Latest developments in randomized marine acquisition and source separation

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Source separation for simultaneous towed-streamer acquisition - sparsity vs. rank

Collaborators: Rajiv Kumar and Felix J. Herrmann

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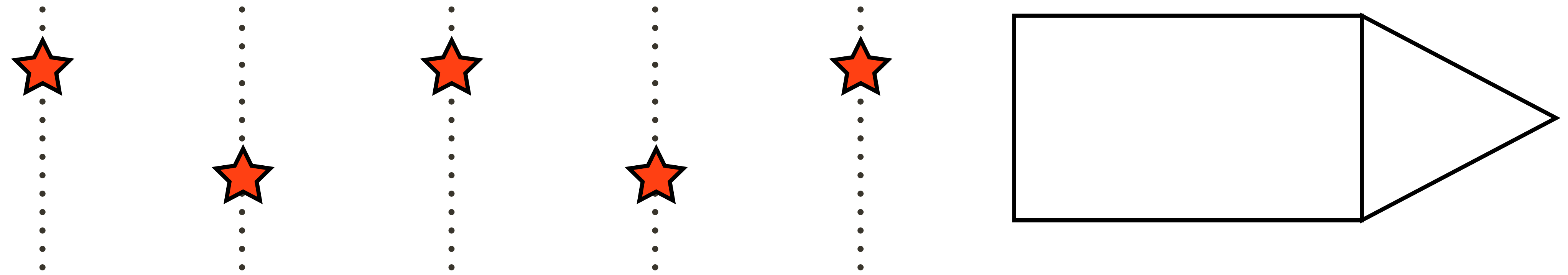
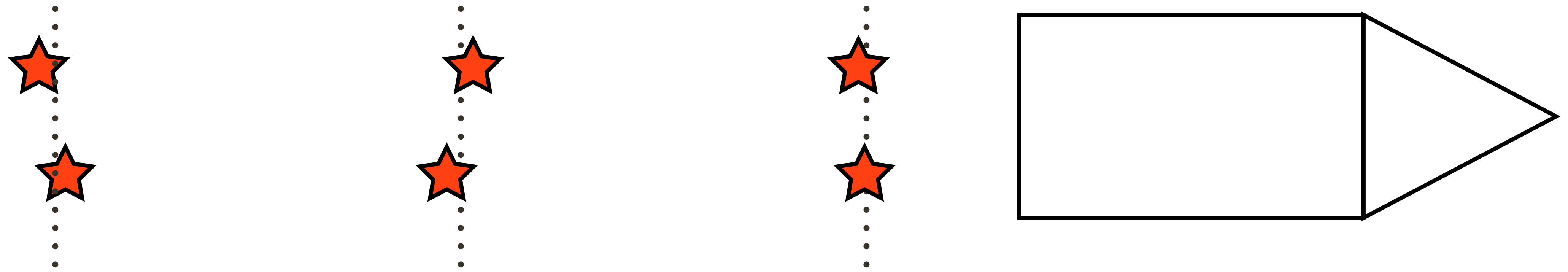
Periodic vs. jittered marine acquisition

periodically sampled spatial grid



almost periodically sampled spatial grid

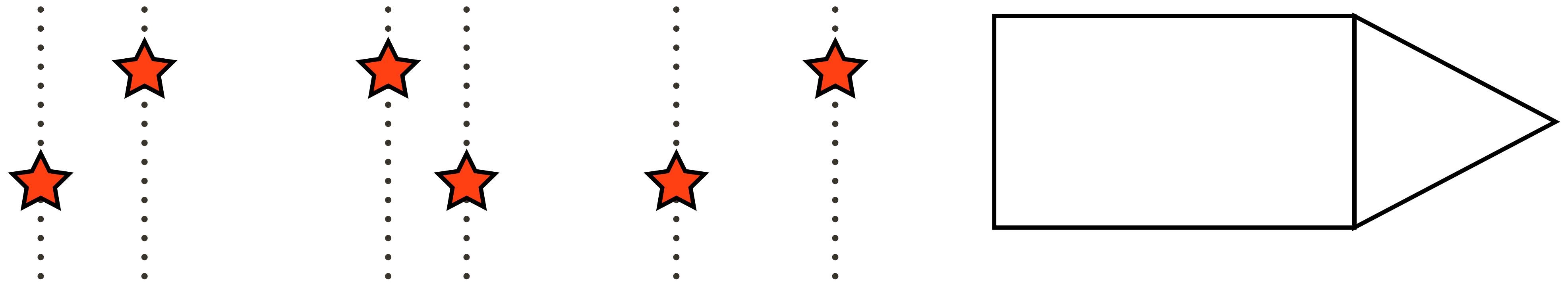
(over/under acquisition)



randomly jittered sampled spatial grid

(Time-jittered acquisition)

[Wason and Herrmann, 2013]
[Mansour et. al., 2012]

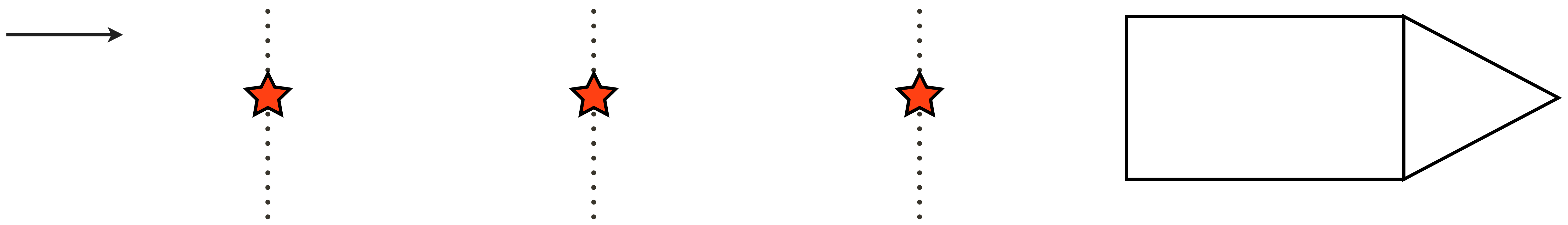


Conventional marine acquisition

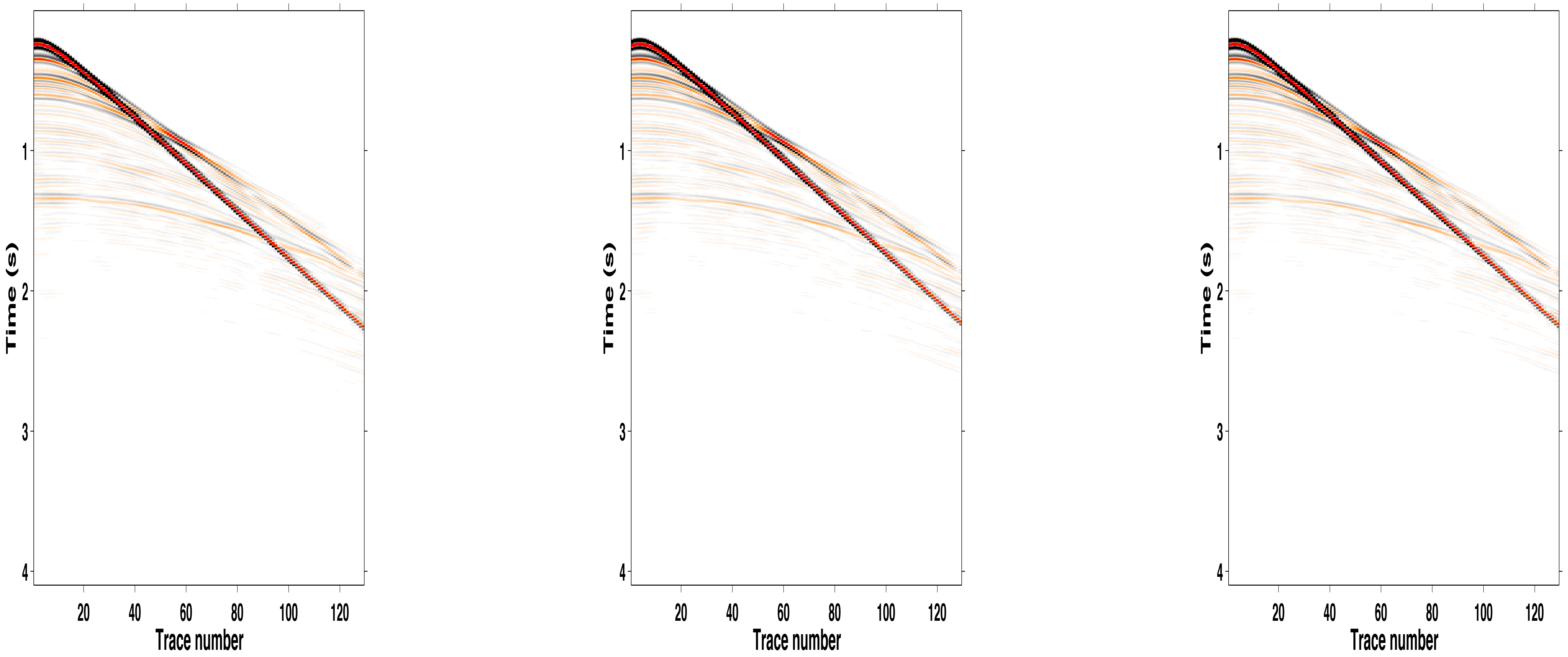
source depth = 6 m

shot 1 shot 2 shot 3

periodically sampled spatial grid

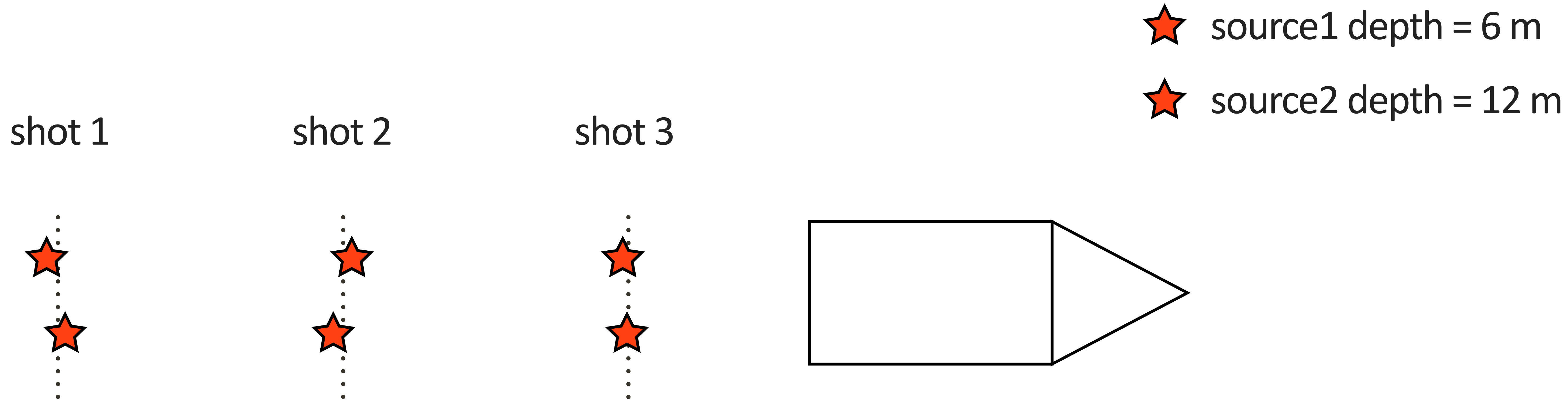


shot 1 shot 2 shot 3



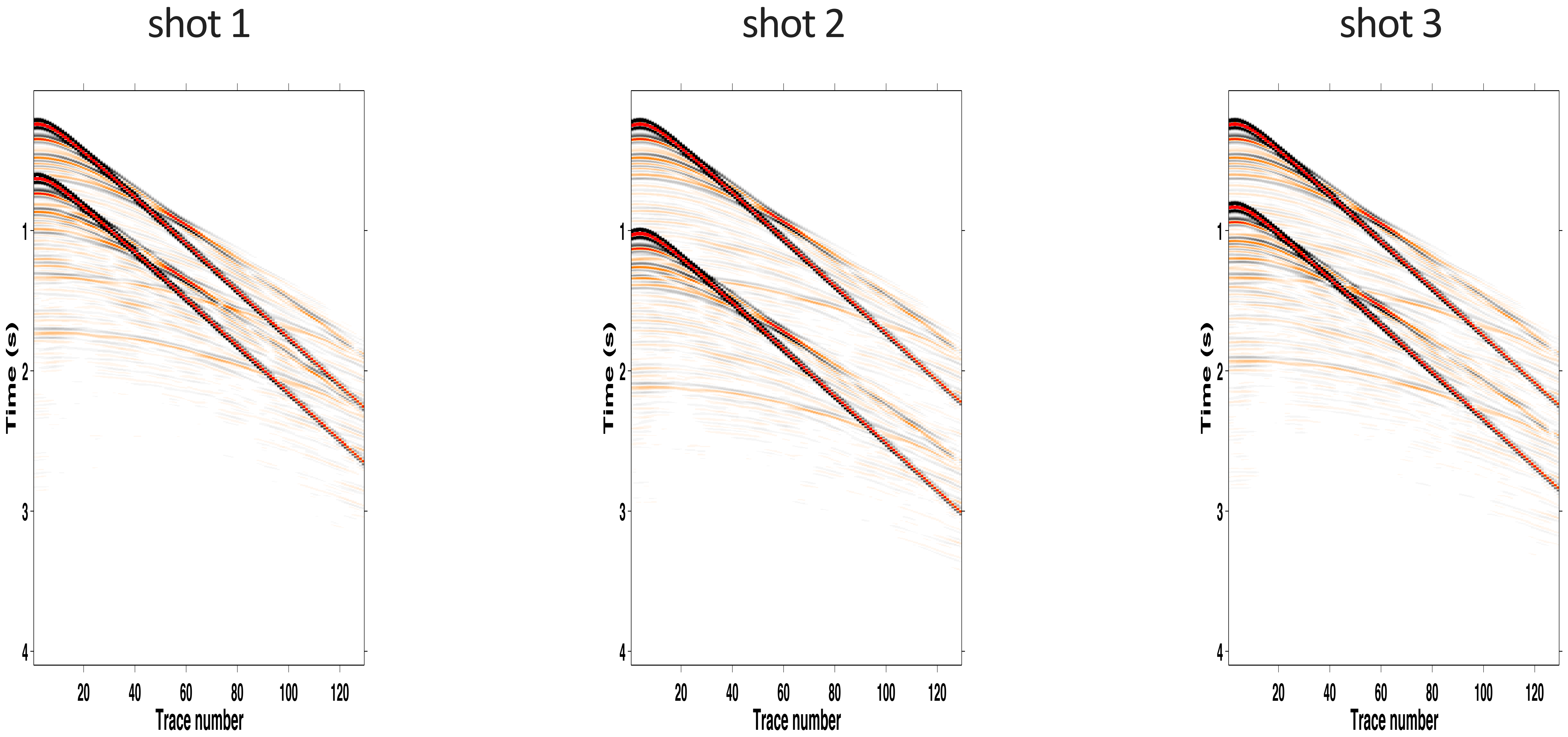
Blended/Simultaneous marine acquisition

[over/under acquisition]



periodically sampled spatial grid →
(almost)

shot-time randomness - ***LOW***



Challenges

- Source separation (or *deblending*)
  - recover individual datasets
- Shot-time randomness
  - low

[Candès and Donoho, 2000; Herrmann, 2008]

Compressed sensing

Successful sampling & reconstruction scheme

- exploit *structure* via *sparsifying* transform
  - *fast decay* of "transform domain" coefficients
- sampling
  - randomly blended data *decreases* sparsity in "transform domain"
- optimization
  - via *sparsity-promotion*

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Matrix completion

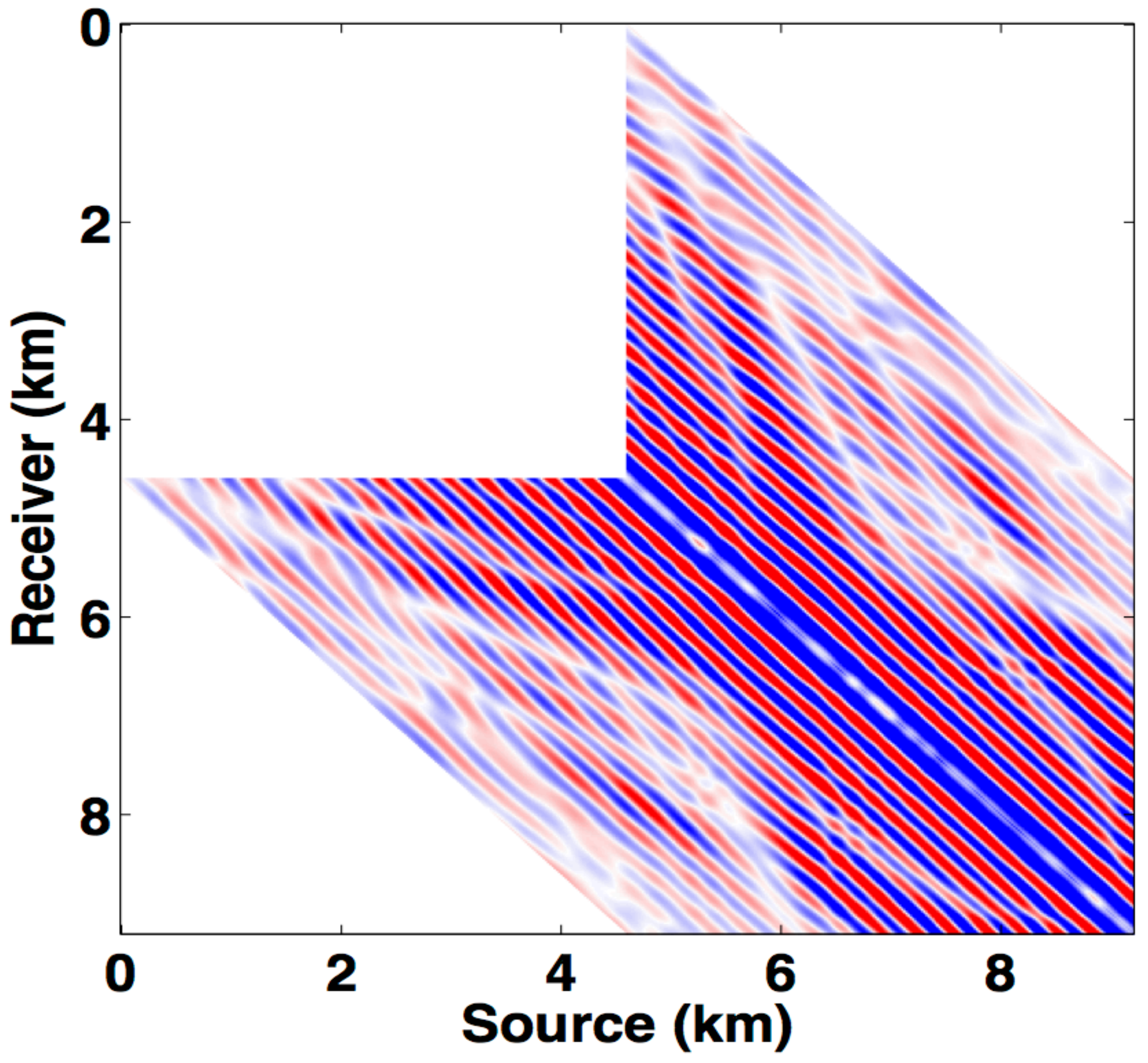
Successful reconstruction scheme

- exploit *structure*
  - *low-rank / fast decay* of singular values
- sampling
  - randomly blended data *increases* rank in “transform domain”
- optimization
  - via *rank-minimization (nuclear norm-minimization)*

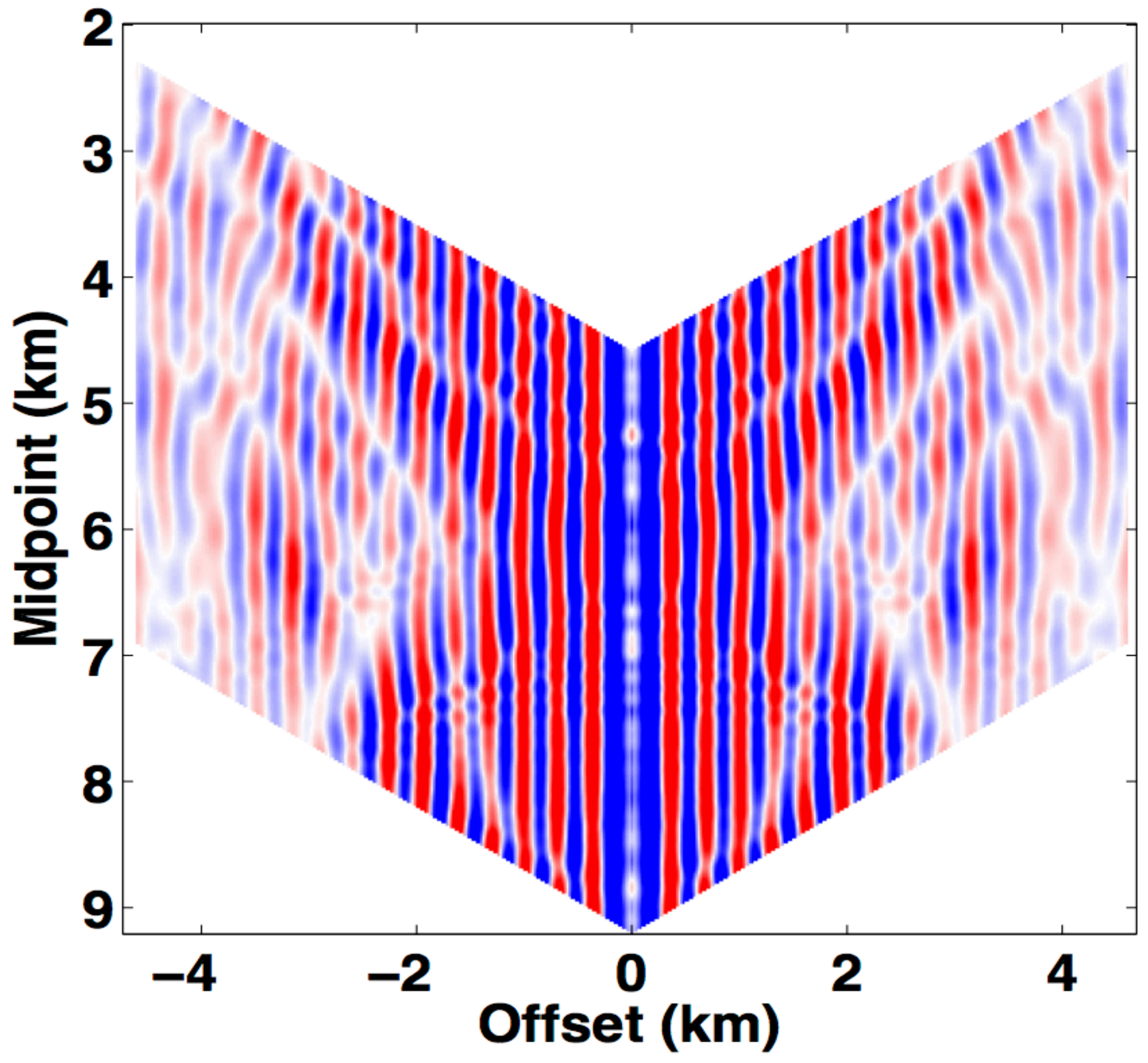
Low-rank structure in which domain?

