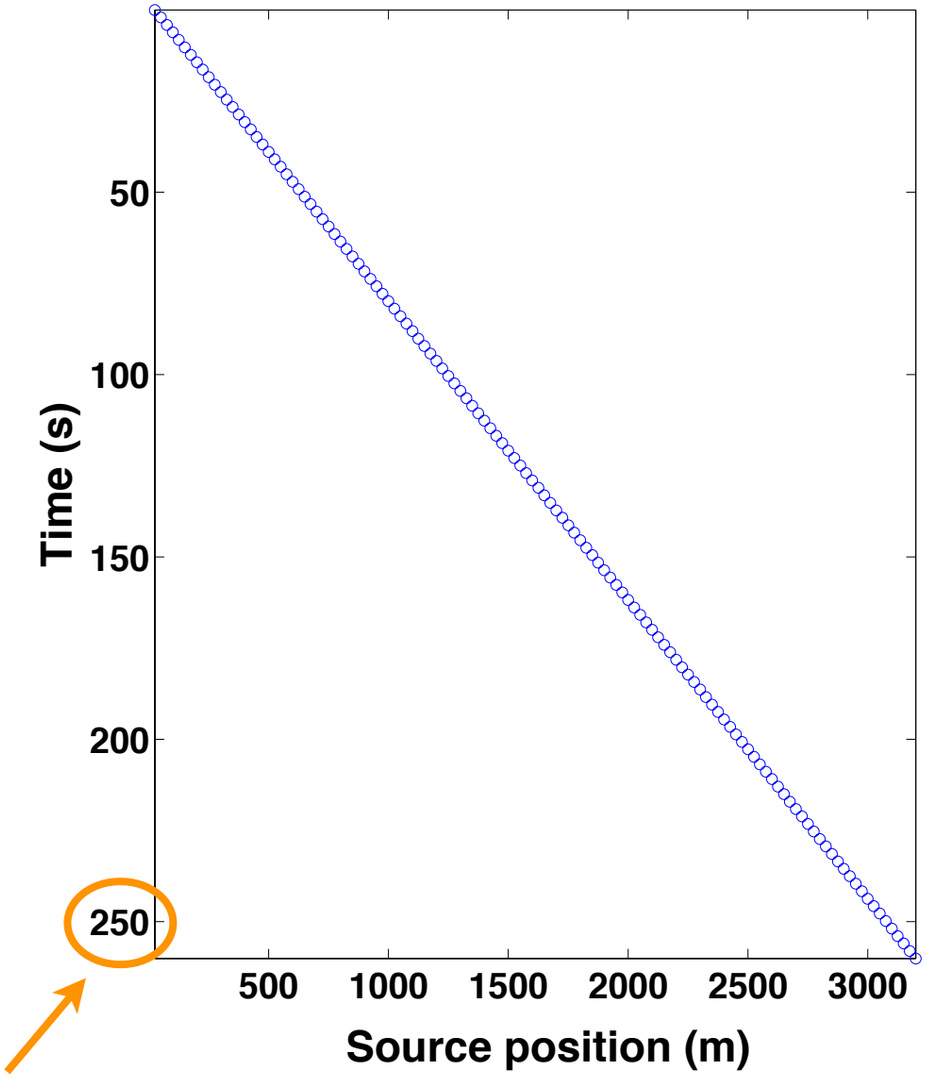


Periodic time-dithering



Sequential vs. simultaneous sources

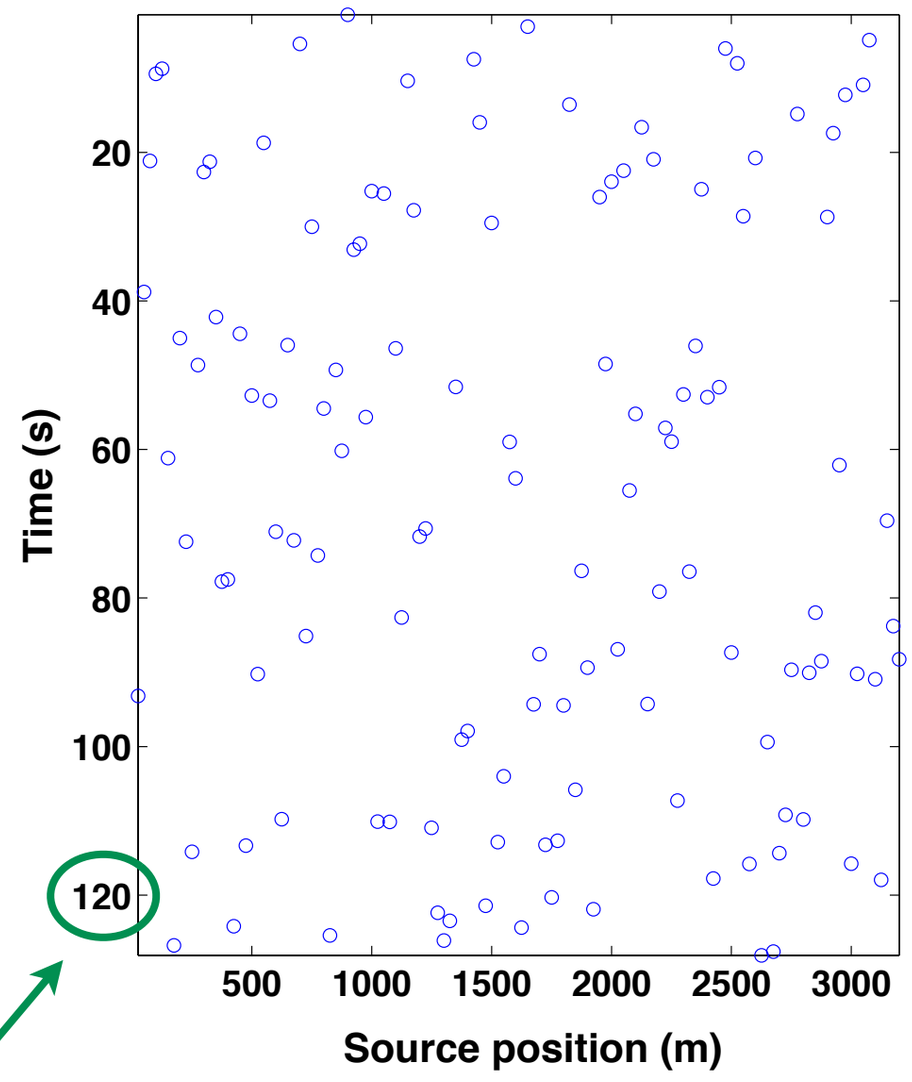
Conventional sequential acquisition



Conventional survey time:

$$t = N_s \times N_t$$

"Ideal" simultaneous acquisition

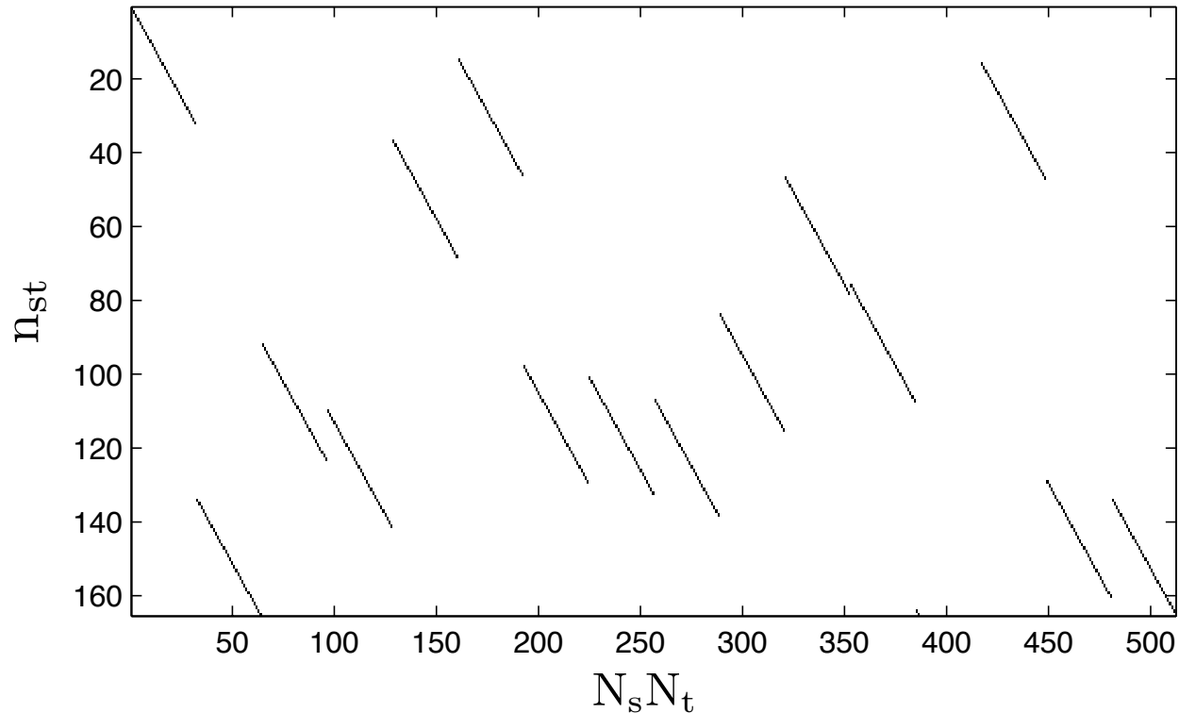


Theoretical survey time:

