Latest developments in marine (4D) acquisition

Haneet Wason, Felix Oghenekohwo, and Felix J. Herrmann

SLIM
University of British Columbia

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Carry home messages

Randomization of field-data acquisition

- has solid theoretical underpinnings from compressive sensing
- can lead to improved wavefield reconstruction from “low-cost” acquisition
- new insights how to acquire data

Randomization and repeatability in time-lapse acquisition

- could put an end to insisting on repeatability
- exploits what time-lapse surveys have in common rather than how they differ
- improved time-lapse signals from severely undersampled data

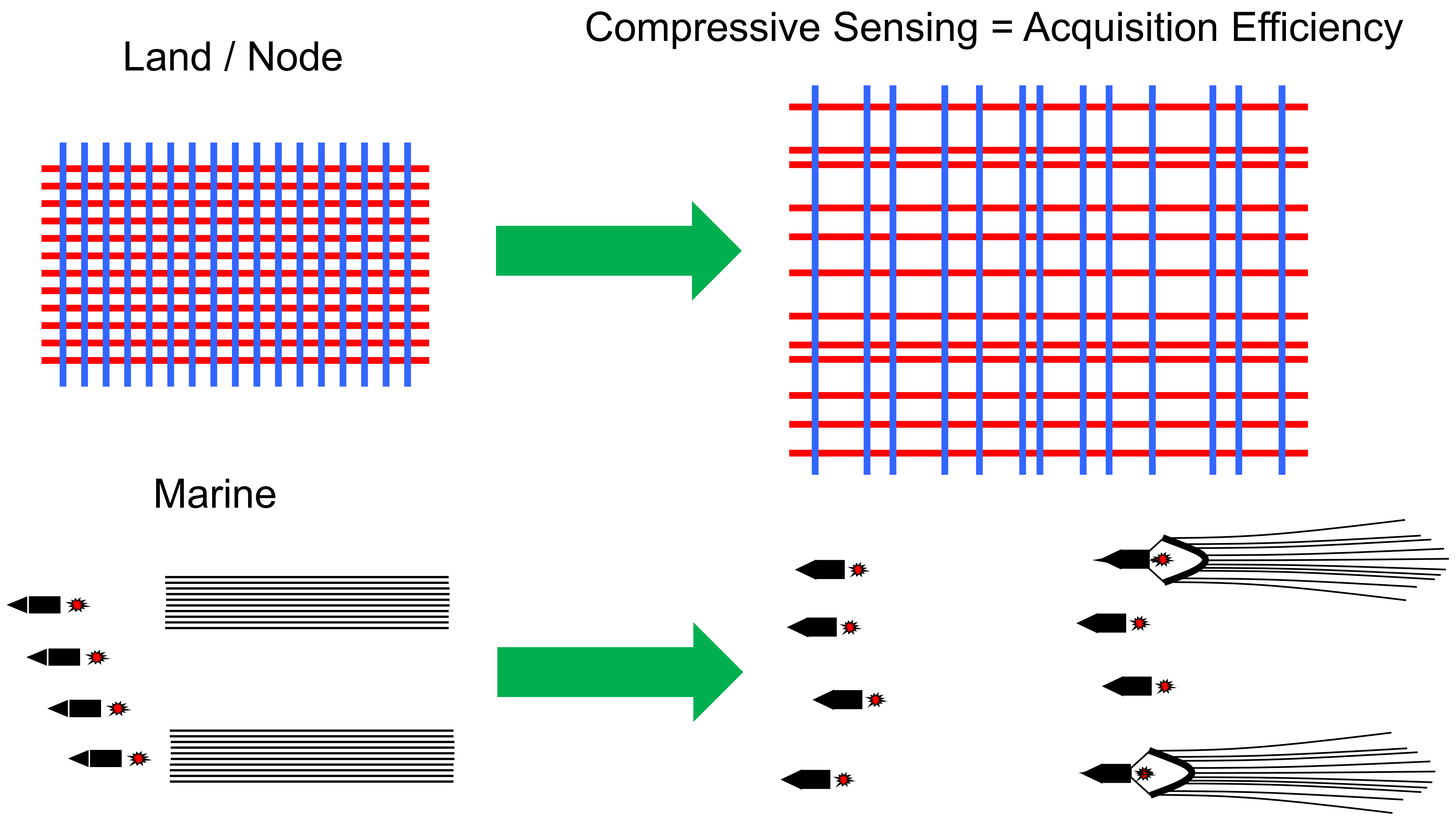
Mosher, C. C., Keskula, E., Kaplan, S. T., Keys, R. G., Li, C., Ata, E. Z., ... & Sood, S. (2012, November). Compressive Seismic Imaging. In *2012 SEG Annual Meeting*. Society of Exploration Geophysicists.

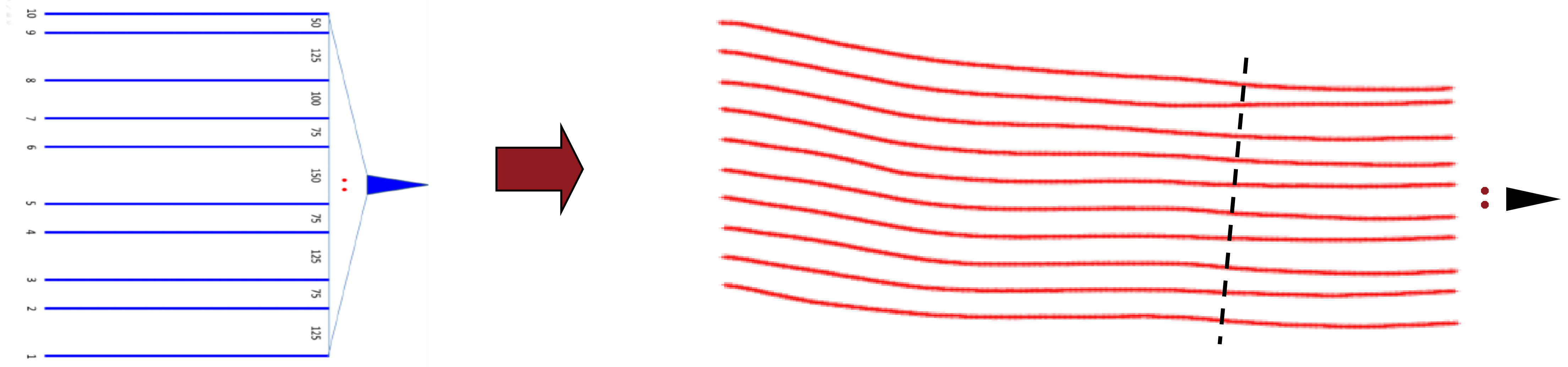
Randomized undersampling

– examples from industry (ConocoPhilips)

Deliberate & natural randomness in acquisition

(thanks to Chuck Mosher)





Designed

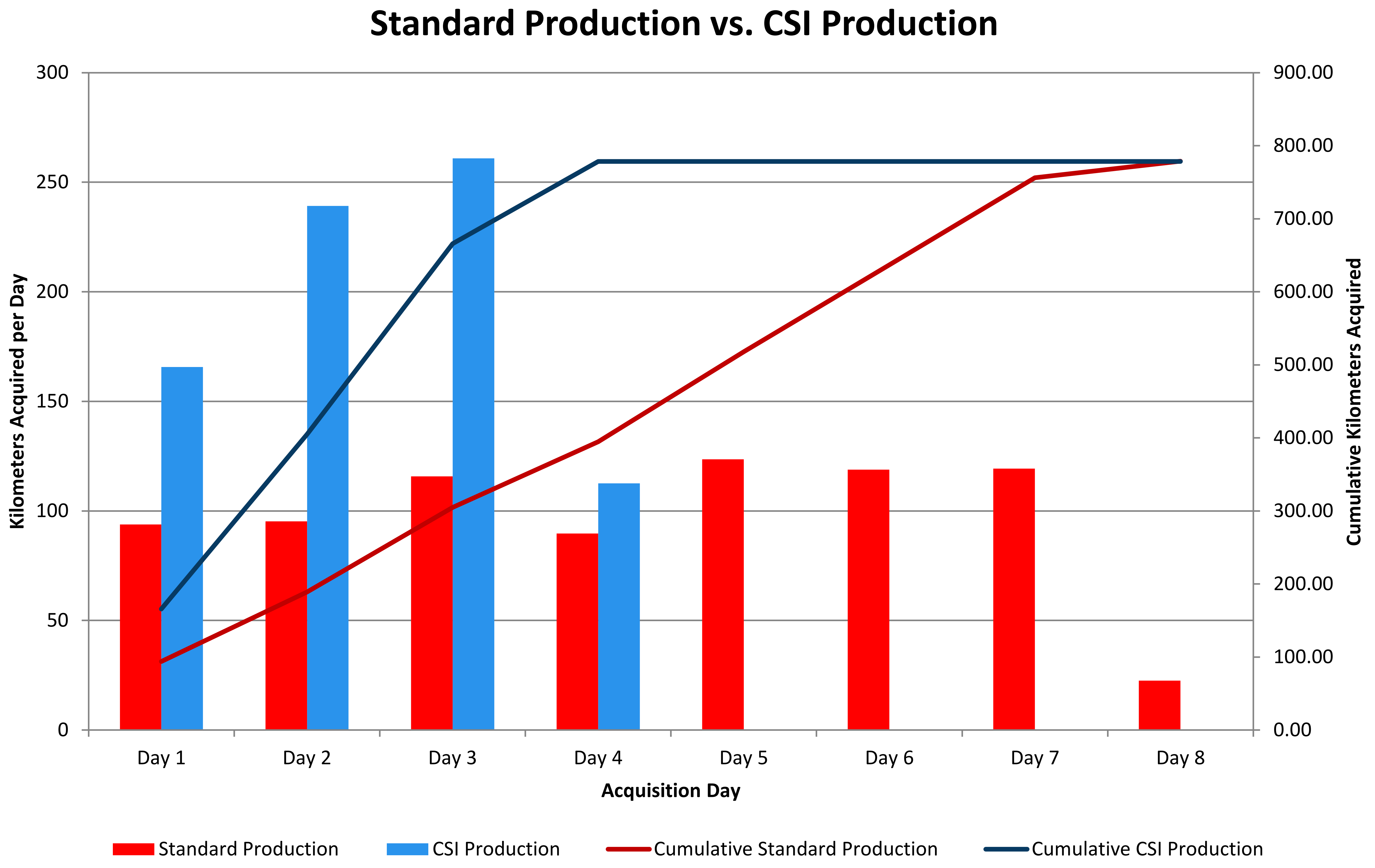
Actually Acquired

Bottom line

– examples from industry (ConocoPhilips)

Economics

(thanks to Chuck Mosher)



Felix J. Herrmann, Michael P. Friedlander, and Ozgur Yilmaz, "Fighting the Curse of Dimensionality: Compressive Sensing in Exploration Seismology", *Signal Processing Magazine, IEEE*, vol. 29, p. 88-100, 2012
Felix J. Herrmann, "Randomized sampling and sparsity: Getting more information from fewer samples", *Geophysics*, vol. 75, p. WB173-WB187, 2010

Compressive sensing *paradigm*

Find **representations that reveal** ***structure***

- *transform*-domain *sparsity* (e.g., Fourier, curvelets, etc.)

Sample **to** ***break*** **the** ***structure***

- *randomized* acquisition (e.g., *jittered* sampling, time *dithering*, *encoding*, etc.)
- destroy *sparsity*

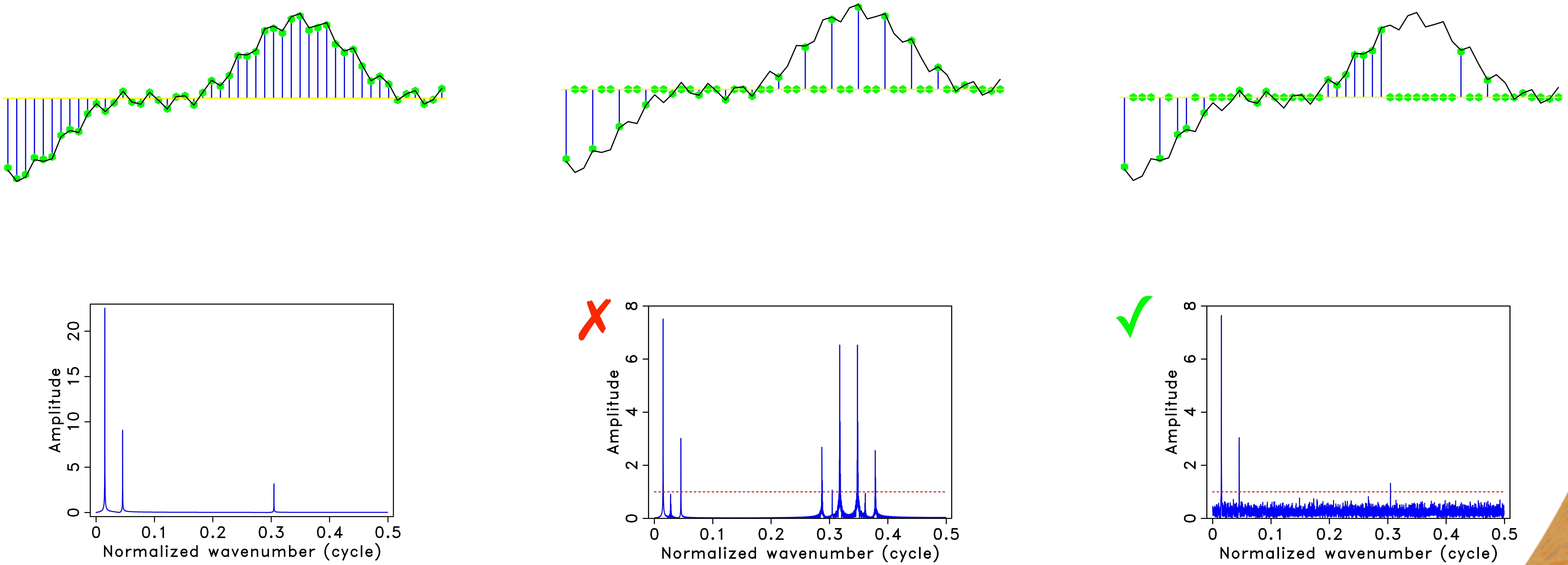
Recover ***structure*** **by promoting**

- *sparsity* via *one*-norm *minimization*

Felix J. Herrmann and Gilles Hennenfent, “Non-parametric seismic data recovery with curvelet frames”, *GJI*, vol. 173, p. 233-248, 2008.
Gilles Hennenfent and Felix J. Herrmann, “Simply denoise: wavefield reconstruction via jittered undersampling”, *Geophysics*, vol. 73, p. V19-V28, 2008.
Felix J. Herrmann, “Randomized sampling and sparsity: Getting more information from fewer samples”, *Geophysics*, vol. 75, p. WB173-WB187, 2010.

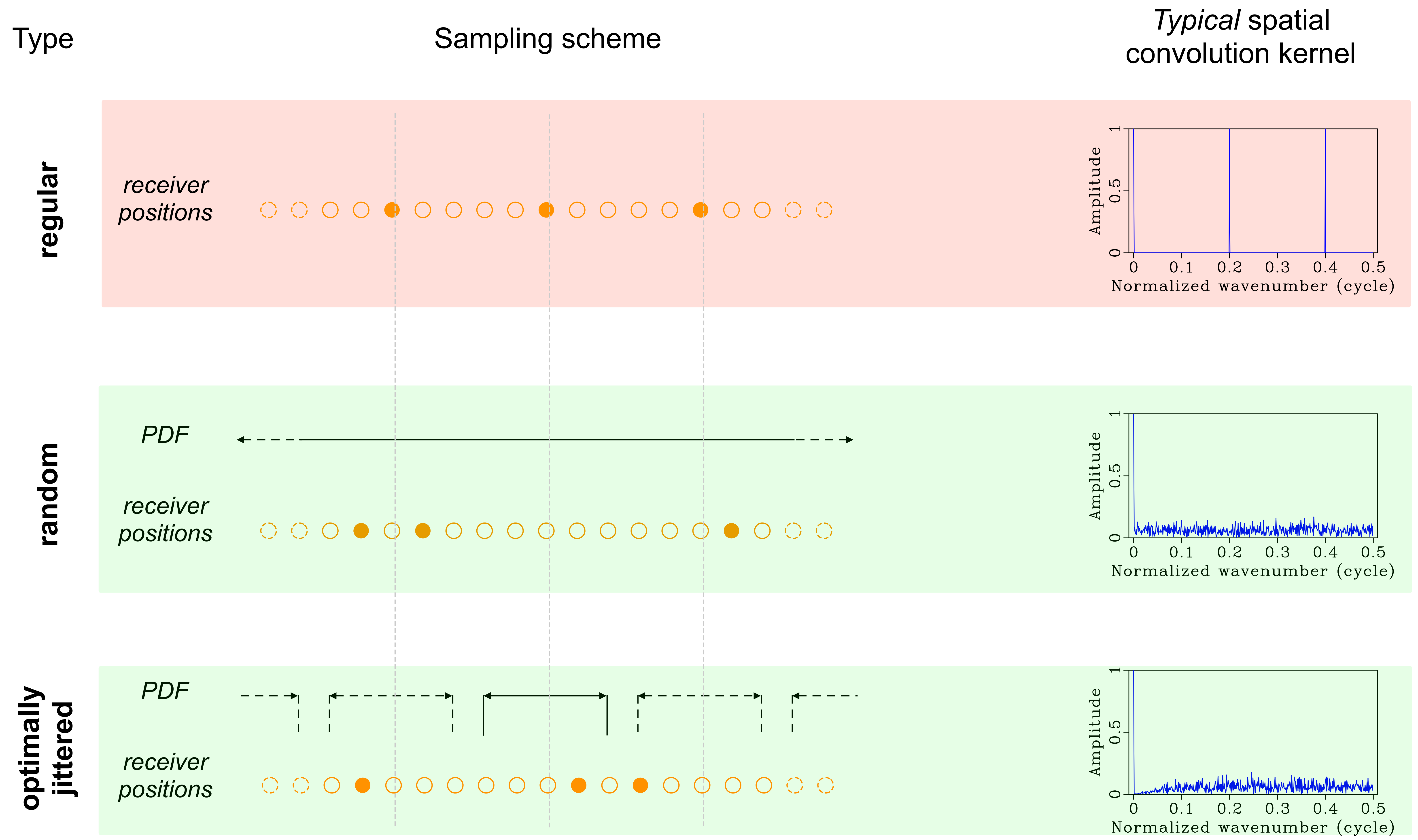
Golden oldies

– sparse time-harmonic signals

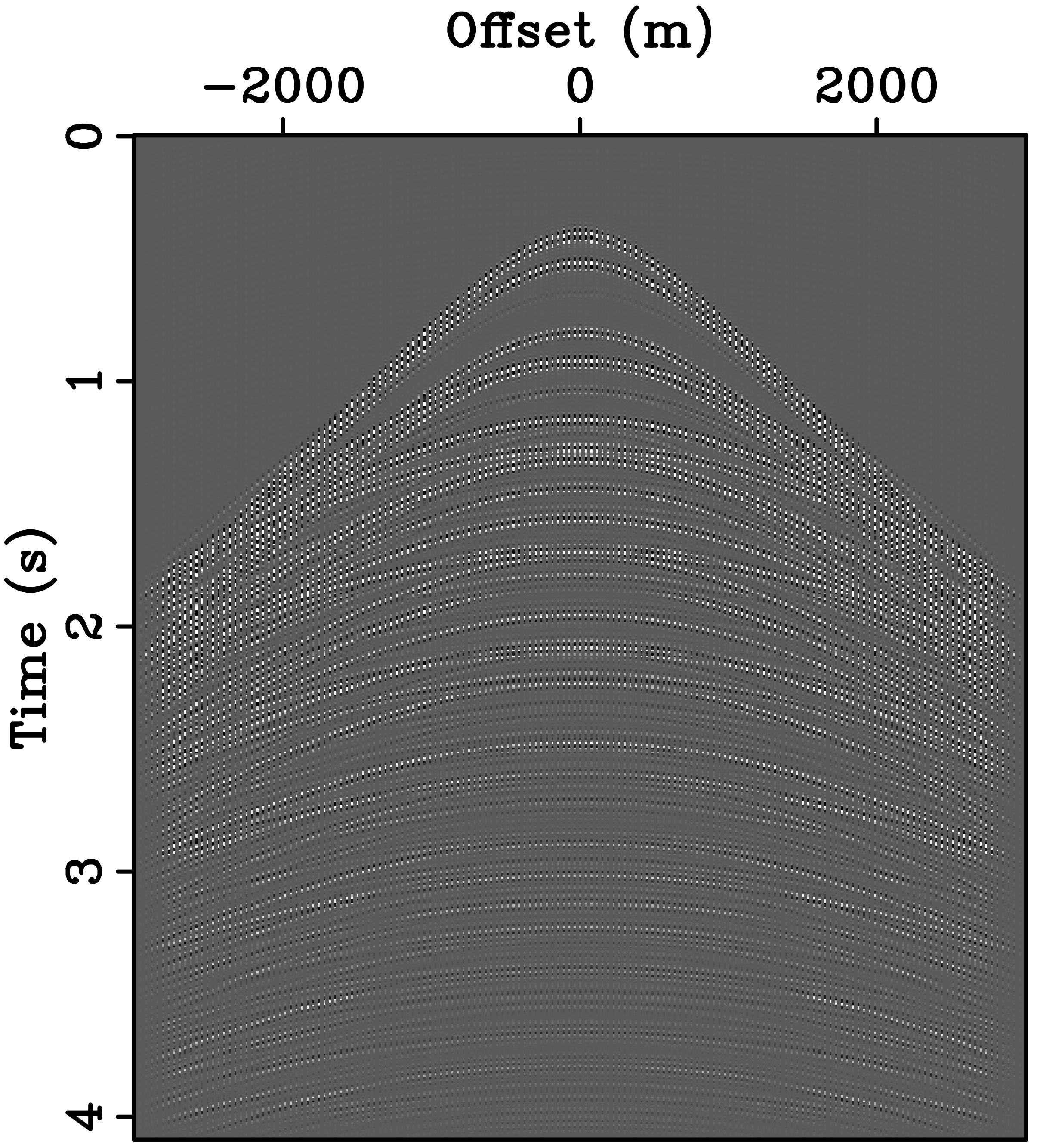


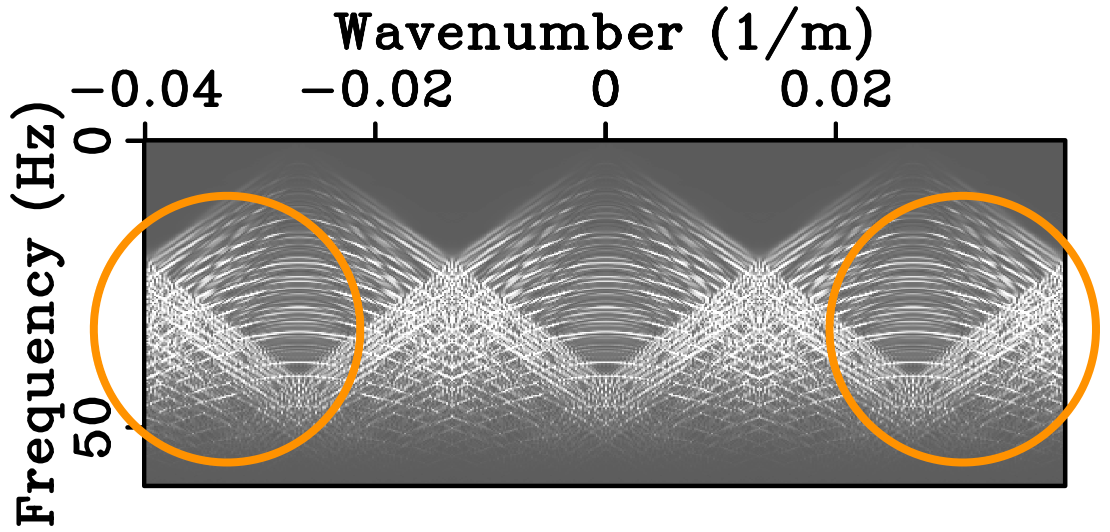
Gilles Hennenfent and Felix J. Herrmann, "Simply denoise: wavefield reconstruction via jittered undersampling", *Geophysics*, vol. 73, p. V19-V28, 2008.