- frequency slice at 5 Hz

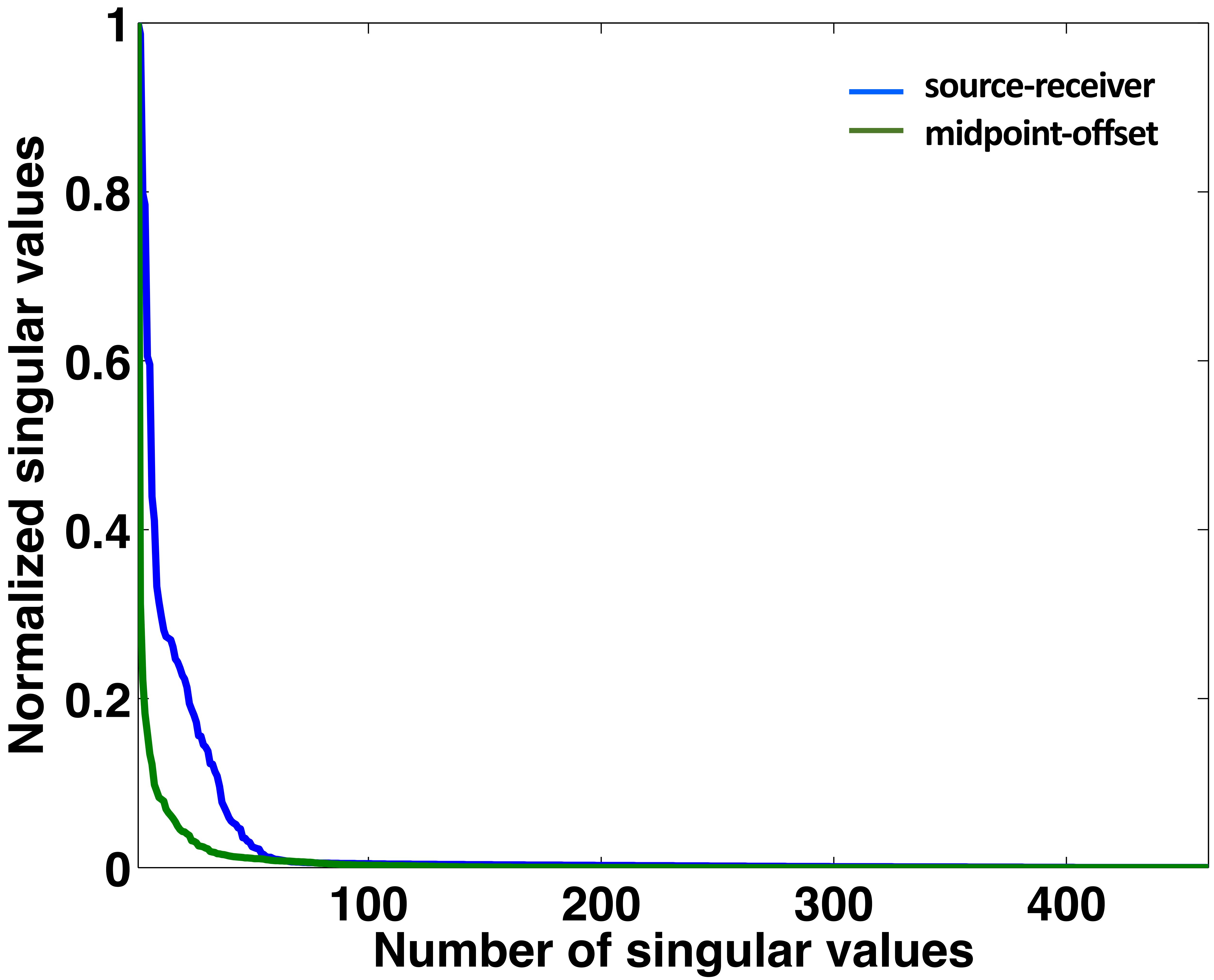
source-receiver domain
(with reciprocity)



midpoint-offset domain
(with reciprocity)



Decay of singular values

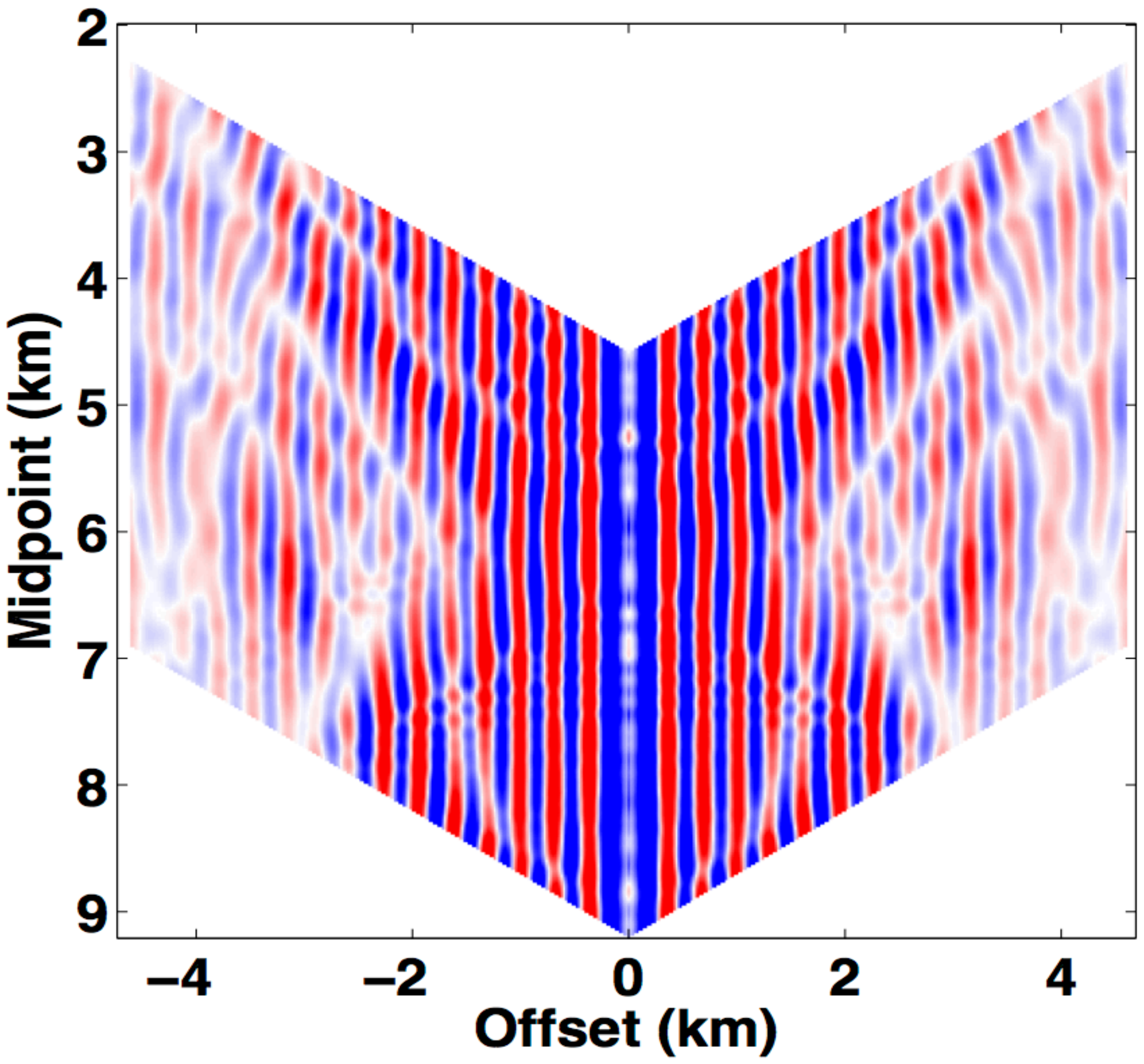


low-rank in midpoint-offset domain

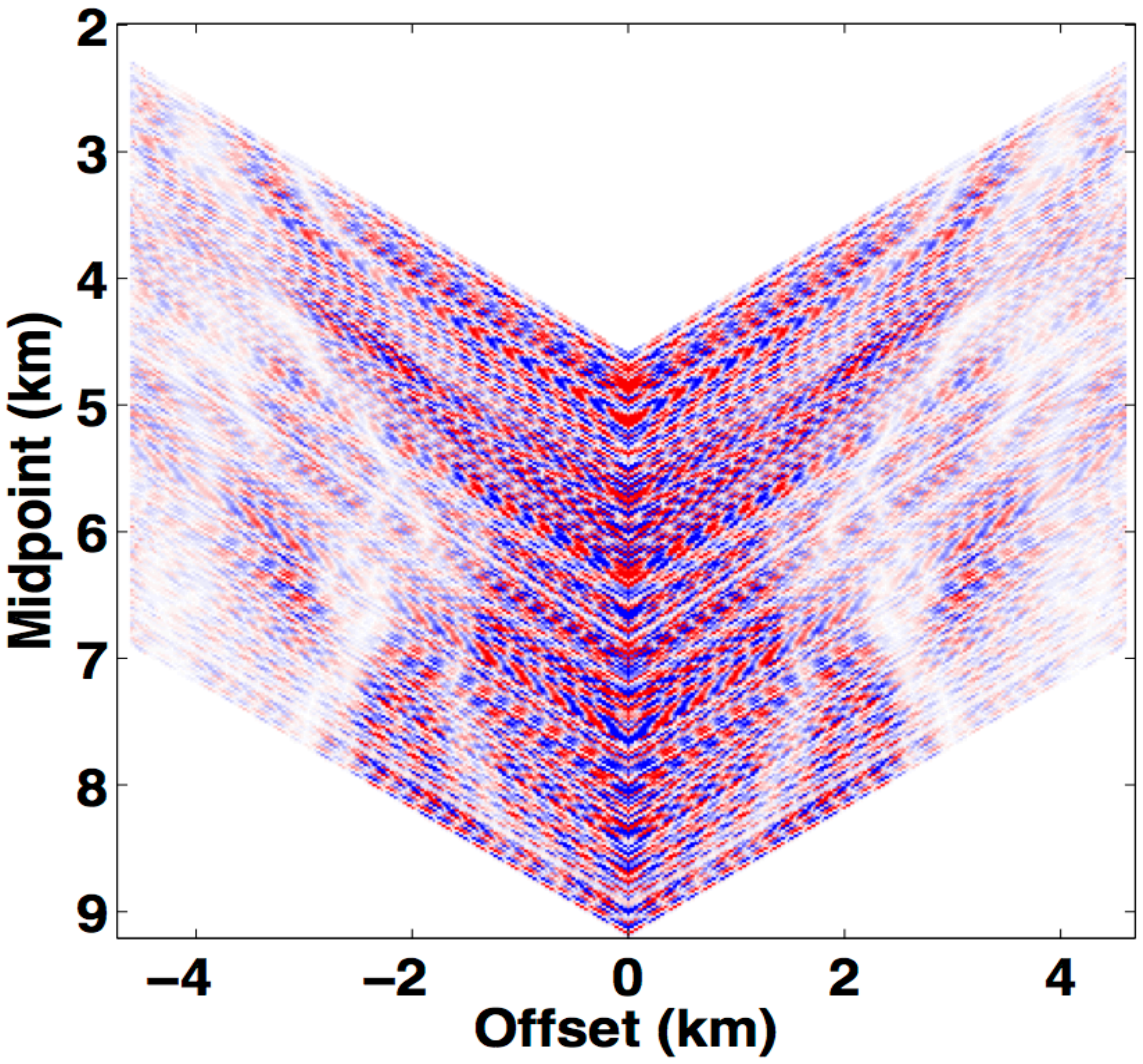
How to destroy the structure?

- add random time delays

without delays

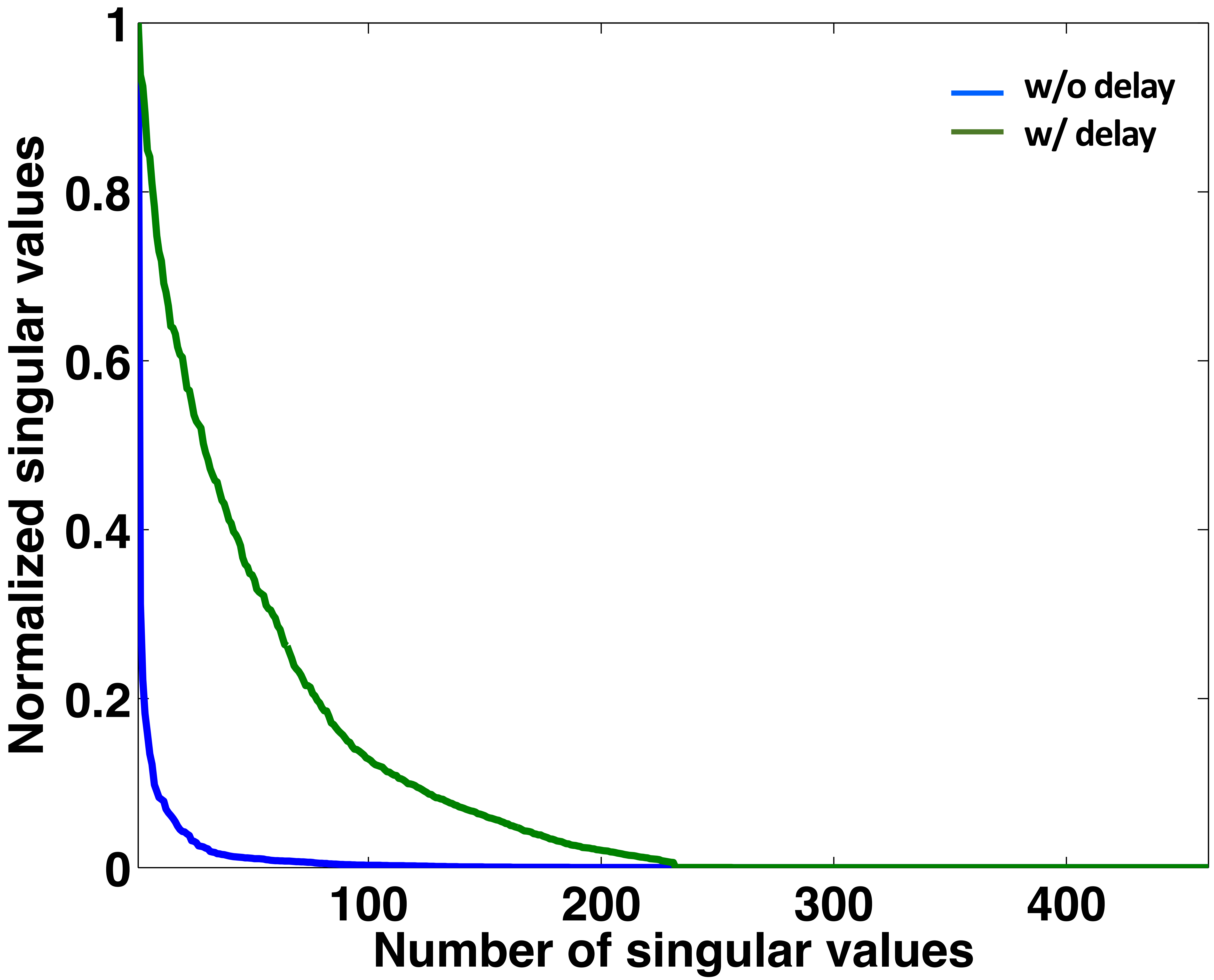


with random delays (< 1s)



Decay of singular values

- midpoint-offset domain



random time delays increase the rank

Rank-minimization

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

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

for blended acquisition:

$\mathbf{b}$: blended data

unblended data matrix

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

$$\mathcal{A} := [\mathbf{M}\mathbf{T_1}\mathbf{S^H} \quad \mathbf{M}\mathbf{T_2}\mathbf{S^H}]$$

↑ ↑

time delay matrices

Rank-minimization

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 $\mathbf{X}$

Rank-minimization

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

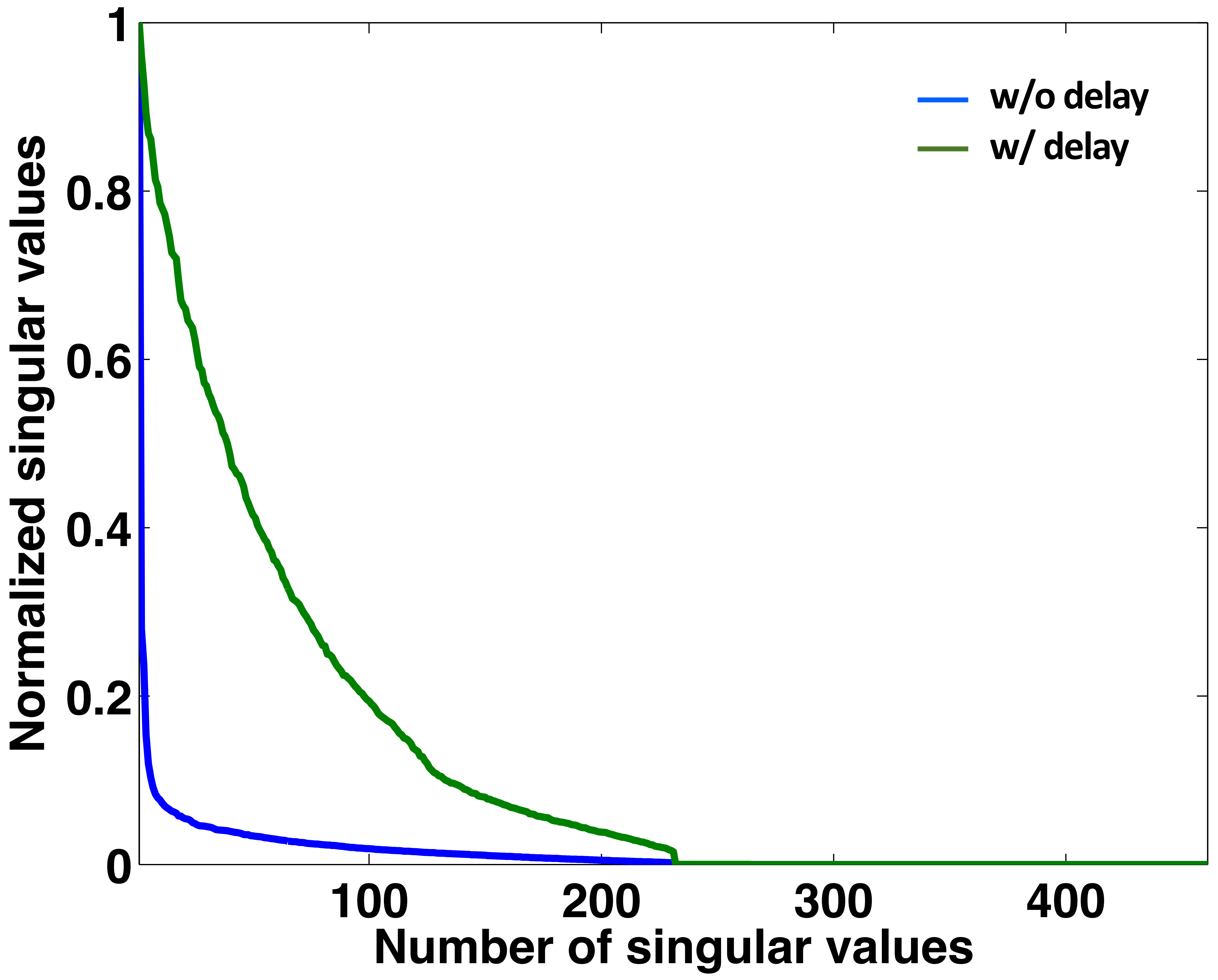
[Recht, et. al., 2010]

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

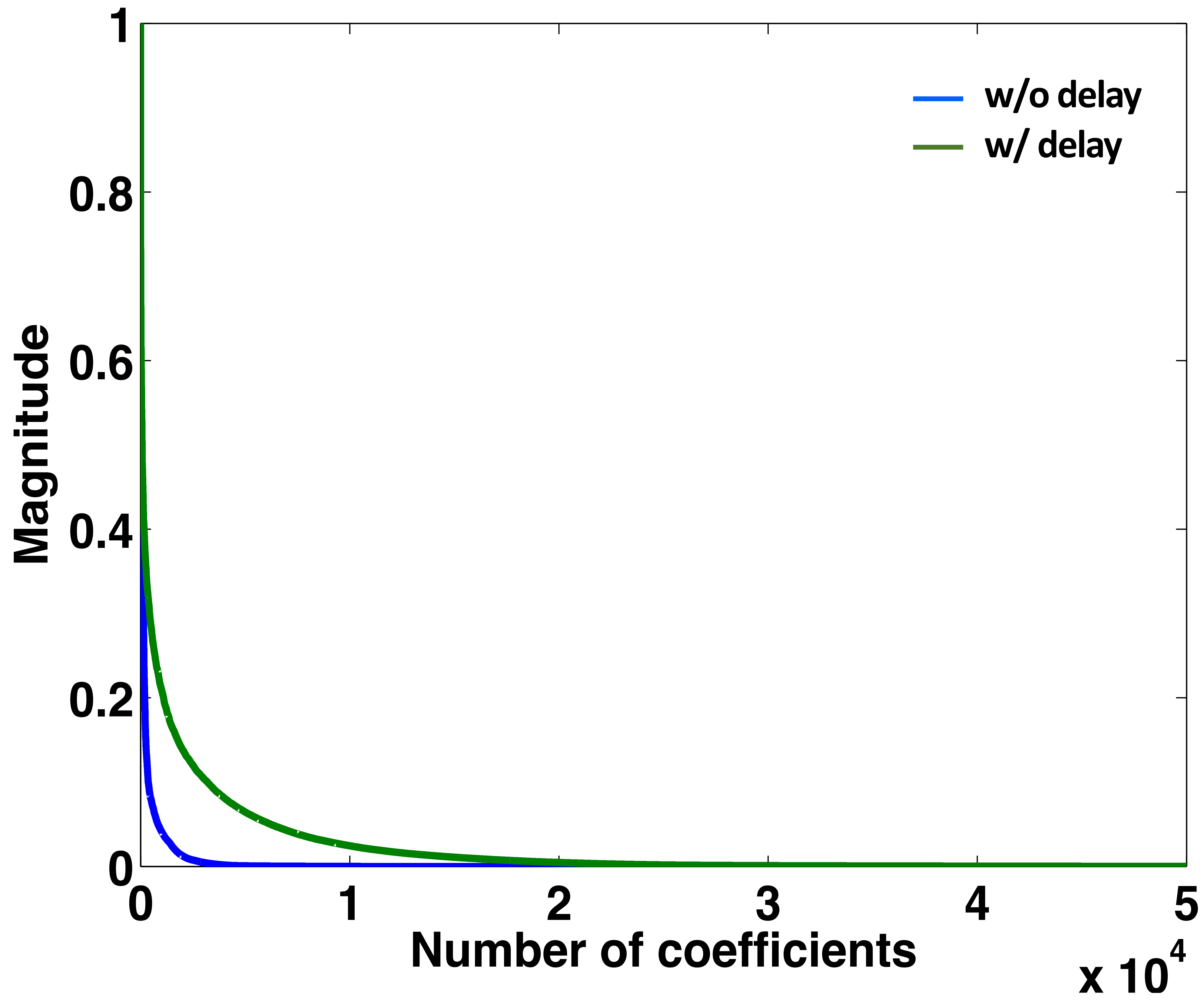
sum of singular values of $\mathbf{X}$

Rank vs. sparsity

rank-minimization
(midpoint-offset domain)



sparsity-promotion
(source-receiver domain)