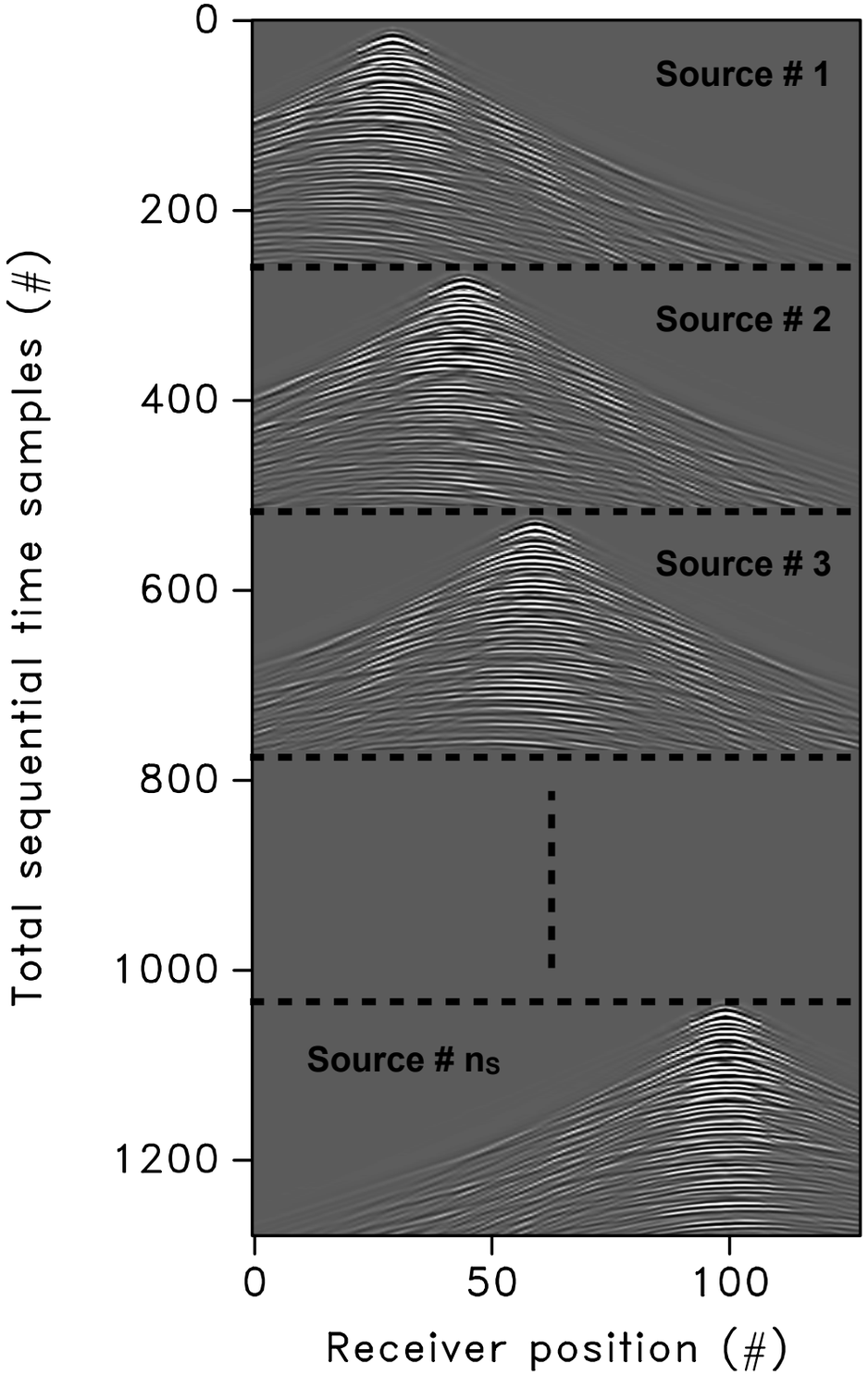
$$t = n_{st} \ll n_s \times N_t$$

"Ideal" simultaneous acquisition

$\mathbf{RM}$

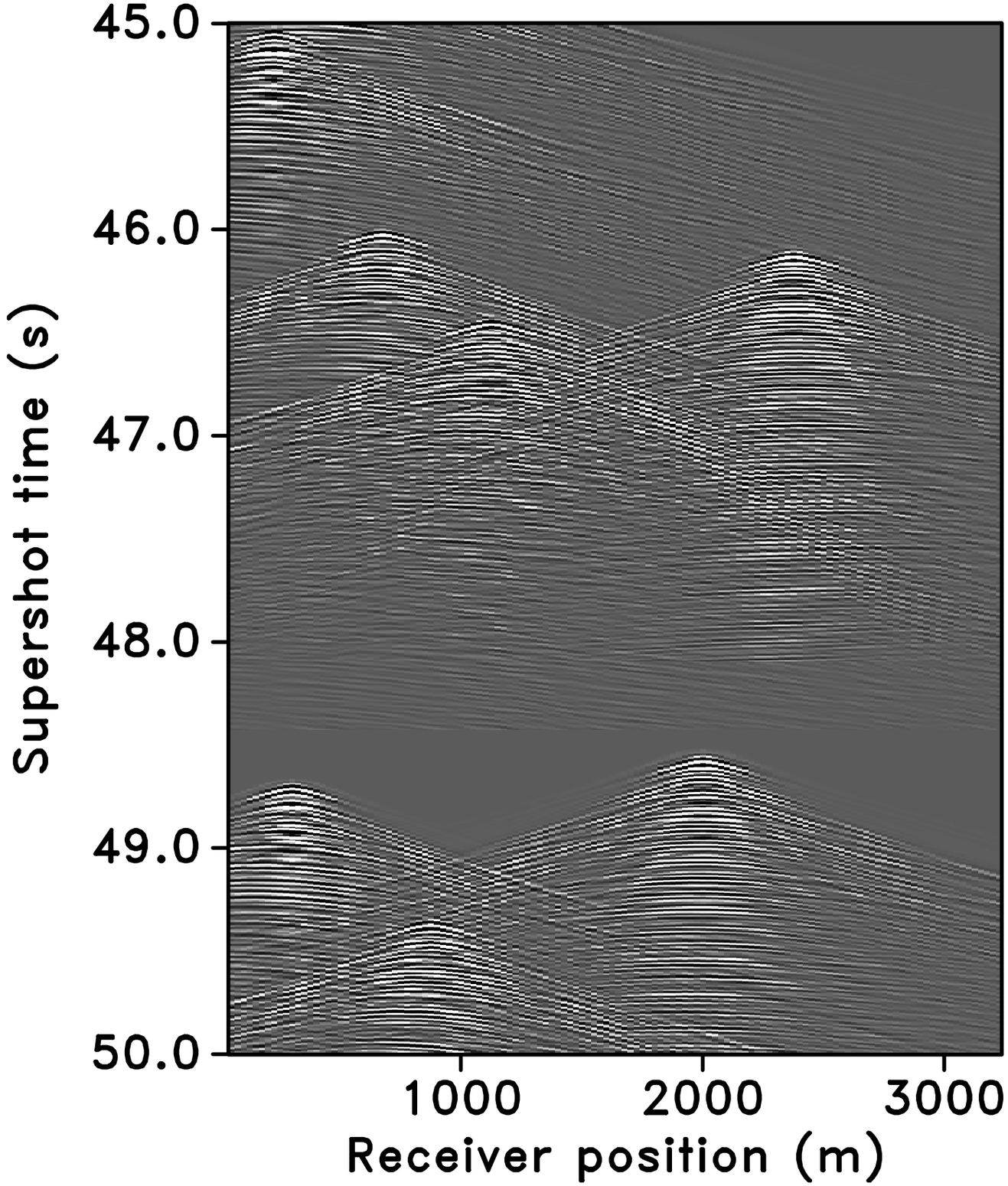


$\mathbf{d}$



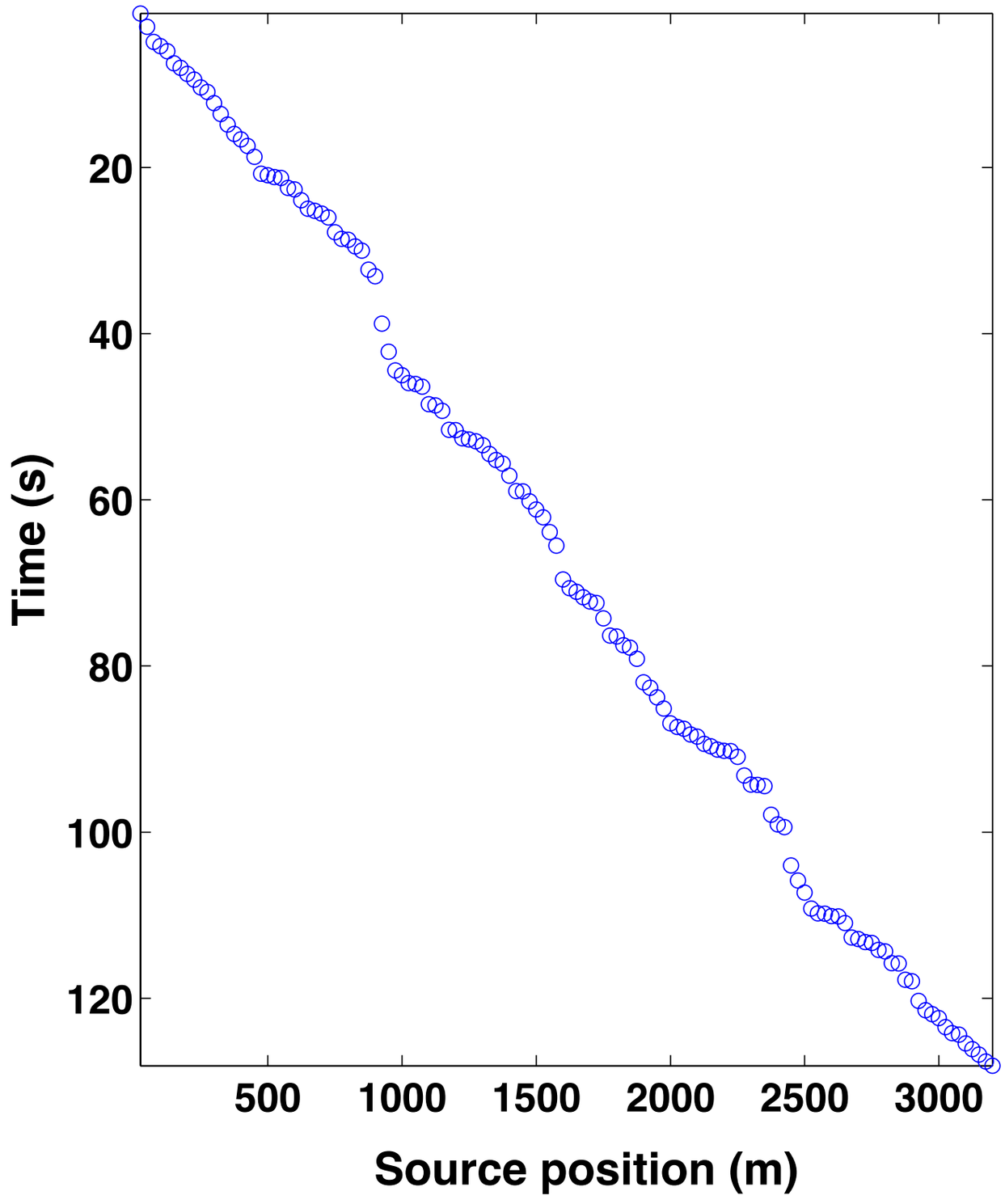
series of sequential shots →