Jittered sampling

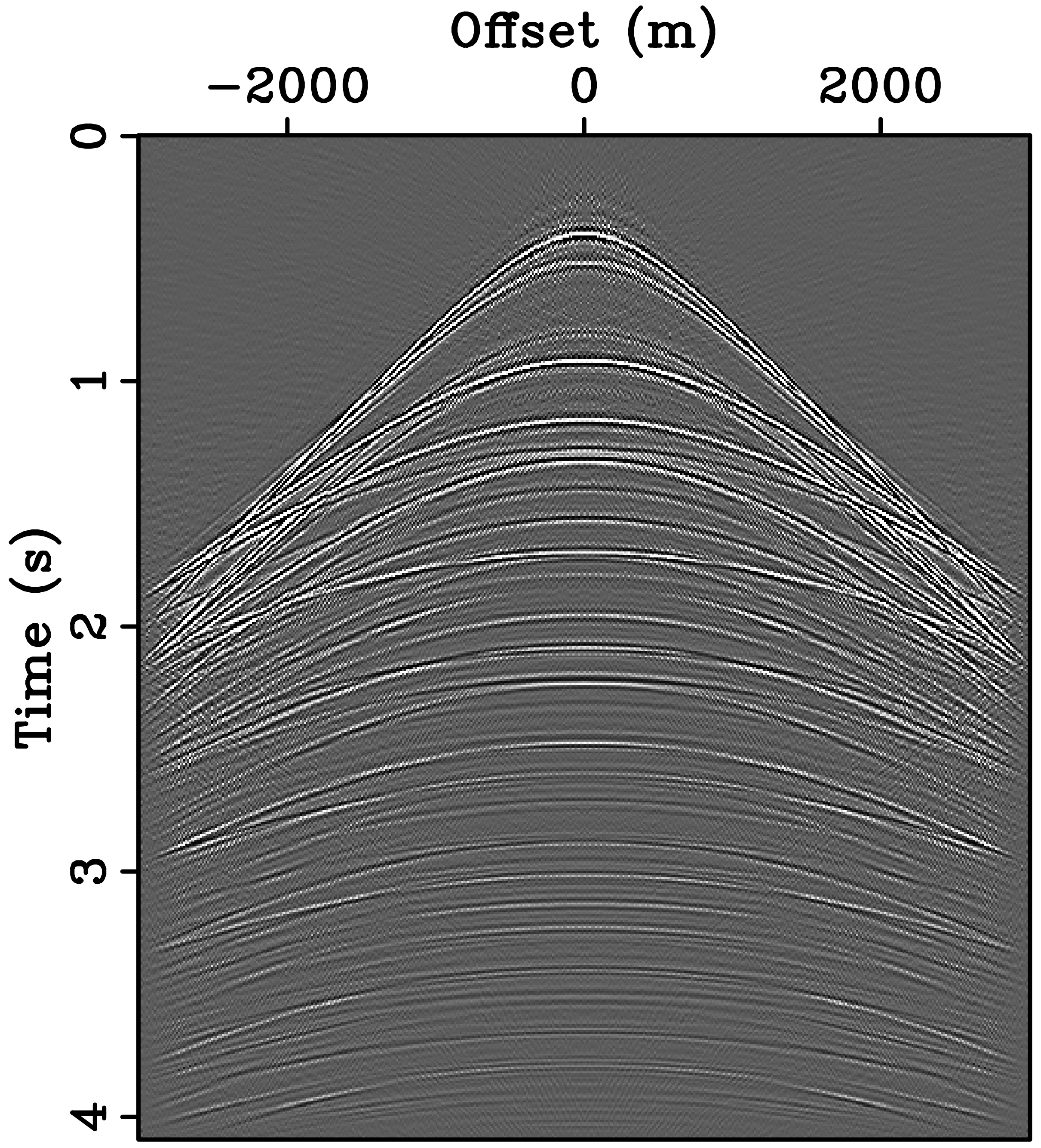


Periodic sampling

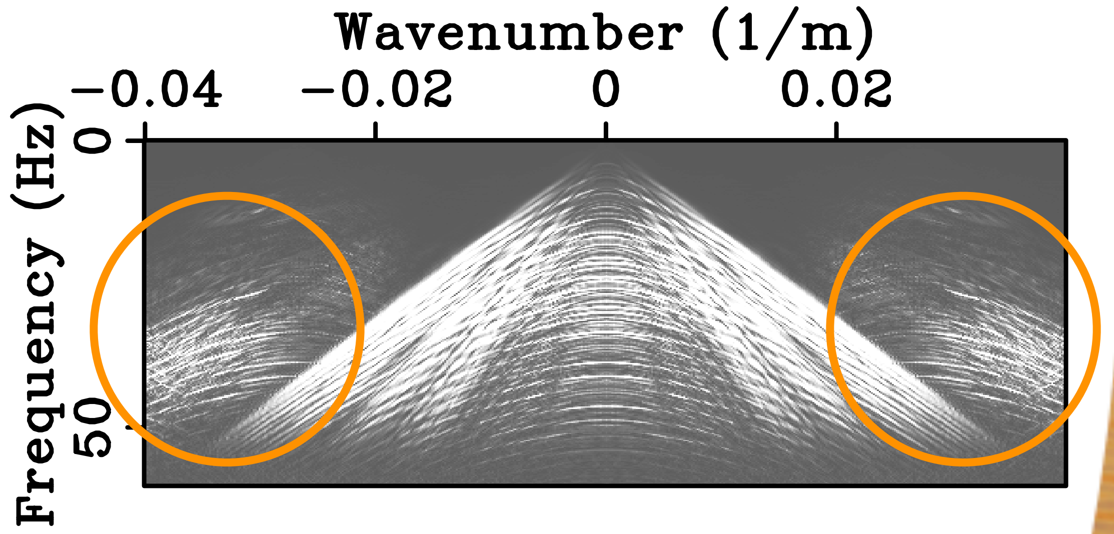




*3-fold under*sampled

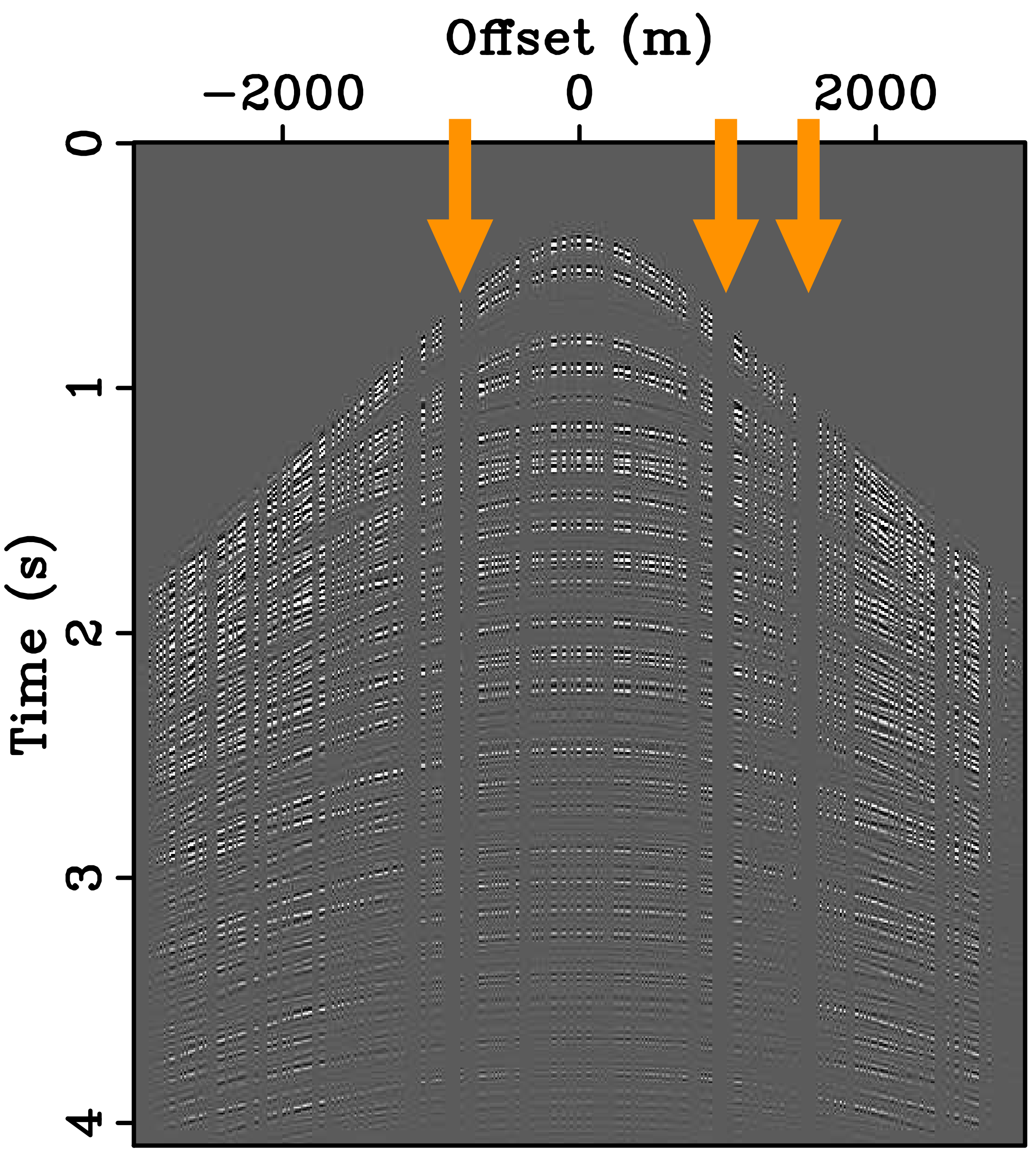


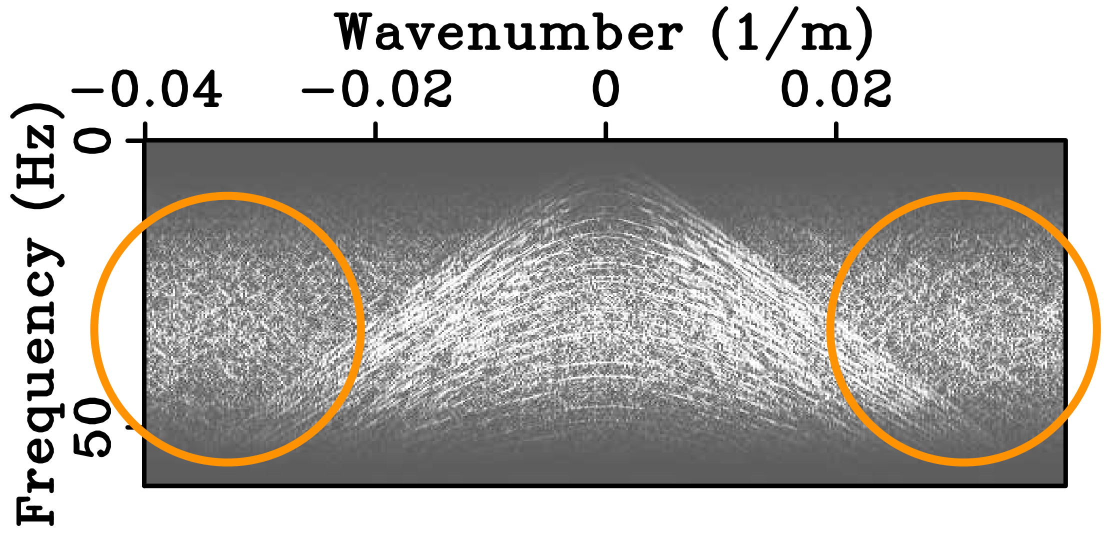
SNR = 6.92 dB



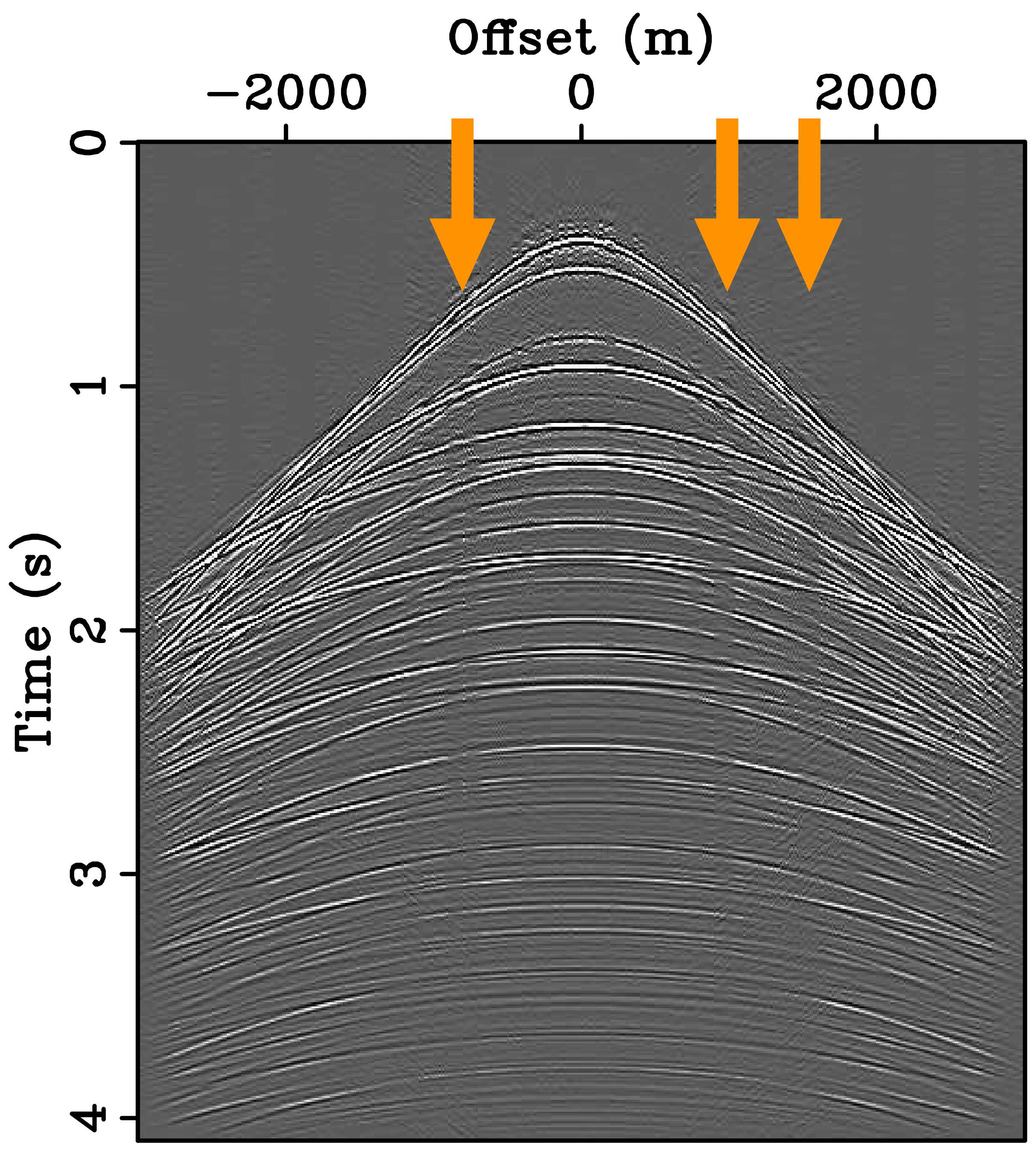
recovered

Uniform random sampling

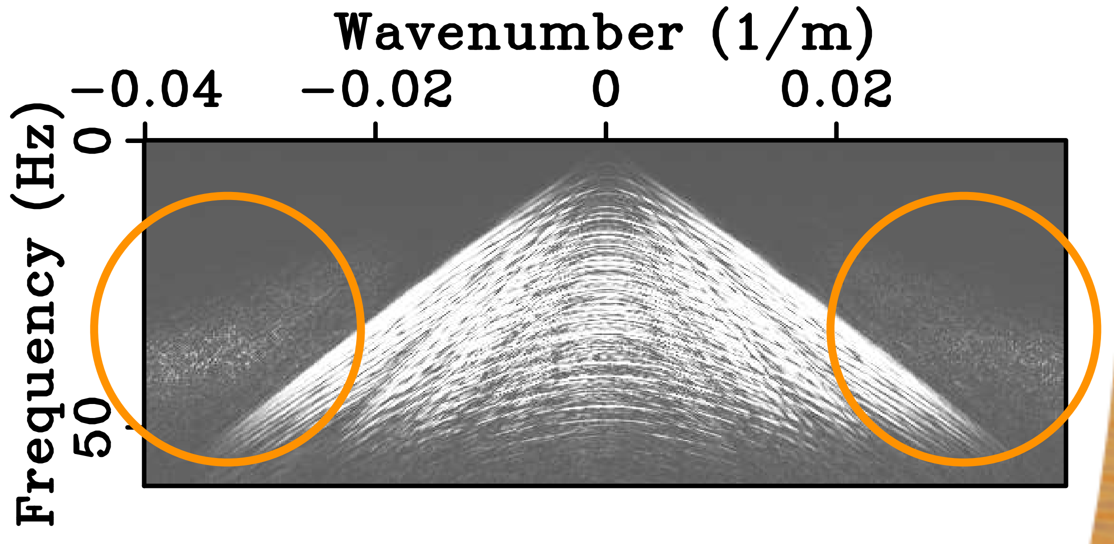




*3-fold under*sampled

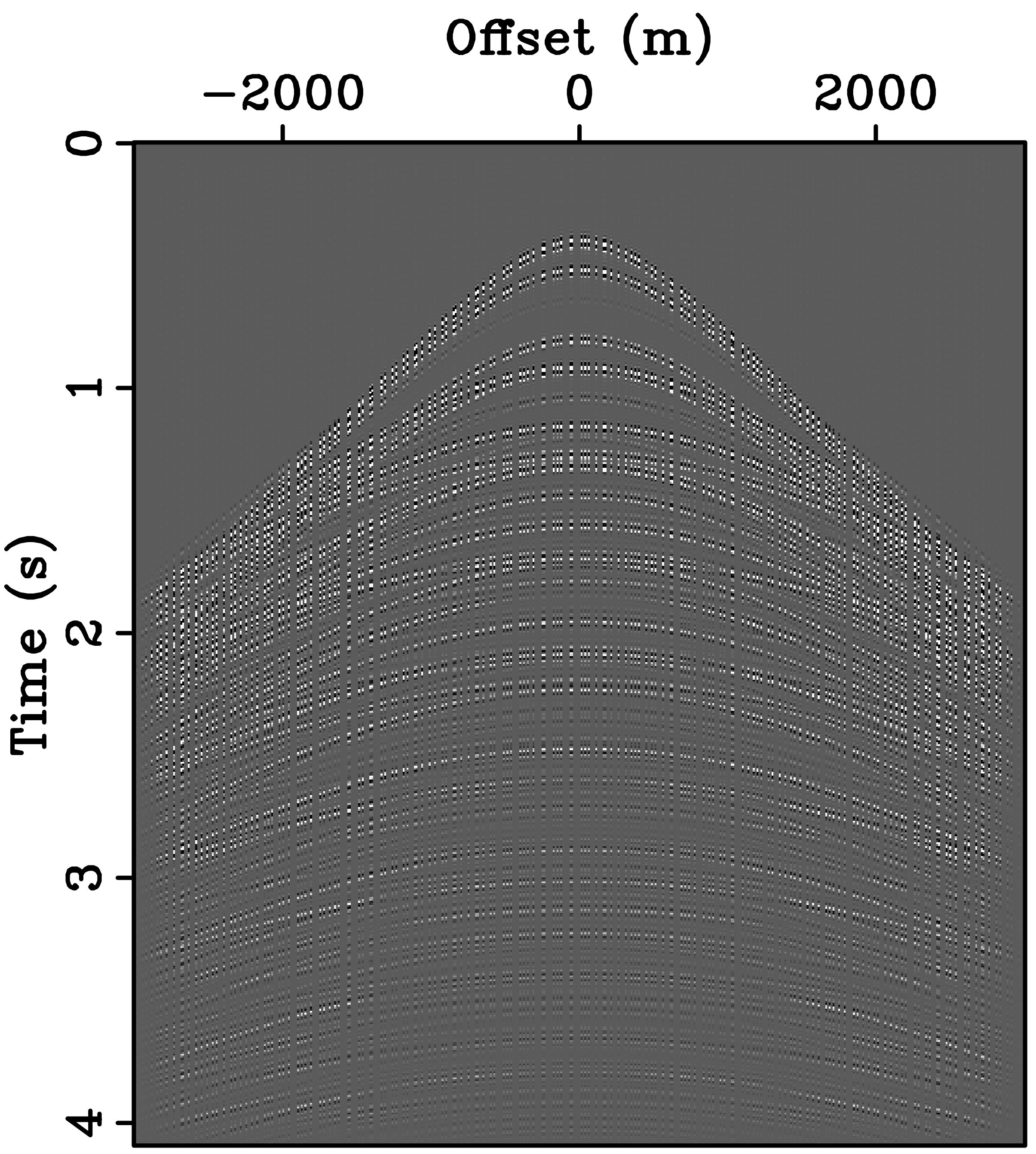


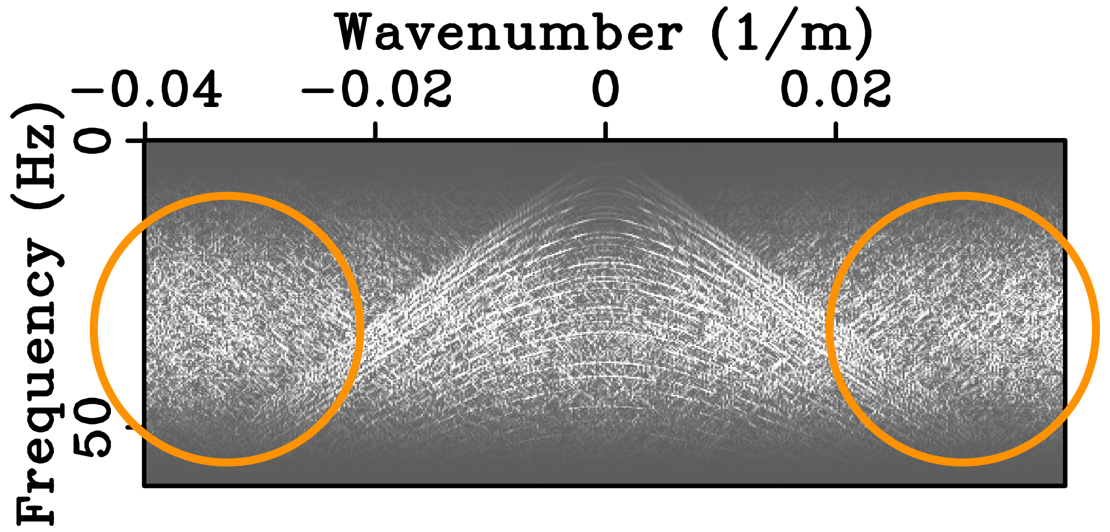
SNR = 9.72 dB



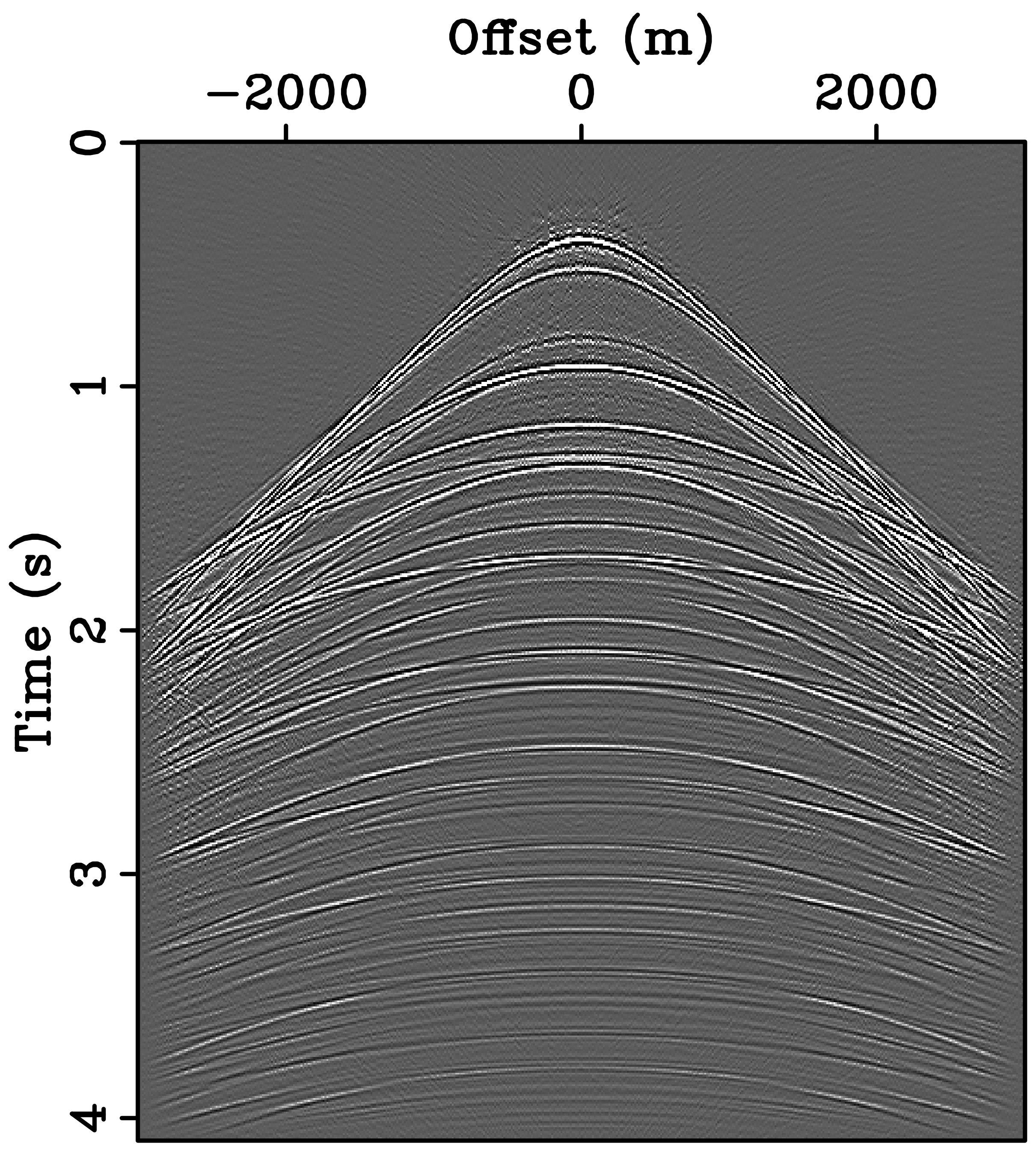
recovered

Jittered sampling

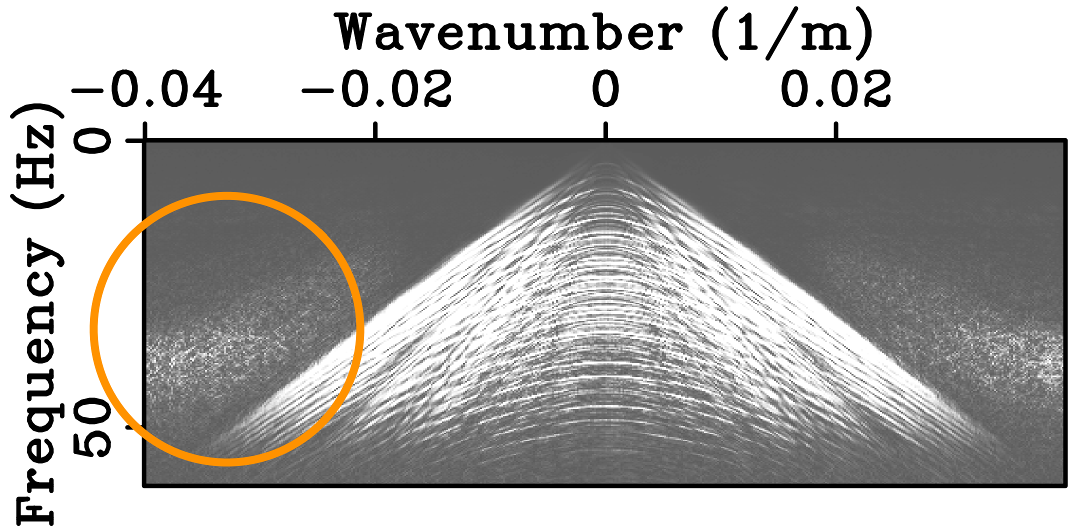




*3-fold under*sampled



SNR = 10.42 dB



recovered

Time-*jittered* marine acquisition

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Objective

Shorten marine acquisition times & increase source sample density.

Question:

Does increased variability of firing times improve recovery?

Objective

Shorten marine acquisition times & increase source sample density.

Questions:

Does increased variability of firing times improve recovery?

If transform-domain recovery fails are there alternatives?

Regular vs. jittered locations

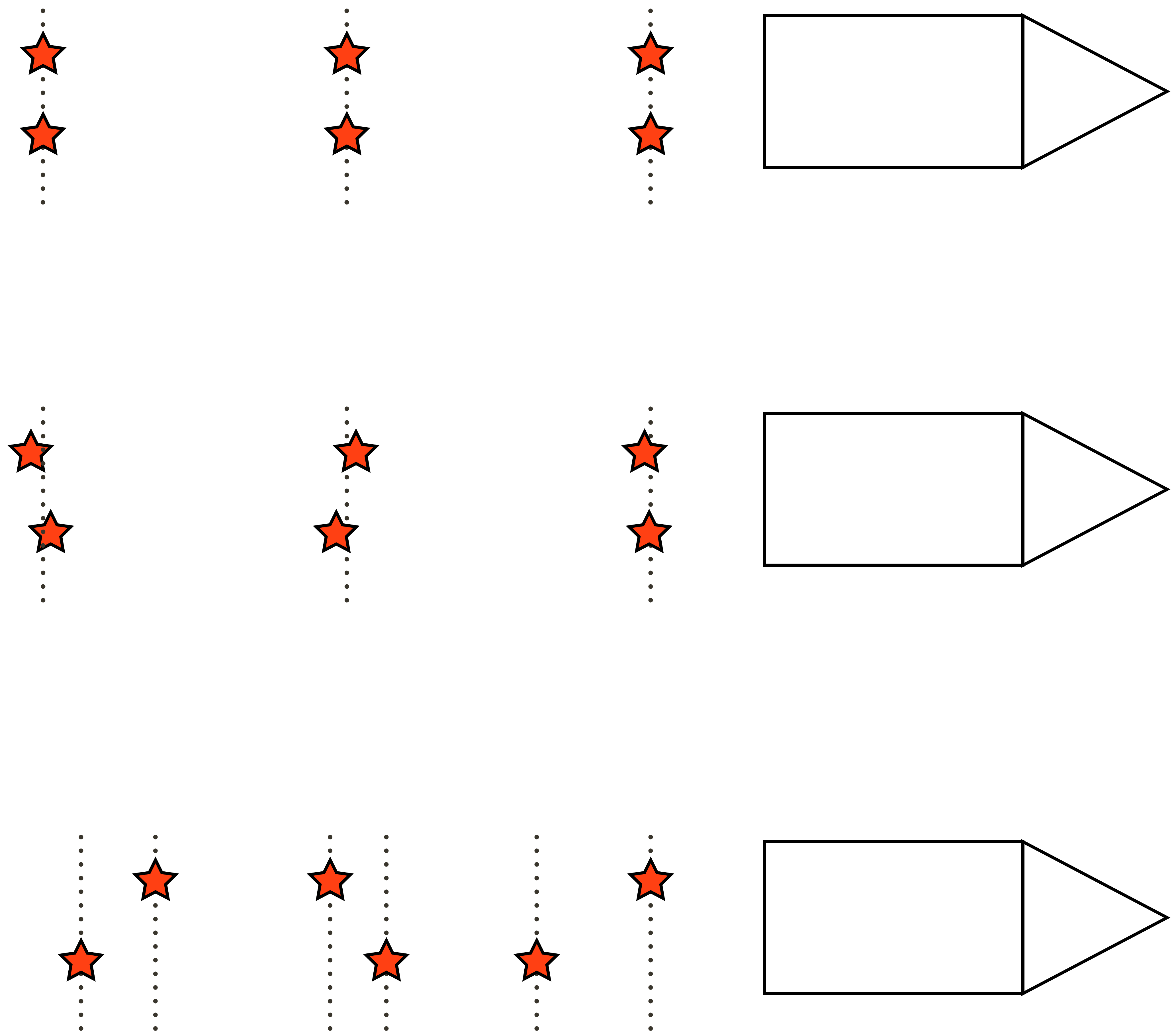
regularly sampled spatial grid

almost regularly sampled spatial grid

(low variability)

irregularly sampled spatial grid

(high variability)



Jittered sampling in marine

High-variability:

- transform-based deblending

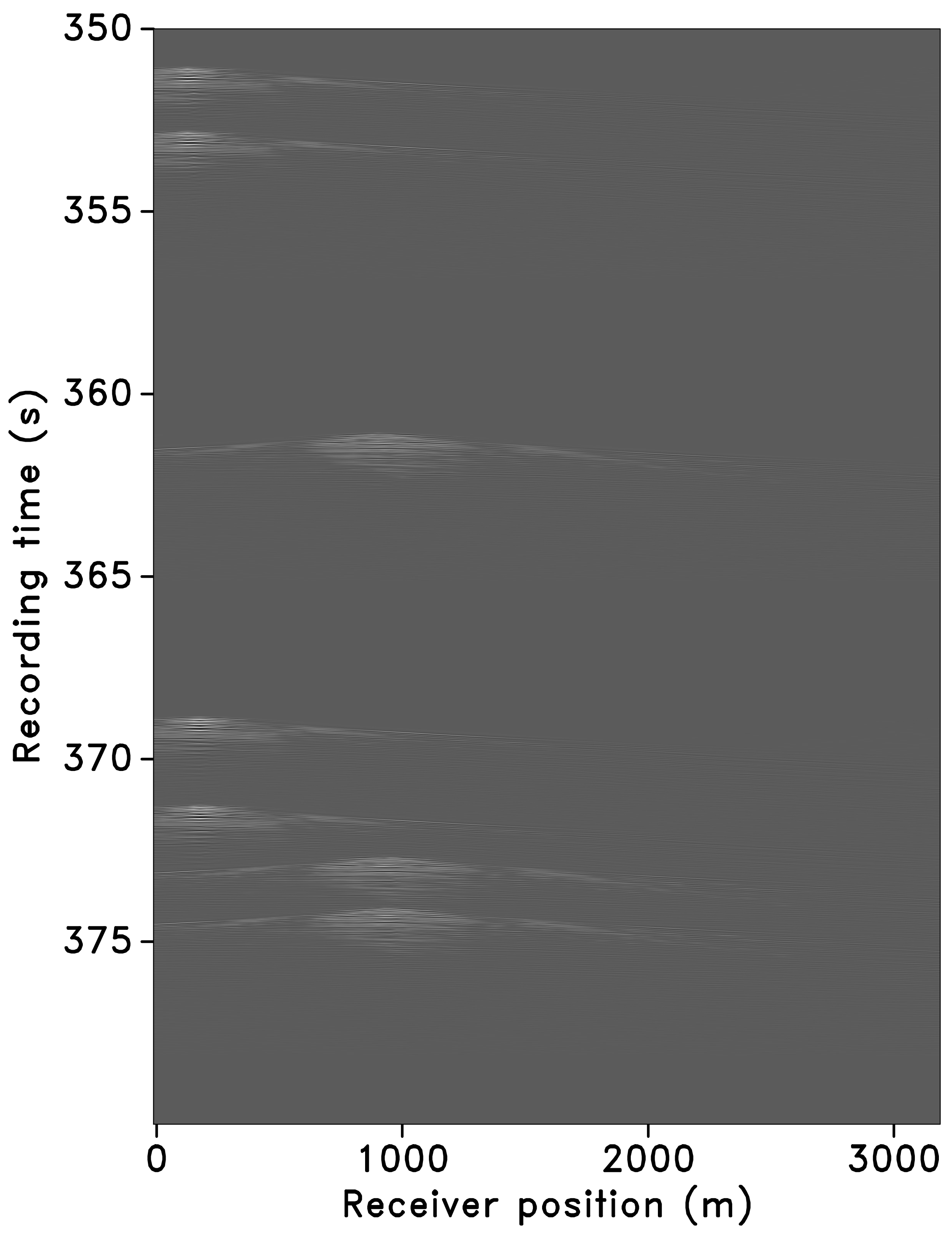
Low-variability:

