Improved seismic survey design by maximizing the spectral gap with global optimization

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SLIM
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ML4Seismic

Rajiv Kumar, Curt Da Silva, Okan Akalin, Aleksandr Y. Aravkin, Hassan Mansour, Ben Recht, and Felix J. Herrmann, “Efficient matrix completion for seismic data reconstruction”, Geophysics, vol. 80, pp. V97-V114, 2015.
Oscar Lopez, Rajiv Kumar, Nick Moldoveanu and Felix J. Herrmann, “Graph Spectrum Based Seismic Survey Design”, Submitted to Geophysics , 2020.

Motivations

Seismic data

- expensive to acquire

Random subsampling

- increasingly employed in seismic data acquisition
- reduce cost

Matrix completion (MC)

- reconstruct fully sampled wavefields from sparsely sampled seismic data
- computationally efficient method

Goal: Automatically generate sampling schemes that favor recovery by MC.

Oscar Lopez, Rajiv Kumar, Nick Moldoveanu and Felix J. Herrmann, “Graph Spectrum Based Seismic Survey Design”, Submitted to Geophysics , 2020.
Bhojanapalli, Srinadh, and Prateek Jain. "Universal matrix completion." *International Conference on Machine Learning*. PMLR, 2014.
Burnwal, Shantanu Prasad, and Mathukumalli Vidyasagar. "Deterministic completion of rectangular matrices using asymmetric ramanujan graphs: Exact and stable recovery." *IEEE Transactions on Signal Processing* 68 (2020): 3834-3848.
Mosher, C. C., S. T. Kaplan, and F. D. Janiszewski. "Non-uniform optimal sampling for seismic survey design." *74th EAGE Conference and Exhibition incorporating EUROPEC 2012*. European Association of Geoscientists & Engineers, 2012.

Motivations

Simulation-based acquisition design

- expensive
- time consuming

Uniform & jittered sampling scheme

- not optimal
- is not flexible - i.e., cannot add constraints

Spectral gap (SG) of sampling mask

- the gap between the first & second singular value
- a cheap metric to predict a performance of an acquisition design
- should be large to ensure success of matrix completion

Come up with a quantity to predict wavefield reconstruction w/ MC

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Motivation

relationship between reconstruction quality & sampled matrix

M binary sampling matrix

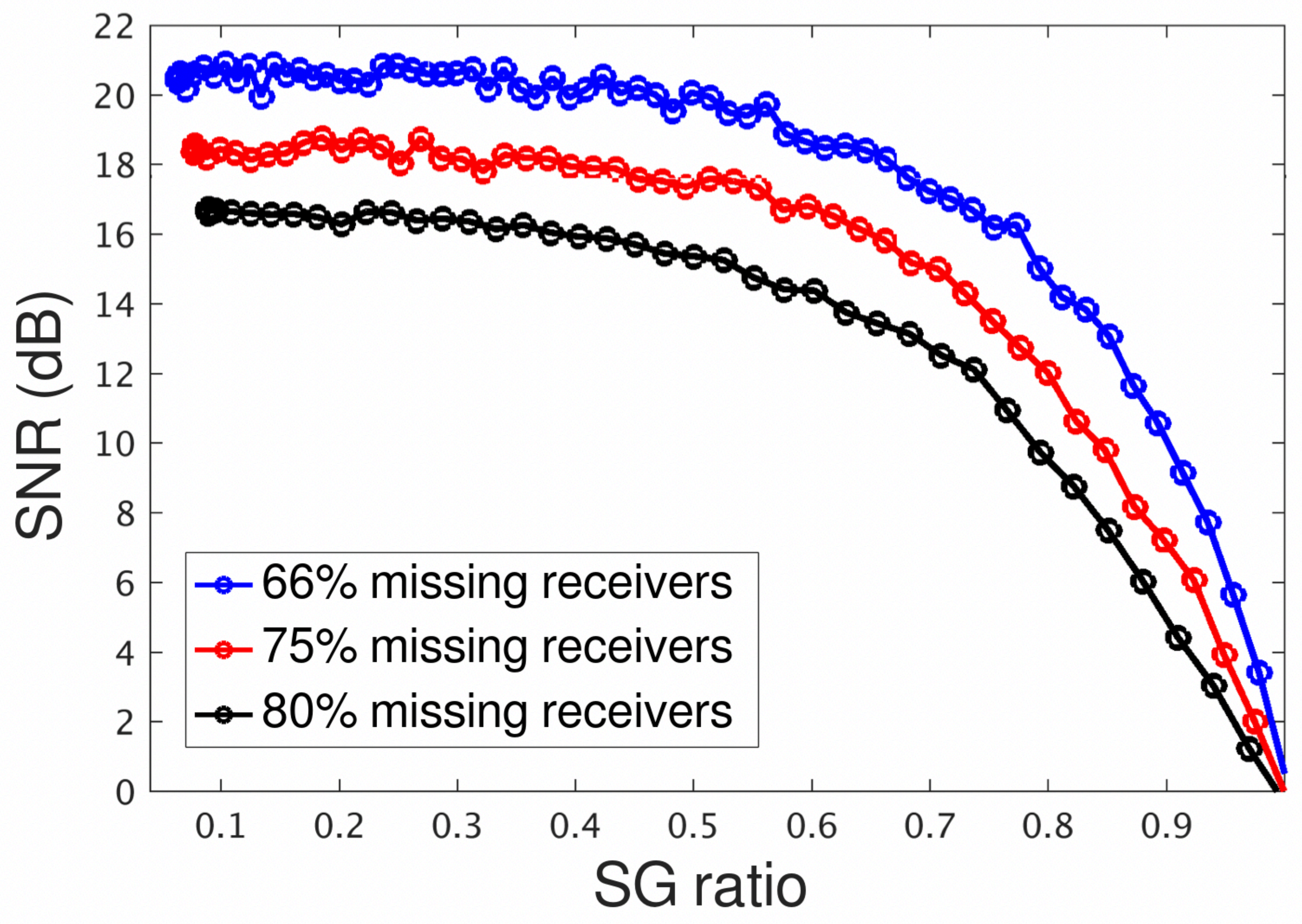
$\sigma_1(\,.\,)$ the first singular value

$\sigma_2(\,.\,)$ the second singular value

$\dfrac{\sigma_2(M)}{\sigma_1(M)}$ SG ratio

an average of 100 experiments

Large spectral gap corresponds to small SG ratio



Problem

Hands-on tutorial:

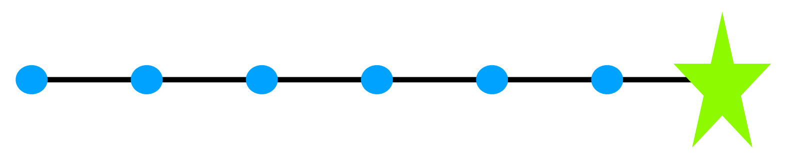
Breakout 2. Acquisition design and wavefield reconstruction (code)

Generate sampling scheme w/o expensive wavefield reconstruction

Take advantage of spectral gap, a cheap metric to evaluate an acquisition mask

Start with 2D acquisition on a grid…

2D acquisition



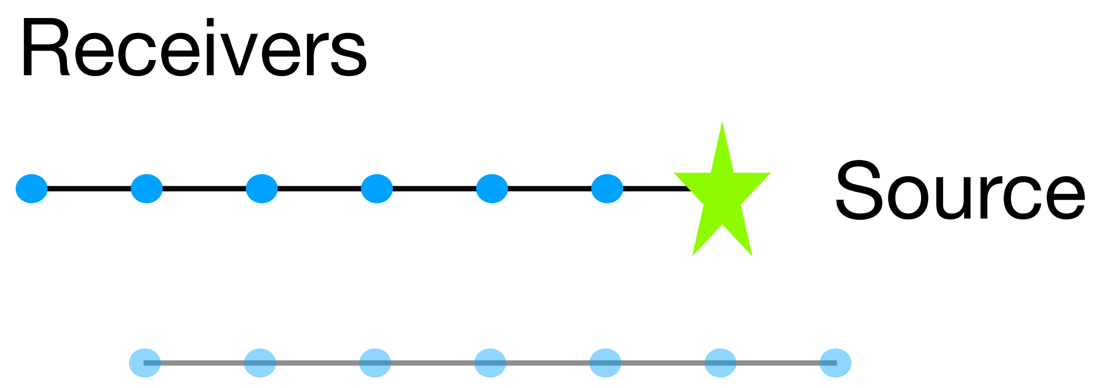
Sampling mask in source-receiver domain

Receivers (rows) × Sources (columns)