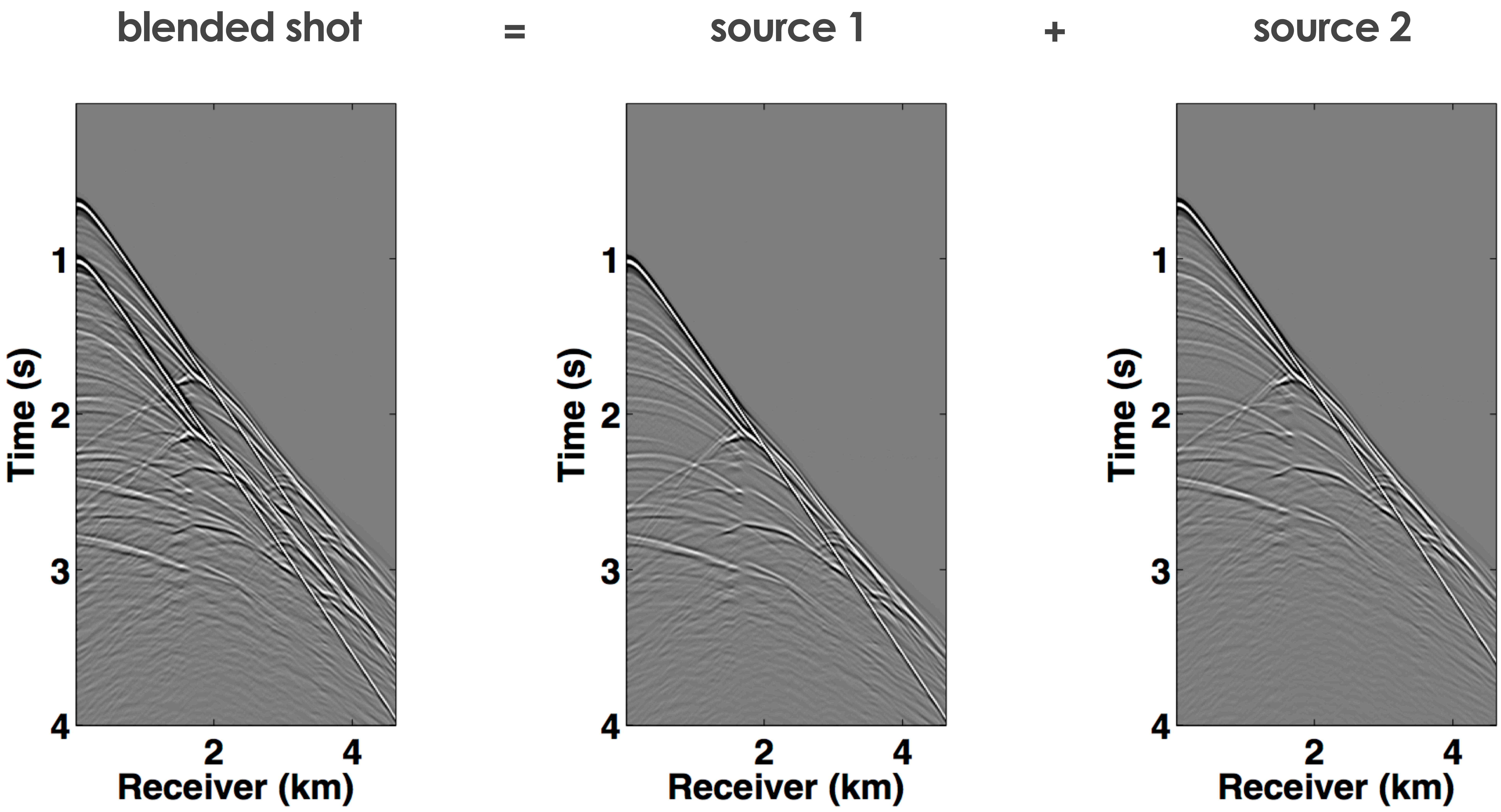


Source separation results

Rank-minimization vs. sparsity-promotion

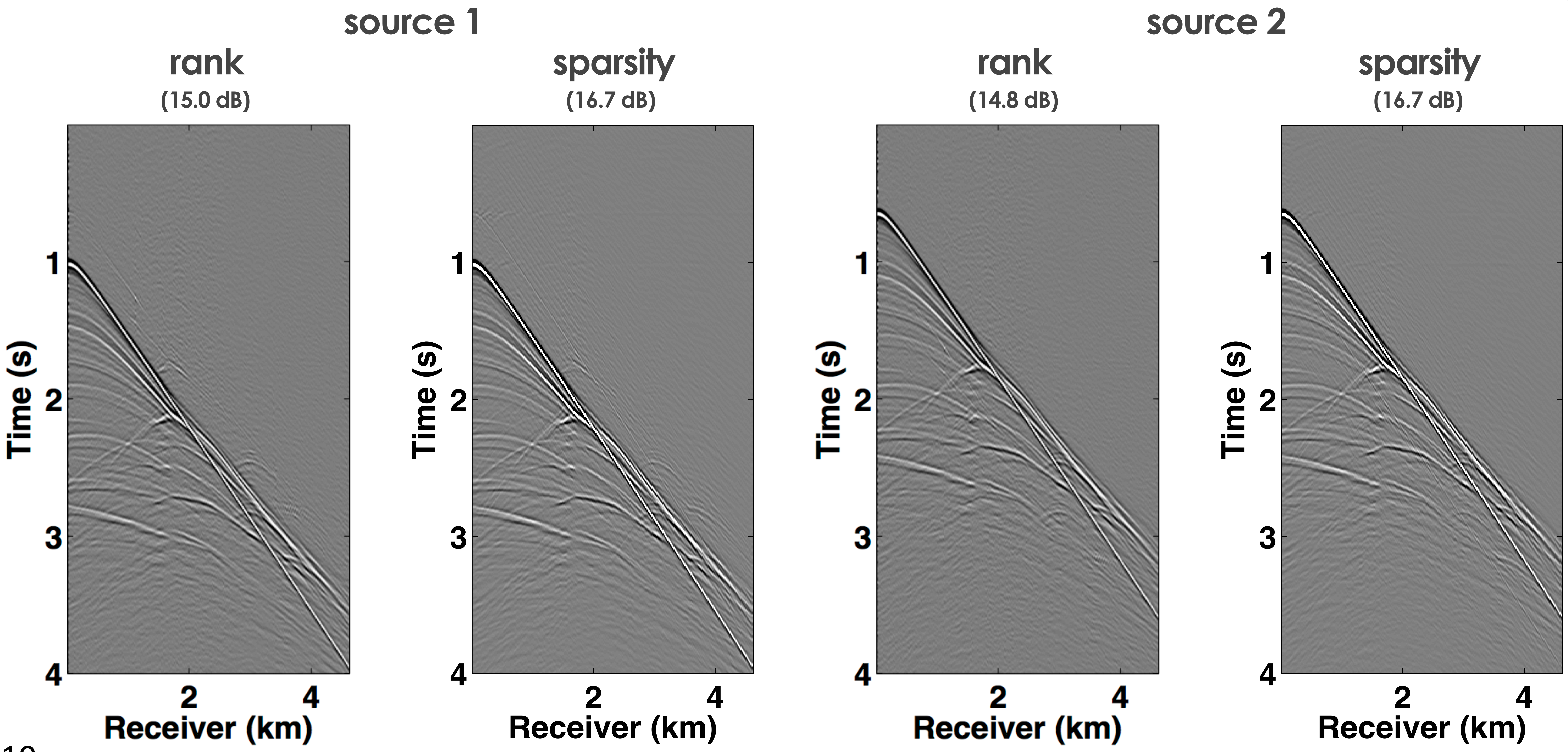
Blended data (w/ delay)

- random time delays (< 1 sec) applied to both sources



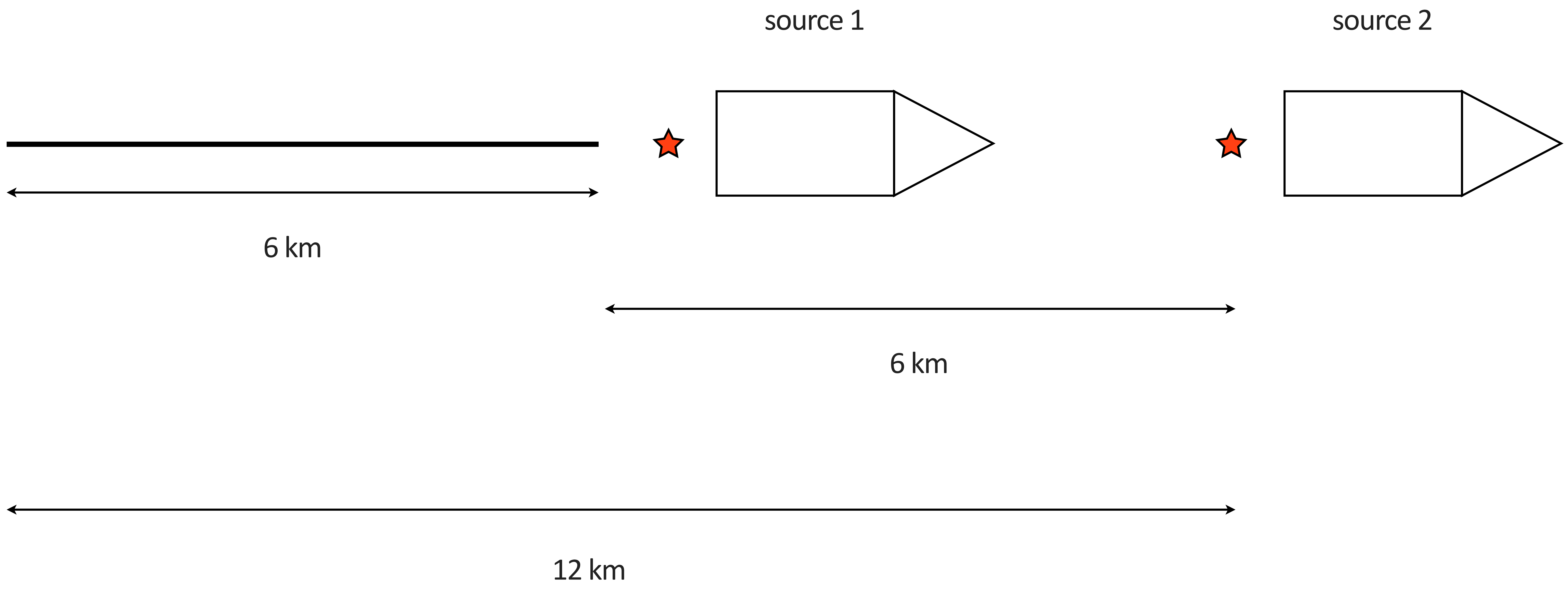
Source separation - rank vs. sparsity

computation time = 5 vs. 62 hours; memory usage = 2.8 vs. 7.0 GB;



Simultaneous long offset acquisition

- adapted from Long, et. al., 2013

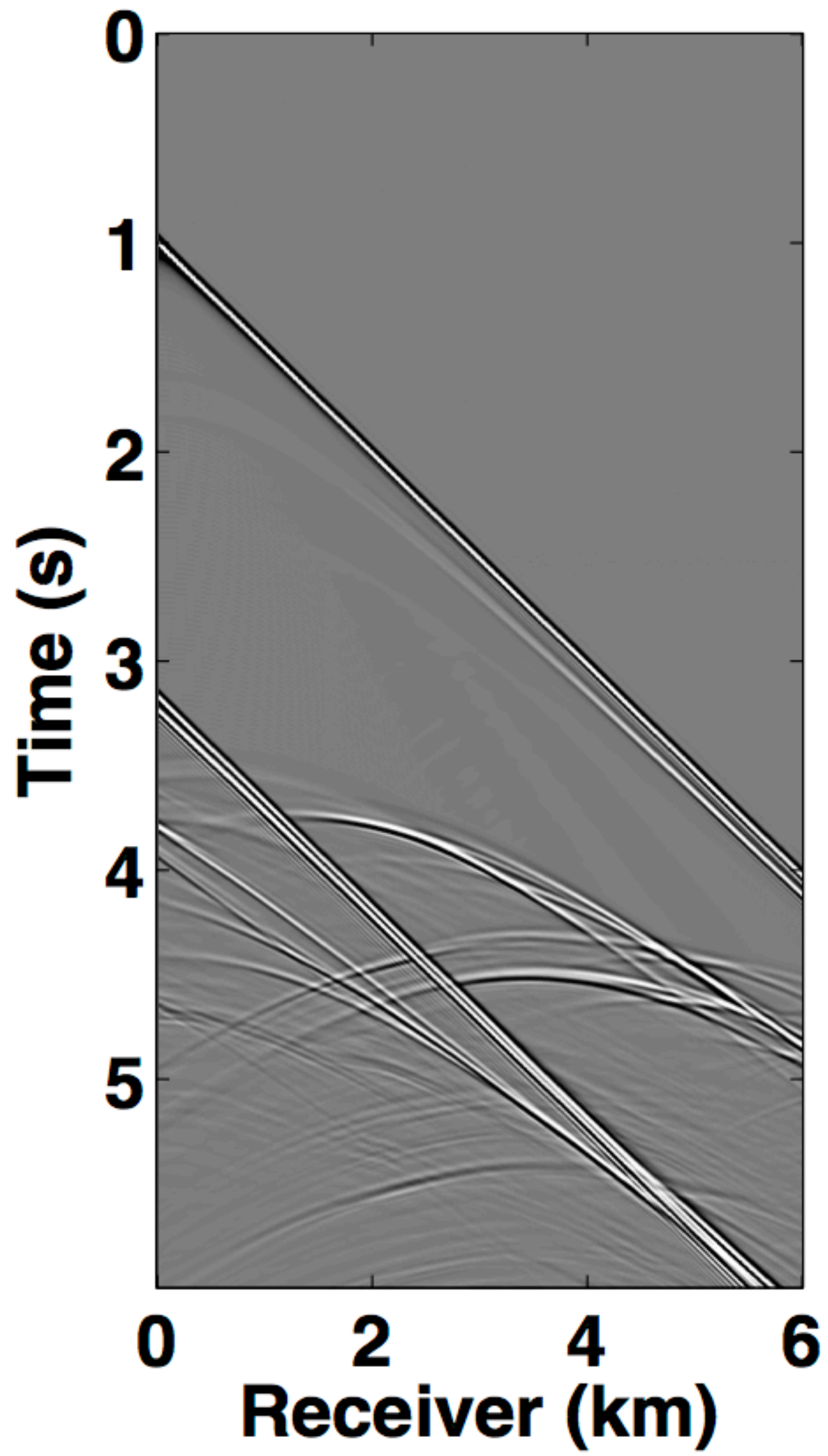


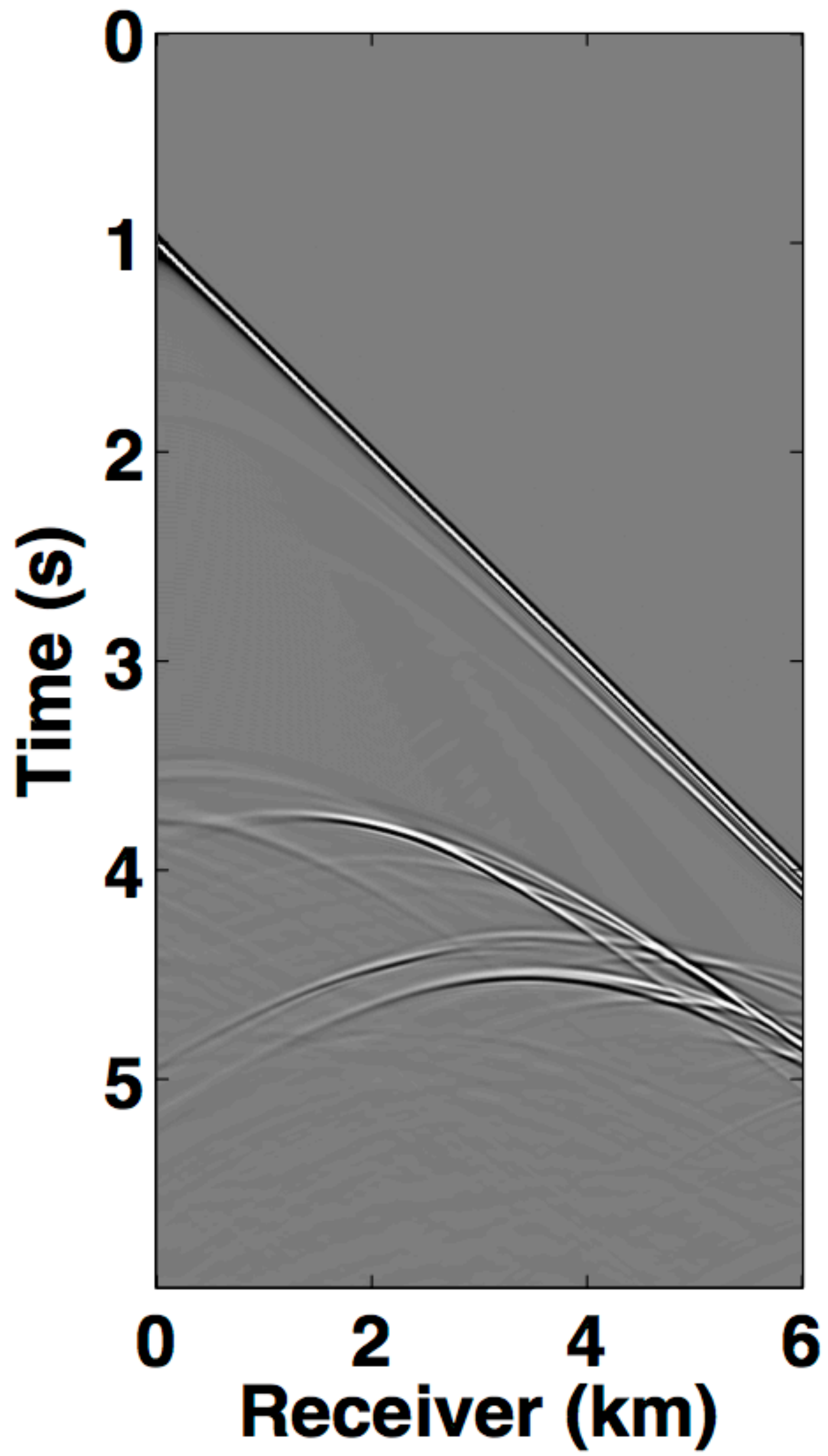
A. S. Long, et. al., "**Simultaneous long offset (SLO) towed streamer seismic acquisition**", presented at the *75th EAGE Conference and Exhibition*, June 2013.

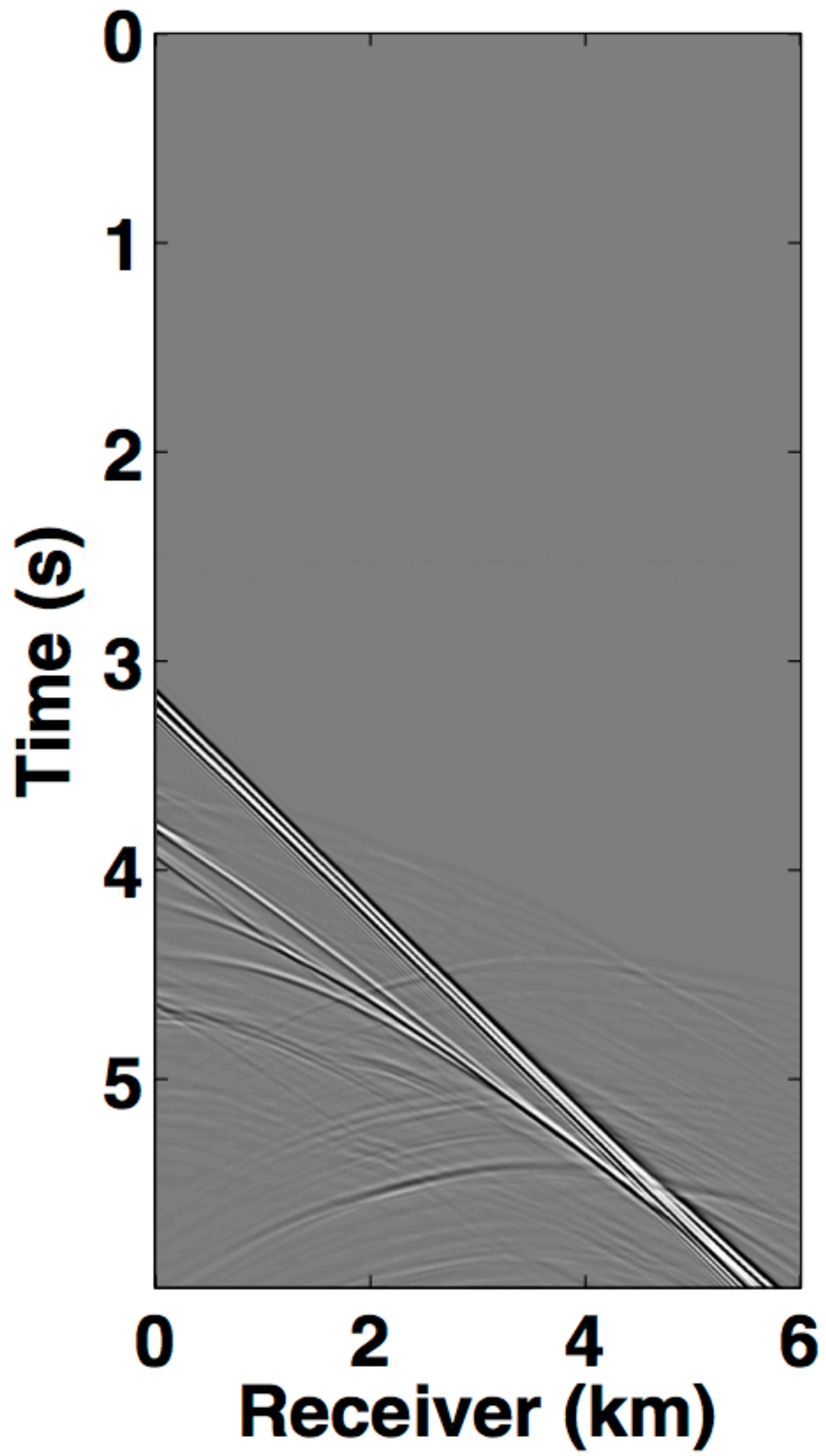
Blended data (w/ delay)

- random time delays (< 1 sec) applied to both sources

blended shot = source 1 + source 2

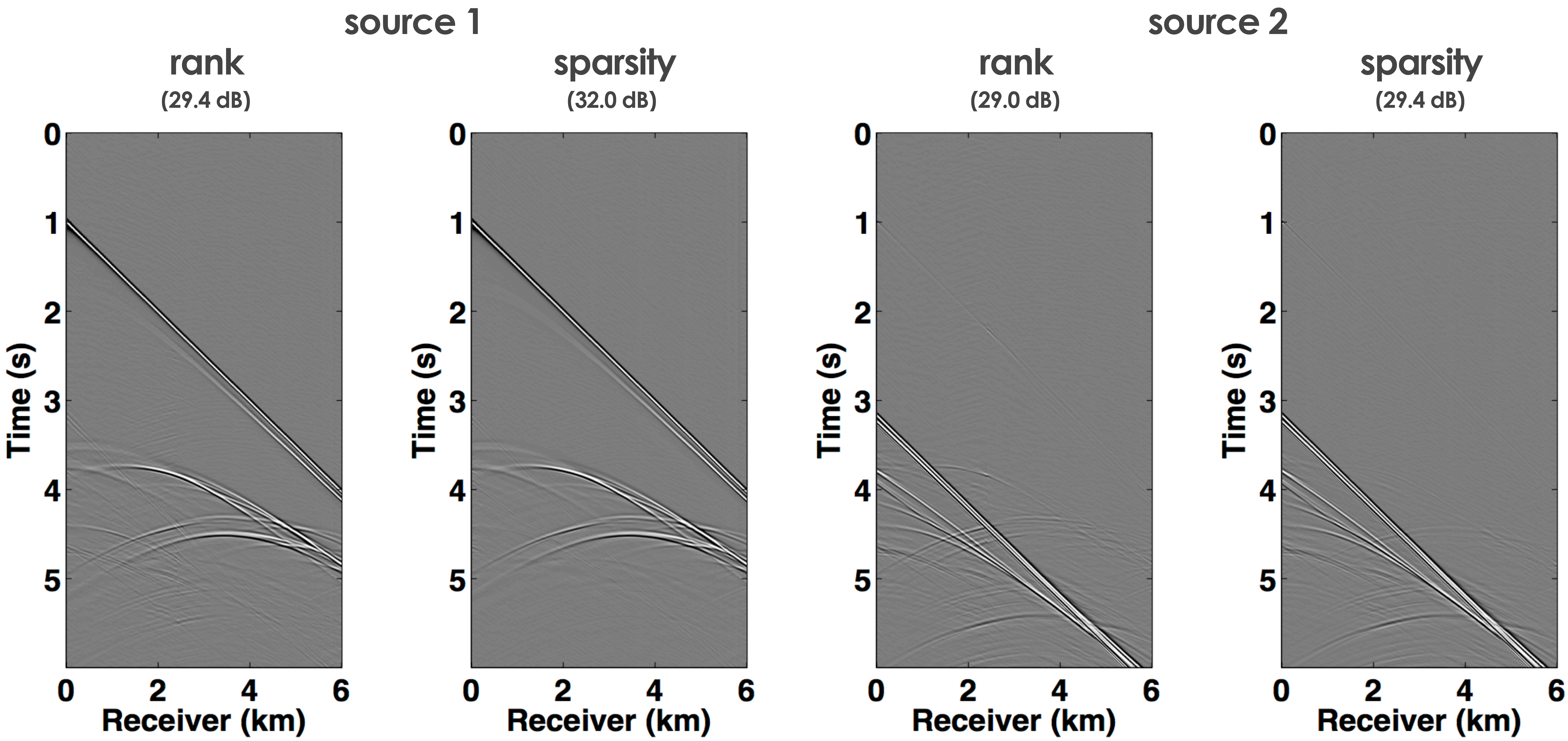






Source separation - rank vs. sparsity

computation time = 19 vs. 183 hours;   memory usage = 6 vs. 12 GB



Rajiv Kumar, Haneet Wason and Felix J. Herrmann, "**Source separation for simultaneous towed-streamer marine acquisition---a compressed sensing approach**", submitted to *Geophysics*, February 2015.

