Enabling large-scale seismic data acquisition, processing and waveform-inversion via rank-minimization

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SLIM

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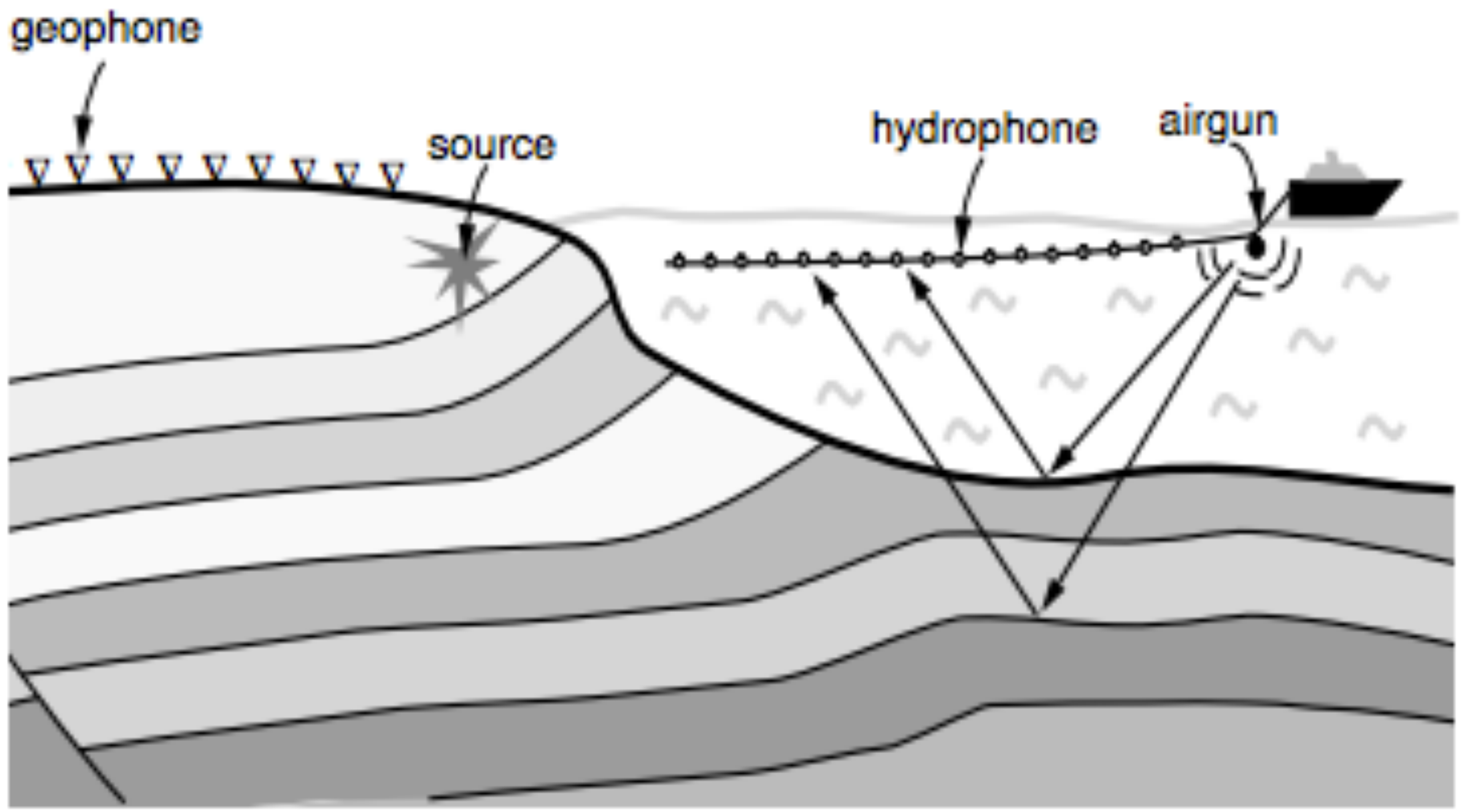
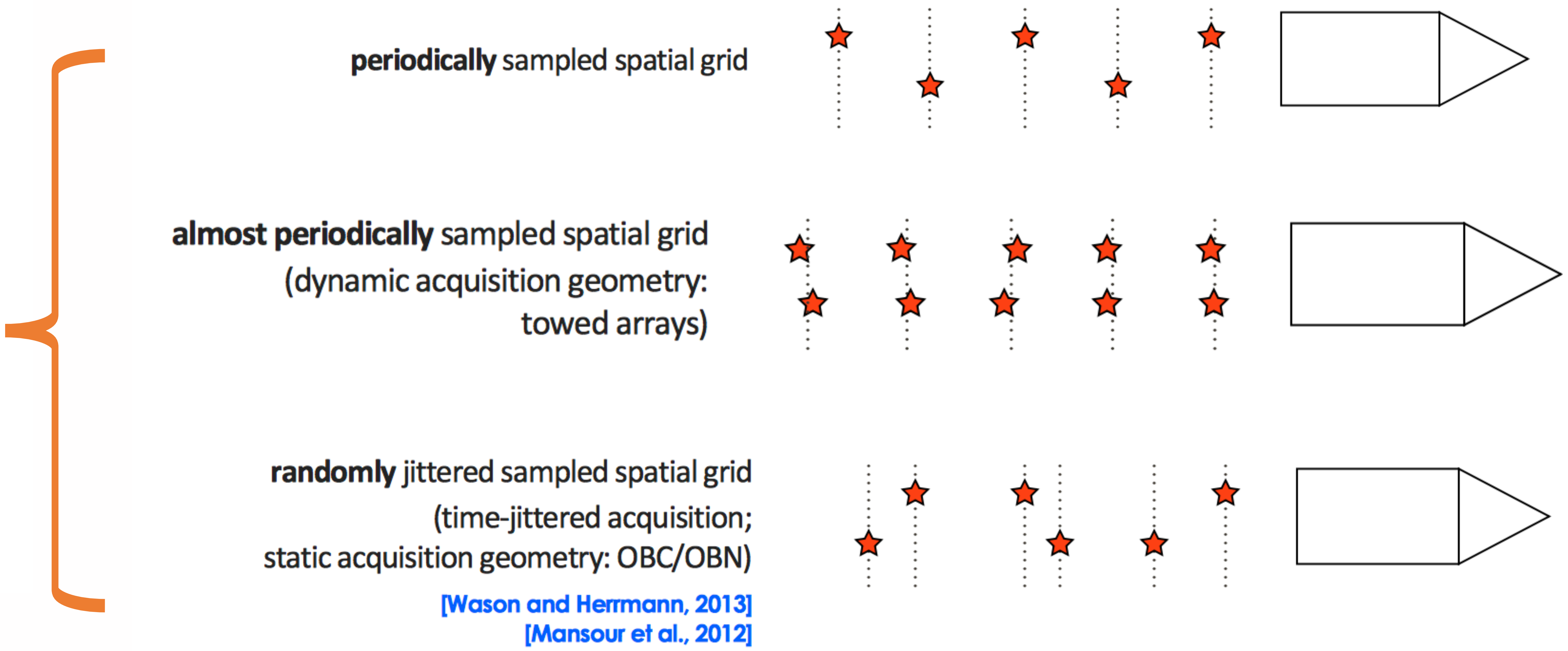
https://archive.epa.gov/esd/archive-geophysics/web/html/marine_seismic_methods.html

Seismic data acquisition



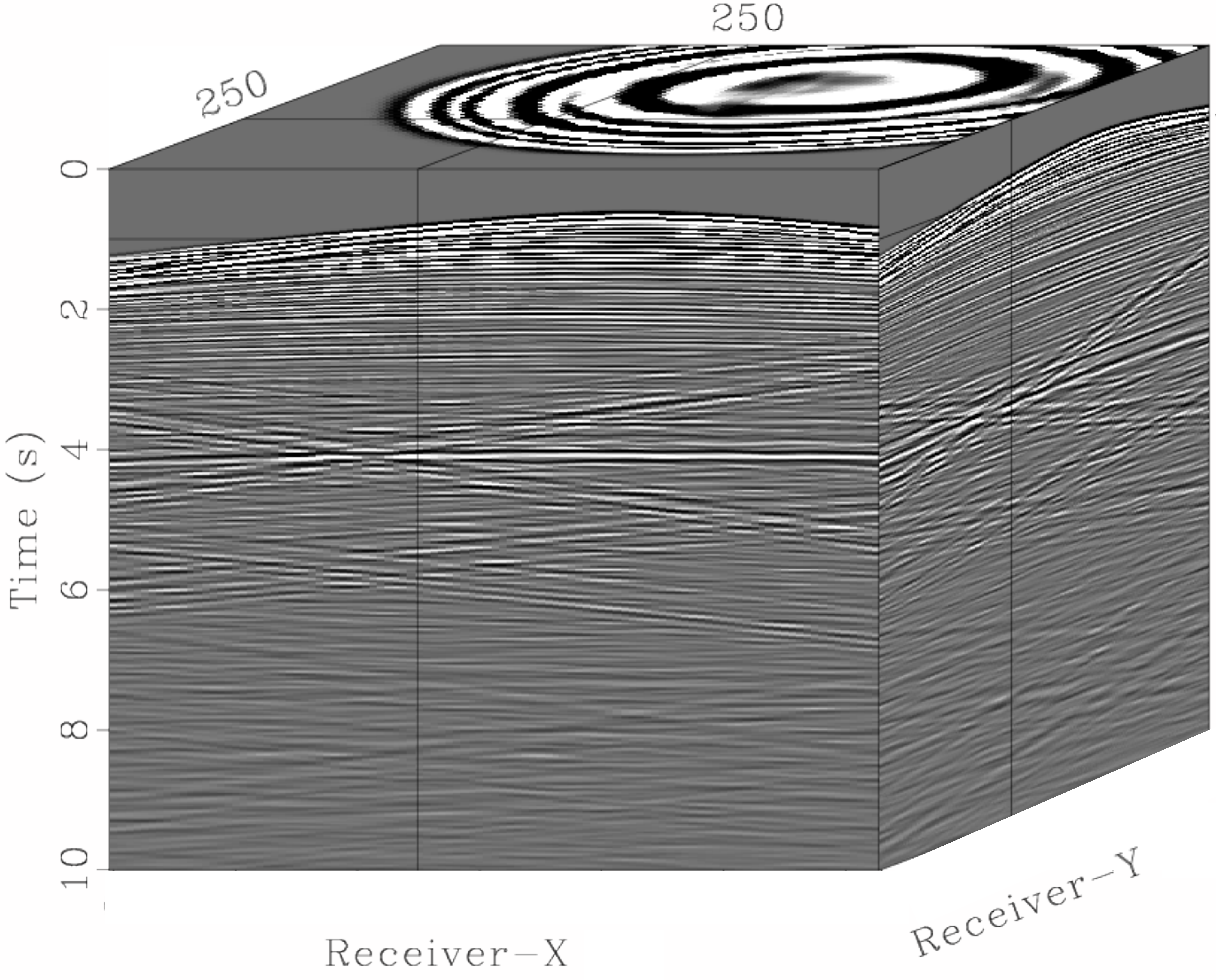


Objective

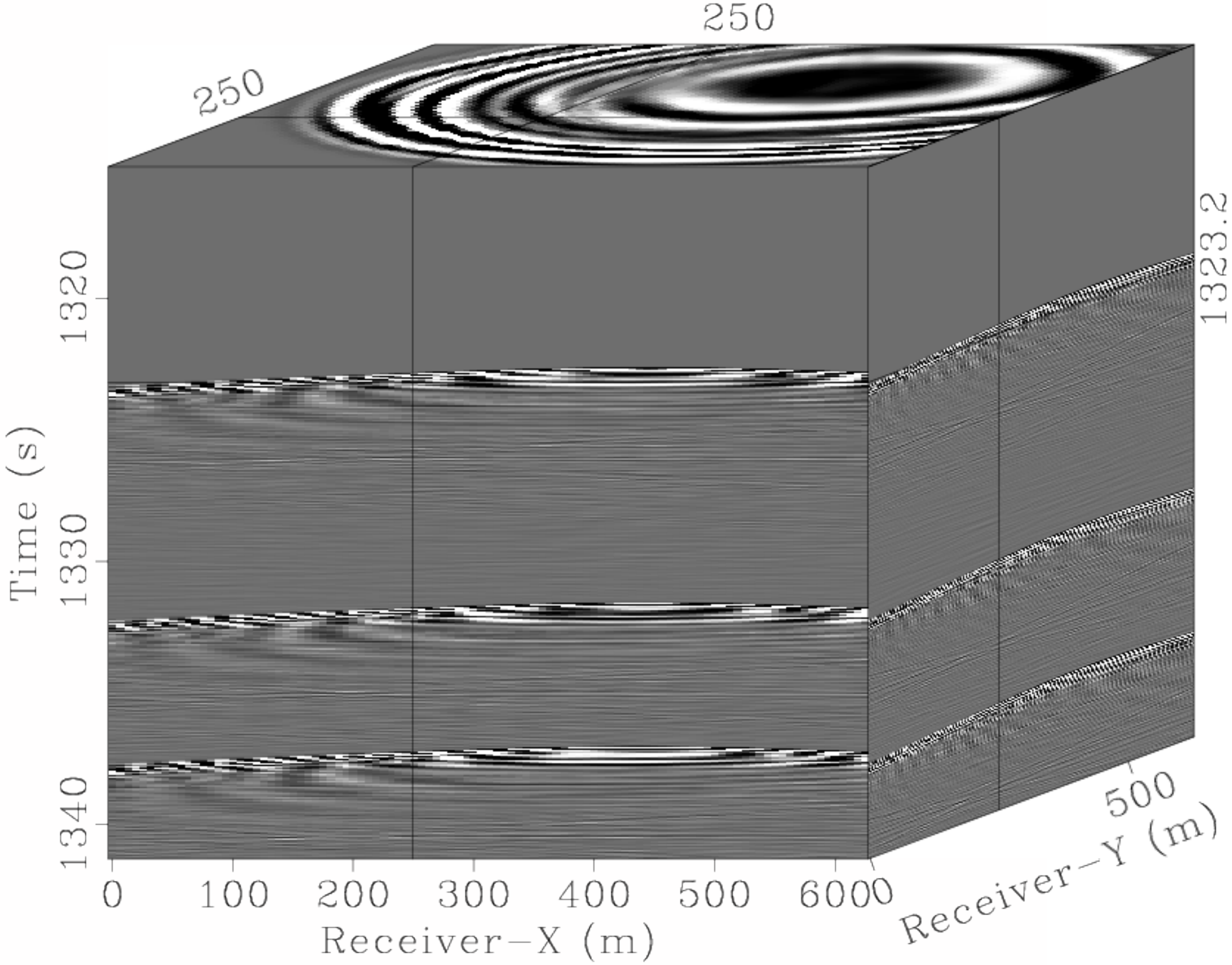
Dense seismic data at regular periodic grid to perform good-quality imaging and inversion

Data Organization
(common-shot gather)

sequential



simultaneous



2D acquisition : time, source, receiver

3D acquisition : time, source-x, source-y, receiver-x, receiver-y

Acquisition Impediments

- Reduce acquisition time and cost
  - coarser sampling in sequential acquisition
  - deploy multiple-vessels for simultaneous acquisition

M. S. AL-BANNAGI, K. FANG, P. G. Kelamis, and G. S. Douglas , 2017, Acquisition footprint suppression via the truncated SVD technique: Case studies from Saudi Arabia: The Leading Edge

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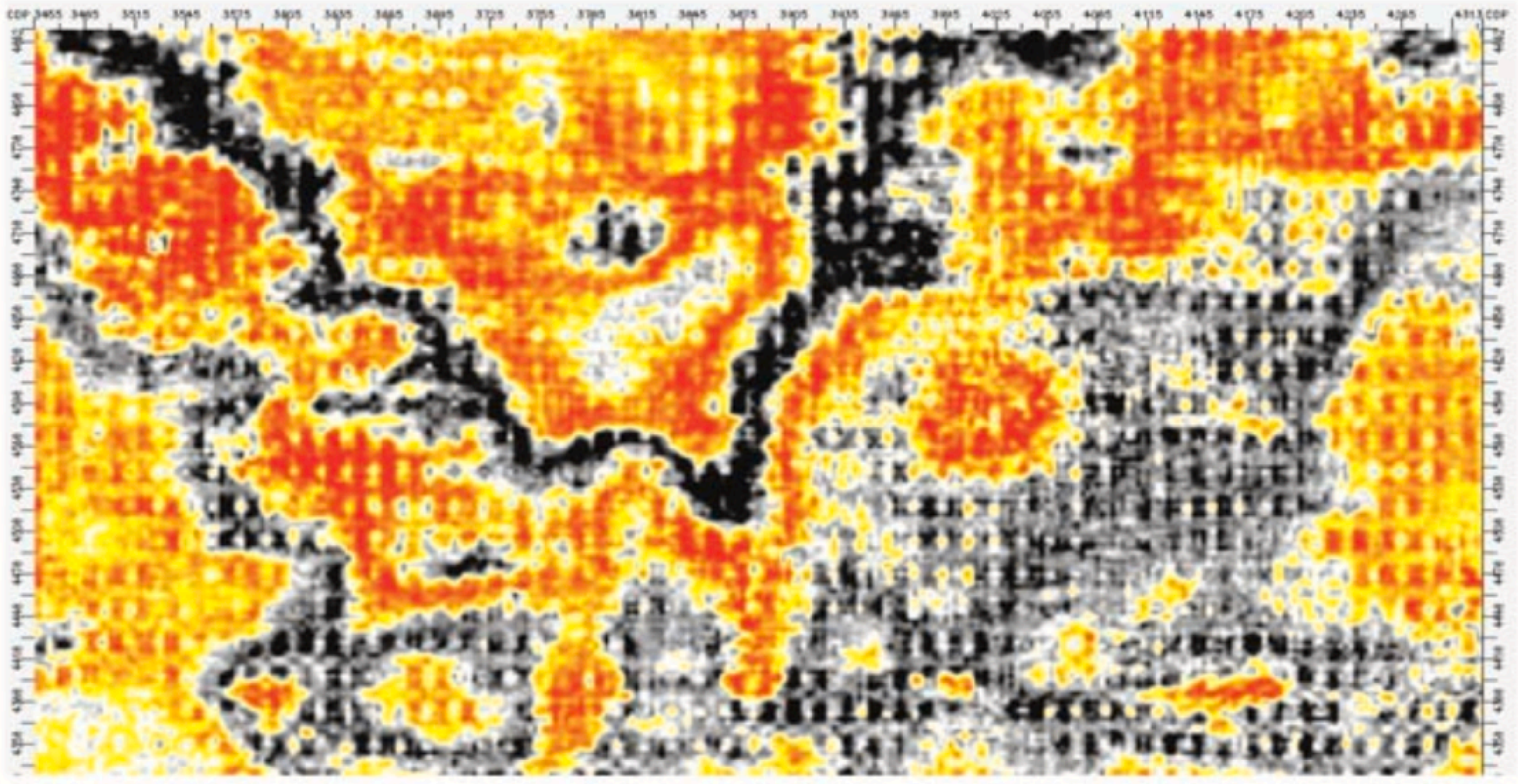
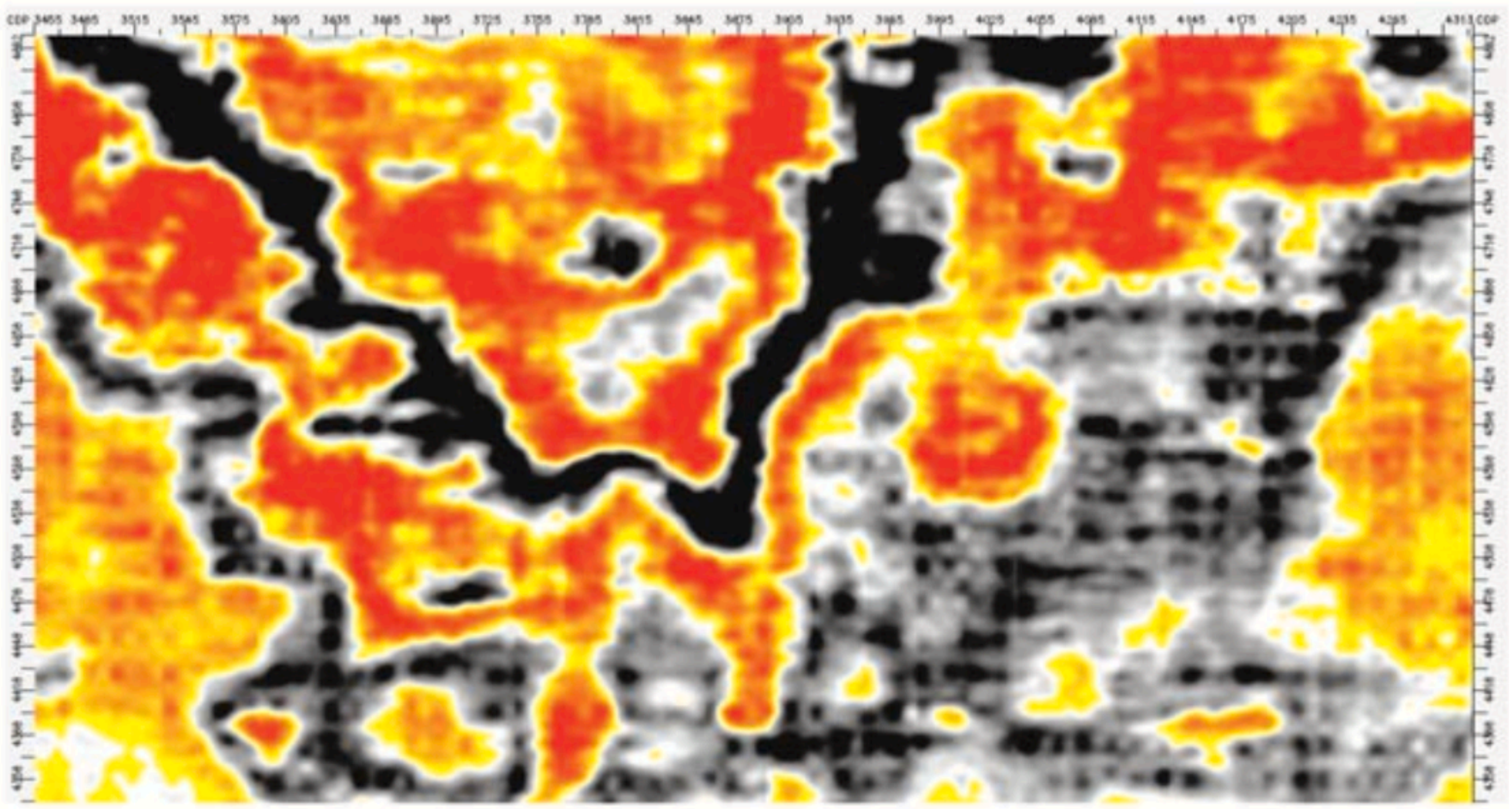
Sequential acquisition artifacts