1						
1						
1						
1						
1						
1						
1						

Sources

2D acquisition



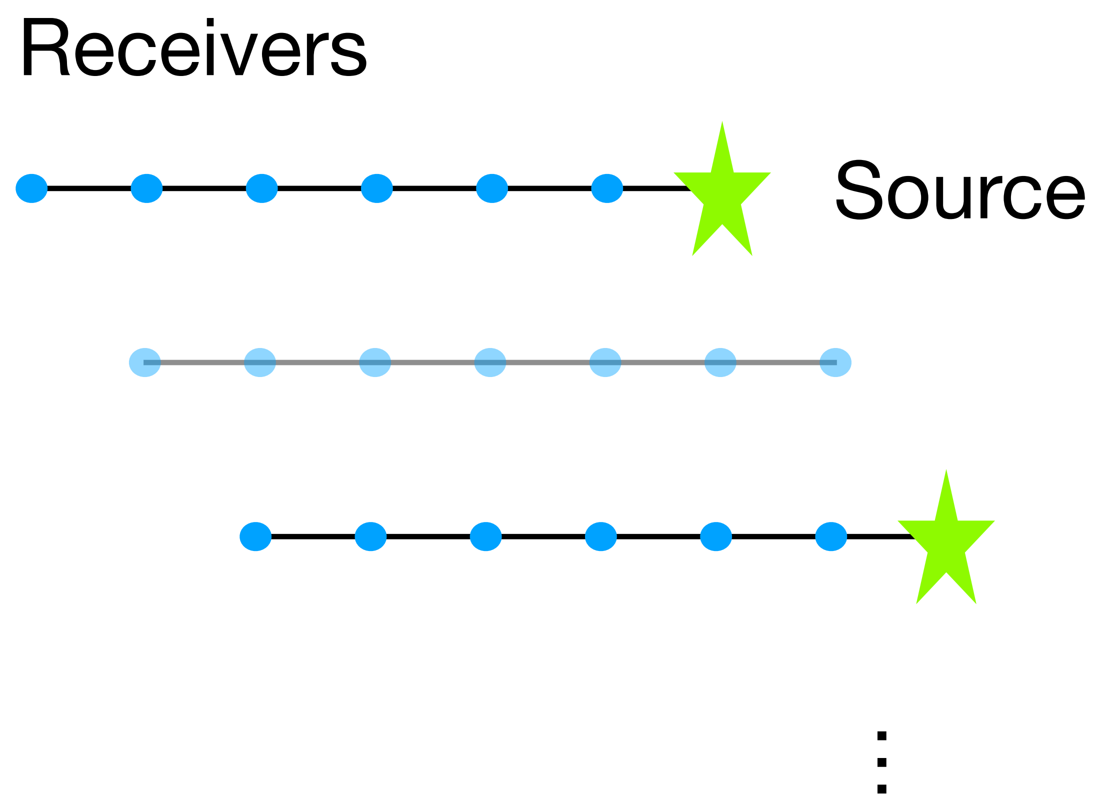
Sampled mask in source-receiver domain

Receivers

1	0					
1	0					
1	0					
1	0					
1	0					
1	0					
1	0					

Sources

2D acquisition

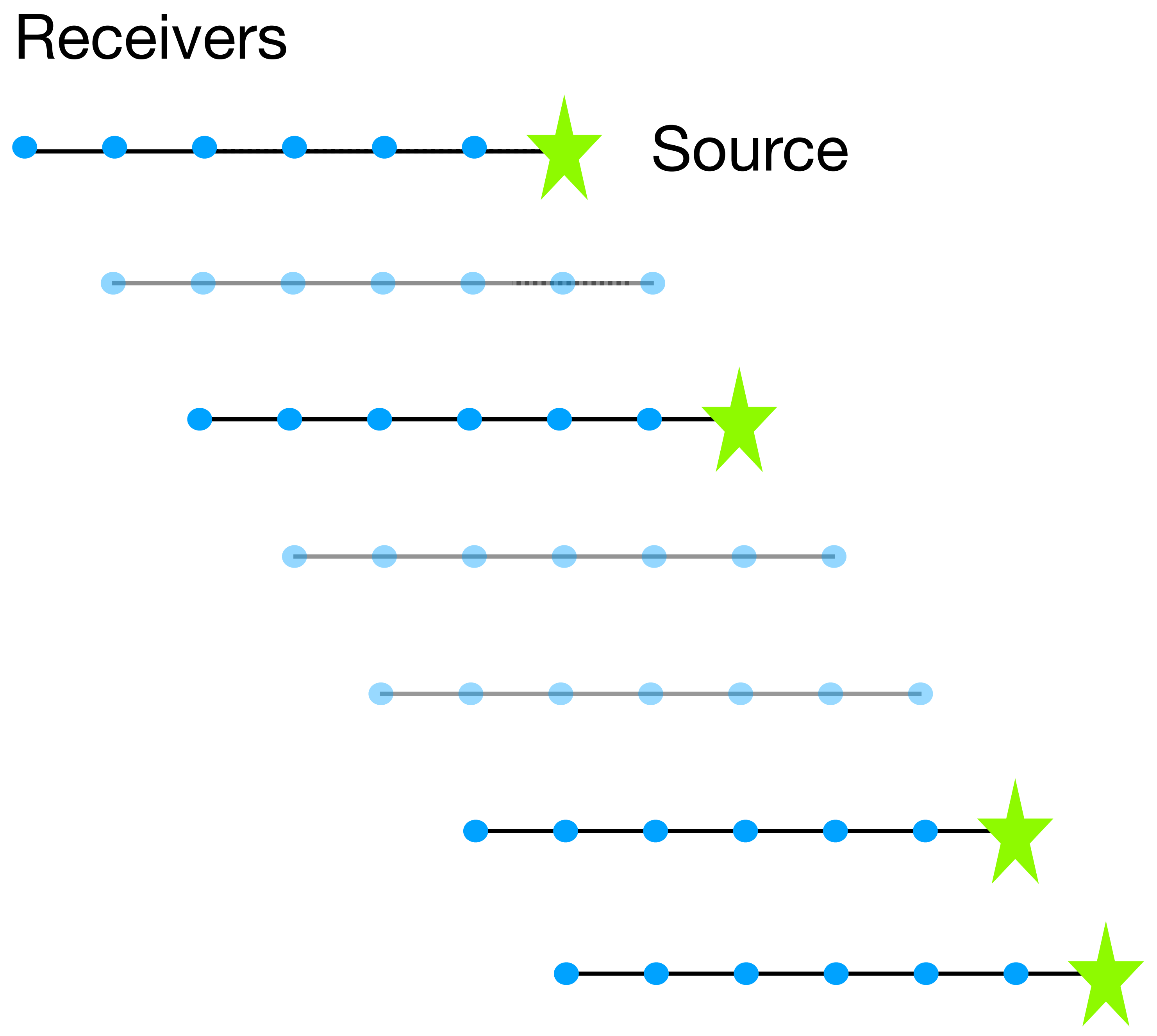


Sampled mask in source-receiver domain

Receivers \ Sources							
	1	0	1				
	1	0	1				
	1	0	1				
	1	0	1				
	1	0	1				
	1	0	1				
	1	0	1				

Sources

2D acquisition



Sampled mask in source-receiver domain

Receivers	1	0	1	0	0	1	1
	1	0	1	0	0	1	1
	1	0	1	0	0	1	1
	1	0	1	0	0	1	1
	1	0	1	0	0	1	1
	1	0	1	0	0	1	1
	1	0	1	0	0	1	1

Sources

2D acquisition

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Sampled mask in source-receiver domain

Receivers / Sources

1	0	1	0	0	1	1
1	0	1	0	0	1	1
1	0	1	0	0	1	1
1	0	1	0	0	1	1
1	0	1	0	0	1	1
1	0	1	0	0	1	1
1	0	1	0	0	1	1

Sources

Sampled mask in midpoint-offset domain

Midpoints / Offsets

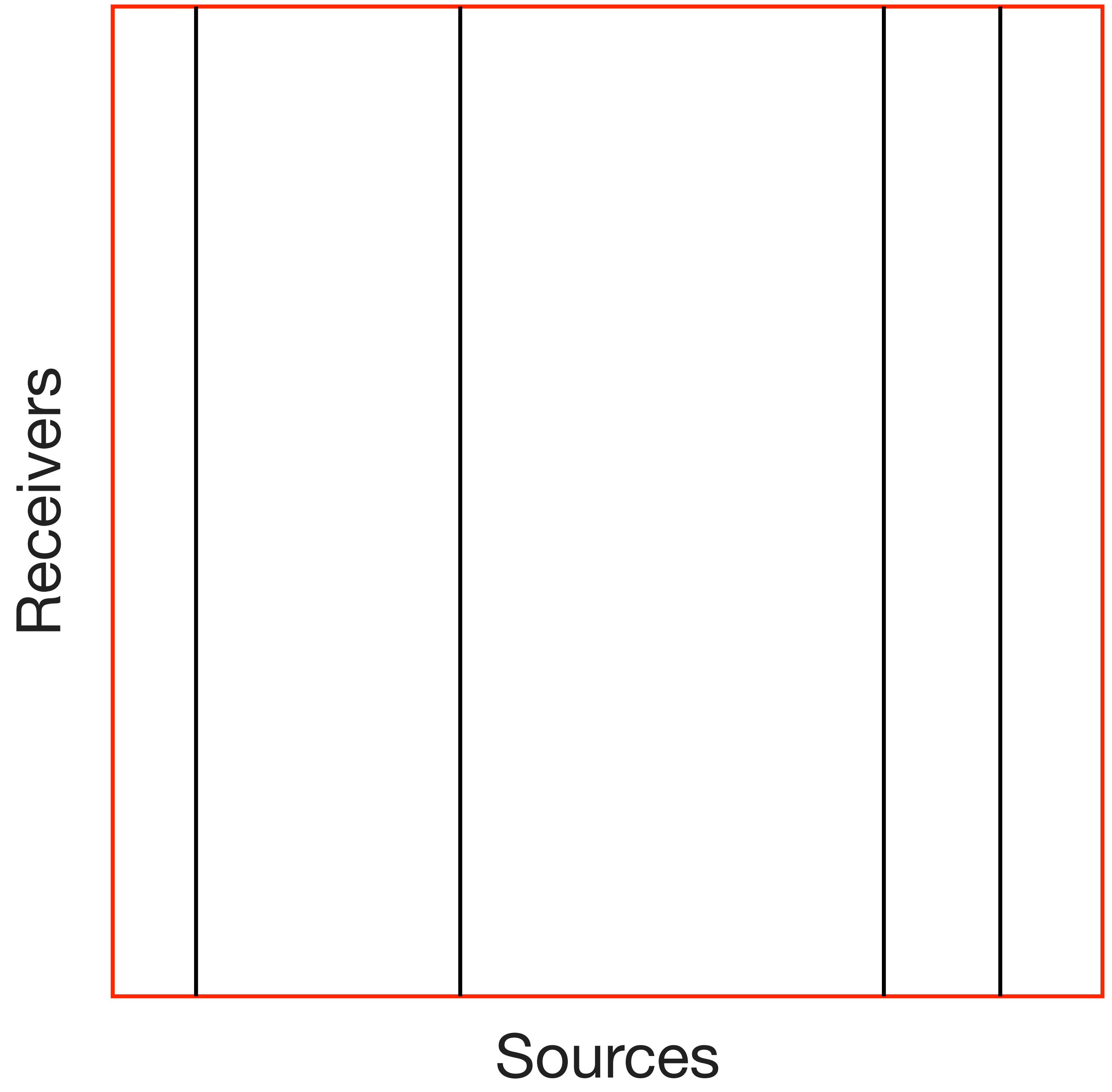
0	0	0	0	0	1	1	0	0	0	0	0	0
0	0	0	1	1	0	0	1	1	0	0	0	0
0	1	1	0	0	1	1	0	0	0	0	1	0
1	0	0	1	1	0	0	0	0	1	1	1	1
0	0	1	0	0	0	0	1	1	1	1	0	0
0	0	0	0	0	1	1	1	1	0	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0