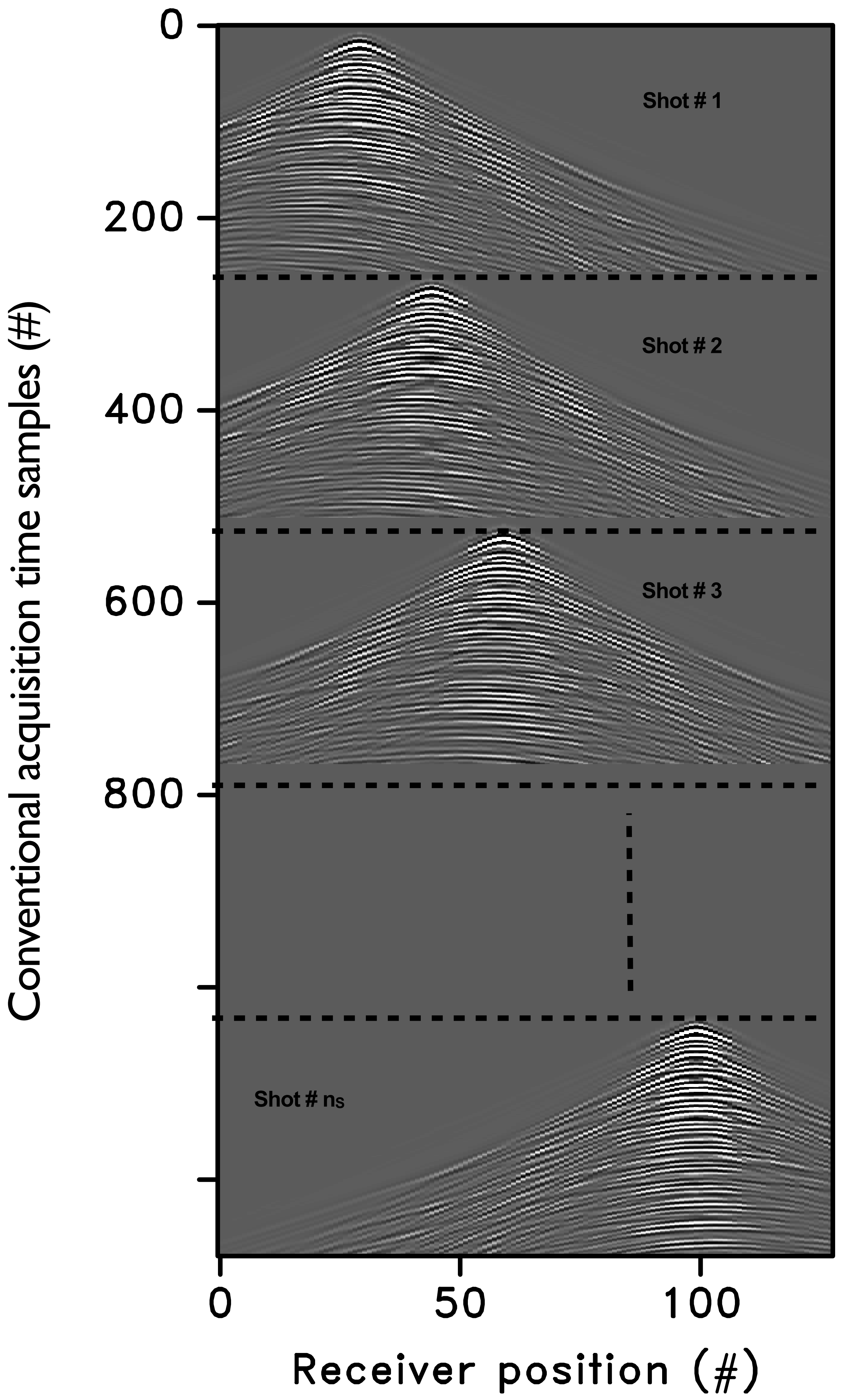
- rank-revealing source separation

acquire in the field on **irregular** grid (**subsampled** shots **w/ overlap** between shot records)

would like to have on **regular** grid (**all** shots **w/o overlaps** between shot records)

b = **M** **d**





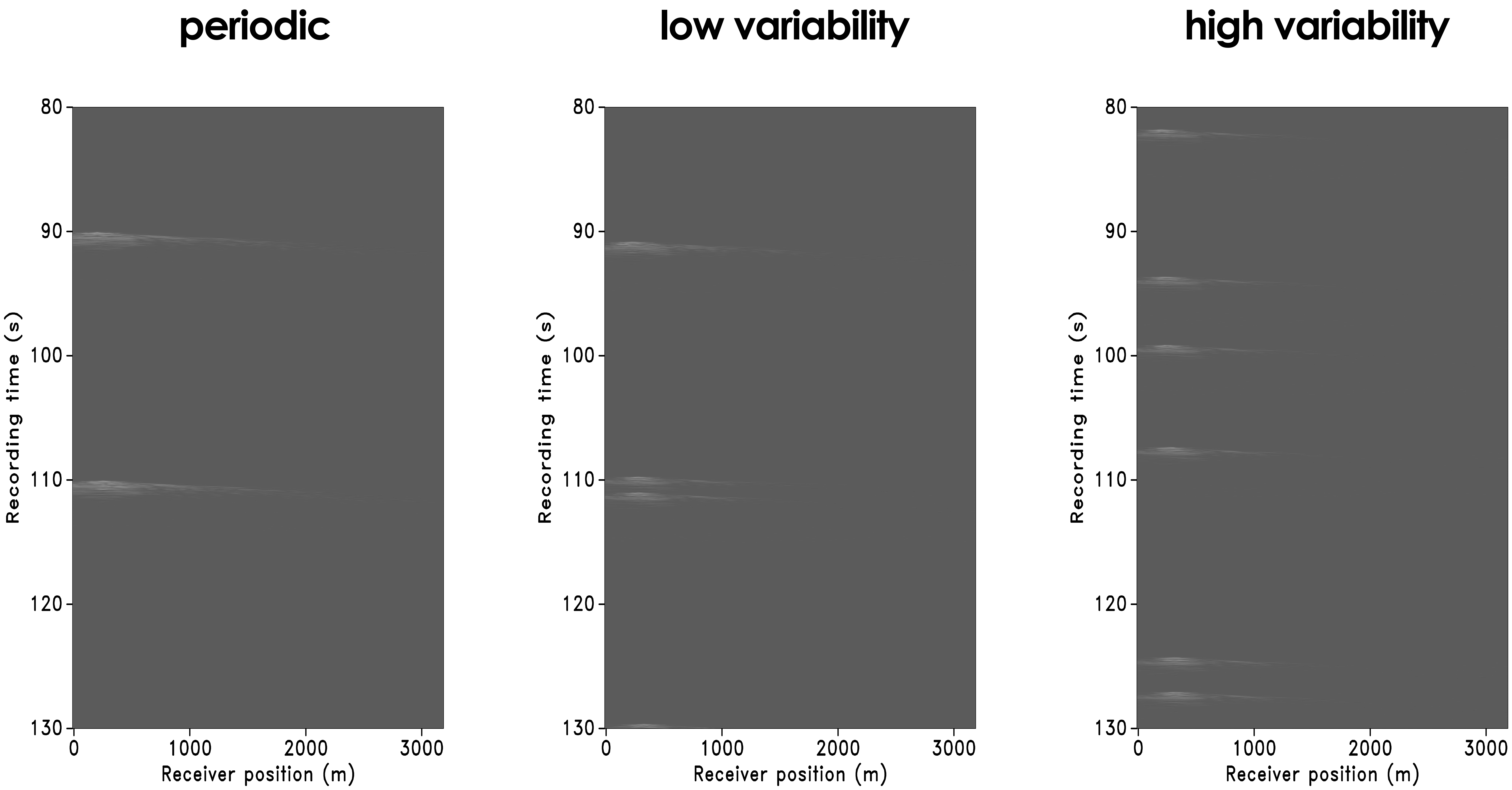
Sparsity-promoting recovery

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

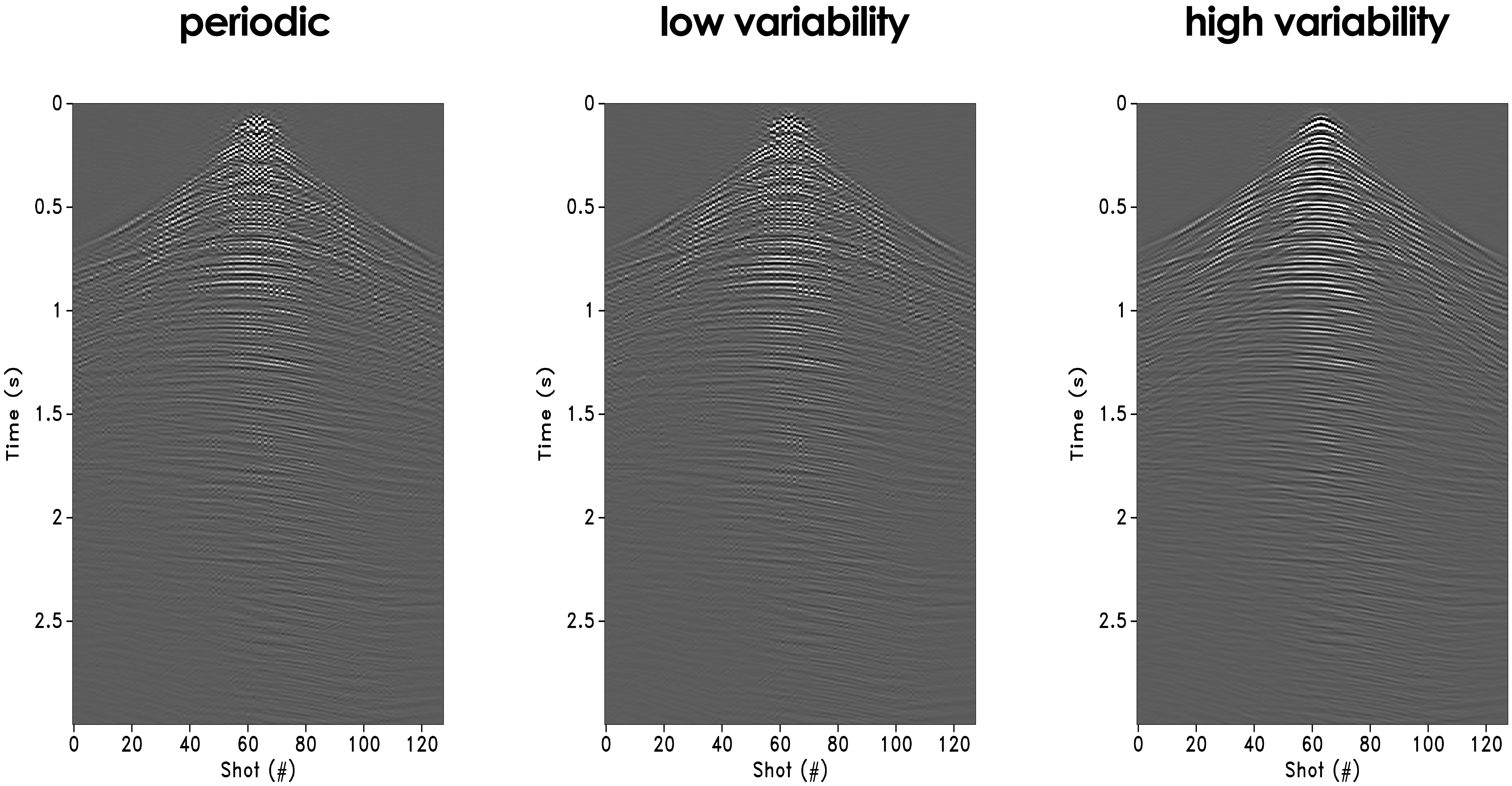
recovered data: $\tilde{\mathbf{d}} = \mathbf{S}^H \tilde{\mathbf{x}}$

$\mathbf{S^H}$	a transform domain synthesis
$\mathbf{A}$	measurement operator : $\mathbf{MS^H}$, $\mathbf{M}$ is a blending operator
$\mathbf{b}$	blended data
$\tilde{\mathbf{x}}$	estimated curvelet coefficients for source separated wavefield

Measurements

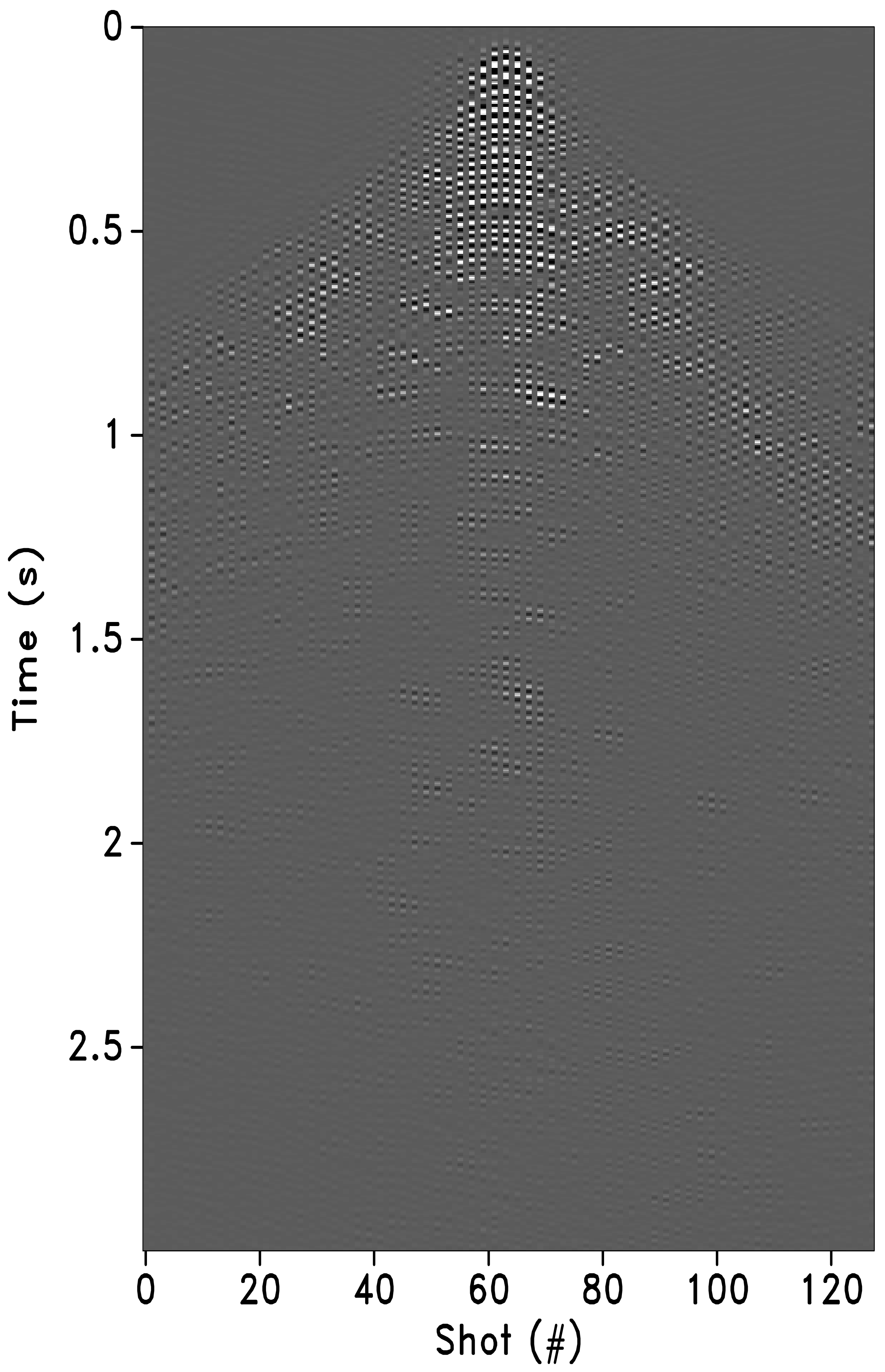


Recovery

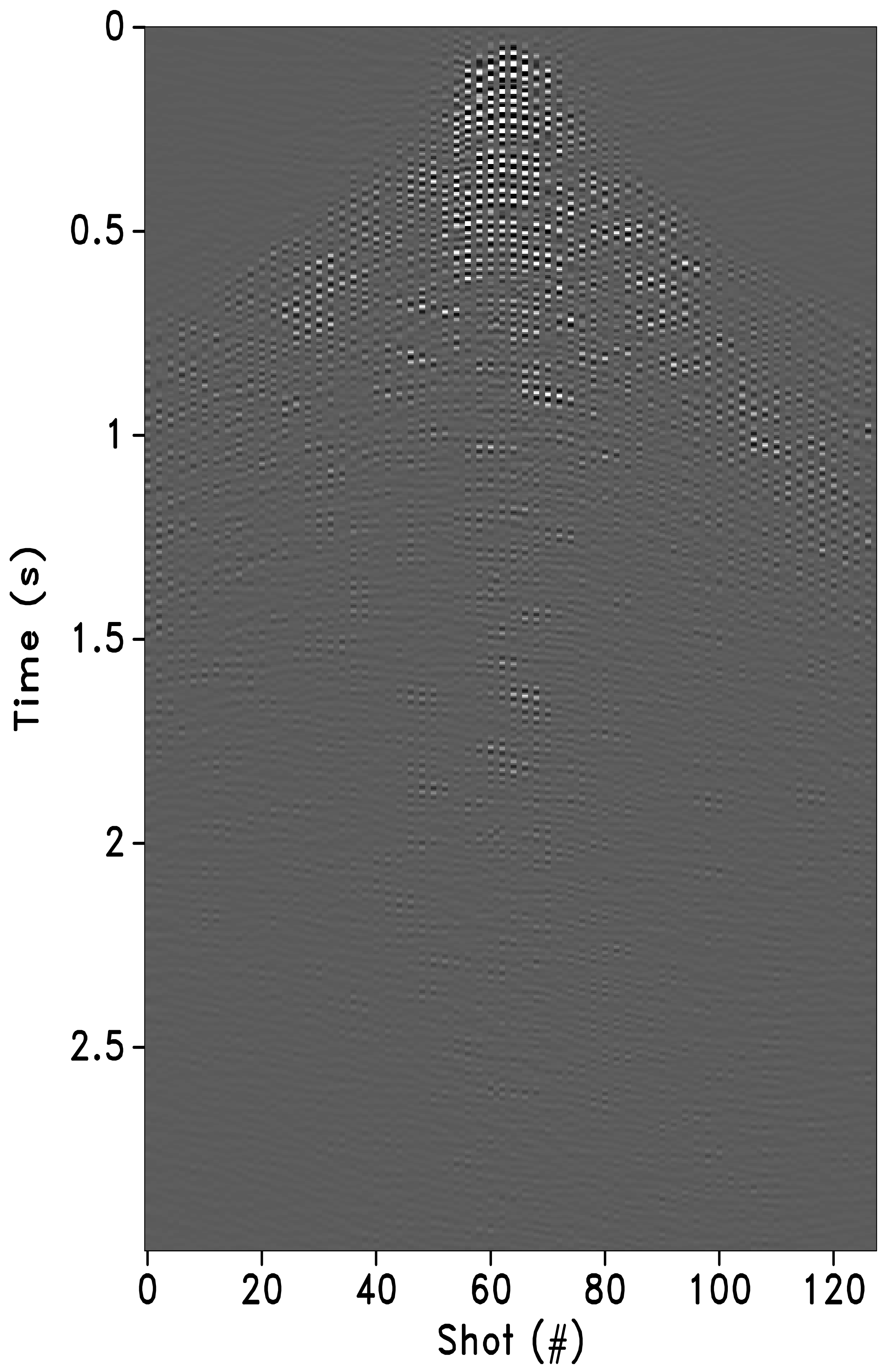

periodic
low variability
high variability
Time (s)
0
0.5
1
1.5
2
2.5
Shot (#)
0 20 40 60 80 100 120

Difference

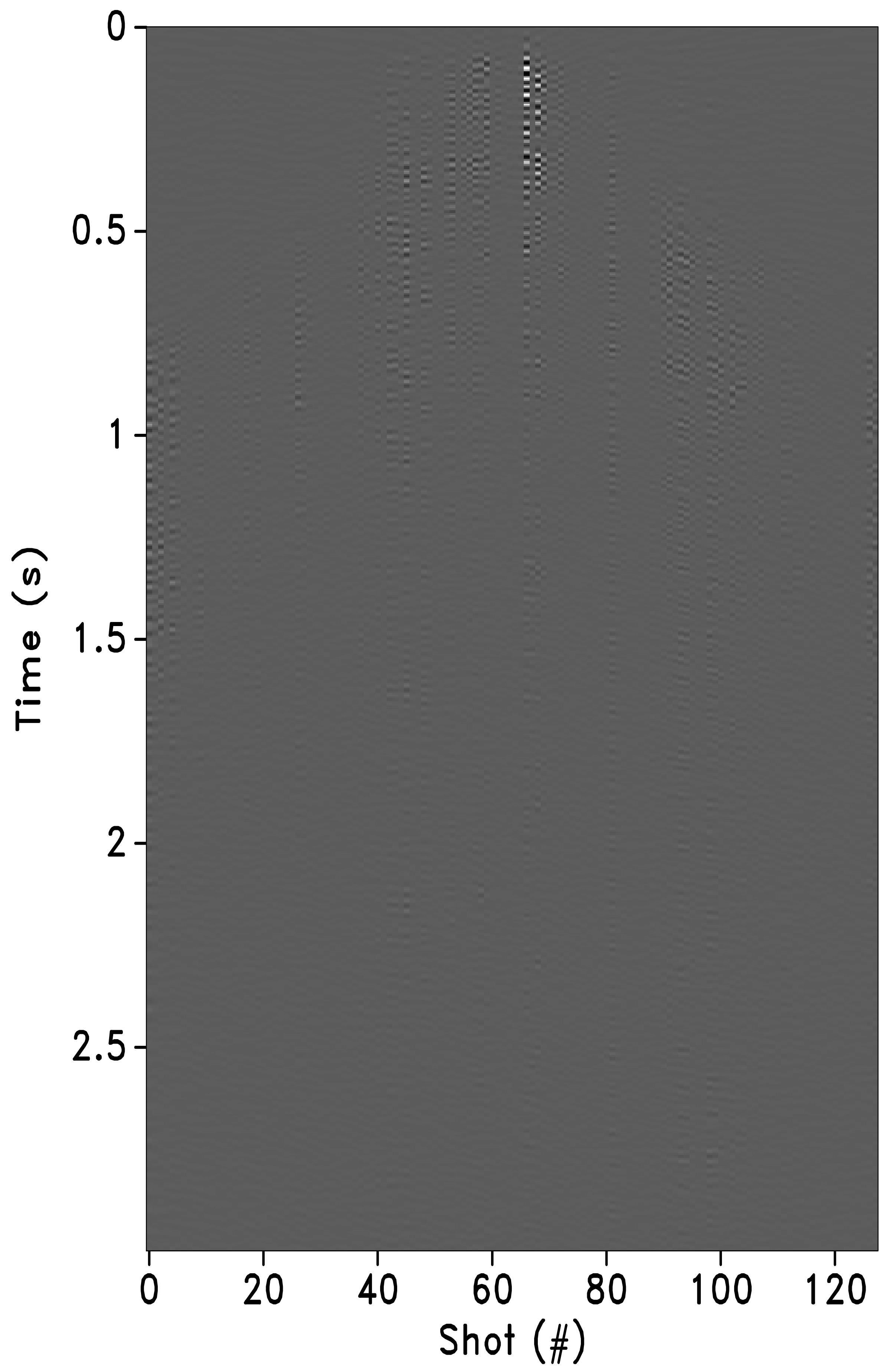
periodic



low variability



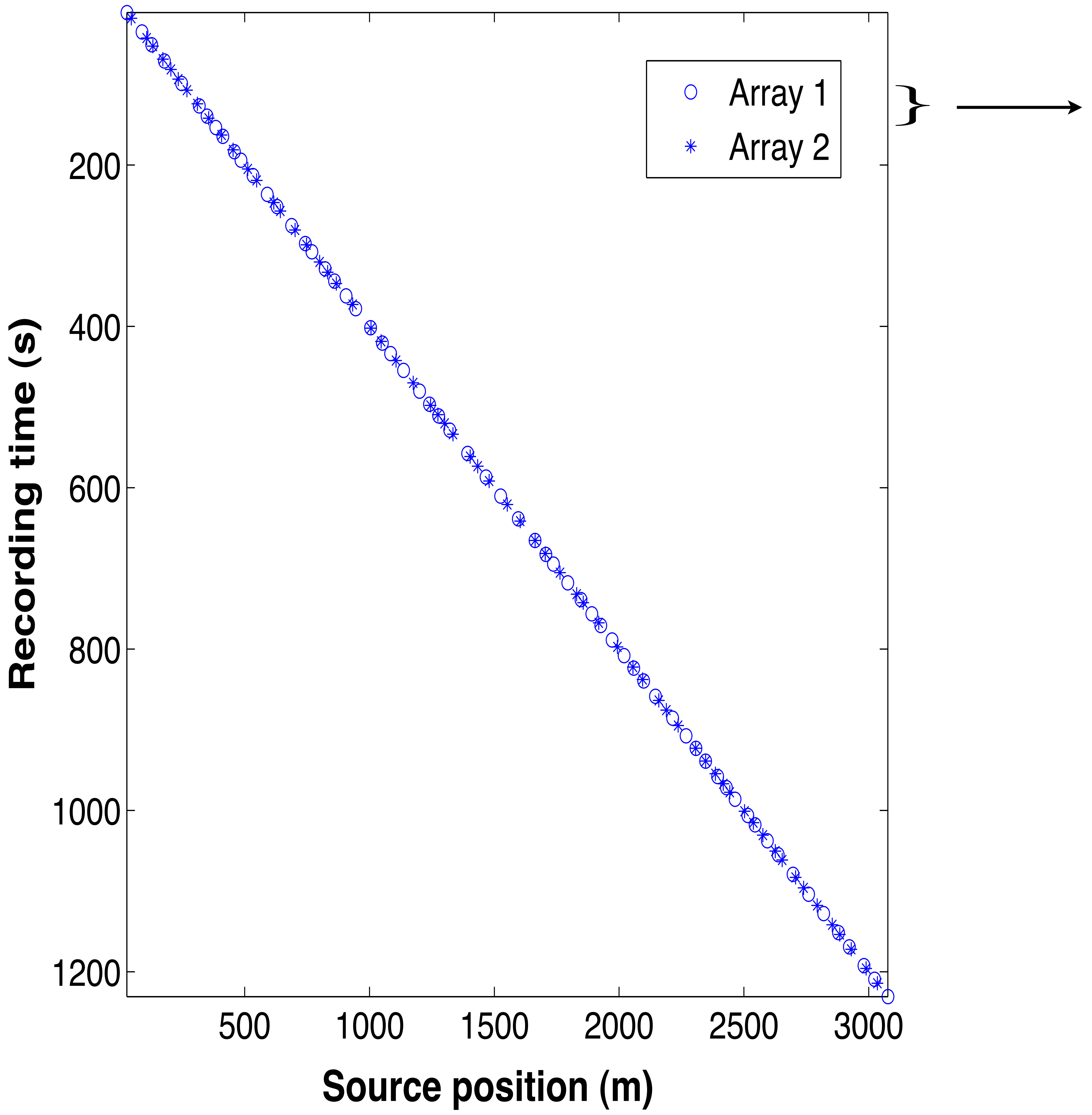
high variability

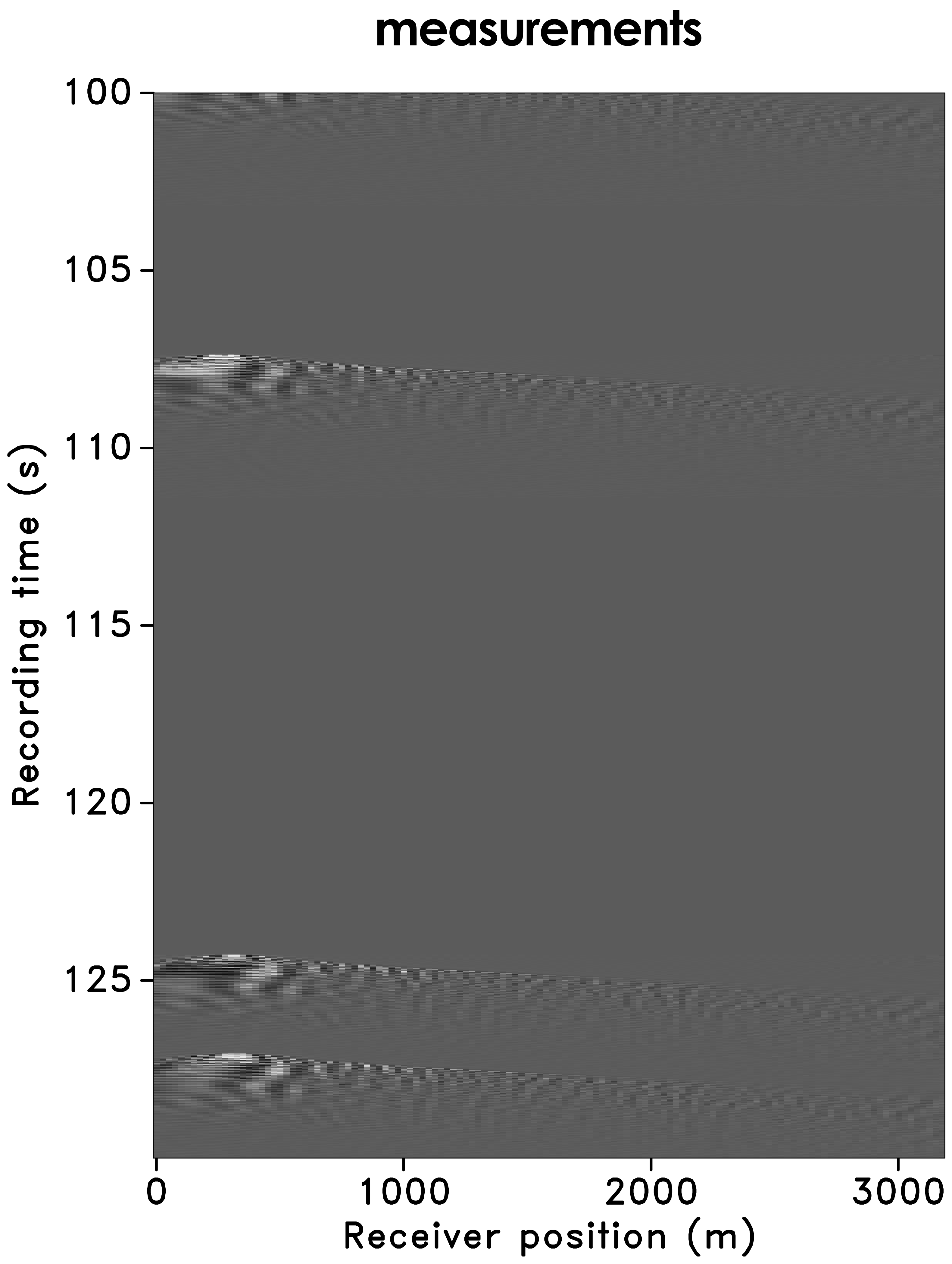


Time-jittered OBC acquisition

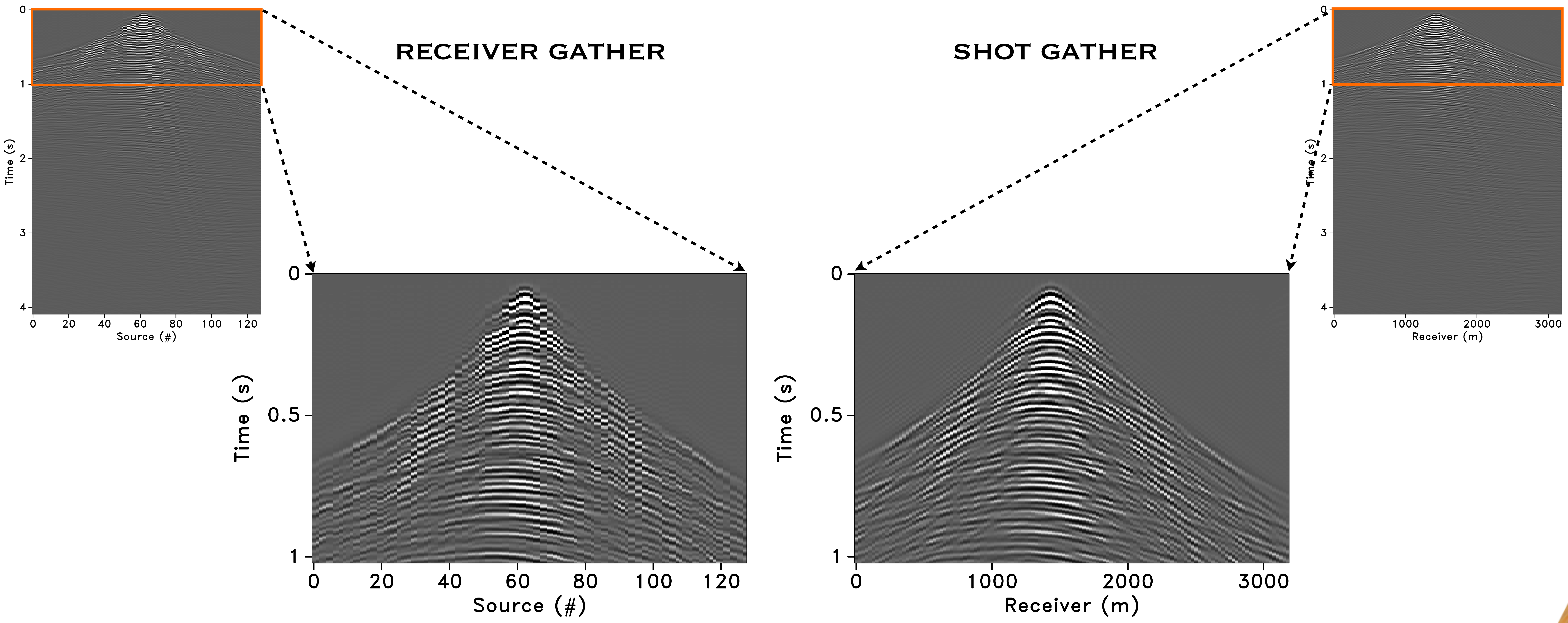
[1 source vessel, speed = 5 knots, underlying grid: 25 m]