“Ideal” simultaneous acquisition



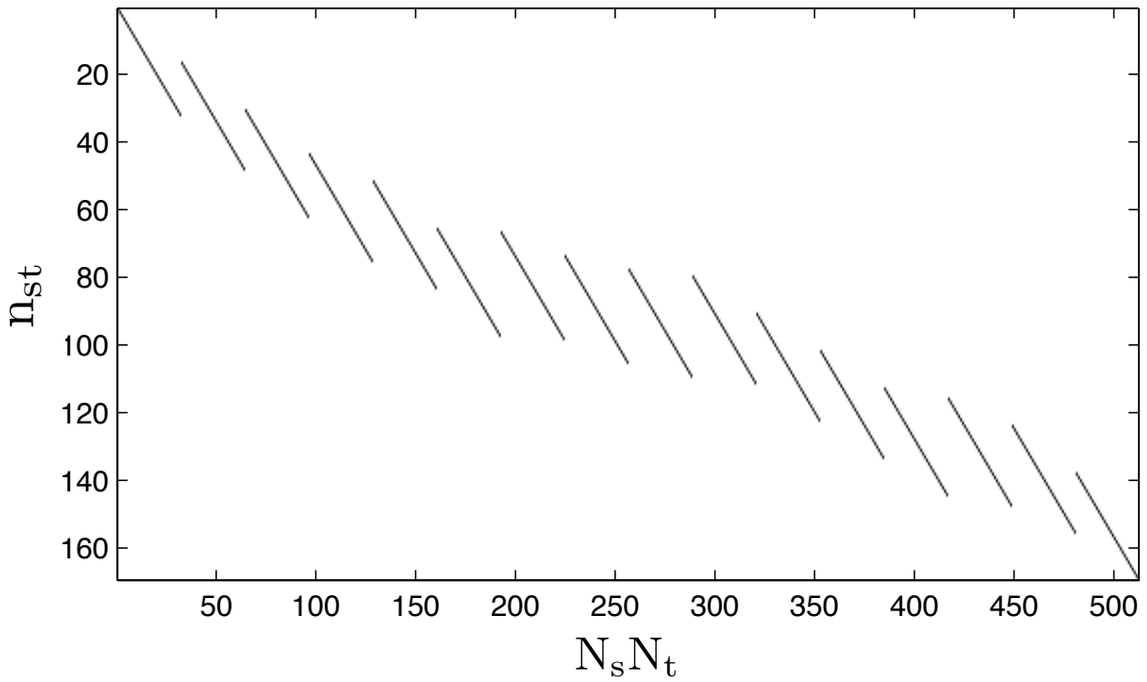
b

Random time-dithering



Random time-dithering

RM



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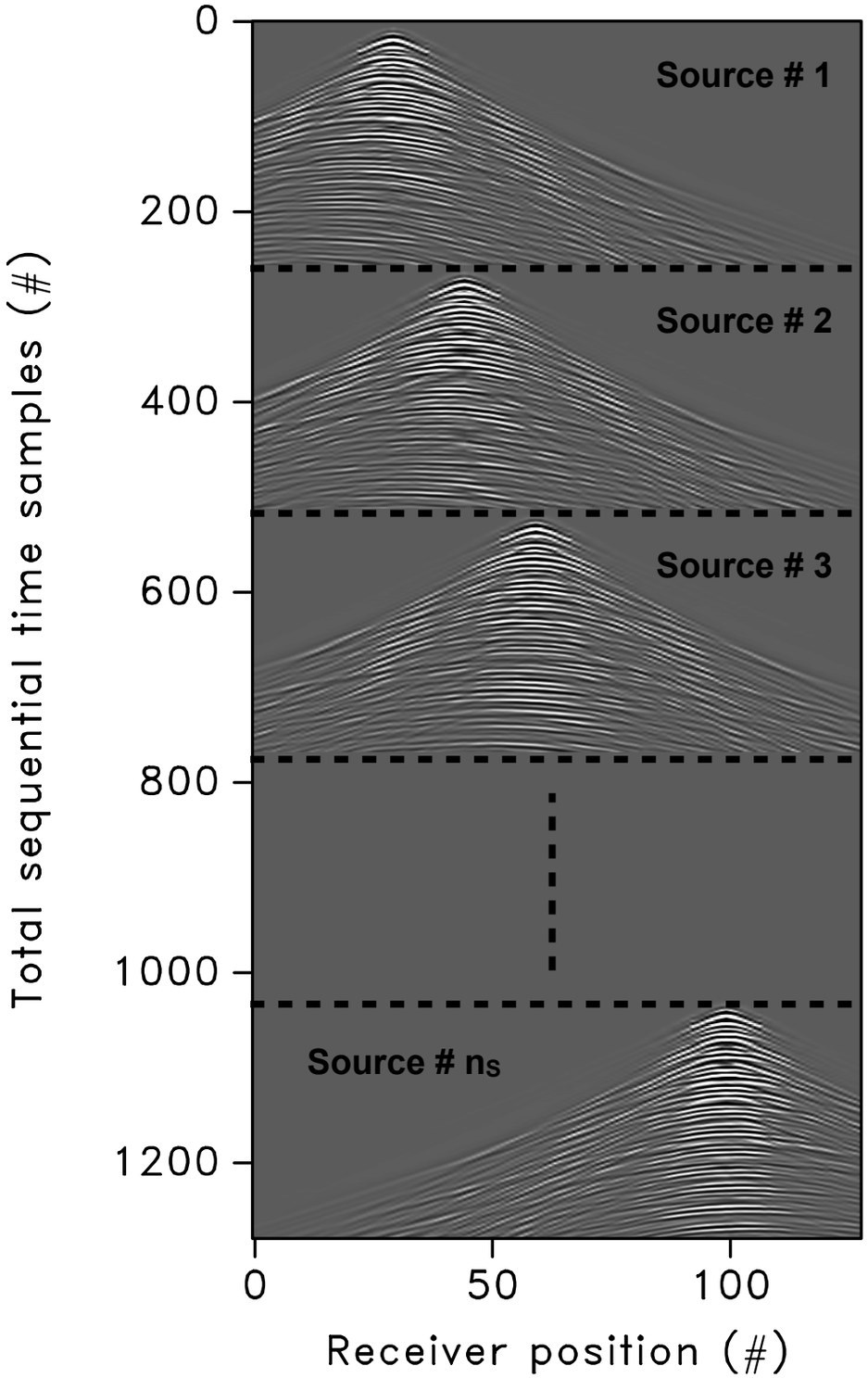
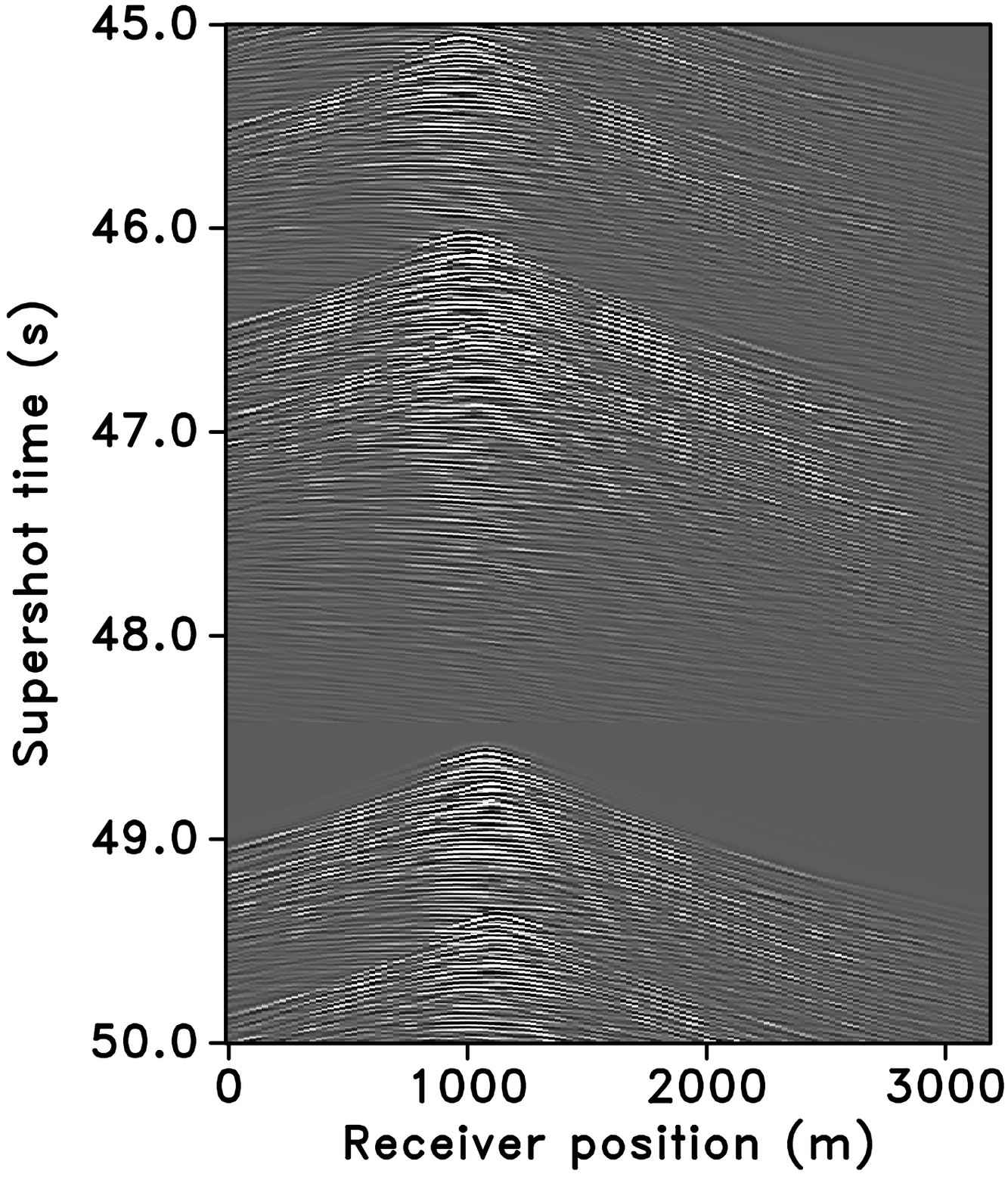