Offsets

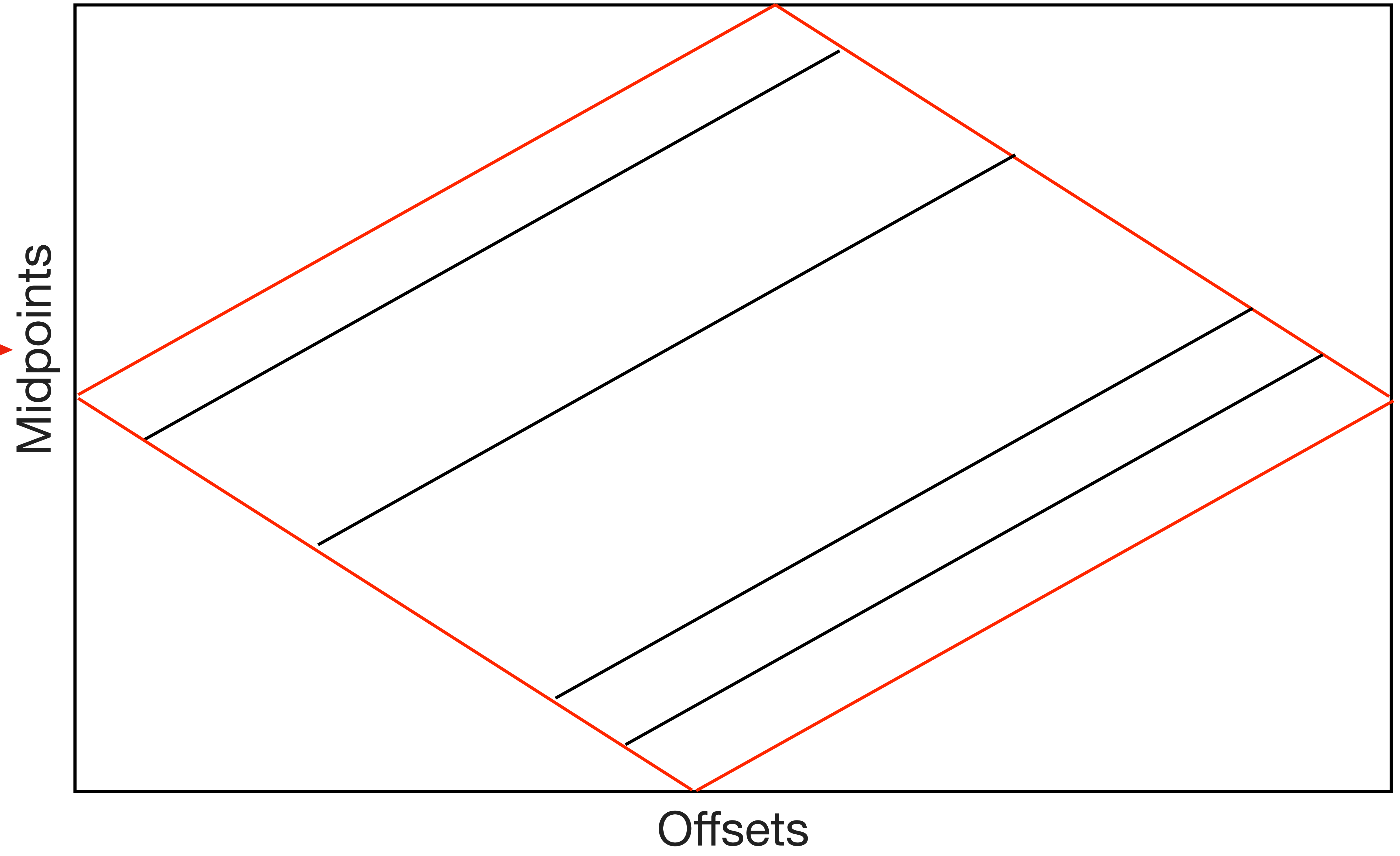
SG ratio = 0.804

2D acquisition

Sampled mask in source-receiver domain



Sampled mask in midpoint-offset domain



SG ratio = 0.804

Optimized problem

2D acquisition

Given n_s source locations & subsampling ratio r, find $m = \lfloor n_s \times r \rfloor \times n_r$ subsampling locations X

$$\underset{X}{\text{minimize}} \quad \frac{\sigma_2(\mathcal{S}X)}{\sigma_1(\mathcal{S}X)} \quad \text{subject to} \quad \|X\|_0 = m, \quad X \in [0,1]^{n_s \times n_r}.$$

- $\mathcal{S}$: an operator that transfers the data from SR domain to midpoint-offset domain
- $\sigma_1(\,.\,)$ and $\sigma_2(\,.\,)$: the first & second singular values
- n_s, the number of sources & n_r, the number of receivers.
- n_m, the number of midpoints & n_o, the number of offsets

Kirkpatrick, Scott, C. Daniel Gelatt, and Mario P. Vecchi. "Optimization by simulated annealing." *science* 220.4598 (1983): 671-680.
Černý, Vladimír. "Thermodynamical approach to the traveling salesman problem: An efficient simulation algorithm." *Journal of optimization theory and applications* 45.1 (1985): 41-51.
From: Ümit V. Çatalyürek; CSE 6140/ CX 4140: Computational Science and Engineering ALGORITHMS

Simulated annealing (SA)
Combinatorial search technique

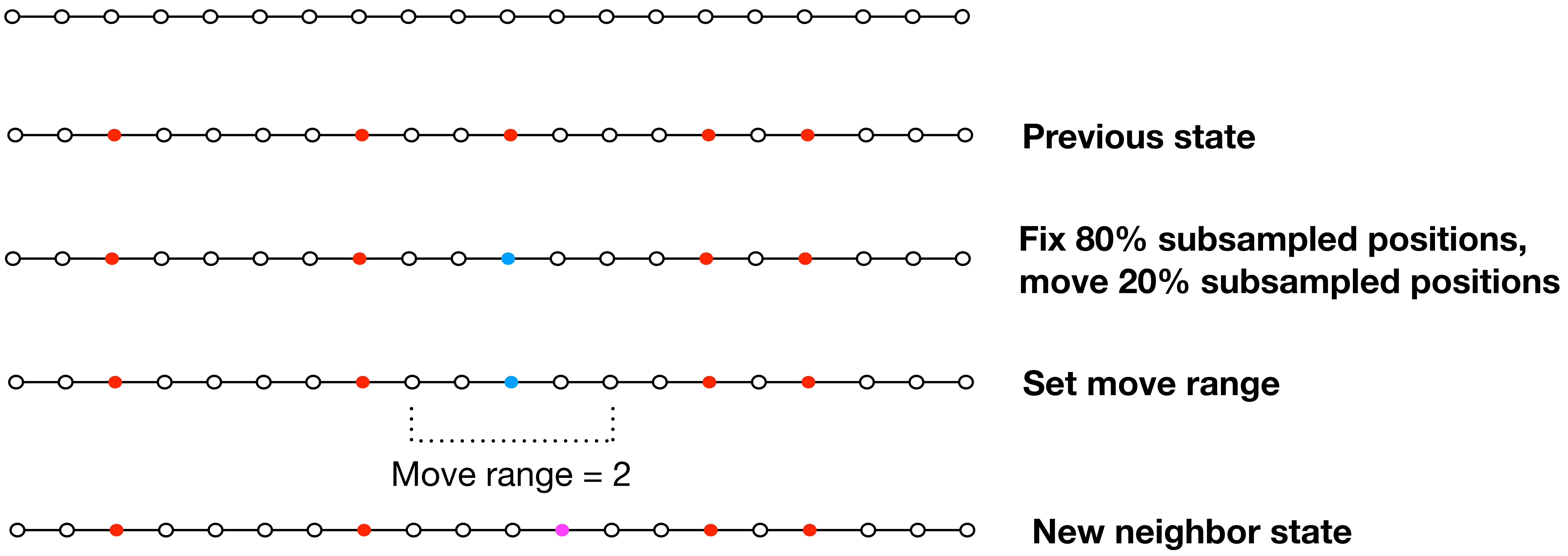
Outline:

- Select a neighbor at random ?
    - If better than current state, update the state (improving move)
    - Otherwise, update current state w/ some probability (worsening move)
- Probability goes down with time

High probability means diversify (many worsening moves)

Low probability means intensify (focus on improving moves)

Select a neighbor at random



○ : all possible locations;
● : initial subsampled locations;
● : to be moved location;
● : the new neighbor subsampled location

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Stylized example w/ equal source/receiver dimension (300×300)

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Experiment 1

Optimal SG ratio w/ simulated annealing

Mask dimension: 300 x 300

Subsampling ratio: $33\ \%$

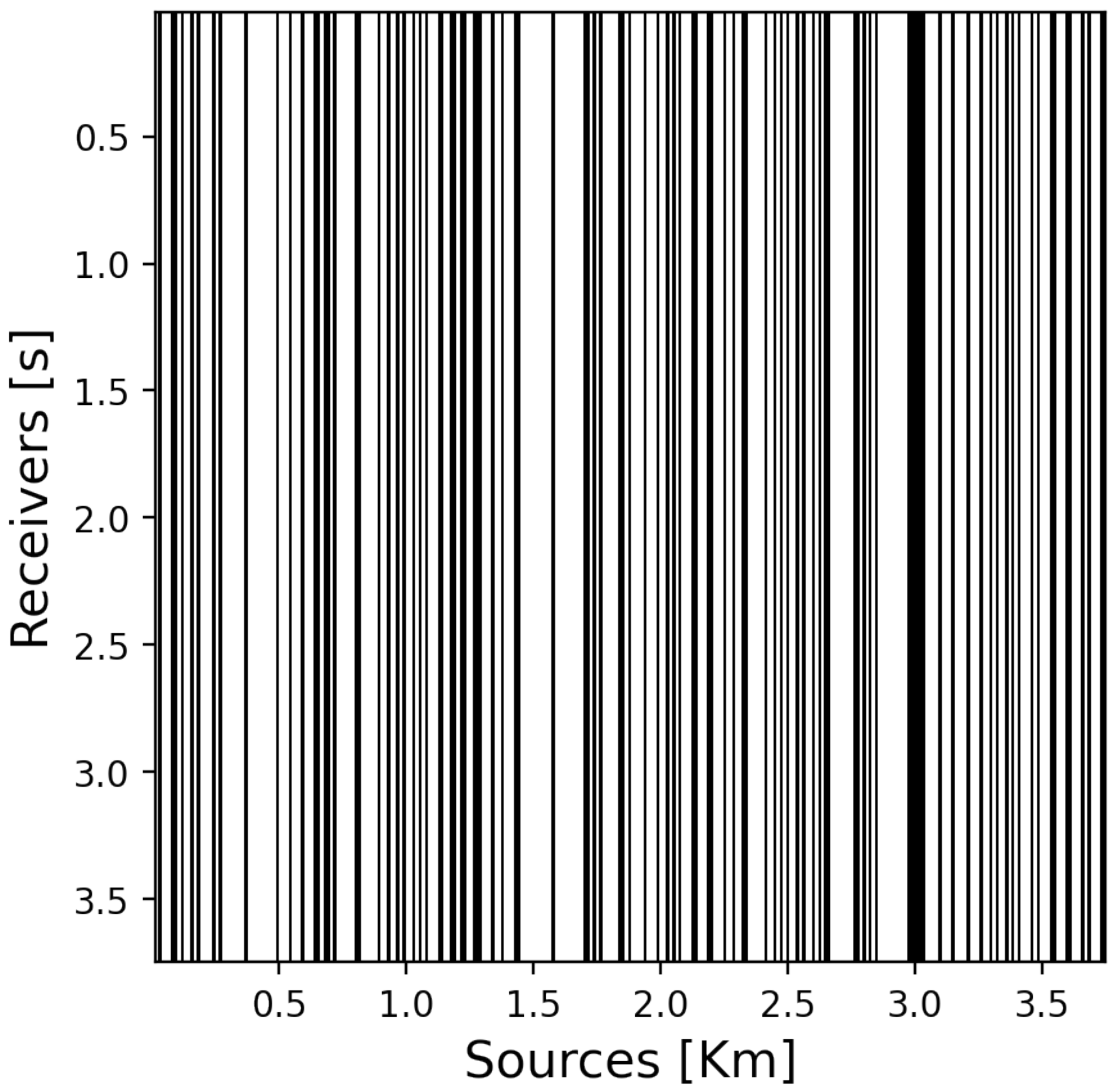
Source and receiver sampling interval: 12.5 m