[# jittered source locations is half # sources (per array) in ideal periodic survey w/o overlap]



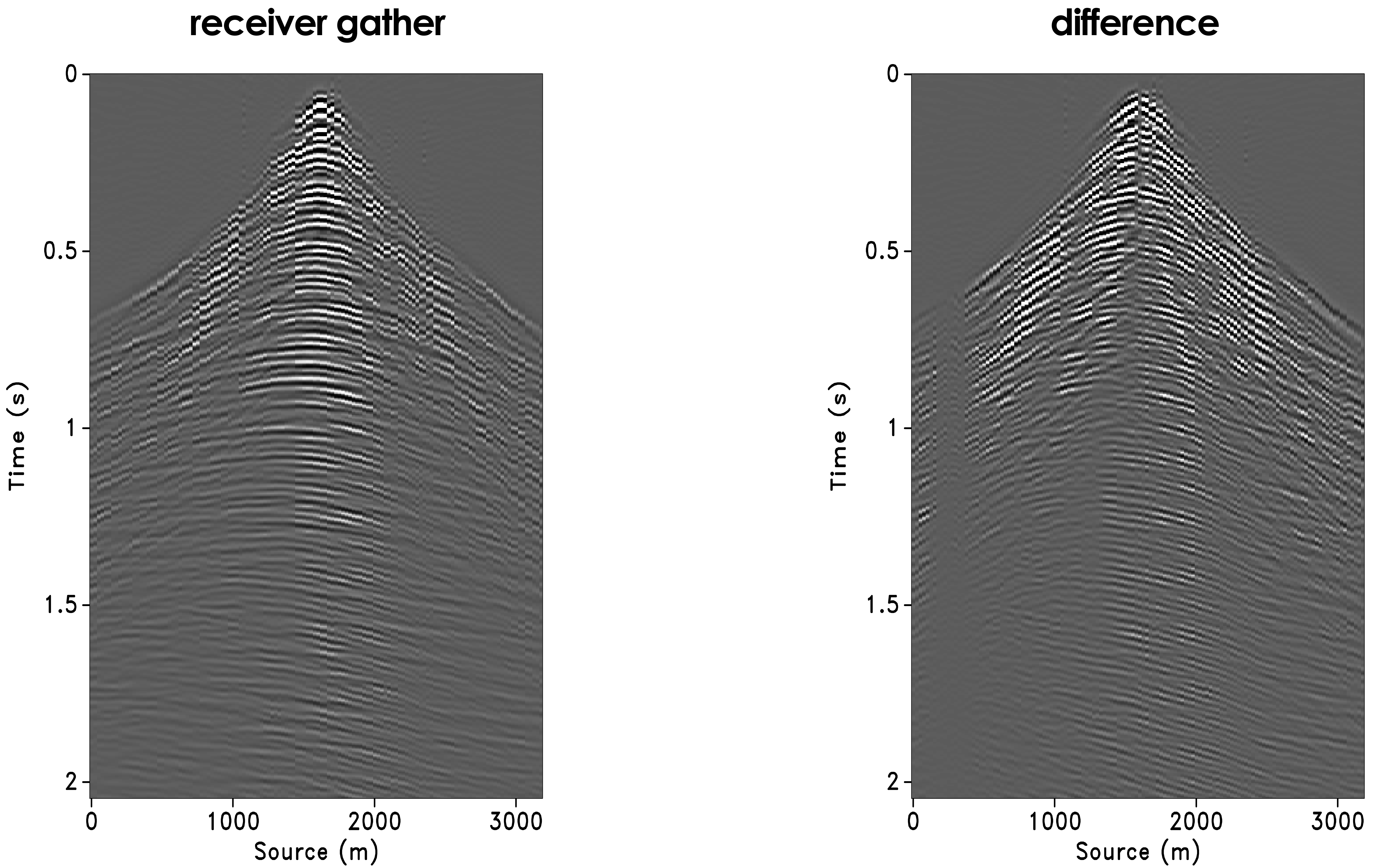


Extra complication – Off the grid



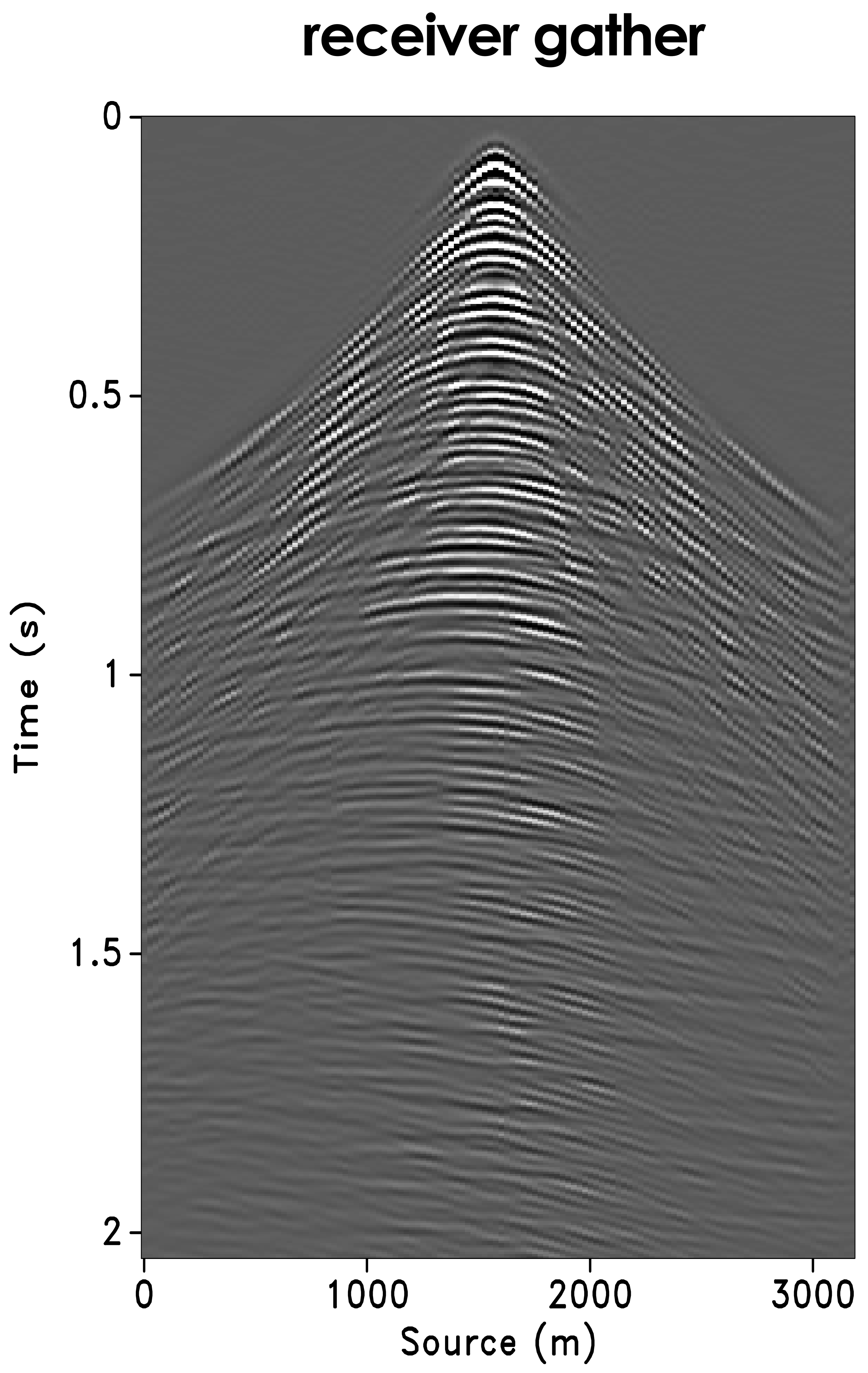
Recovery with FDCT ('binning')

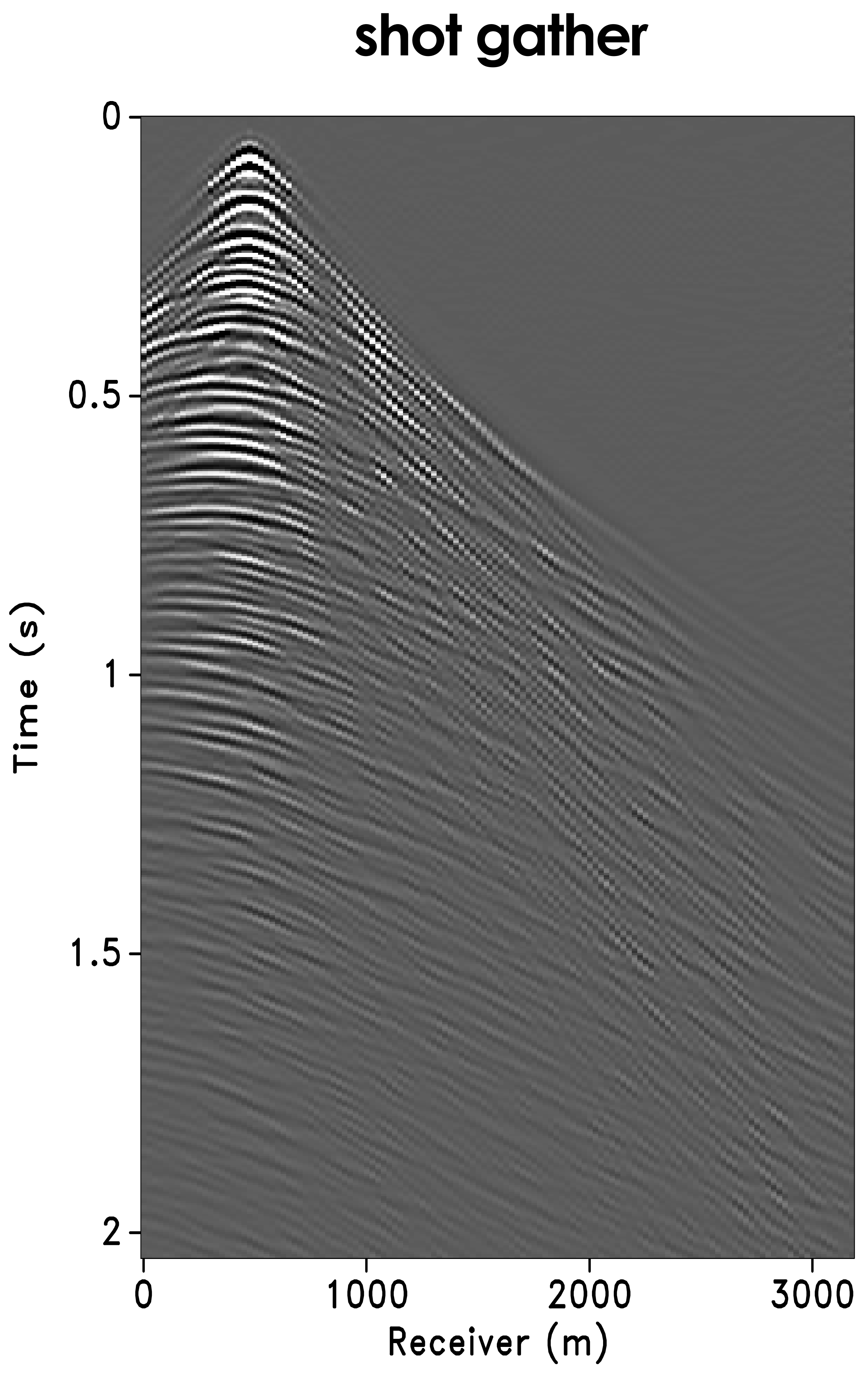
["deblending" from jittered 50m grid to regular 25m grid]



Sparsity-promoting recovery on irregular grid w/ NFDCT (17.1 dB)

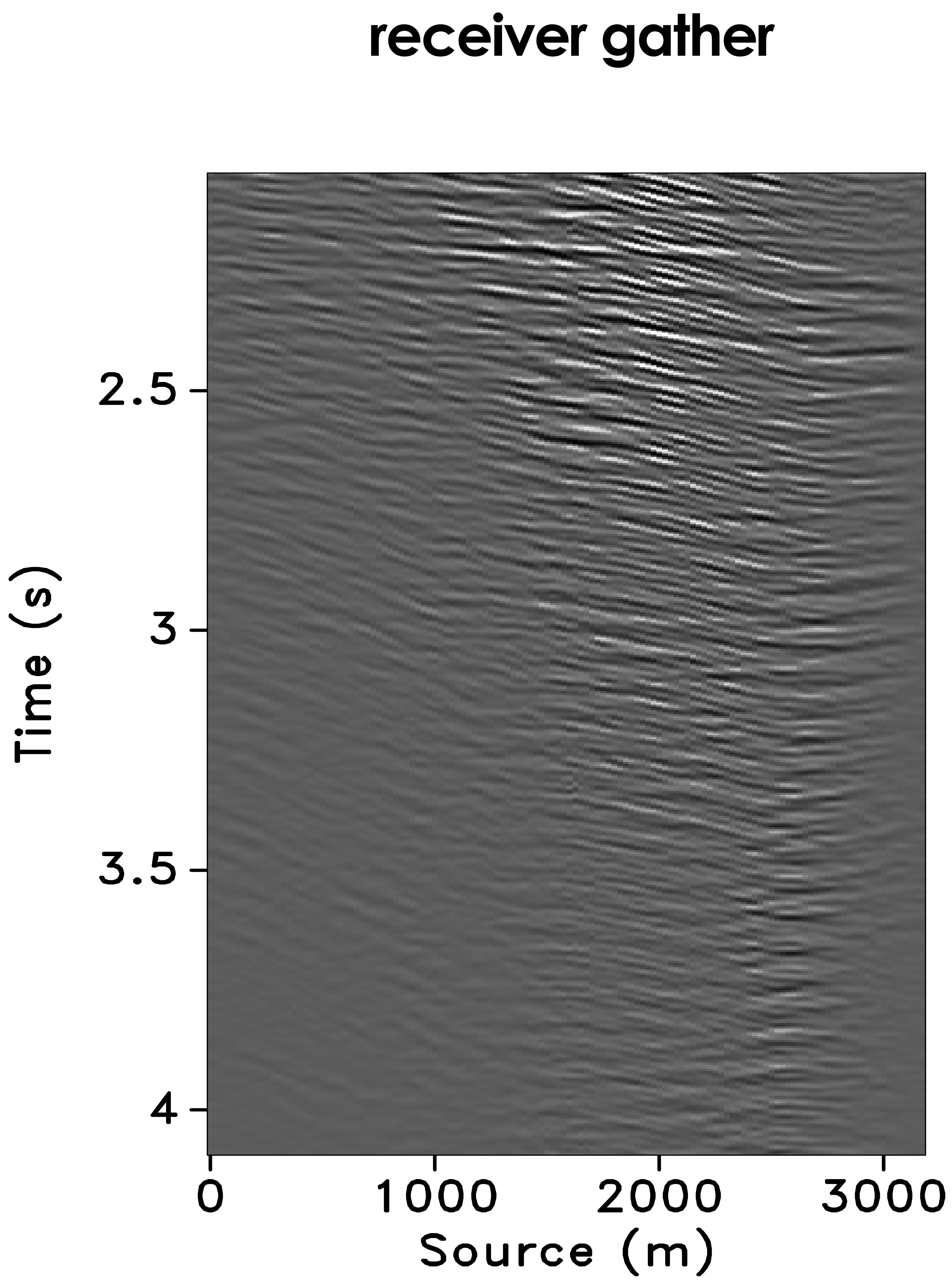
["deblending" from jittered 50m grid to regular 25m grid]

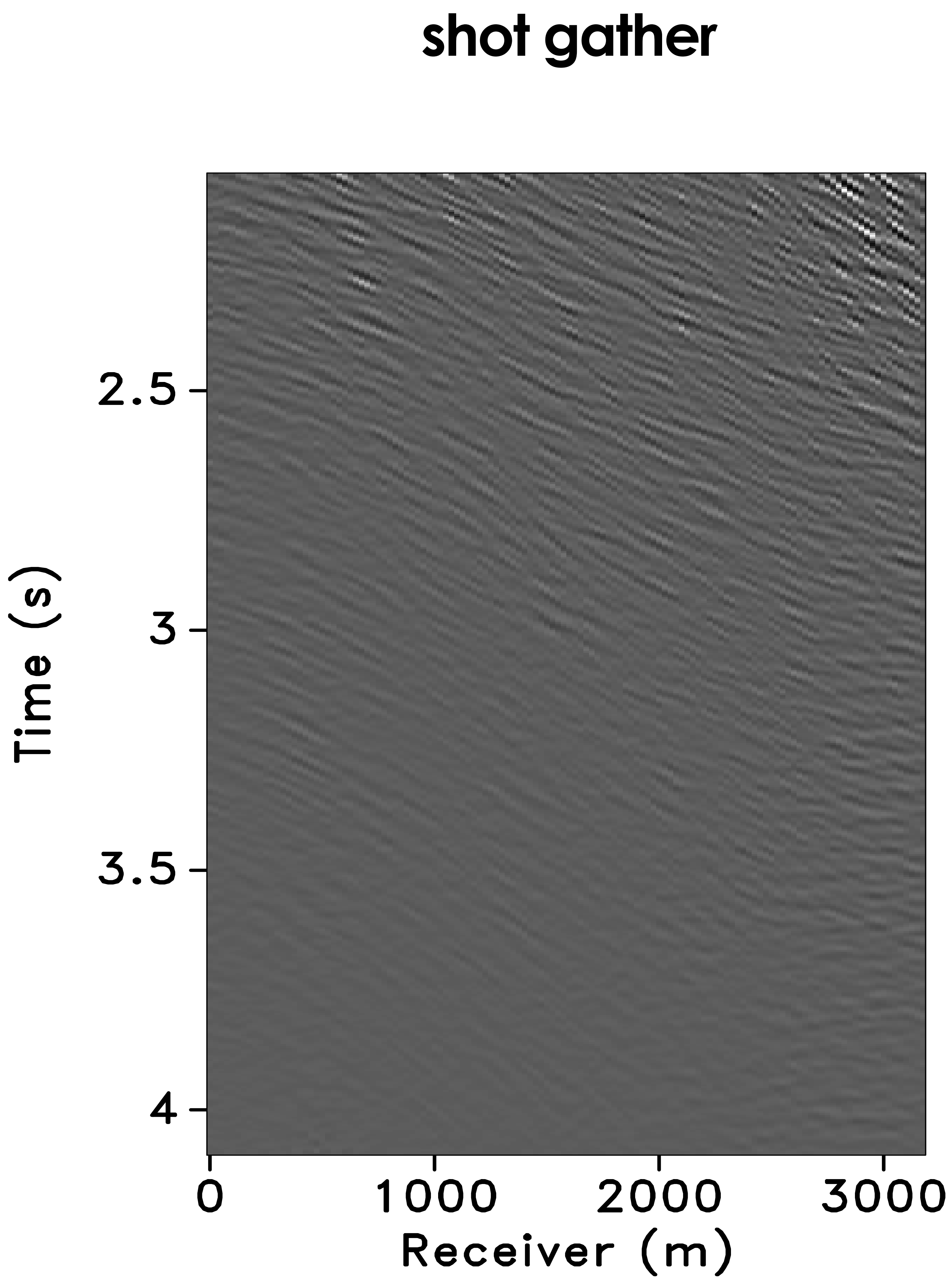




Sparsity-promoting recovery on irregular grid w/ NFDCT (17.1 dB)

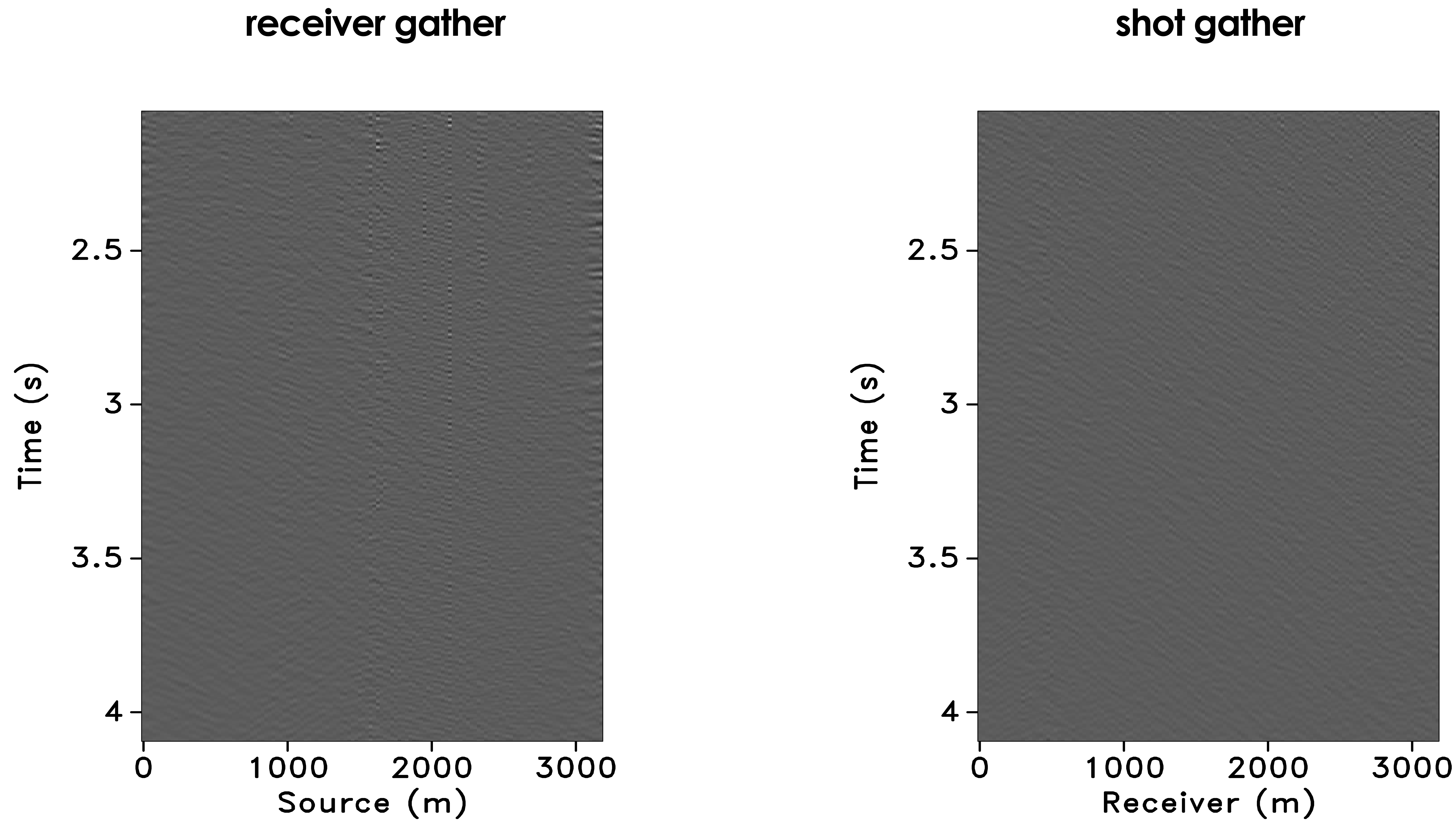
[“deblending” from jittered 50m grid to regular 25m grid]





Sparsity-promoting recovery on irregular grid w/ NFDCT (17.1 dB)

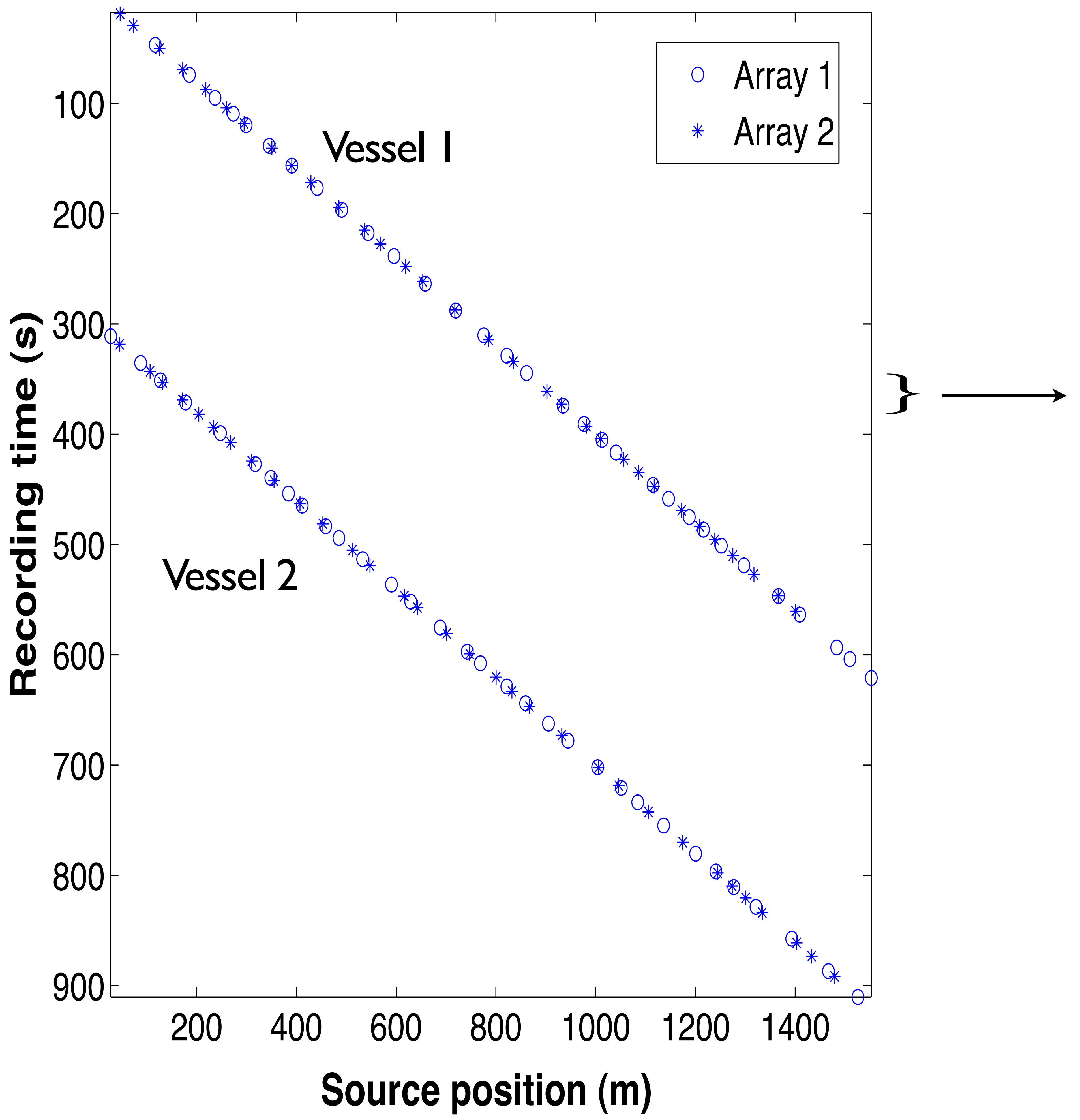
["deblending" from jittered 50m grid to regular 25m grid] (difference)

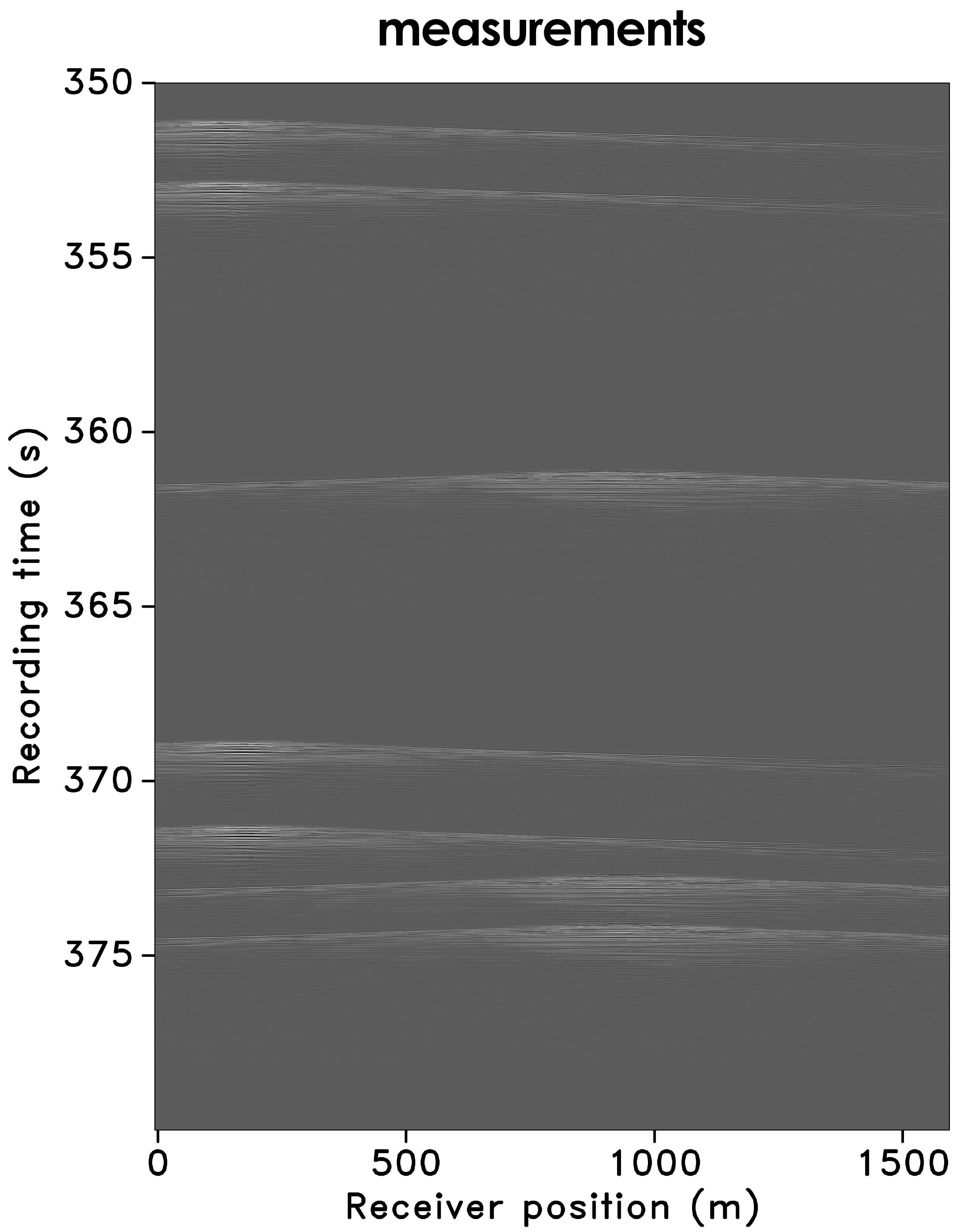


Time-jittered OBC acquisition

[2 source vessels, speed = 5 knots, underlying grid: 12.5 m]