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Summary
– time (in hours), memory (in GB), average SNR (in dB)

	Over/under acquisition			Simultaneous long offset acquisition		
	time	memory	SNR*	time	memory	SNR*
sparsity	62	7.0	16.7	183	12.0	32.0, 29.4
rank	5	2.8	15.0, 14.8	19	6.0	29.4, 29.0

* average SNR for source 1, source 2

Observations & Future work

Source separation for *low variability* acquisition scenarios can be treated *both* as a *sparsity-promoting* & *rank-minimization* problem

Get comparable results for both separation techniques, however, the rank-minimization technique is computationally faster

Future work: show results for real datasets

References

Aravkin, A. Y., J. V. Burke, and Friedlander, M. P., 2012, Variational properties of value functions, *Submitted to SIAM Journal on Optimization, ArXiv: 1211.3724.*

van den Berg, E., and Friedlander, M. P., 2008, Probing the Pareto frontier for basis pursuit solutions, *SIAM Journal on Scientific Computing, 31, 890-912.*

Candès, E. J., and Demanet, L., 2005, The curvelet representation of wave propagators is optimally sparse, *Comm. Pure Applied Math, 58, 1472–1528.*

Chandrasekaran, S., Dewilde, P., Gu, M., Lyons, W., and Pals, T., 2006, A fast solver for HSS representations via sparse matrices, *SIAM Journal on Matrix Analysis Applications, 29(1), 67–81.*

Donoho, D. L., 2006, Compressed sensing, *IEEE Trans. Inform. Theory, 52, 1289–1306.*

Mansour, H., Wason, H., Lin, T. T. Y., and Herrmann, F. J., 2012, Randomized marine acquisition with compressive sampling matrices: *Geophysical Prospecting, 60, 648–662.*

Oropeza, V., and Sacchi, M., 2011, Simultaneous seismic data denoising and reconstruction via multichannel singular spectrum analysis, *Geophysics, 76(3), V25-V32.*

Recht, B., Fazel, M., and Parrilo, P. A., 2010, Guaranteed minimum rank solutions to linear matrix equations via nuclear norm minimization, *SIAM Review, 52(3), 471–501.*

Wason, H., and Herrmann, F. J., 2013, Time-jittered ocean bottom seismic acquisition, *SEG Technical Program Expanded Abstracts*

Randomization and repeatability in time-lapse marine acquisition

Collaborators: Felix Oghenekohwo and Felix J. Herrmann

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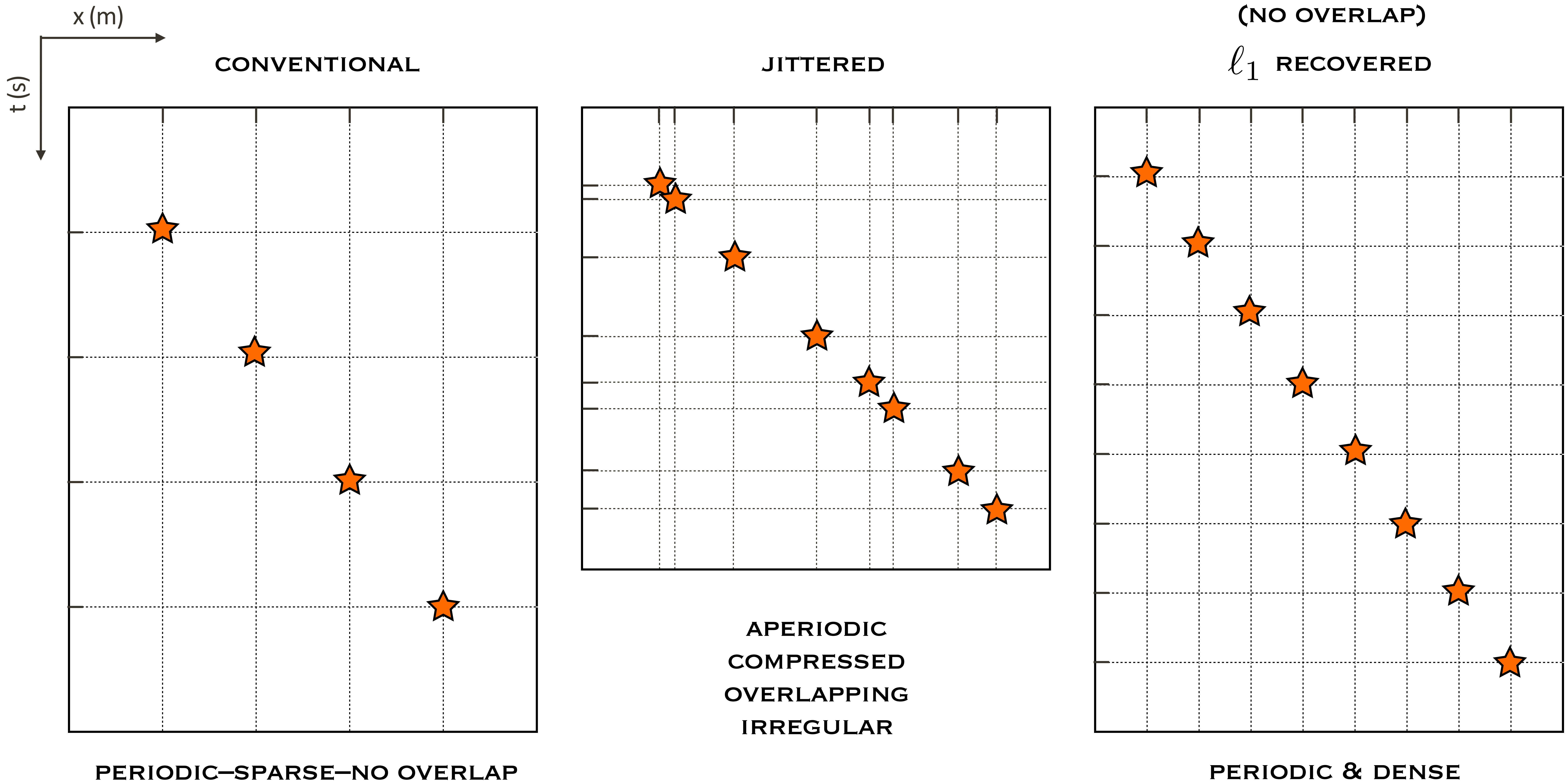
Randomized *jitter* sampling in marine



Motivation

What are the implications of randomization in time-lapse seismic?

Is repetition really possible in time-lapse acquisition?

Felix Oghenekohwo, Haneet Wason, and Felix J. Herrmann, "**Compressive 4D---economic time-lapse seismic with randomized subsampling and joint recovery**", submitted to *Geophysics*, October 2014.
Haneet Wason, and Felix J. Herrmann, "**Time-jittered ocean bottom seismic acquisition**", in *SEG Technical Program Expanded Abstracts*, 2013, p. 1-6.
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

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Time-lapse seismic

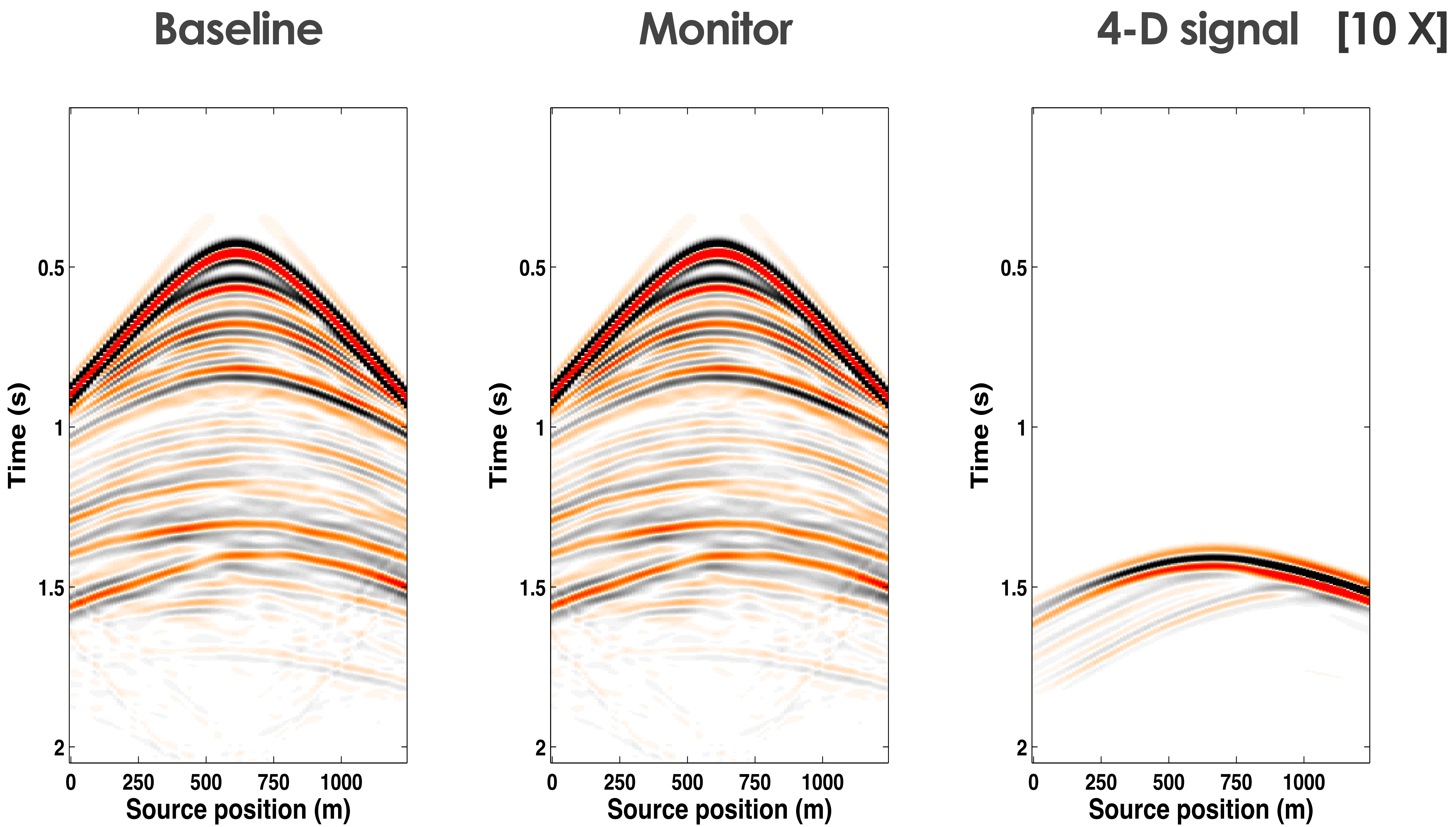
Current acquisition *paradigm*:

- *repeat* **expensive** *dense* acquisitions & *"independent"* processing
- compute *differences* between *baseline* & *monitor* survey(s)
- *hampered* by *practical* challenges to ensure *repetition*

New compressive sampling paradigm:

- **cheap** *sub*sampled acquisition, e.g. via time-*jittered* marine *sub*sampling
- may offer *possibility* to *relax* insistence on *repeatability*
- *exploits* insights from *distributed* compressed sensing

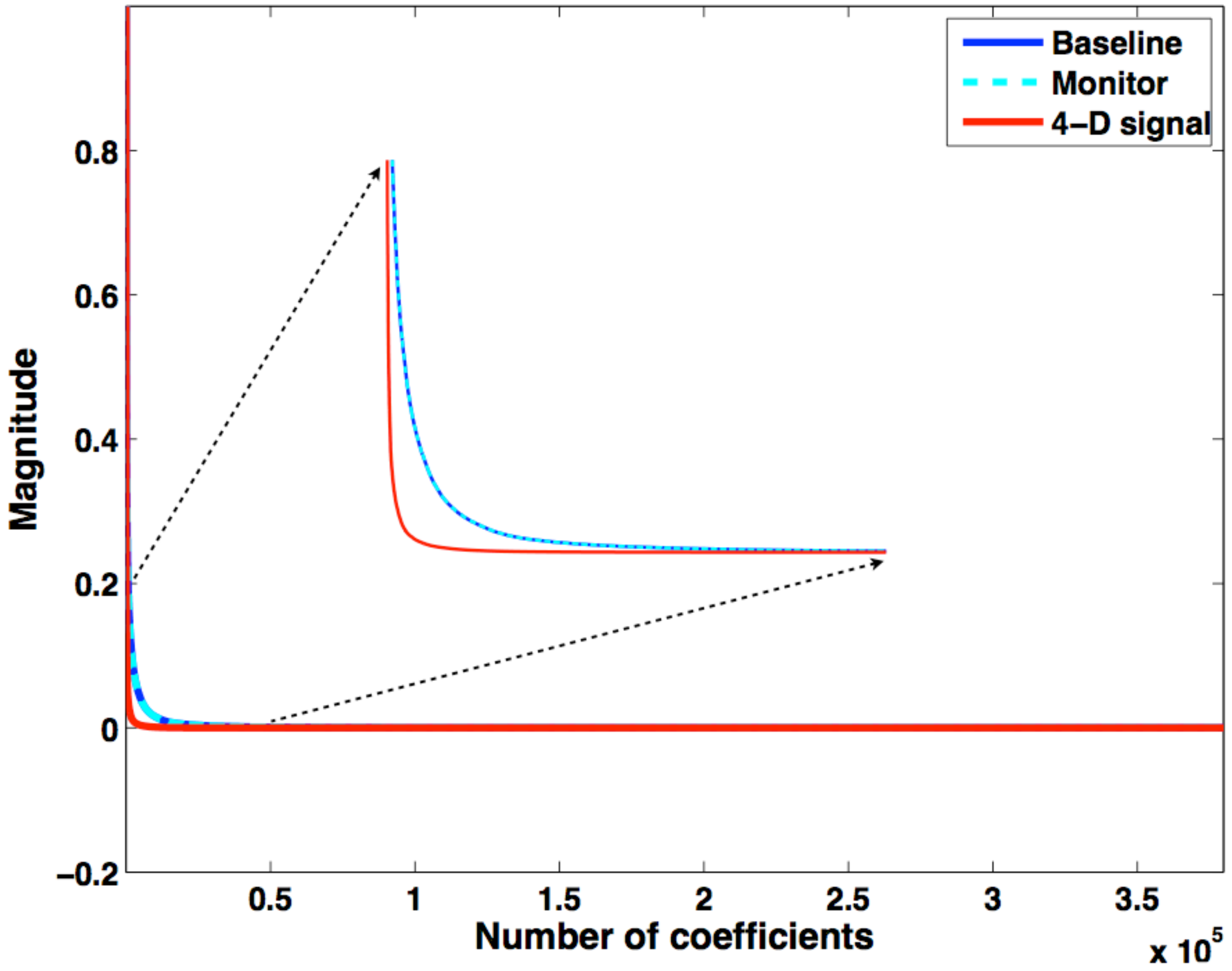
Time-lapse data



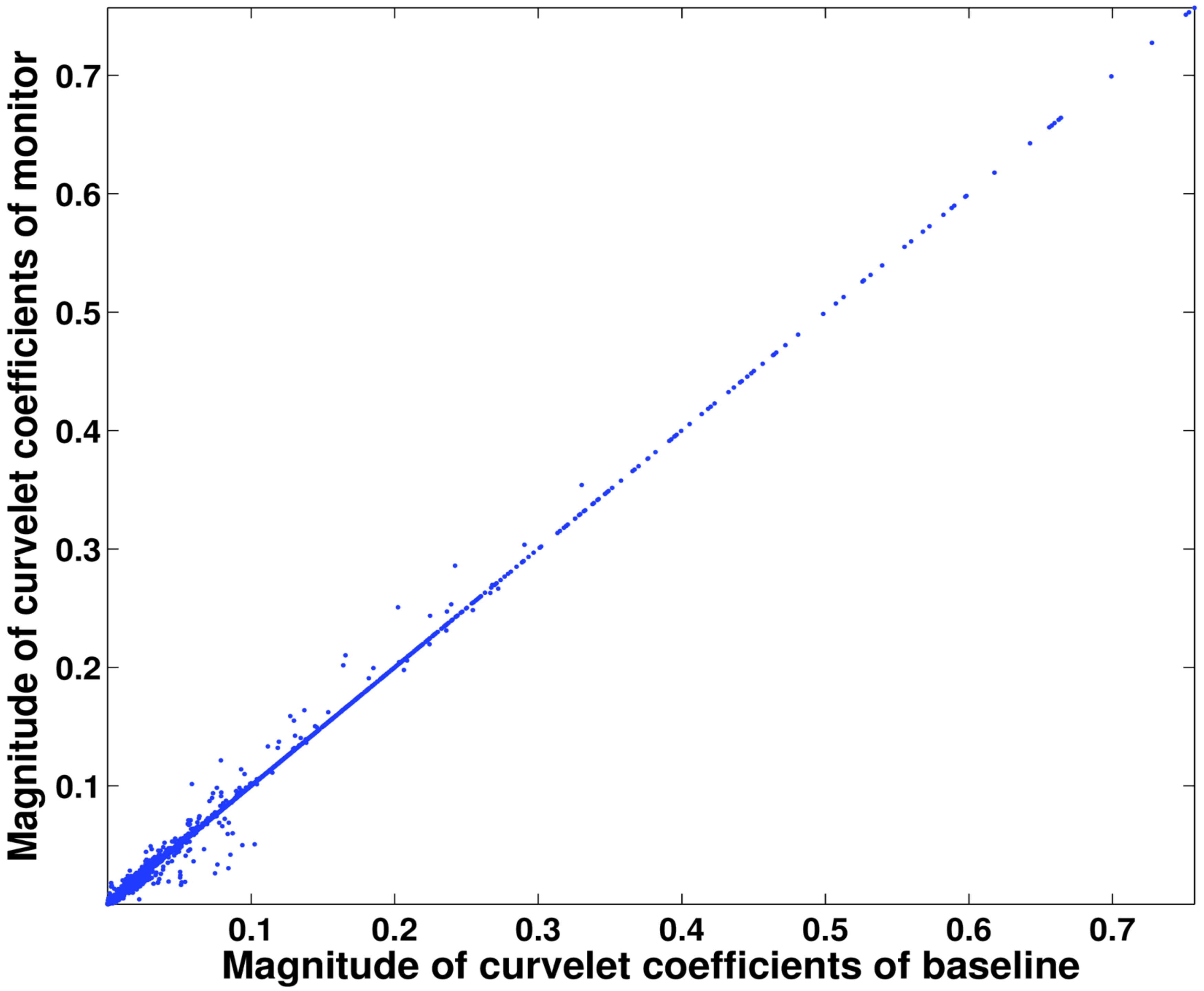
time samples: **512**
receivers: **100**
sources: **100**

sampling
time: **4.0 ms**
receiver: **12.5 m**
source: **12.5 m**

Sparse structure via *curvelets*



significant correlation between the vintages



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Distributed compressed sensing

– *joint* recovery model (JRM)

vintages

$$\mathbf{x}_1 = \mathbf{z}_0 + \mathbf{z}_1$$
$$\mathbf{x}_2 = \mathbf{z}_0 + \mathbf{z}_2$$

→ *differences*

common component

$$\overbrace{\begin{bmatrix} \mathbf{A}_1 & \mathbf{A}_1 & \mathbf{0} \\ \mathbf{A}_2 & \mathbf{0} & \mathbf{A}_2 \end{bmatrix}}^{\mathbf{A}} \overbrace{\begin{bmatrix} \mathbf{z}_0 \\ \mathbf{z}_1 \\ \mathbf{z}_2 \end{bmatrix}}^{\mathbf{z}} = \overbrace{\begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \end{bmatrix}}^{\mathbf{b}}$$

→ *baseline*

→ *monitor*

Key idea:

- use the fact that *different* vintages *share* common information
- invert for *common* components & *differences* w.r.t. the *common* components with *sparse* recovery

Time-lapse seismic
– w/ & w/o repetition

In an *ideal* world $(\mathbf{A}_1 = \mathbf{A}_2)$

- JRM *simplifies* to recovering the *difference* from $(\mathbf{b}_2 - \mathbf{b}_1) = \mathbf{A}_1(\mathbf{x}_2 - \mathbf{x}_1)$
- expect *good* recovery when *difference* is *sparse*
- ***but*** relies on "*exact*" repeatability...

In the *real* world $(\mathbf{A}_1 \neq \mathbf{A}_2)$

- no absolute *control* on *surveys*
- *calibration* errors
- noise...

Context

Acquire randomized subsamplings for the baseline and monitor surveys

Aim: recovery of **both** vintages & time-lapse signal from incomplete data

Questions:

- Process/recover *independently* or *jointly* to exploit *common* features of surveys?
- Should we *repeat* the surveys when doing *randomized sub*sampling?