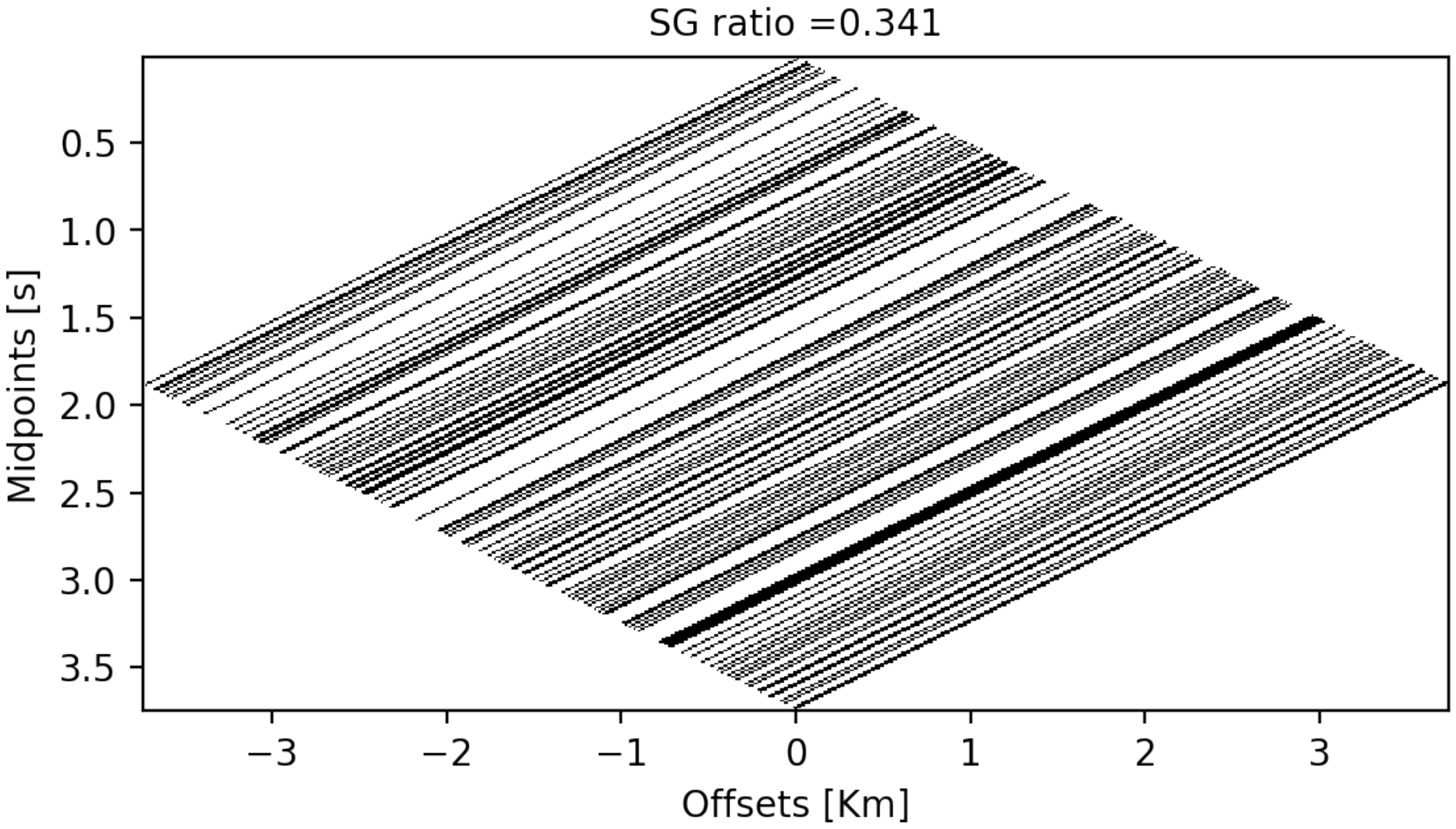
Decrease the SG ratio of given initial subsampling masks:

- uniform random subsampling
- optimal jittered subsampling

Uniform random mask

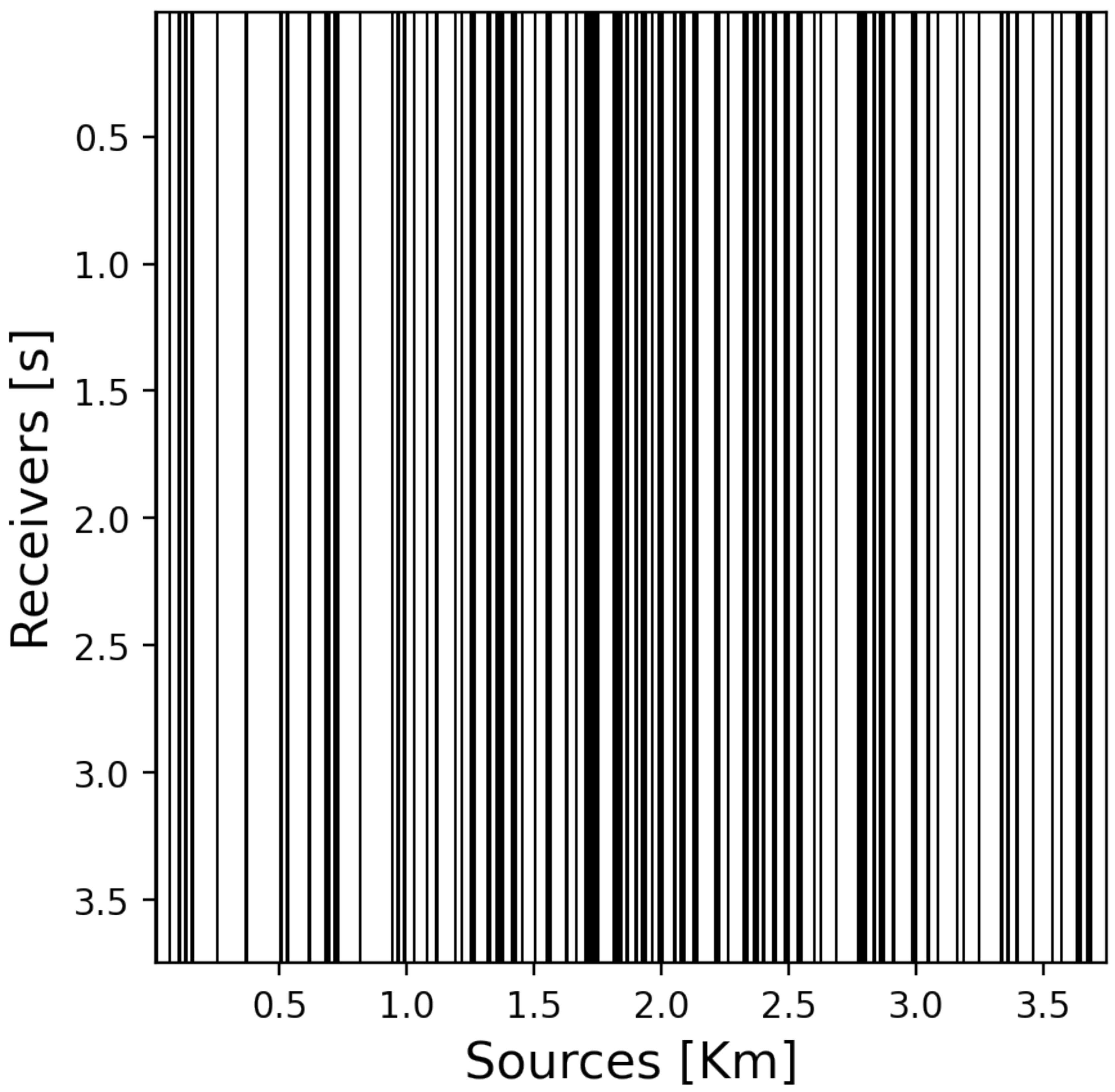
Initial state (input) of the optimal method