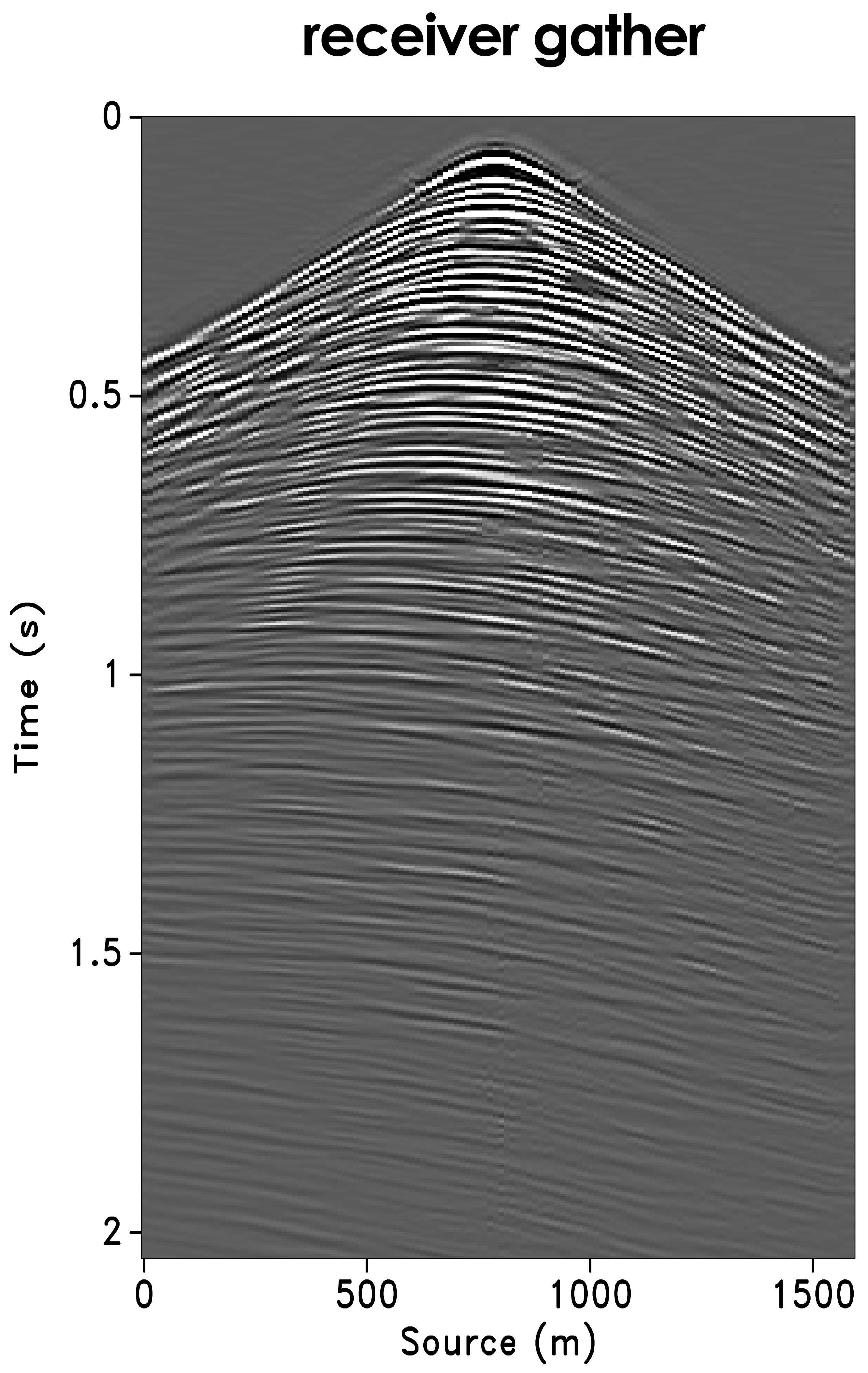
[# jittered source locations is one-fourth # sources (per array) in ideal periodic survey w/o overlap]

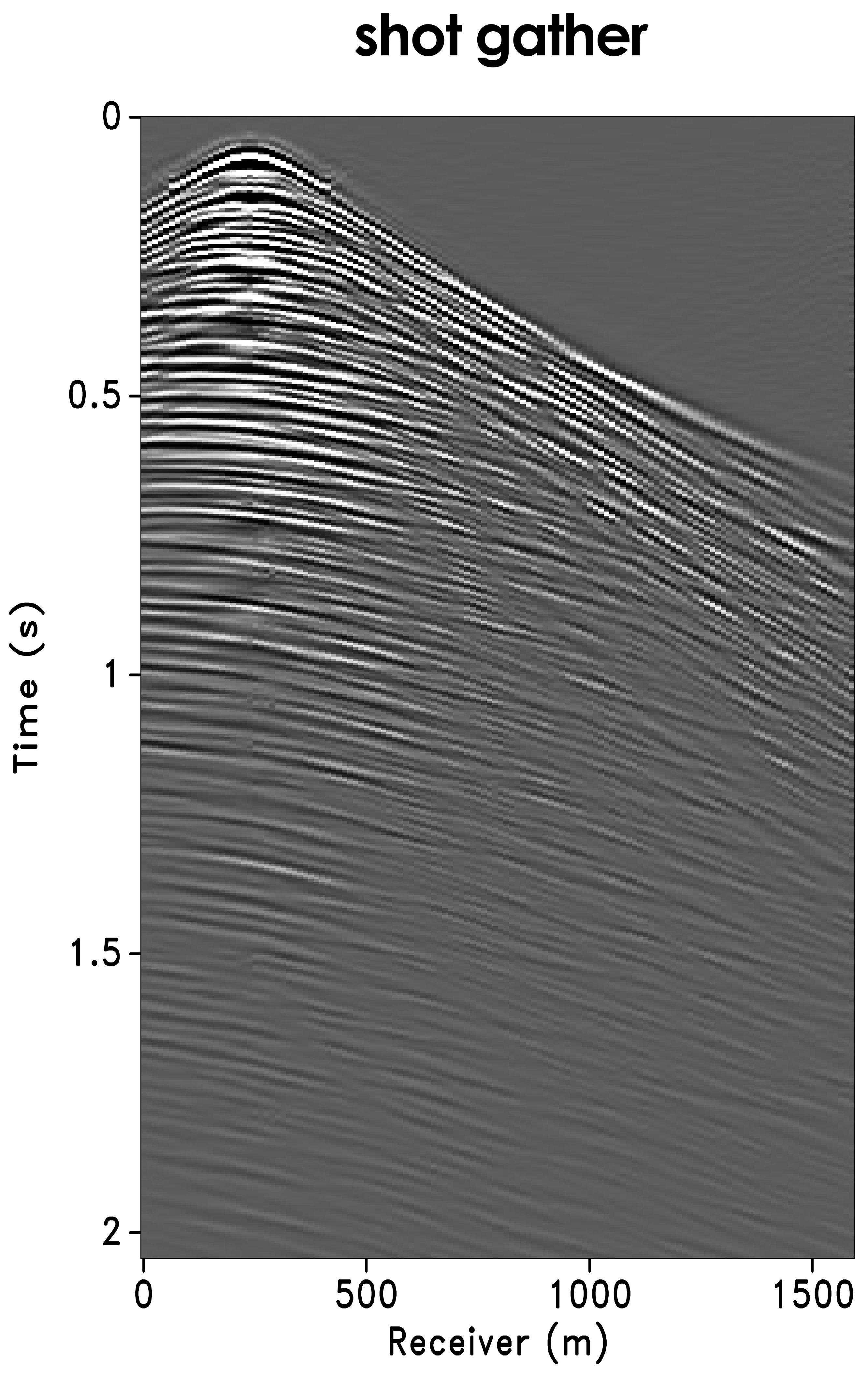




Sparsity-promoting recovery on *irregular* grid with *NFDCT* (16.8 dB)

[“deblending” from *jittered* 50m grid to *regular* 12.5m grid]





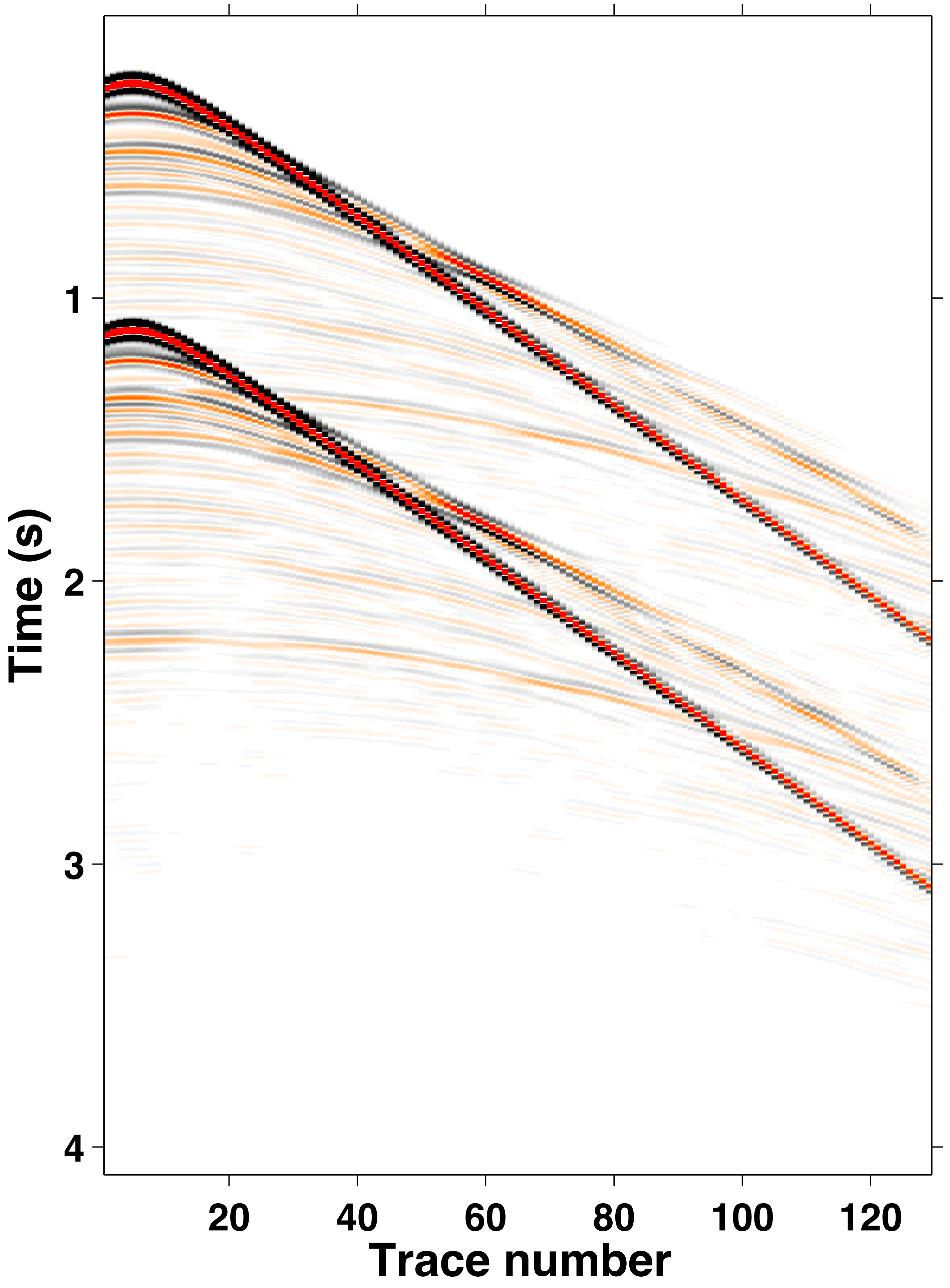
Summary

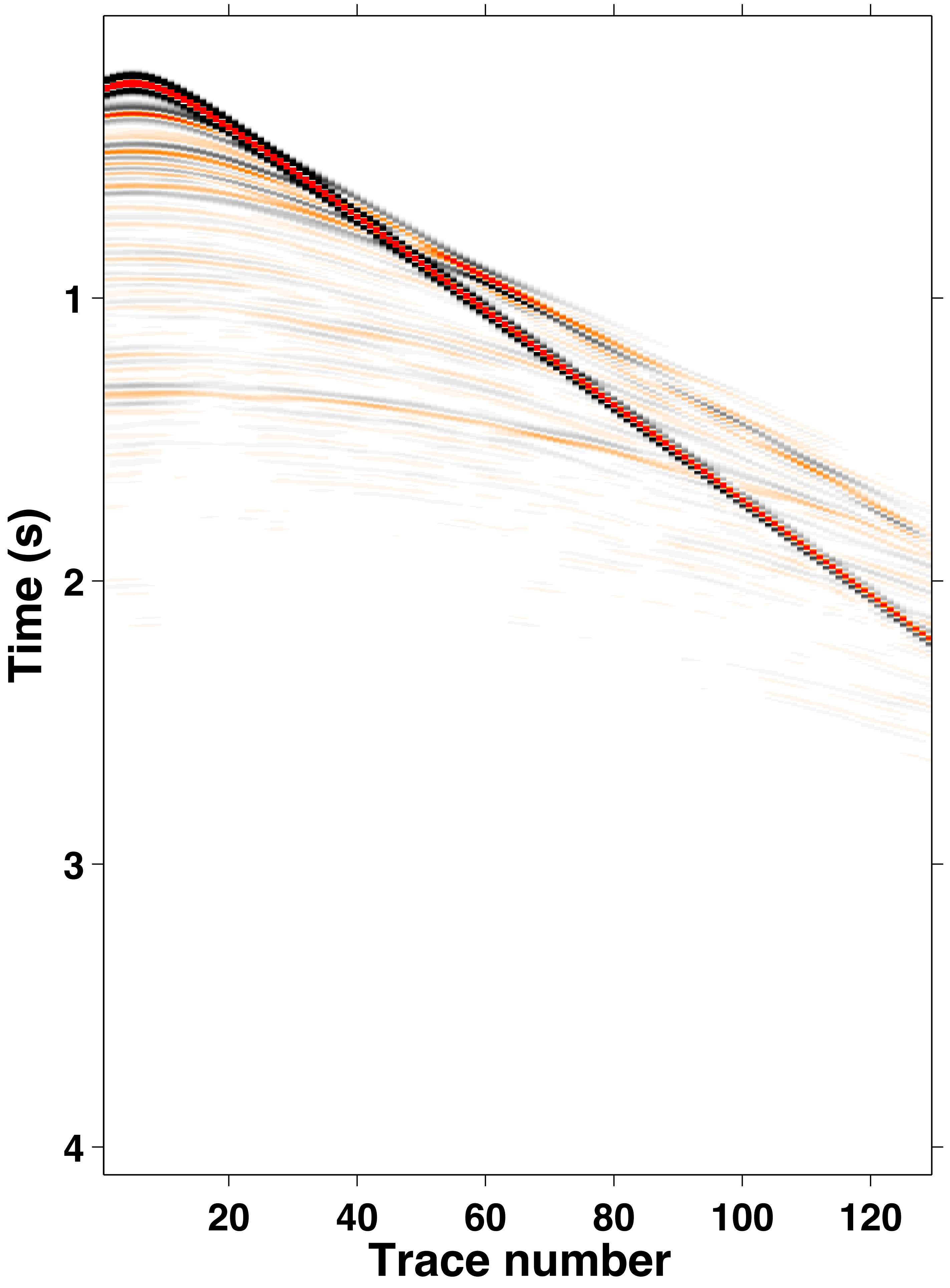
	jittered to regular (m)	recovery with **FDCT** [SNR (dB)]	recovery with **NFDCT** [SNR (dB)]
1 source vessel (2 airgun arrays)	50 to 25	14.2	17.1
	50 to 12.5	11.1	12.5
2 source vessels (2 airgun arrays per vessel)	50 to 25	19.7	21.5
	50 to 12.5	15.0	16.3

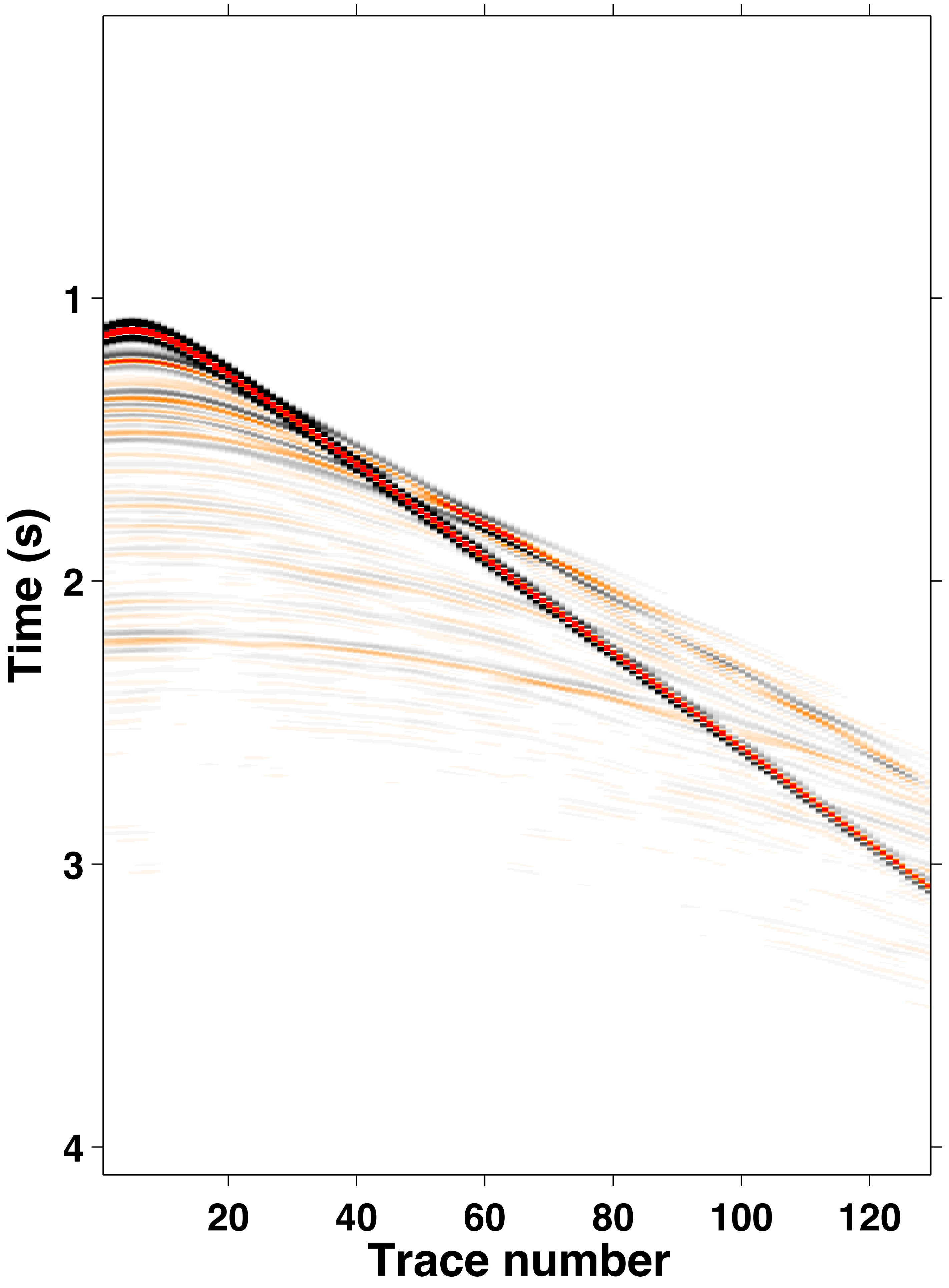
Source separation via rank minimization

Blended data

blended shot = source 1 + source 2 (time-delayed)







[Wason, Kumar, Aravkin & FJH, '14]

SLIM

Rank minimization

$$\min_{\mathbf{X}} \quad \underbrace{\operatorname{rank}(\mathbf{X})} \quad \text{s.t.} \quad \|\mathcal{A}(\mathbf{X}) - \mathbf{b}\|_2 \leq \epsilon$$

number of singular values of $\mathbf{X}$

for blended acquisition:

$\mathbf{b}$: blended data

$$\mathcal{A} := \begin{bmatrix} \mathbf{MS^H} & \mathbf{MTS^H} \end{bmatrix}$$

↑ time delay matrix

unblended data matrix for

$$\mathbf{X} = \begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \end{bmatrix} \begin{matrix} \longleftarrow \text{source 1} \\ \longleftarrow \text{source 2} \end{matrix}$$

Rank minimization

prohibitively expensive
(search over all possible values of rank)

$$\min_{\mathbf{X}} \quad \underbrace{\operatorname{rank}(\mathbf{X})} \quad \text{s.t.} \quad \|\mathcal{A}(\mathbf{X}) - \mathbf{b}\|_2 \leq \epsilon$$

number of singular values of $\mathbf{X}$

Nuclear-norm minimization

convex relaxation of rank-minimization

[Recht, et. al., 2010, Aravkin et.al., '13]

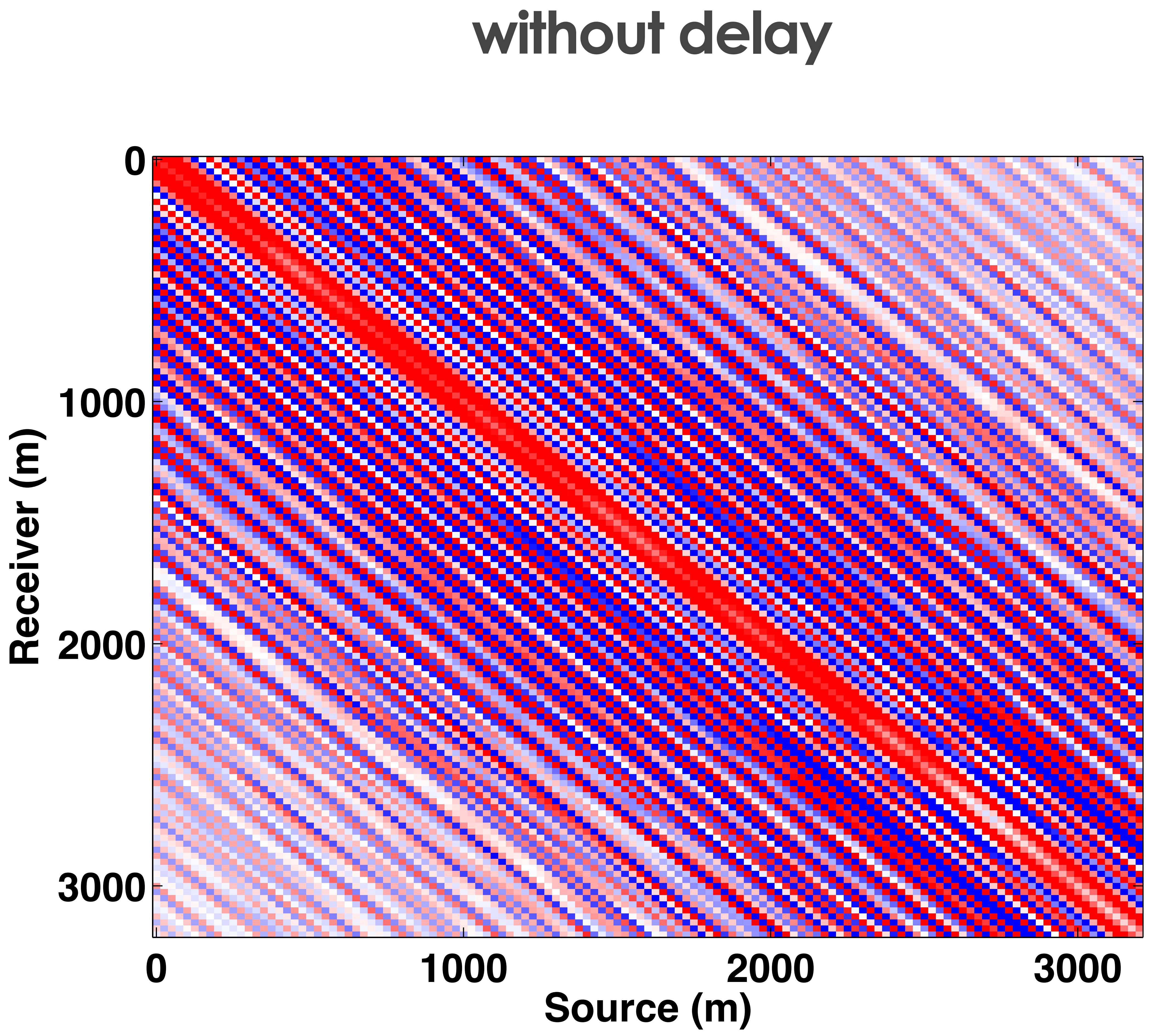
$$\min_{\mathbf{X}} \quad \underbrace{||\mathbf{X}||_*} \quad \text{s.t.} \quad \|\mathcal{A}(\mathbf{X}) - \mathbf{b}\|_2 \leq \epsilon$$

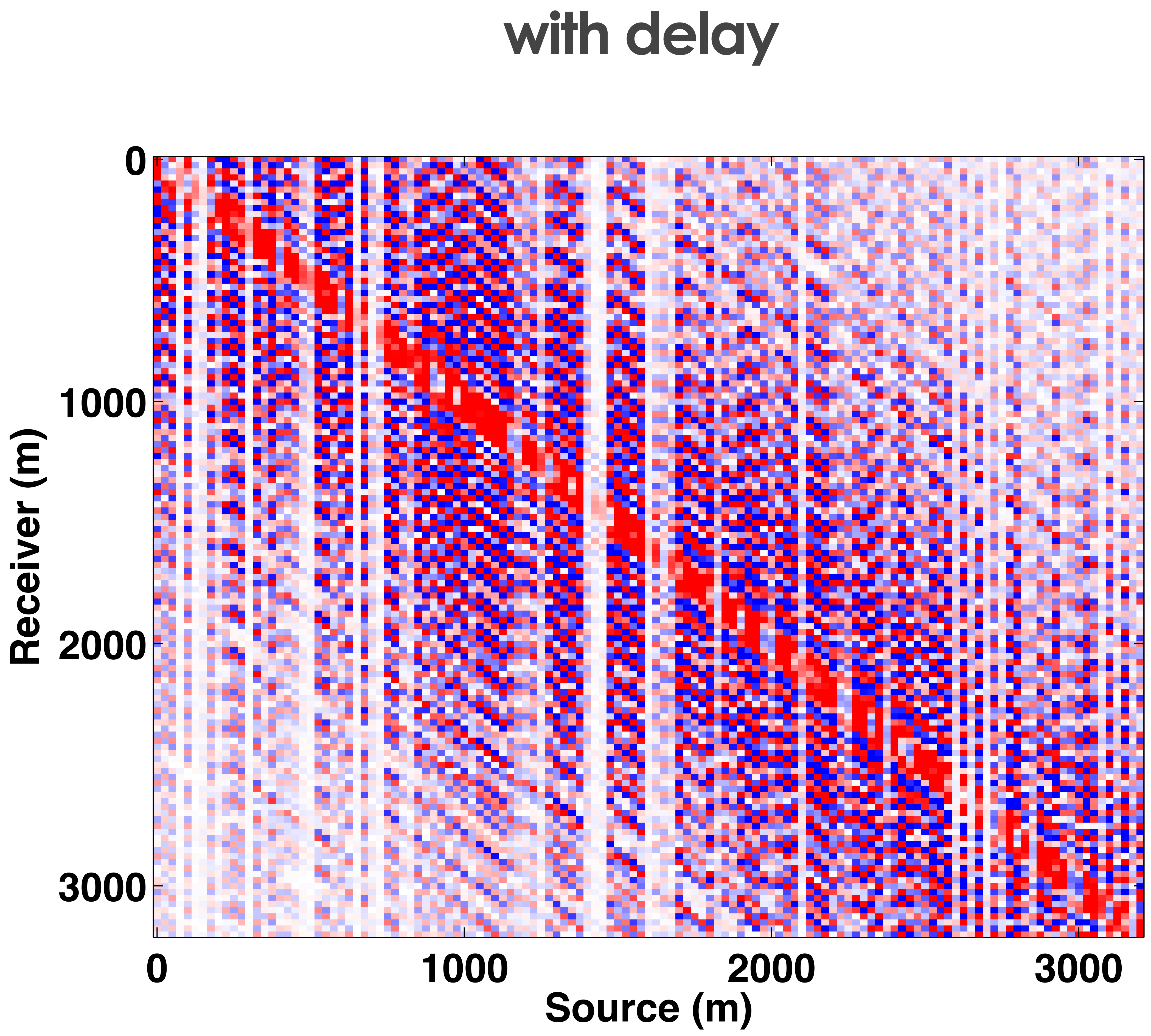
sum of singular values of $\mathbf{X}$

Haneet Wason, Rajiv Kumar, Aleksandr Y. Aravkin, and Felix J. Herrmann, "Source separation via SVD-free rank minimization in the hierarchical semi-separable representation". 2014.

Low-rank structure – frequency slice at 25 Hz

in source-receiver domain?