Synthetic seismic case study

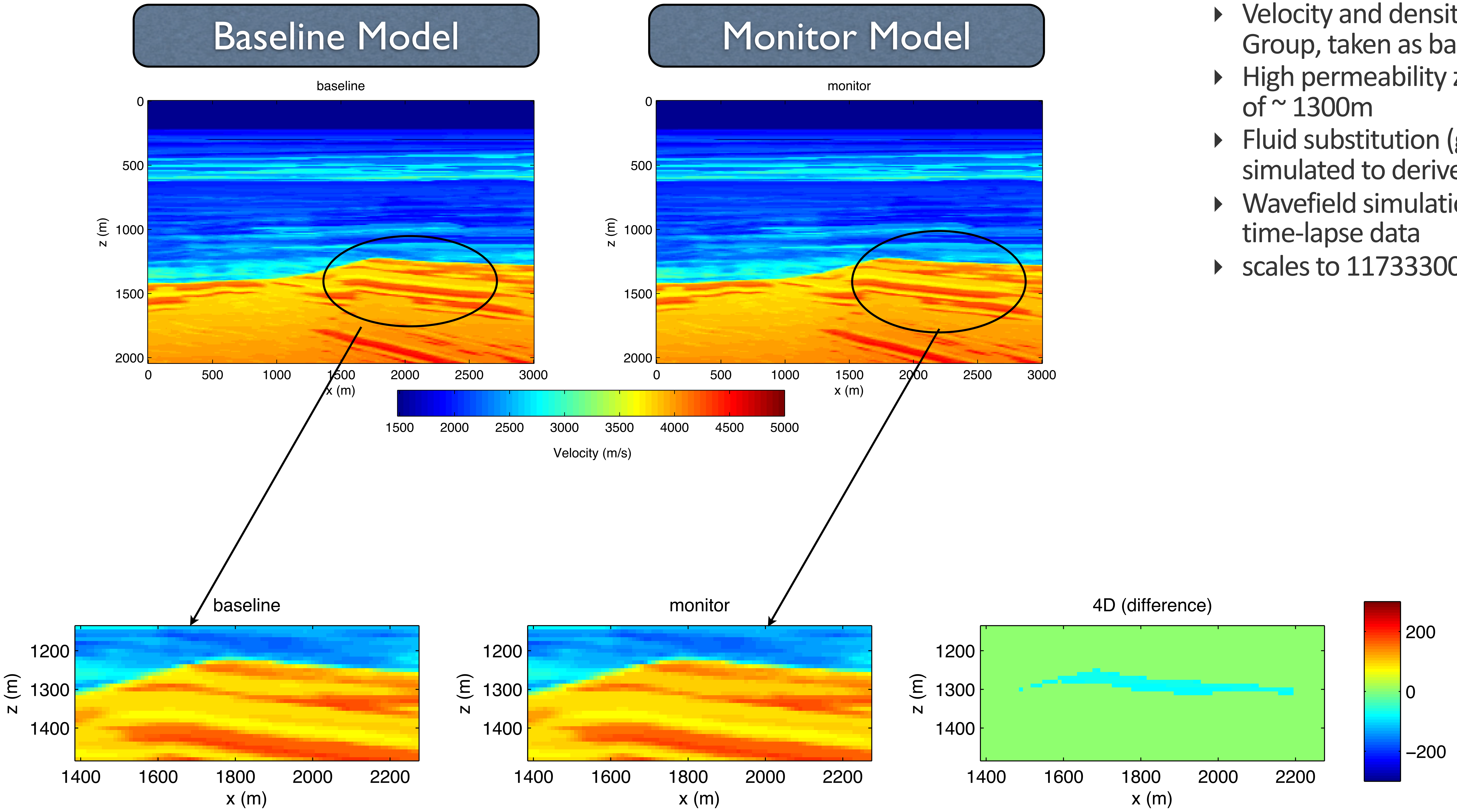
Time-jittered marine acquisition on the grid

% repetition => "*exact*" repetition

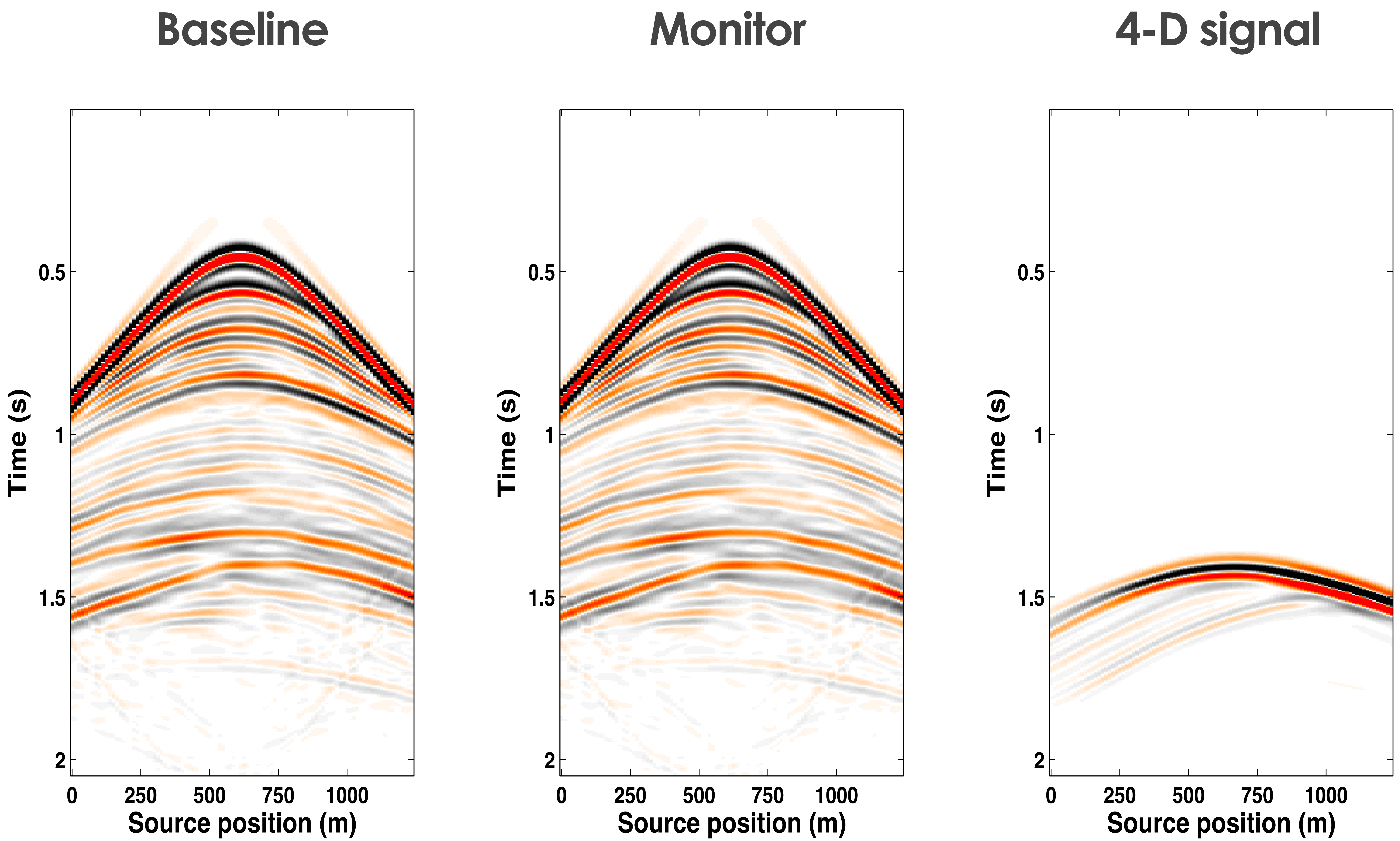
No calibration errors

Method

- Velocity and density model provided by BG Group, taken as baseline
- High permeability zone identified at a depth of ~ 1300m
- Fluid substitution (gas/oil replaced with brine) simulated to derive monitor velocity model
- Wavefield simulation to generate synthetic time-lapse data
- scales to 11733300 x 114882048



Simulated time-lapse data
– time-domain finite differences

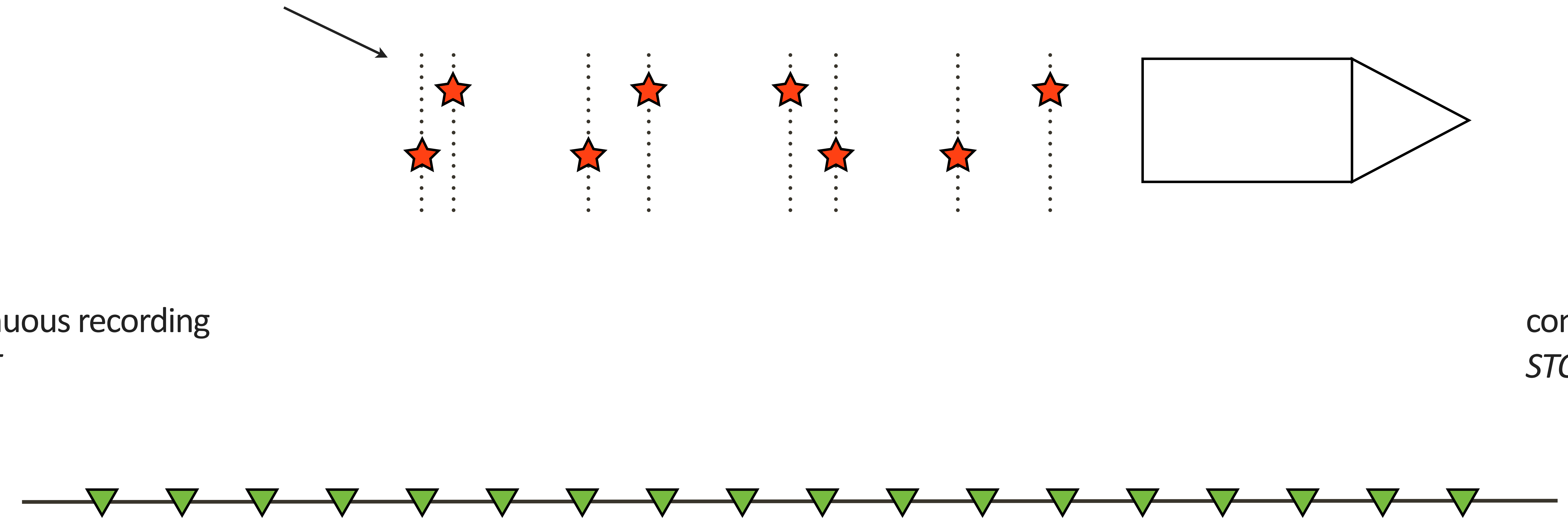


time samples: **512**
receivers: **100**
sources: **100**

sampling
time: **4.0 ms**
receiver: **12.5 m**
source: **12.5 m**

Time-jittered marine acquisition

irregularly sampled spatial grid

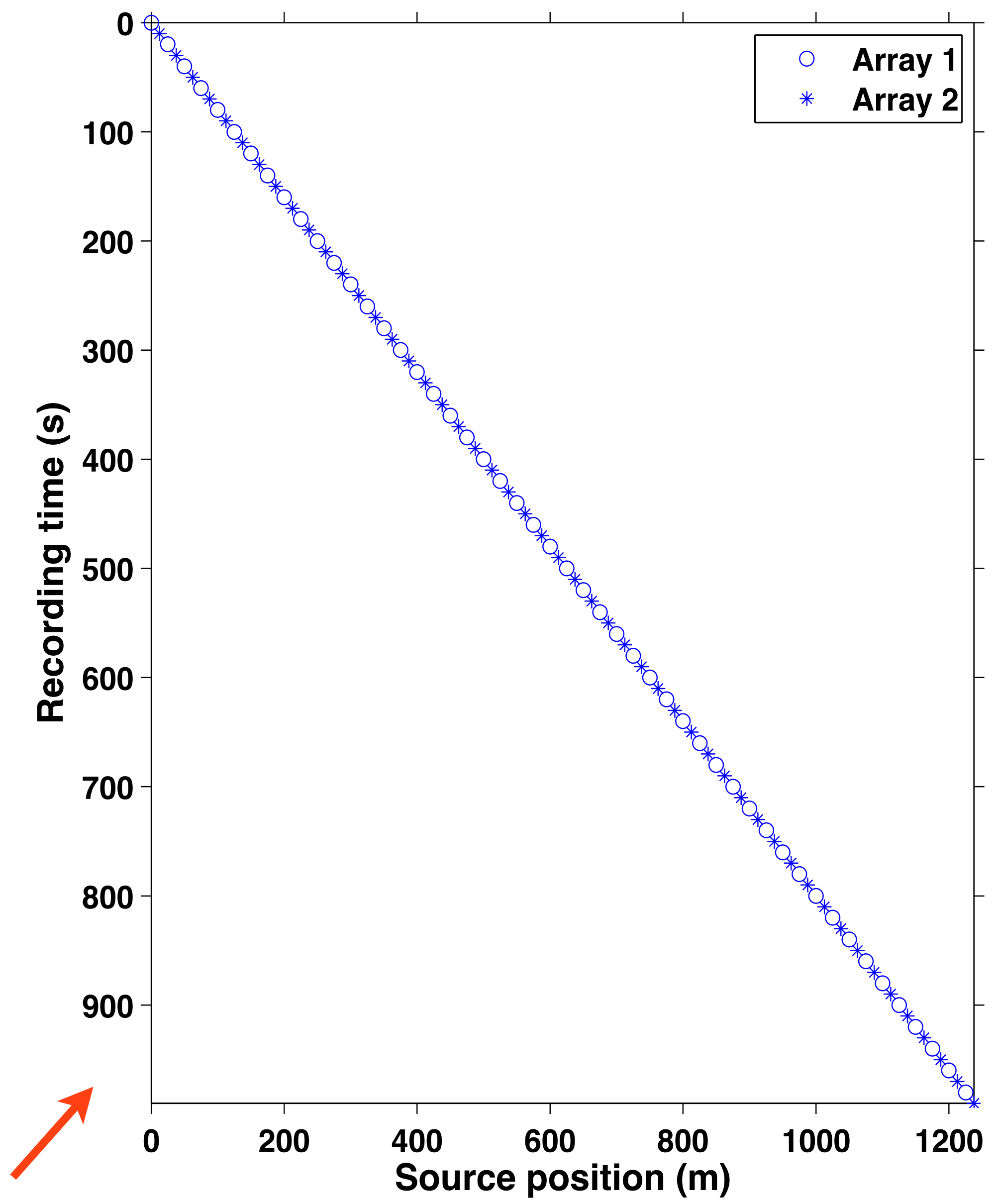


continuous recording
START

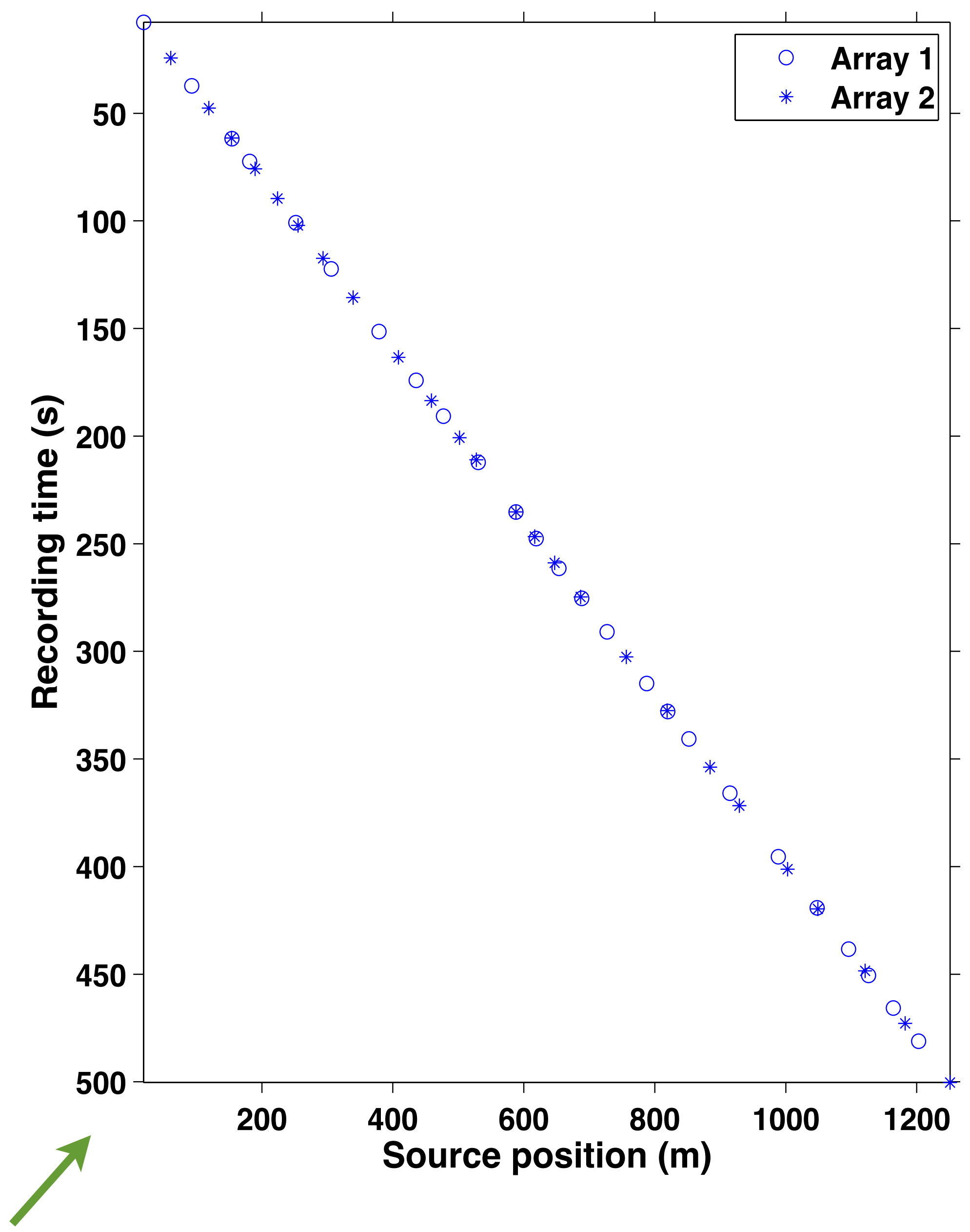
continuous recording
STOP

Conventional vs. *time-jittered* sources
– *subsampling* ratio = 2, 2 source arrays

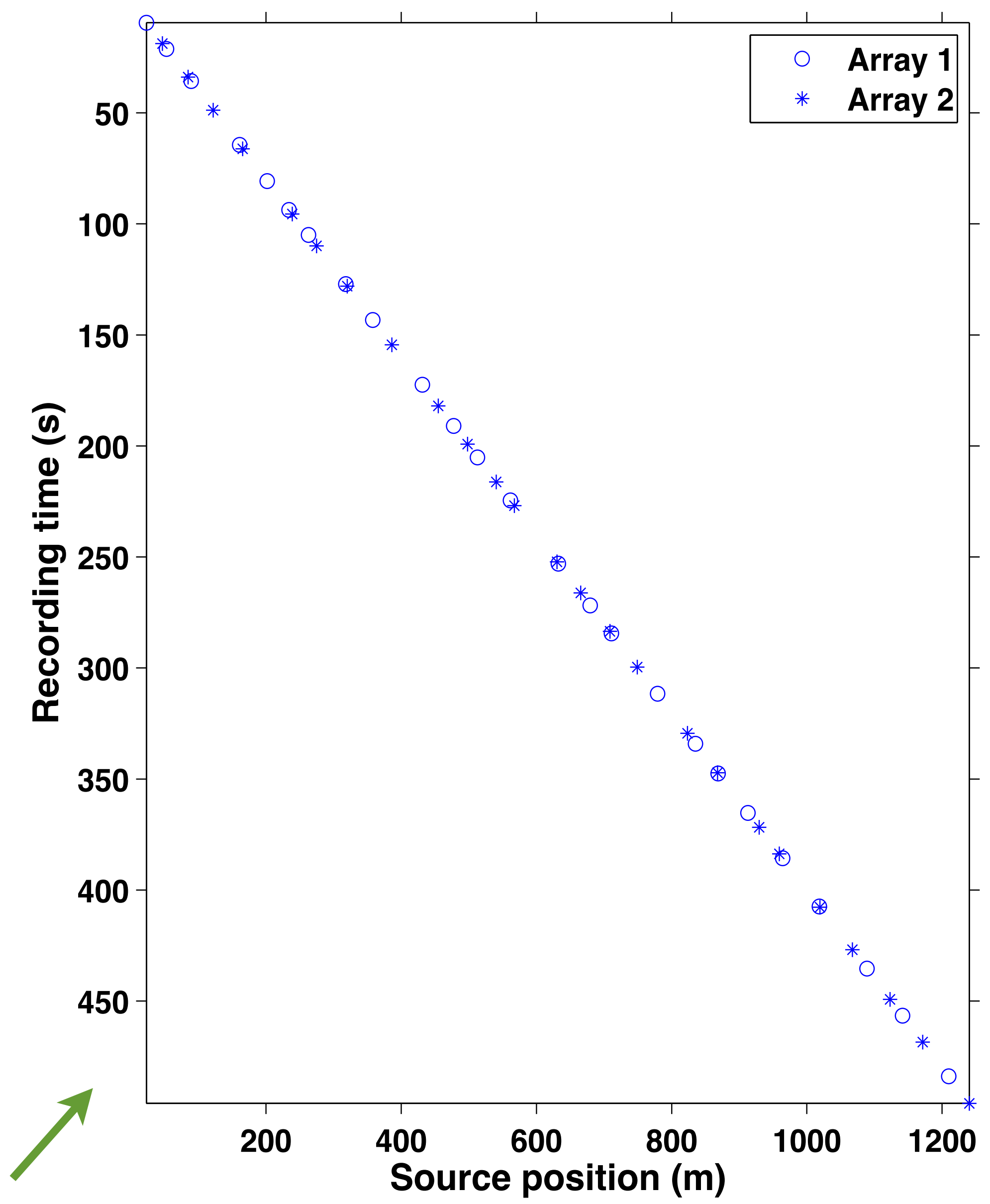
conventional



jittered acquisition 1 (baseline)



jittered acquisition 2 (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**

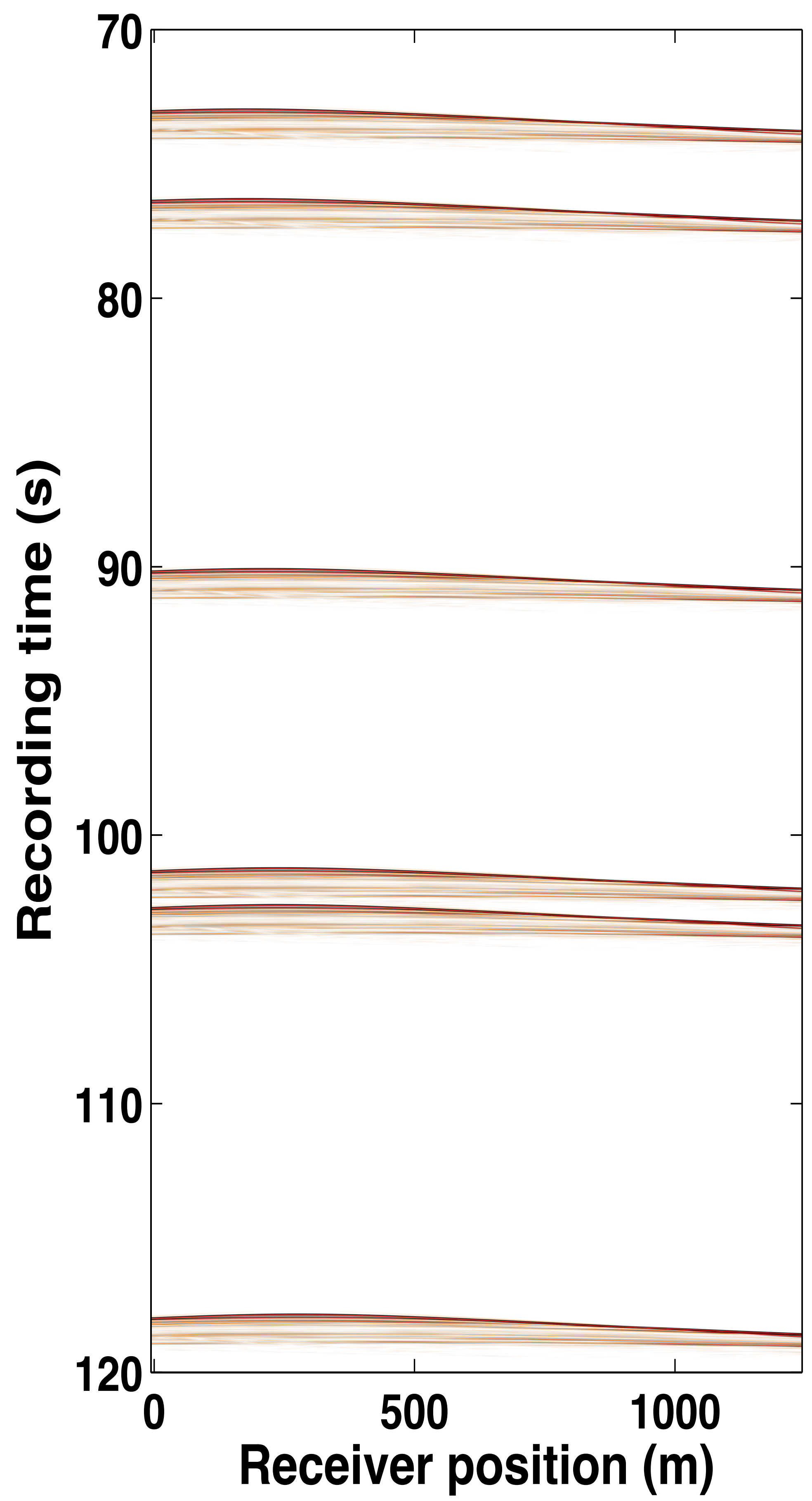
[BLENDING & SUBSAMPLING]
spatial subsampling factor = 2