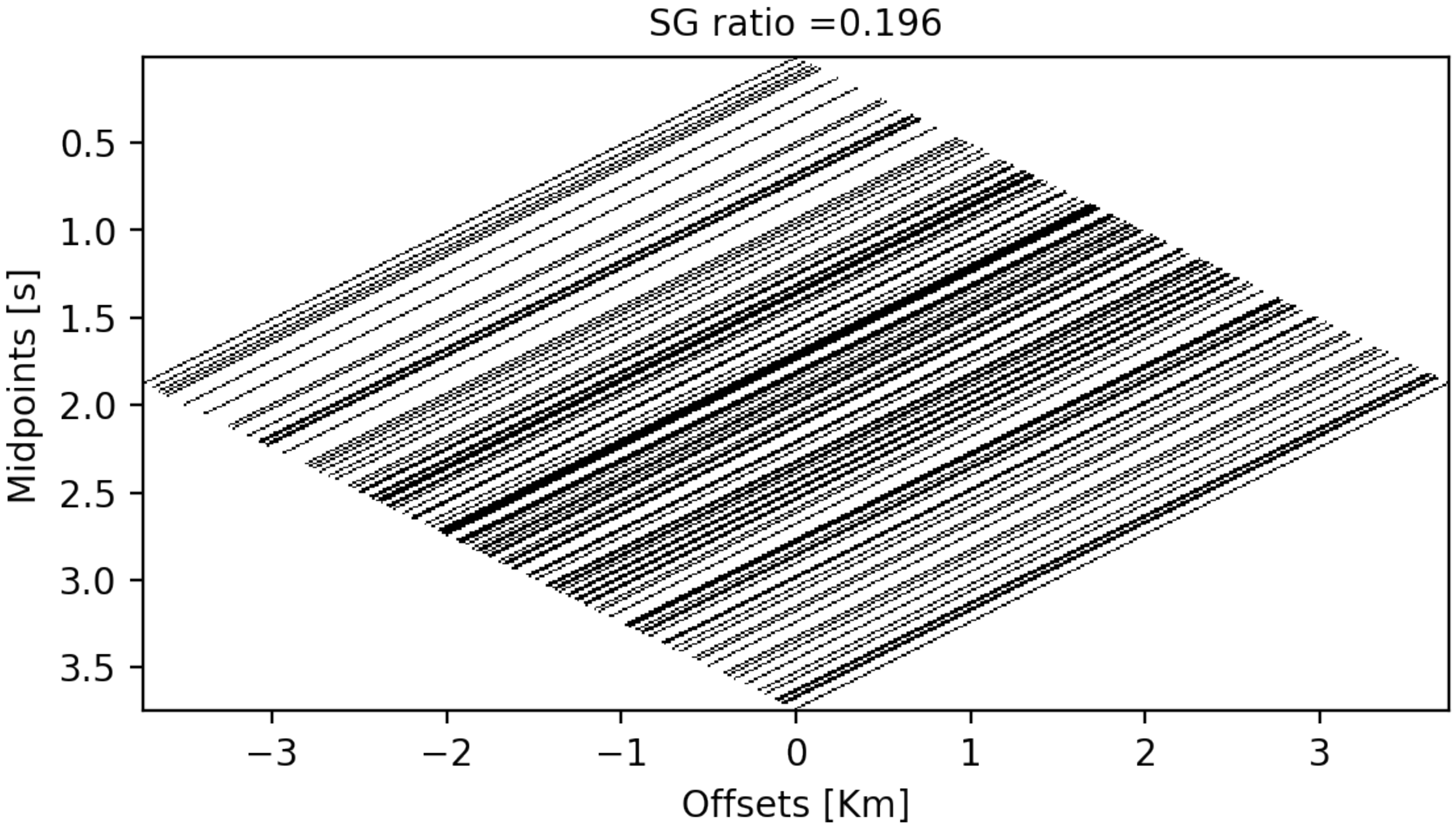




Improved random mask

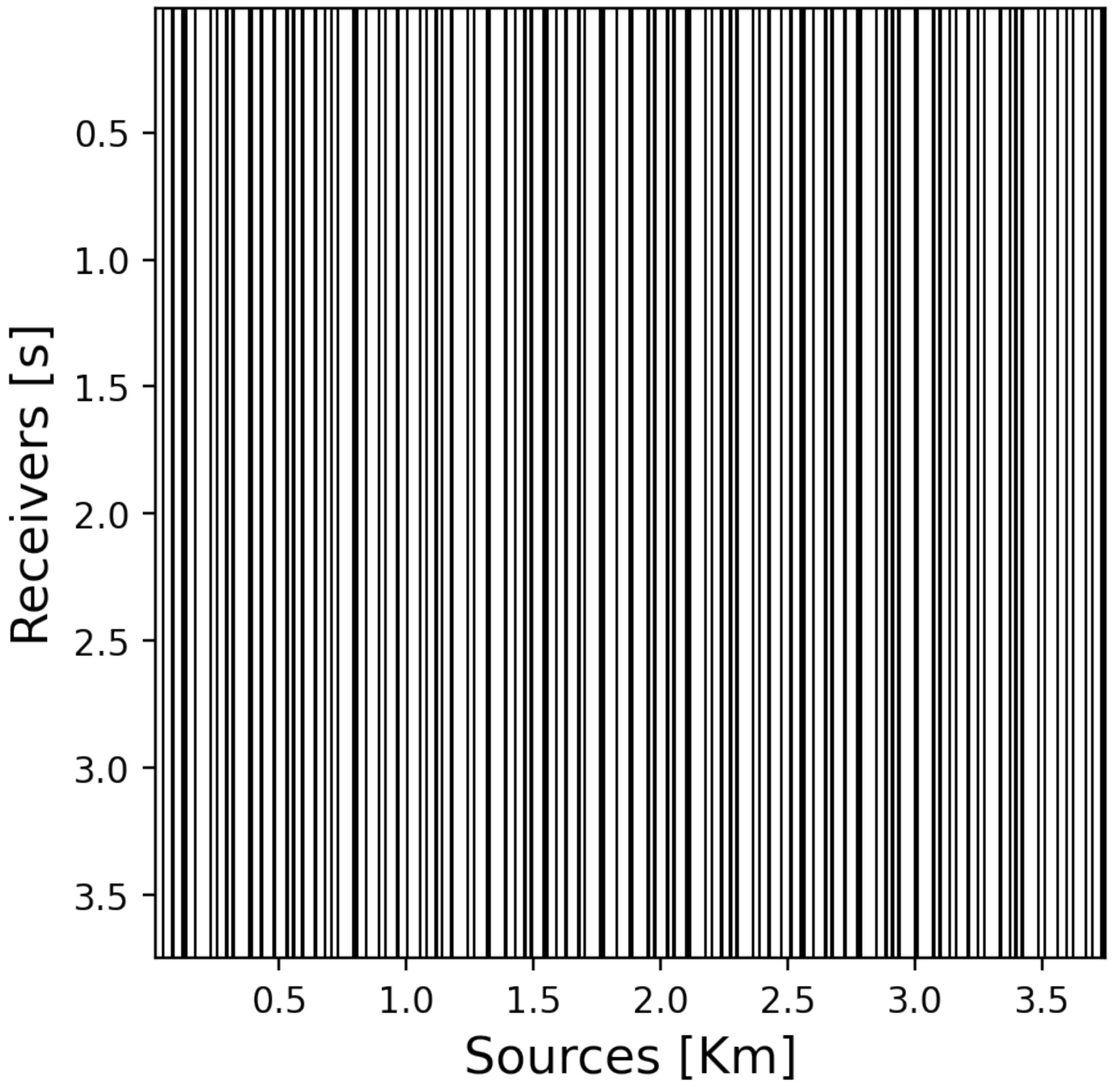
Output of the optimal method w/ SA algorithm

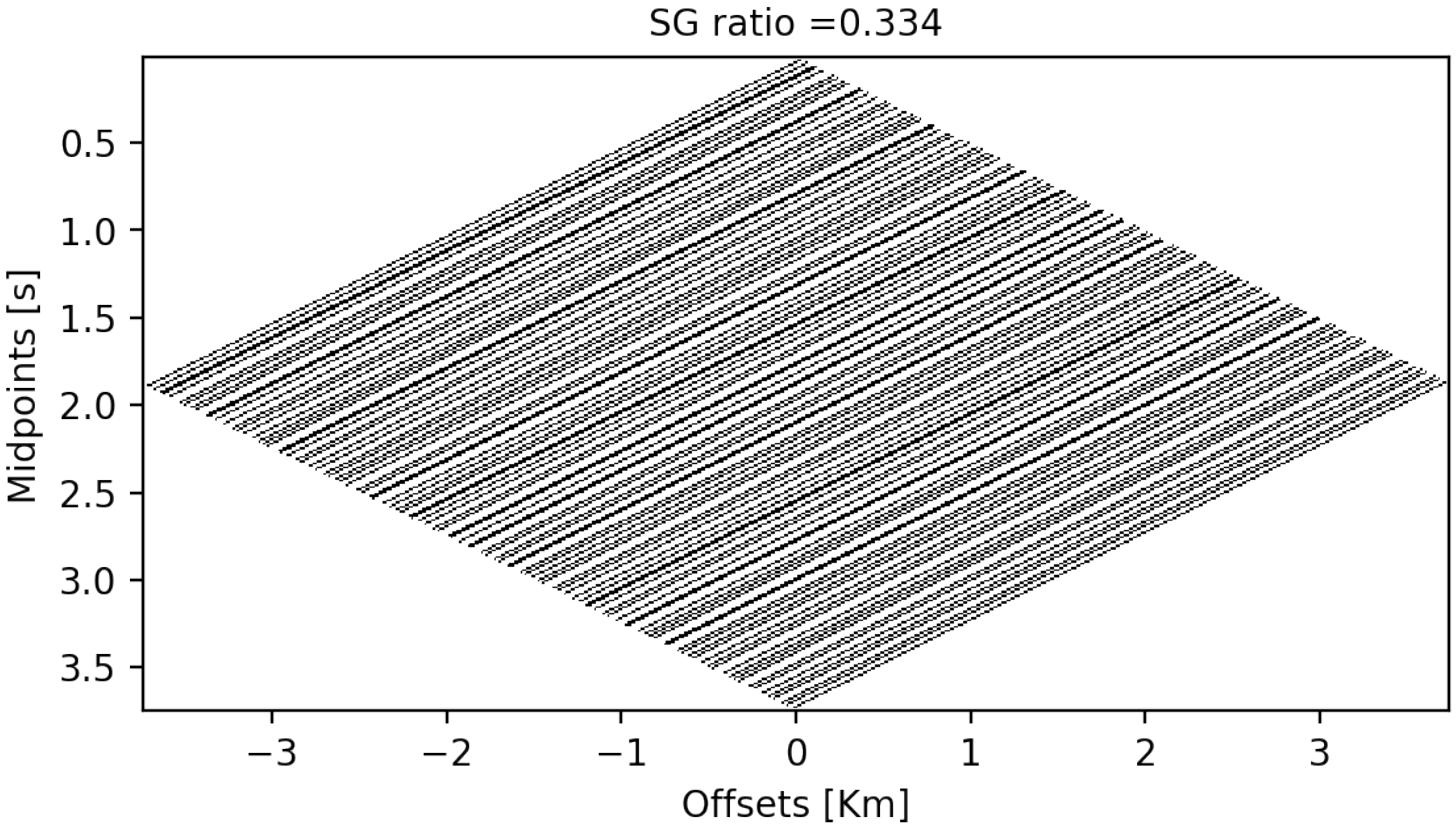




Optimal jittered mask

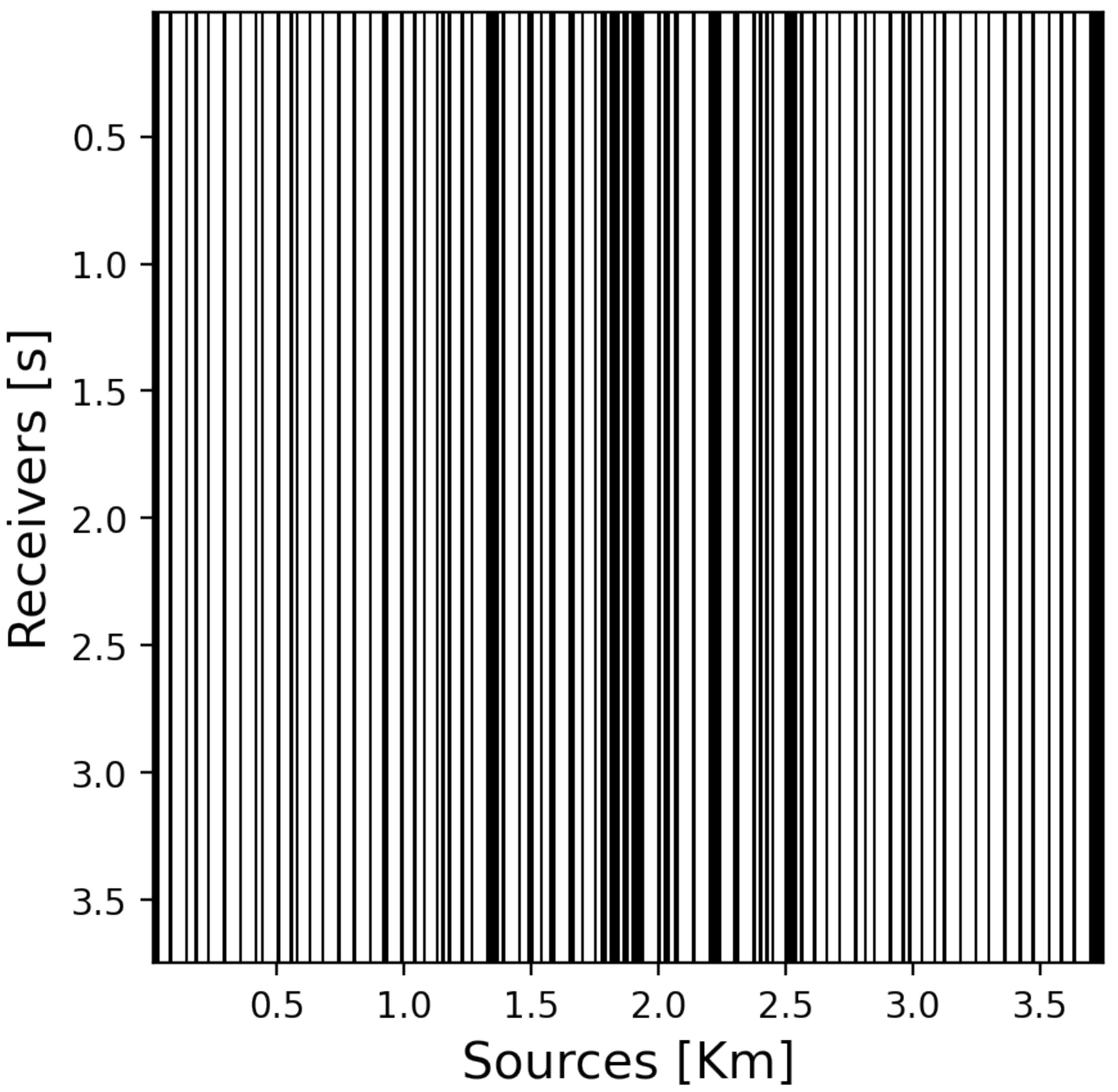
Initial state (input) of the optimal method

