Source separation for simultaneous towed-streamer acquisition via compressed sensing

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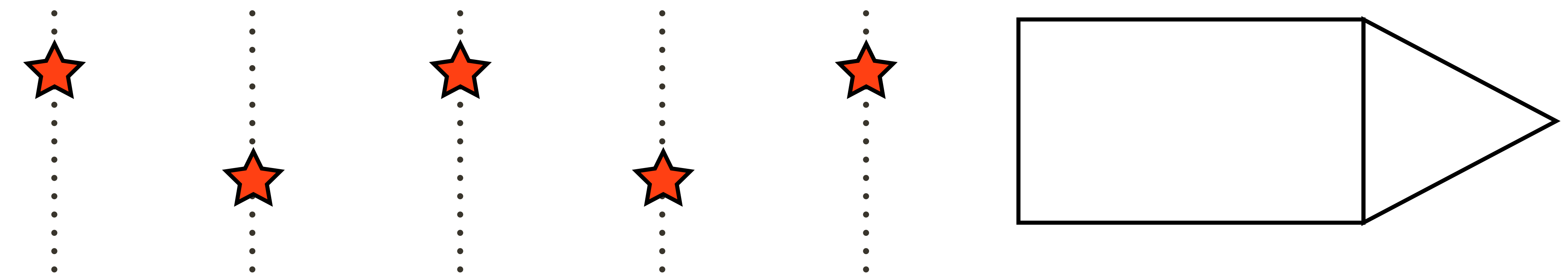
Periodic vs. jittered marine acquisition

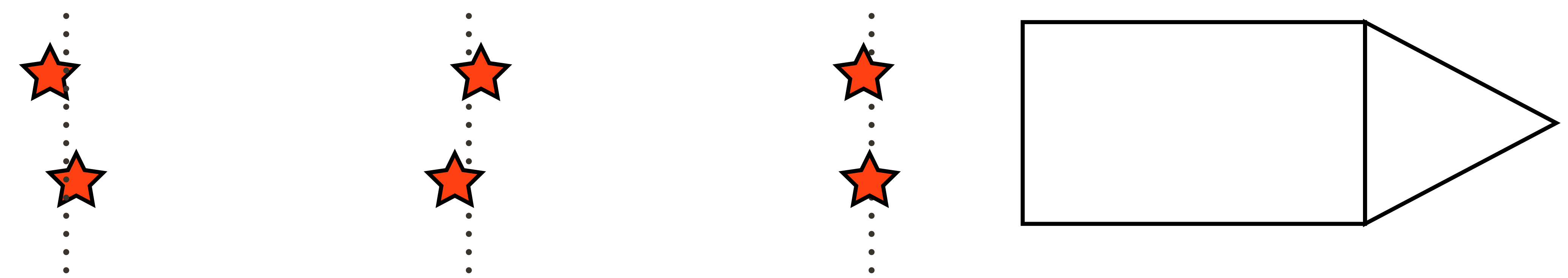
shot-time randomness

periodically sampled spatial grid



NONE

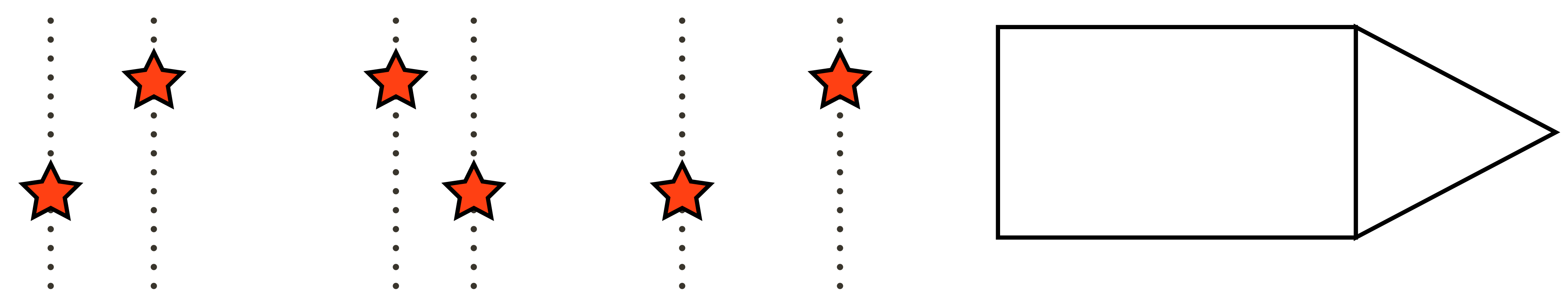
almost periodically sampled spatial grid
(over/under acquisition, towed arrays)



LOW

randomly jittered sampled spatial grid
(Time-jittered acquisition, OBC/OBN)