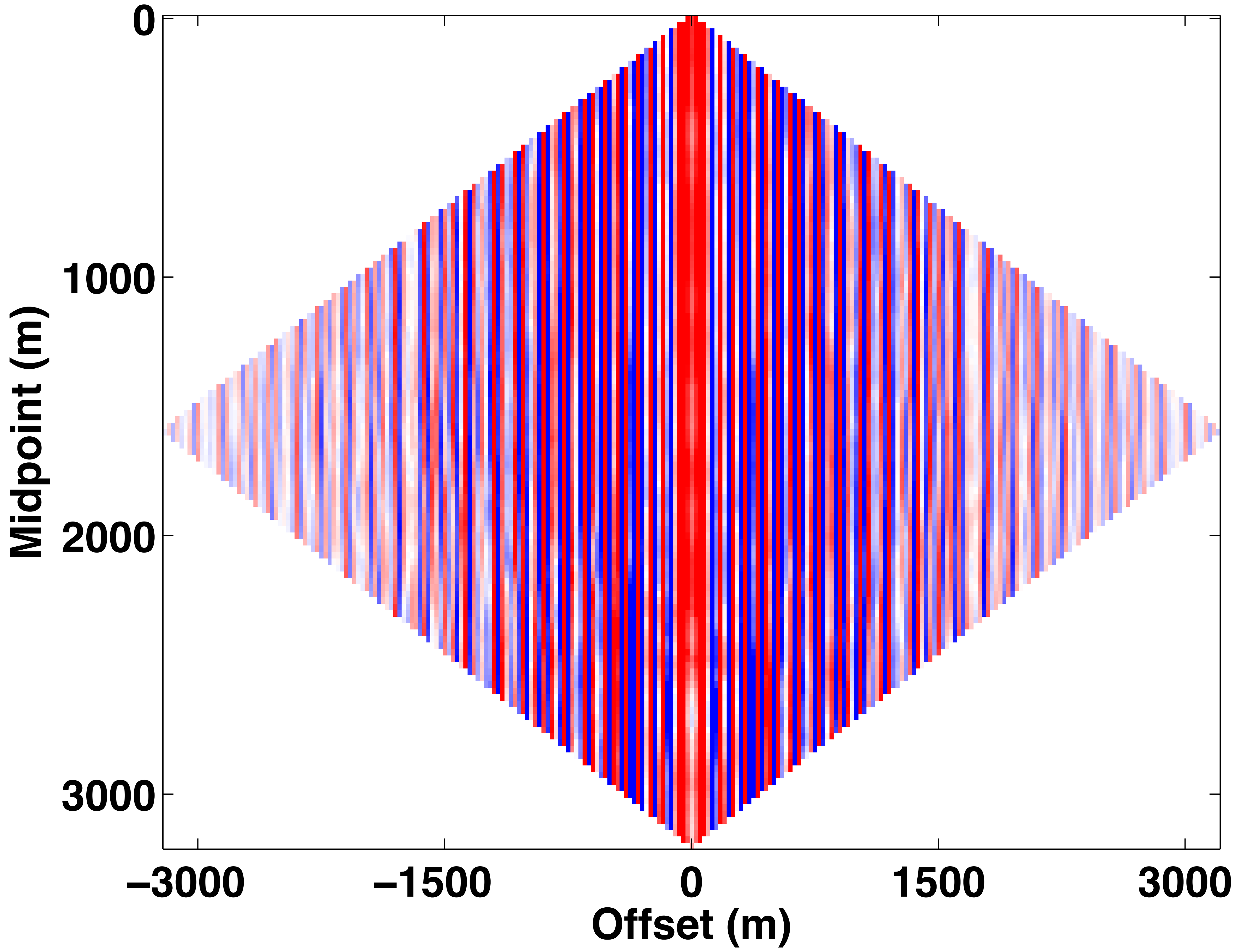




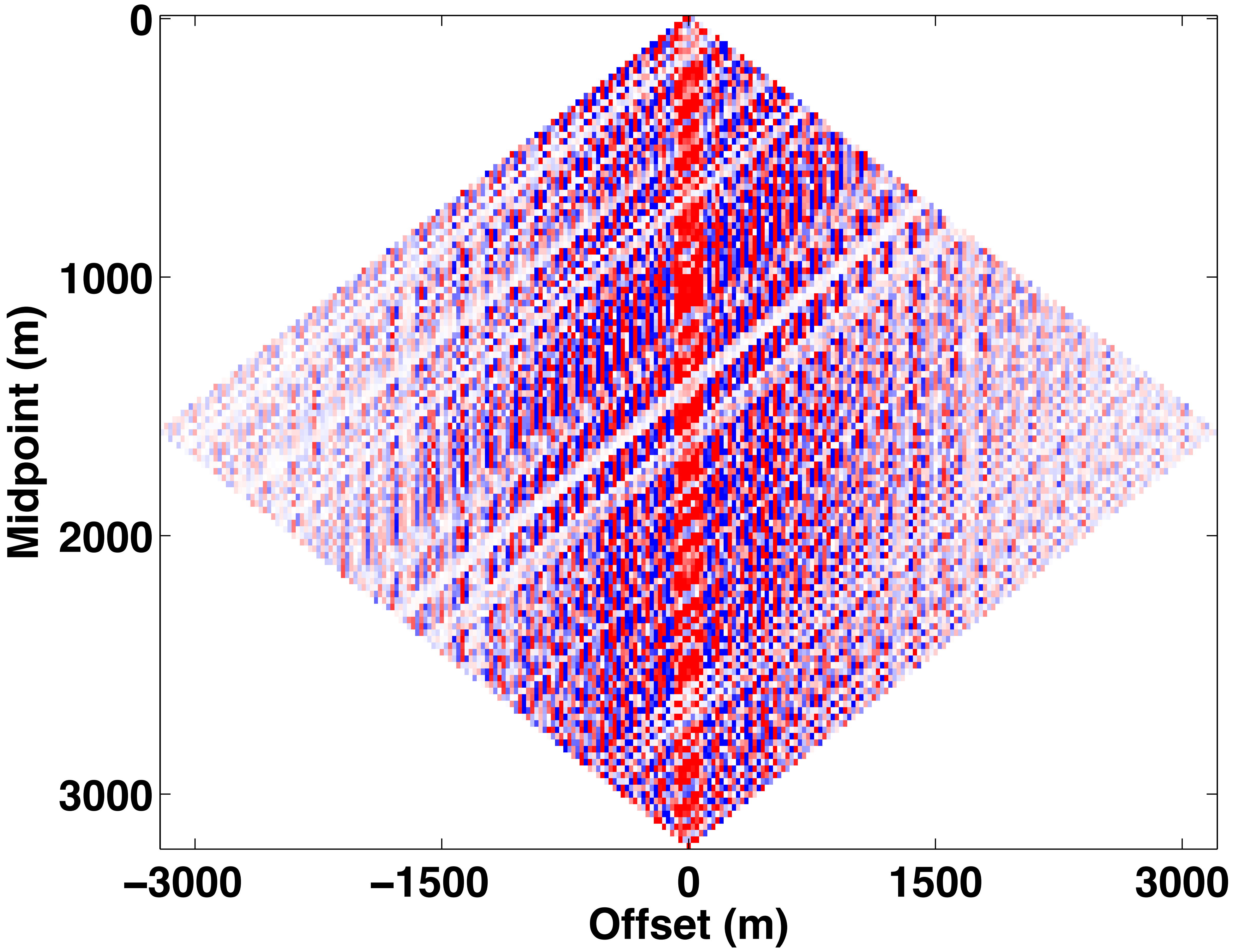
Low-rank structure – frequency slice at 25 Hz

in midpoint-offset domain?

without delay

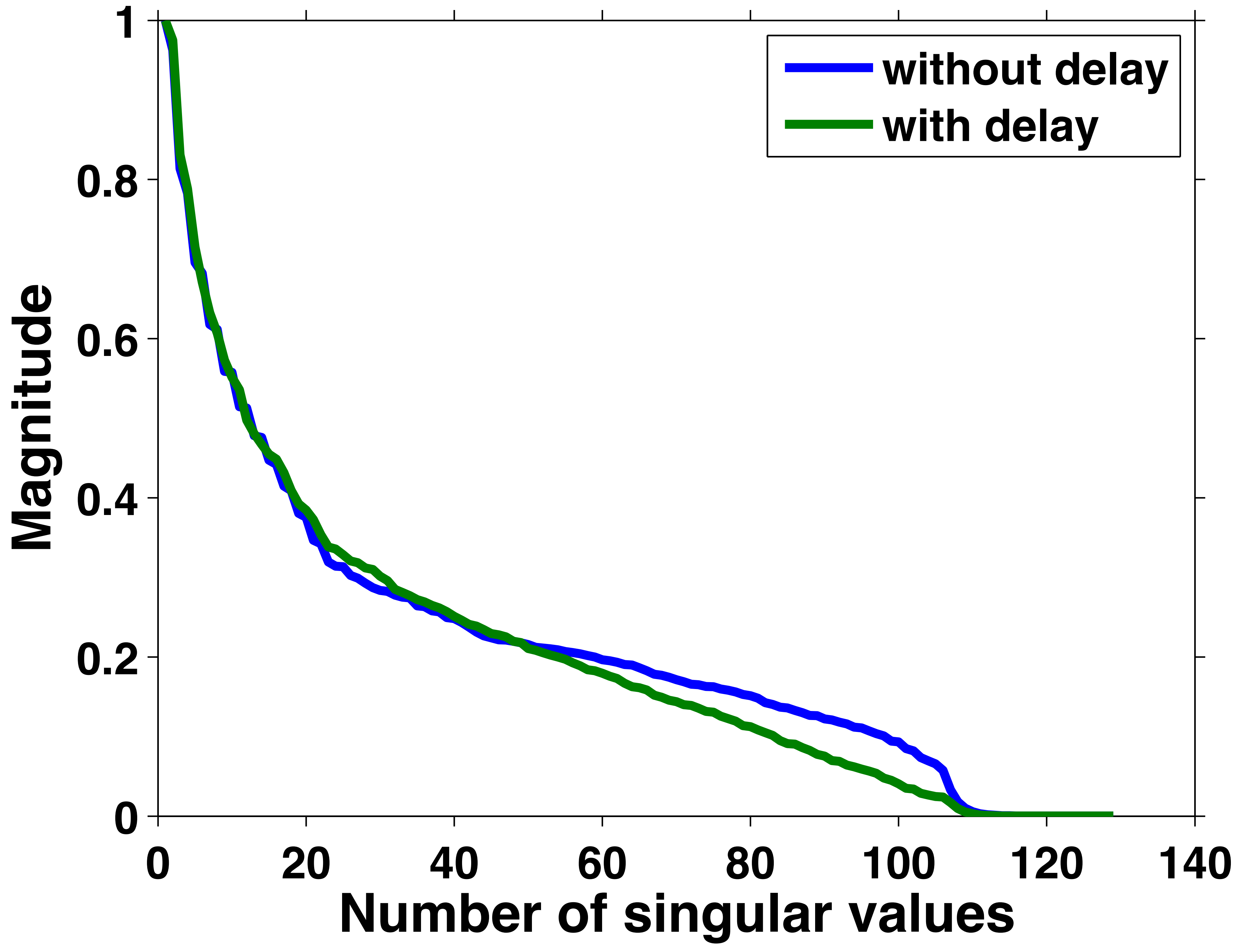


with delay

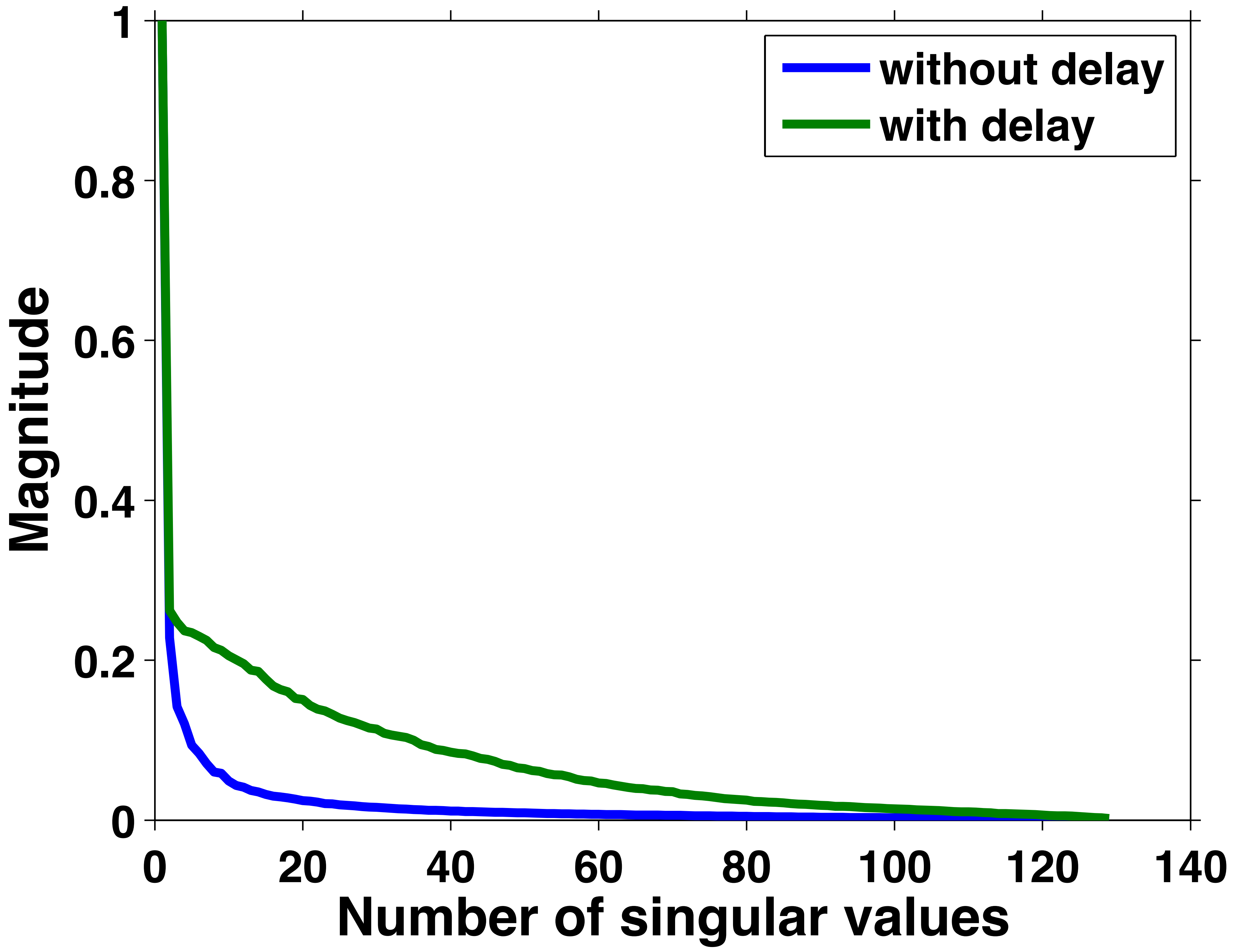


Decay of singular values

source-receiver domain

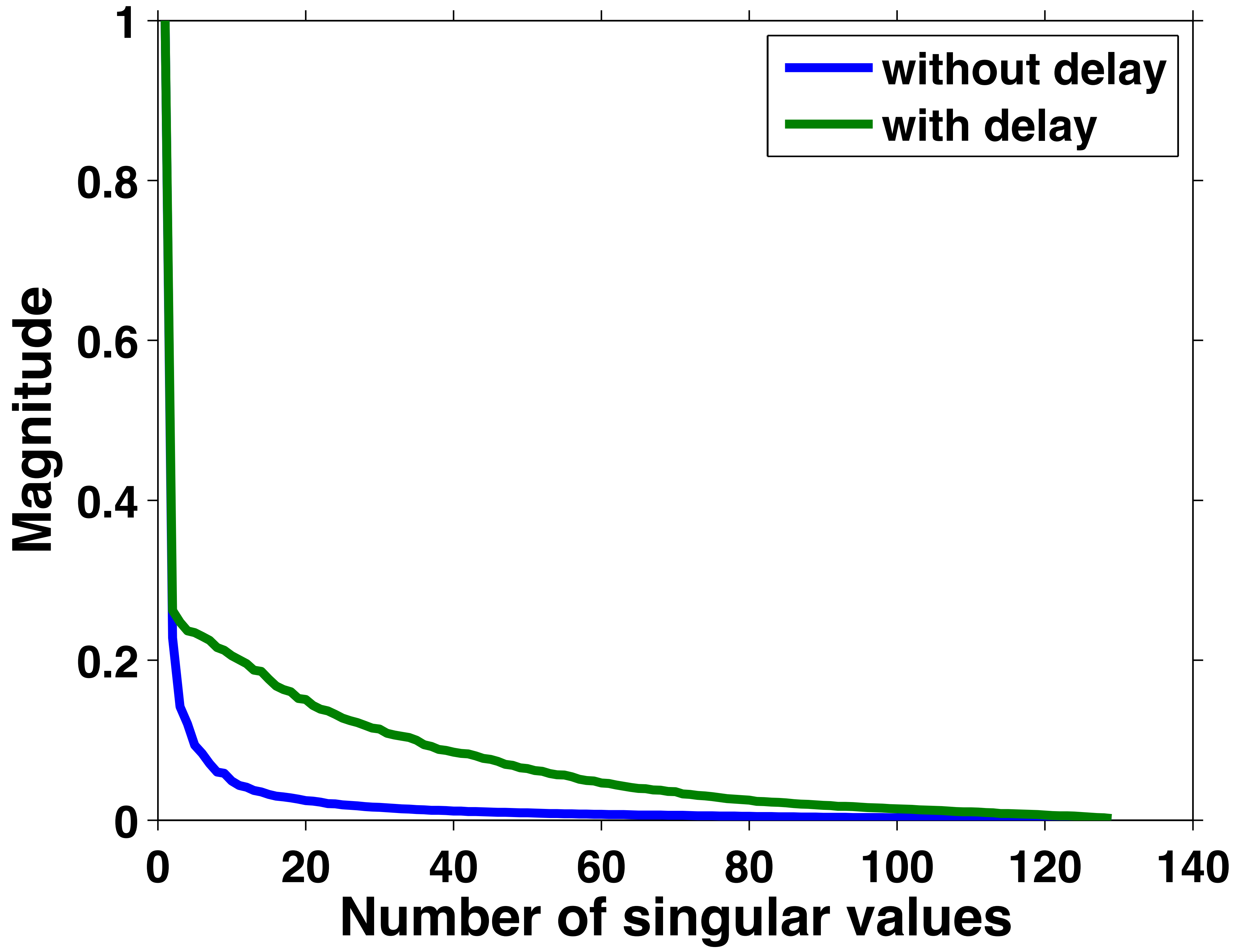


midpoint-offset domain

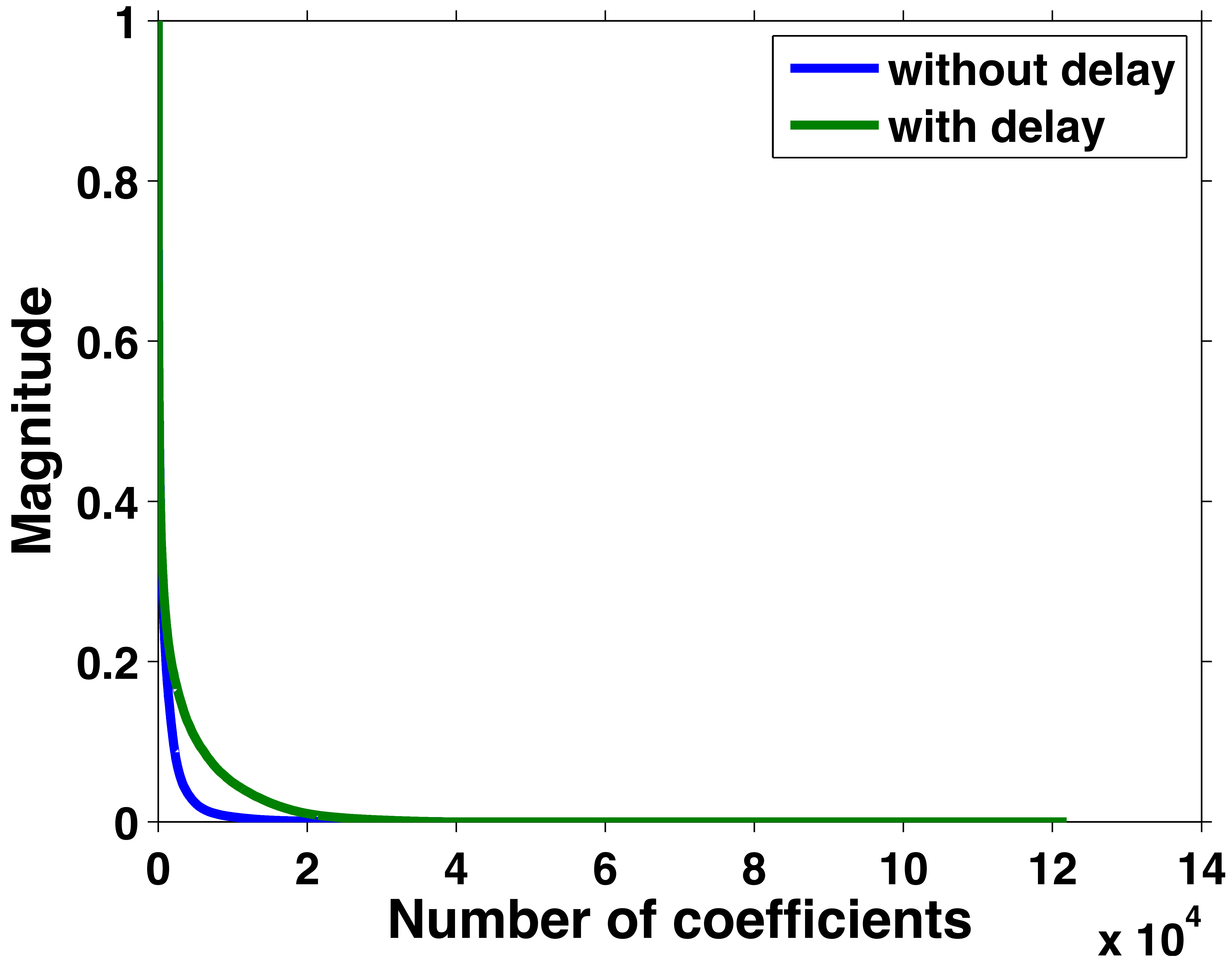


Rank vs. sparsity

rank-minimization
(midpoint-offset domain)

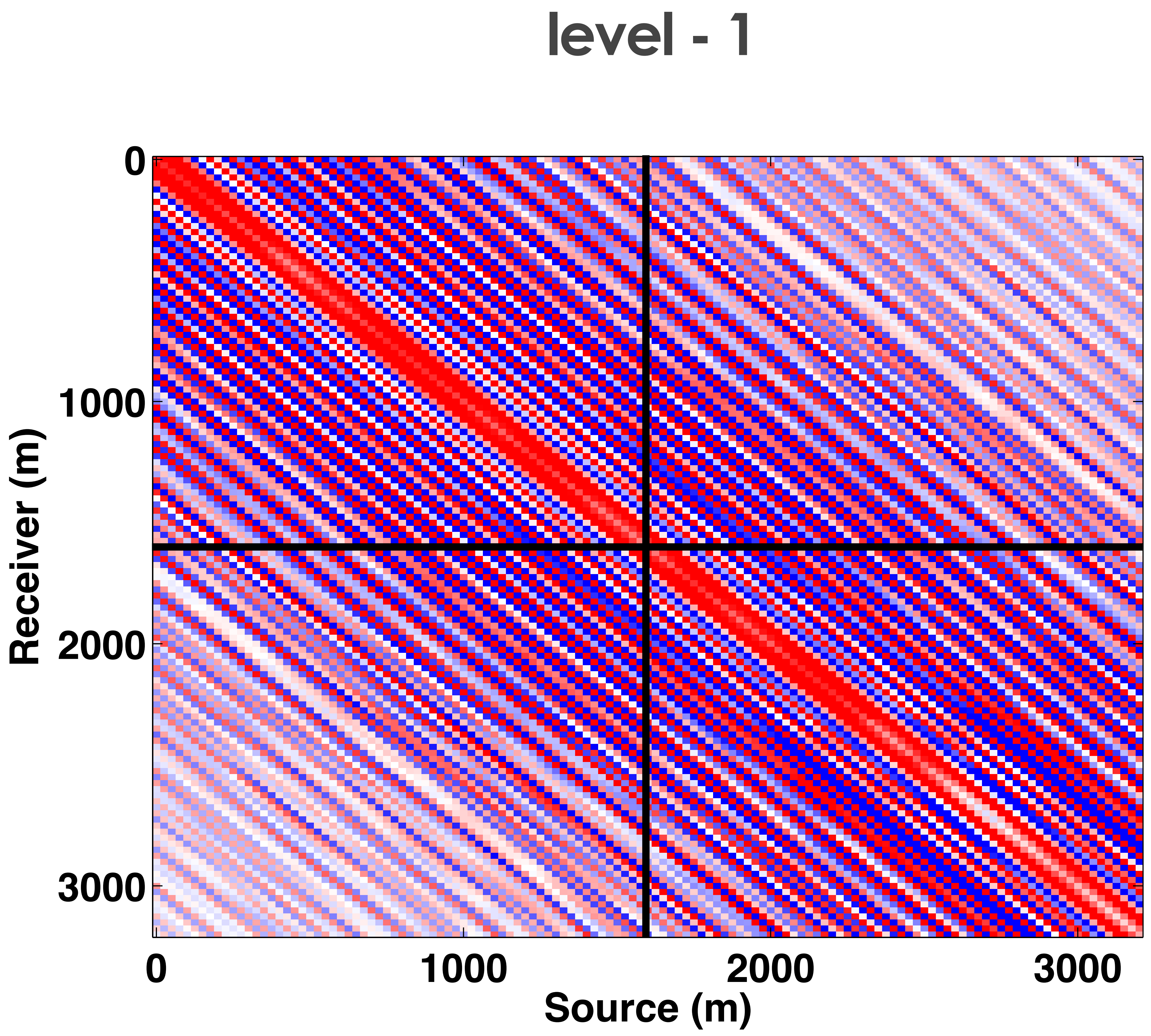


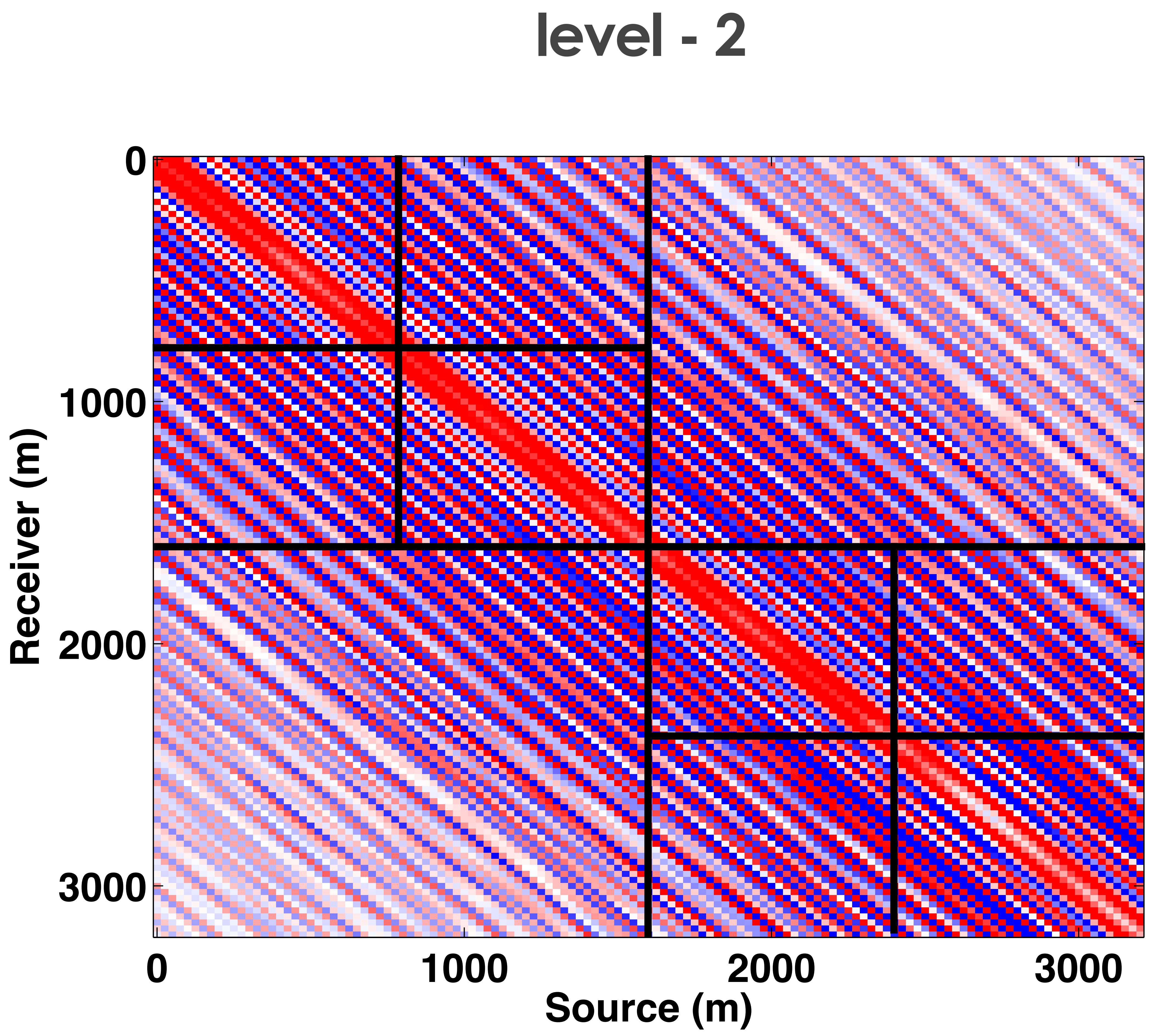
sparsity-promotion
(source-receiver domain)



HSS representation

[Chandrasekaran, et. al., 2006]