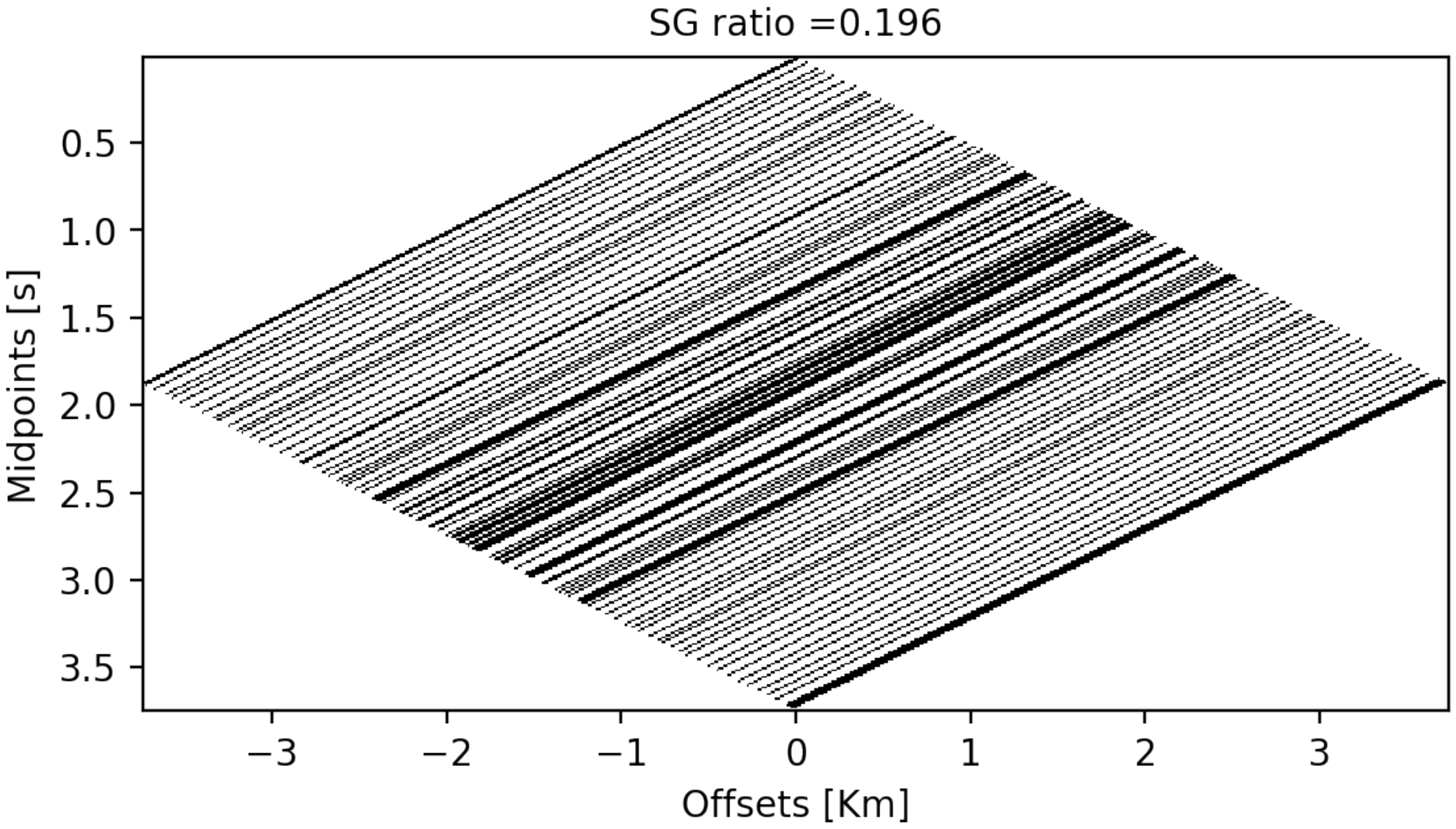




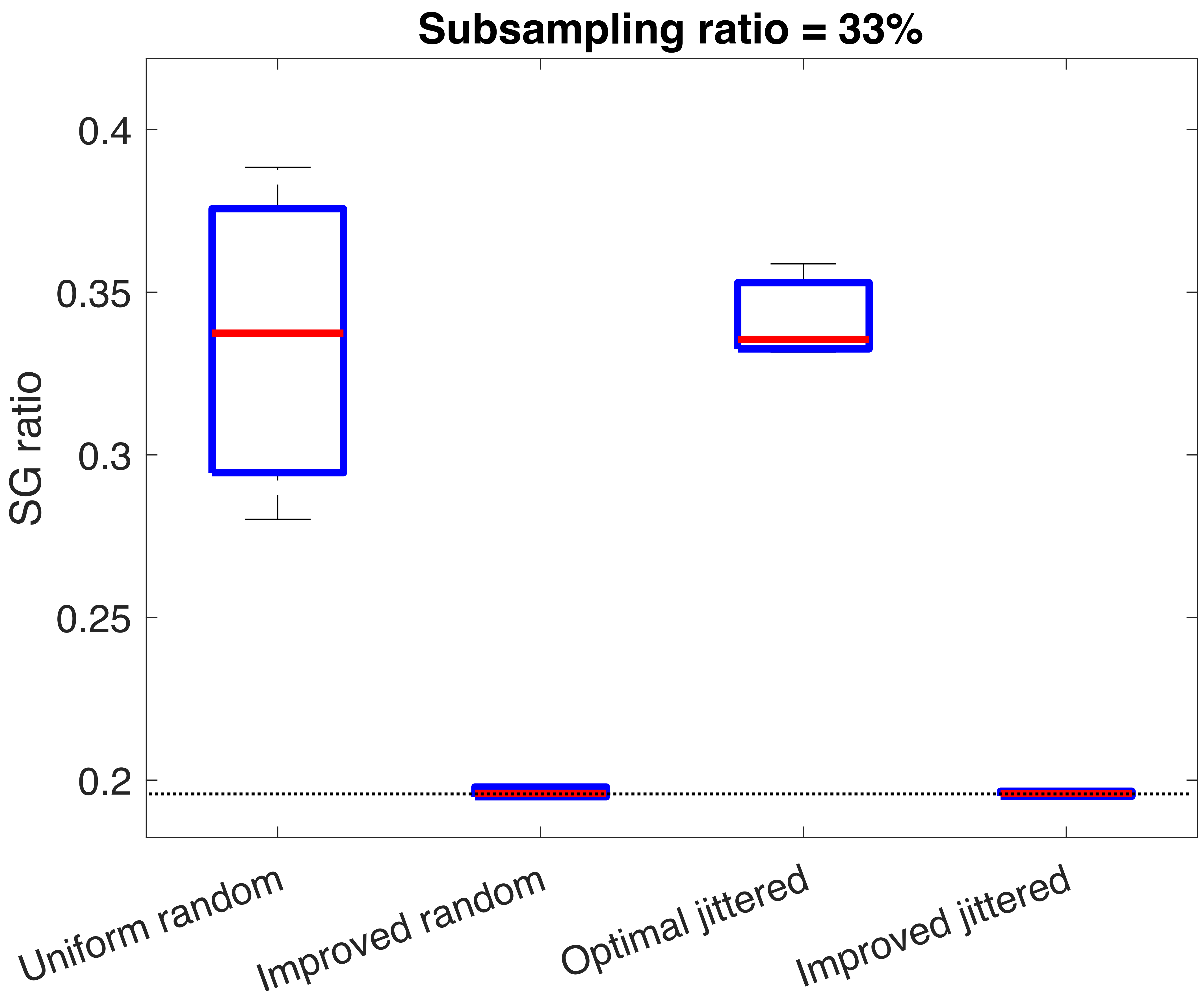
Improved jittered mask

Output of the optimal method w/ SA algorithm





SG ratio comparison
W/ 10 independent tests



Synthetic example

Rajiv Kumar, Curt Da Silva, Okan Akalin, Aleksandr Y. Aravkin, Hassan Mansour, Ben Recht, and Felix J. Herrmann, "Efficient matrix completion for seismic data reconstruction", Geophysics, vol. 80, pp. V97-V114, 2015.

Experiment 2

Test masks by using wavefield reconstruction (LR matrix completion)

Data dimension: 300 x 300 x 1024 (nr x ns x nt)

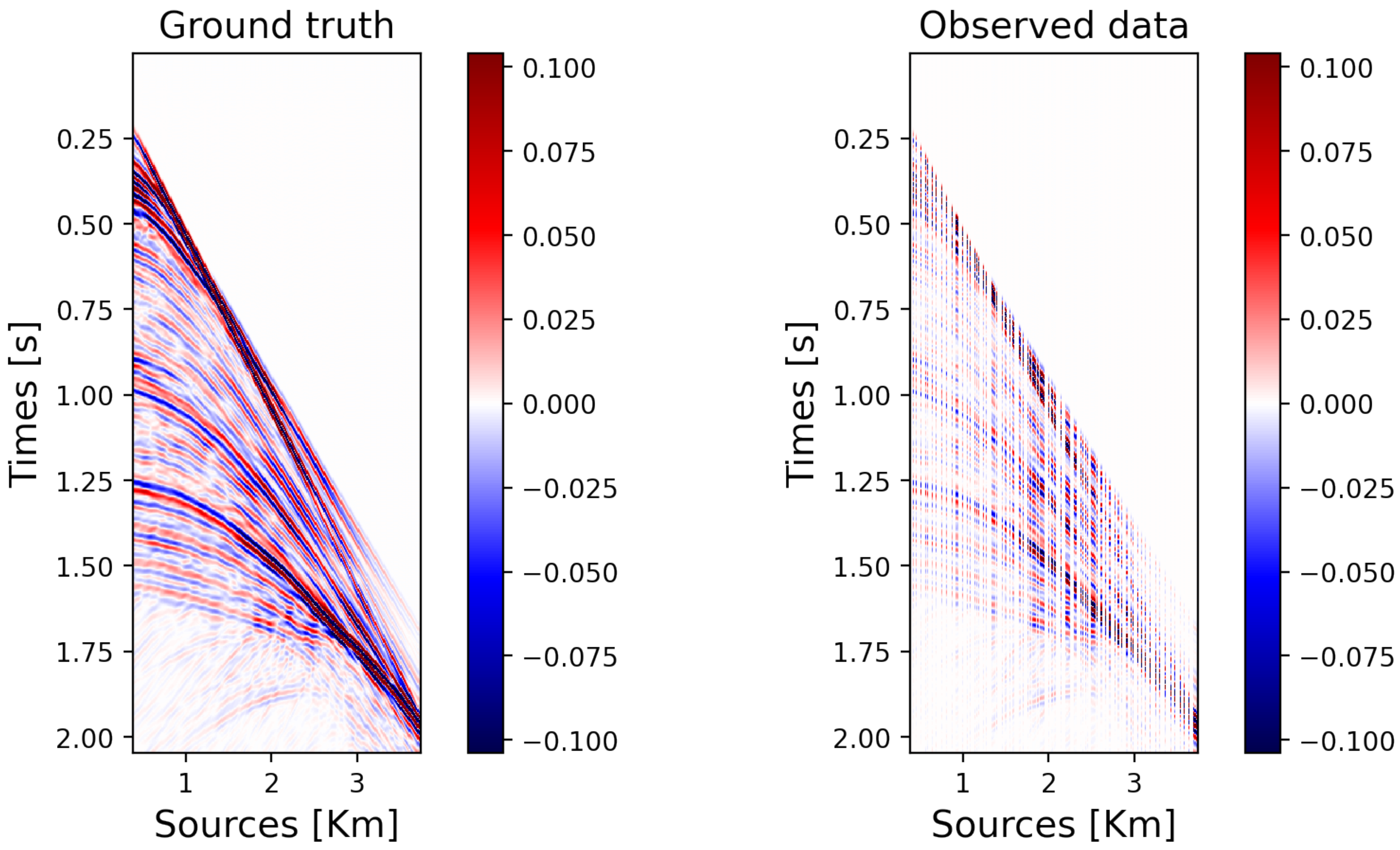
Dimension of each frequency slice: 300 x 300