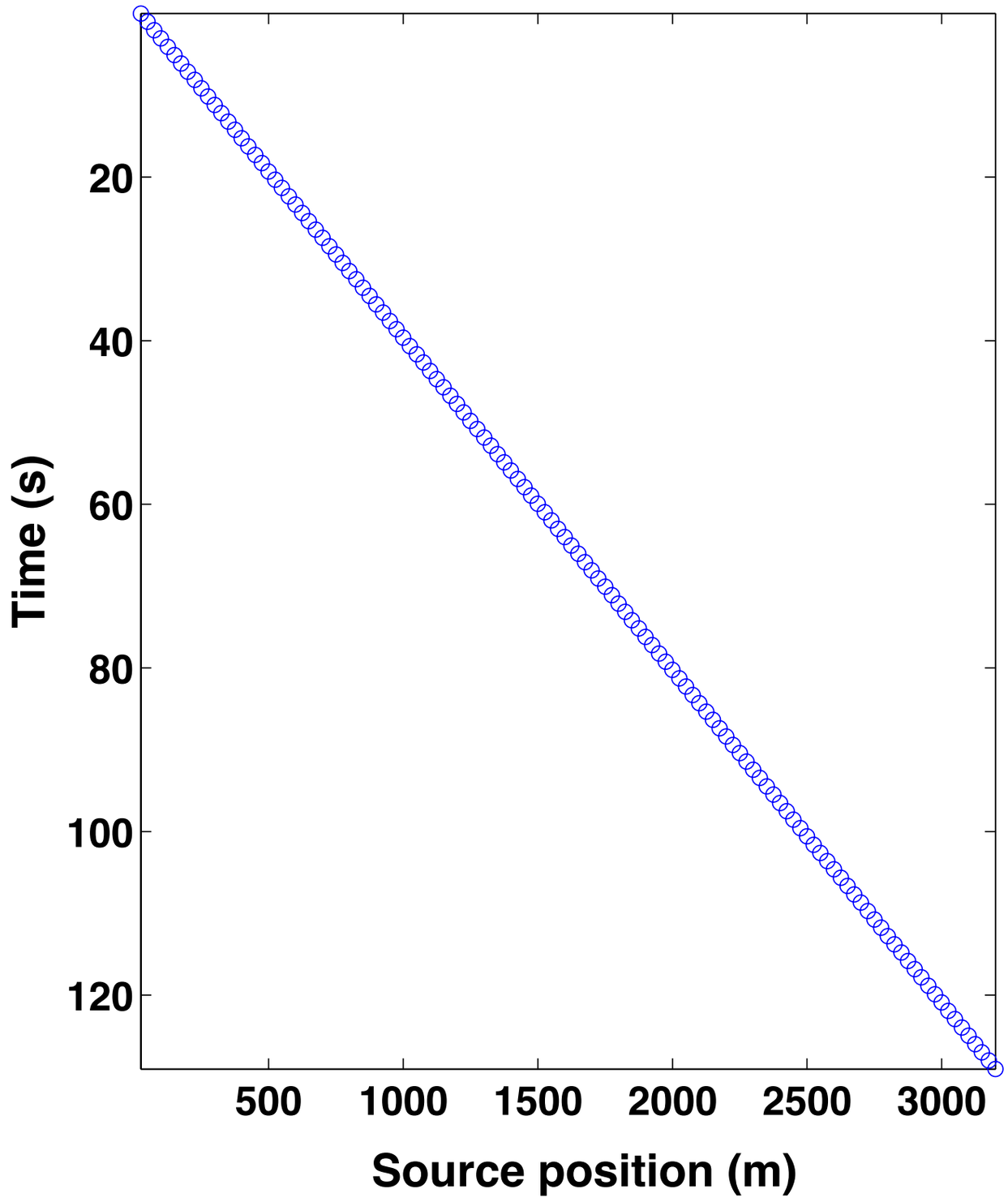
series of
sequential shots

Random time-dithering



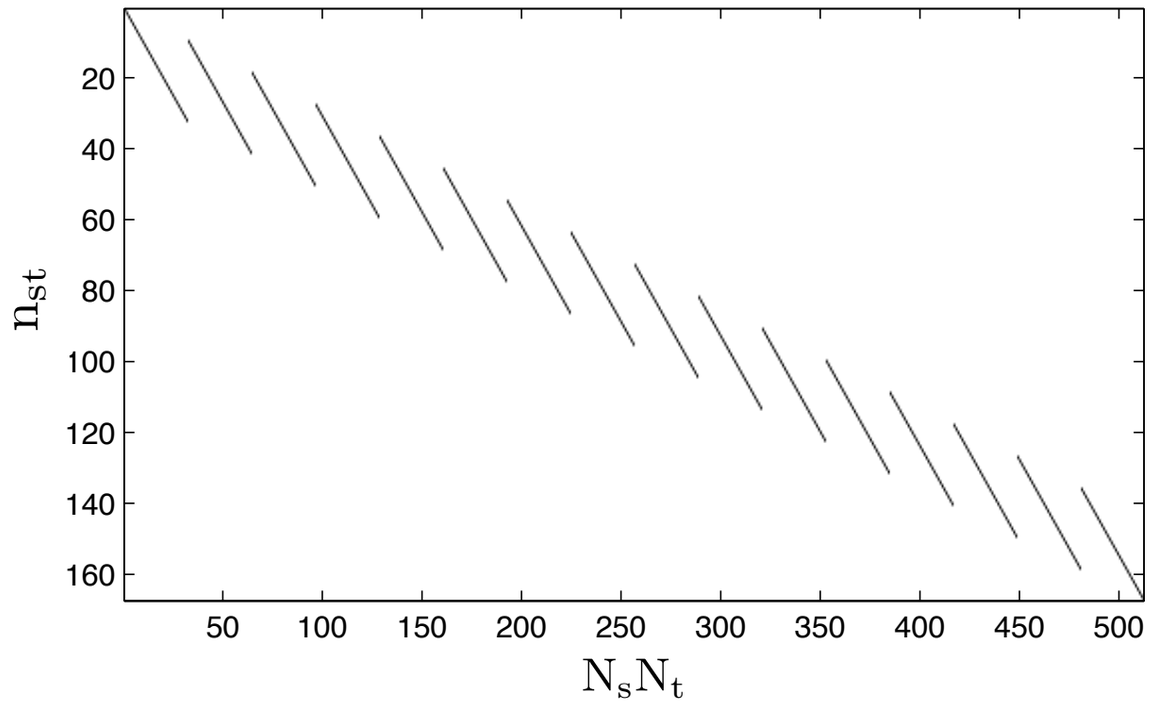
b

Periodic time-dithering



Periodic time-dithering

RM



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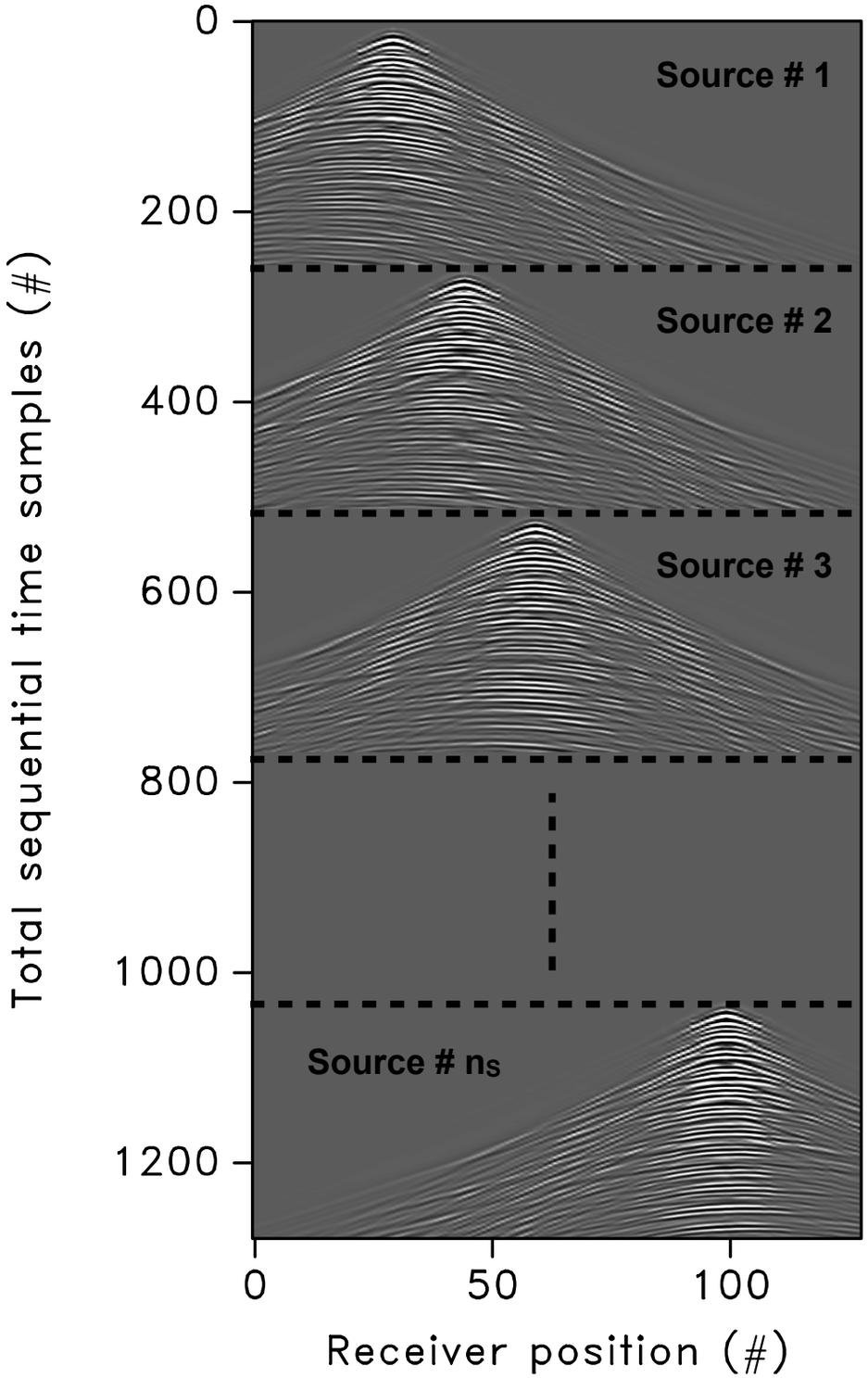
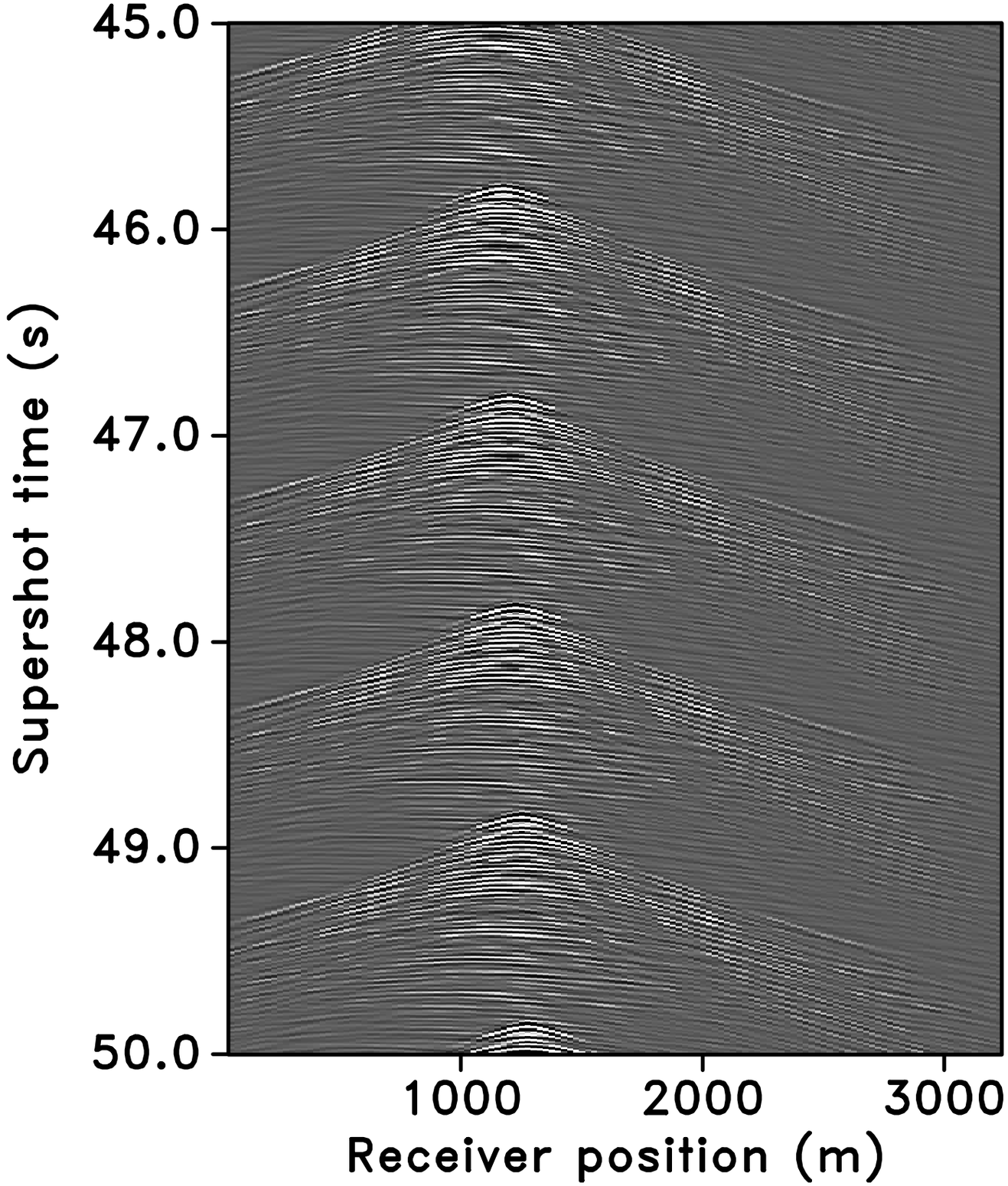


series of
sequential shots

Periodic time-dithering



b

Outline

- Compressed sensing (CS) overview
  - design
  - recovery
- *Design* of *efficient* marine acquisition
- Experimental results of *sparsity*-promoting processing

Experimental setup

- Three sampling schemes:
  - Simultaneous acquisition
  - Random time-dithering
  - Periodic time-dithering

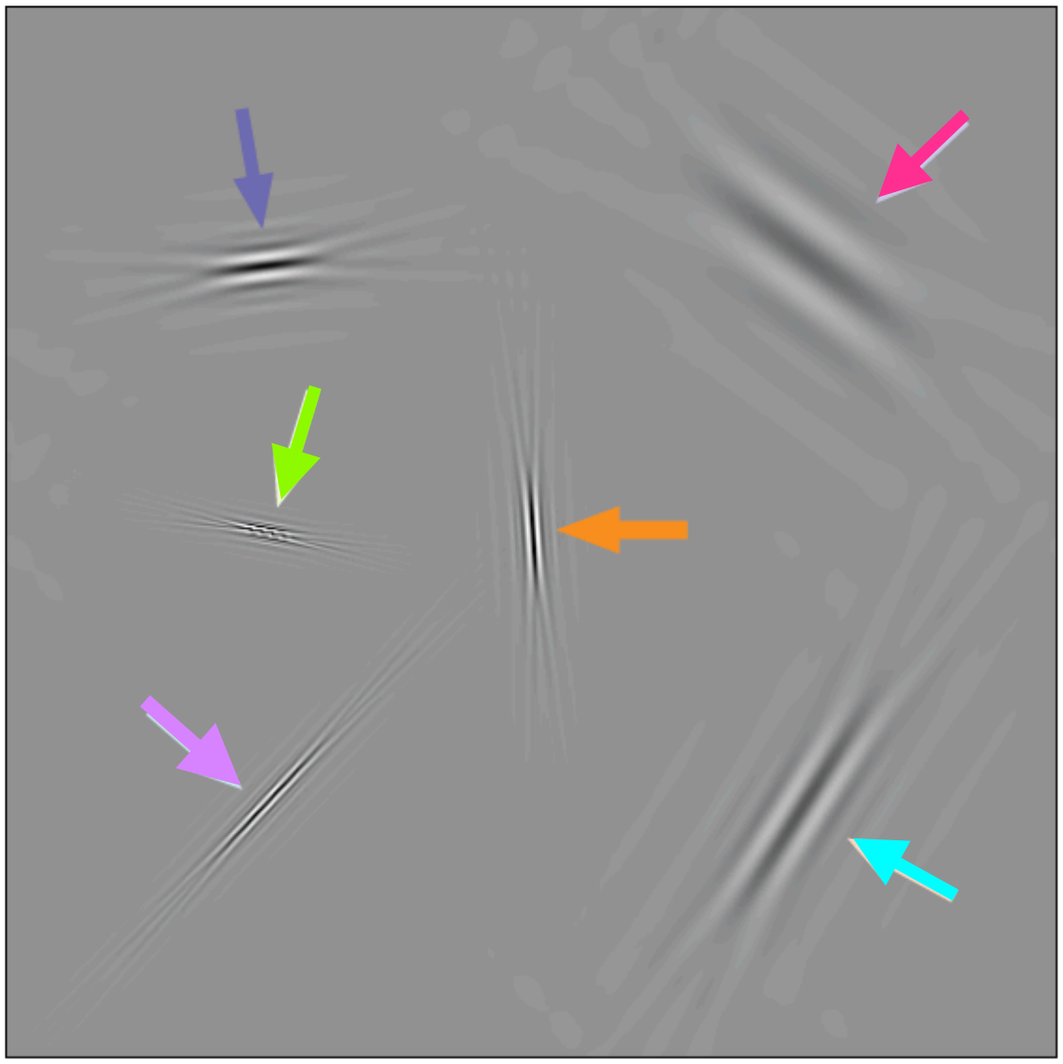
- Fully sampled sequential data (a seismic line from the Gulf of Suez) with $\mathbf{N_s} = 128$ sources, $\mathbf{N_r} = 128$ receivers, and $\mathbf{N_t} = 512$ time samples