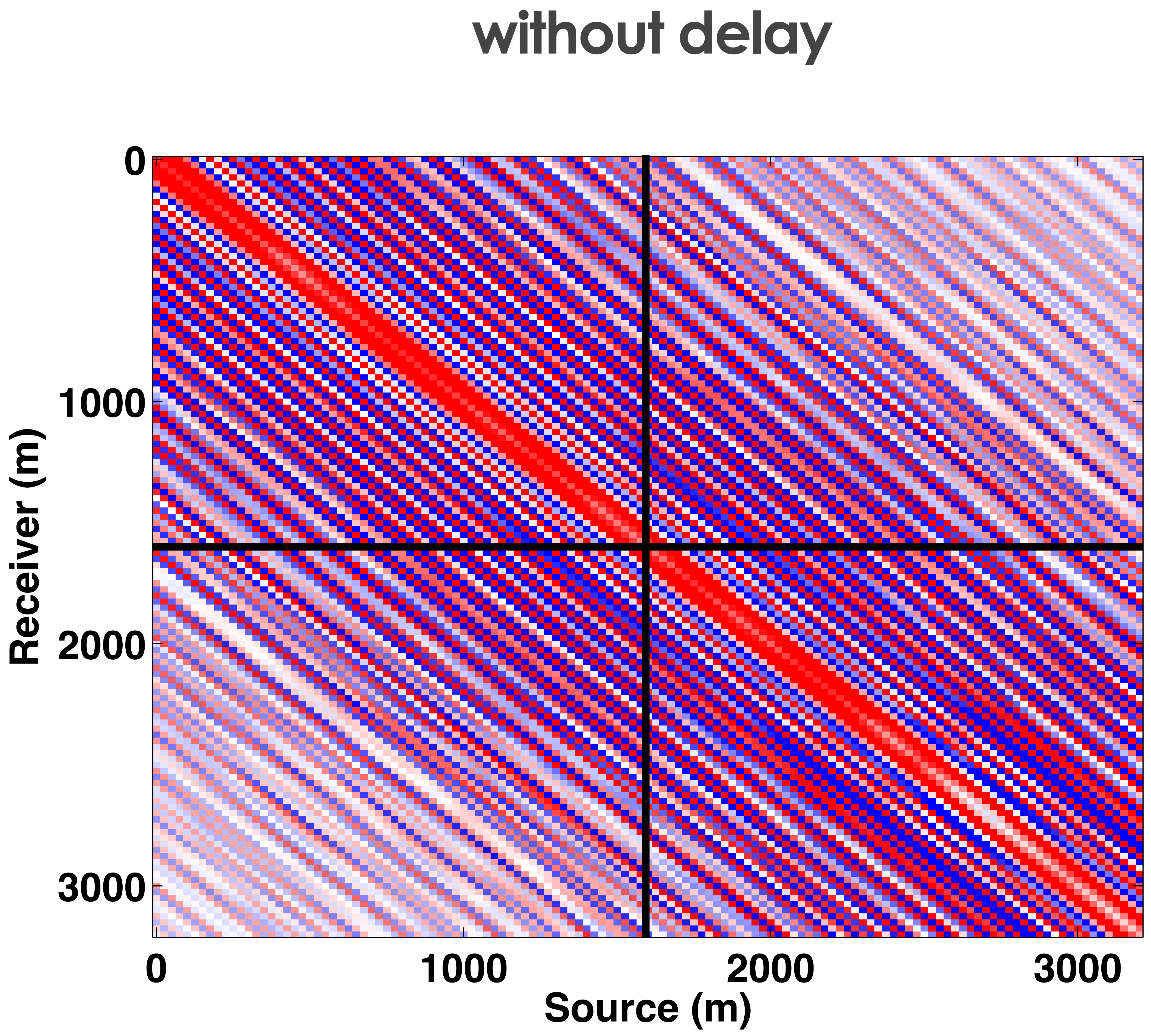


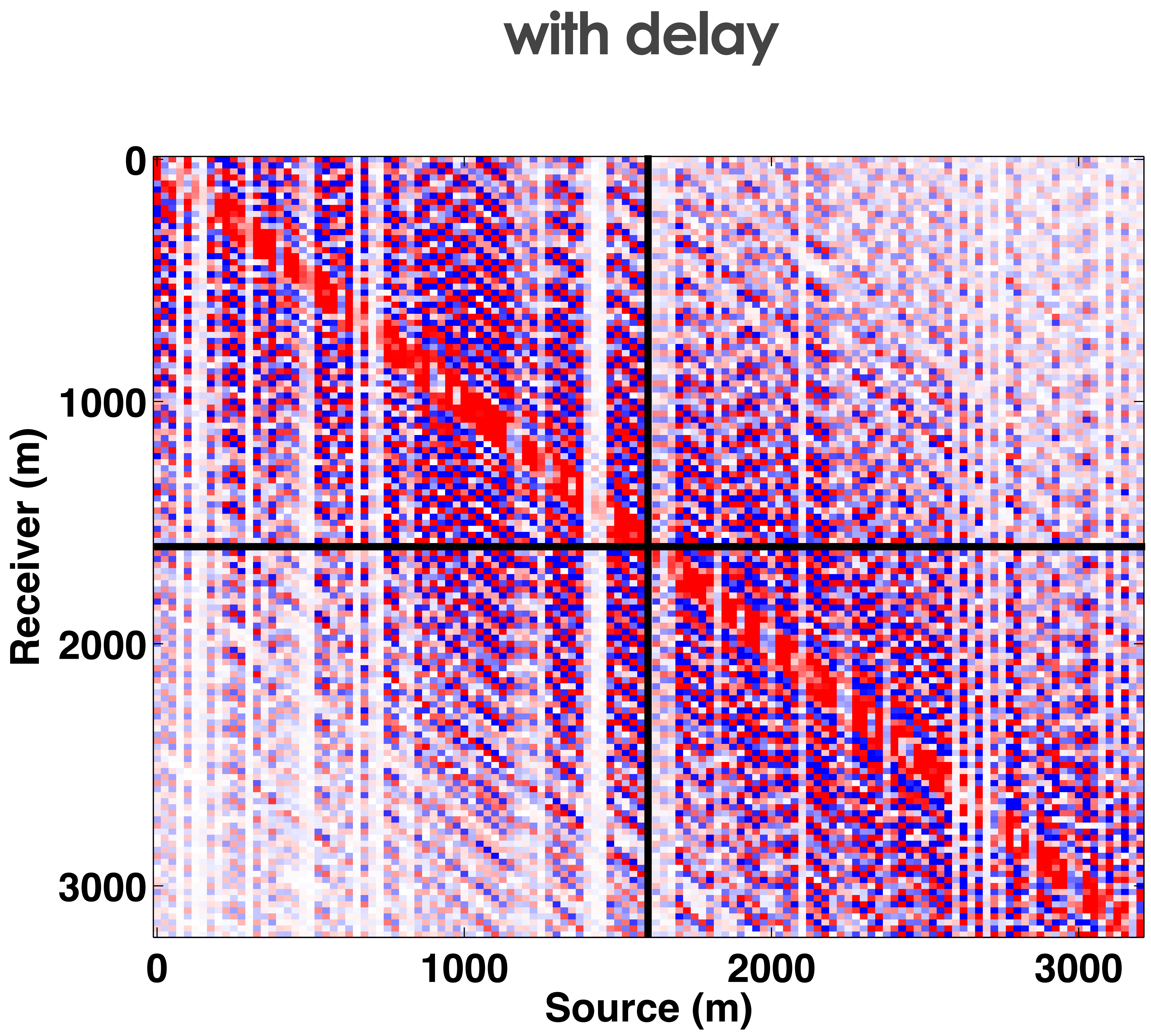


HSS representation

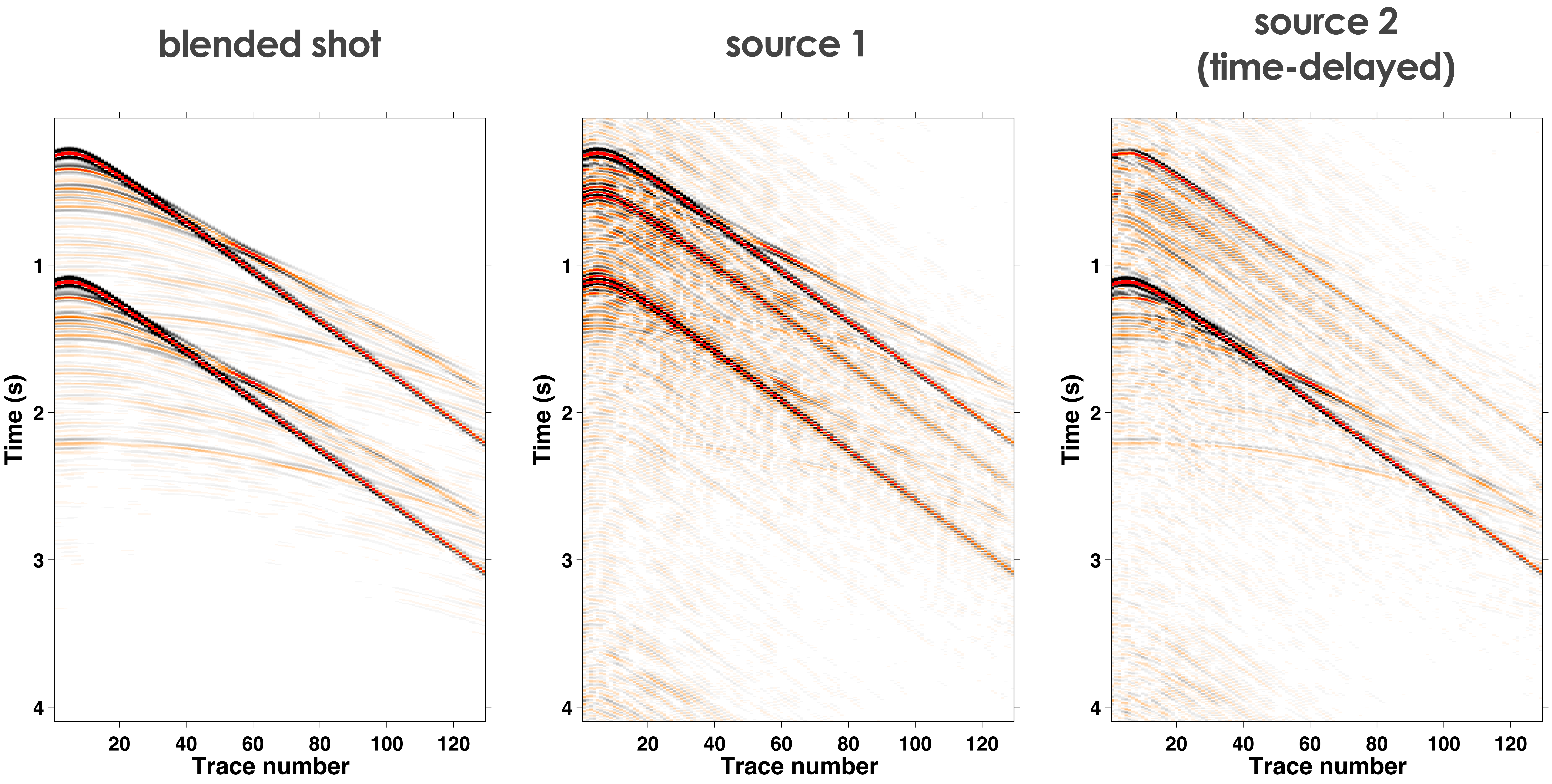
[Chandrasekaran, et. al., 2006]

level - 1

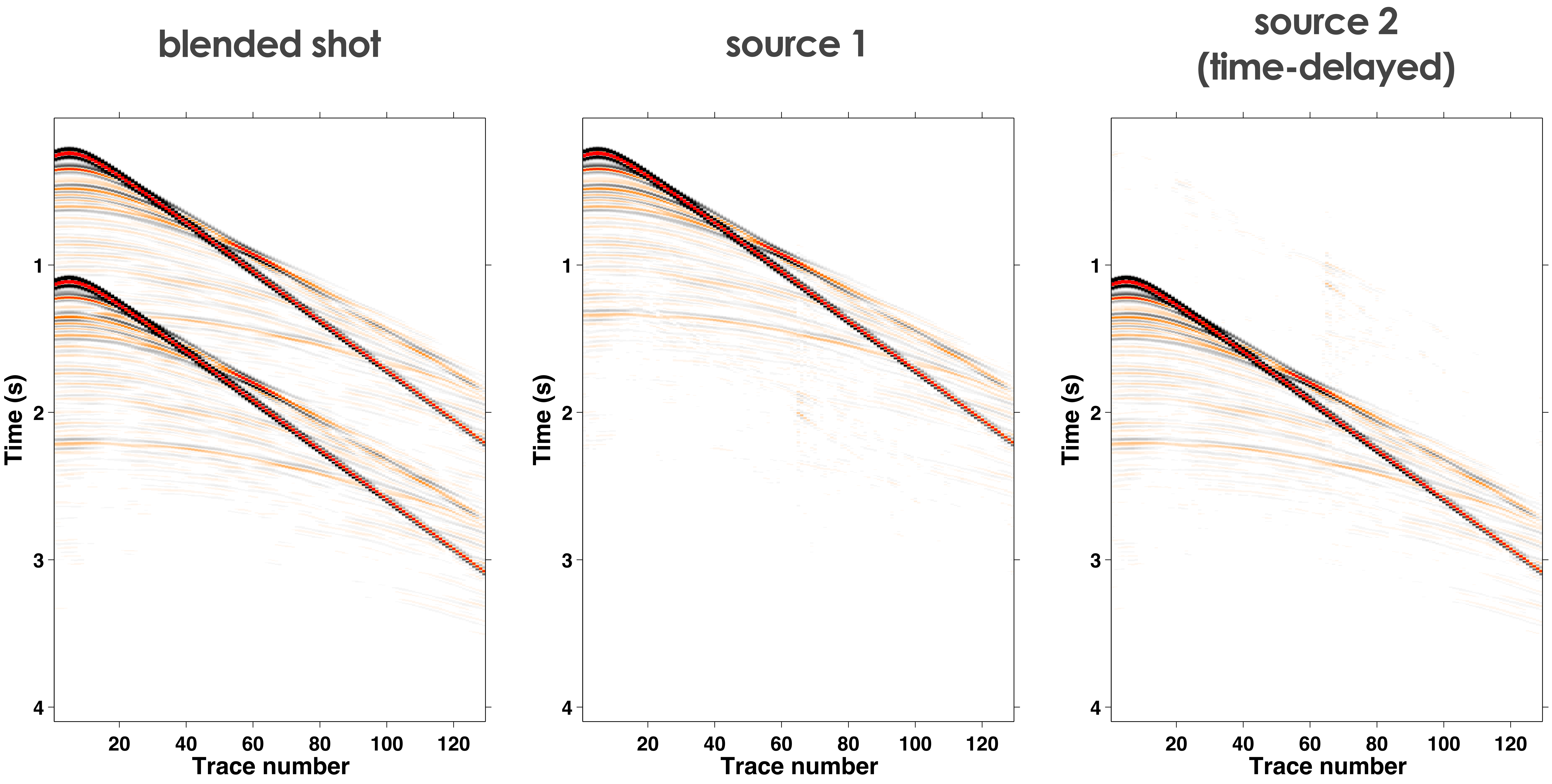




Source separation via sparsity-promotion



Source separation via rank-minimization



SLIM

Haneet Wason and Felix J. Herrmann, “Time-jittered ocean bottom seismic acquisition”, SEG, 2013
Hassan Mansour, Haneet Wason, Tim T.Y. Lin, and Felix J. Herrmann, “Randomized marine acquisition with compressive sampling matrices”, Geophysical Prospecting, vol. 60, p. 648-662, 2012

Observations

Recoveries entail joint interpolations & deblendings/source separations

Question:

Does increased variability of firing times improve curvelet recovery?

- ✓ yes, but only for ocean bottom acquisition – towed arrays are more challenging

Haneet Wason and Felix J. Herrmann, "Time-jittered ocean bottom seismic acquisition", SEG, 2013
Hassan Mansour, Haneet Wason, Tim T.Y. Lin, and Felix J. Herrmann, "Randomized marine acquisition with compressive sampling matrices", Geophysical Prospecting, vol. 60, p. 648-662, 2012
Haneet Wason, Rajiv Kumar, Aleksandr Y. Aravkin, and Felix J. Herrmann, "Source separation via SVD-free rank minimization in the hierarchical semi-separable representation". 2014.

Observations

Recoveries entails joint interpolations & deblendings

Questions:

Does increased variability of firing times improve curvelet recovery?

- ✓ yes, but only for node acquisition since it is challenging for towed arrays

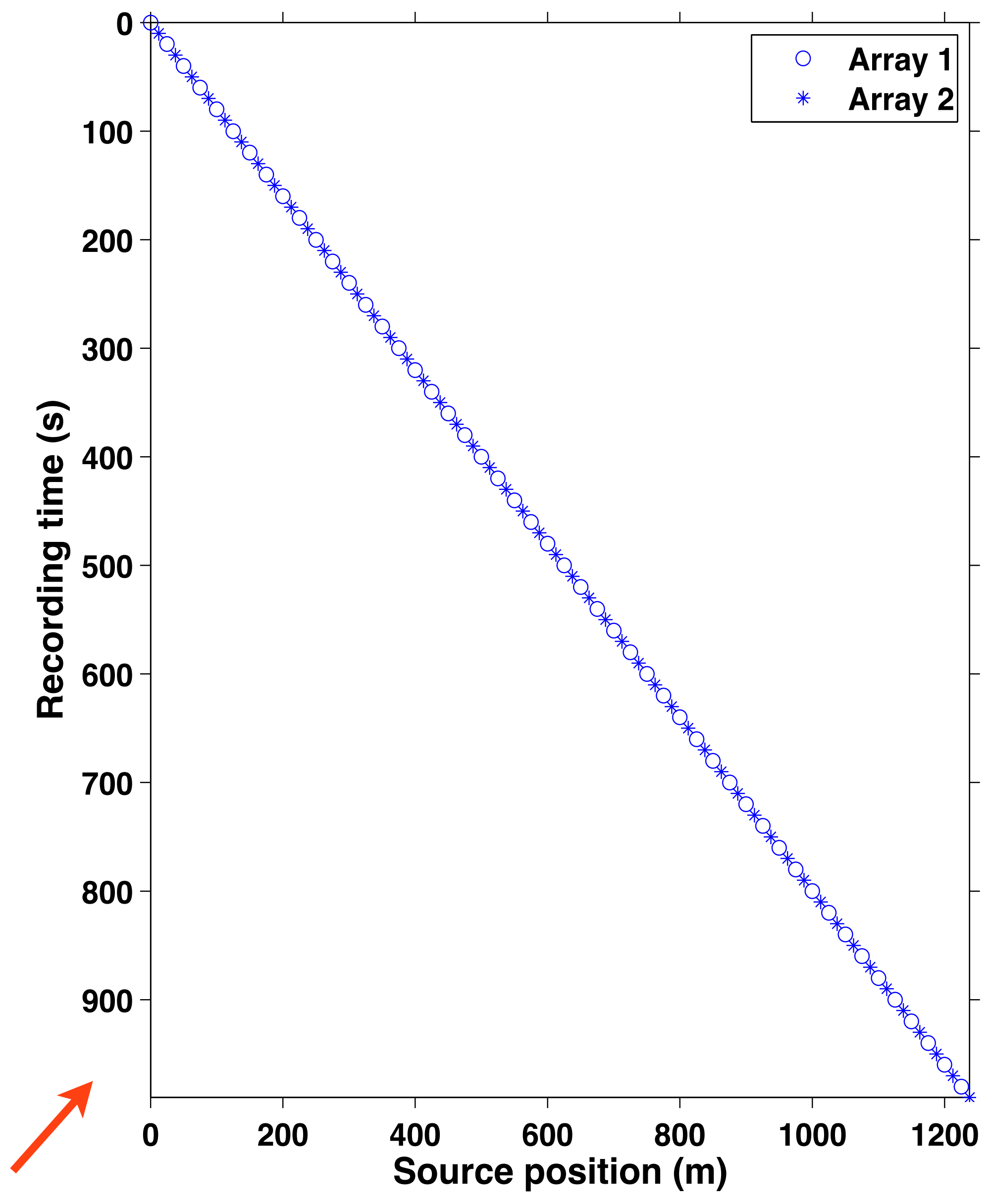
If transform-domain recovery fails are there alternatives?

- ✓ yes, rank revealing techniques succeed where curvelet-domain methods fails

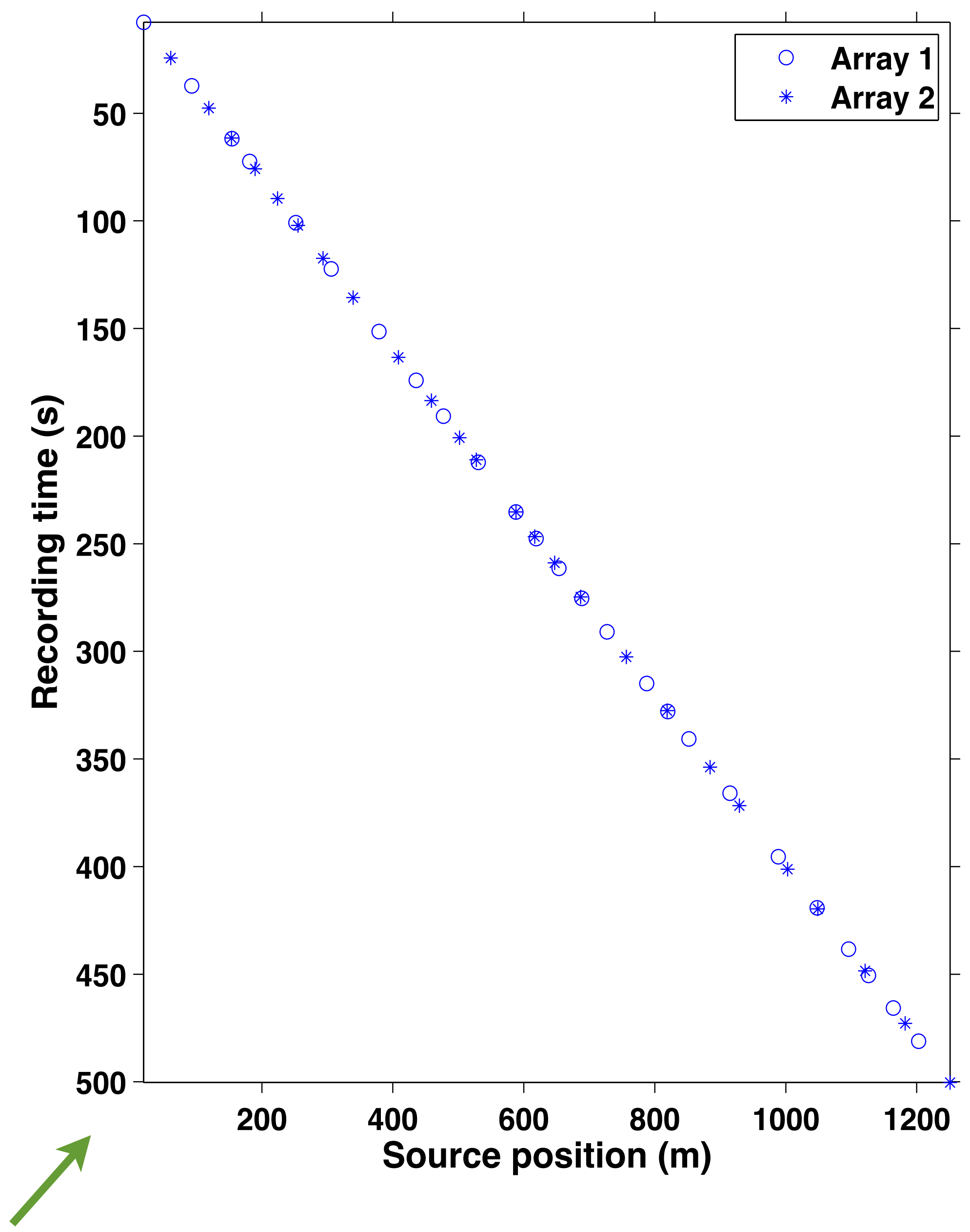
Conventional vs. *time-jittered* sources

– *under*sampling ratio = 2, 2 source arrays

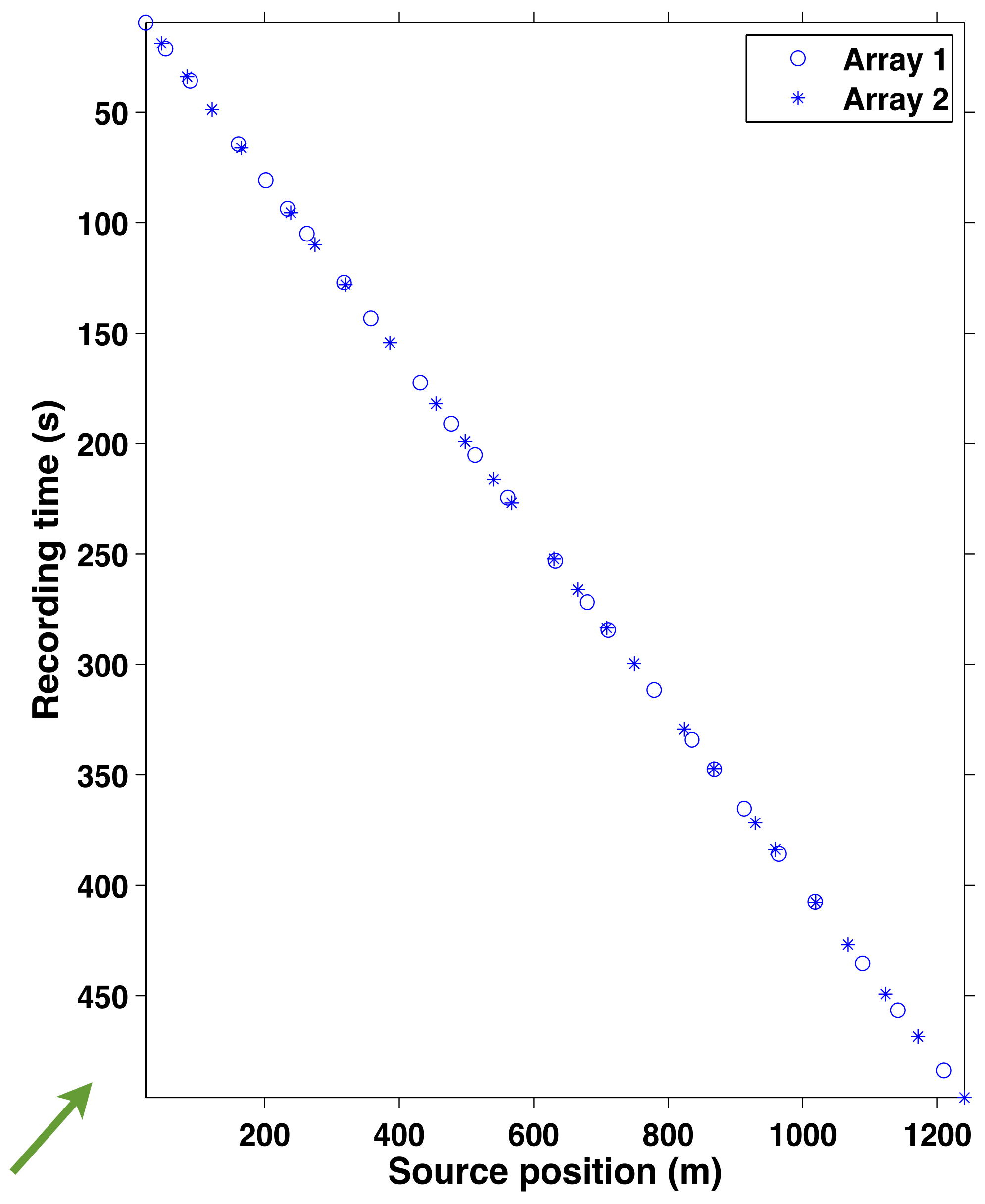
conventional



jittered acquisition 1 (for baseline)



jittered acquisition 2 (for monitor)



***"unblended"* shot gathers**
number of shots = **100** (per array)
shot record length: 10.0 s
spatial sampling: **12.5 m**
vessel speed: **1.25 m/s**
recording time = 100 x 10.0 = **1000.0 s**

[BLENDING & UNDERSAMPLING]
spatial undersampling factor = 2

→

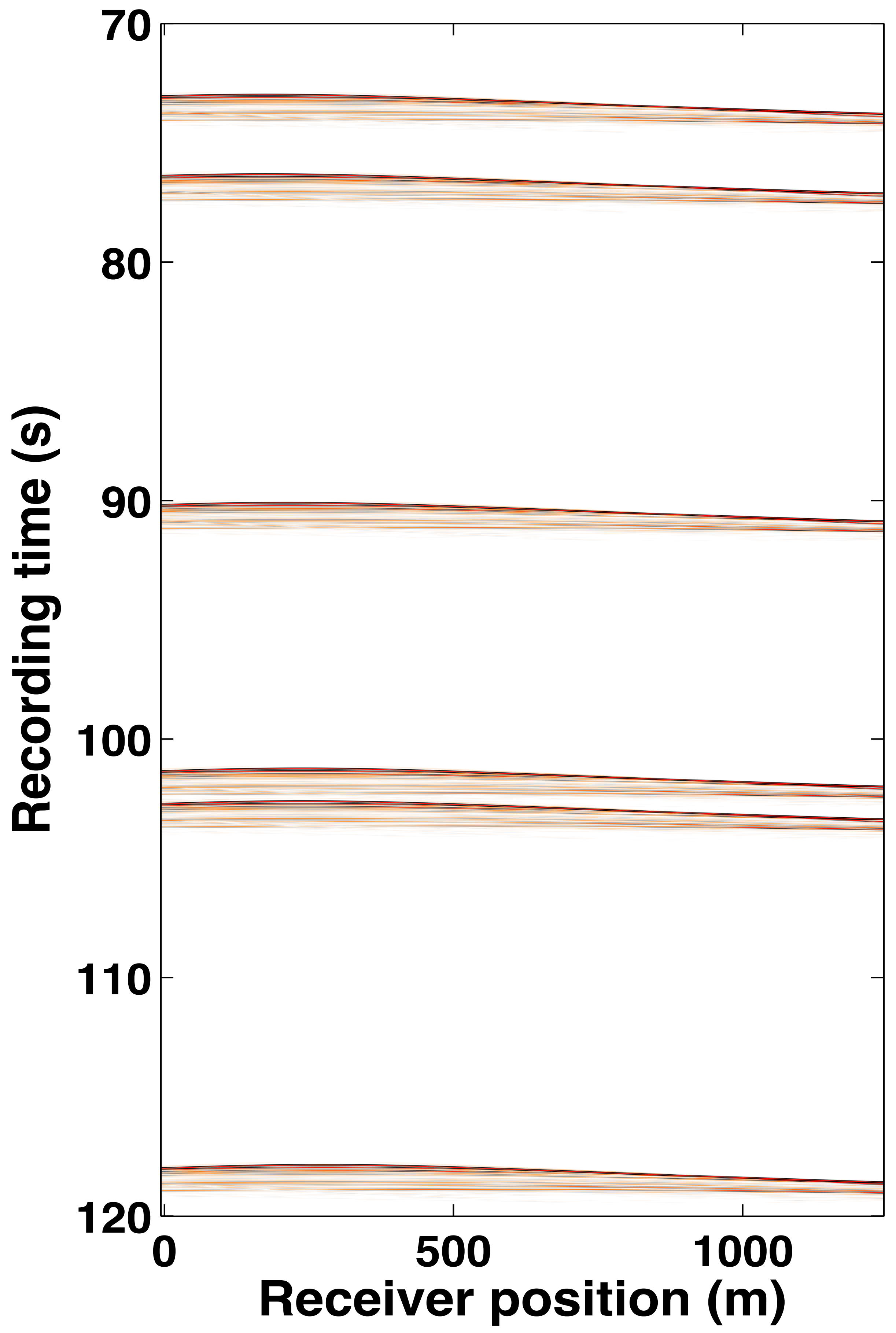
←

spatial sampling ***increase*** factor = 2
[DEBLENDING & INTERPOLATION]

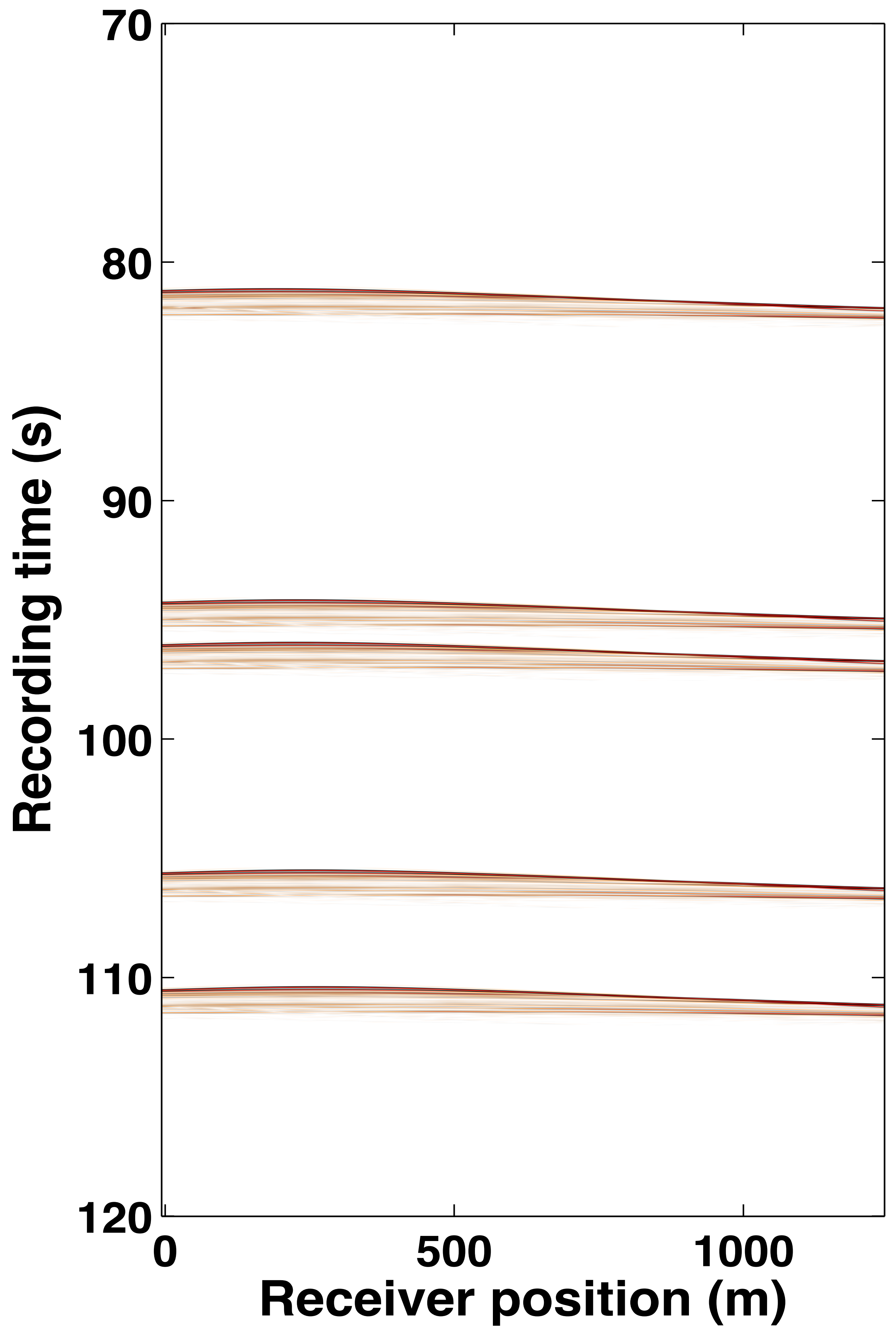
***"blended"* shot gathers**
number of shots = 100/2 = **50** (25 per array)
spatial sampling: **50.0 m (*jittered*)**
vessel speed: **2.50 m/s**
recording time ≈ 1000.0 s/2 = **500.0 s**