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

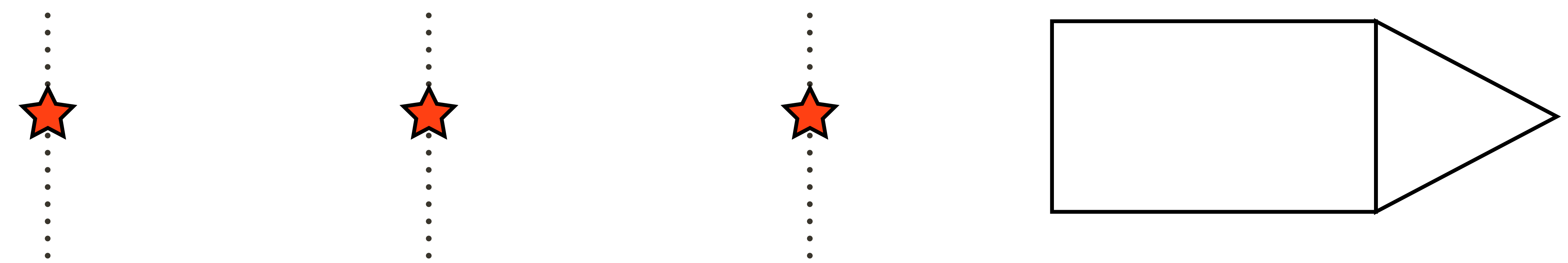


HIGH

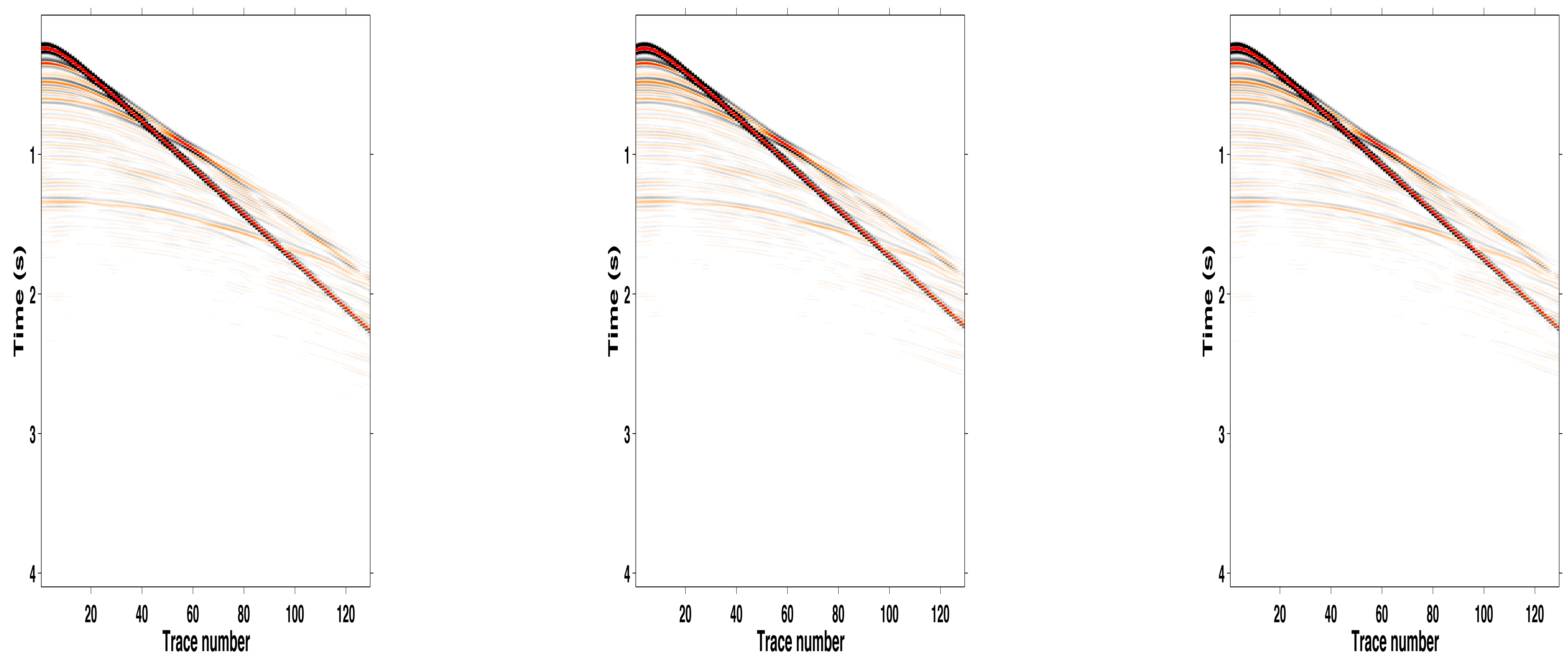
Conventional marine acquisition

shot 1 shot 2 shot 3

periodically sampled spatial grid



shot 1 shot 2 shot 3

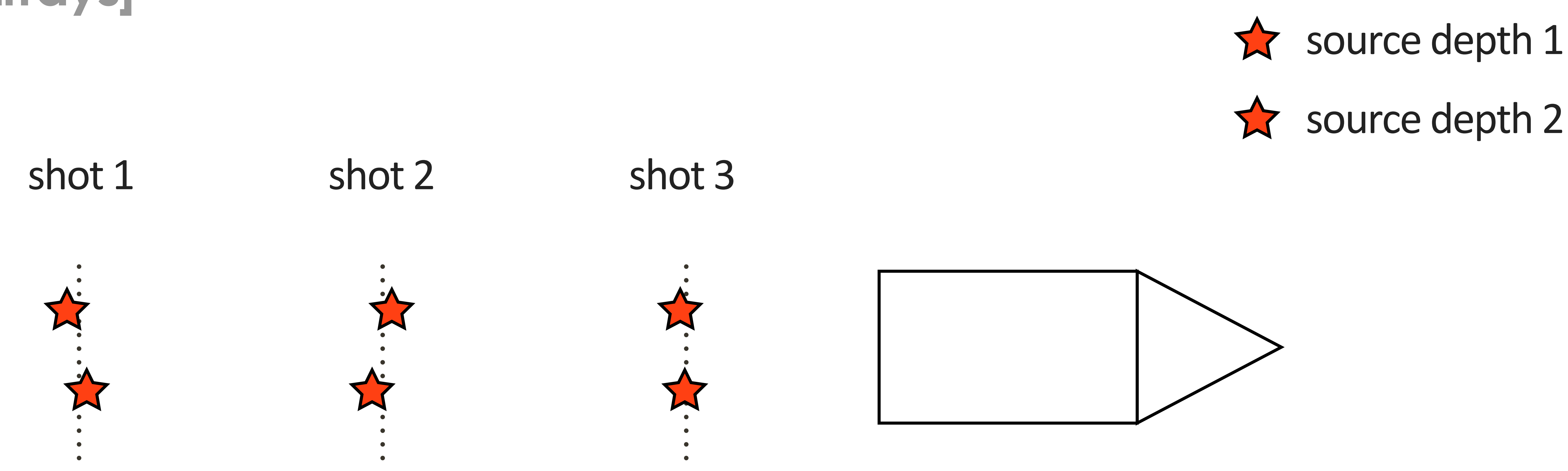


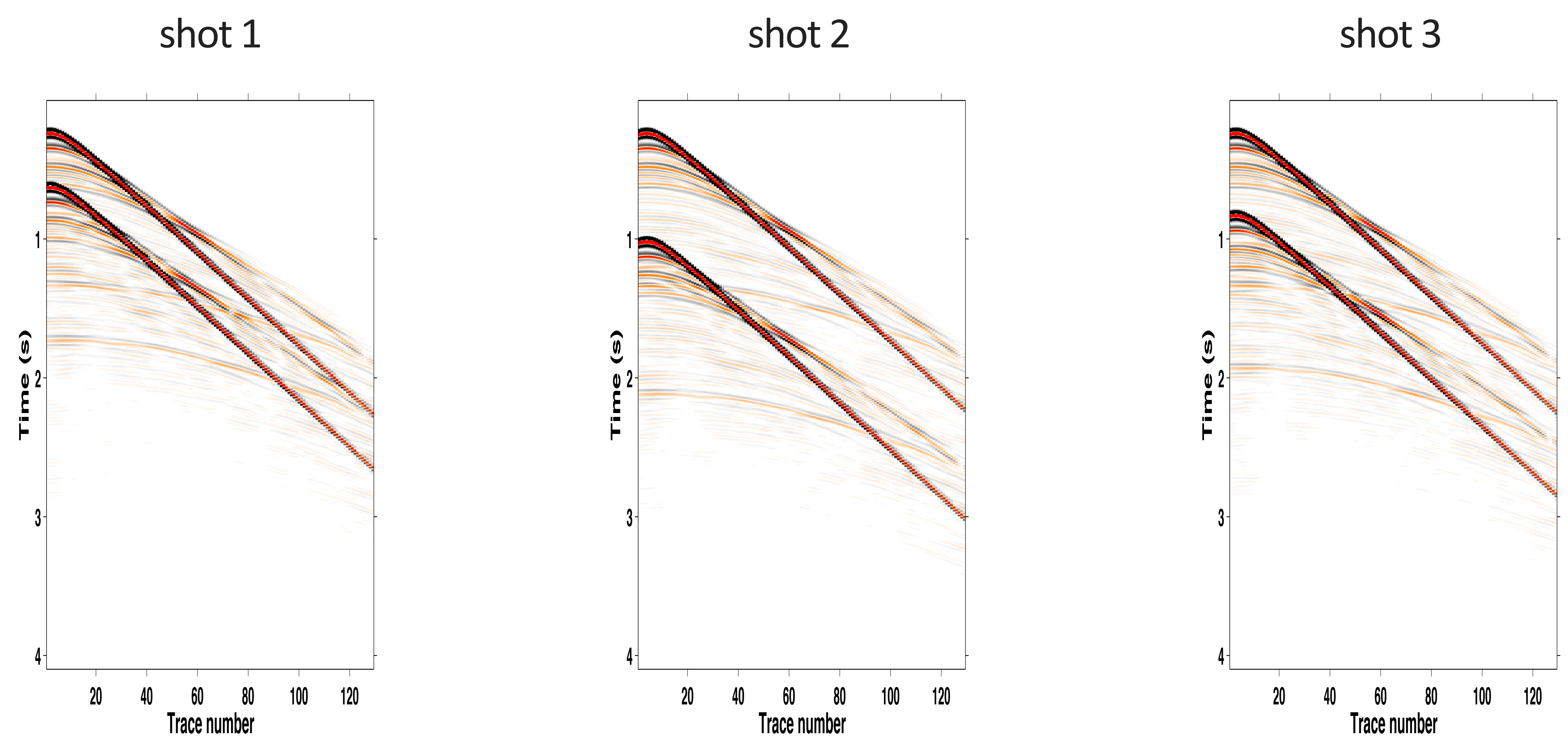
Simultaneous marine acquisition

[over/under acquisition, towed arrays]

almost periodically sampled spatial grid

shot-time randomness - **LOW**





Challenges

Source separation (or *deblending*)

- recover individual datasets

Shot-time randomness

- low

[Candès and Donoho, 2000; Hennenfent and Herrmann, 2008; Herrmann, 2010]

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*

[Candès and Plan, 2009; Oropeza and Sacchi, 2011]

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)*

[Kumar et. al., 2015a]

Low-rank structure

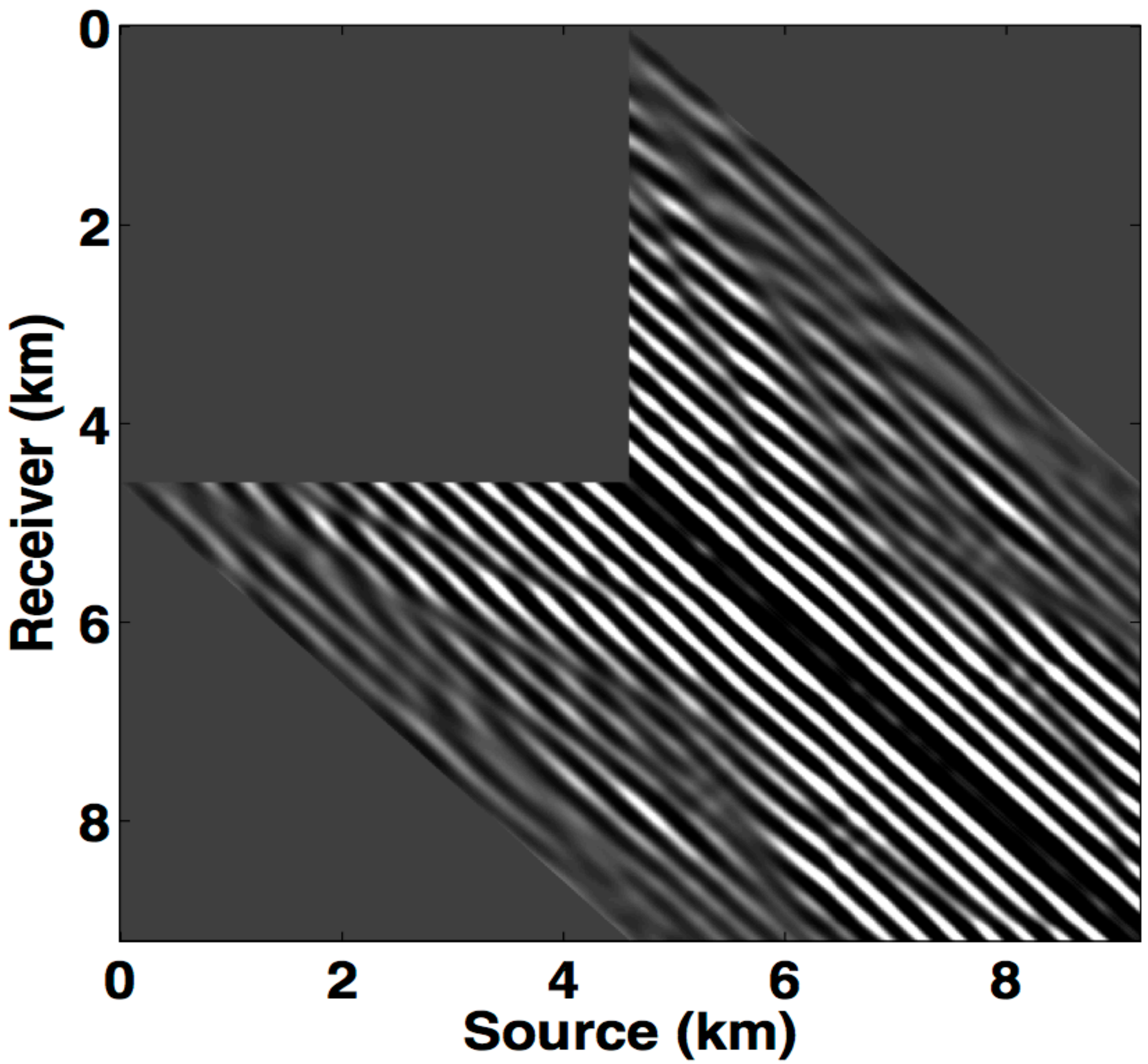
In which domain?

source-receiver or *midpoint-offset*

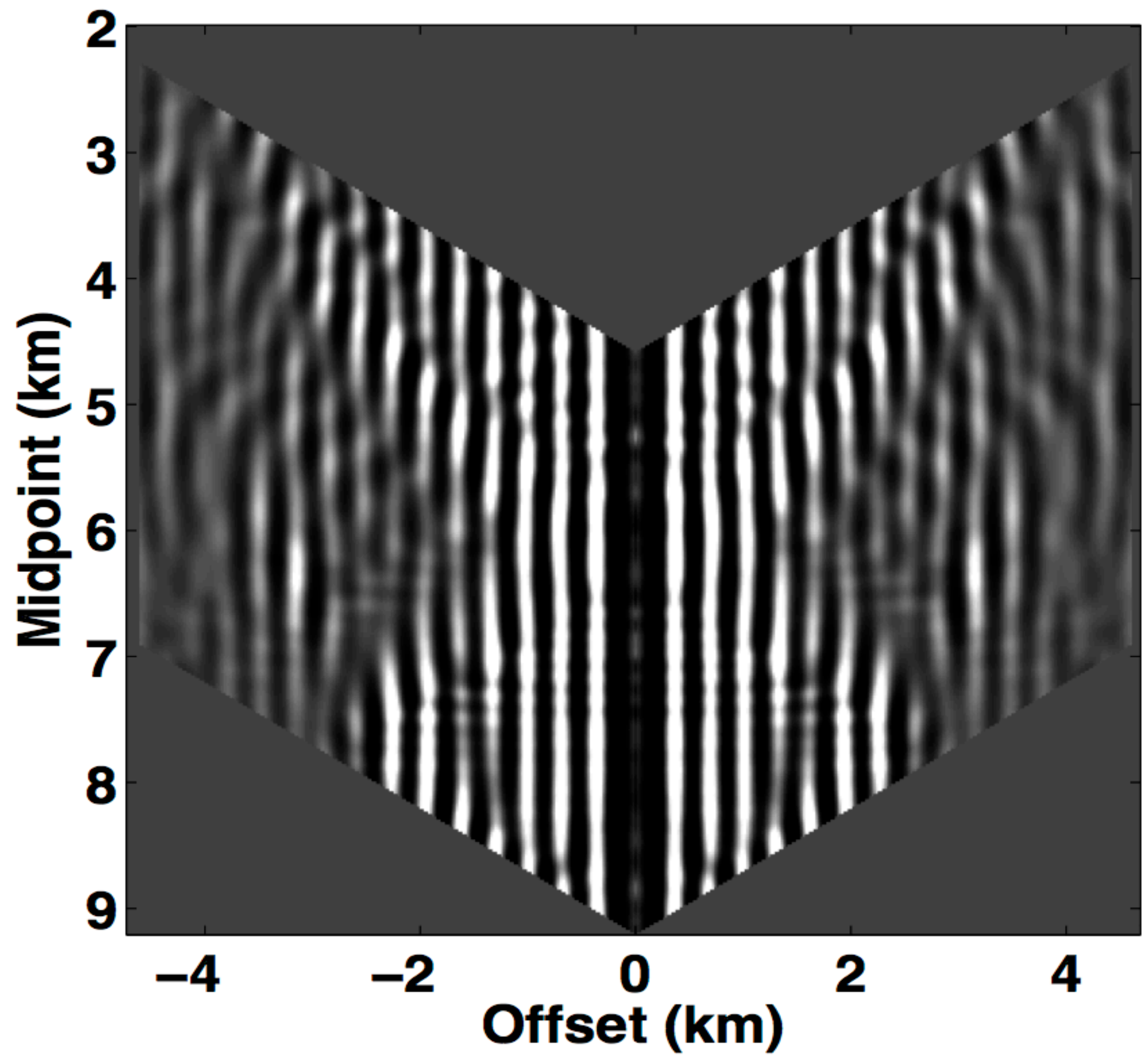
In which domain?