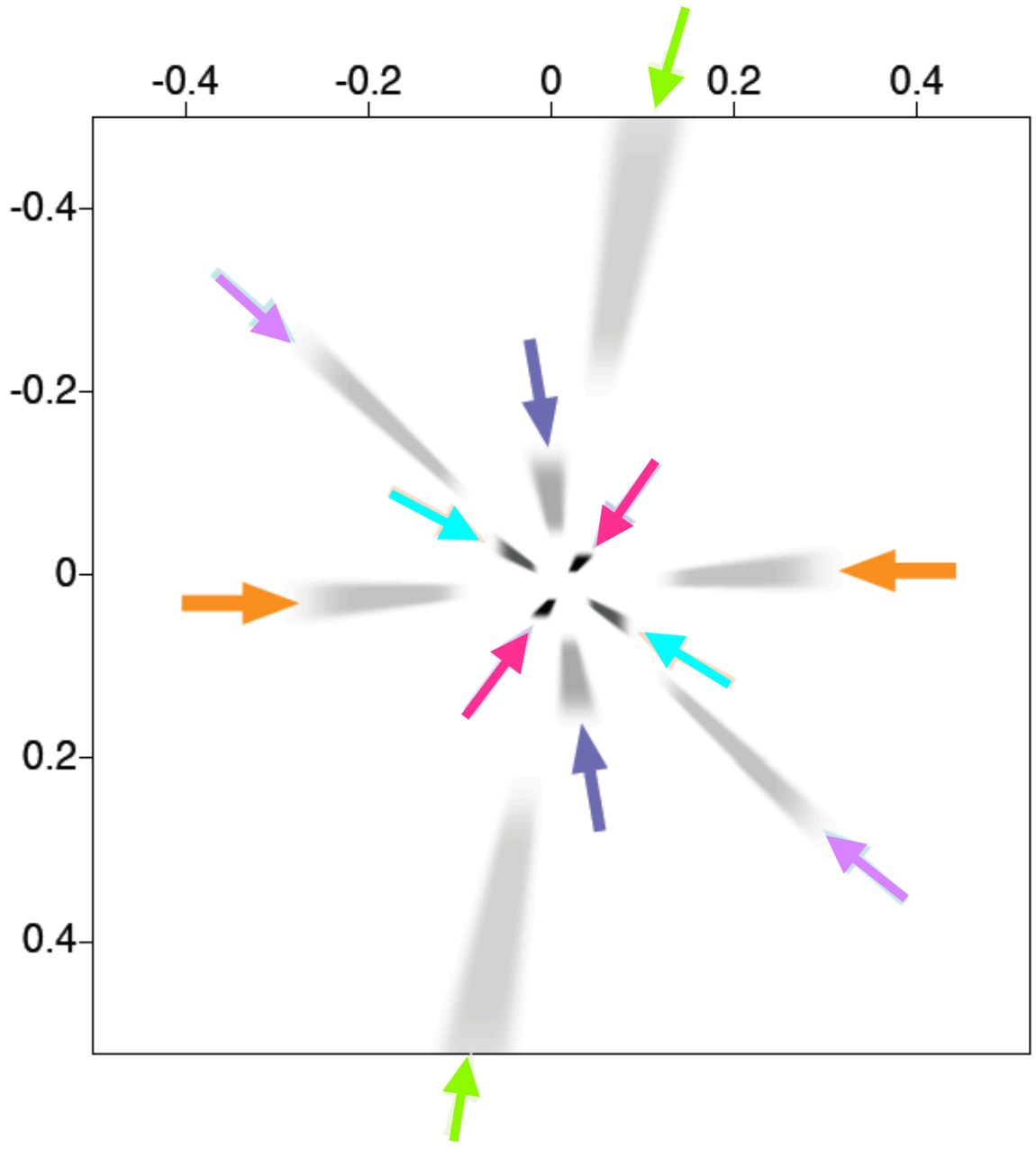
- Subsampling ratio, $\gamma = 0.5$

- Recover prestack data from simultaneous data
  - ℓ_1 minimization
  - sparsifying transform: 3-D curvelet

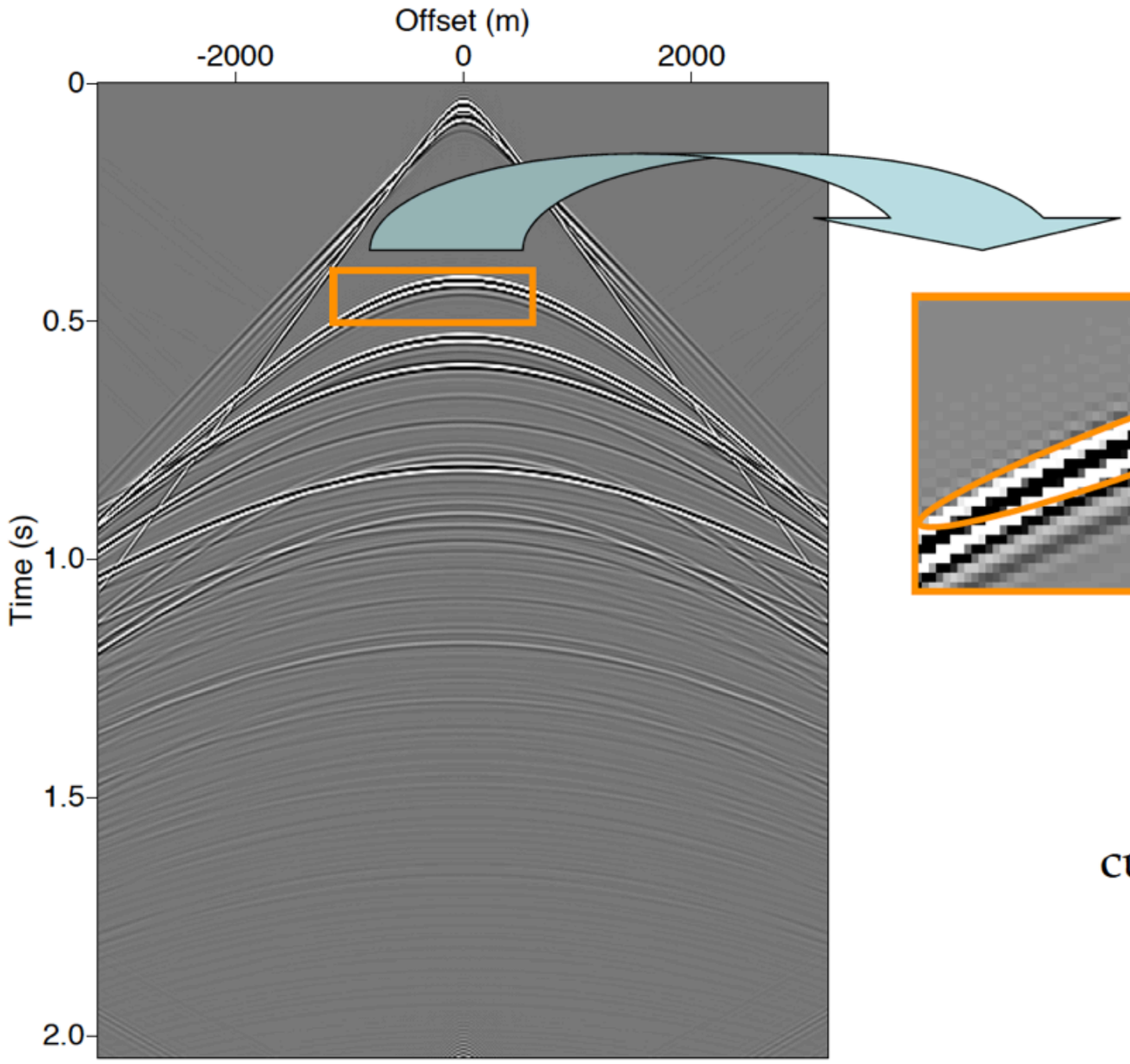
- All sources see the same receivers
  - marine acquisition with ocean-bottom nodes