Source sampling interval: 12.5 m

Receiver sampling interval: 12.5 m

Time sampling interval: 0.002 s

2D synthetic Compass dataset



Scenarios

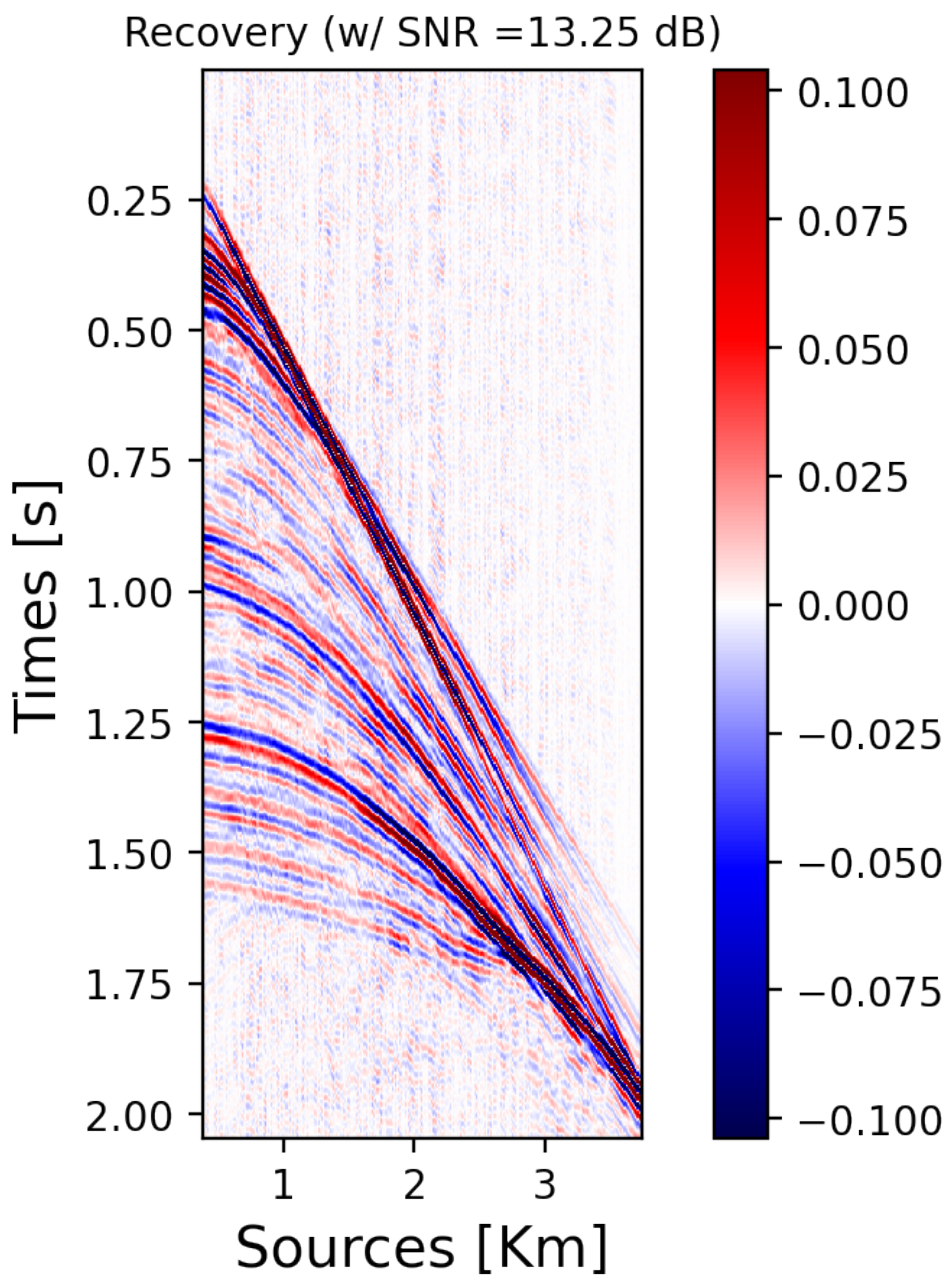
Use wavefield reconstruction to recover the subsampled data w/ 4 masks

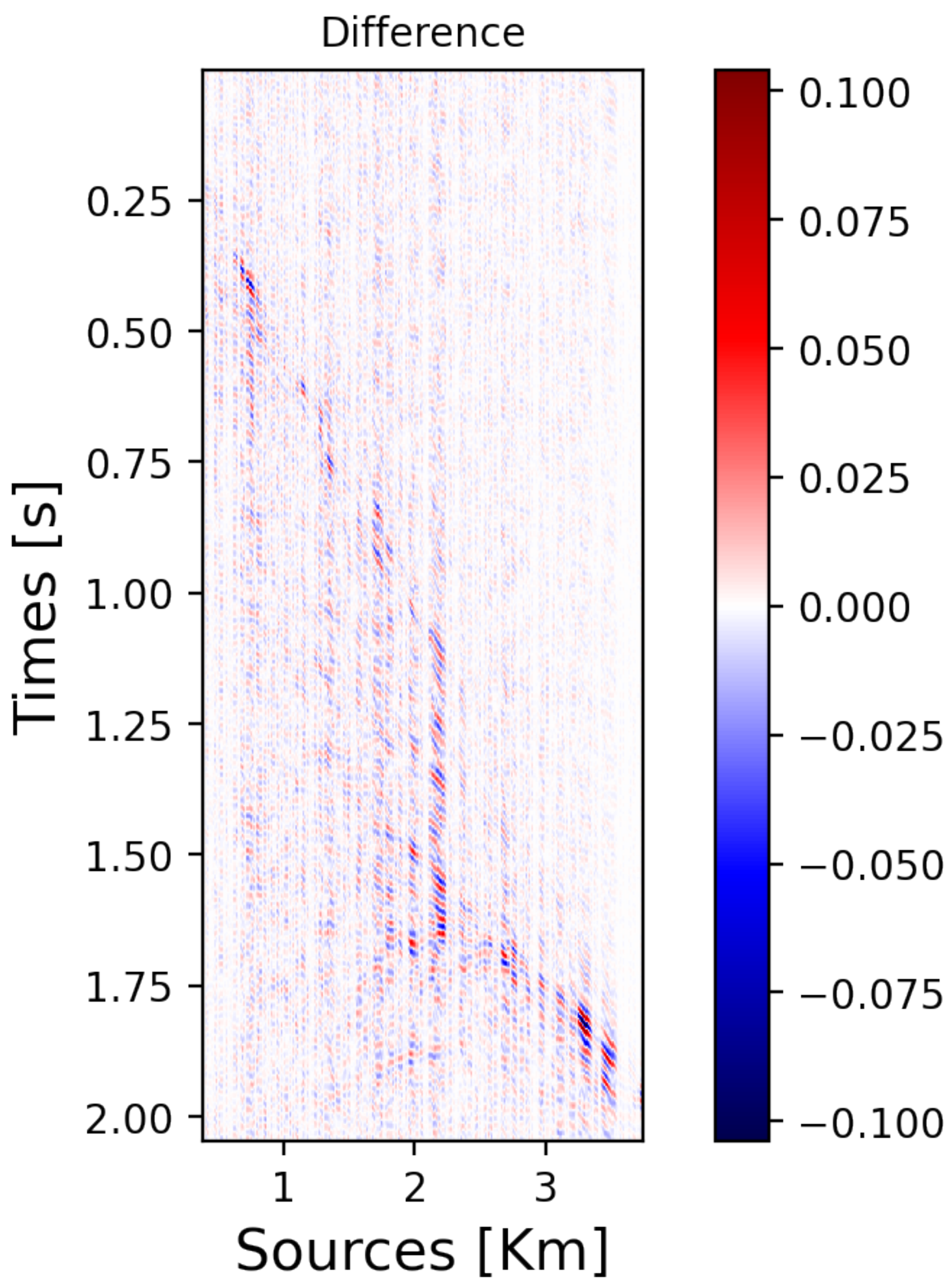
- Uniform random
- Improved random mask w/ proposed optimized method
- Optimal jittered (w/ max gap control)
- Improved jittered subsampling w/ proposed optimized method