Imaging (before interpolation)



Imaging (after interpolation)



Chengbo Li*, Charles C. Mosher, Yi Tao and Yu Zhang, 2017, A low-rank approximation method for ice-break noise attenuation of simultaneous vibroseis data : SEG

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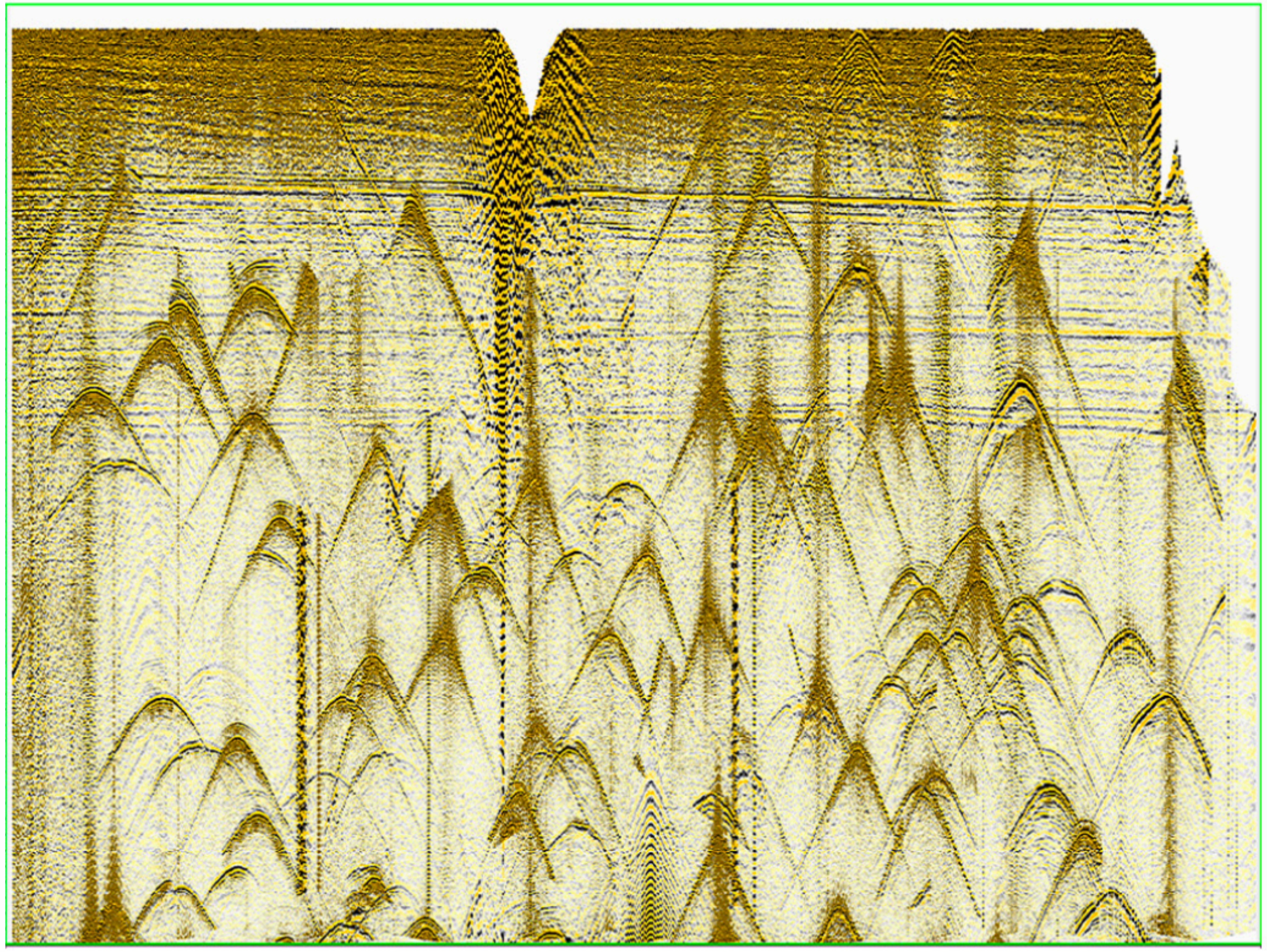
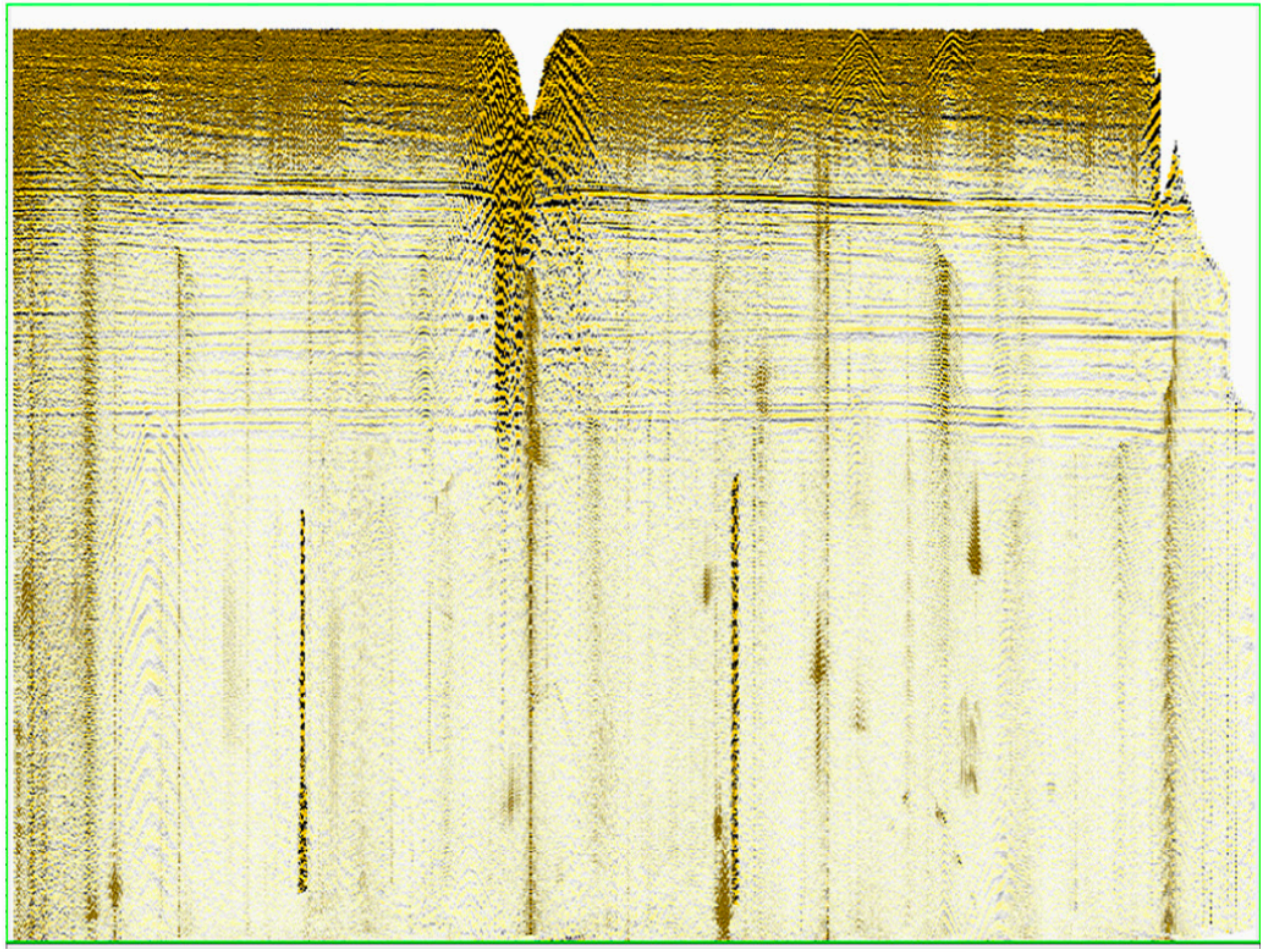
Simultaneous acquisition artifacts



Stacking before source-separation



Stacking after source-separation

Contributions: Chapter 2-5

Designed *computationally scalable* and *memory efficient* large-scale low-rank based seismic data processing method for

- interpolation
- source-separation

[Candes and Plan 2010, Oropeza and Sacchi 2011]

Matrix completion

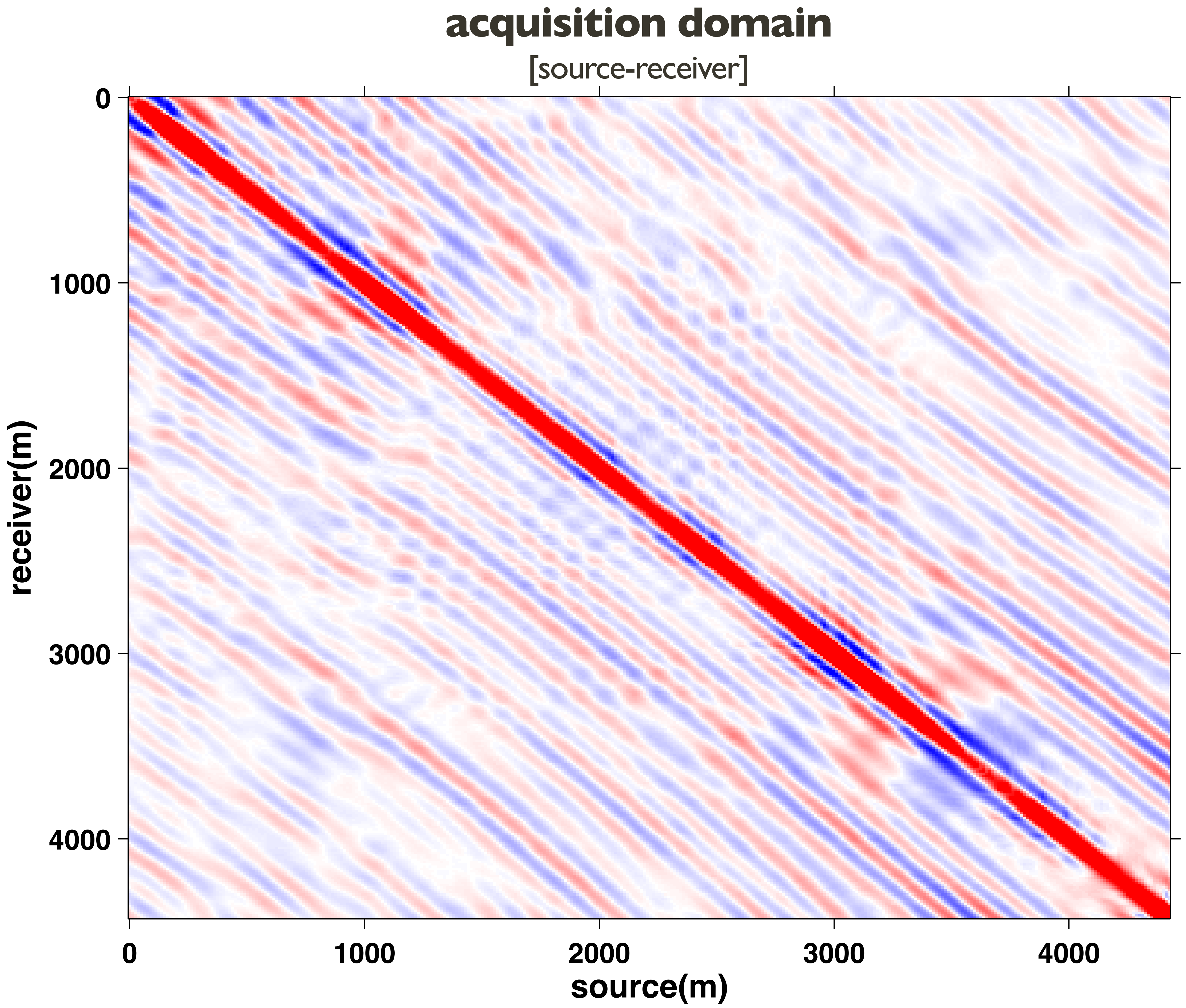
- signal structure
  - *low rank/fast decay* of singular values

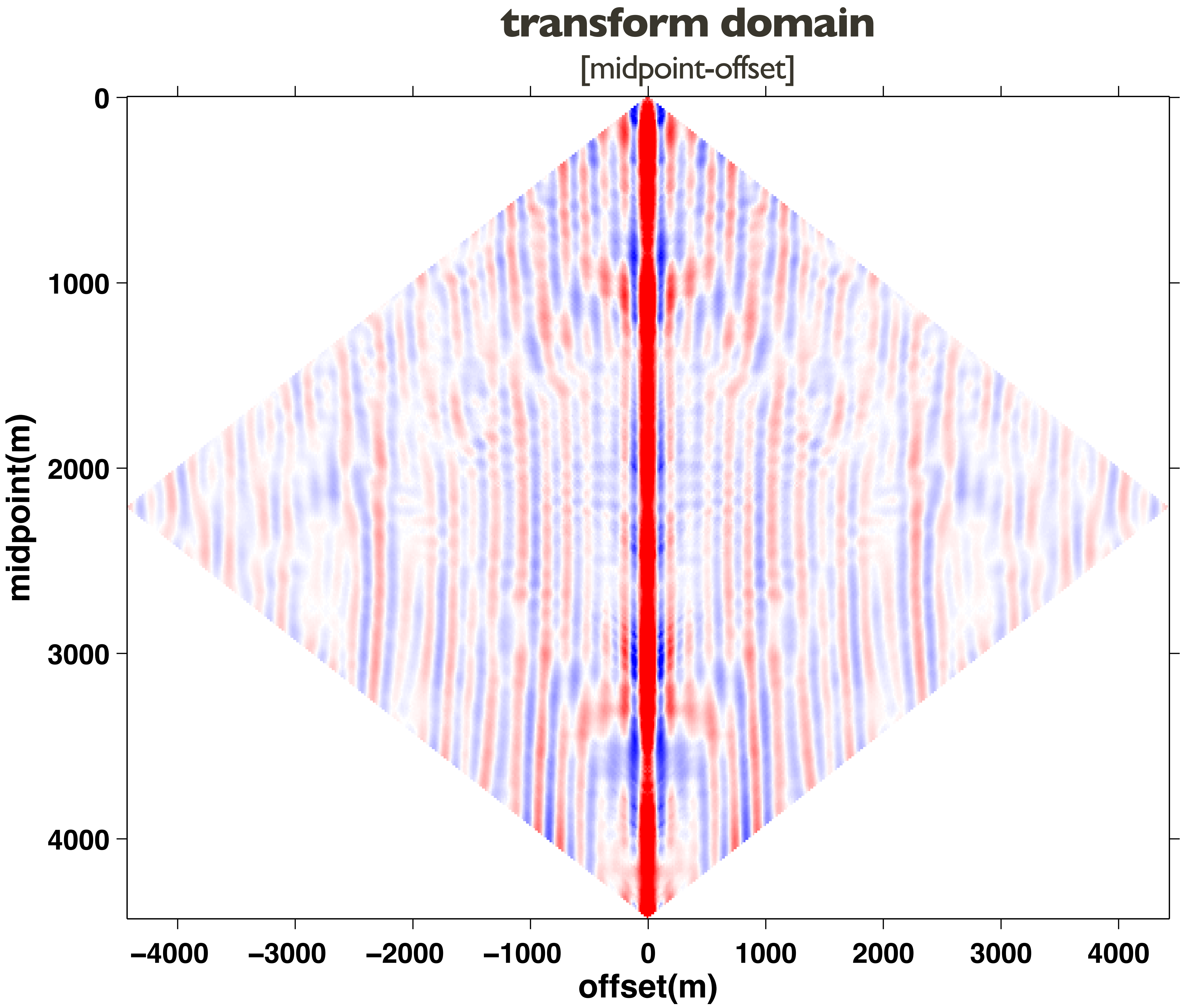
- sampling scheme
  - missing data *increase* rank in "transform domain"