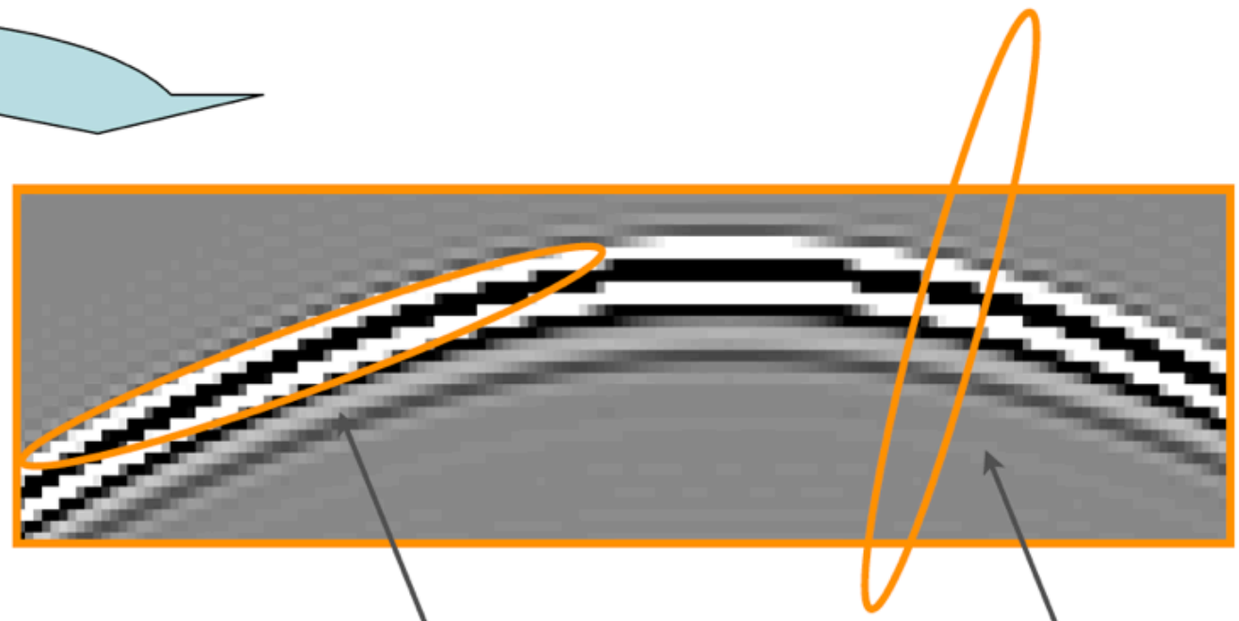
Curvelets





Detect the wavefronts

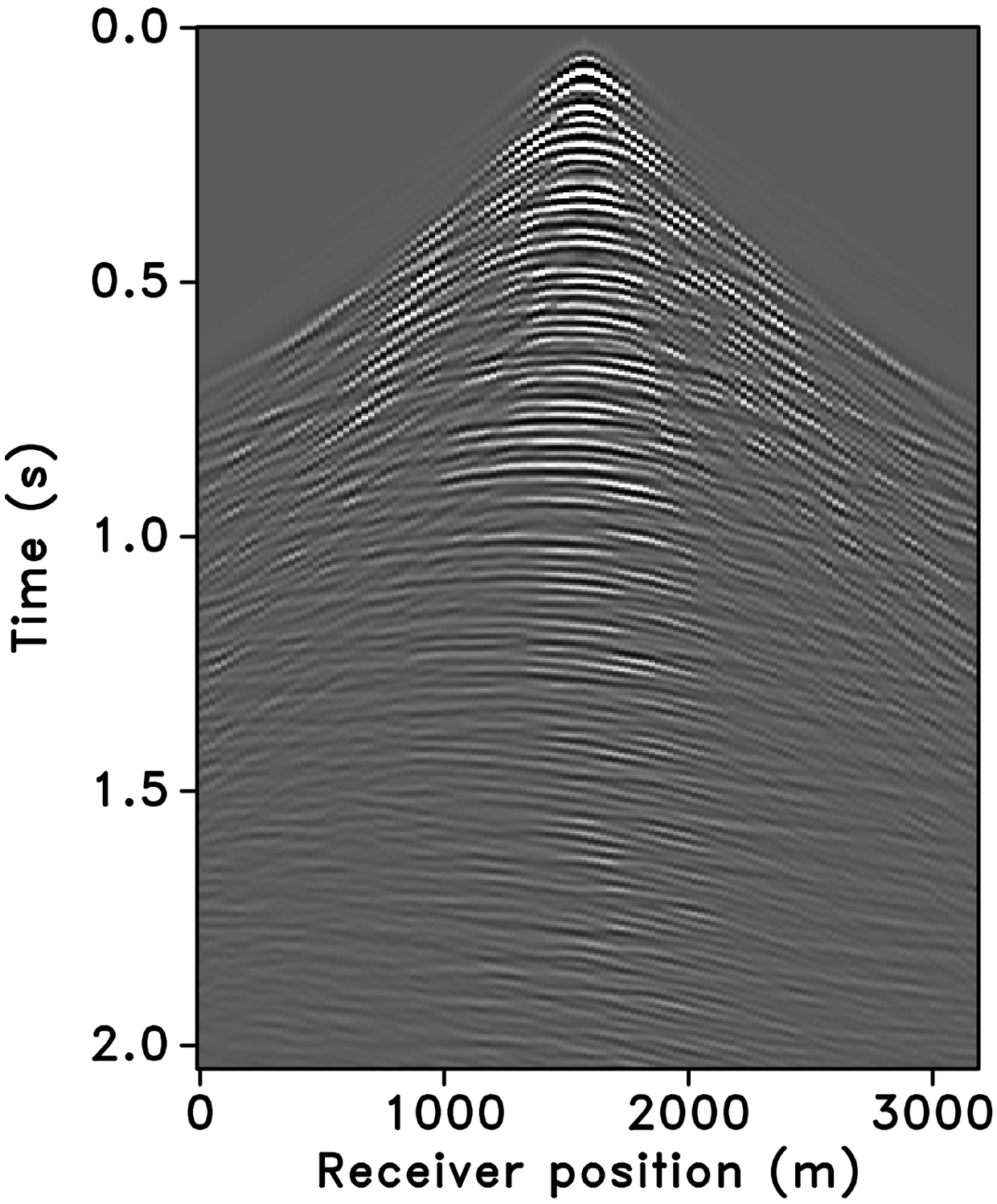




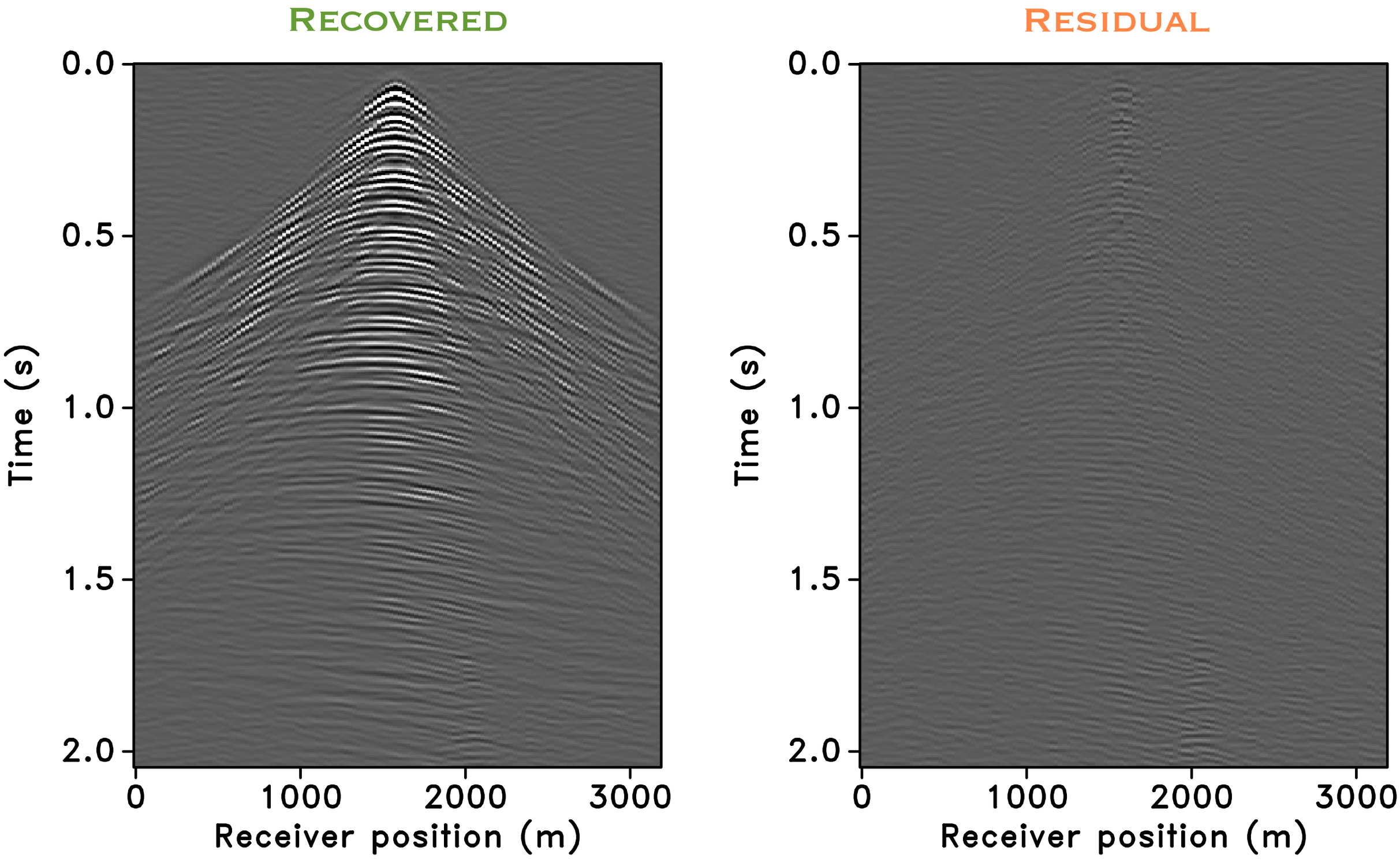
Significant curvelet coefficient

Curvelet coefficient~0

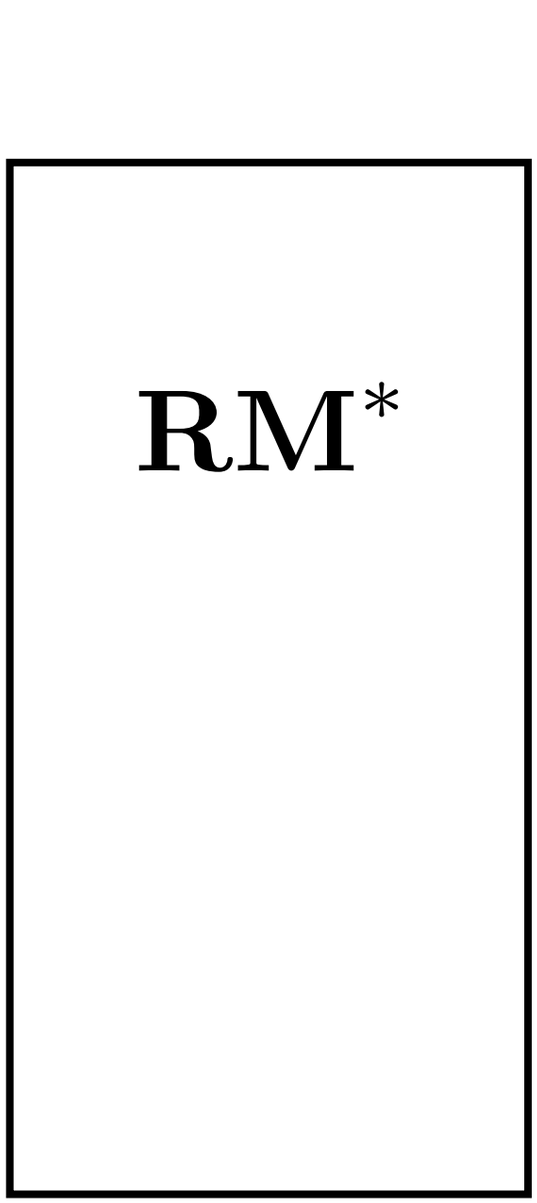
Original data - sequential acquisition (common-shot gather)