[frequency slice at 5 Hz]

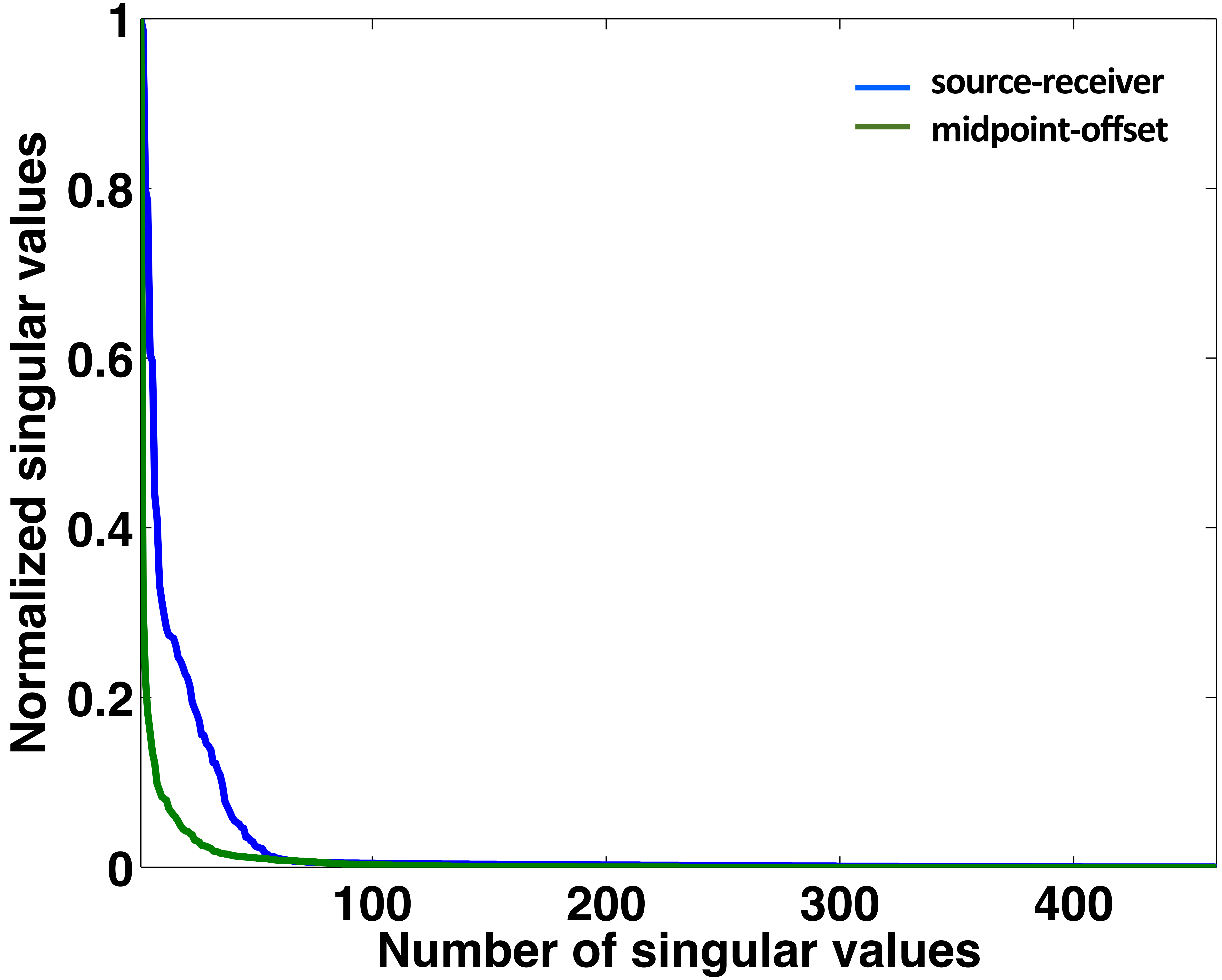
source-receiver domain
(with reciprocity)



midpoint-offset domain
(with reciprocity)



Decay of singular values



low-rank in midpoint-offset domain

Rajiv Kumar, Haneet Wason and Felix J. Herrmann, 2015. "**Source separation for simultaneous towed-streamer marine acquisition---a compressed sensing approach**", *Geophysics*, 80, WD73-WD88.

Sampling scheme

sample to *break* the structure

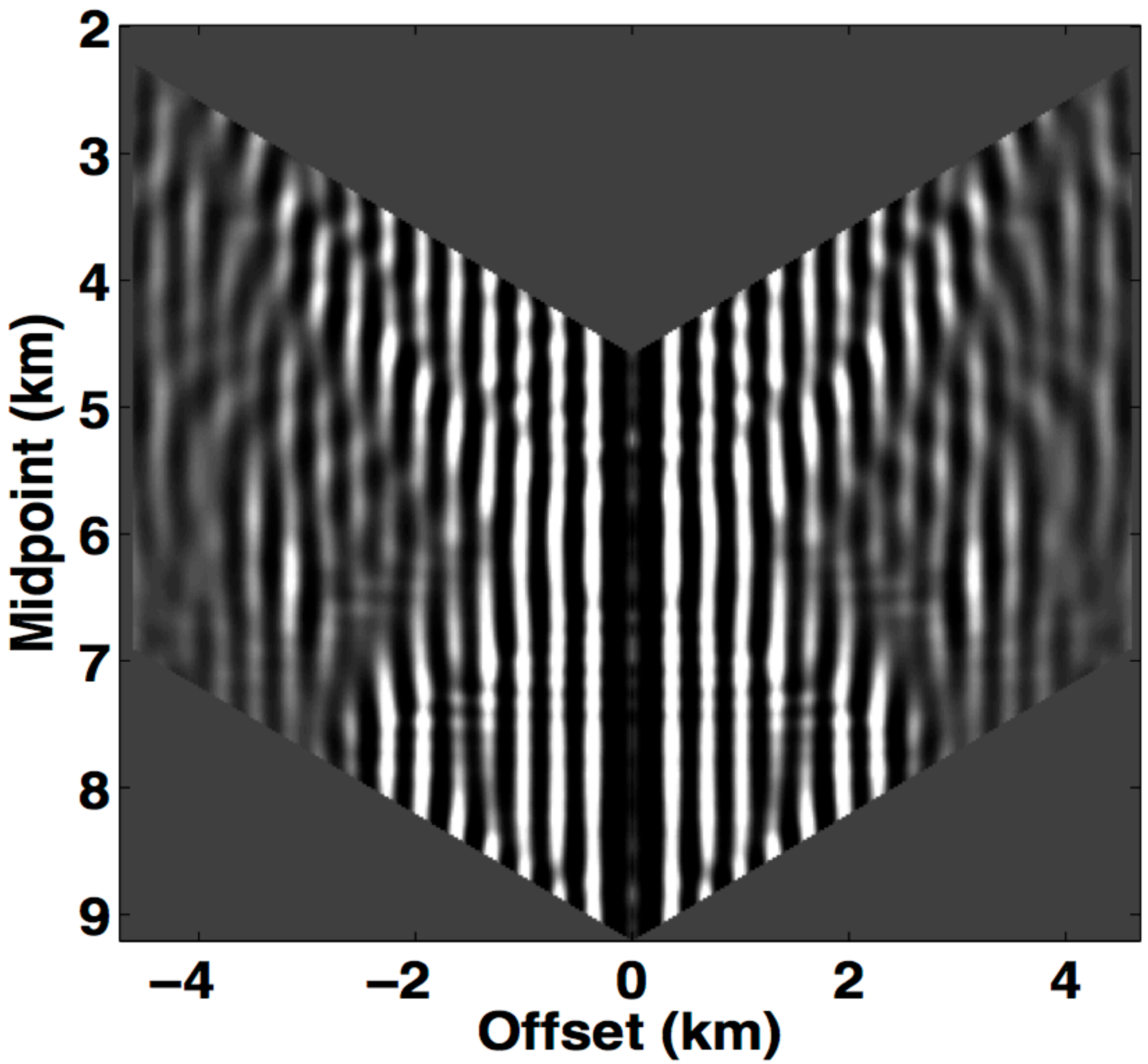
random time delays break the structure

How to destroy the structure?

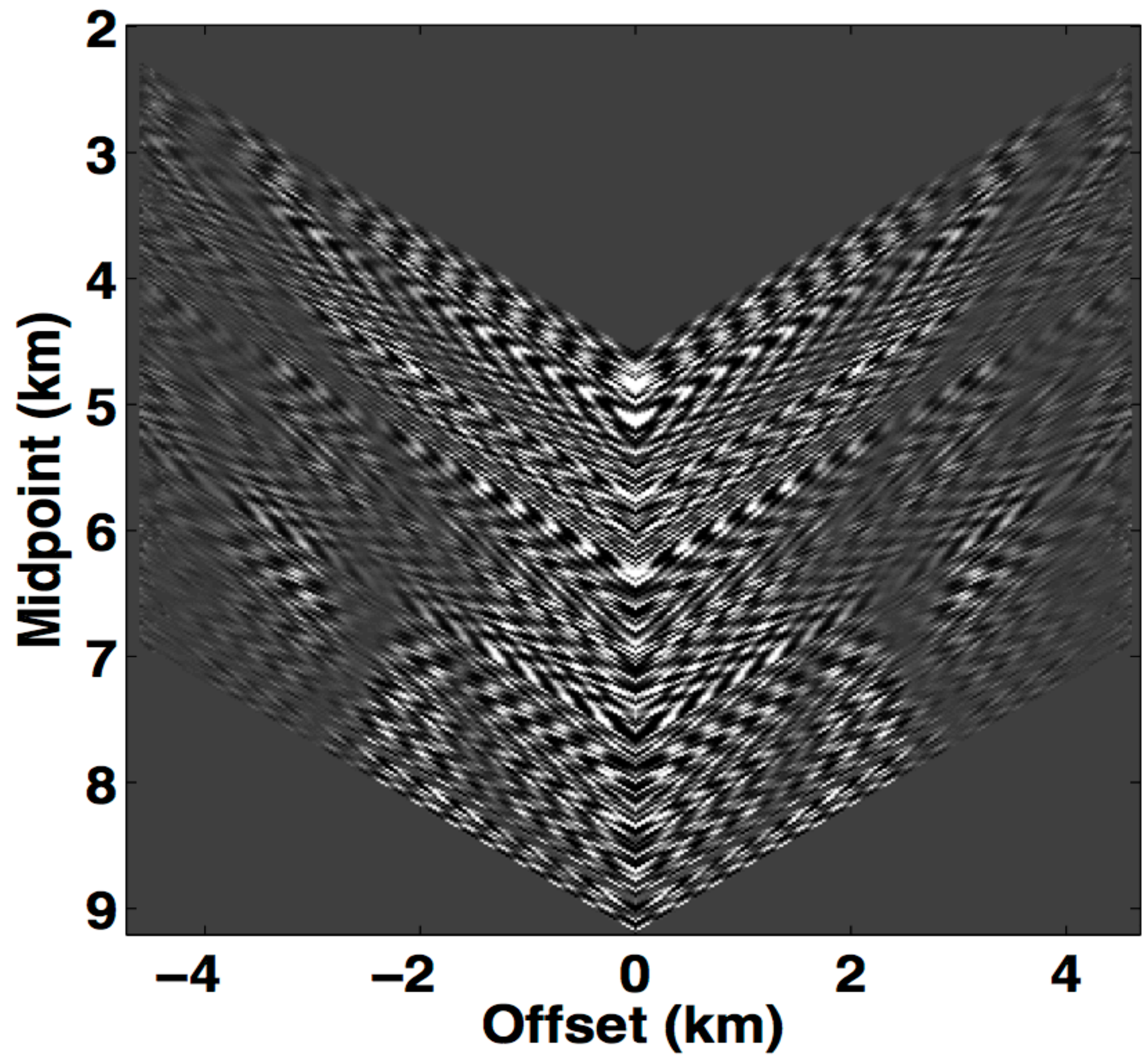
- add random time delays

no missing traces!

without delays

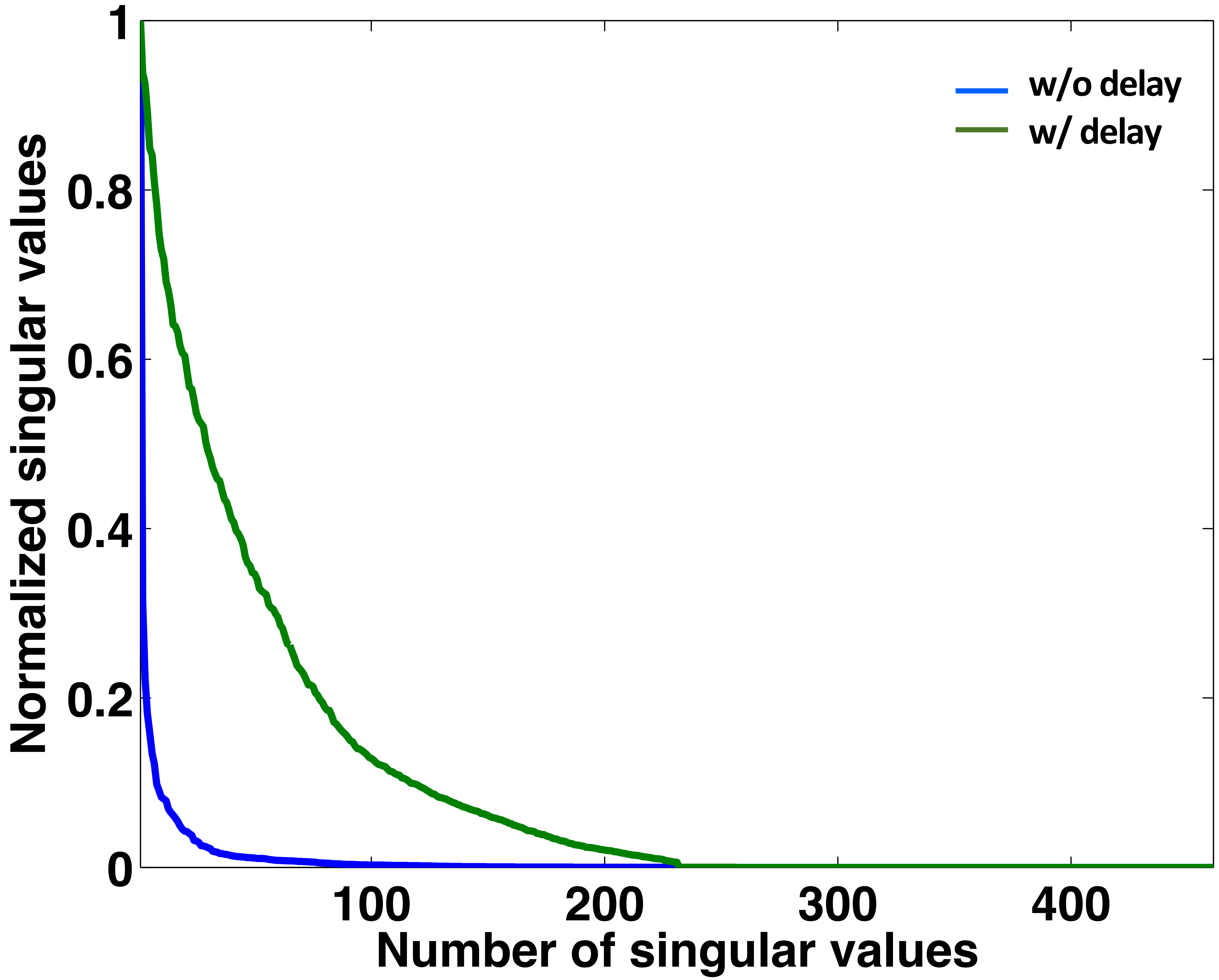


with random delays (< 1s)