- recovery using *rank penalization* scheme

Low-rank structure

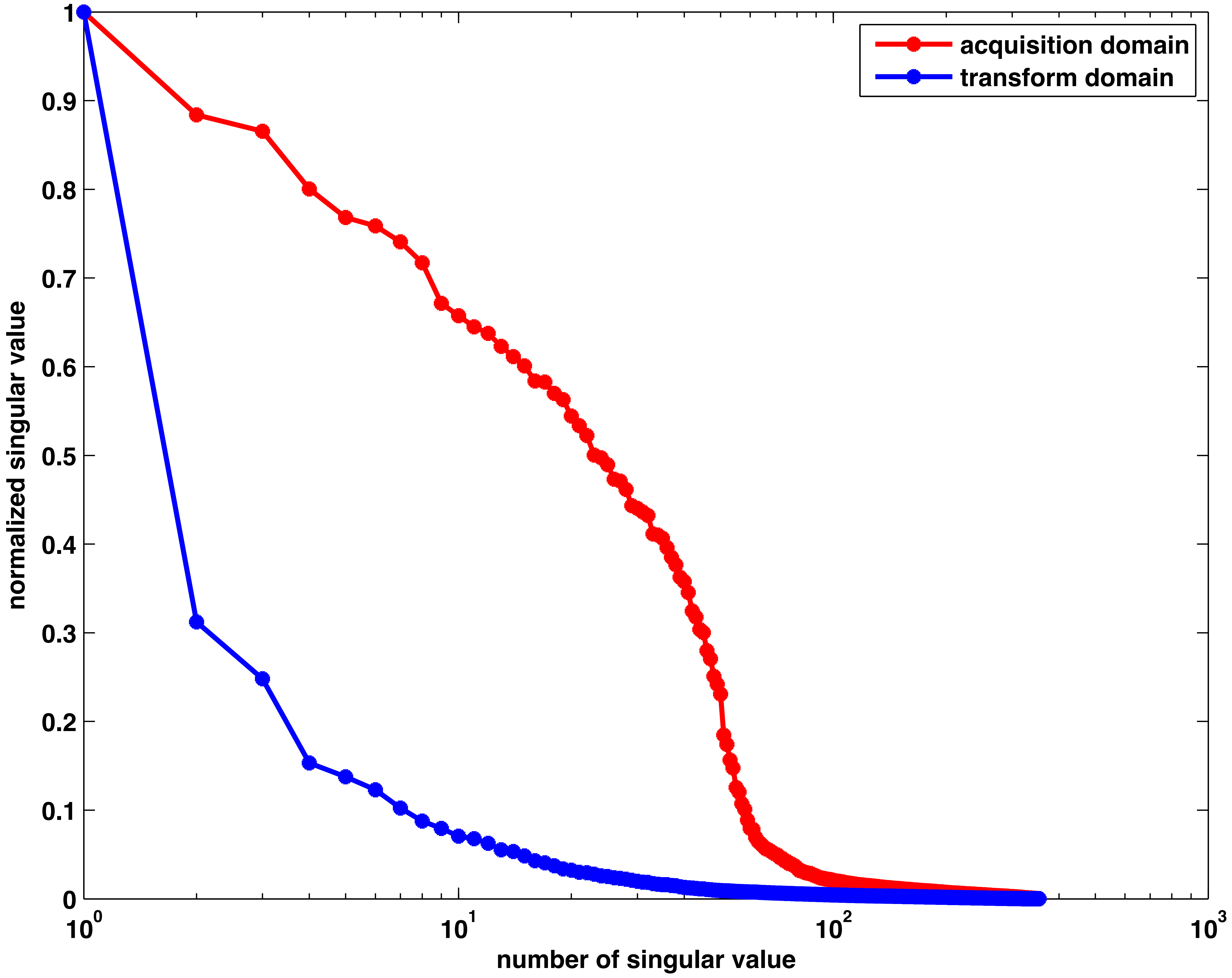
2-D acquisition



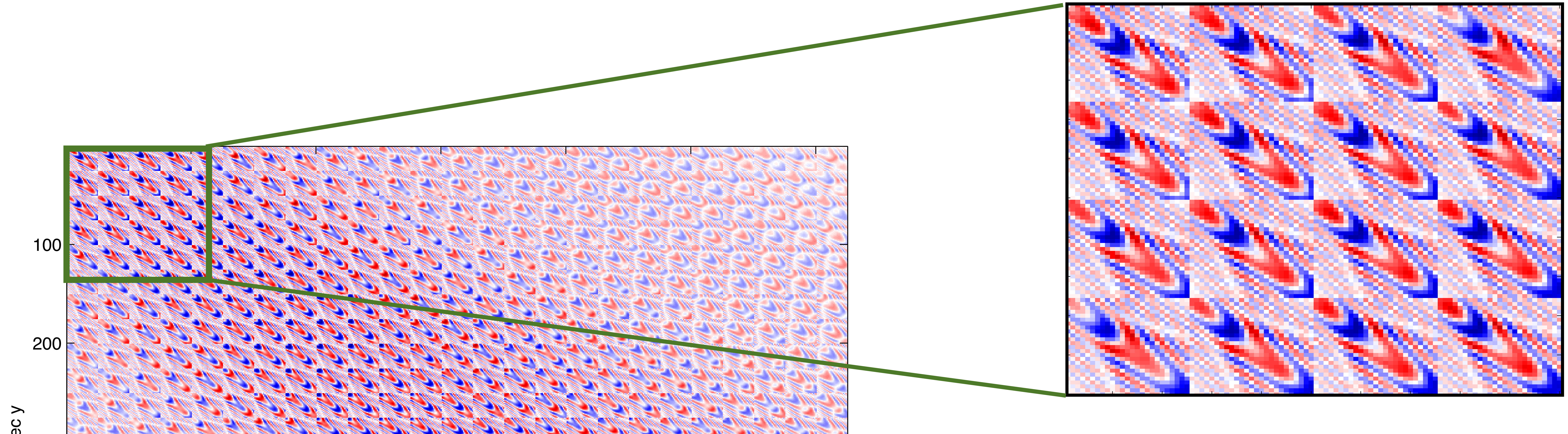


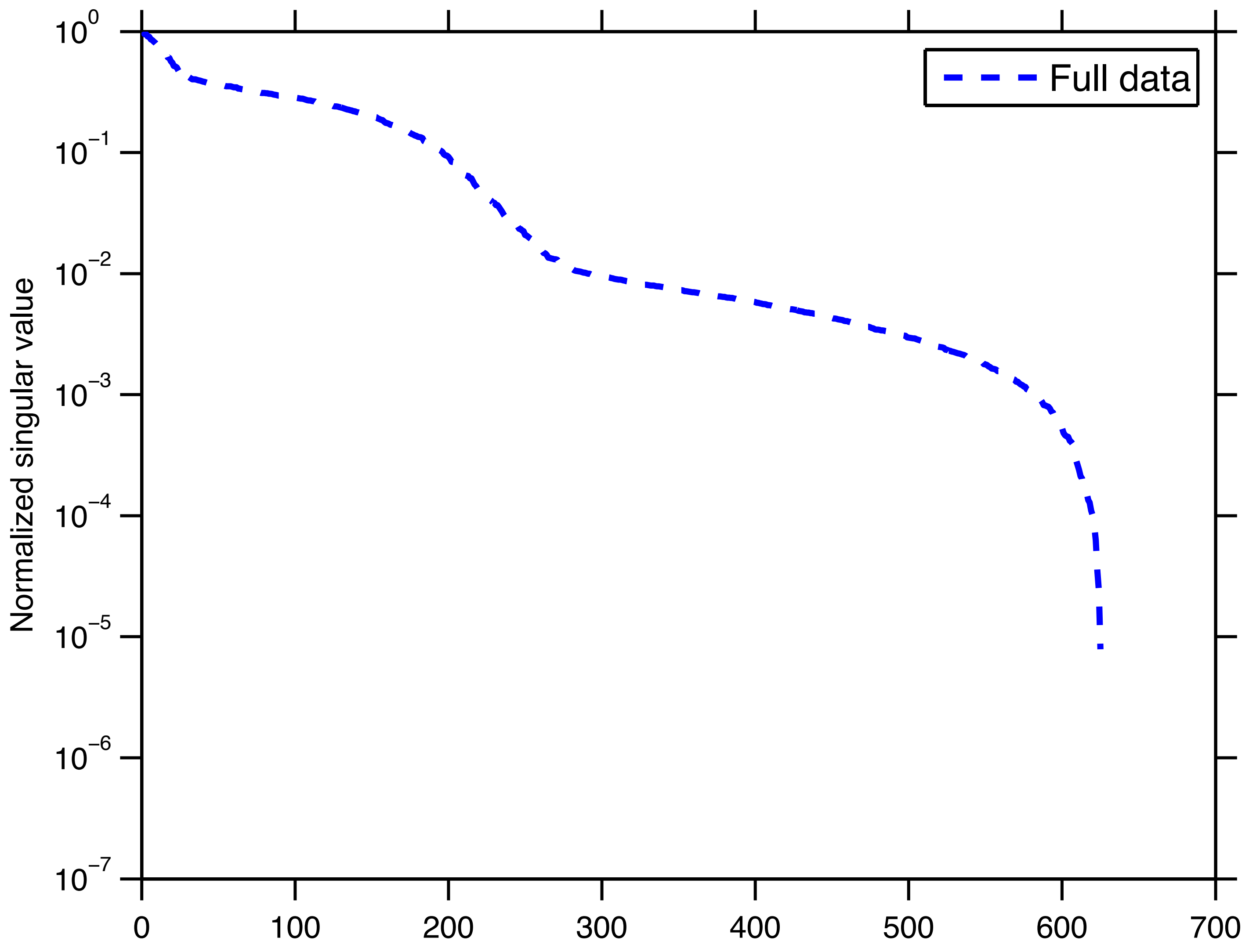
Singular value decay

2-D acquisition

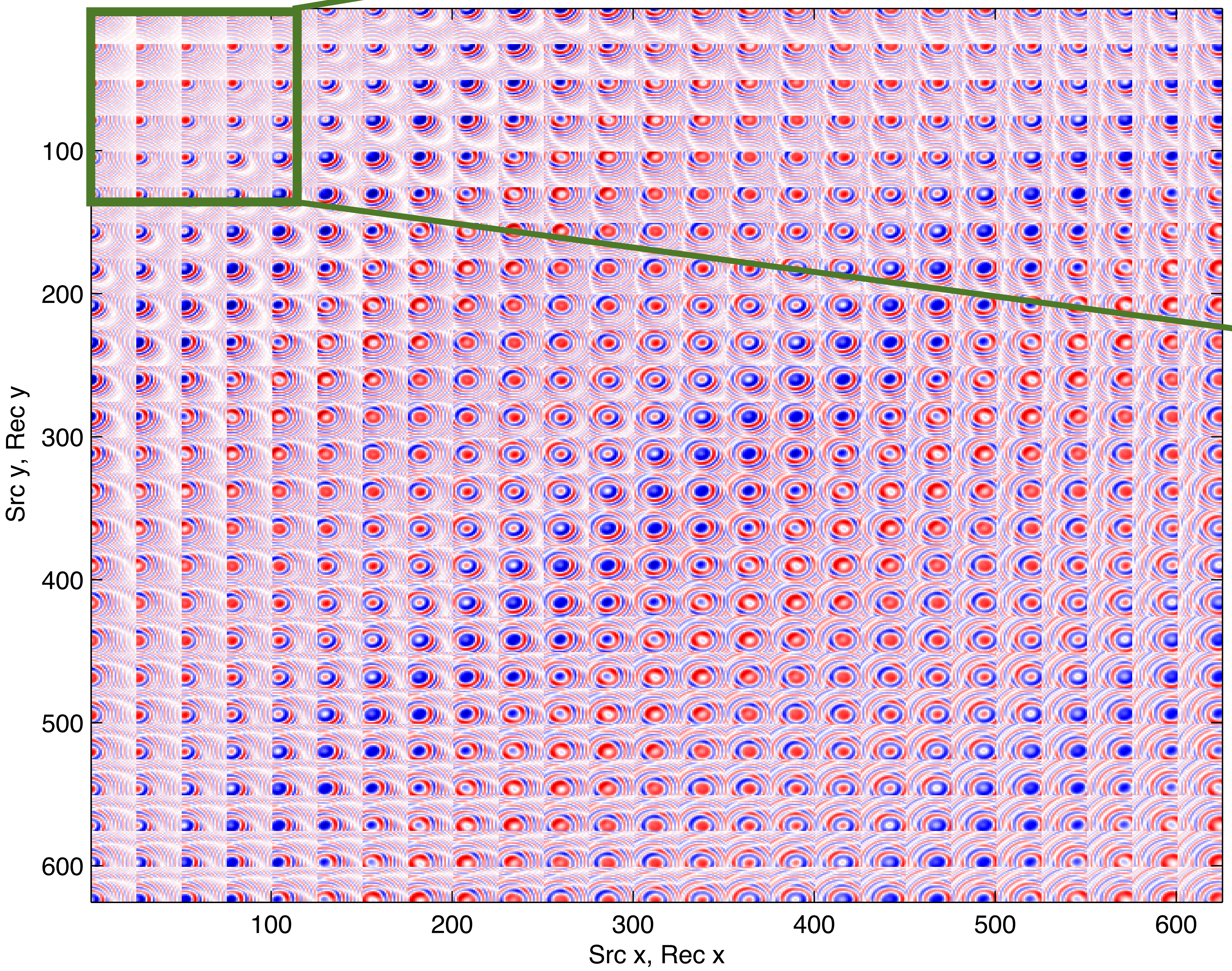


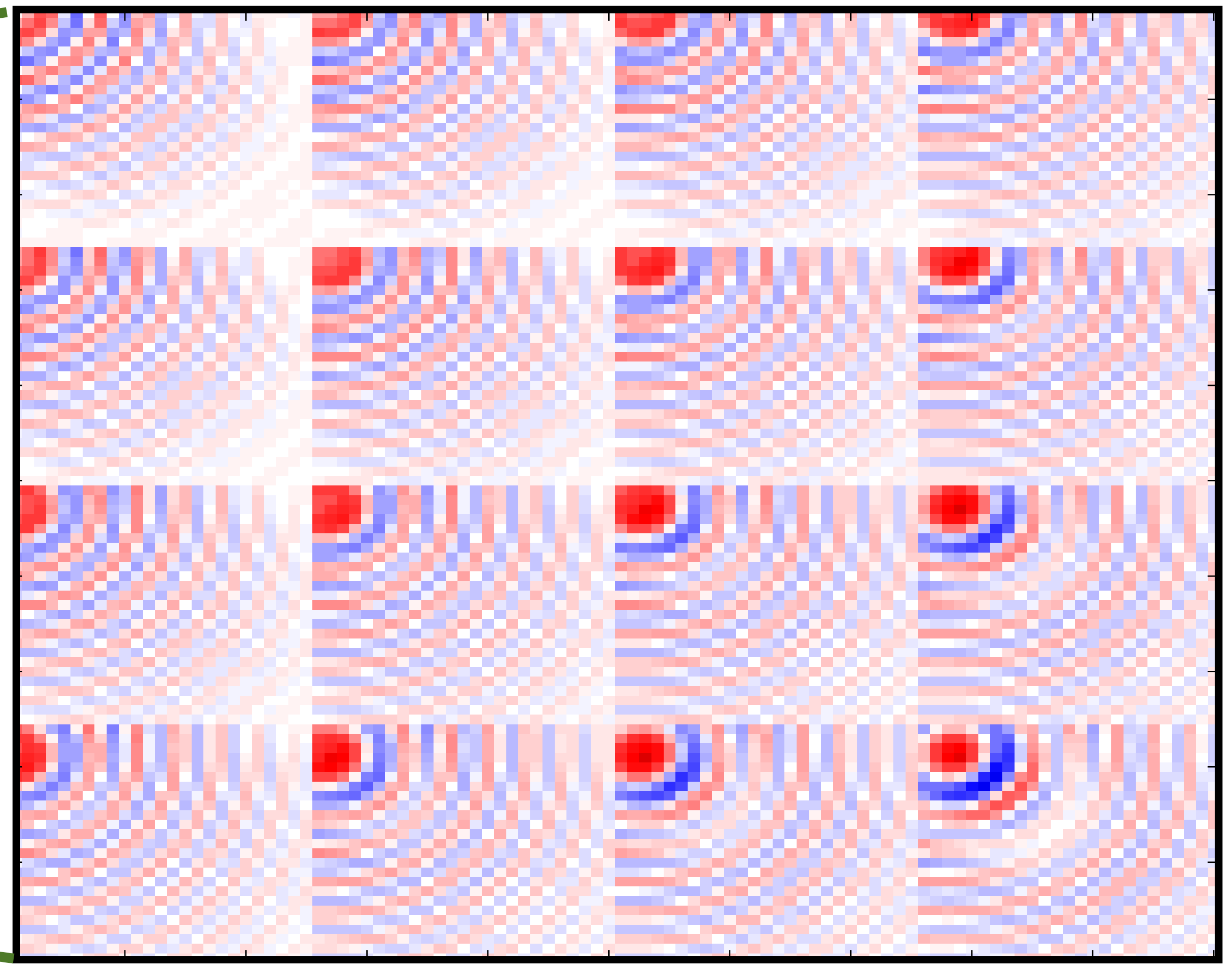
Low-rank structure
conventional 5D data, monochromatic slice, Sx-Sy matricization

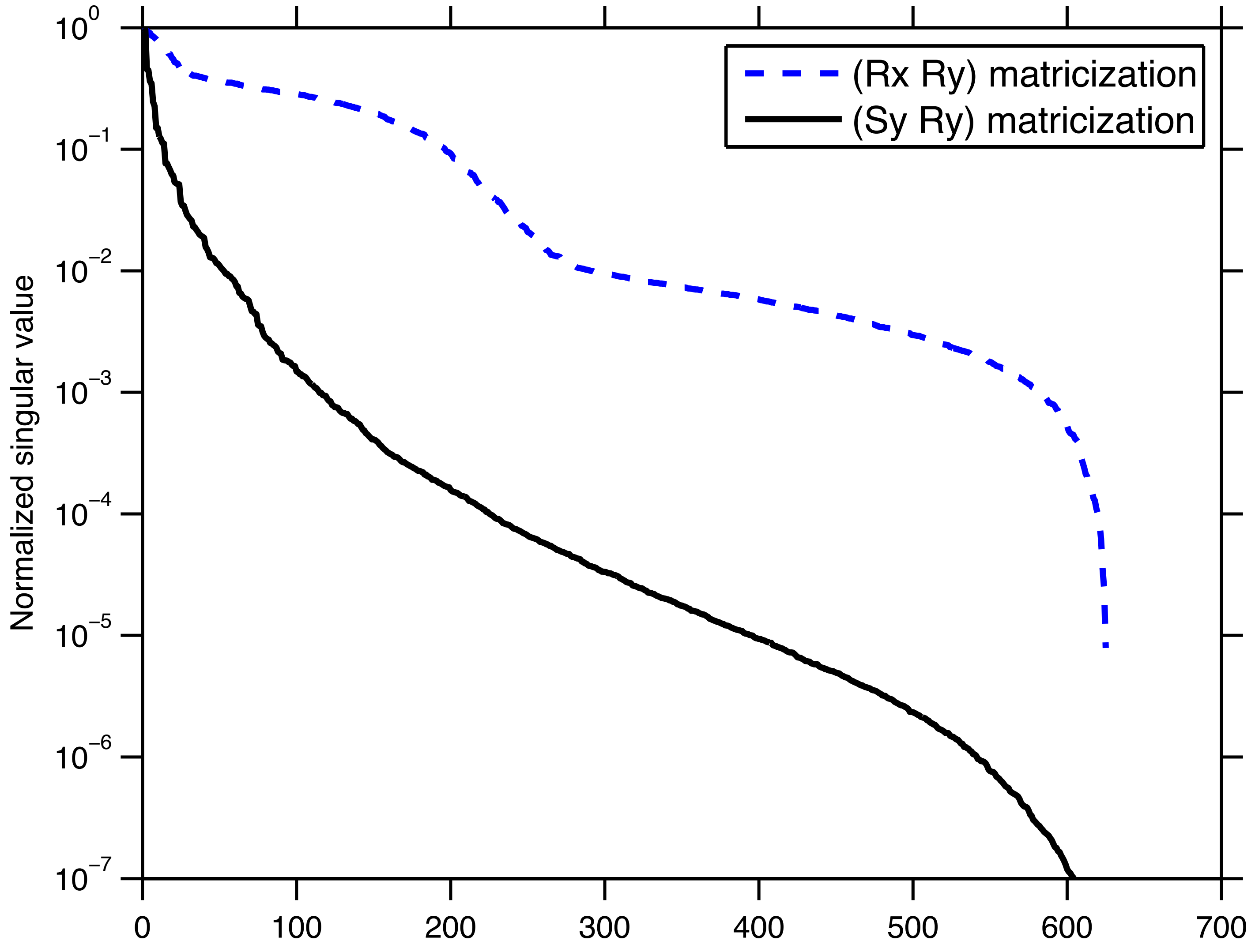




Low-rank structure
conventional 5D data, monochromatic slice, Sx-Rx matricization







Matrix completion

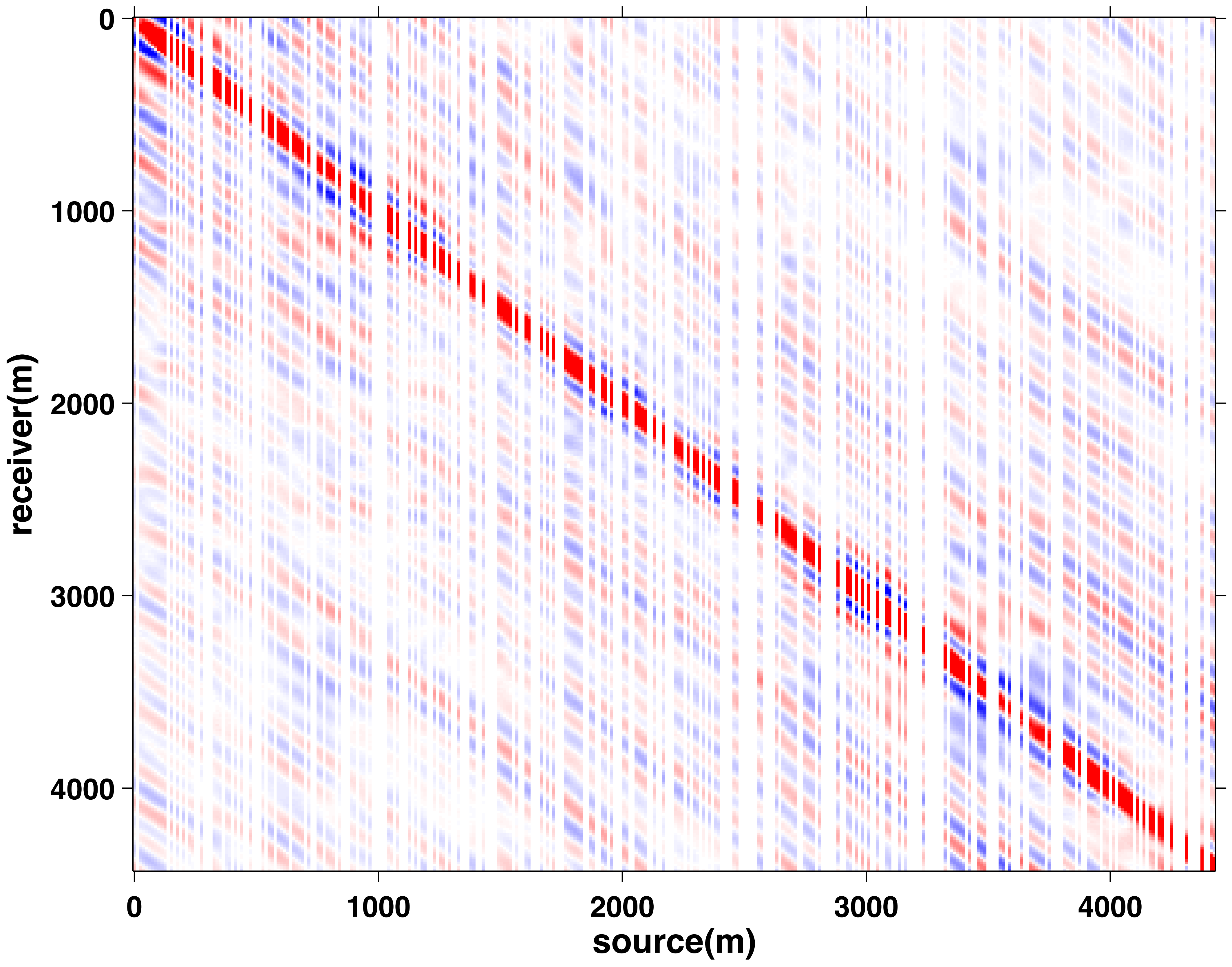
- signal structure
  - *low rank/fast decay* of singular values
- sampling scheme
  - missing data *increase* rank in "transform domain"
- recovery using *rank penalization* scheme