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

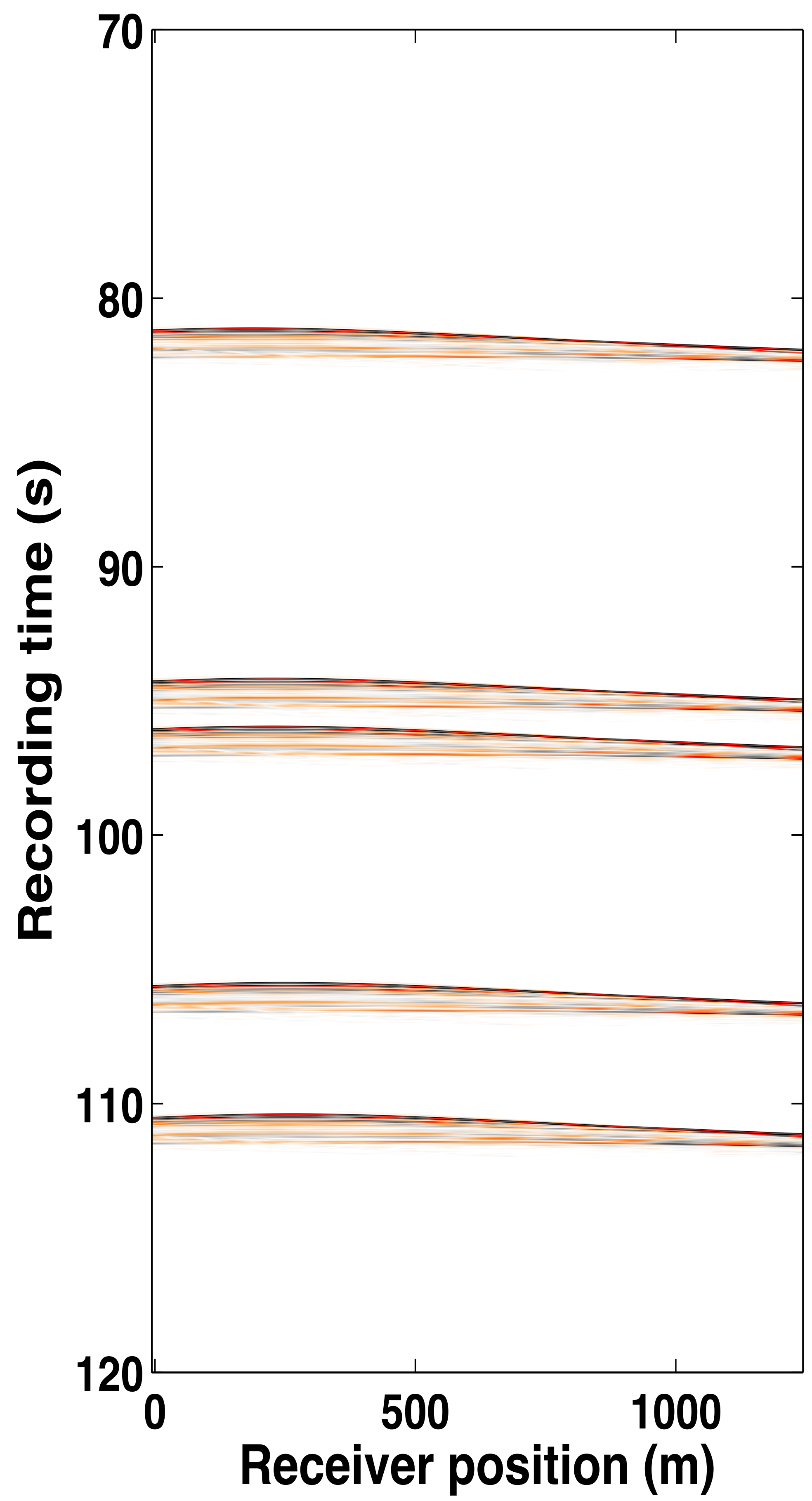
"blended" **shot gathers**
number of shots = 100/2 = **50** (25 per array)
spatial sampling: **50.0 m (*jittered*)**
vessel speed: **2.50 m/s**
recording time ≈ 1000.0 s/2 = **500.0 s**

Measurements
– *subsampled and blended*

Baseline

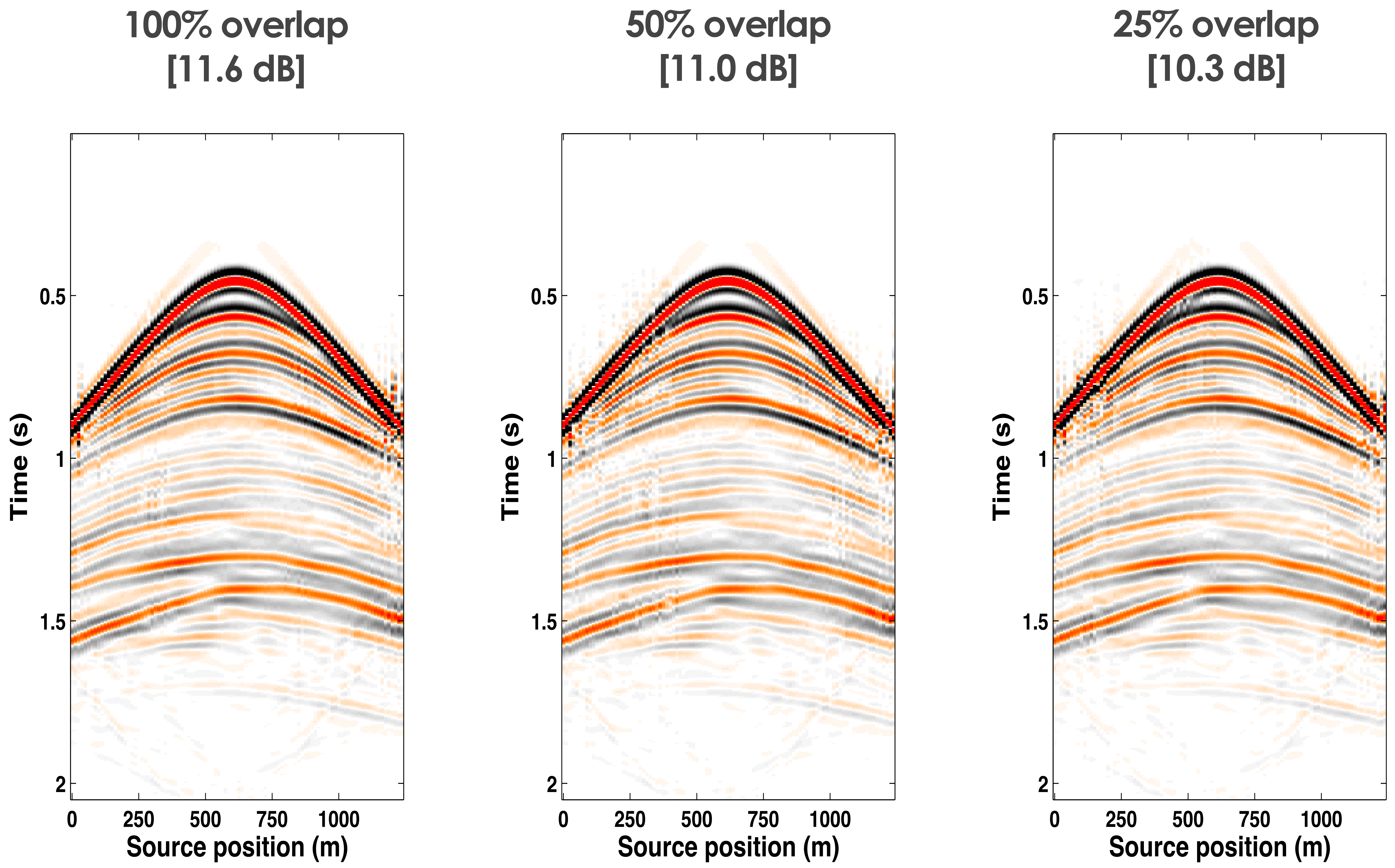


Monitor



Monitor recovery

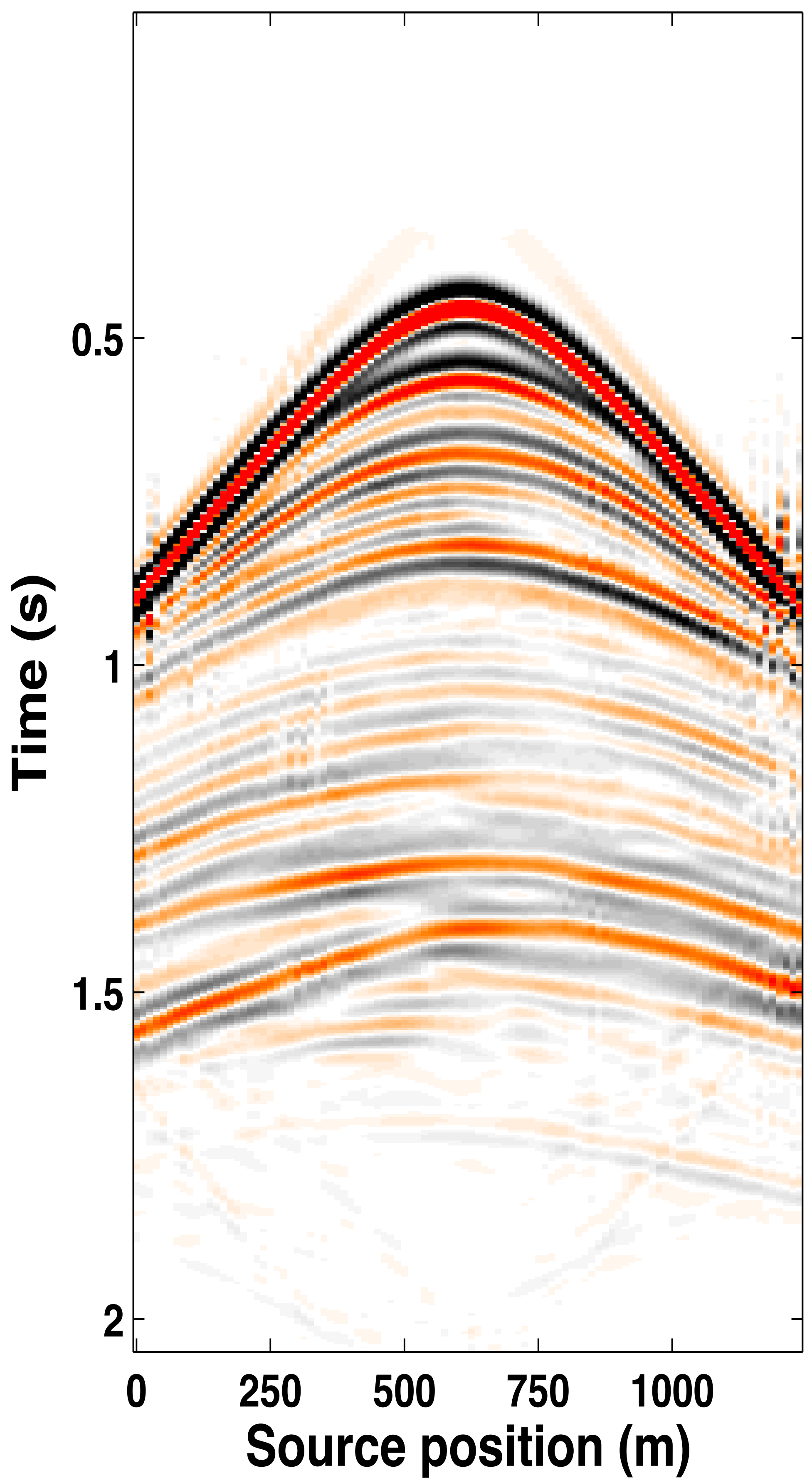
– Independent recovery



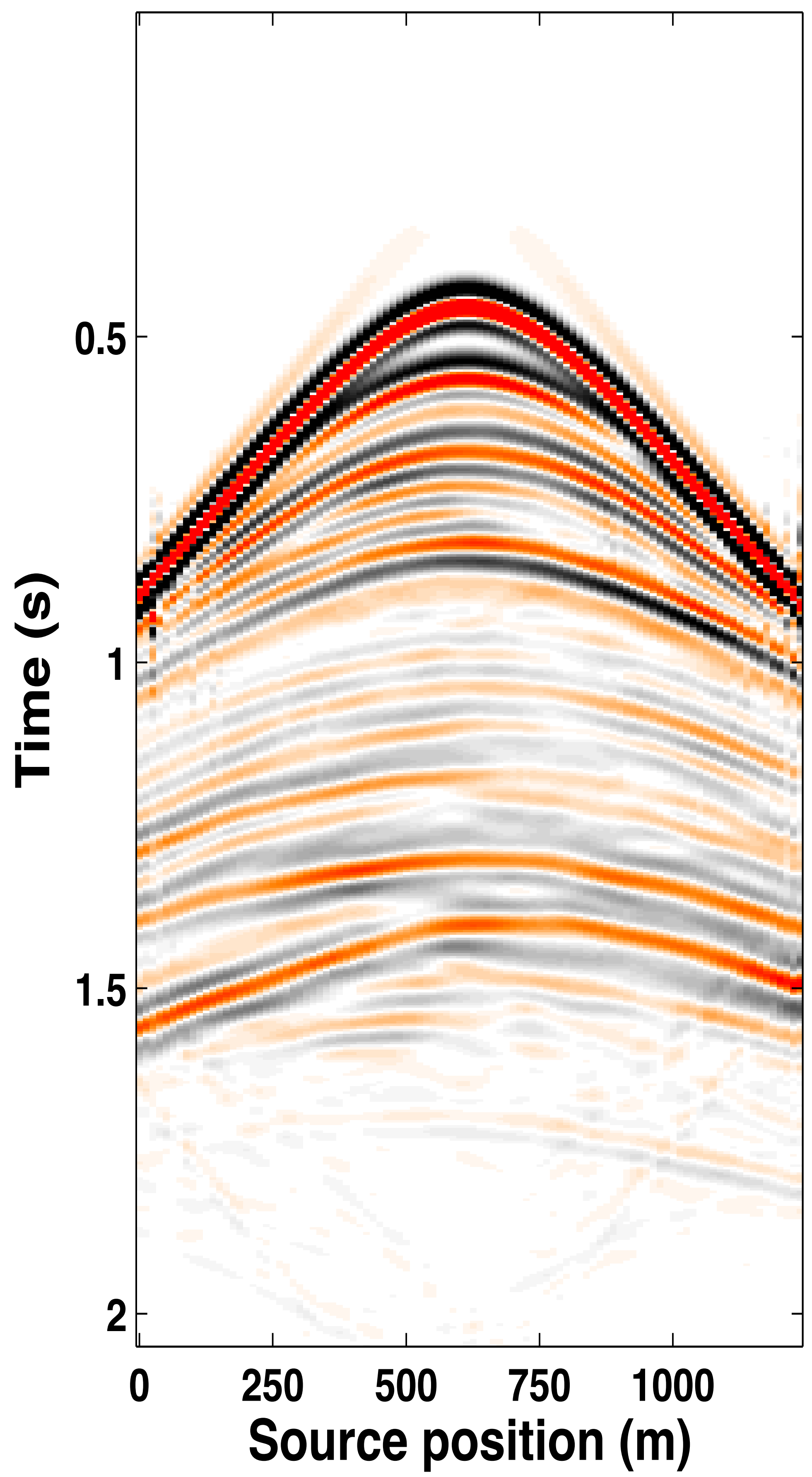
Monitor recovery

– Joint recovery

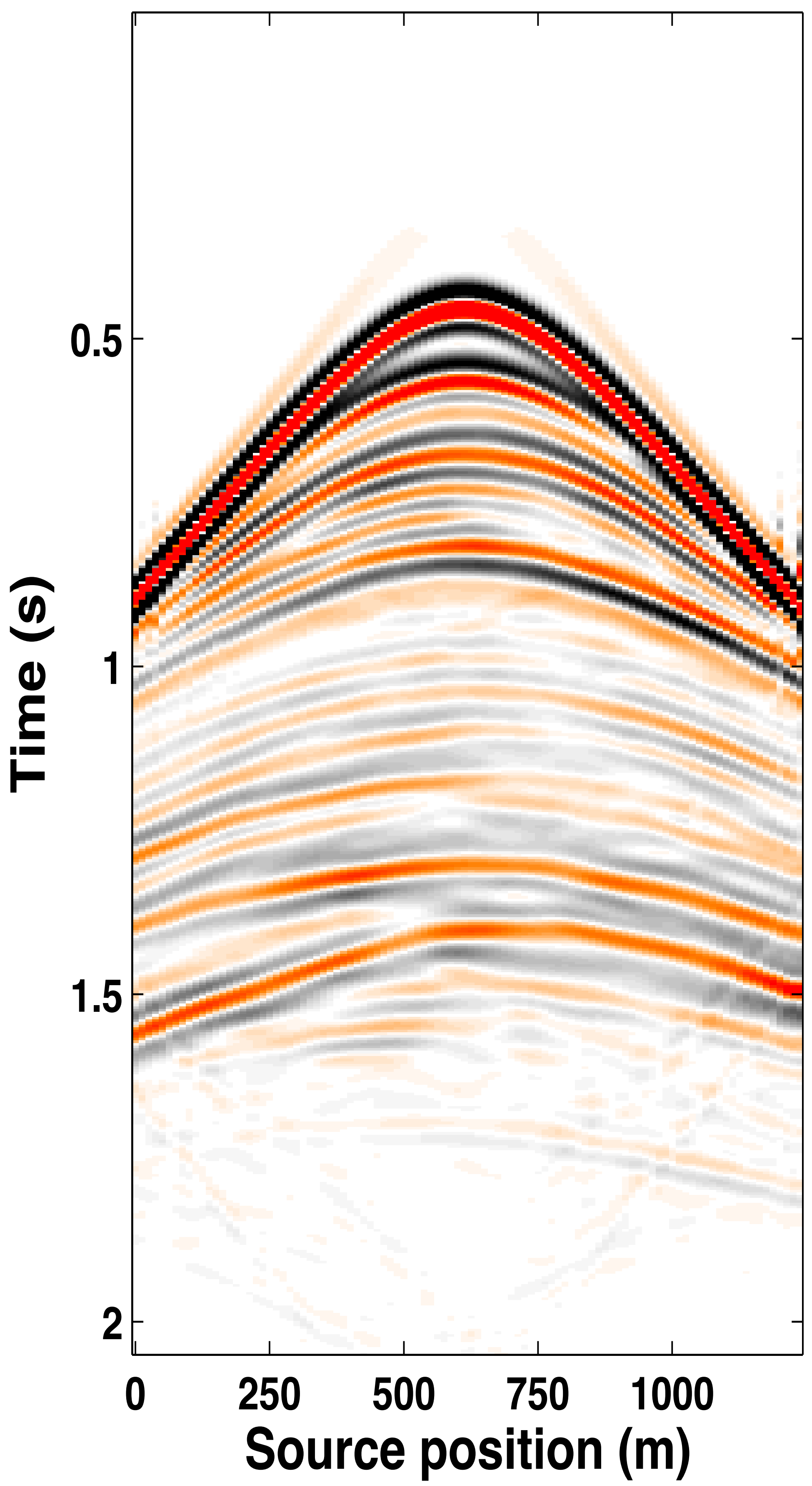
100% overlap
[11.6 dB]



50% overlap
[15.7 dB]

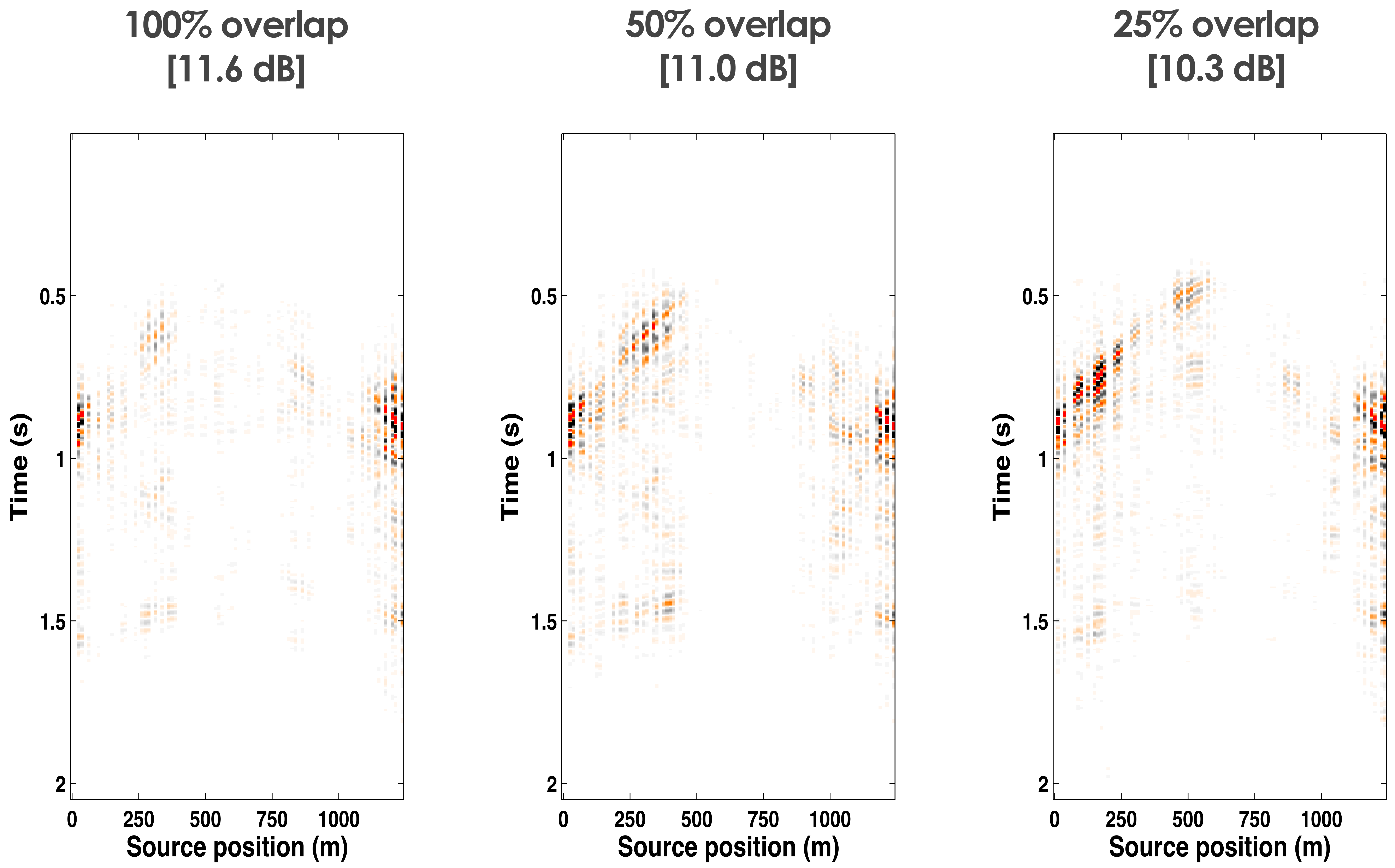


25% overlap
[18.6 dB]