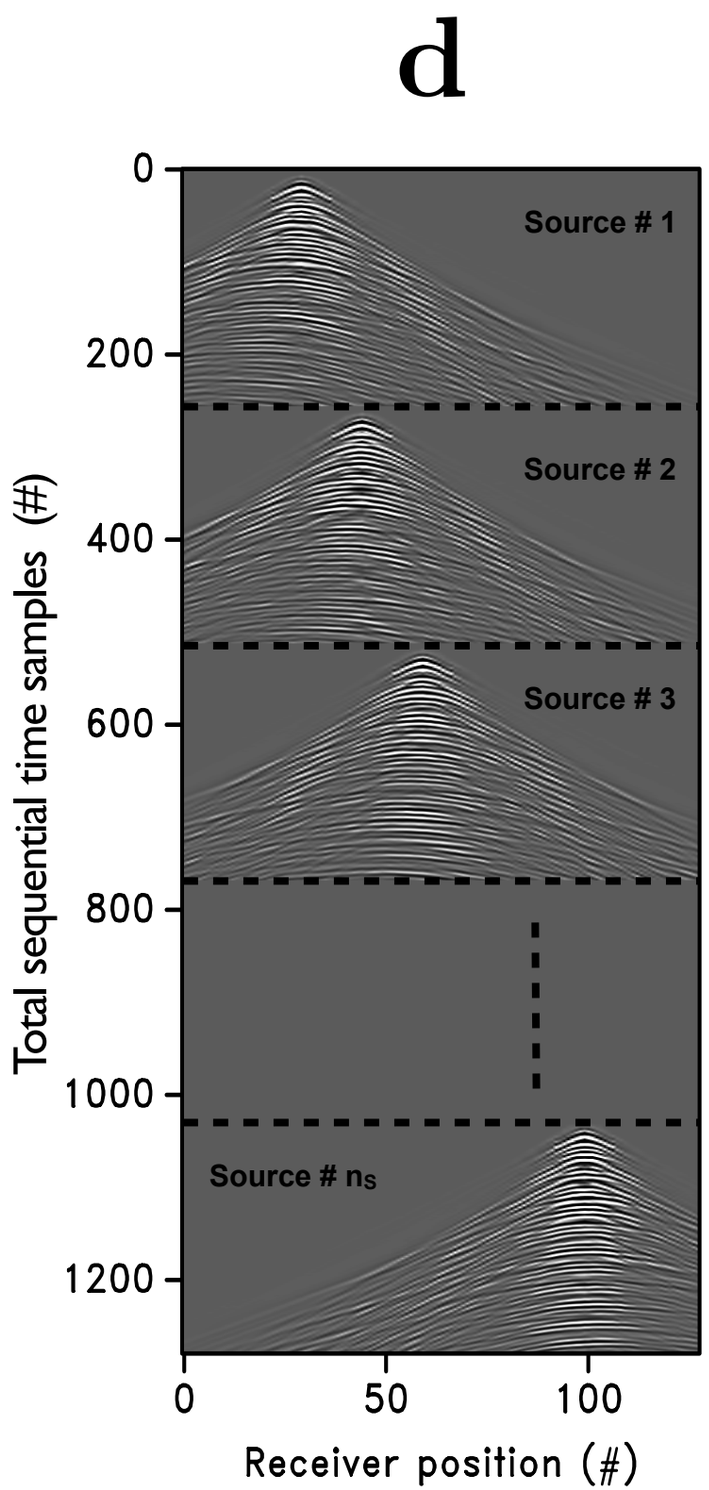


"Ideal" simultaneous acquisition
Sparsity-promoting recovery : 10.5 dB



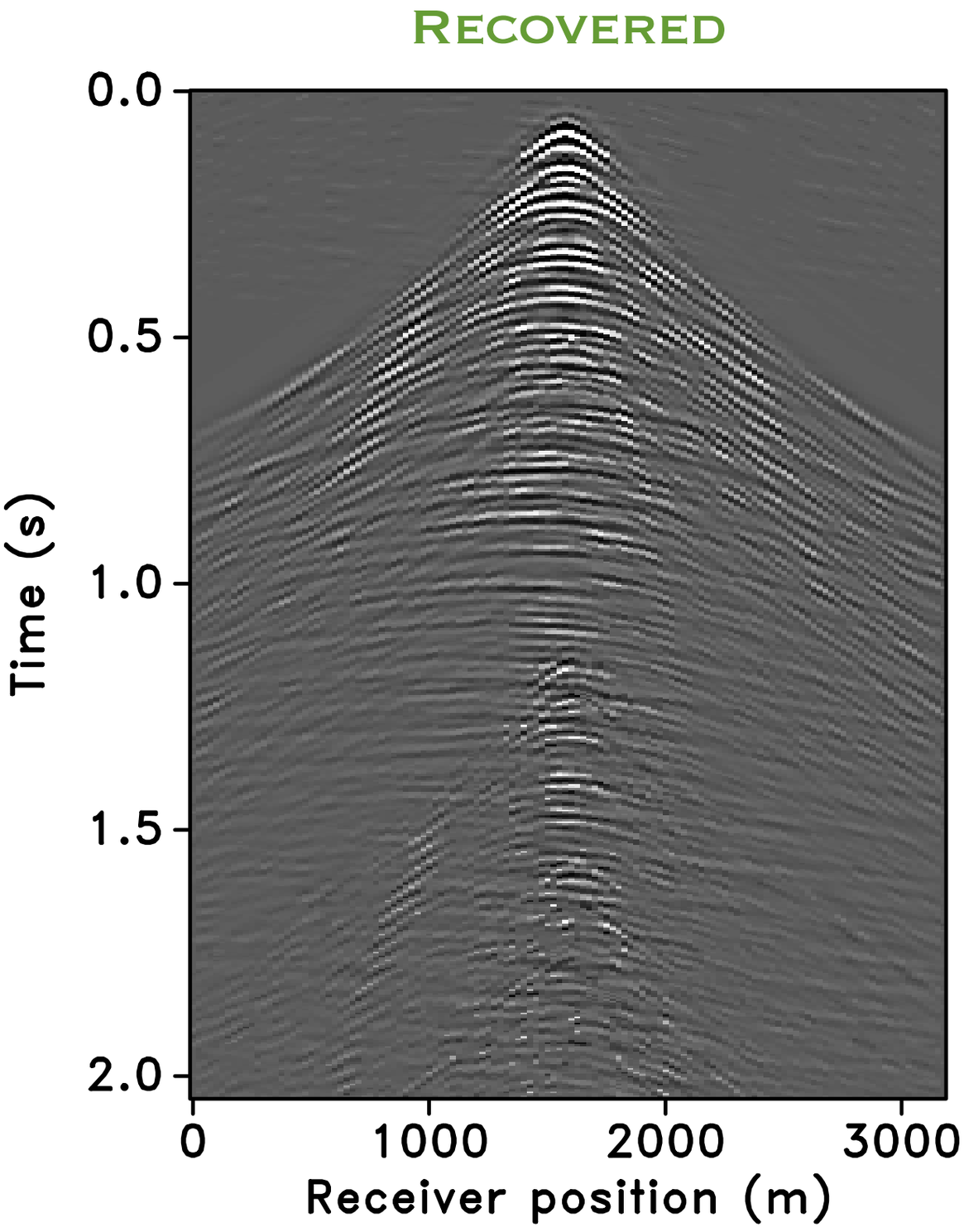
Conventional recovery

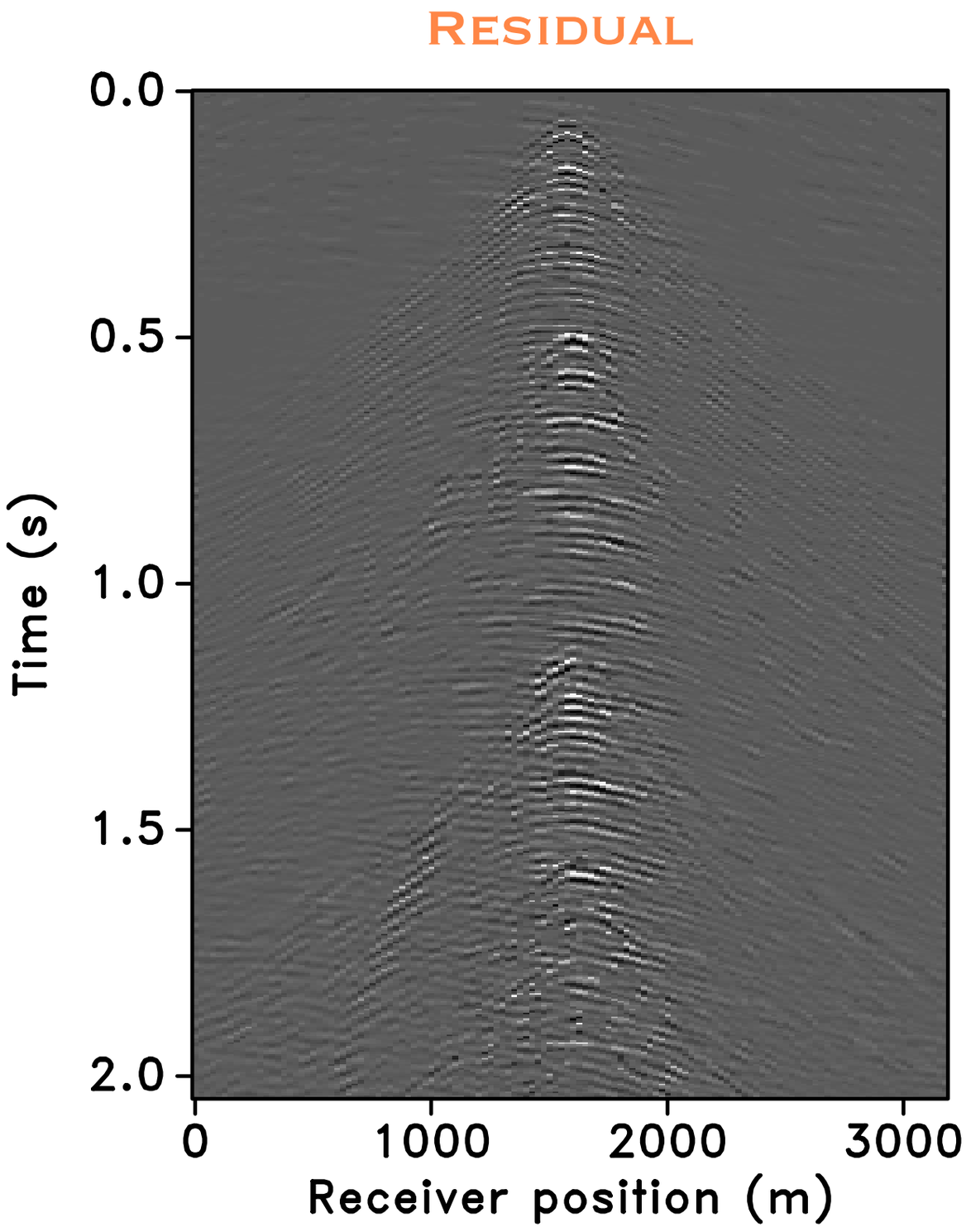




2-D median filtering in midpoint-offset domain

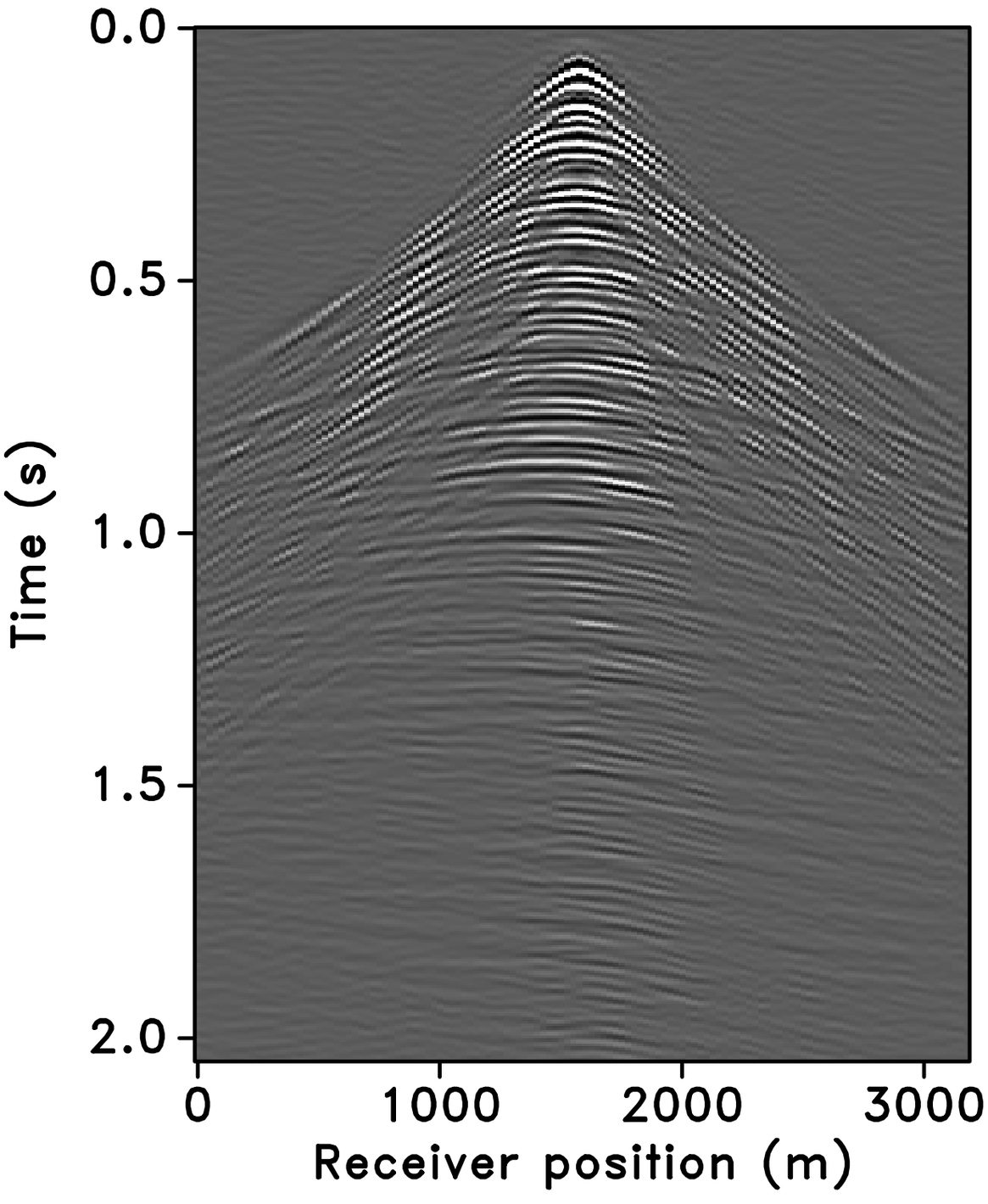
Random time-dithering
Conventional recovery : 3.92 dB