2-D acquisition

uniform-random sampling

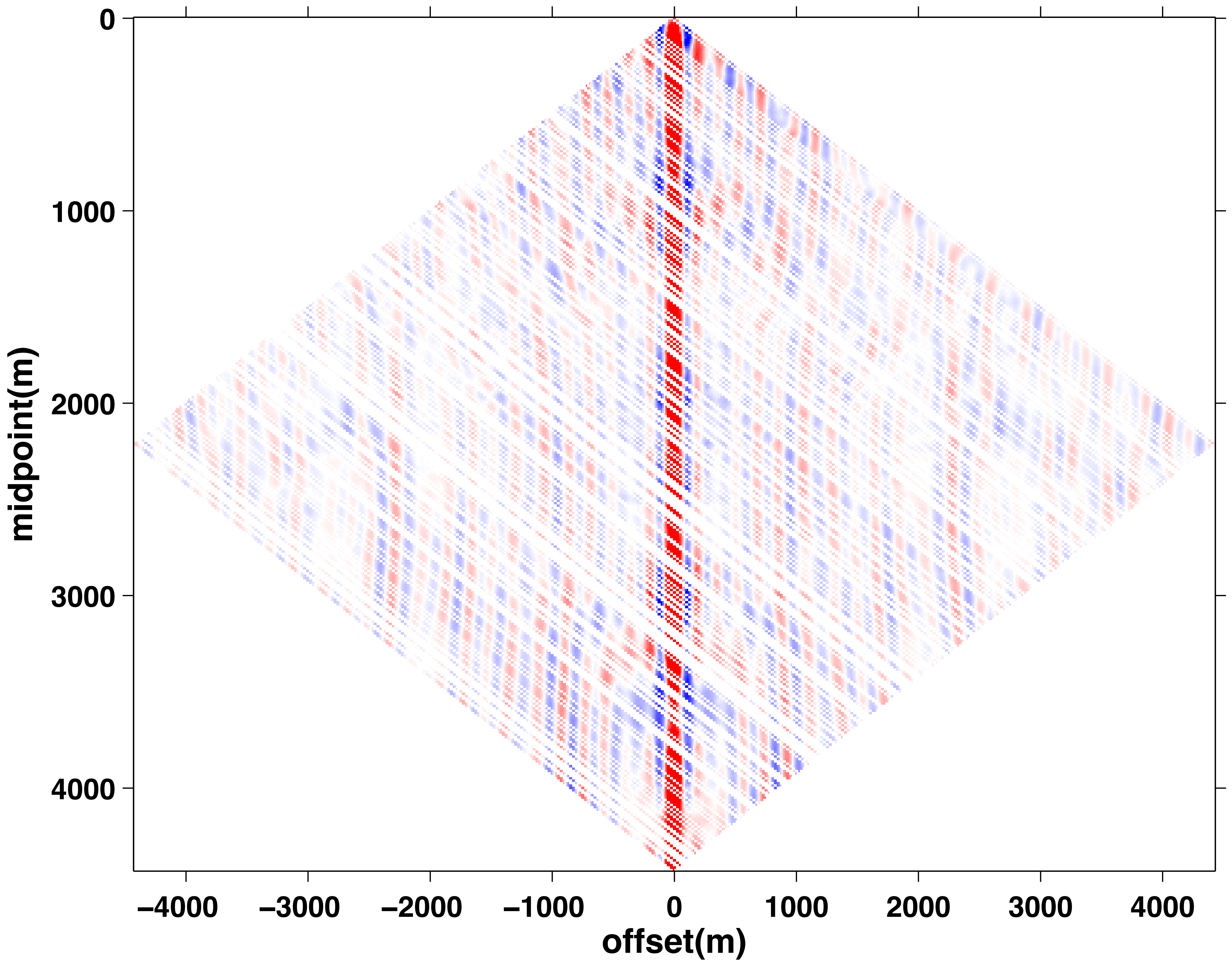
acquisition domain

missing columns *do not* increase rank



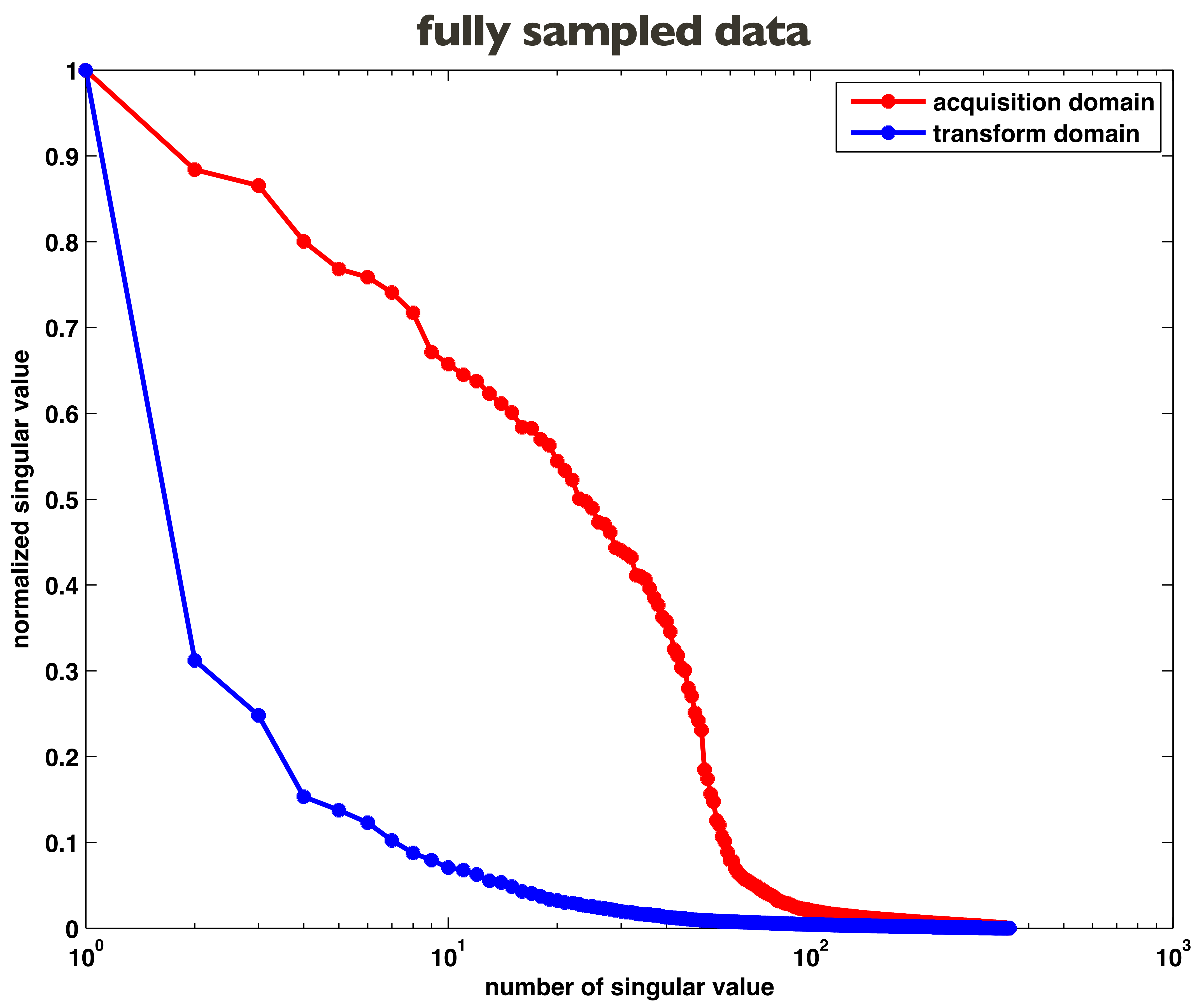
transform domain

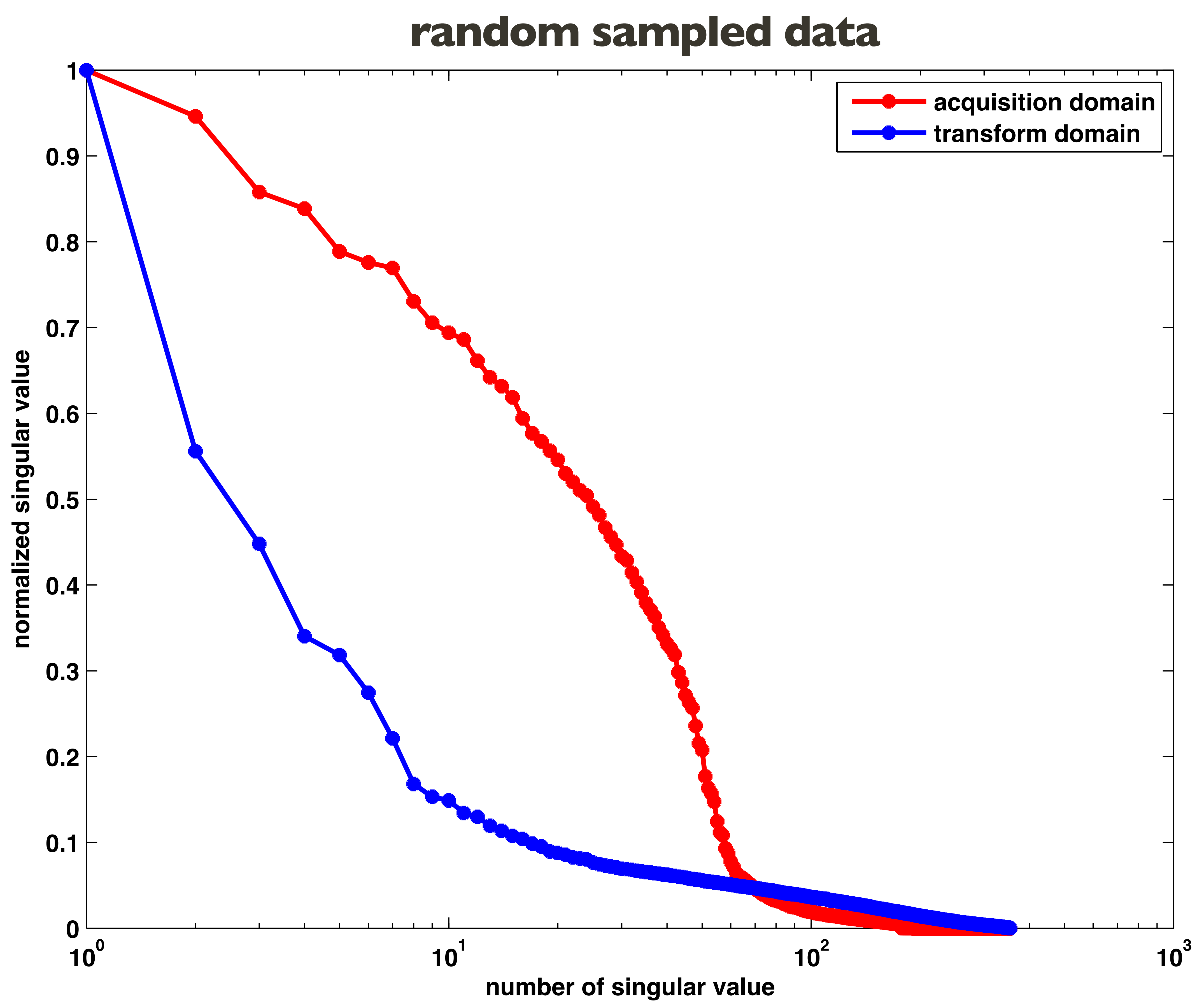
missing columns *do* increase rank



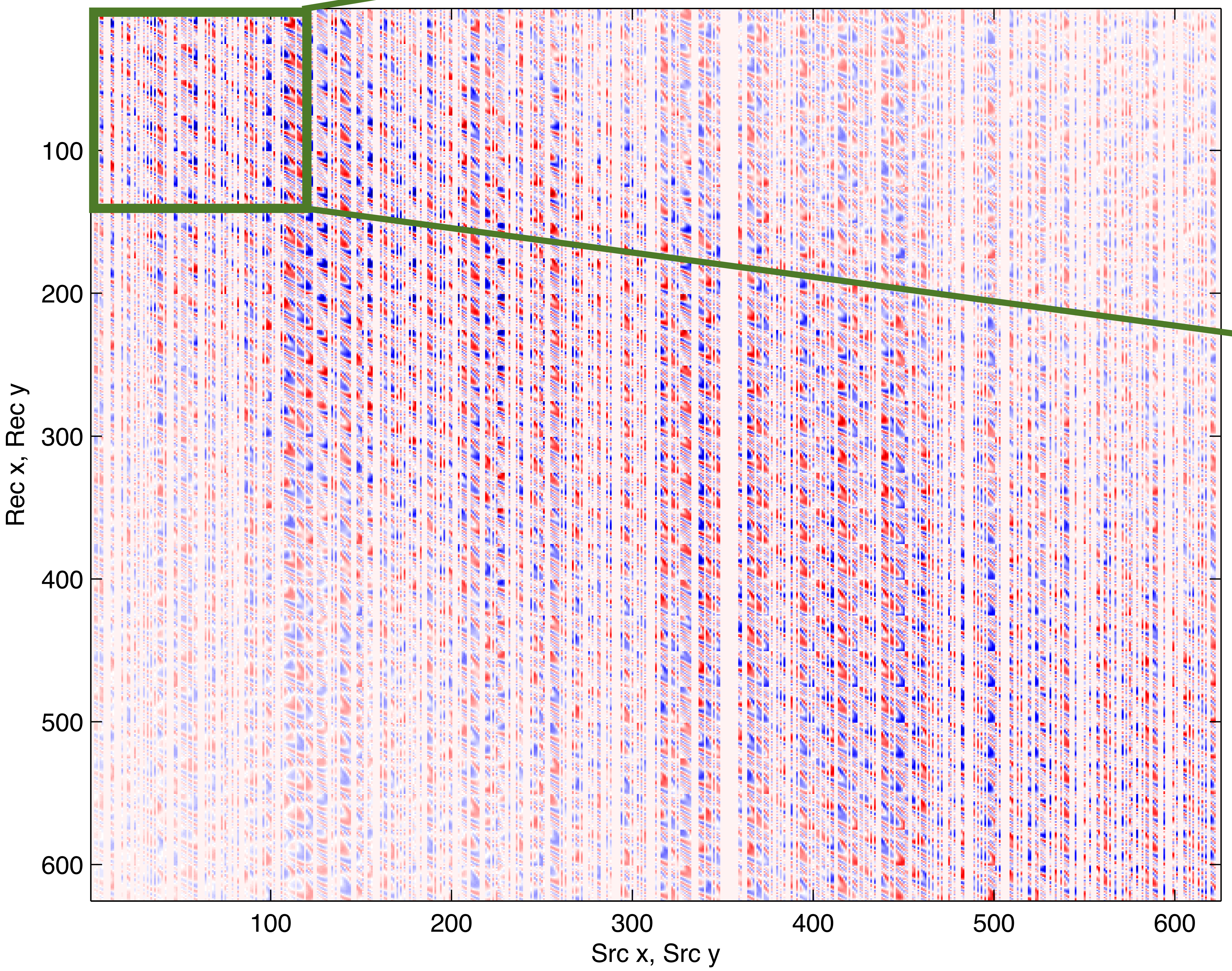
Randomized sampling

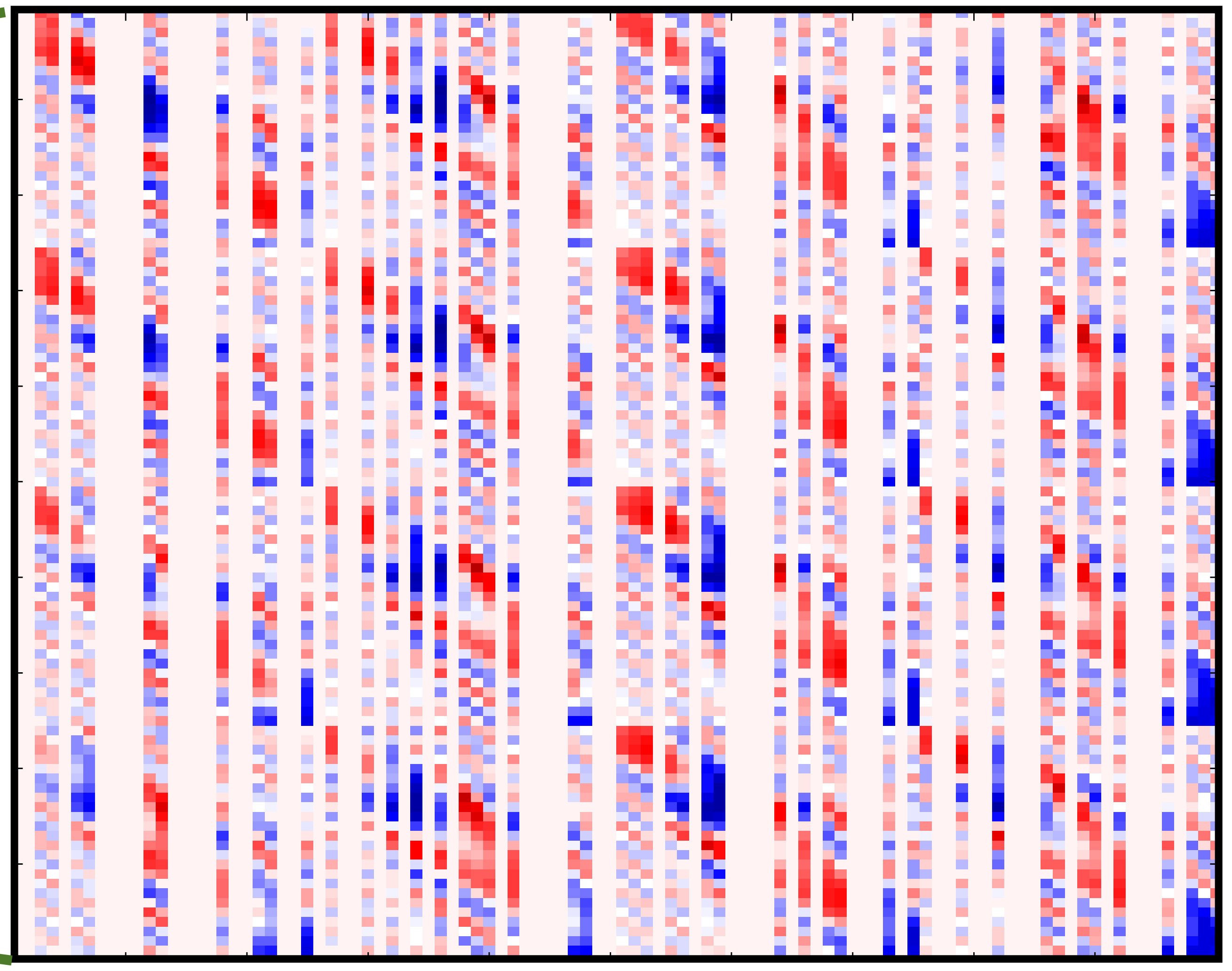
singular value decay

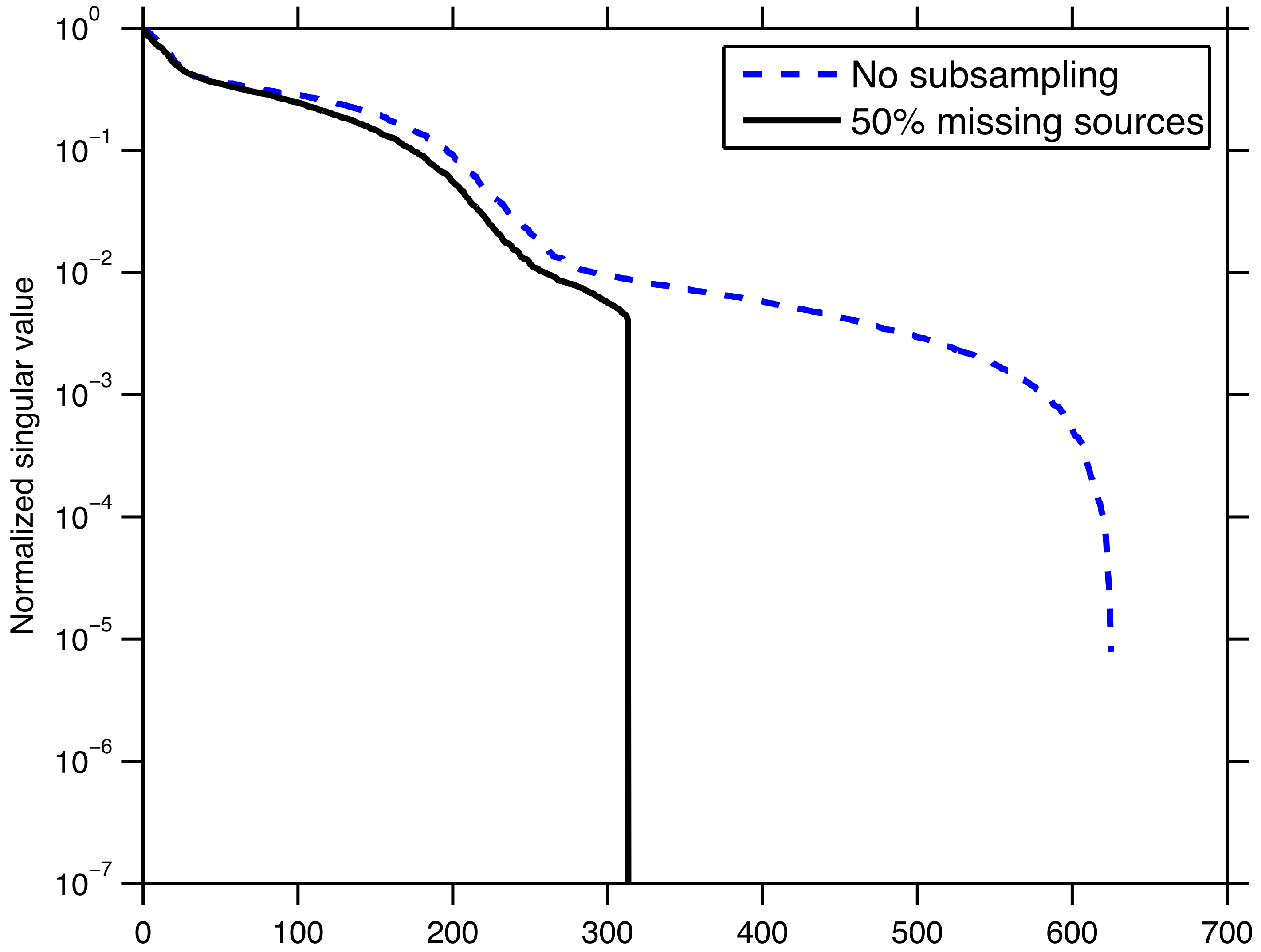




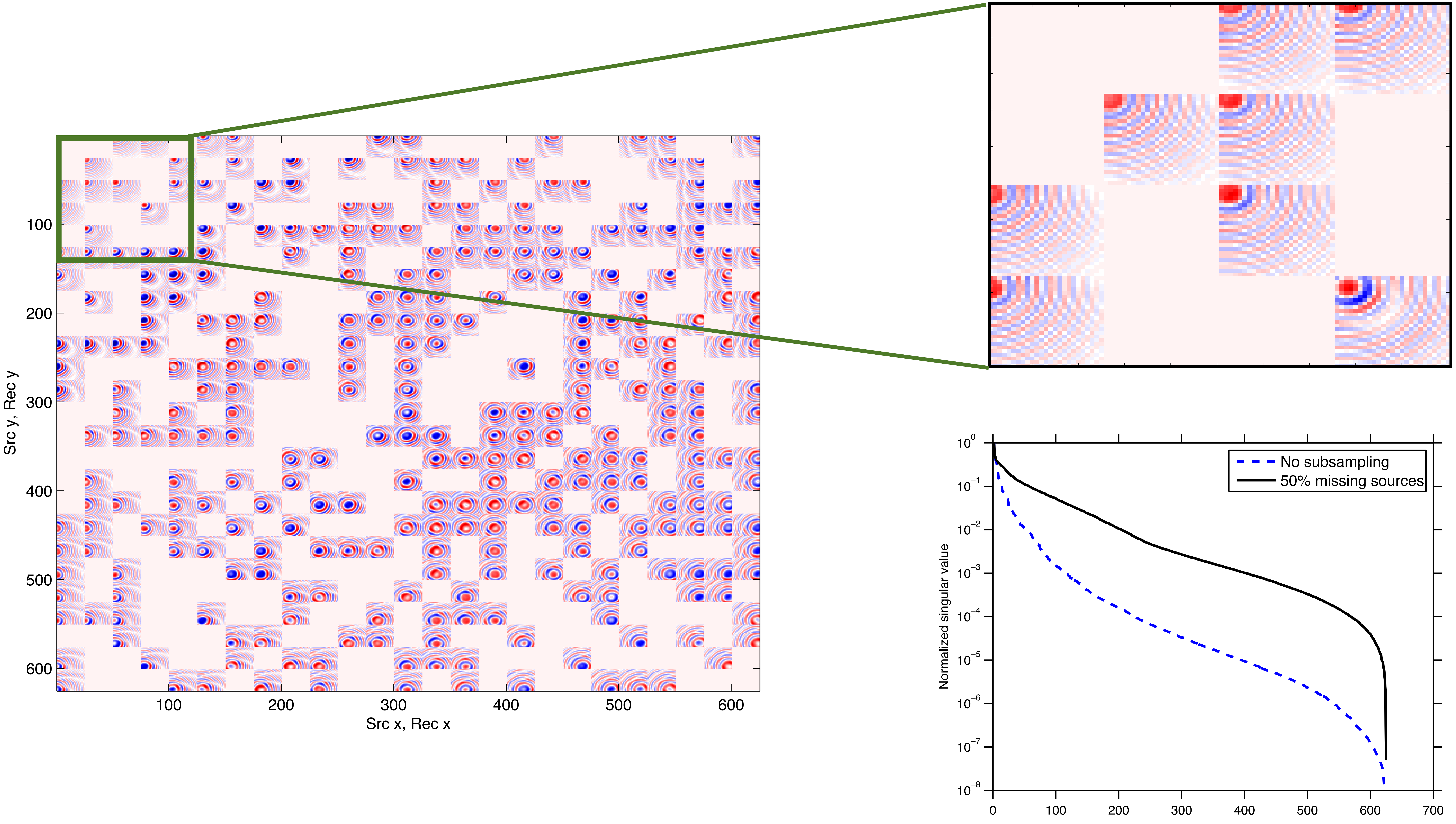
Low-rank structure
time-jittered data, monochromatic slice, Sx-Sy matricization







Low-rank structure
time-jittered data, monochromatic slice, Sx-Rx matricization



Matrix completion

- signal structure
  - *low rank/fast decay* of singular values
- sampling scheme
  - missing data *increase* rank in "transform domain"
- recovery using *rank penalization* scheme

Nuclear-norm minimization

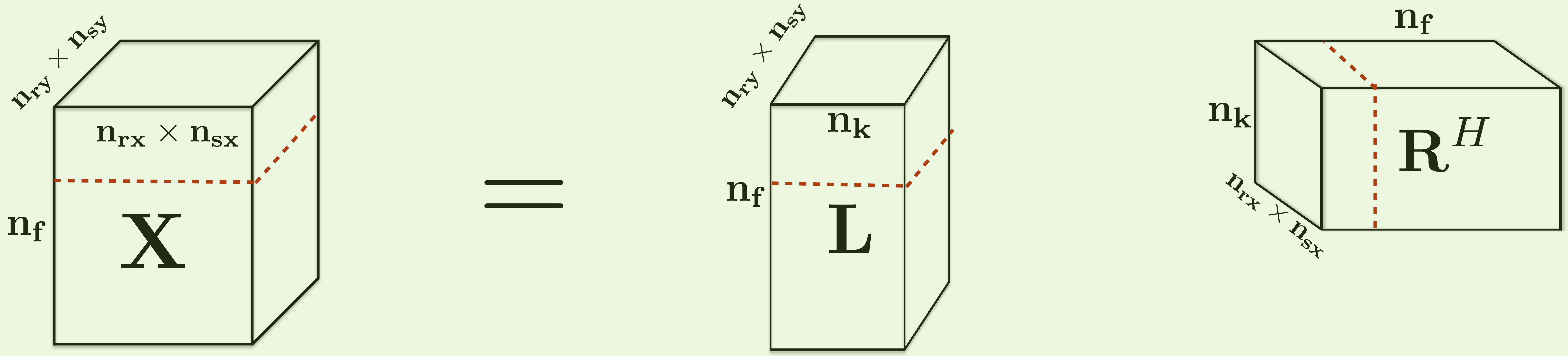
convex relaxation of rank-minimization

[Recht et. al., 2010]

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

[Rennie and Srebro 2005, Lee et. al. 2010, Recht and Re 2011]

$$\mathbf{X} = \mathbf{L}\mathbf{R}^H$$



$\mathbf{X} \in \mathbb{C}^{\mathrm{n_f} \times \mathrm{n_{rx}} \times \mathrm{n_{sx}} \times \mathrm{n_{ry}} \times \mathrm{n_{sy}}}$ $\quad$ $\mathbf{L} \in \mathbb{C}^{\mathrm{n_f} \times \mathrm{n_{rx}} \times \mathrm{n_{sx}} \times \mathrm{n_k}}$ $\quad$ $\mathbf{R} \in \mathbb{C}^{\mathrm{n_f} \times \mathrm{n_{ry}} \times \mathrm{n_{sy}} \times \mathrm{n_k}}$