Monitor residual

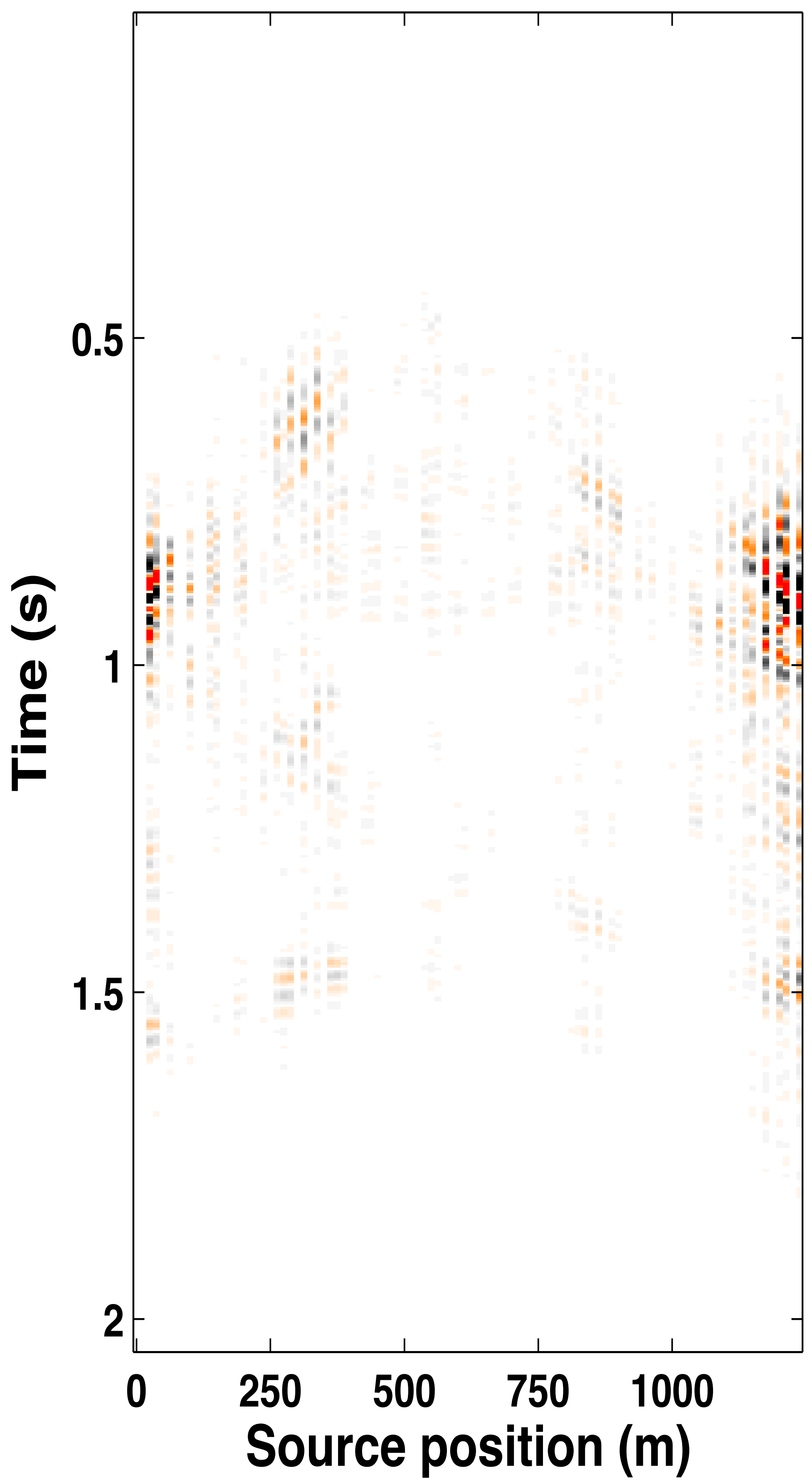
– Independent residual



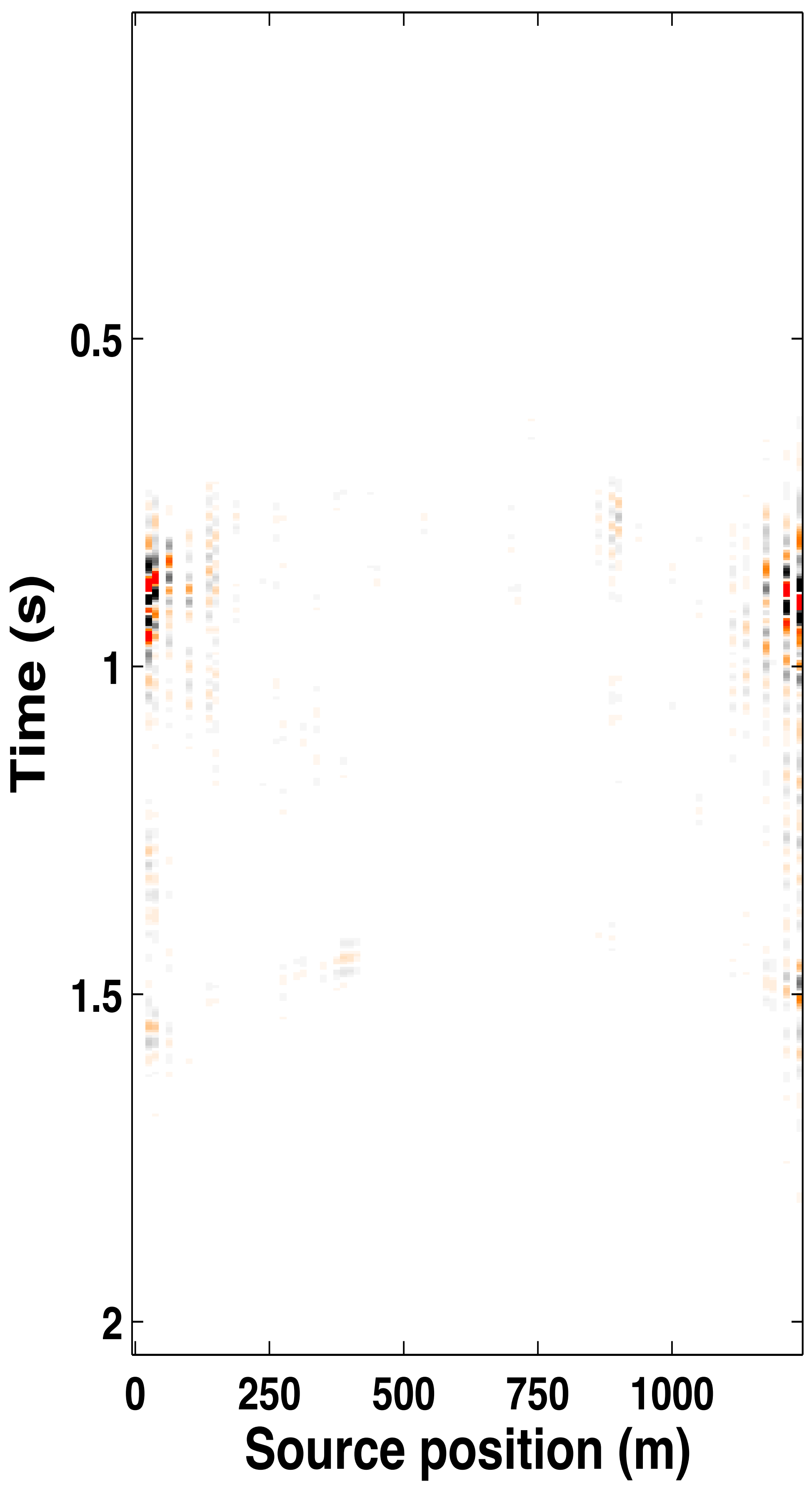
Monitor residual

– Joint residual

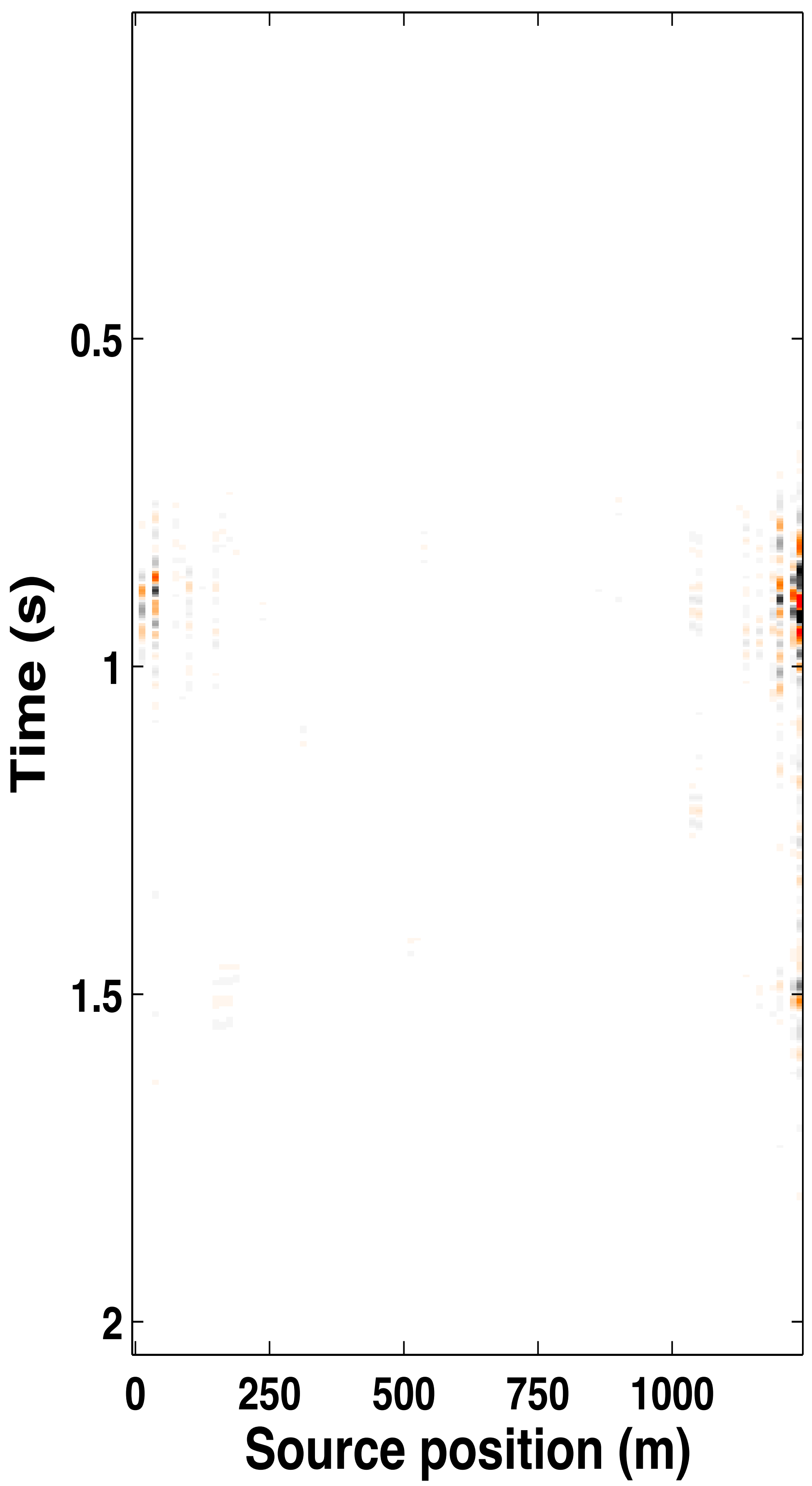
100% overlap
[11.6 dB]



50% overlap
[15.7 dB]



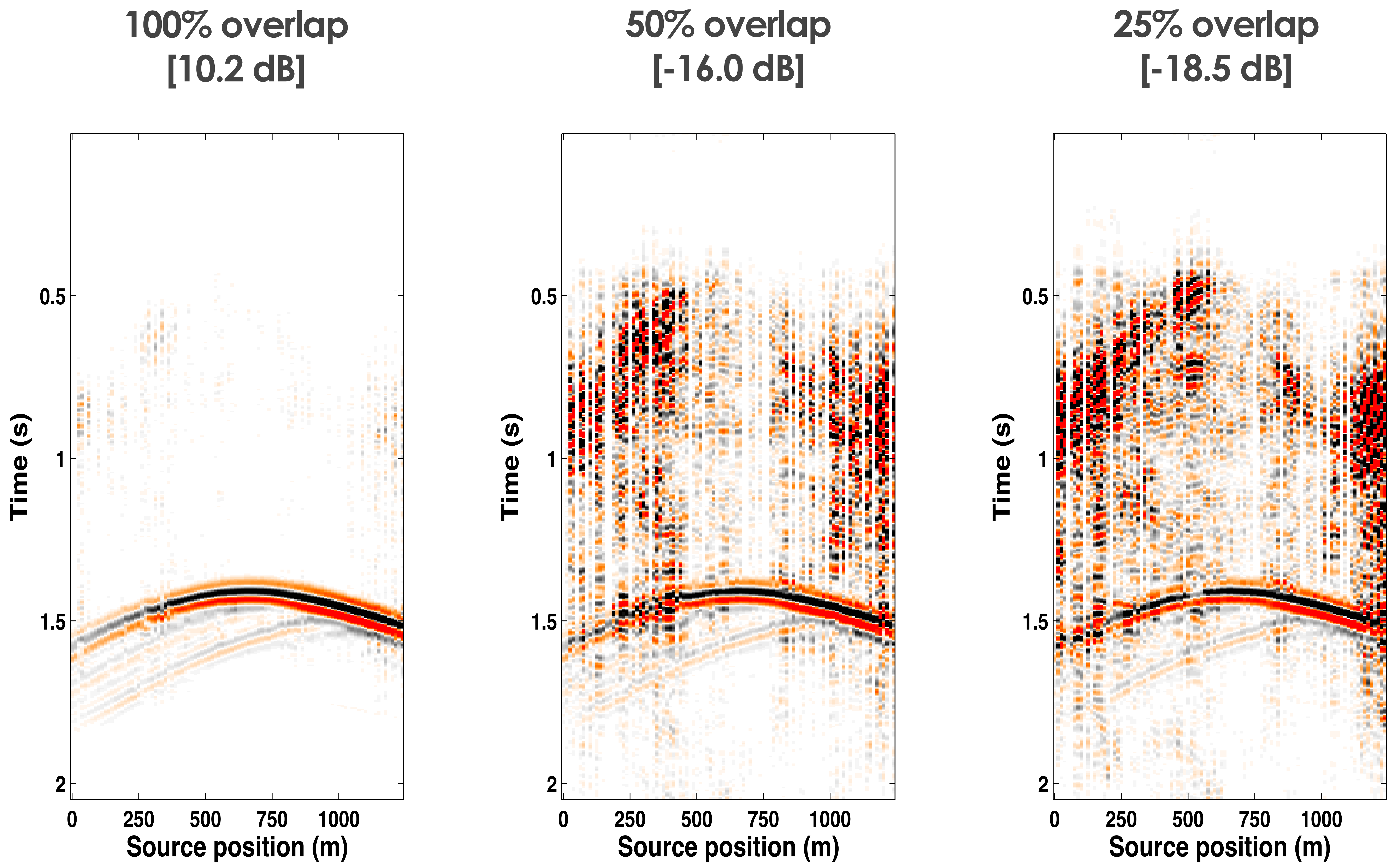
25% overlap
[18.6 dB]



4-D recovery

– Independent recovery

[colormap scale: 10 X]

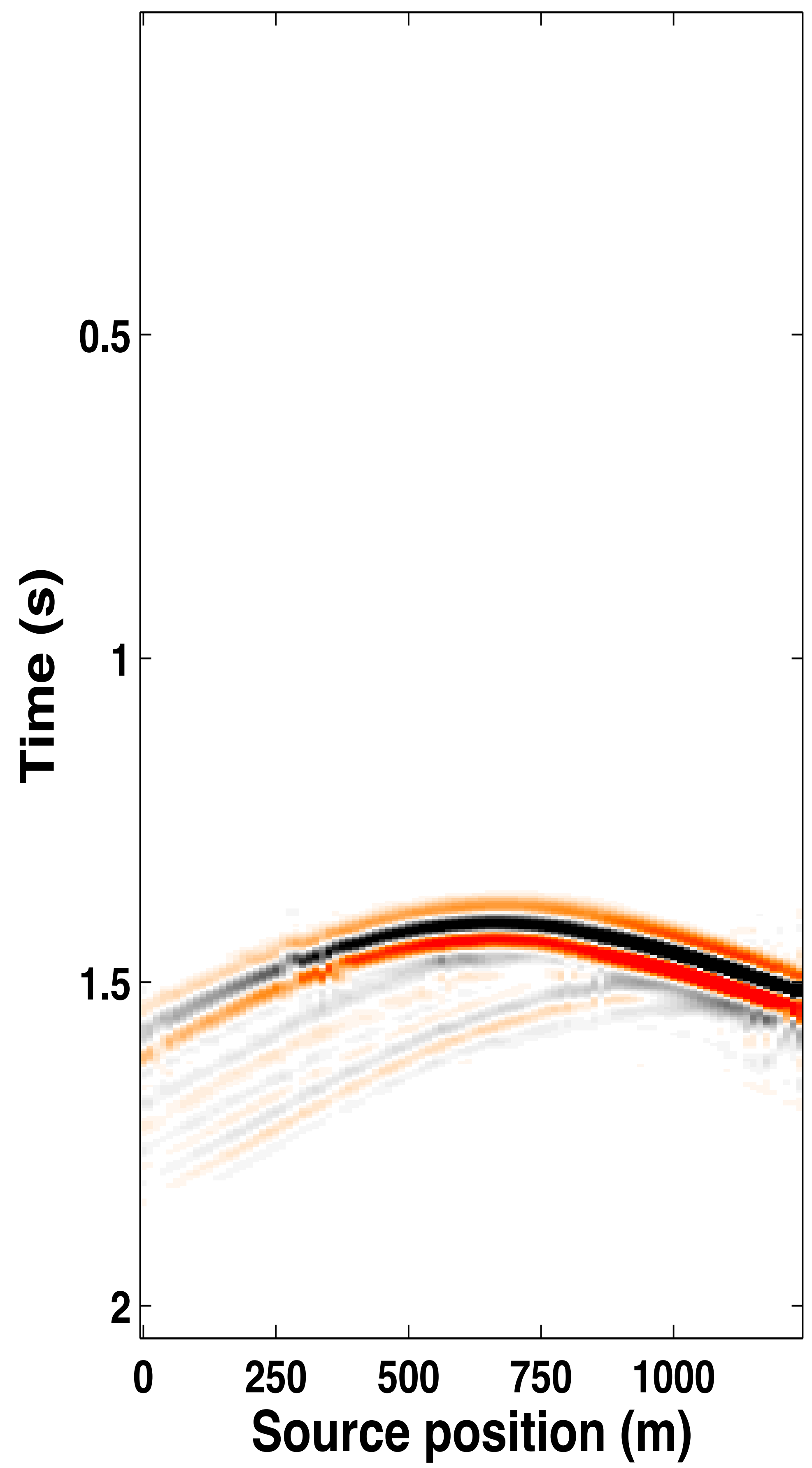


4-D recovery

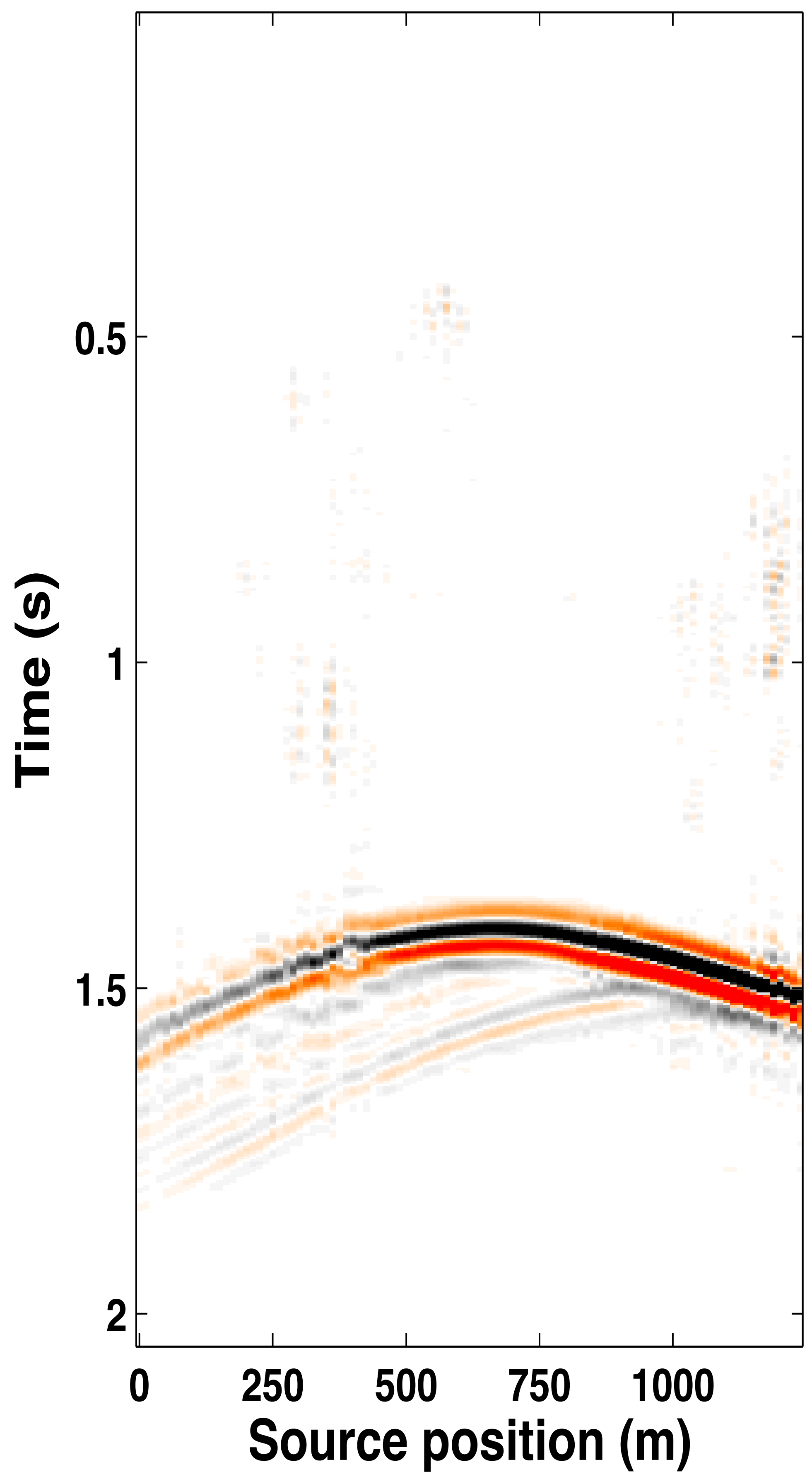
– Joint recovery

[colormap scale: 10 X]