Decay of singular values

[midpoint-offset domain]



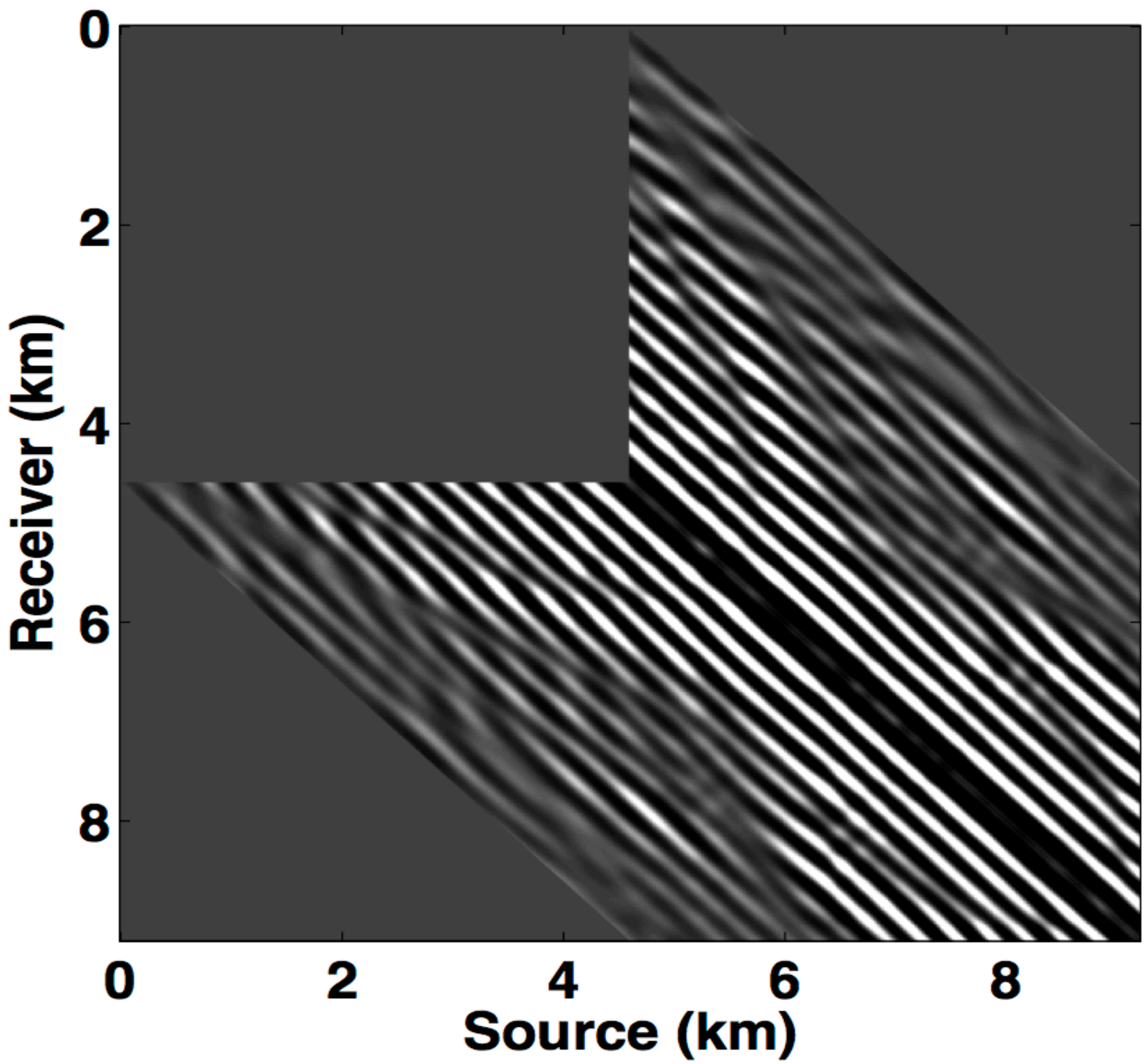
random time delays increase the rank

Do high frequencies have low-rank structure?

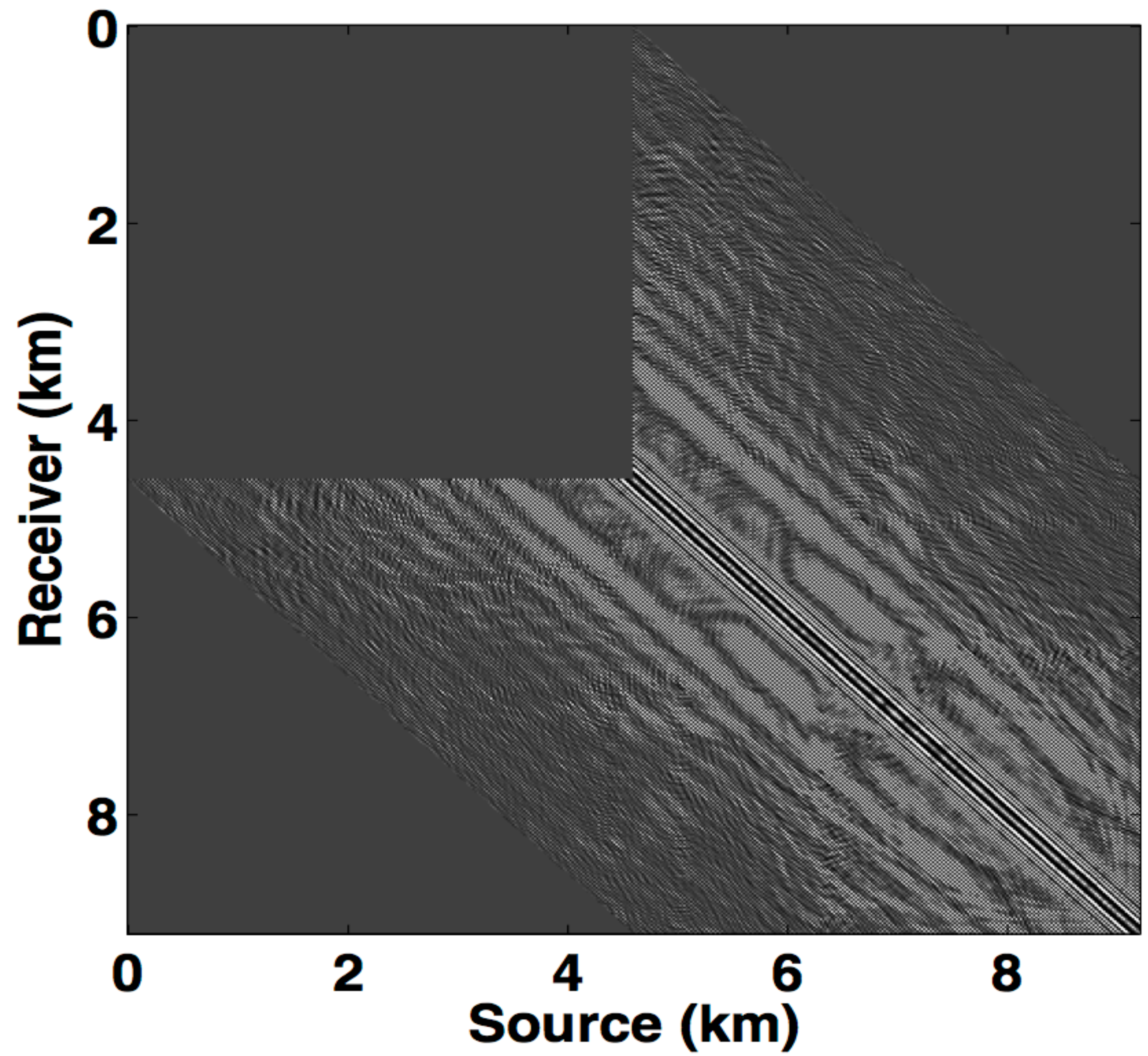
Low vs. high frequency

[source-receiver domain]