[Rennie and Srebro 2005]

Factorized formulation

- Upper-bound on nuclear norm is defined as

$$\|\mathbf{L}\mathbf{R}^H\|_* \leq \frac{1}{2}\left\|\begin{bmatrix}\mathbf{L}\\ \mathbf{R}\end{bmatrix}\right\|_F^2$$

where $\|\cdot\|_F^2$ is sum of squares of all entries

- choose k *explicitly* & avoid costly *SVD's*

Computational cost

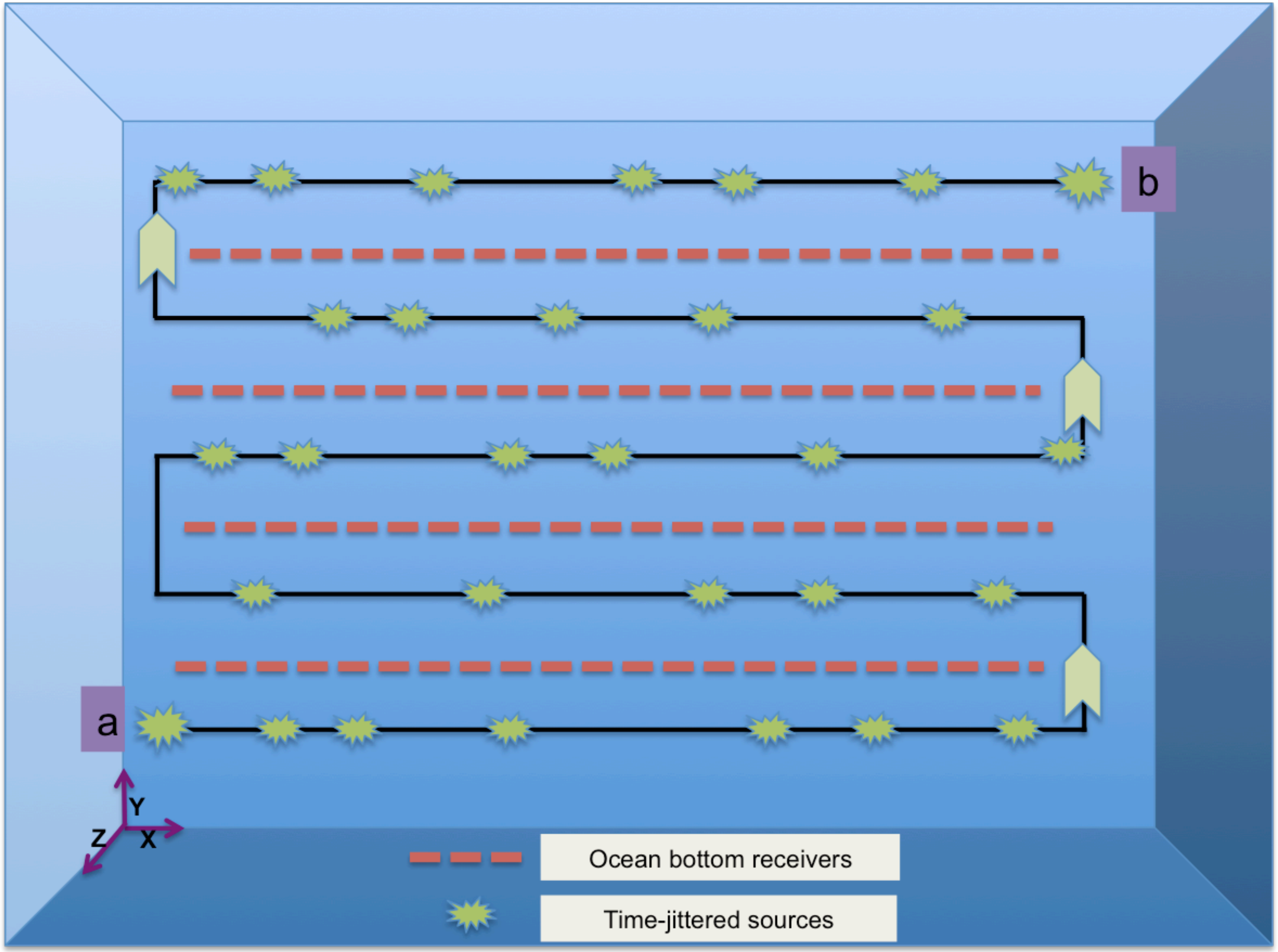
matrix completion v/s curvelet-based methods

2D interpolation

- 1001 time-samples, 355 sources, 355 receivers
- 50% and 75% subsampling scenario

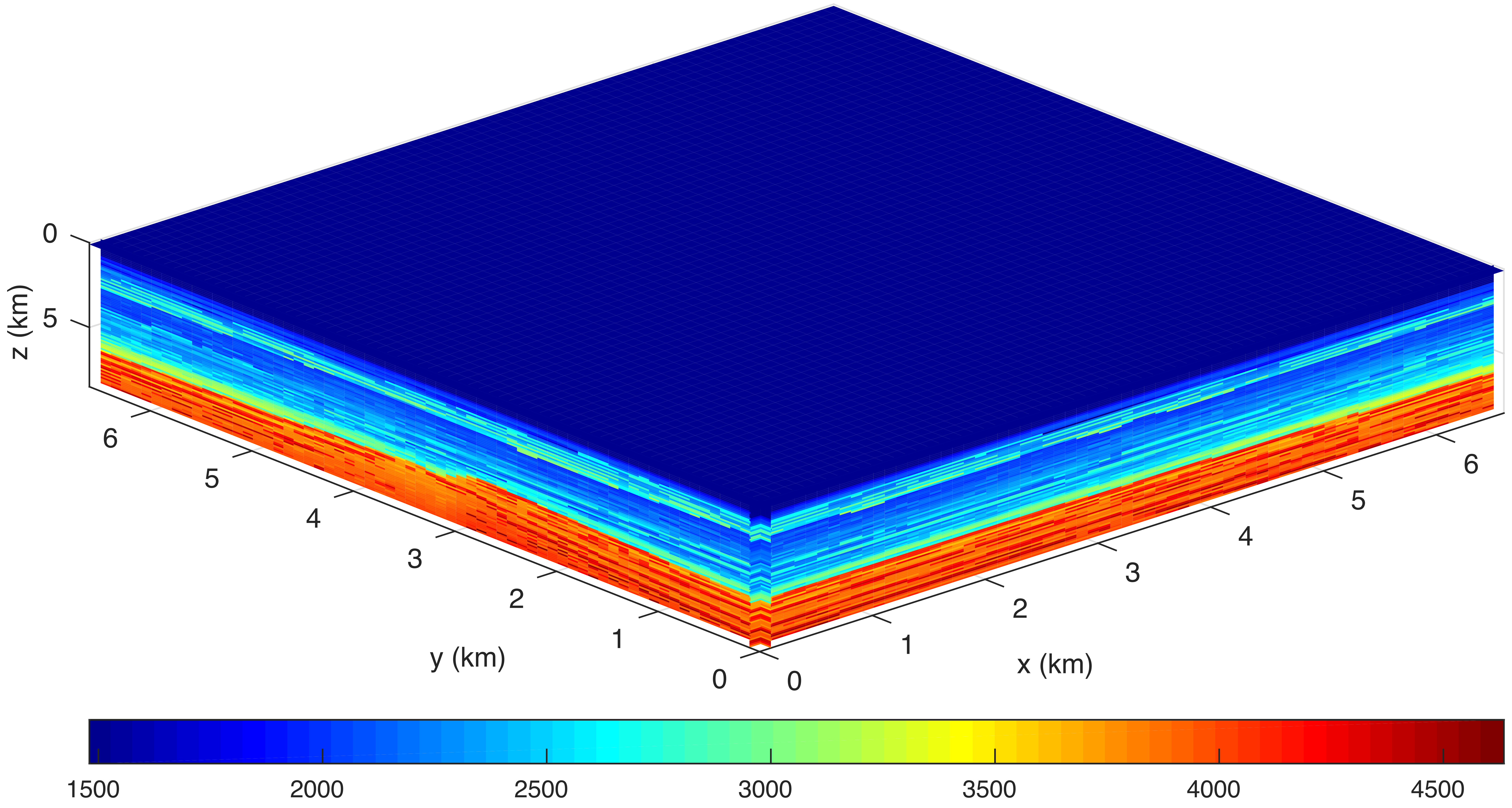
		50%		75%	
	σ	0.1	0.08	0.1	0.08
Matrix completion w/ SVD	SNR (dB)	17.3	18.3	11.6	11.5
	time (sec)	812	937	790	765
Matrix completion w/o SVD	SNR (dB)	17.6	18.4	12.6	13.1
	time (sec)	8	10	8	7
Curvelet-based sparsity promotion	SNR (dB)	17.4	18.6	12.5	12.8
	time (sec)	879	989	817	1010

Acquisition setup



- 10s temporal length
- 25 m flip-flop shooting
  - source-sampling ranges from 25 m to 175 m
  - effective 50 m source sampling for each airgun array
  - acquired 400 sources
- 10201 receivers
- Ricker wavelet with central frequency of 20 Hz
- size of the recovered 5D seismic data volume is 0.3 TB