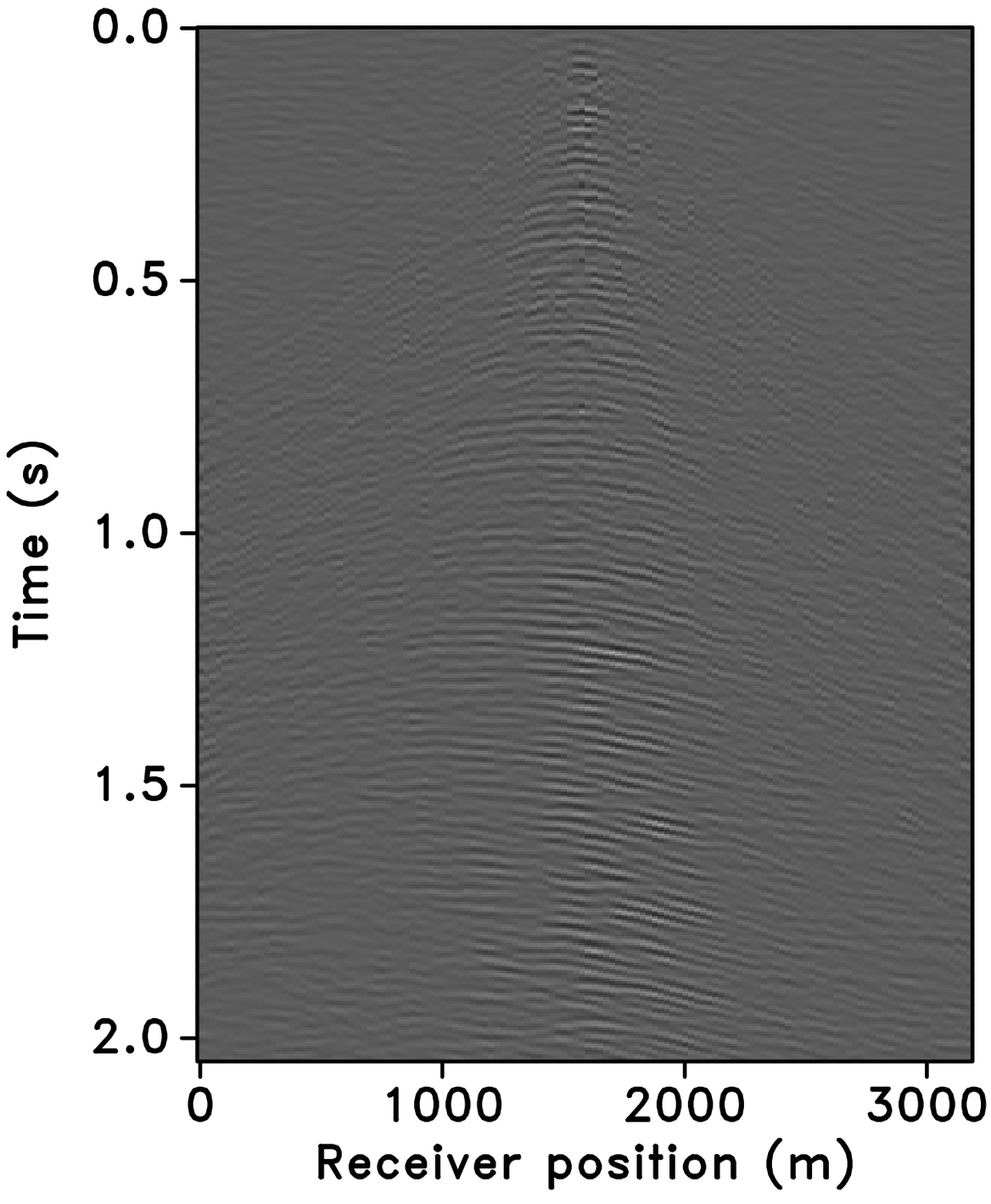


Random time-dithering
Sparsity-promoting recovery : 8.06 dB

RECOVERED

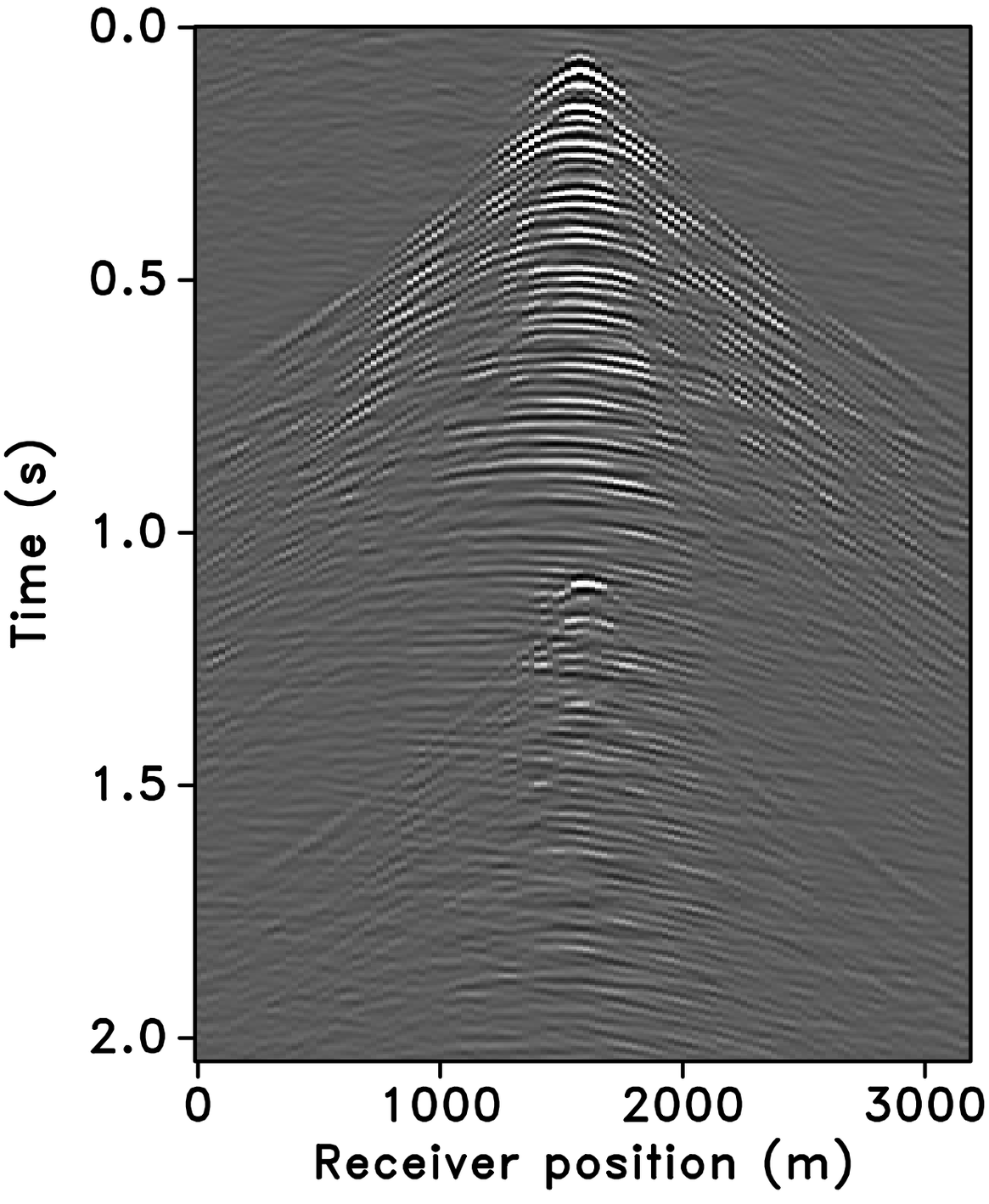


RESIDUAL

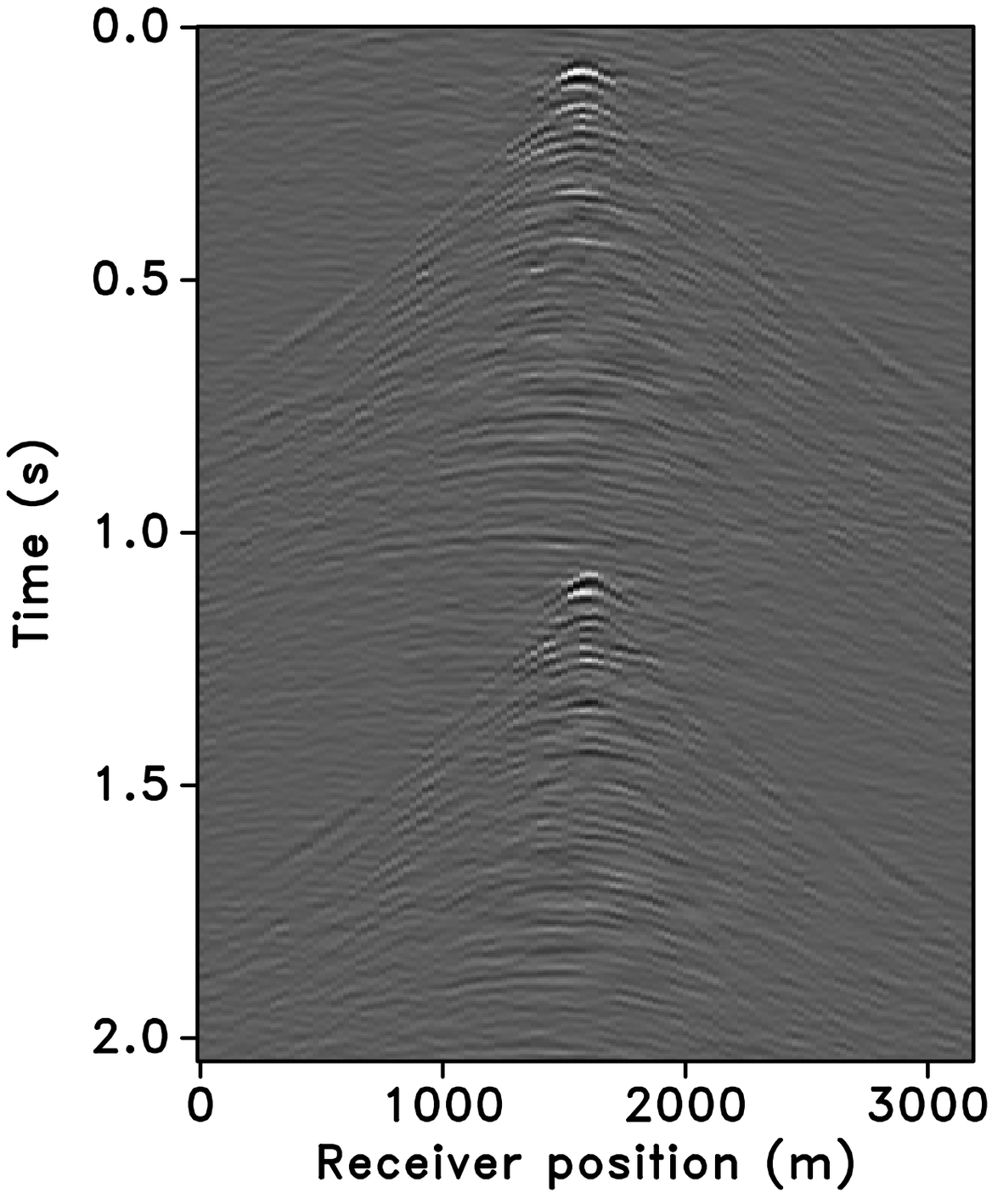


Periodic time-dithering
Sparsity-promoting recovery : 4.80 dB

RECOVERED



RESIDUAL



SNR (dB)

Subsampling ratio	Simultaneous acquisition	Random time-shifting	Constant time-shifting
0.75	13.0	11.2	6.93
0.50	10.5	8.06	4.80
0.33	8.31	5.33	7.32
0.25	6.55	4.35	2.85
0.10	2.82	1.14	1.60

Conclusions

Simultaneous acquisition is a *linear subsampling* system

Critical for reconstruction quality:

- *design* of sampling schemes (i.e., acquisition scenarios)
- appropriate *sparsifying* transform
- *sparsity*-promoting solver

Only dither: efficient marine acquisition "without" simultaneous sourcing

Future plans

- Extensions to marine acquisition with *coil shooting*
- Randomized sampling with ocean-bottom nodes
- Use different transforms for *sparsity*-promoting processing

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Acknowledgements

E. J. Candès, L.demanet, D. L. Donoho, and L. Ying for CurveLab(www.curvelet.org)

E. van den Berg and M. Friedlander for SPGl1 (www.cs.ubc.ca/labs/scl/spgl1)

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NSERC CRSNG

This work was in part financially supported by the Natural Sciences and Engineering Research Council of Canada Discovery Grant (22R81254) and the Collaborative Research and Development Grant DNOISE II (375142-08). This research was carried out as part of the SINBAD II project with support from the following organizations: BG Group, BP, Chevron, ConocoPhillips, Petrobras, BGP, PGS, Total SA, and WesternGeco.

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Thank you!

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