low frequency

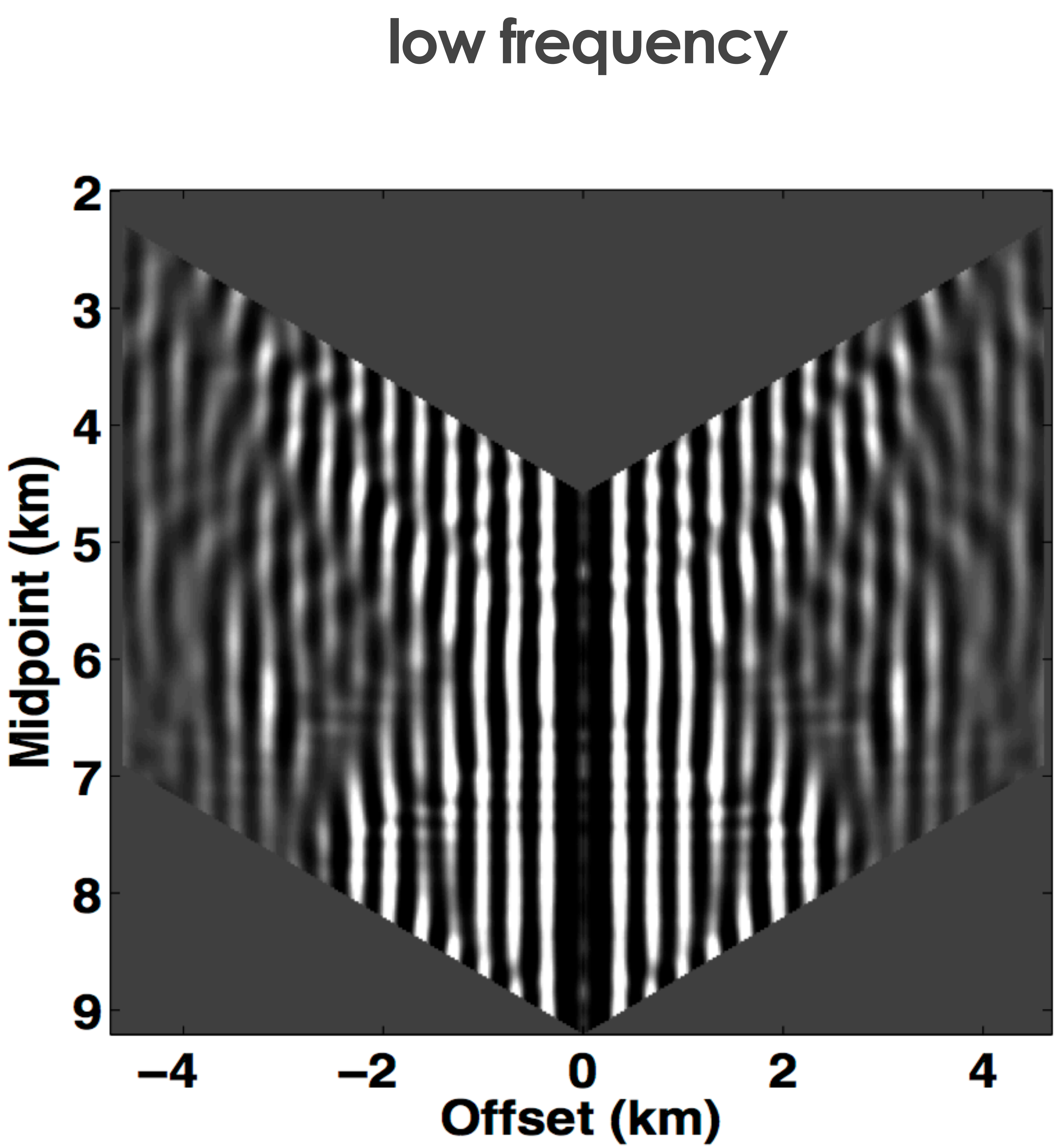


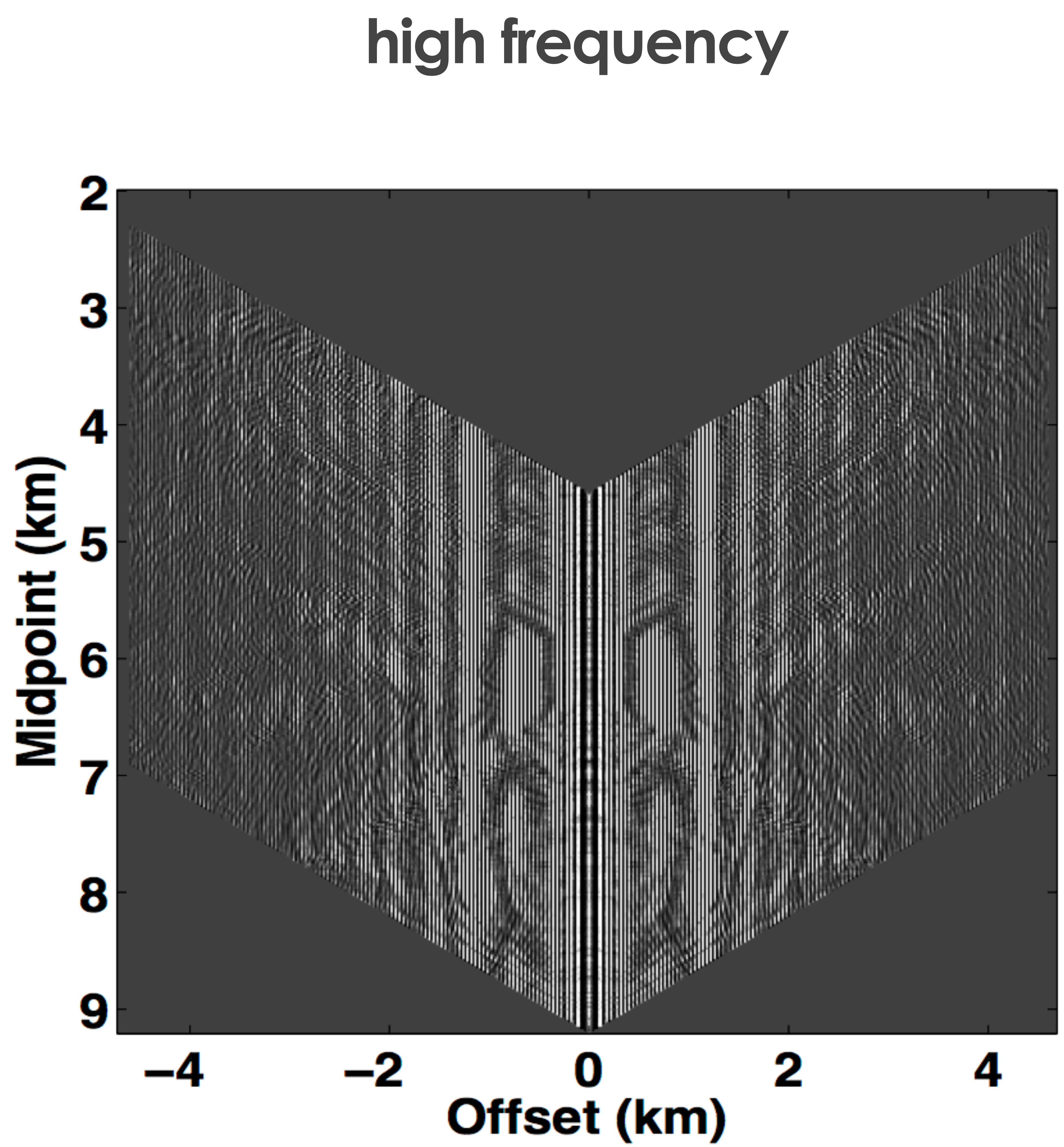
high frequency



Low vs. high frequency

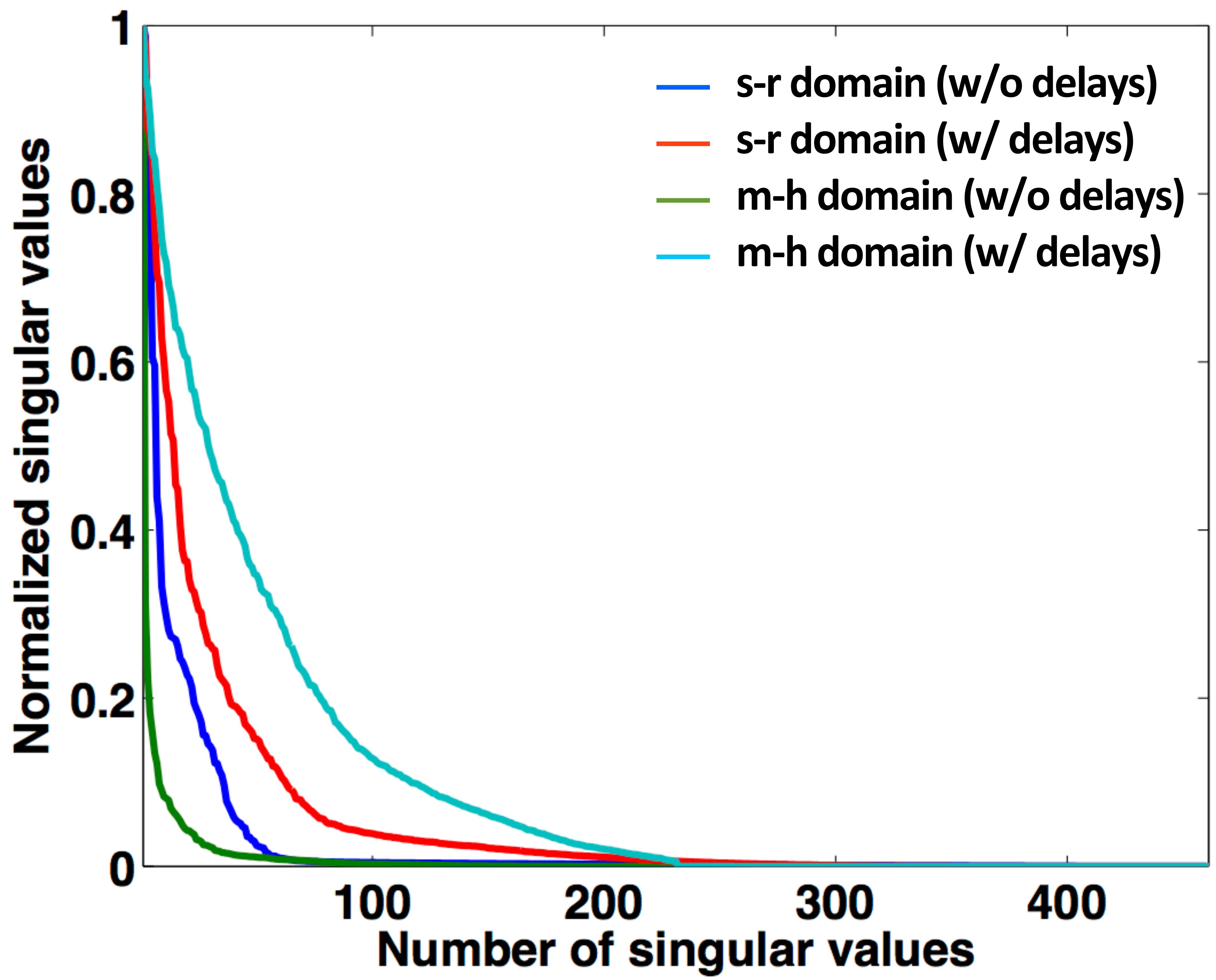
[midpoint-offset domain]