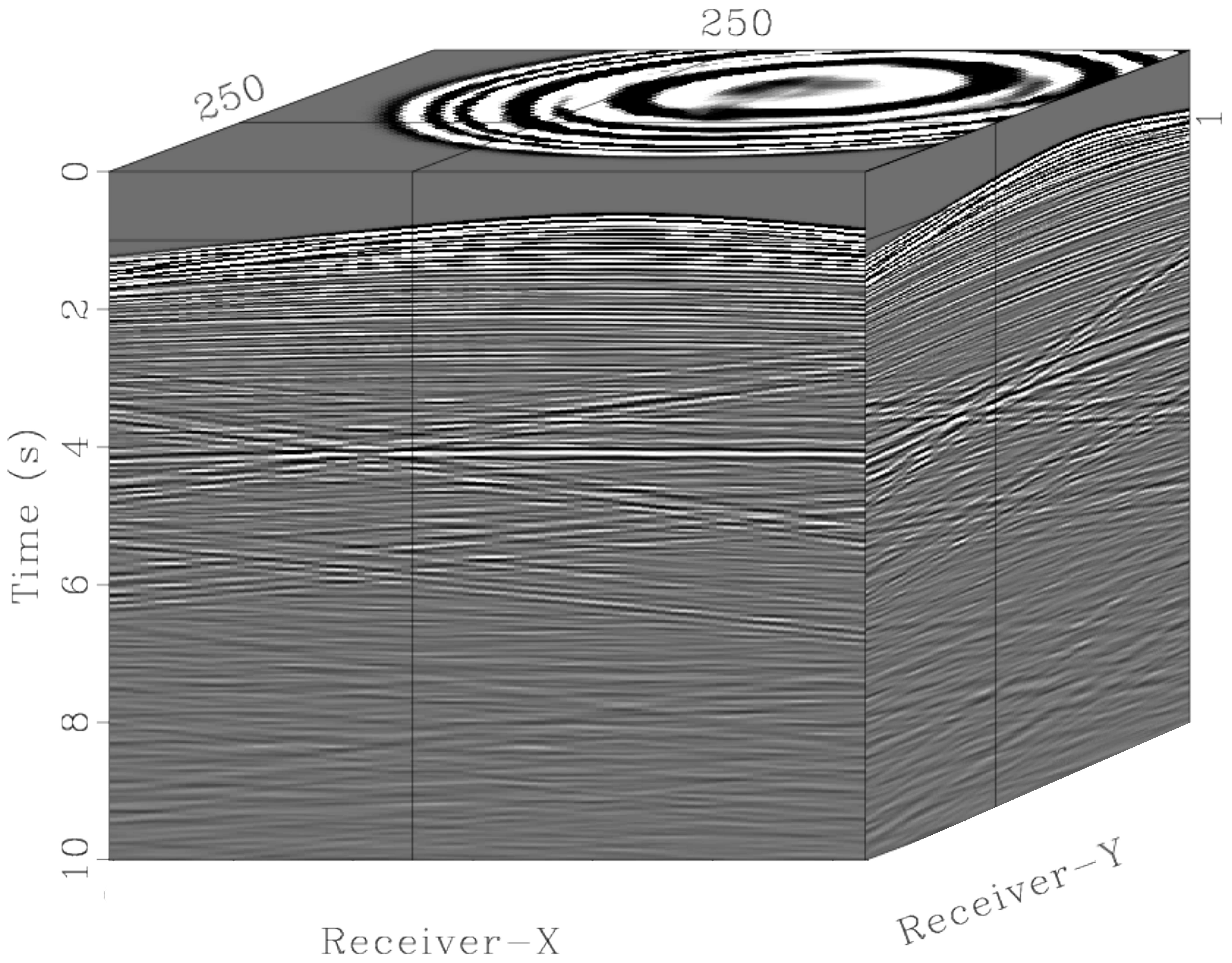
3D BG Compass model



Optimization information

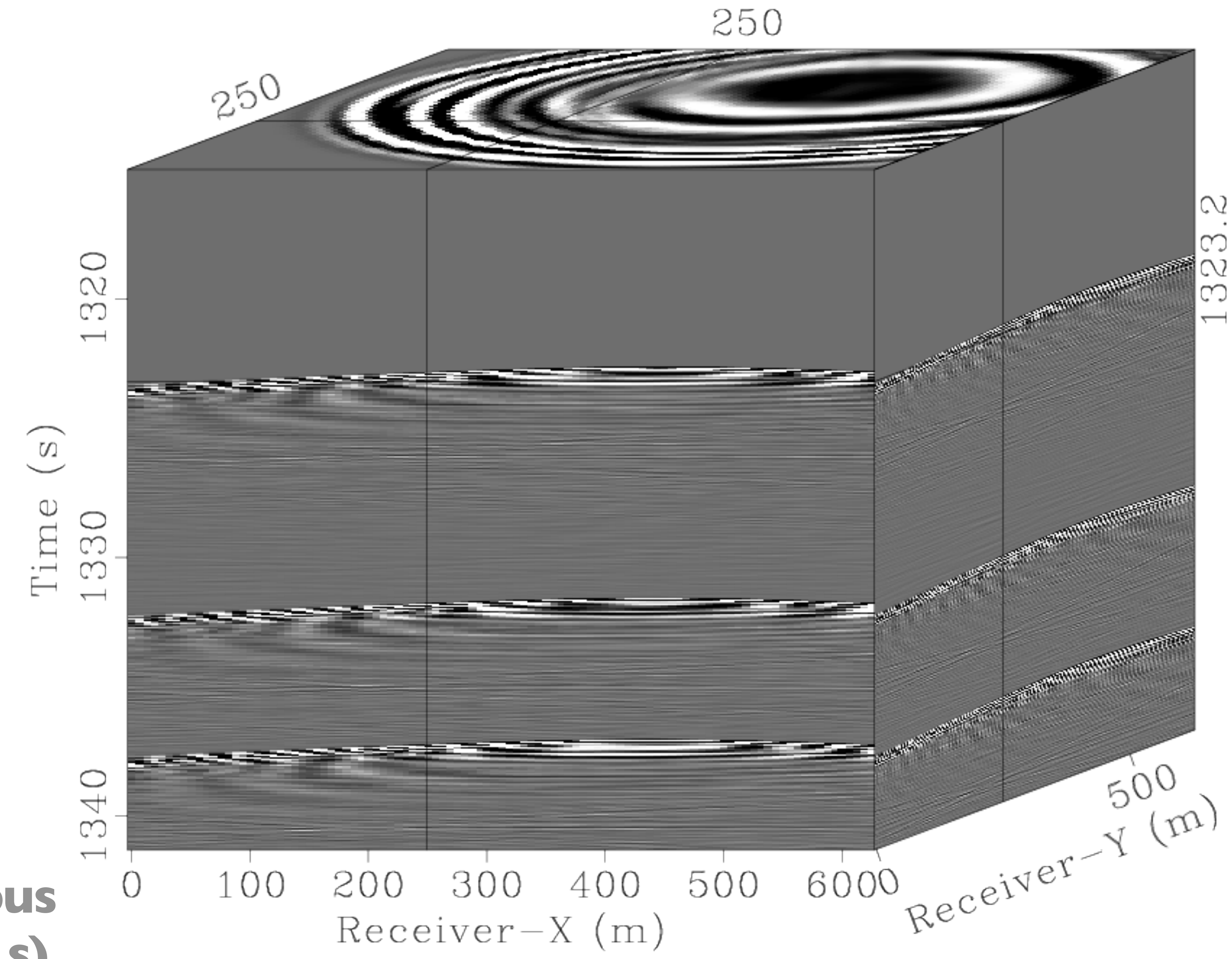
- Parallelized factorization framework over sources and receivers
- 200 iterations, computational time 42 hours, fixed 100 rank values across frequencies
- Separation + interpolation @ 6.25 m grid, recovered 1600 sources
- SENAI Yemoja cluster: 30 nodes, 128 GB RAM each, 20-core processors
- 300 Parallel Matlab workers (10 per node), multithread - full core utilization

Conventional data
common-shot gather, @6.25 m source sampling



Observed v/s recovered

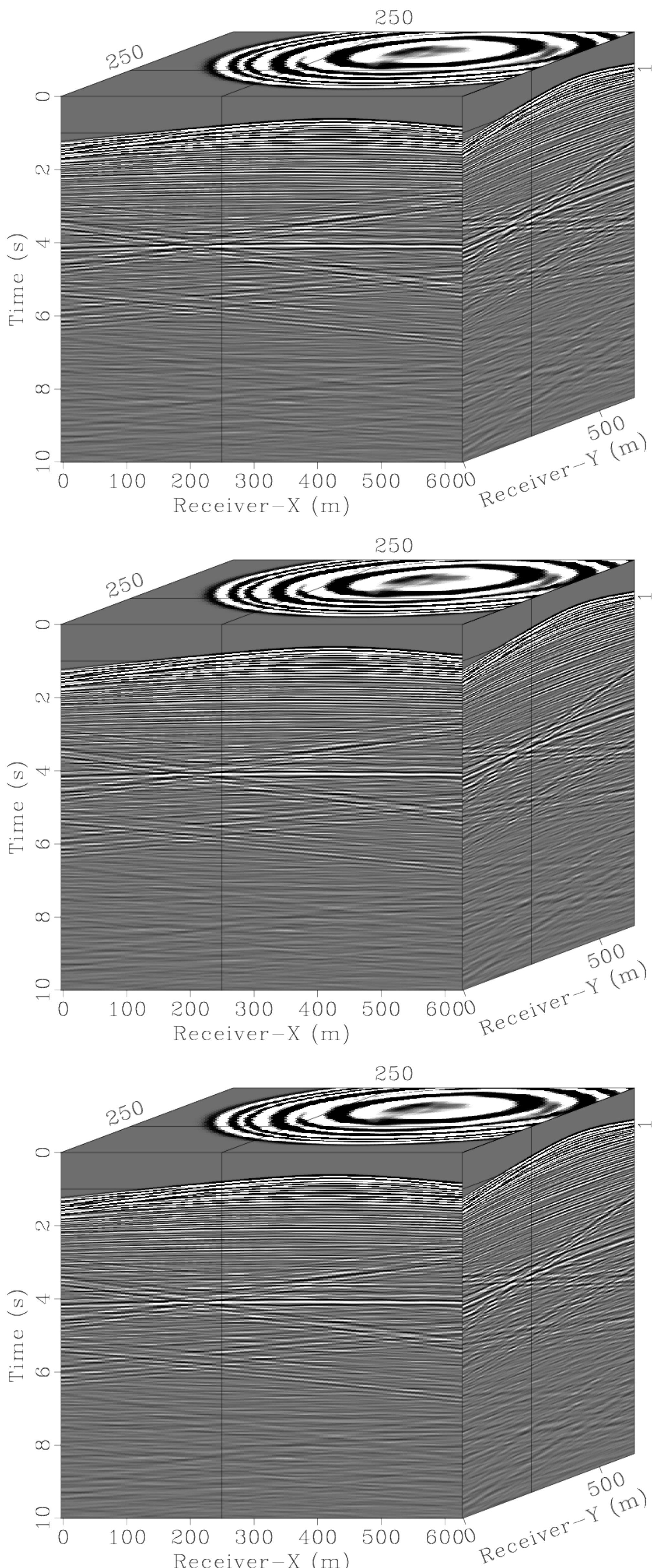
Observed data @ 25 m flip-flop (overlapping & missing shots)



continuous data (30 s)

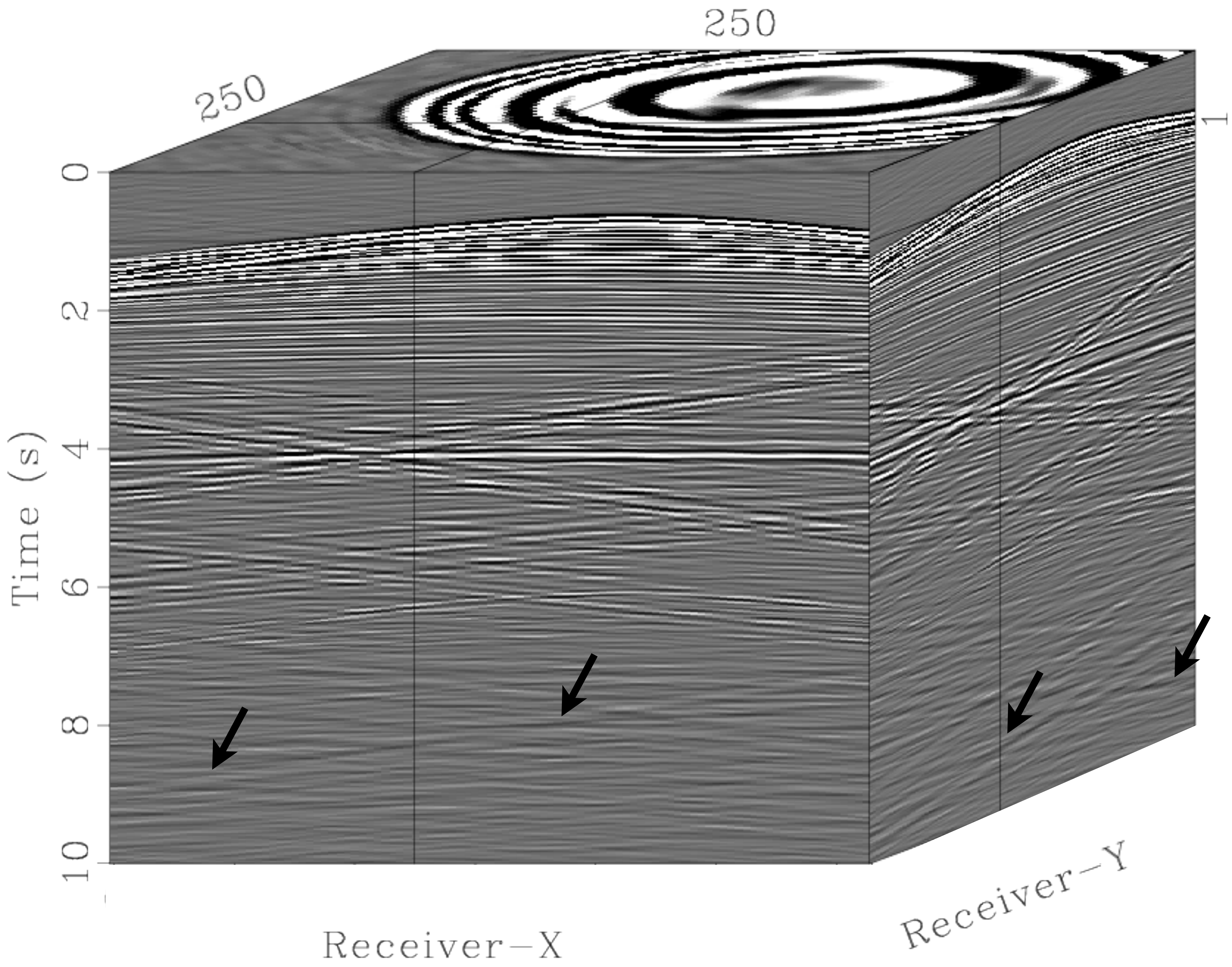
Recovery

Separation + Interpolation (recovered grid @ 6.25m)

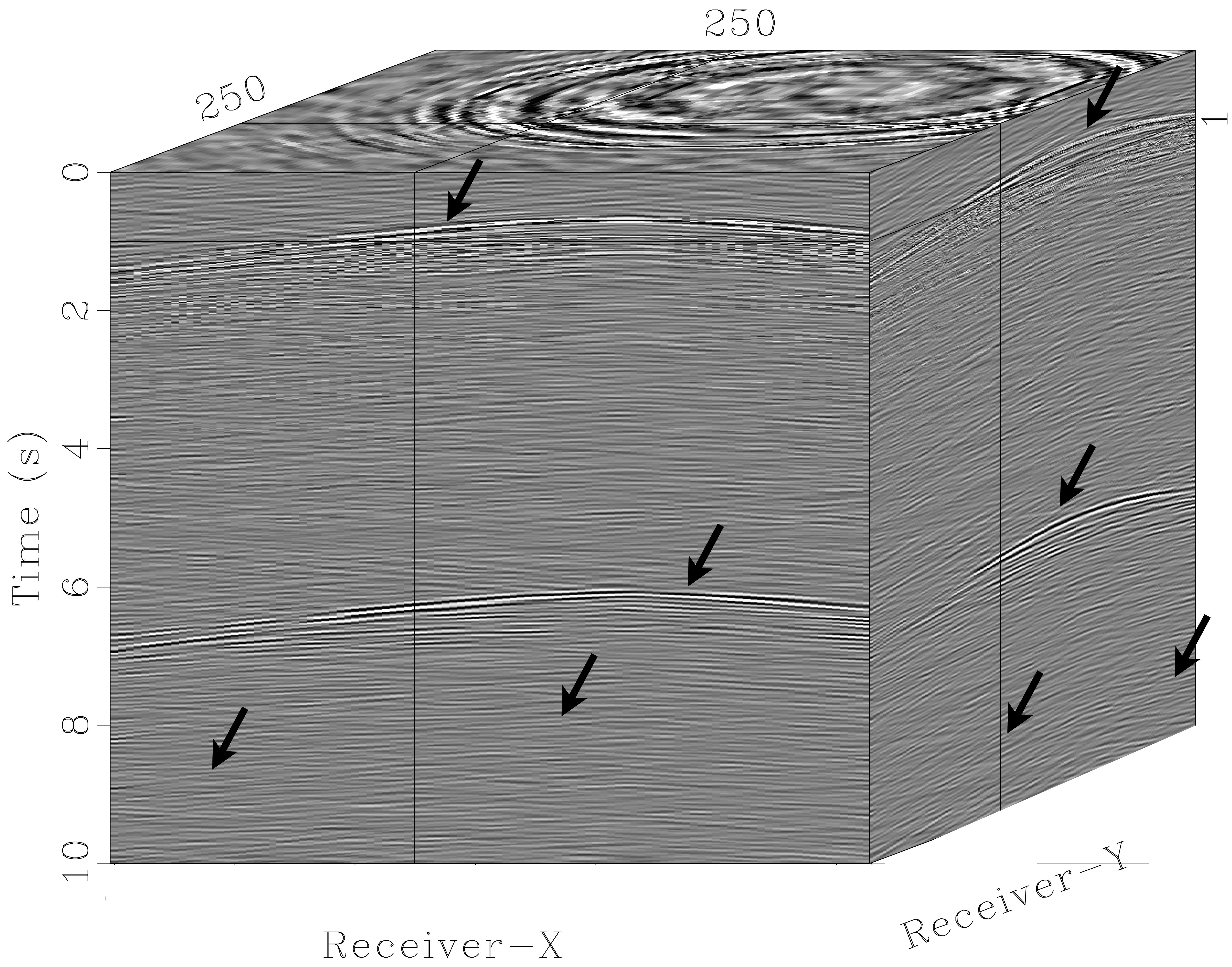


After Source-Separation

common-shot gather, SNR = 21dB, preserved late-arrivals energy



Residual
10x magnified



reconstructed late-arrivals

Benefits of LR framework

- **4X** up-sampling (@ 6.25m) & saving in acquisition time
- size of final recovered data volume is **0.3 TB**
  - no need to save fully sampled seismic data volume
- save $\mathbf{L}$ and $\mathbf{R}$ factors
  - compression rate is **98%**
  - size of final compressed 5D seismic volume is **~7 GB**

Contributions: Chapter 6

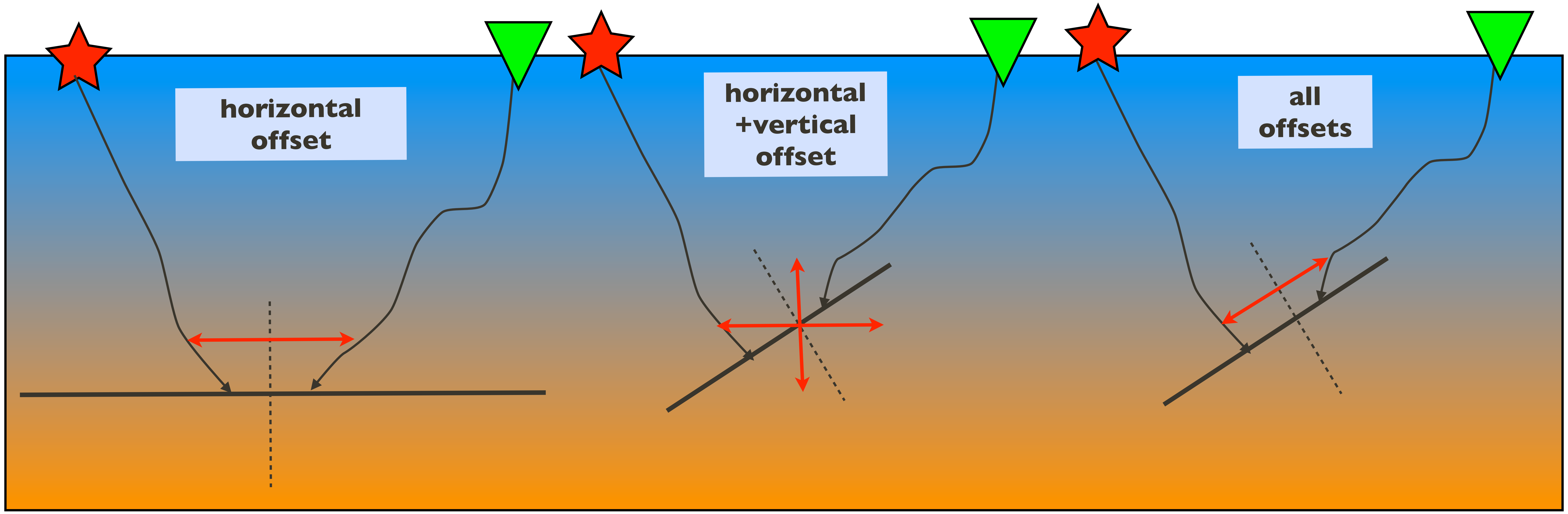
Derive two-way wave-equation based factorization principle to form full-subsurface *extended-image volume to perform*

- Velocity analysis
- Targeted imaging
- QC tool for validating the velocity inversion

What is extended image-volumes?