Measurements
– *undersampled and blended*

baseline

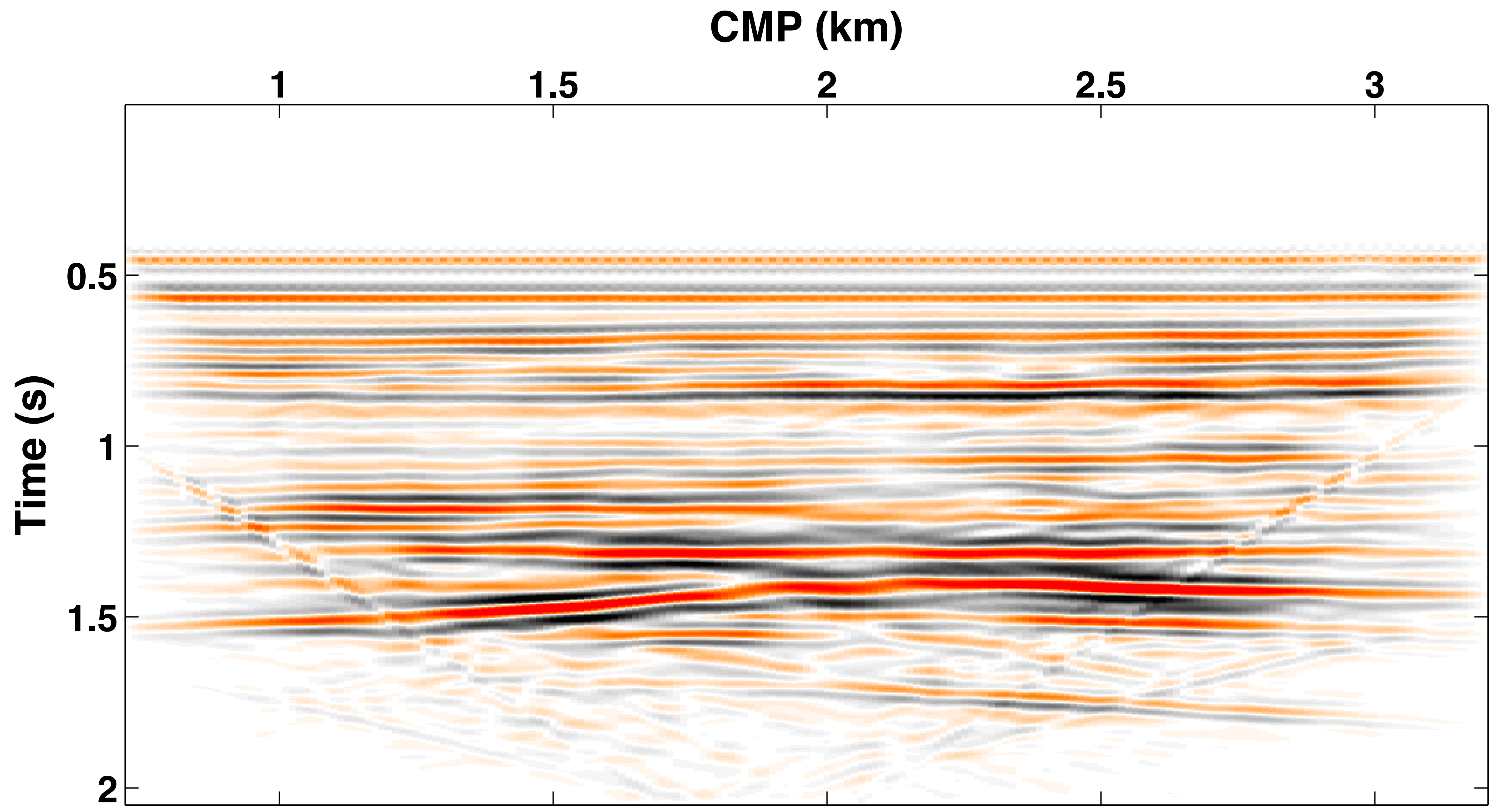


monitor



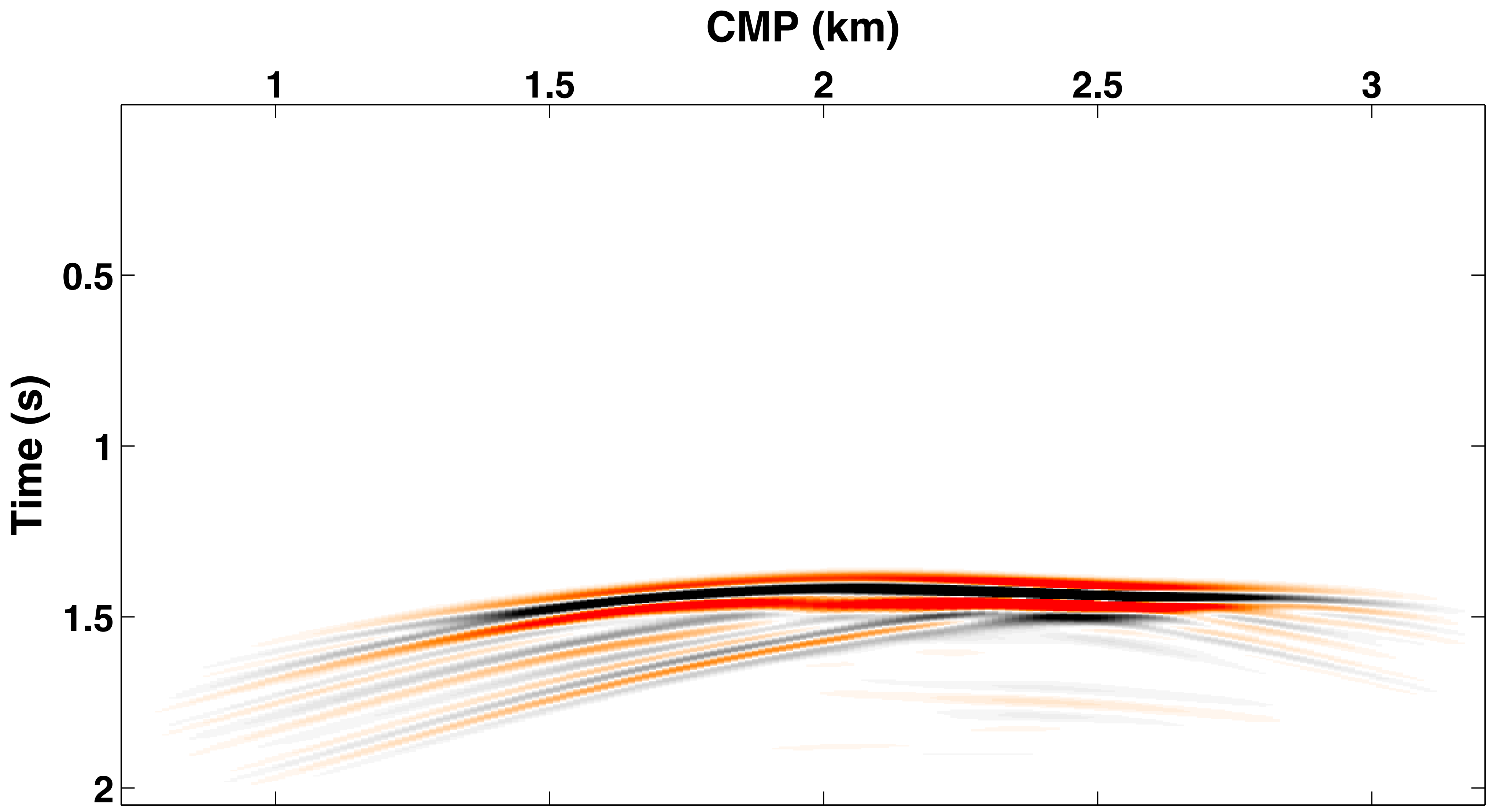
Stacked sections

Original baseline



Original 4-D signal

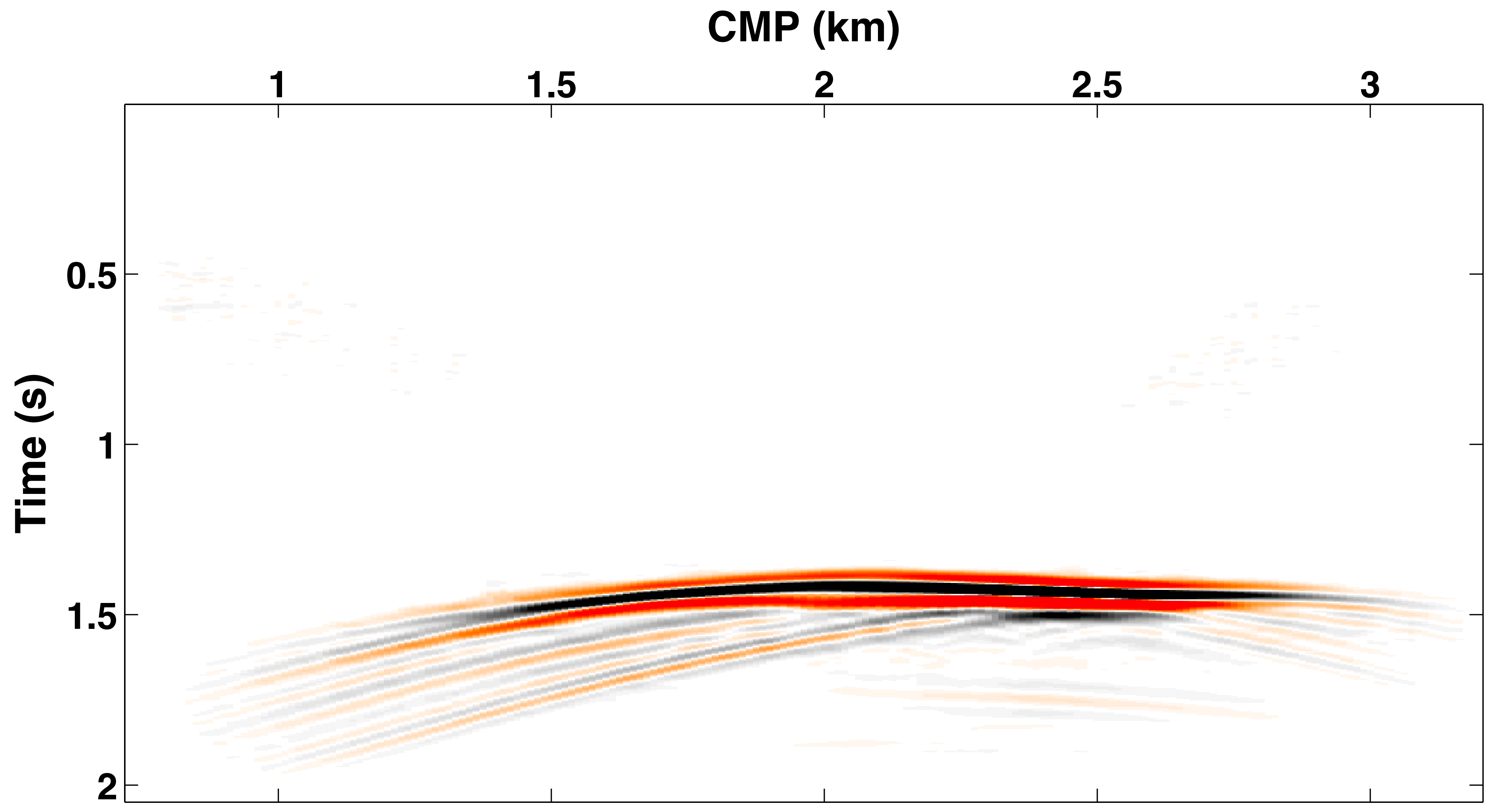
10 X



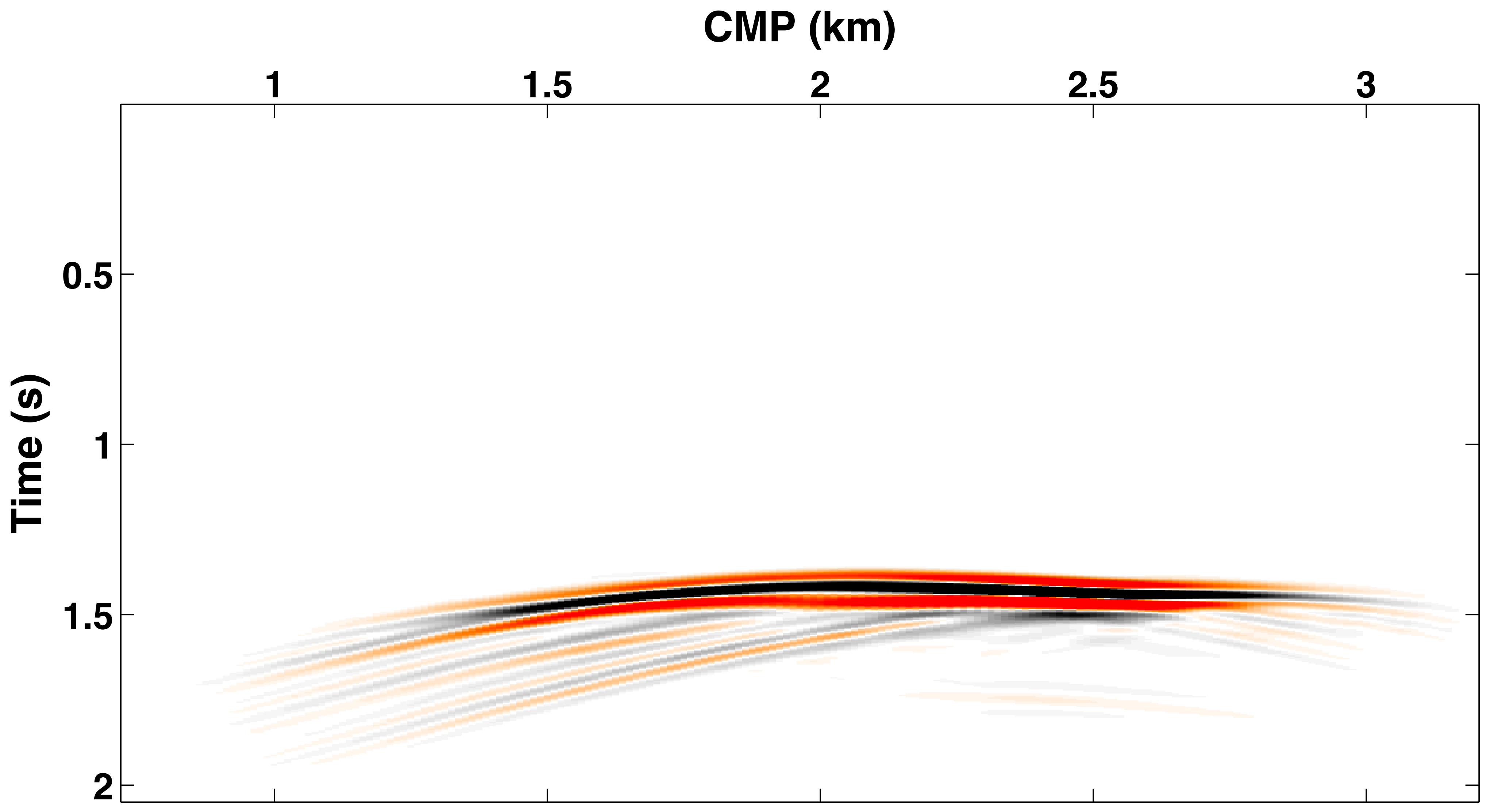
Stacked sections

– 100% overlap in *acquisition* matrices

IRS
(22.7 dB)



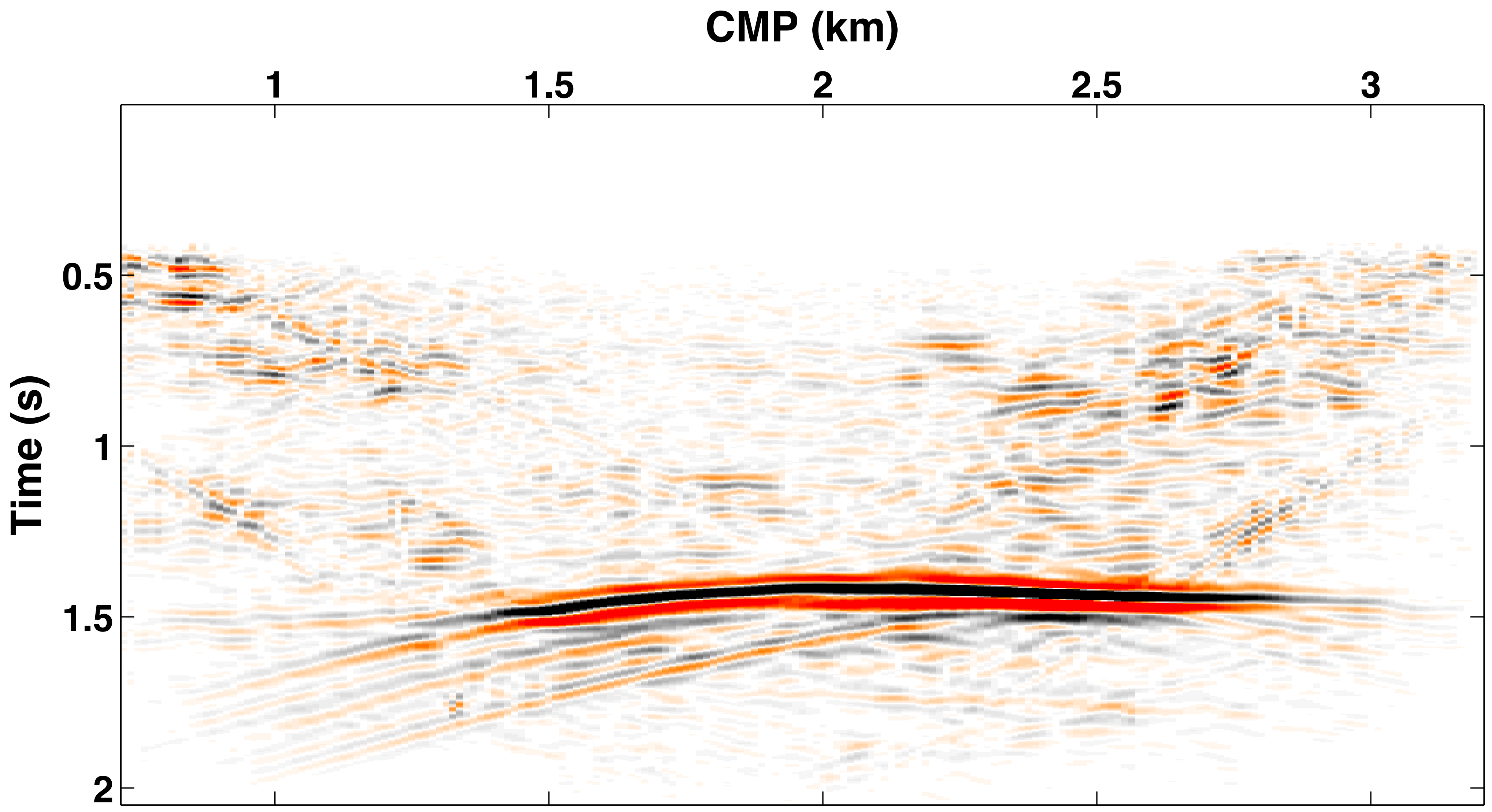
JRM
(22.4 dB)



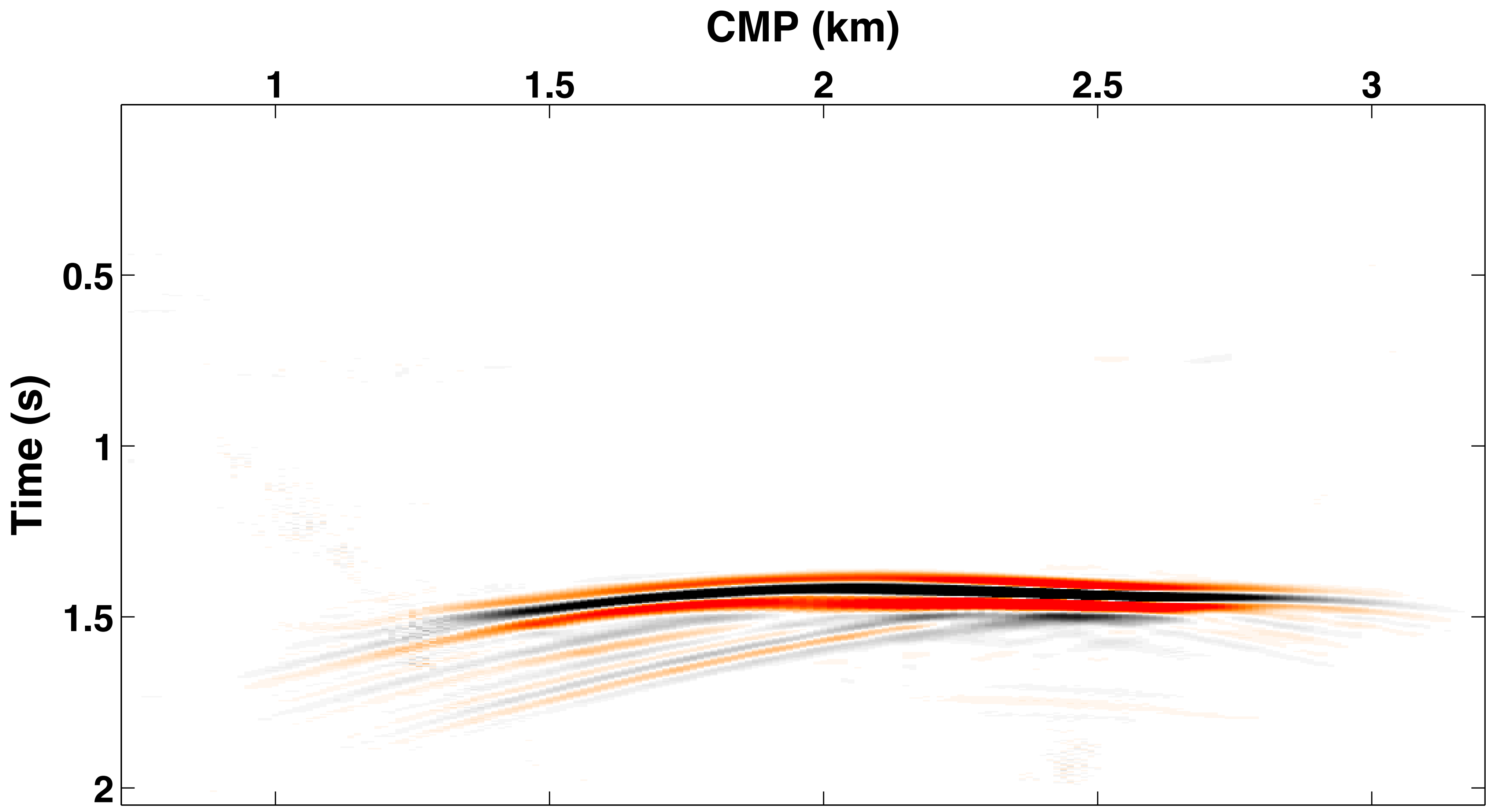
Stacked sections

– 50% overlap in *acquisition* matrices

IRS
(9.7 dB)



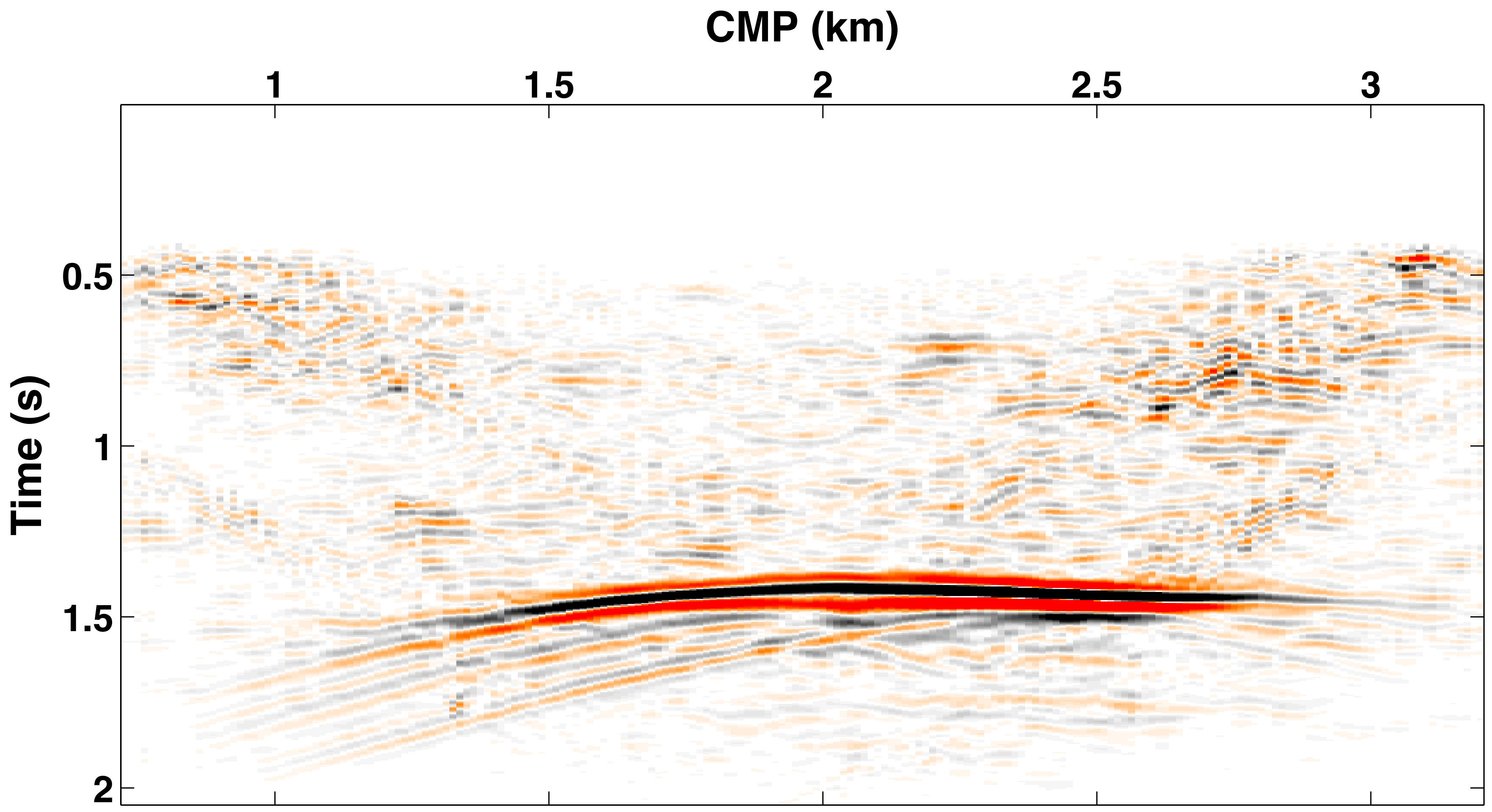
JRM
(18.2 dB)



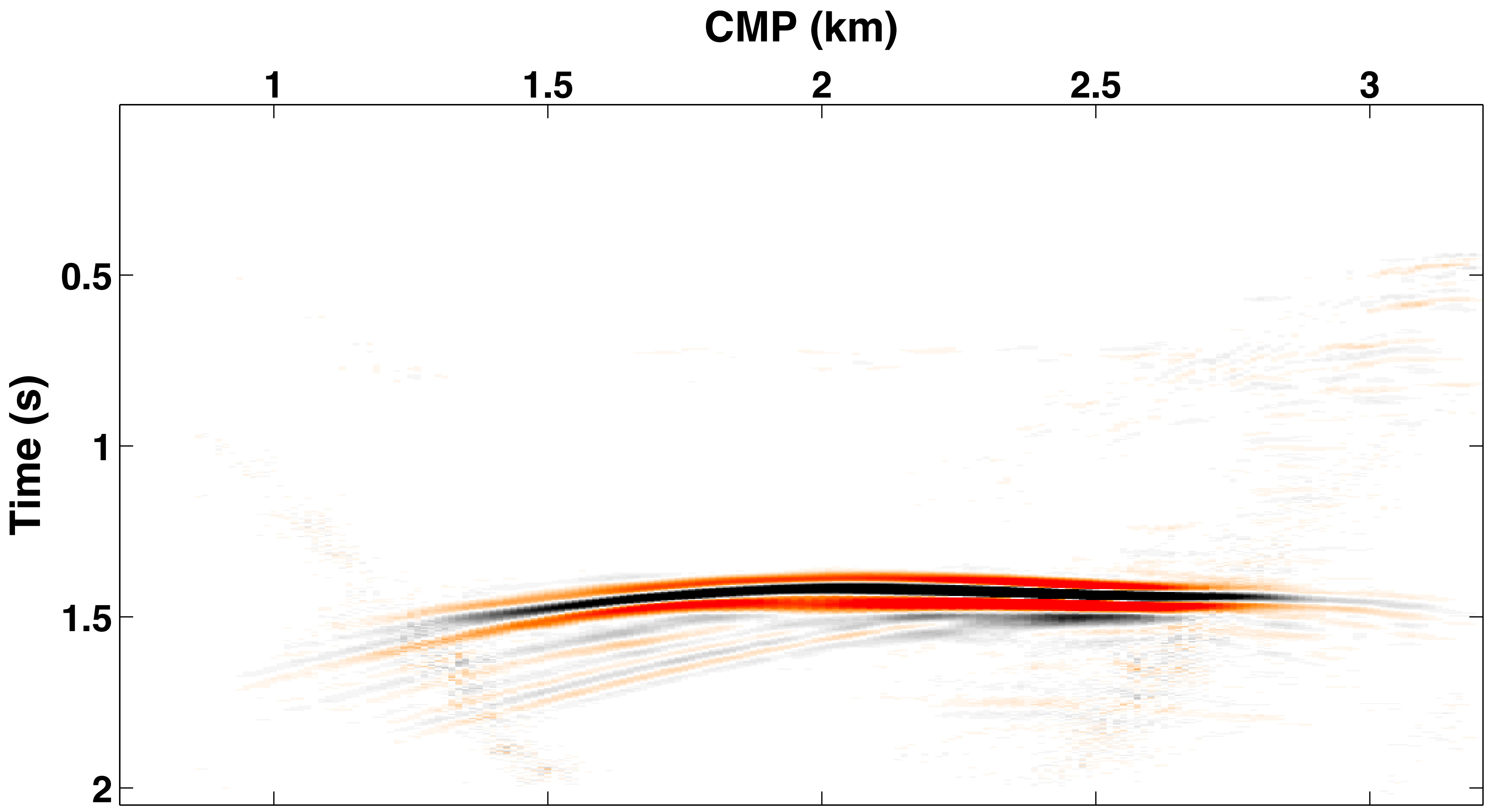
Stacked sections

– 20% overlap in *acquisition* matrices

IRS
(10.2 dB)



JRM
(14.7 dB)



Summary (SNR (dB))

overlap	baseline		monitor		4-D signal	
	IRS	JRM	IRS	JRM	IRS	JRM
100%	23.0	21.6	23.1	21.7	22.7	22.4
50%	23.0	28.9	25.5	28.9	9.7	18.2
20%	23.0	31.8	23.5	31.9	10.2	14.7