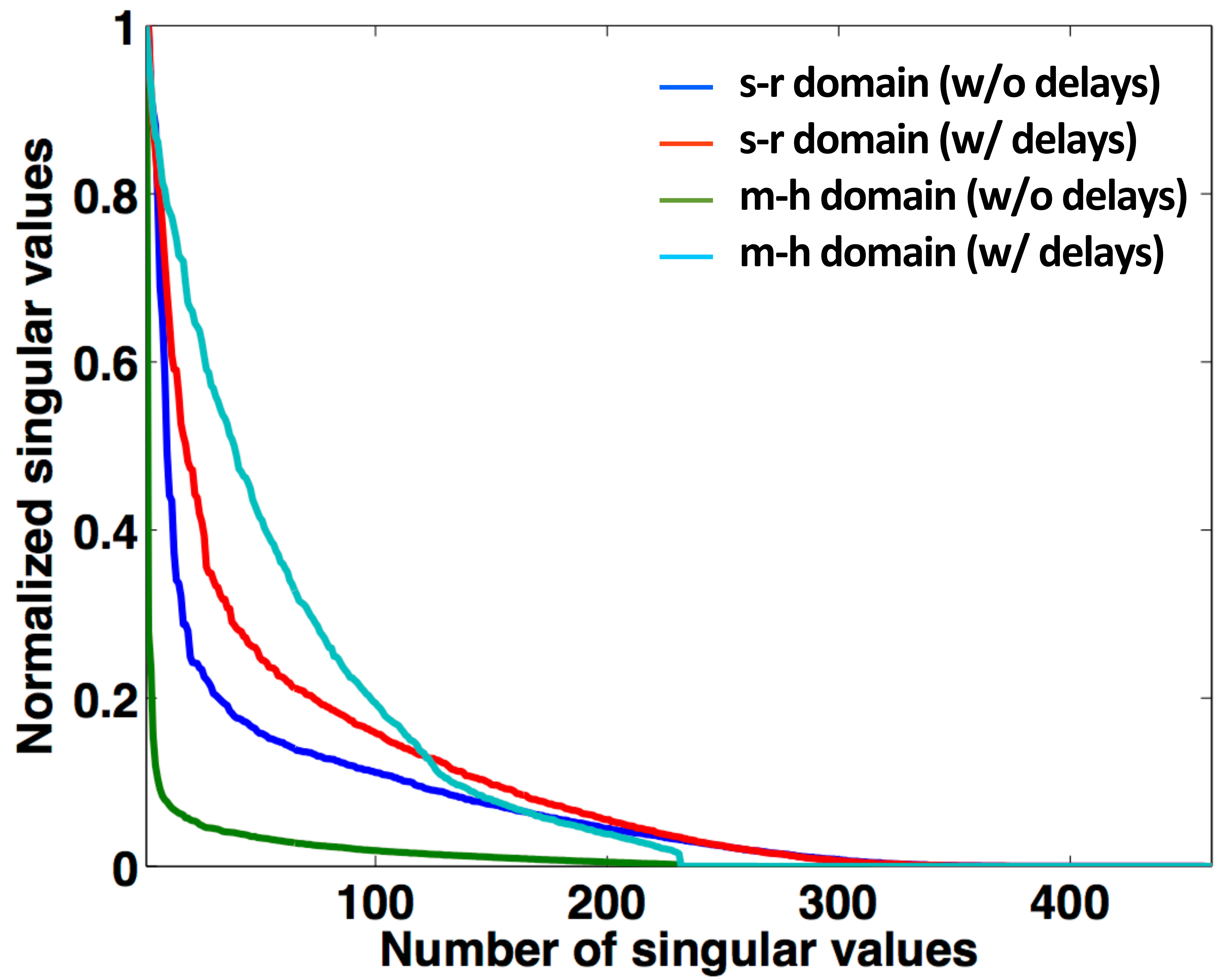


Decay of singular values

low frequency



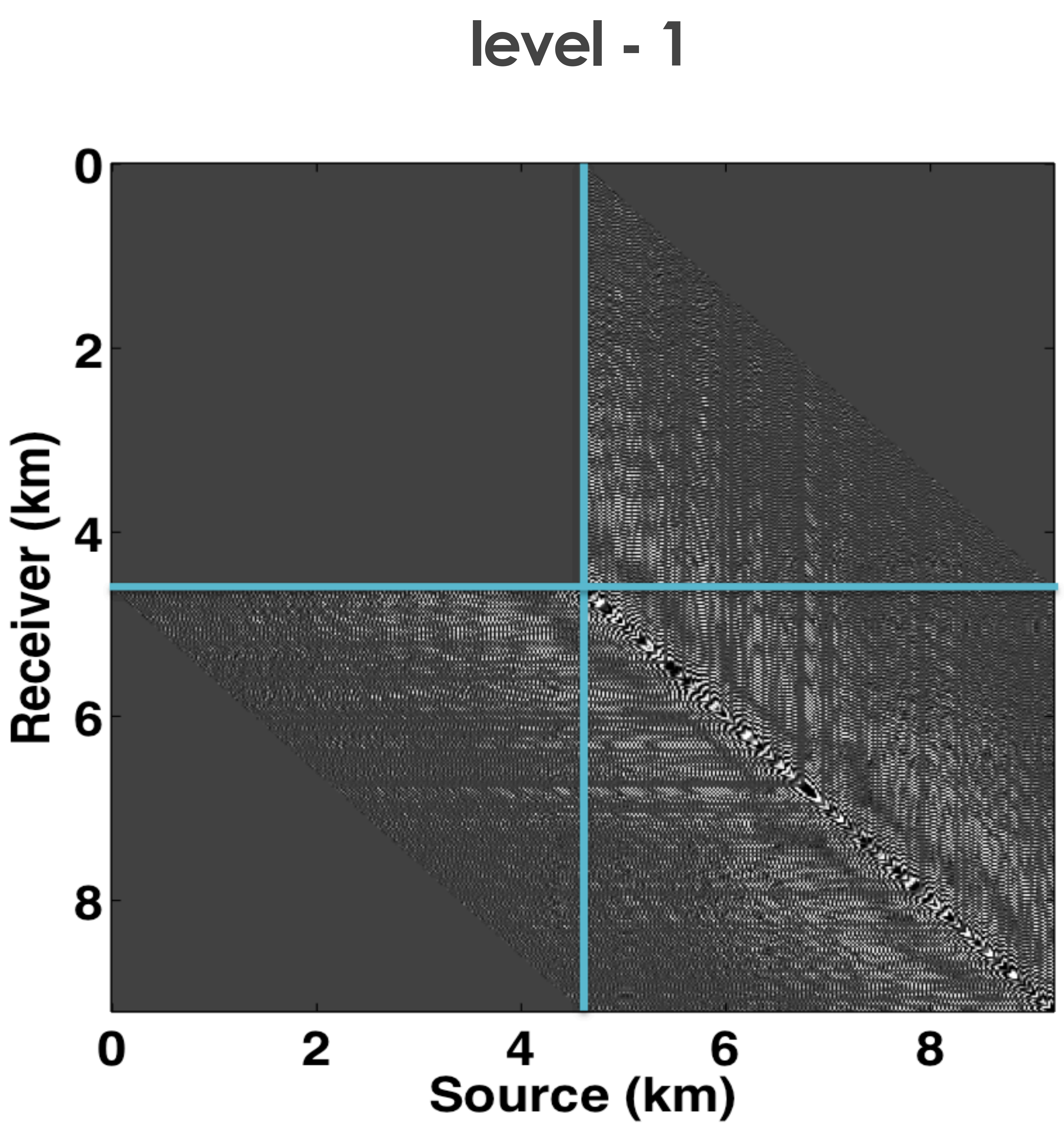
high frequency

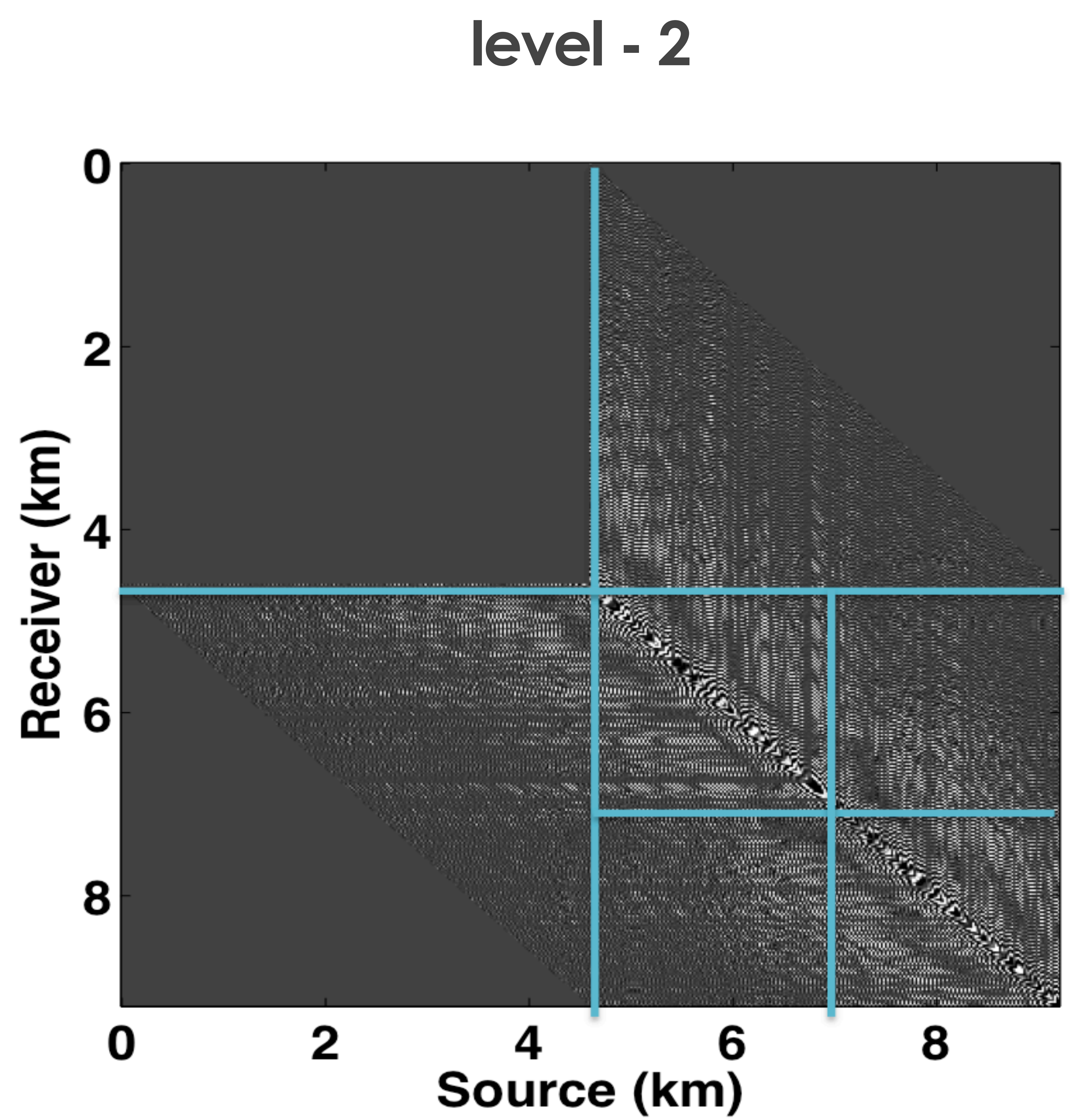


Hierarchical semi-separable (HSS) representation

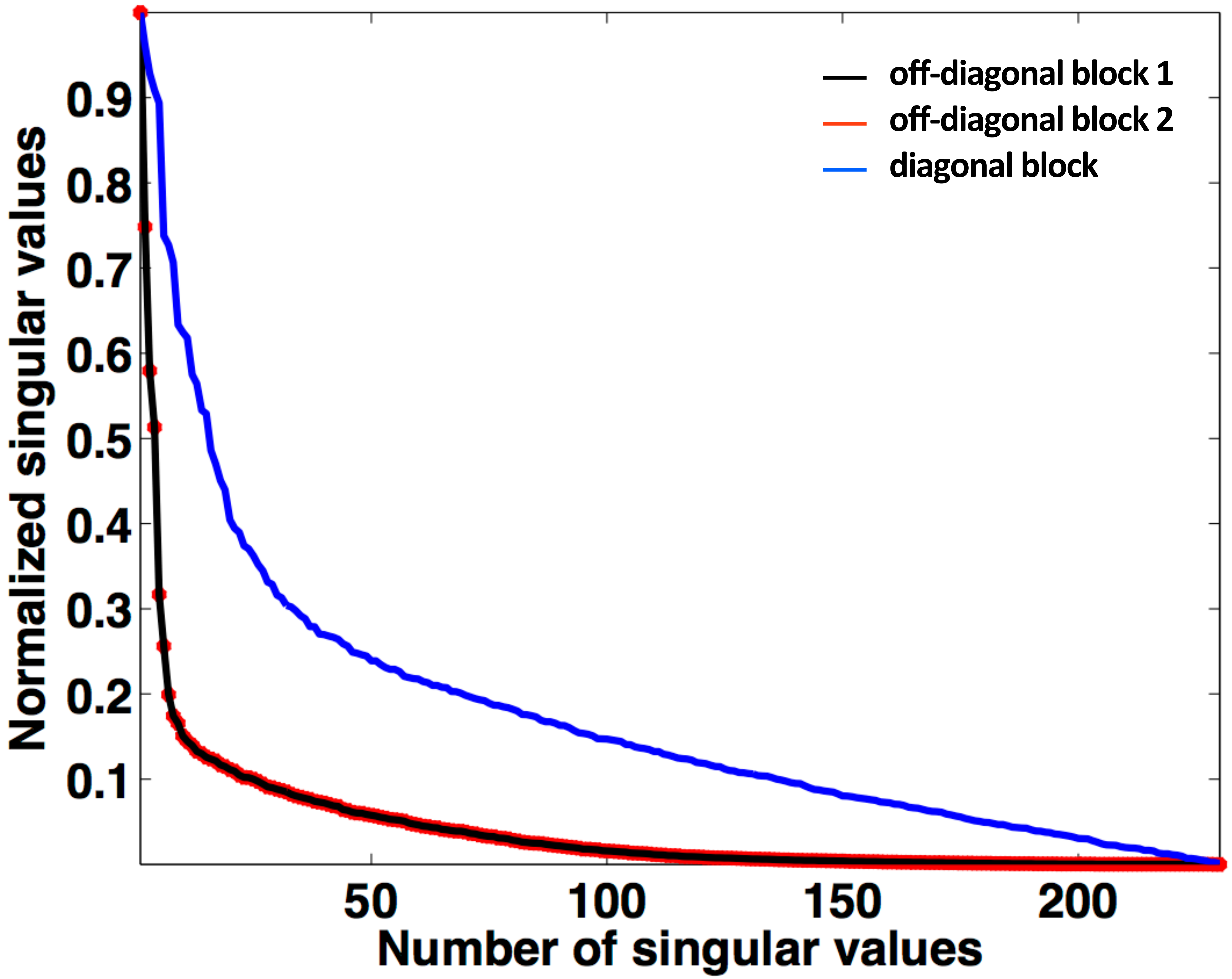
HSS representation

[Chandrasekaran et. al., 2006]





Decay of singular values of HSS sub-blocks



off-diagonal blocks have low-rank structure

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:

unblended data matrix

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

$\mathbf{b}$: blended data

$$\mathcal{A} := \begin{bmatrix} \mathbf{M}\mathbf{T_1}\mathbf{S^H} & \mathbf{M}\mathbf{T_2}\mathbf{S^H} \end{bmatrix}$$

↑ ↑

time delay matrices

Rank minimization

expensive
(search over all possible values of rank)

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

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

Rank minimization

expensive
(search over all possible values of rank)