- Mapping of seismic data recorded at the surface to each and every grid point in the subsurface

- This mapping preserves energy from data-domain to image-domain



Extended images

Given two-way wave equations, source and receiver wavefields are defined as

$$H(\mathbf{m})U = P_s^T Q$$
$$H(\mathbf{m})^* V = P_r^T D$$

Organize wavefields in monochromatic data *matrices* where each *column* represents a *common* shot gather

Express image volume *tensor* for *single* frequency as a *matrix*

$$E = UV^*$$

Extended images

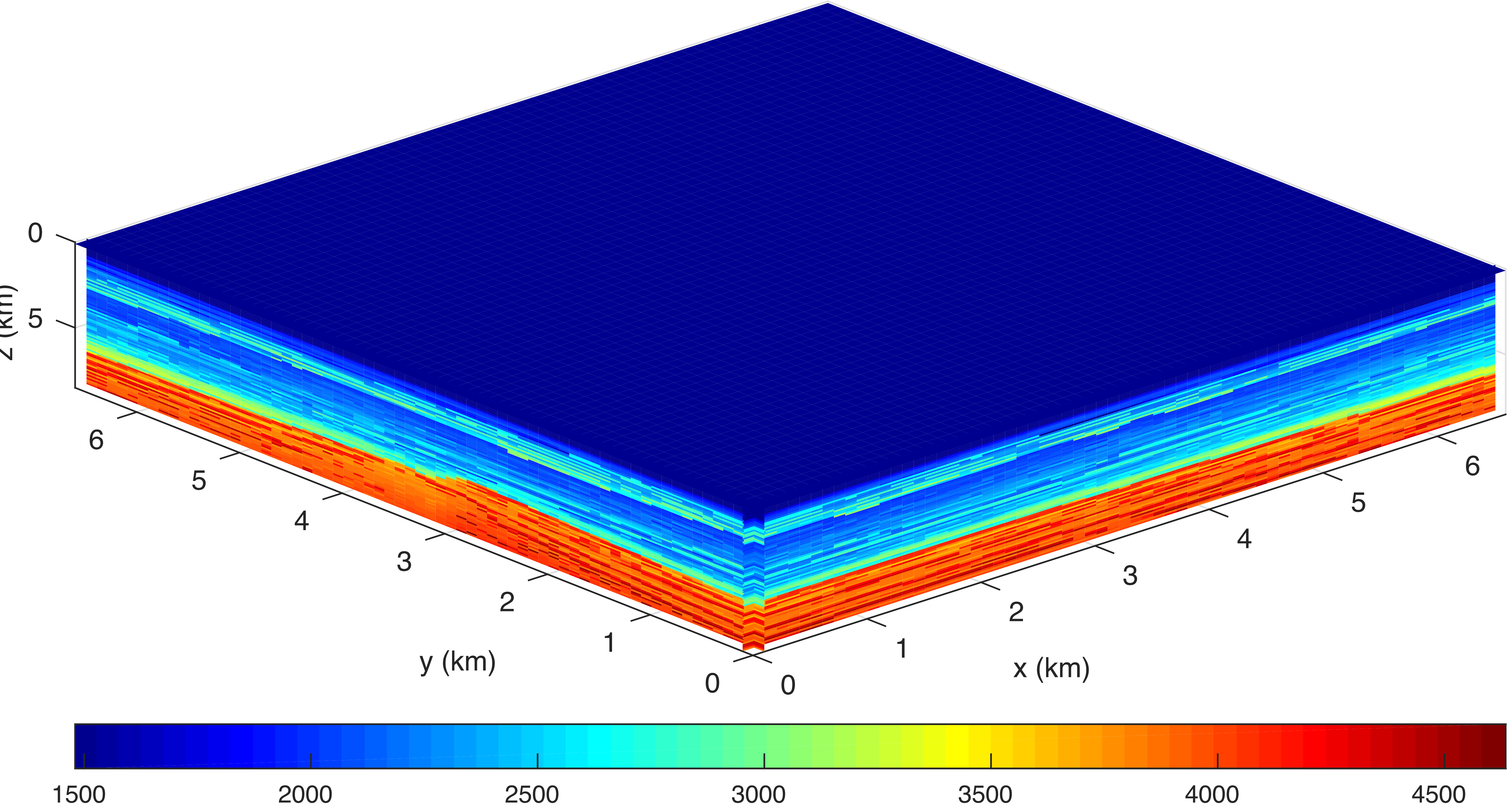
Too expensive to compute *(storage and computational time)*

Instead, *probe* volume with *tall* matrix $W = [\mathbf{w}_1, \ldots, \mathbf{w}_l]$

$$\widetilde{E} = EW = H^{-1} P_s^T Q D^* P_r H^{-1} W$$

where $\mathbf{w}_i = [0, \ldots, 0, 1, 0, \ldots, 0]$ represents *single* scattering points

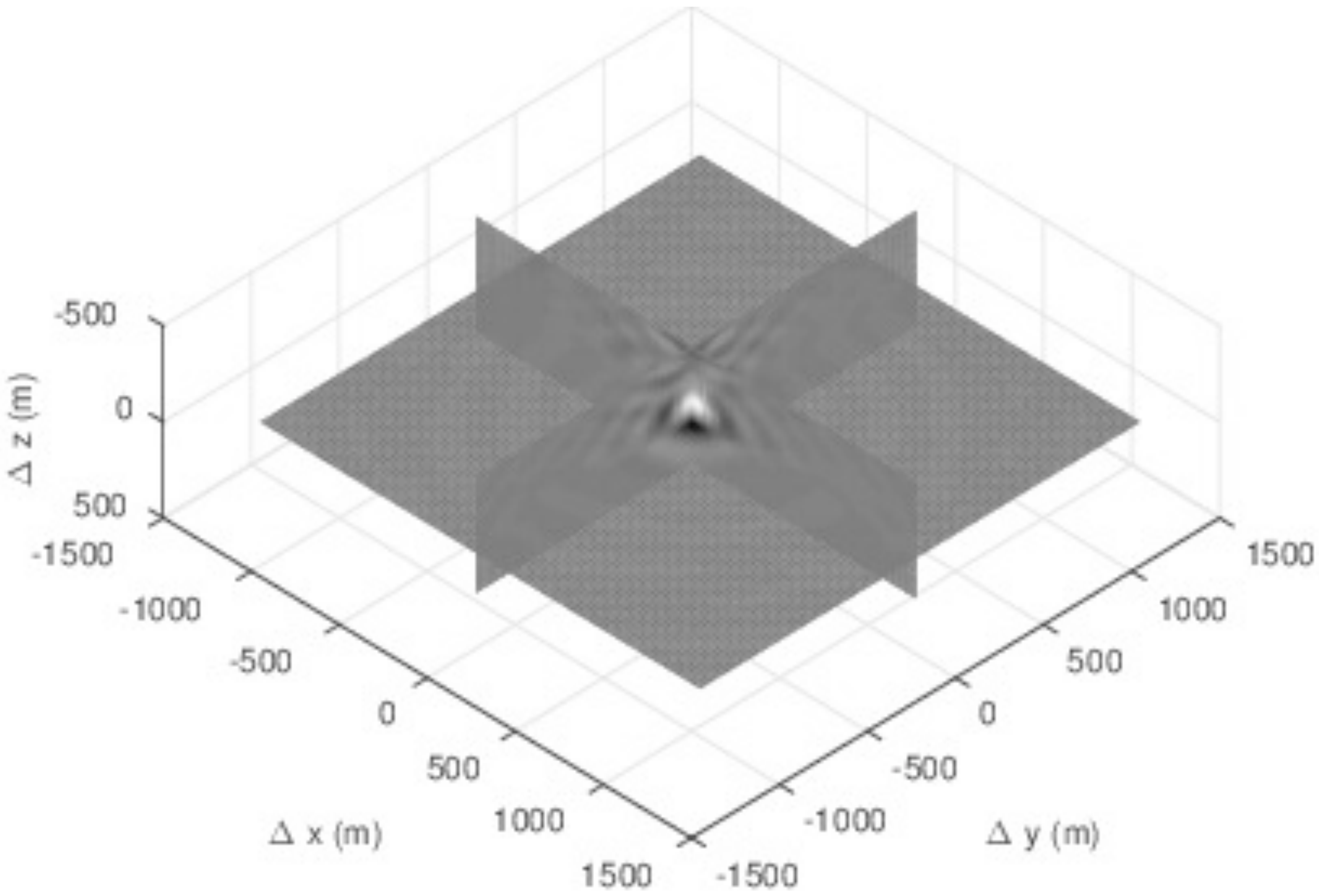
3D BG Compass model



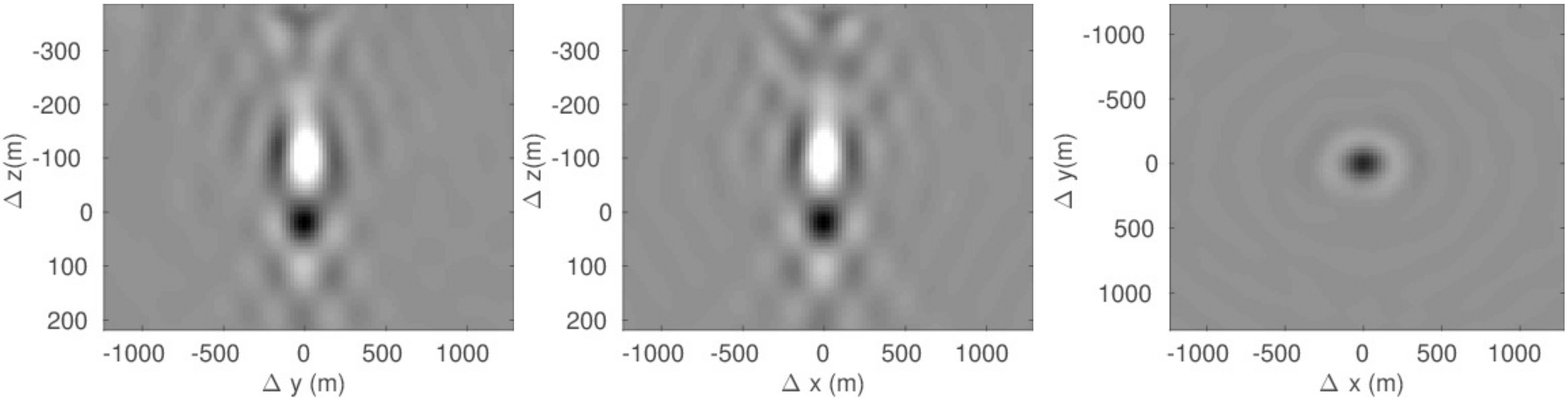
Experimental details

- 1200 source (75 m spacing)
- 2500 receivers (50 m spacing)
- 5-12 Hz
- OBN acquisition
- peak frequency 15 Hz
- One probing vector
- **1500 times faster then conventional method**

Common-image point gather



Cross section across common-image point gather

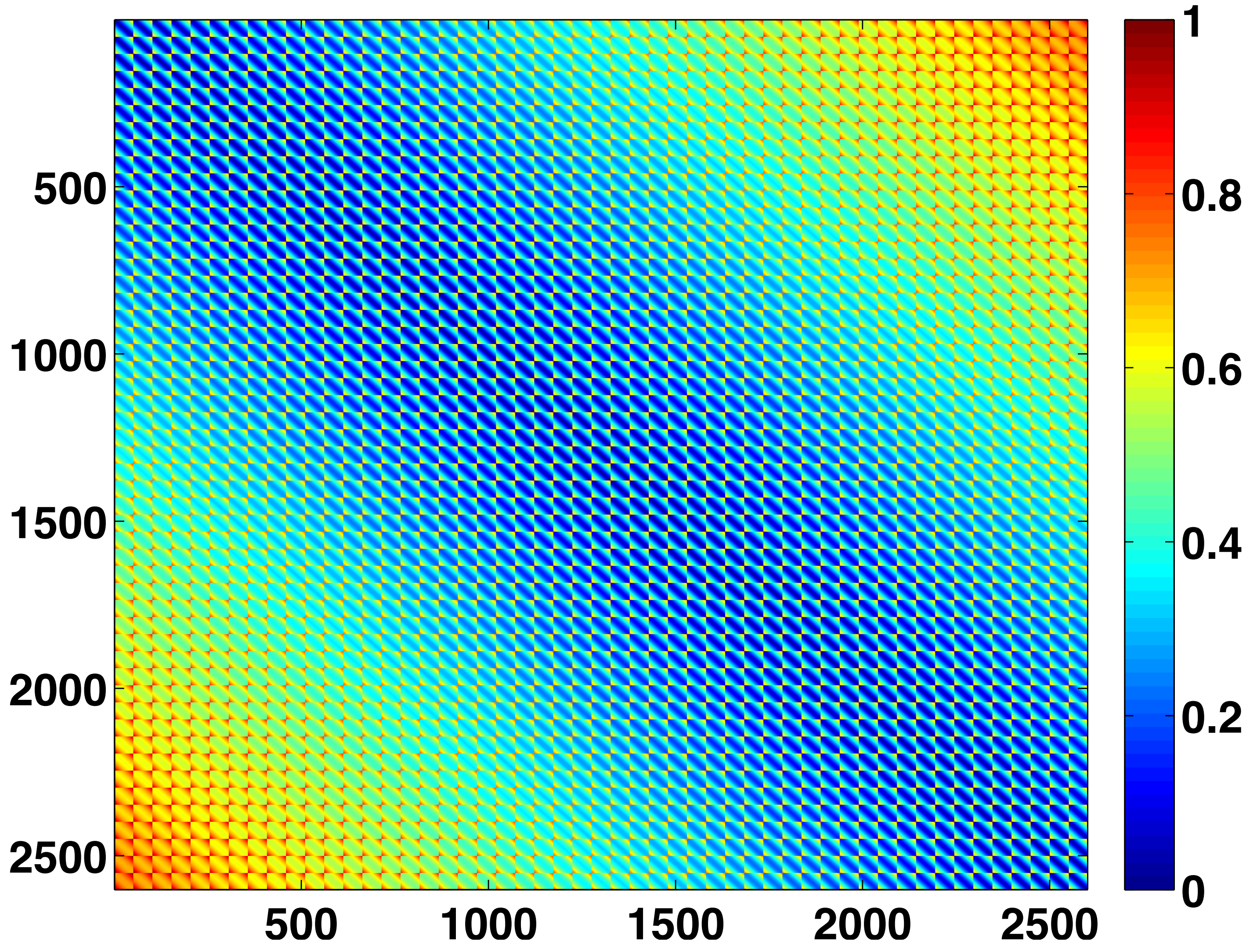


Wave-equation based velocity analysis

Biondo & Symes, '04 , Symes 2008, Sava & Vasconcelos, '11

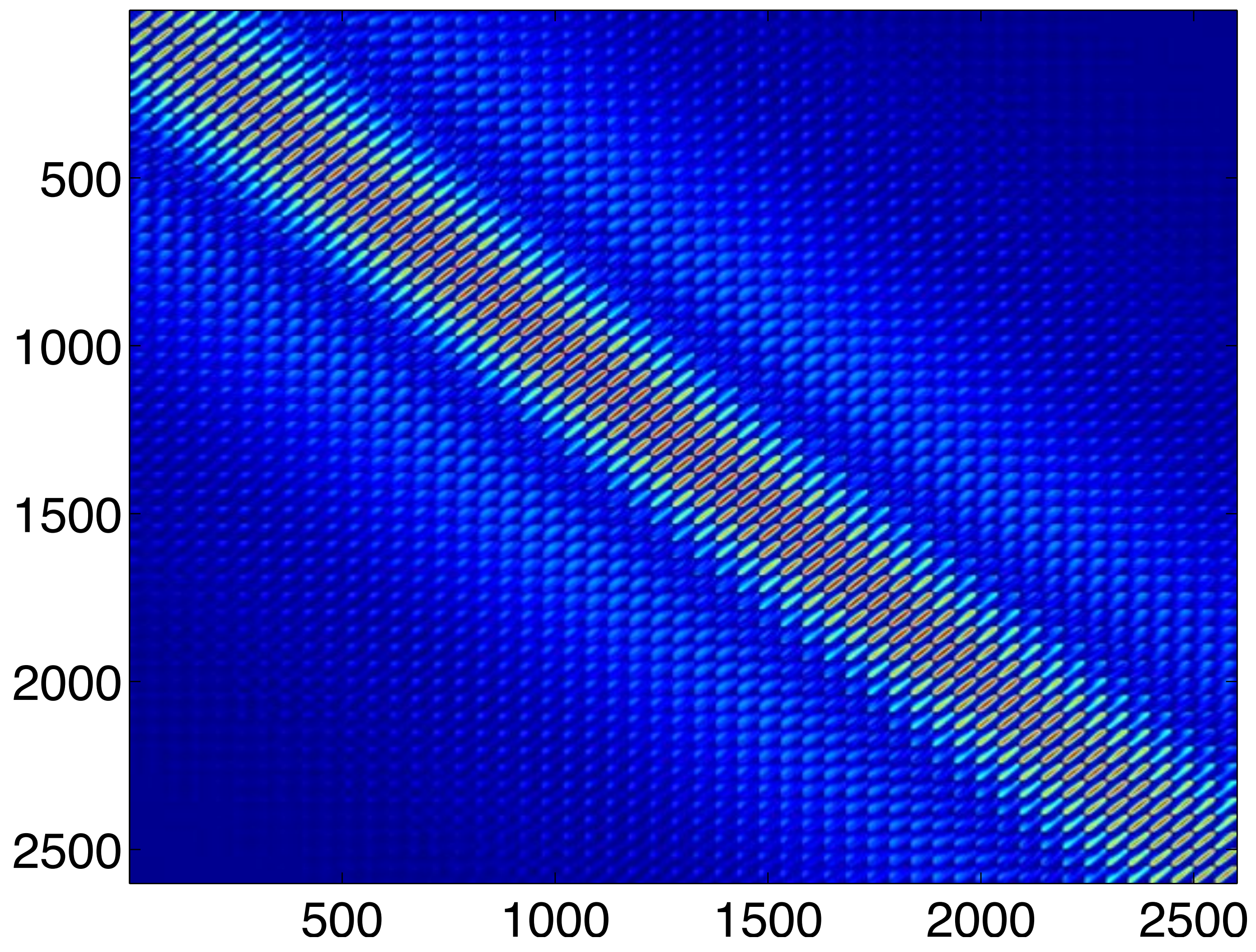
WEMVA

conventional approach



h

$.*$



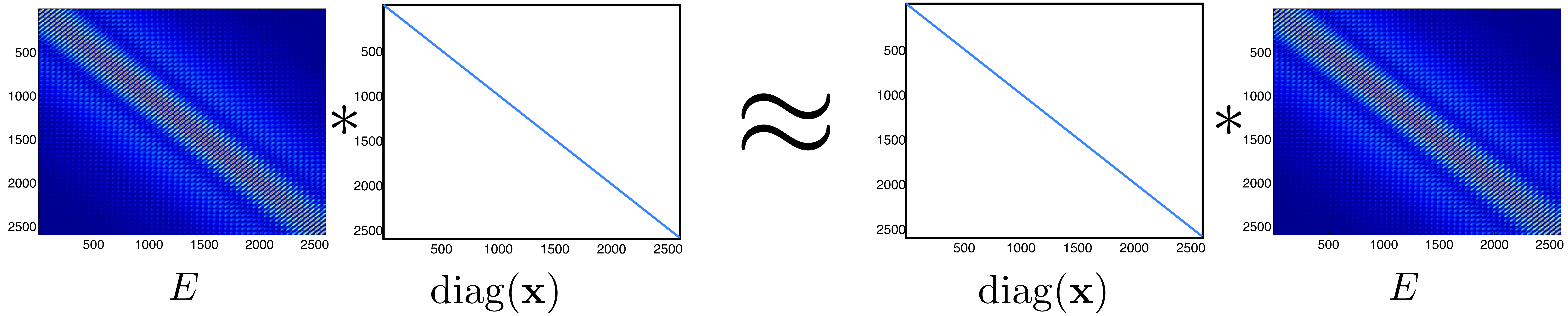
E

$.*$ **stand for element-wise multiplication**

Focusing

propose method approach

$$E\,\mathrm{diag}(\mathbf{x}) \approx \mathrm{diag}(\mathbf{x})\,E$$



$\ast$ **matrix-matrix multiplication**

SLIM

Fast WEMVA w/ *randomized* probing

Measure the error in some norm

$$\min_{\mathbf{m}} ||E(\mathbf{m})\mathsf{diag}(\mathbf{x}) - \mathsf{diag}(\mathbf{x})E(\mathbf{m})||_?^2$$