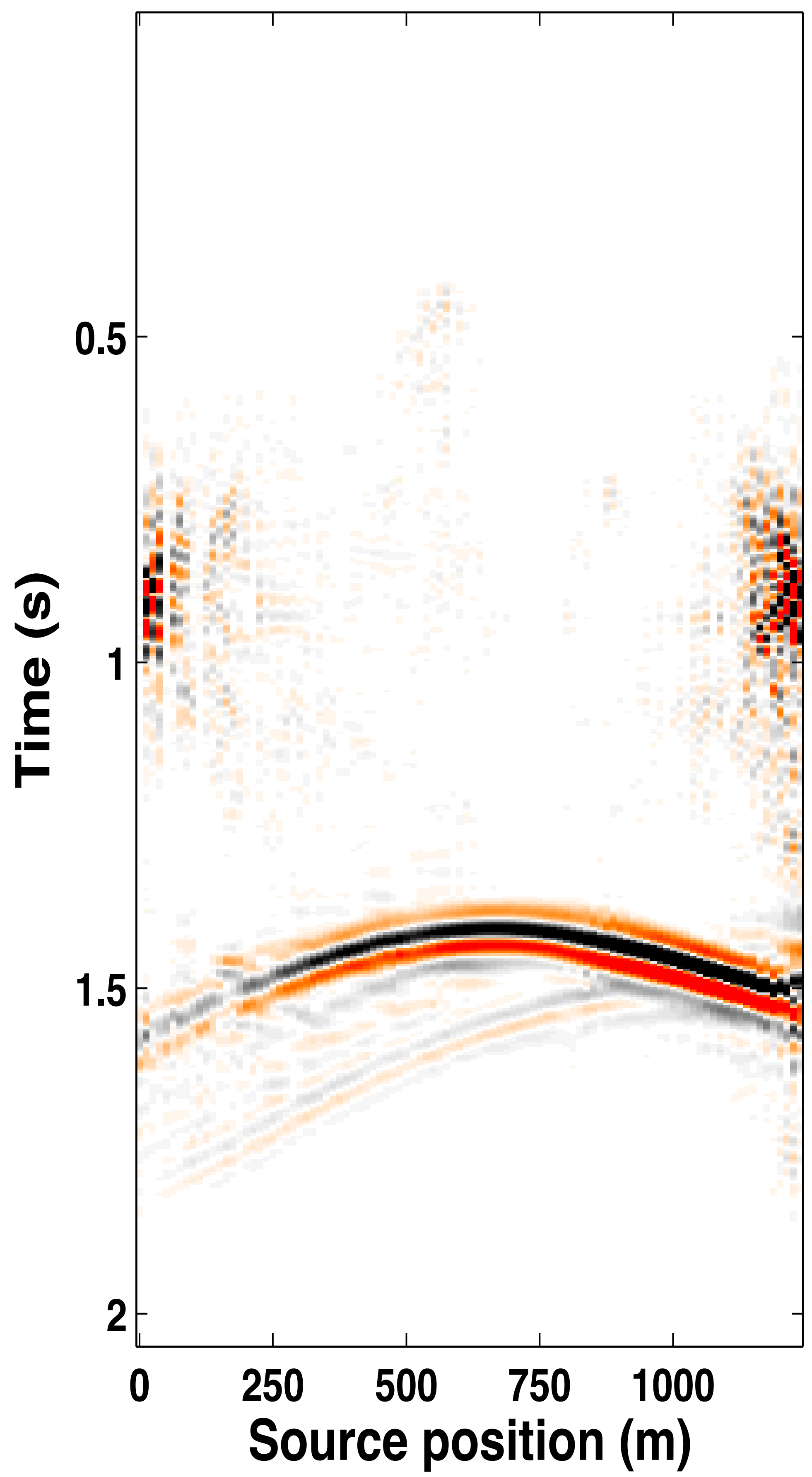
100% overlap
[12.8 dB]



50% overlap
[4.0 dB]



25% overlap
[-1.9 dB]



SLIM

Observations

Seismic synthetics show that we do ***not*** necessarily have to insist on full *repetition* depending on the recovery of the vintages

Questions:

Process/recover *independently* or *jointly* to exploit *common* features of surveys?

- processing *jointly* leads to *improved* recovery of ***both*** *vintages* & *time*-lapse signal

Should we *repeat* the surveys when doing *randomized sub*sampling?

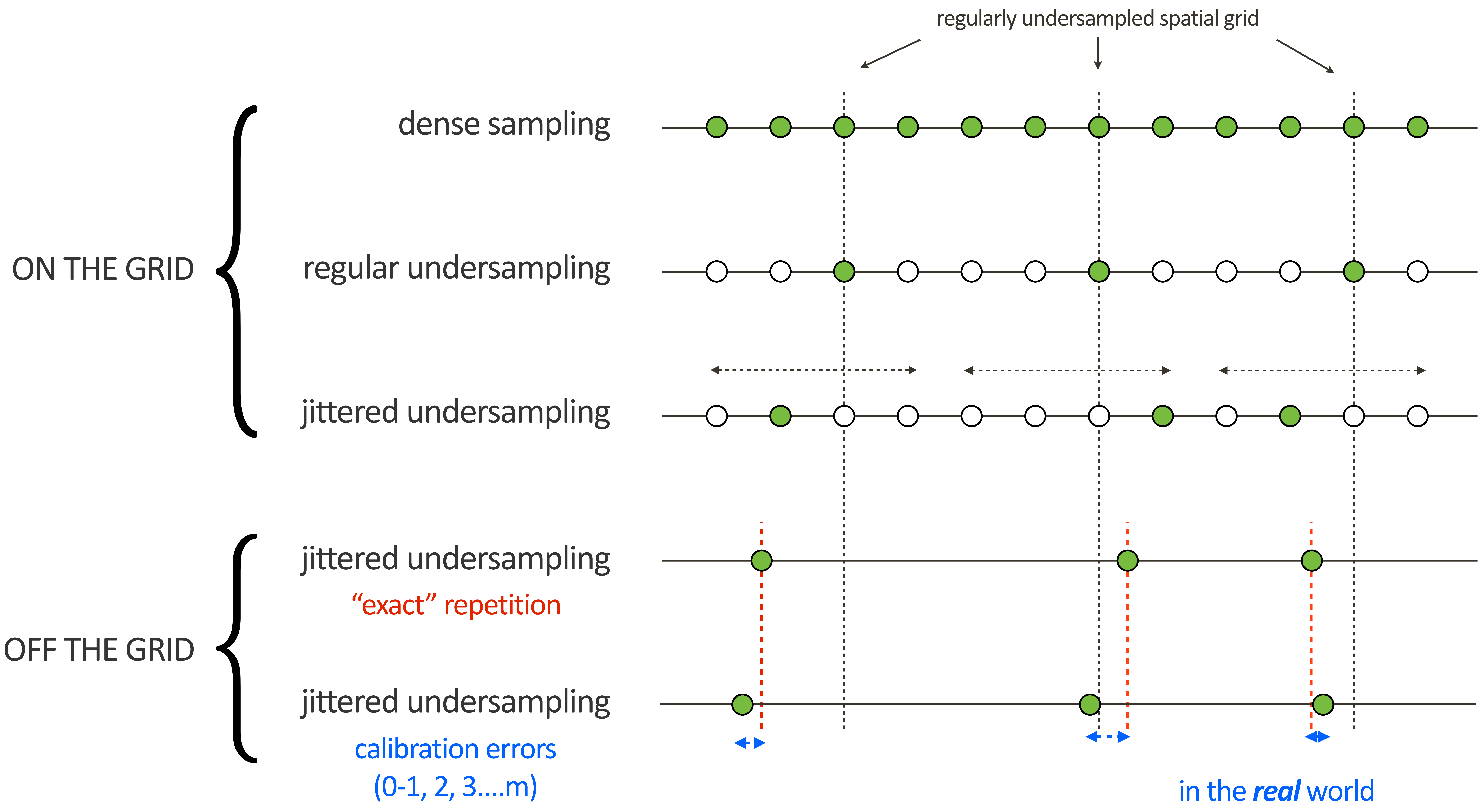
Is repetition "in-the-field" really possible?

Notion of repetition

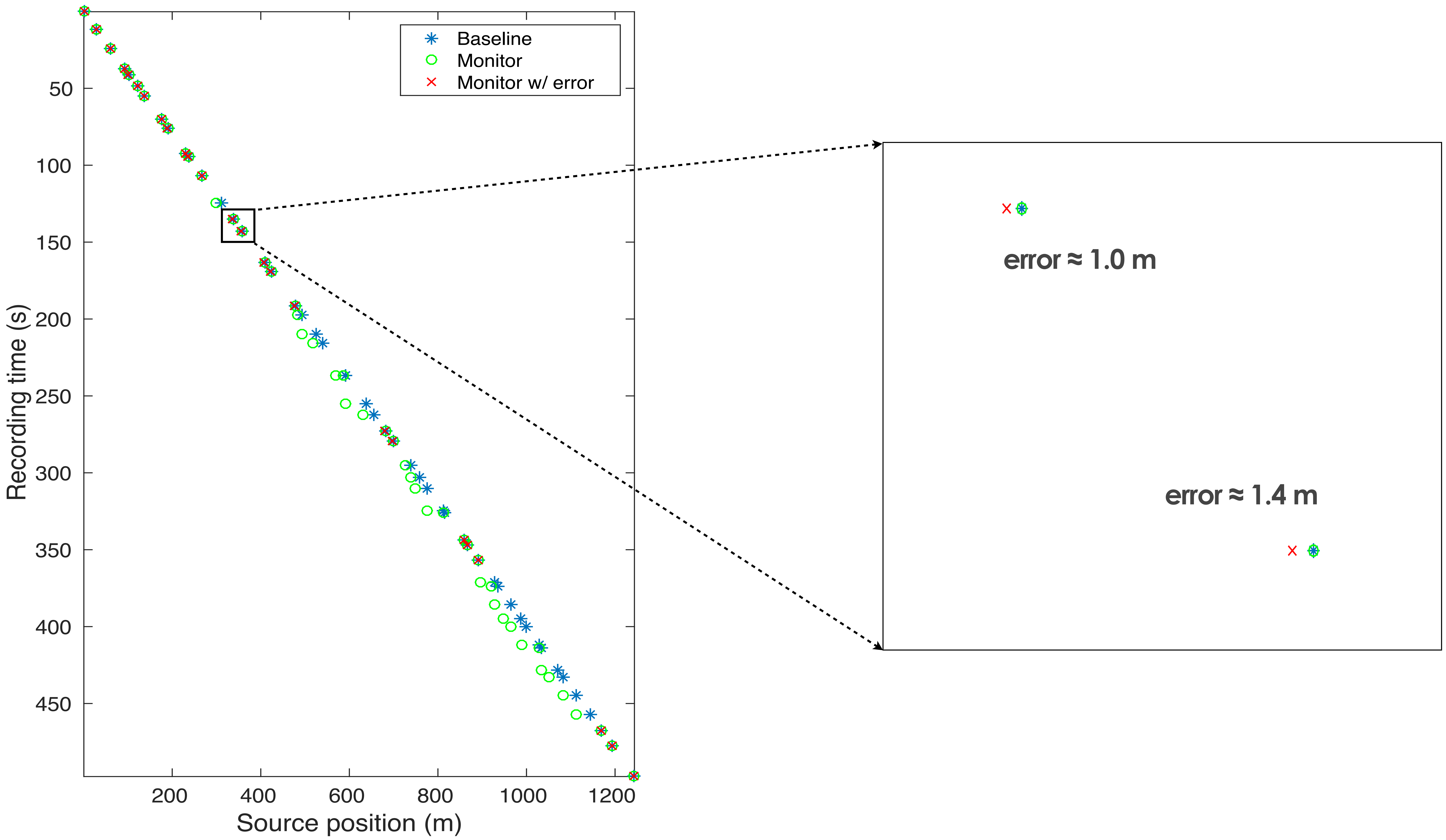
Time-jittered marine acquisition off the grid

With & without calibration errors

Randomized sampling in marine



4-D time-jittered marine acquisition

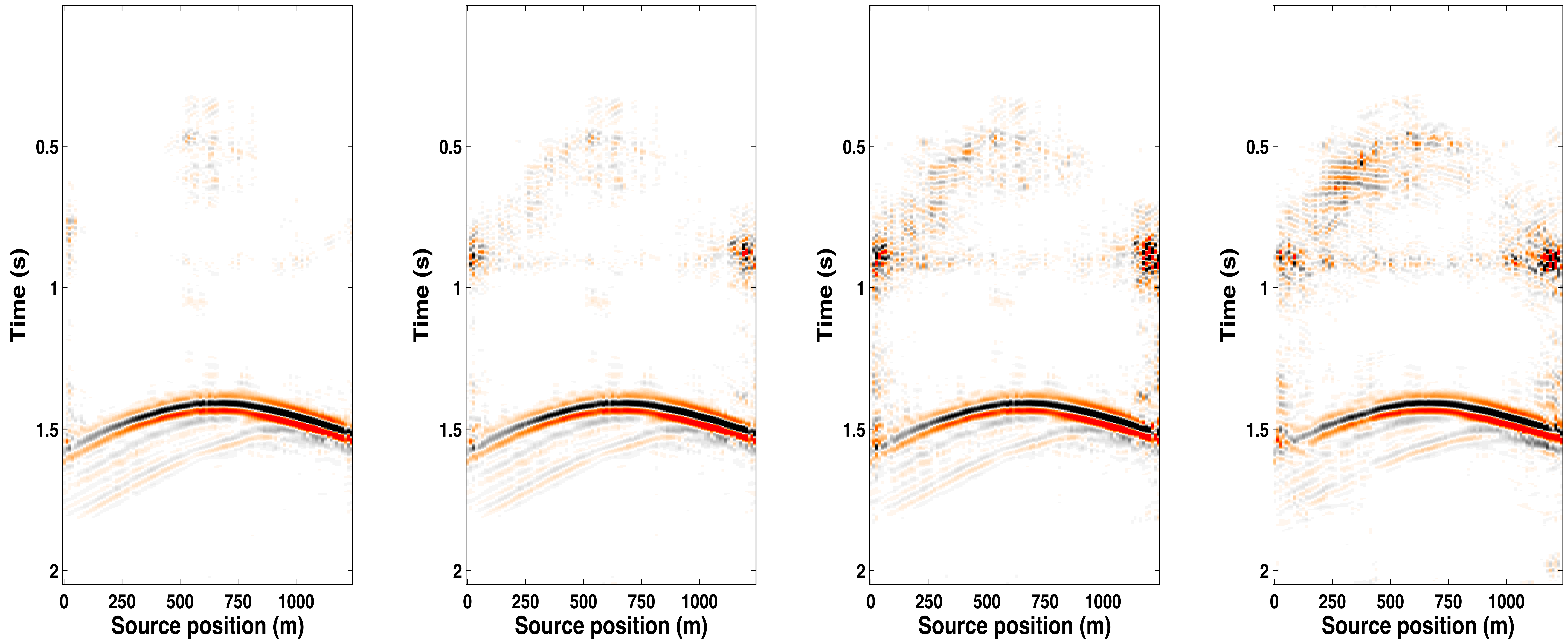


4-D recovery - JRM

– **50% overlap** in acquisition matrices

0% overlap

no error [12.2 dB] | error ≈ 1.0 m [8.5 dB] | error ≈ 2.8 m [3.8 dB] | [2.0 dB]



On the contrary,

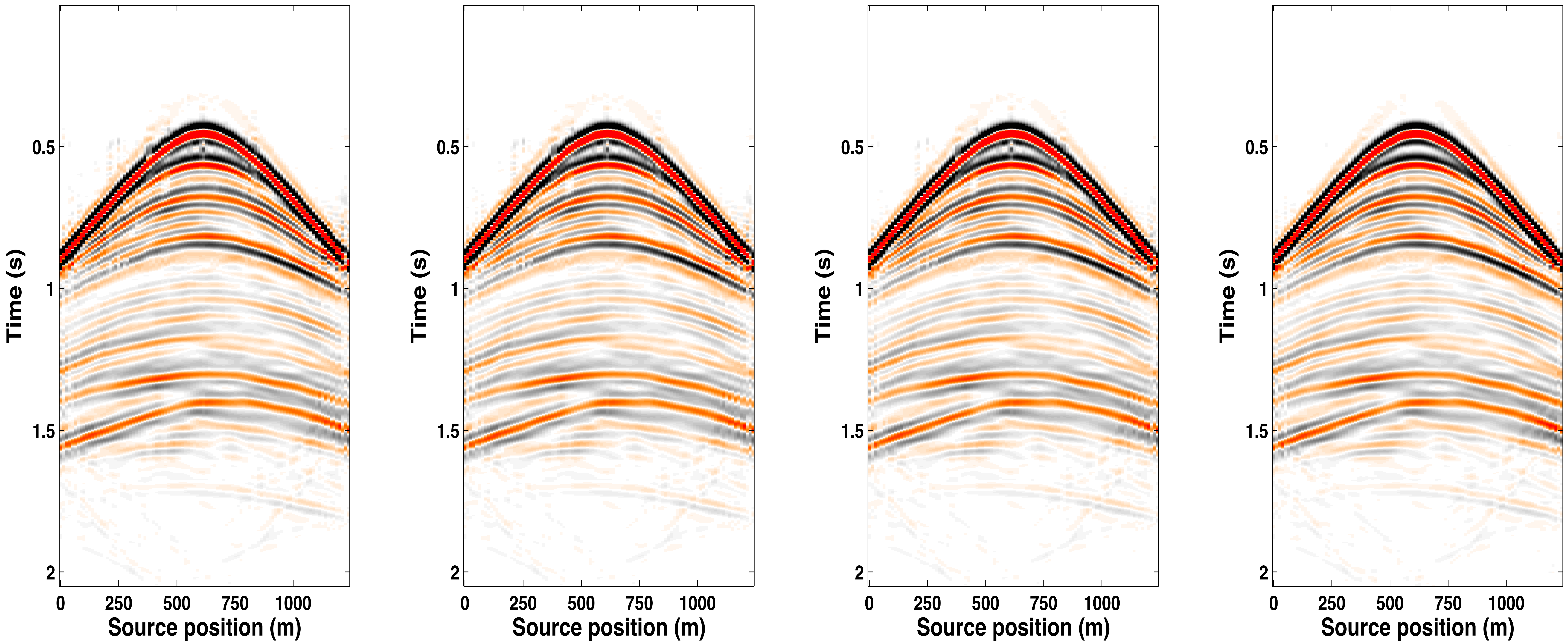
calibration errors improve recovery of the vintages!

Monitor recovery - JRM

– 50% overlap in acquisition matrices

0% overlap

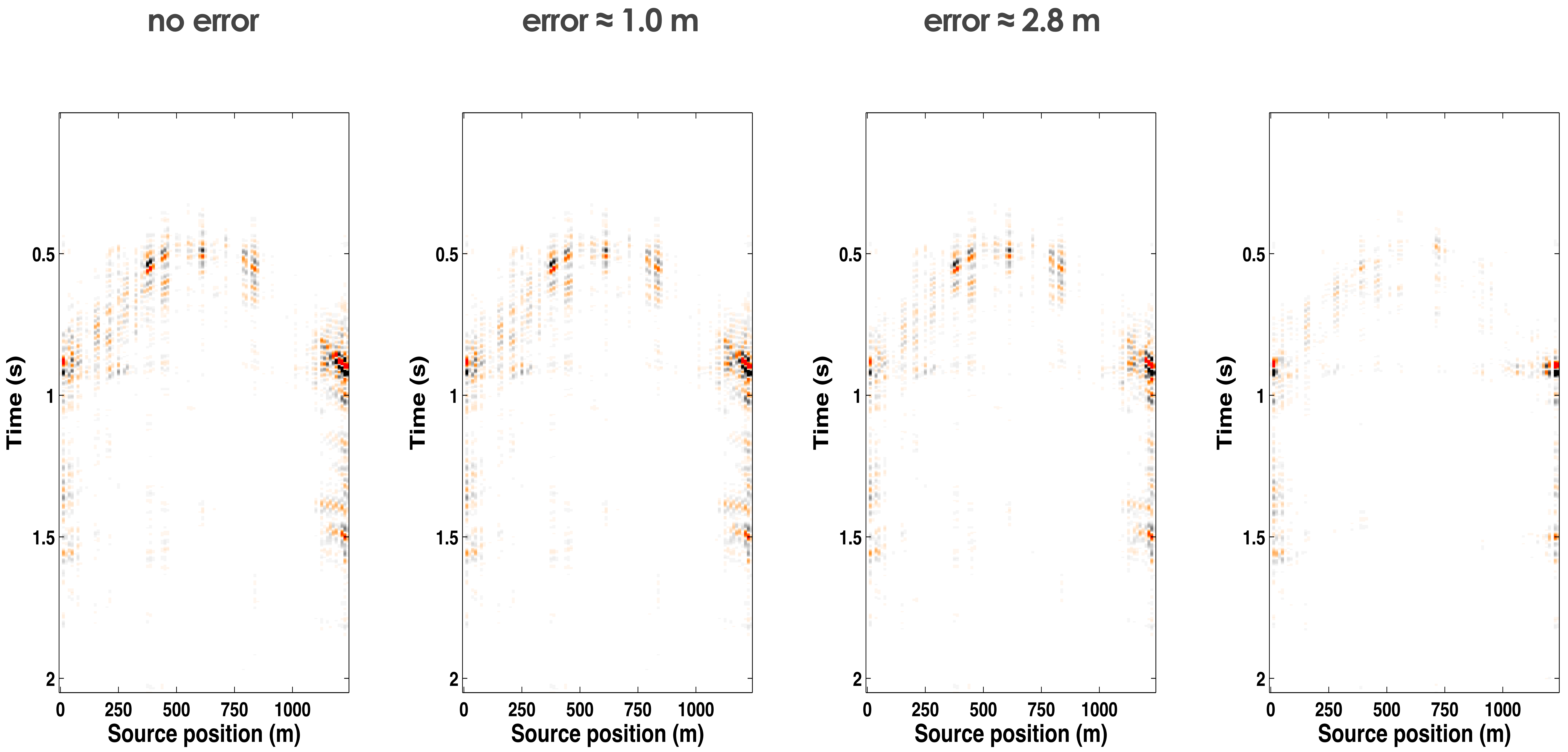
no error [13.9 dB]	error ≈ 1.0 m [14.5 dB]	error ≈ 2.8 m [15.5 dB]	[18.3 dB]



Monitor residual - JRM

– 50% overlap in acquisition matrices

0% overlap



SLIM

Observations

In the given context of randomized subsampling, calibration errors

- *deteriorate* recovery of the *time-lapse* signal
- *improve* recovery of the *vintages*

“Exact” repeatability of the surveys seems essential for good recovery of the time-lapse signal

Observations

Seismic synthetics show that we do ***not*** necessarily have to insist on full *repetition* depending on the recovery of the vintages

Questions:

Process/recover *independently* or *jointly* to exploit *common* features of surveys?

- processing *jointly* leads to *improved* recovery of ***both*** *vintages & time*-lapse signal

Should we *repeat* the surveys when doing *randomized sub*sampling?

- no, as long as one samples *sufficiently* to recover *both vintages* jointly
- calibration errors do *not* allow "*exact*" repeatability which is essential for good recovery of the time-lapse signal

Future work

Application to field datasets

Software release: *Time-jittered marine acquisition "off-the-grid"*

Acknowledgements

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