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

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

Nuclear-norm minimization

convex relaxation of rank-minimization

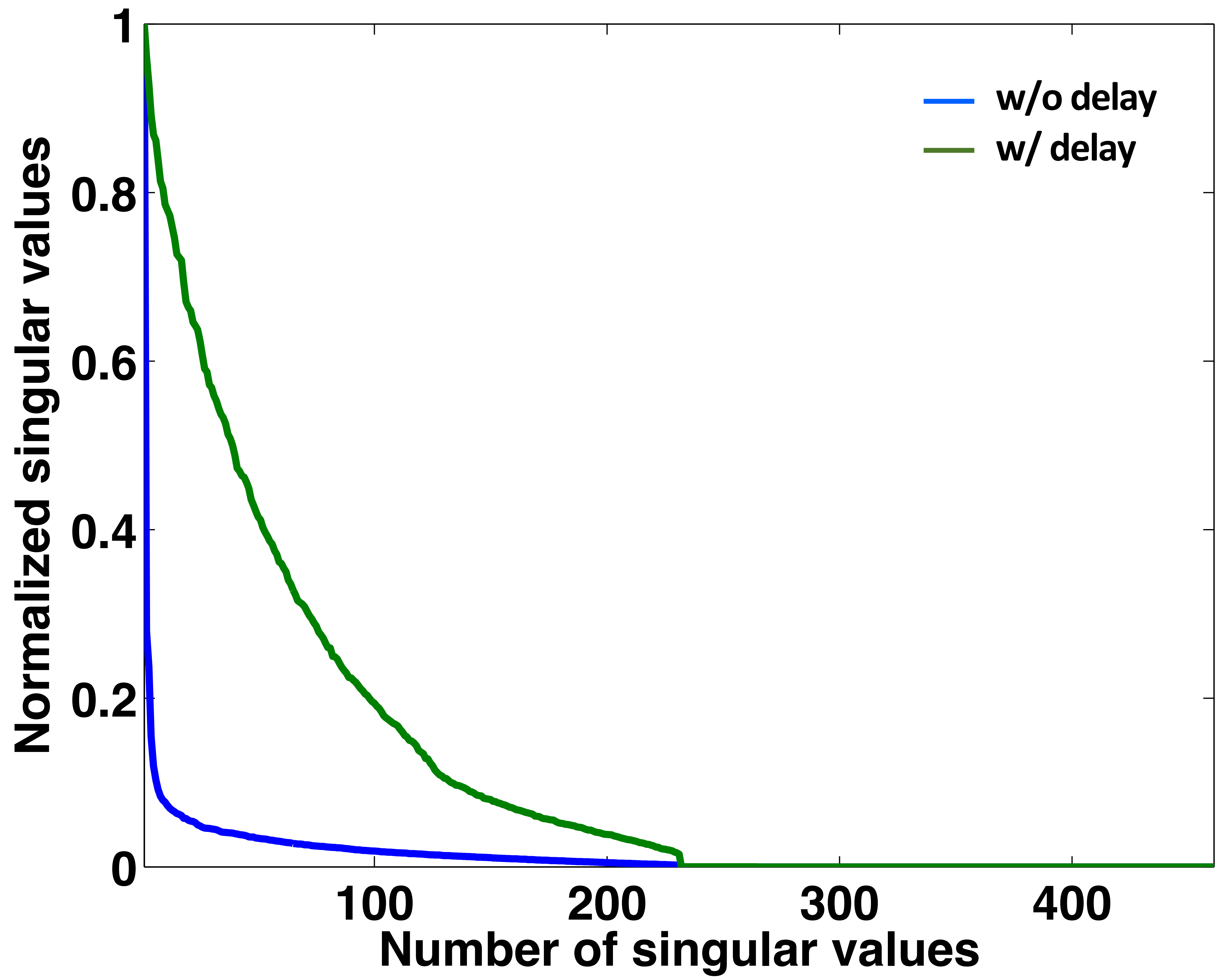
[Recht et. al., 2010]

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

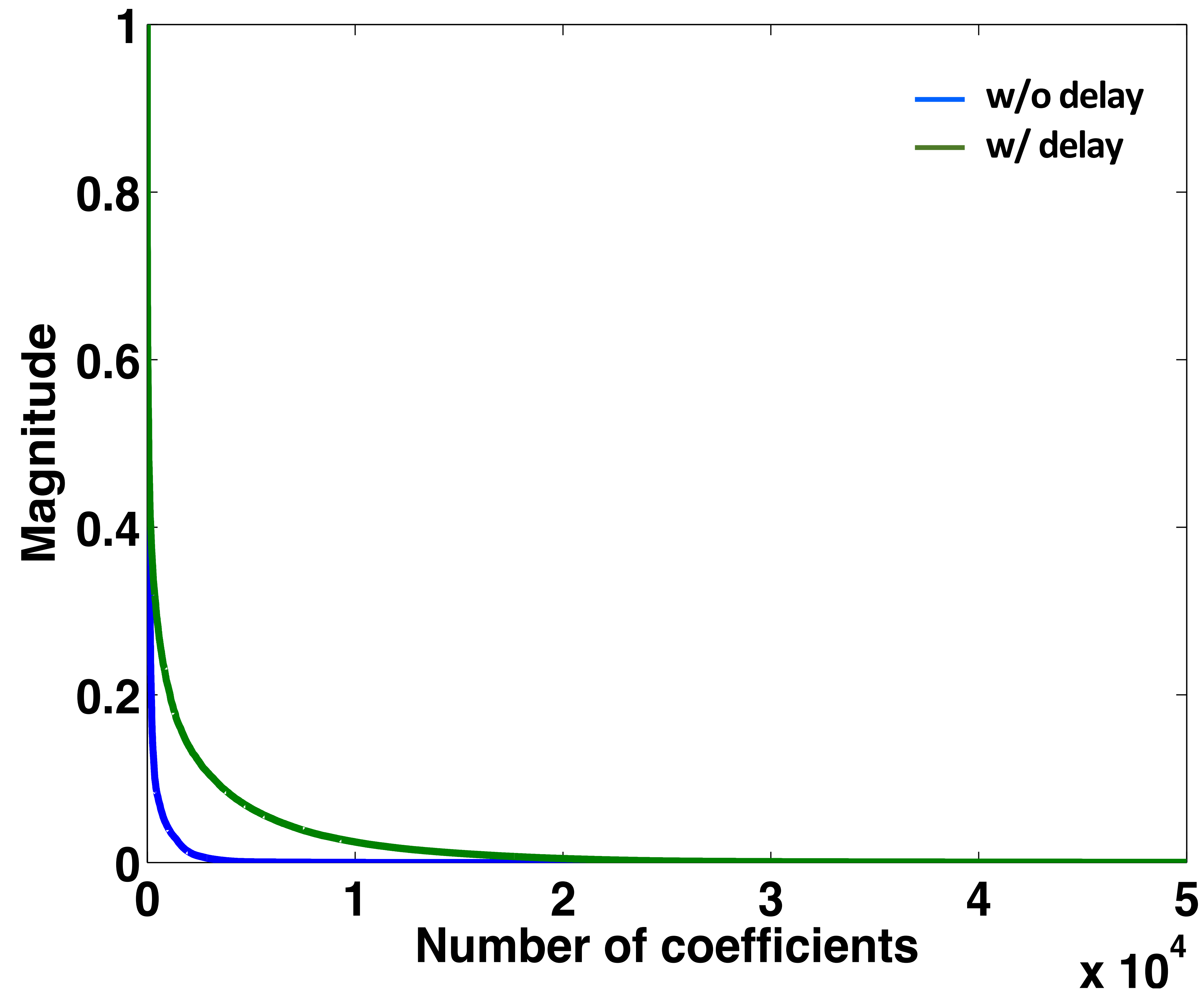
sum **of singular values of** $\mathbf{X}$

Rank vs. Sparsity

rank-minimization (midpoint-offset domain)



sparsity-promotion (source-receiver domain)



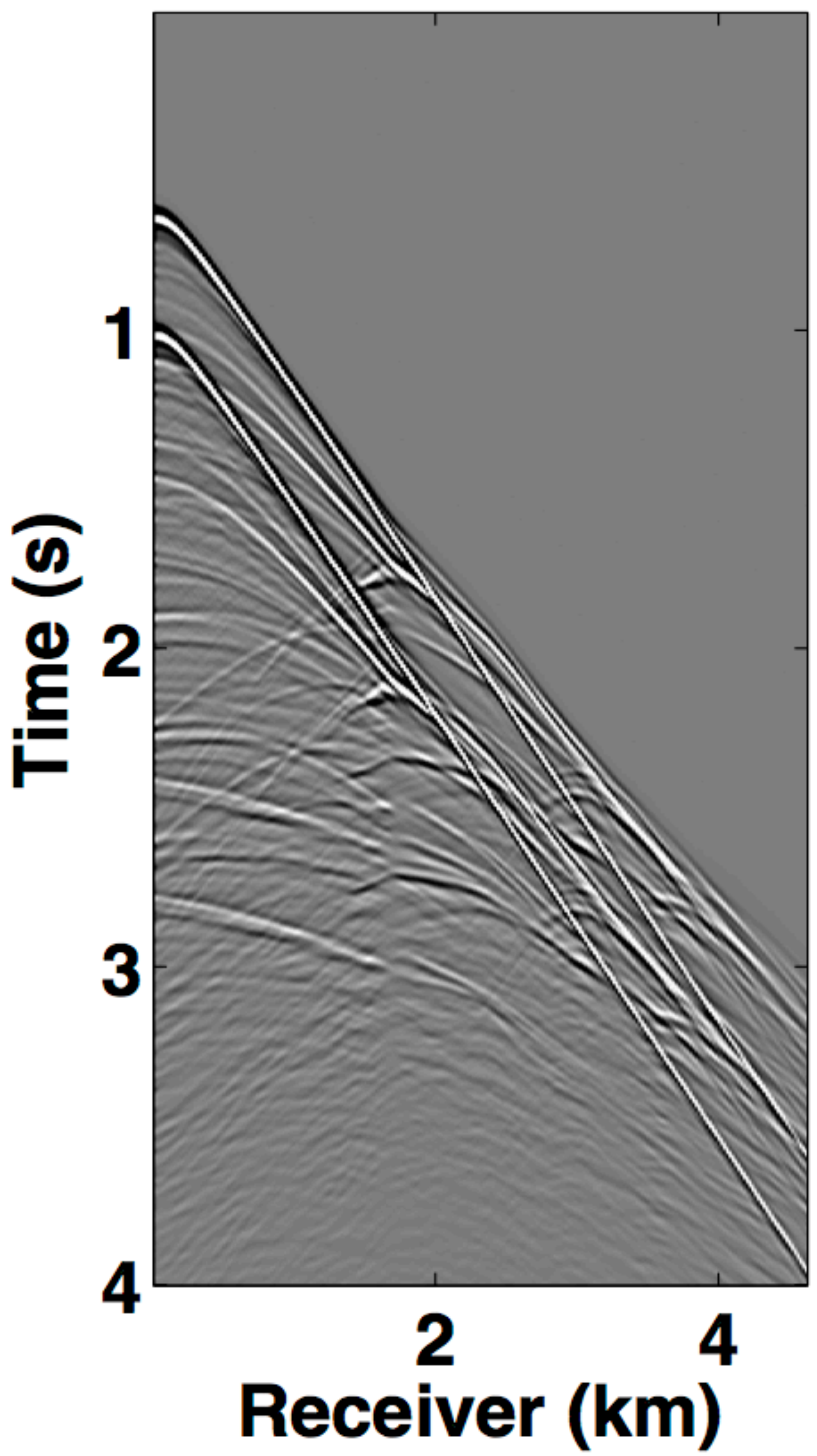
Source separation results

Rank minimization vs. sparsity promotion

Blended data (w/ delay)

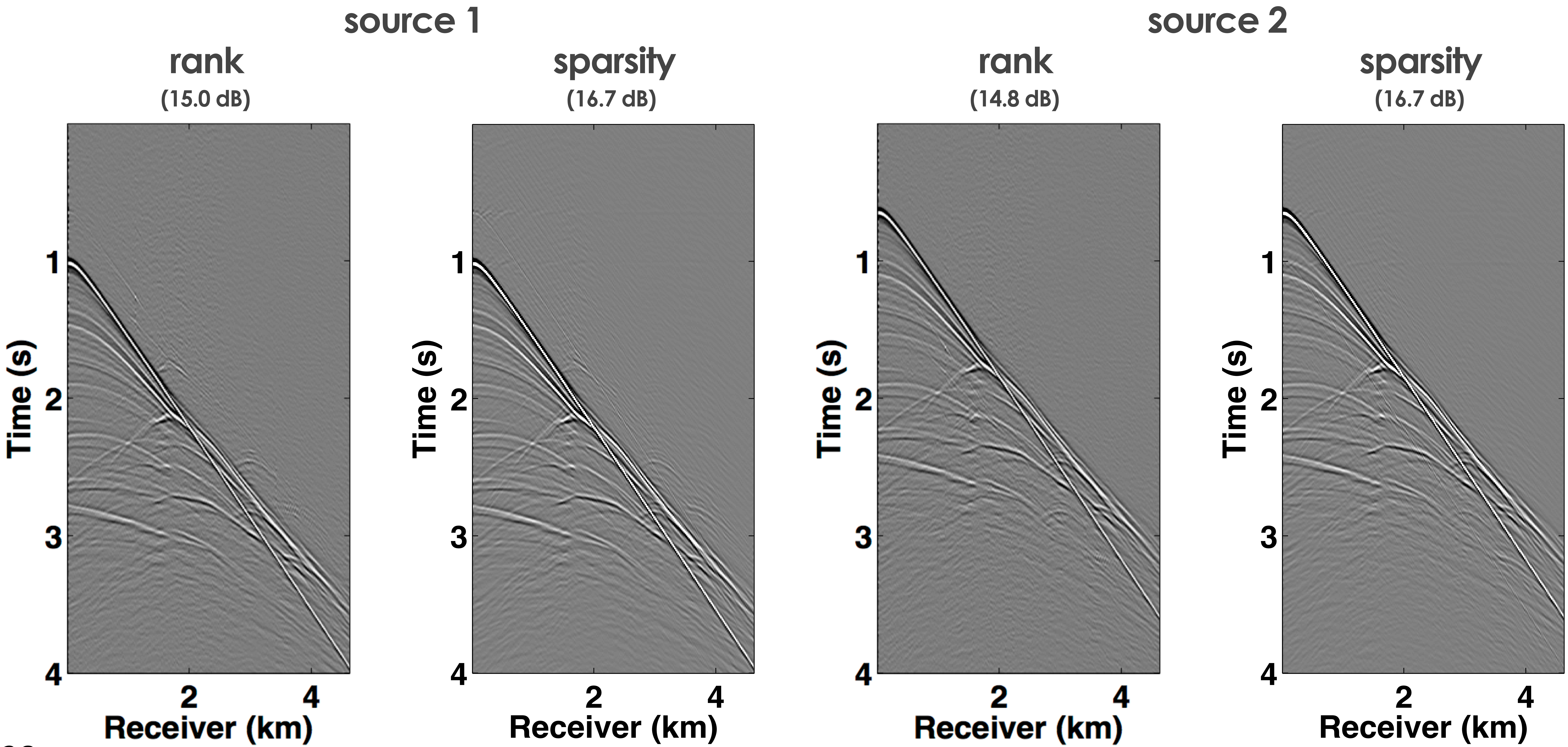
- random time delays (< 1 sec) applied to both sources