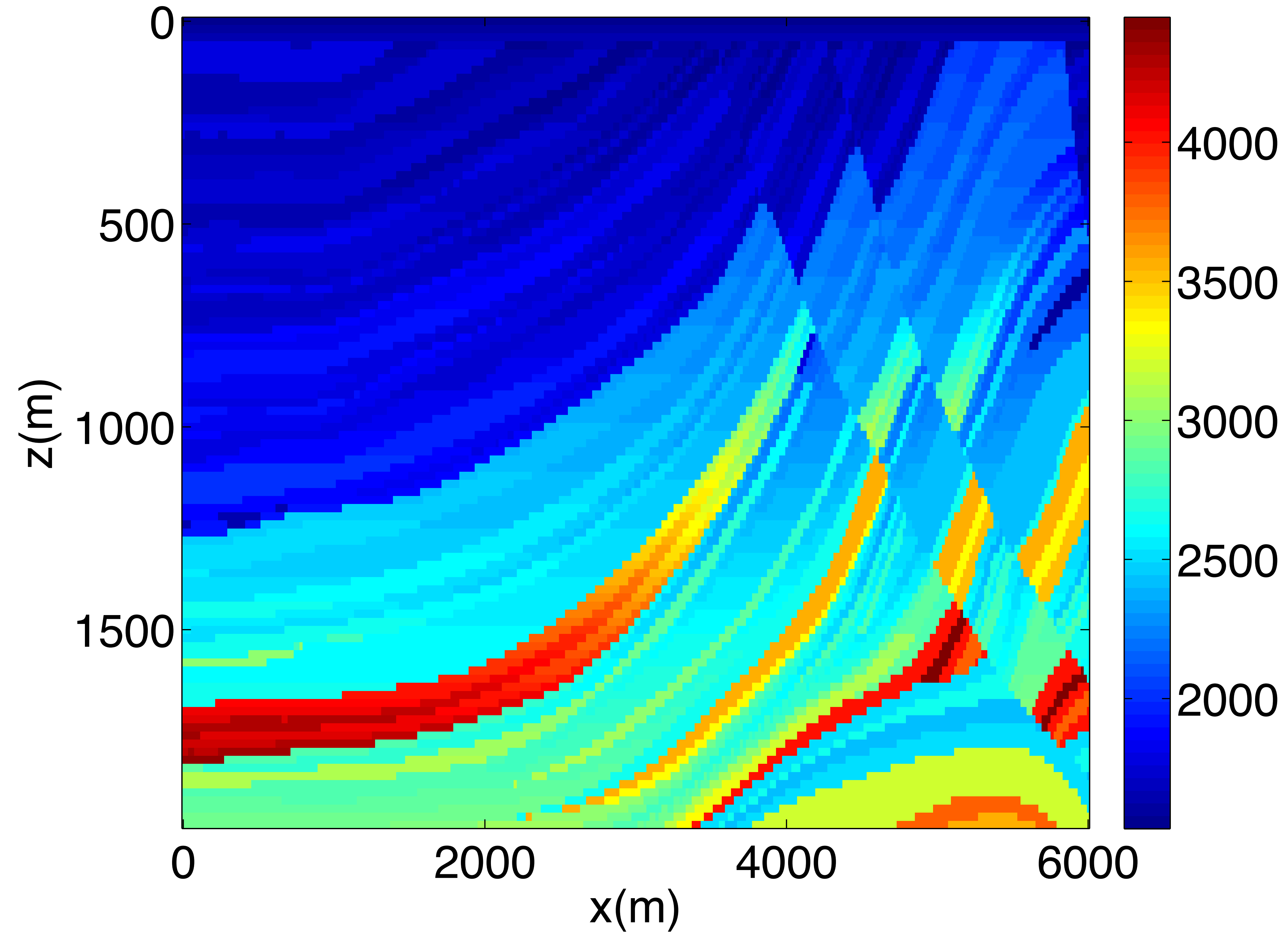
The *Frobenius* norm can be estimated via randomized trace estimation : Avron and Toledo, 2011

$$\begin{aligned} ||A||_F^2 &= \mathsf{trace}(A^T A) \\ &\approx \sum_{i=1}^{K} \mathbf{w}_i^T A^T A \mathbf{w}_i = \sum_{i=1}^{K} ||A\mathbf{w}_i||_2^2 \end{aligned}$$

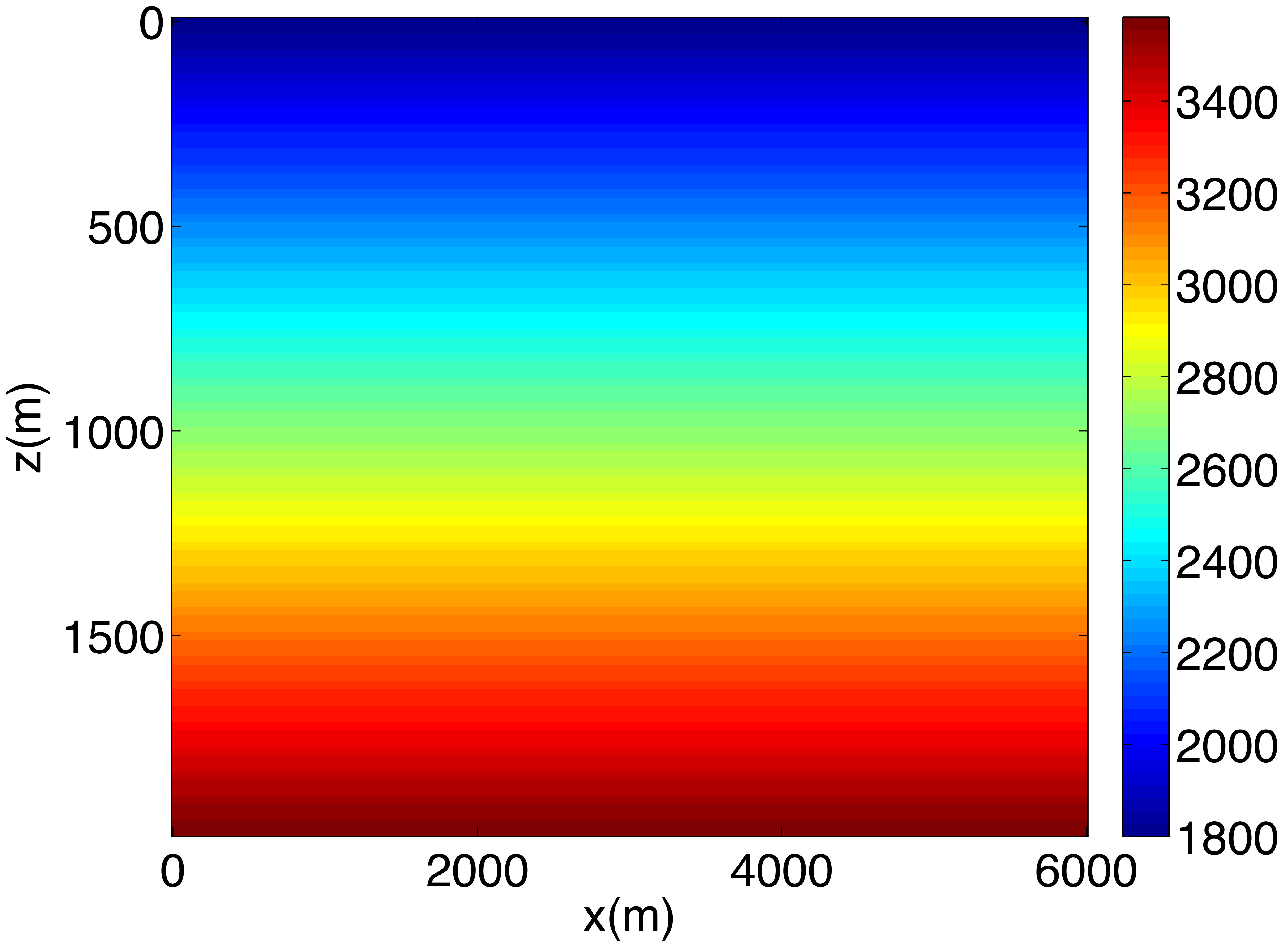
where $\sum_{i=1}^{K} \mathbf{w}_i \mathbf{w}_i^T \approx I$

Randomized probing

reflection data



true model

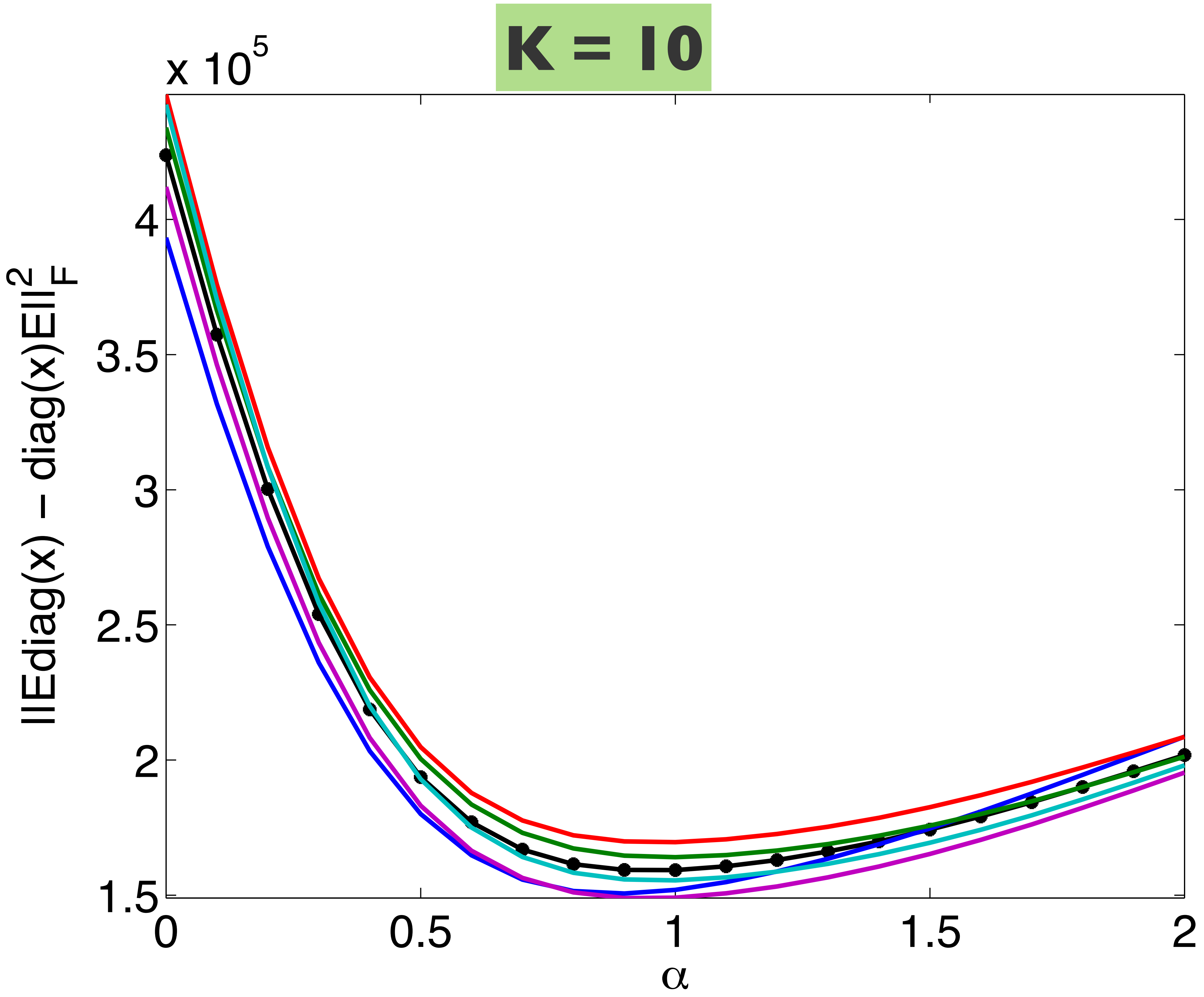


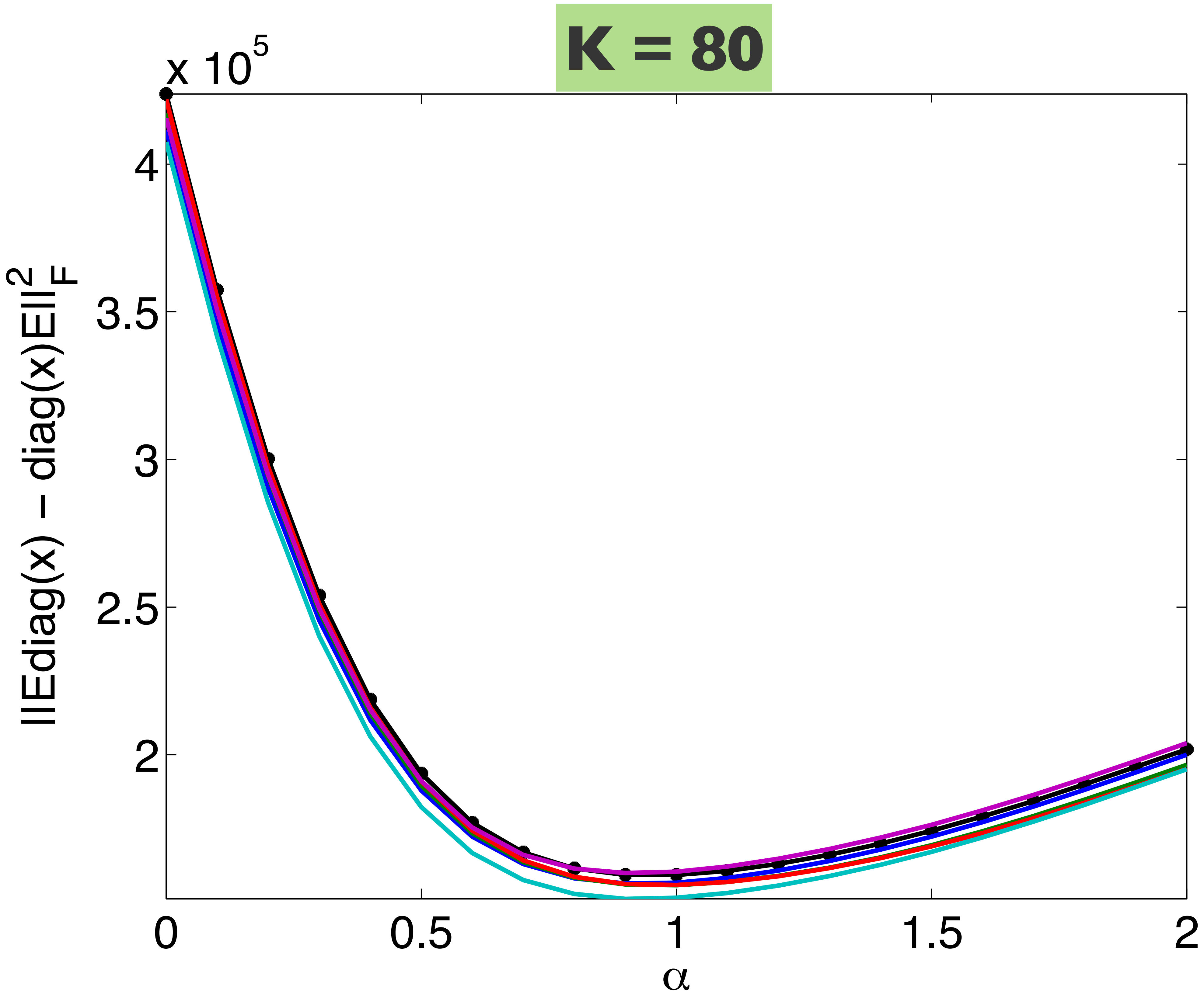
initial model

Randomized probing

reflection

- **Exact**
- **different color represents different random realization**





Experimental details

350 source (40 m spacing) , 700 receivers (20 m spacing)

5-25 Hz

split-spread acquisition

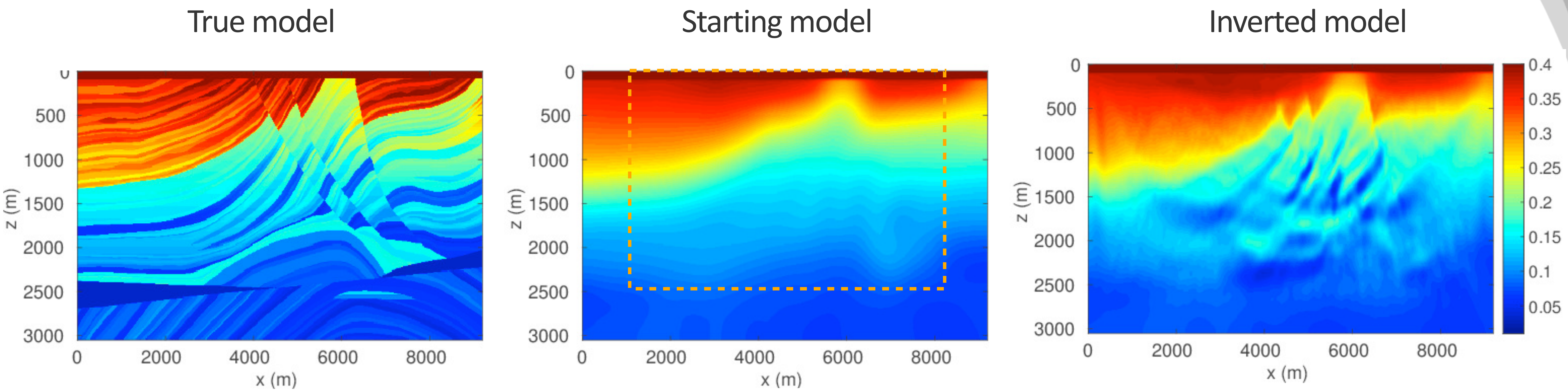
recording length 6s, sampling interval 4ms

peak frequency 20 Hz

25 LBFGS iterations

100 probing vectors

Marmousi model



Observations

100X computational and memory savings while forming the full-subsurface image volumes in 3D

Efficient way to extract informations from image volumes

Very fast (2D/3D) target-imaging tool

60X reduction in memory and computational cost in 2D WEMVA, a step closer to 3D WEMVA

Journal Publications

1. R. Kumar, H. Wason, S. Sharan and F. J. Herrmann. "Highly repeatable 3D compressive full-azimuth towed-streamer time-lapse acquisition|a numerical feasibility study at scale." The Leading Edge, 2017.

2. R. Kumar, O. Lopez, D. Damek, A. Y. Aravkin and F. J. Herrmann. "Beating level-set method for 5D seismic data interpolation|alternating primal-dual approach." IEEE Transactions of Computational Imaging, 2017.

3. C. Evren Yarman, R. Kumar, and J. Rickett. "A model based data driven dictionary learning for seismic data representation." Geophysical Prospecting, 2017.

4. O. Lopez, R. Kumar, O. Yilmaz and F. J. Herrmann. "Off-the-grid low-rank matrix recovery and seismic data reconstruction." IEEE Journal of Signal Processing, 2016.

5. T. van Leeuwen, R. Kumar and F. J. Herrmann. "Enabling affordable omnidirectional subsurface extended image volumes via probing." Geophysical Prospecting, 2016.

6. R. Kumar, H. Wason and F. J. Herrmann. "Source separation for simultaneous towed-streamer marine acquisition|a compressed sensing approach." Geophysics, vol. 80, p. WD73-WD88, 2015.

7. R. Kumar, C. Da Silva, O. Akalin, A. Y. Aravkin, H. Mansour, B. Recht and F. J. Herrmann. "Effcient matrix completion for seismic data reconstruction." Geophysics, vol. 80, p. V97-V114, 2015.

8. A. Y. Aravkin, R. Kumar, H. Mansour, B. Recht and F. J. Herrmann. "Fast methods for denoising matrix completion formulations, with applications to robust seismic data interpolation." SIAM Journal on Scientic Computing, vol. 36, p. S237-S266, 2014.

9. F. J. Herrmann, I. Hanlon, R. Kumar, T. van Leeuwen, X. Li, B. Smithyman, H. Wason, A. Calvert, M. Javanmehri and E. Takougang. "Frugal full-waveform inversion: From theory to a practical algorithm." The Leading Edge, 32(9), 1082-1092, 2013.

Thank you !

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