blended shot = source 1 + source 2



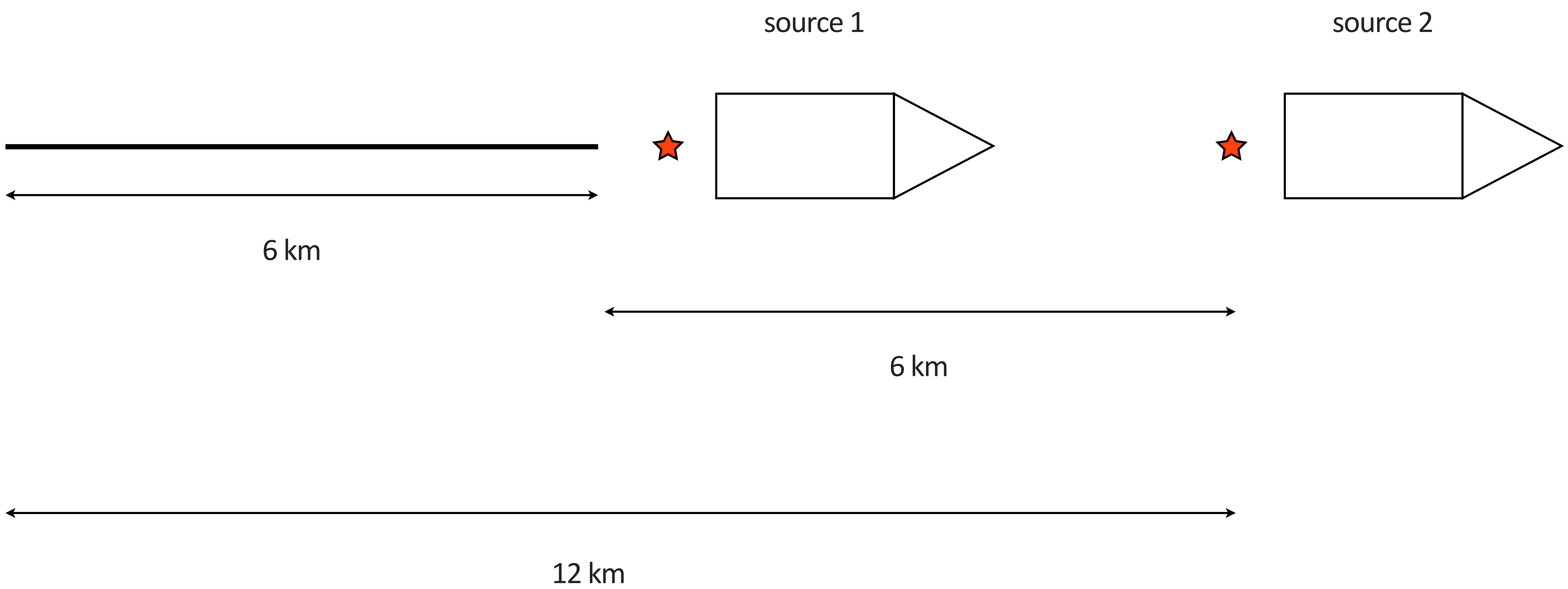
Source separation - rank vs. sparsity

computation time (all data) = 5 vs. 62 hours; memory usage = 2.8 vs. 7.0 GB



Simultaneous long offset acquisition

[adapted from Long et. al., 2013]

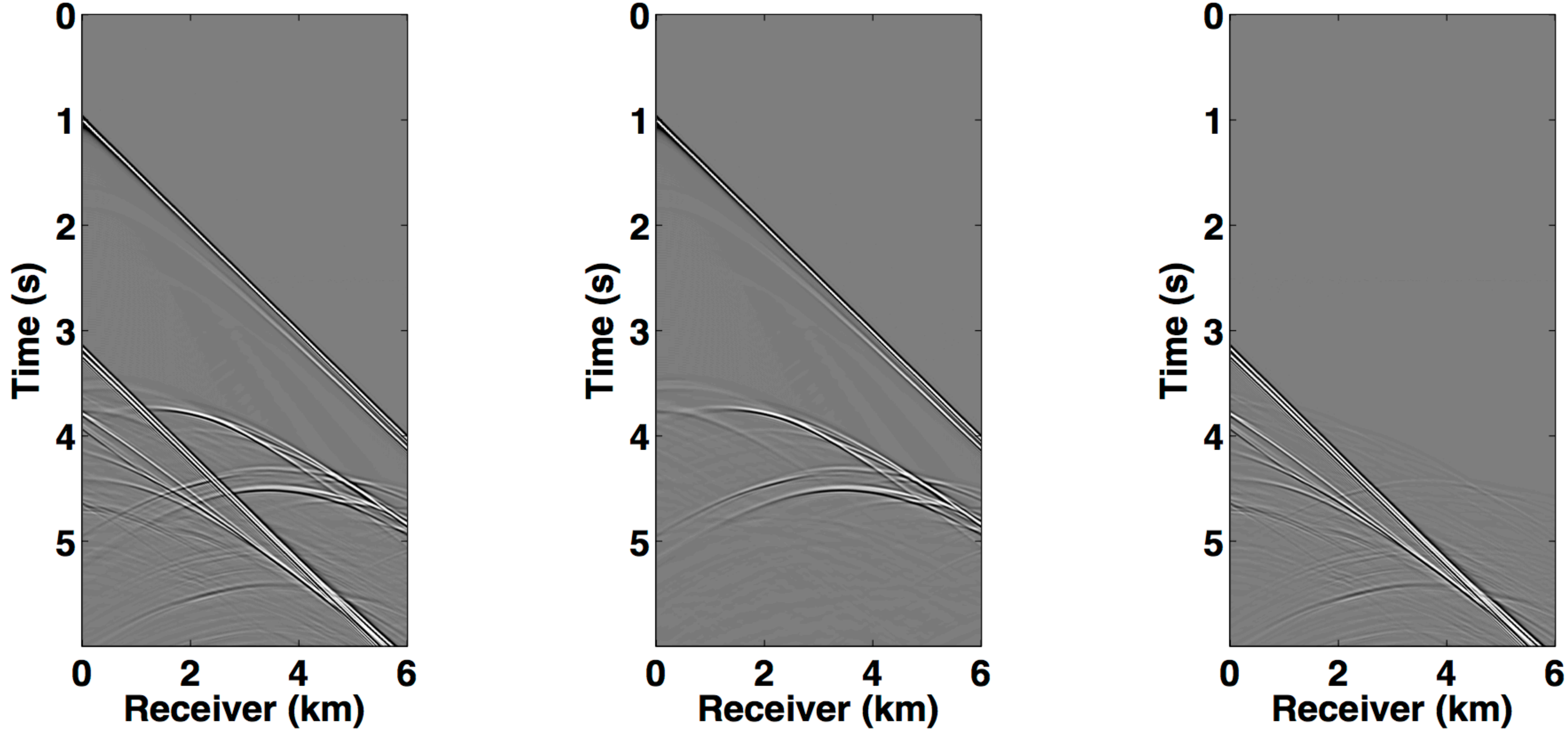


A. S. Long et. al., "**Simultaneous long offset (SLO) towed streamer seismic acquisition**", presented at the *75th EAGE Conference and Exhibition*, June 2013.

Blended data (w/ delay)

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

blended shot = source 1 + source 2

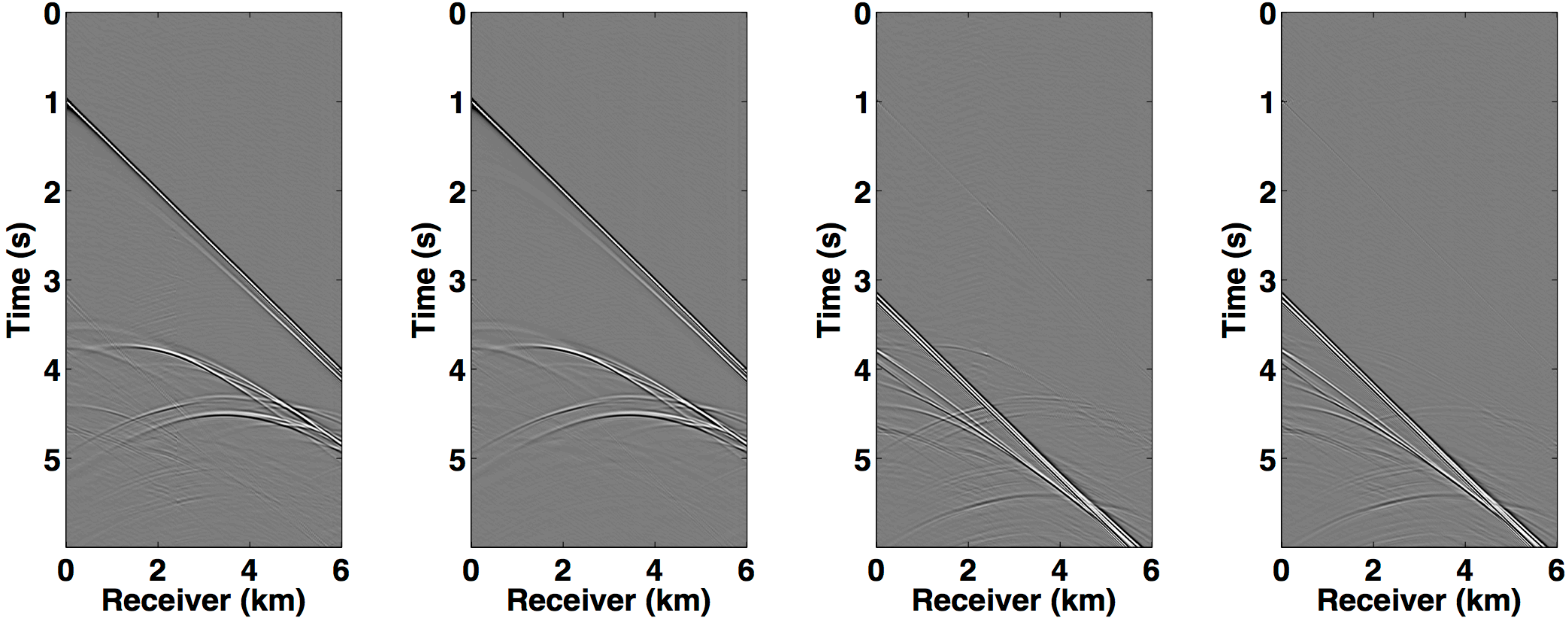


Source separation - rank vs. sparsity

computation time (all data) = 19 vs. 183 hours; memory usage = 6 vs. 12 GB

source 1 — rank (29.4 dB) | sparsity (32.0 dB)

source 2 — rank (29.0 dB) | sparsity (29.4 dB)



Rajiv Kumar, Haneet Wason and Felix J. Herrmann, 2015. “**Source separation for simultaneous towed-streamer marine acquisition---a compressed sensing approach**”, *Geophysics*, 80, WD73-WD88.

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Experiment 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

Summary

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

Spectral gap analysis

- data with time delays
- data with time delays + missing traces

Source separation + trace interpolation for 3D seismic data

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