Recovery & difference

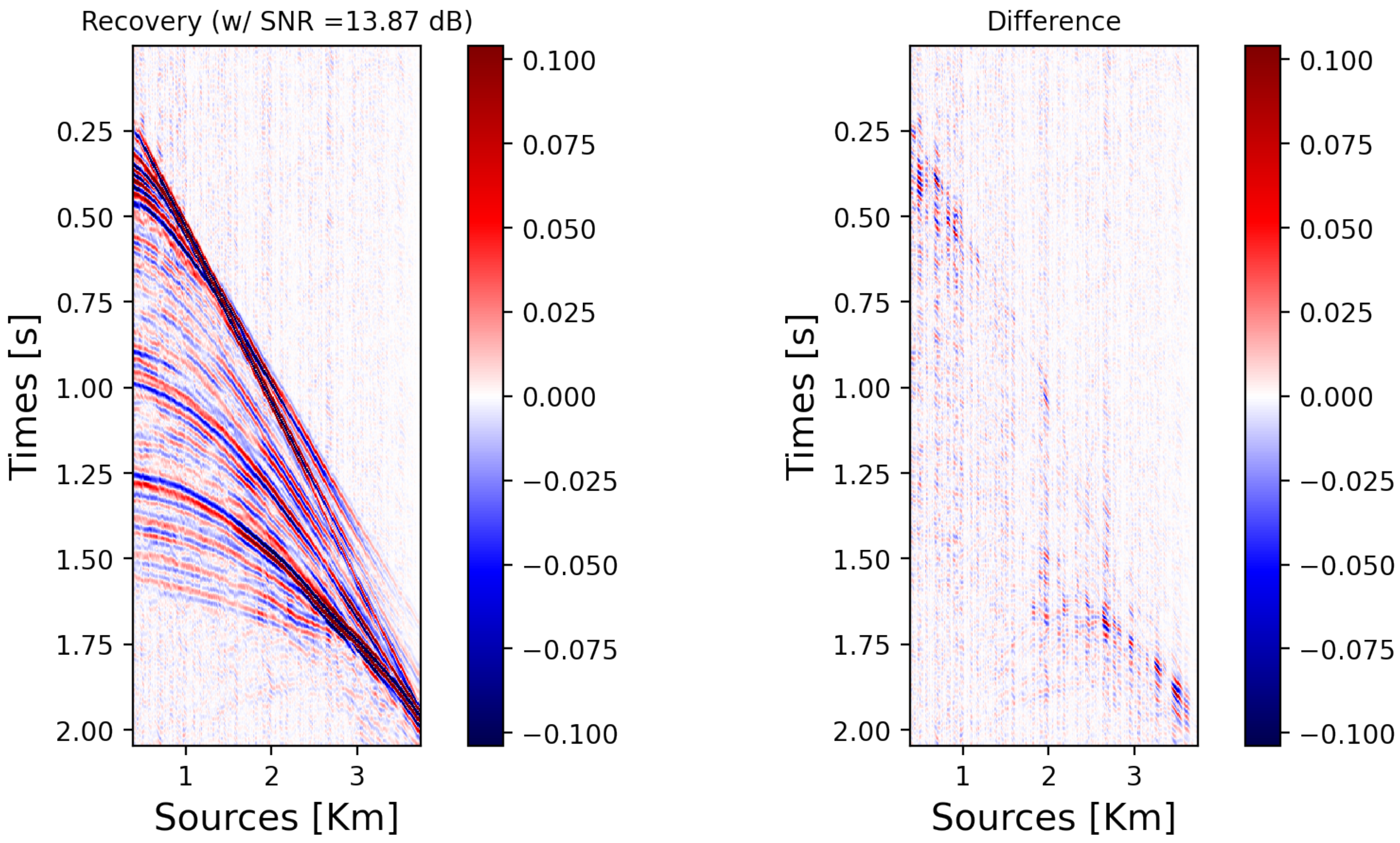
Uniform random mask

Difference = ground truth - recovery

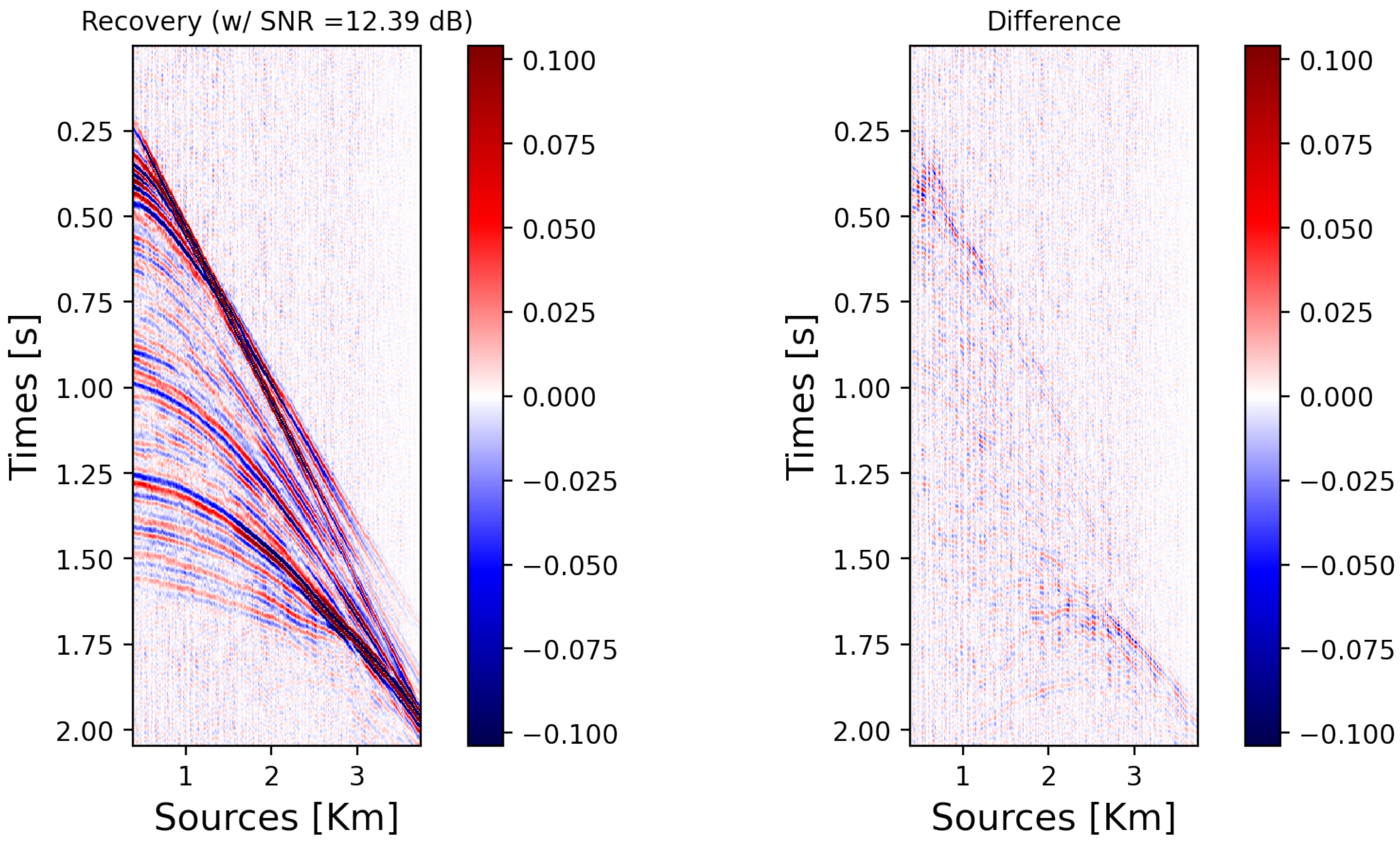




Recovery & difference
Improved uniform random mask



Recovery & difference
Optimal jittered mask



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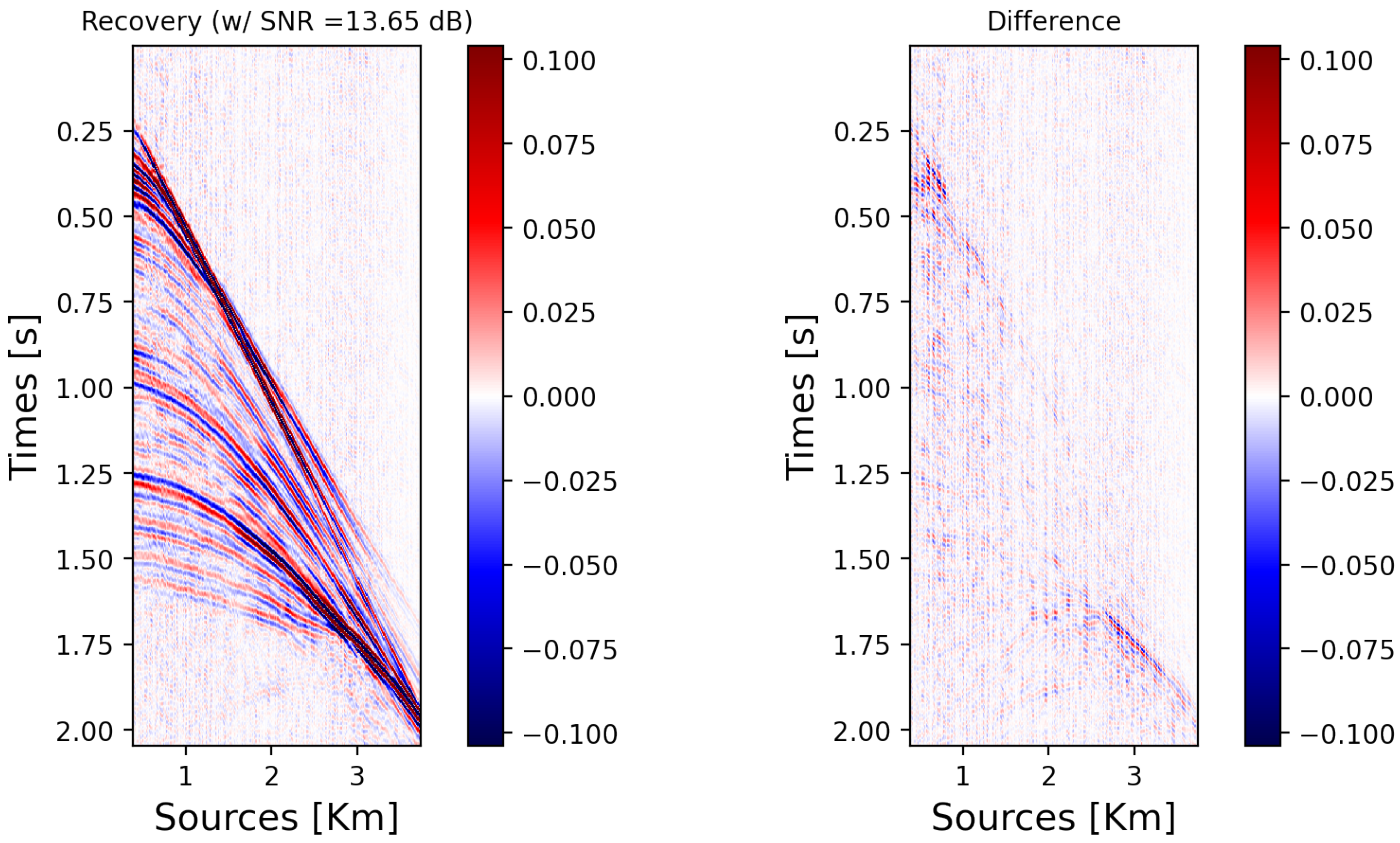
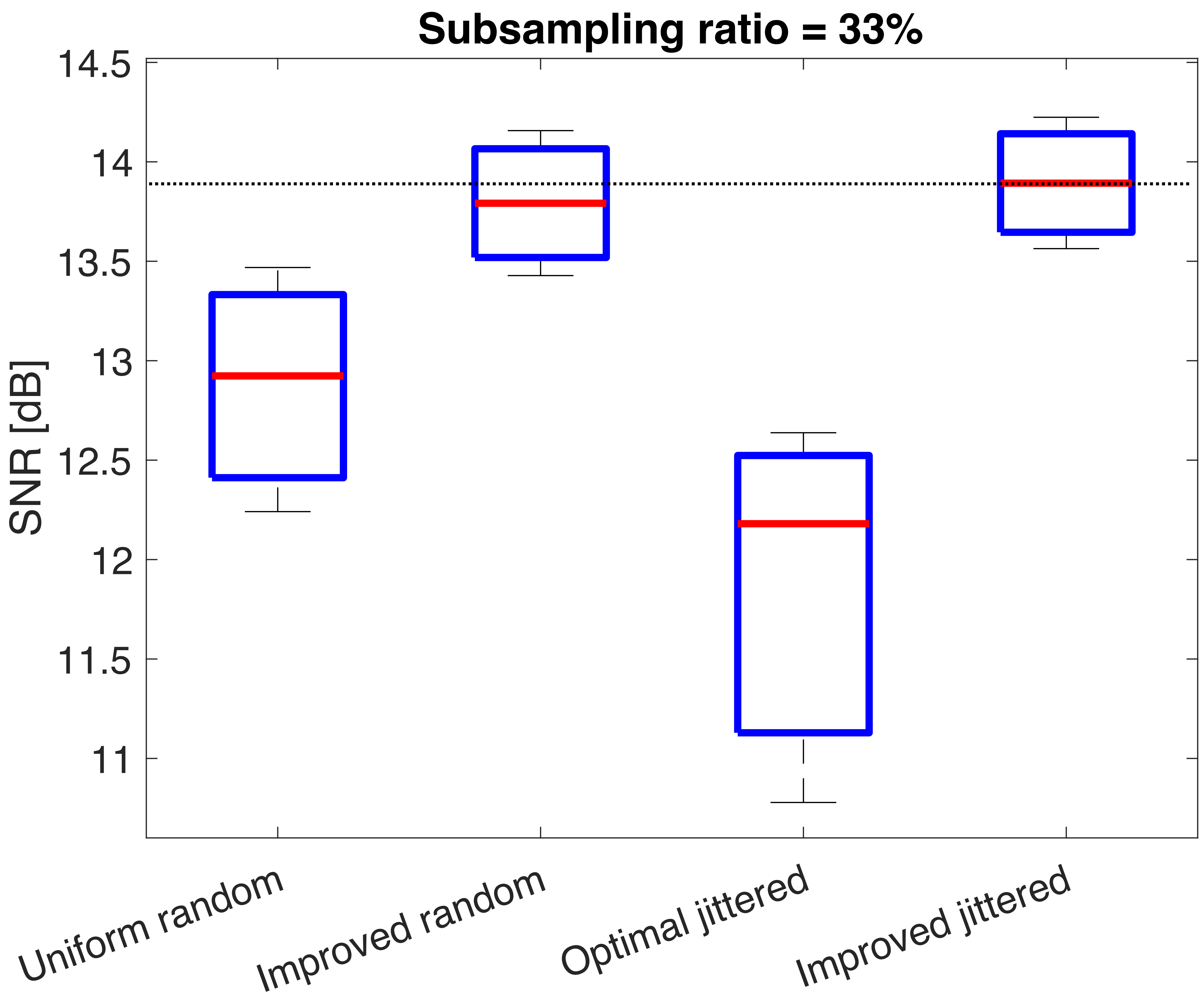
Recovery & difference

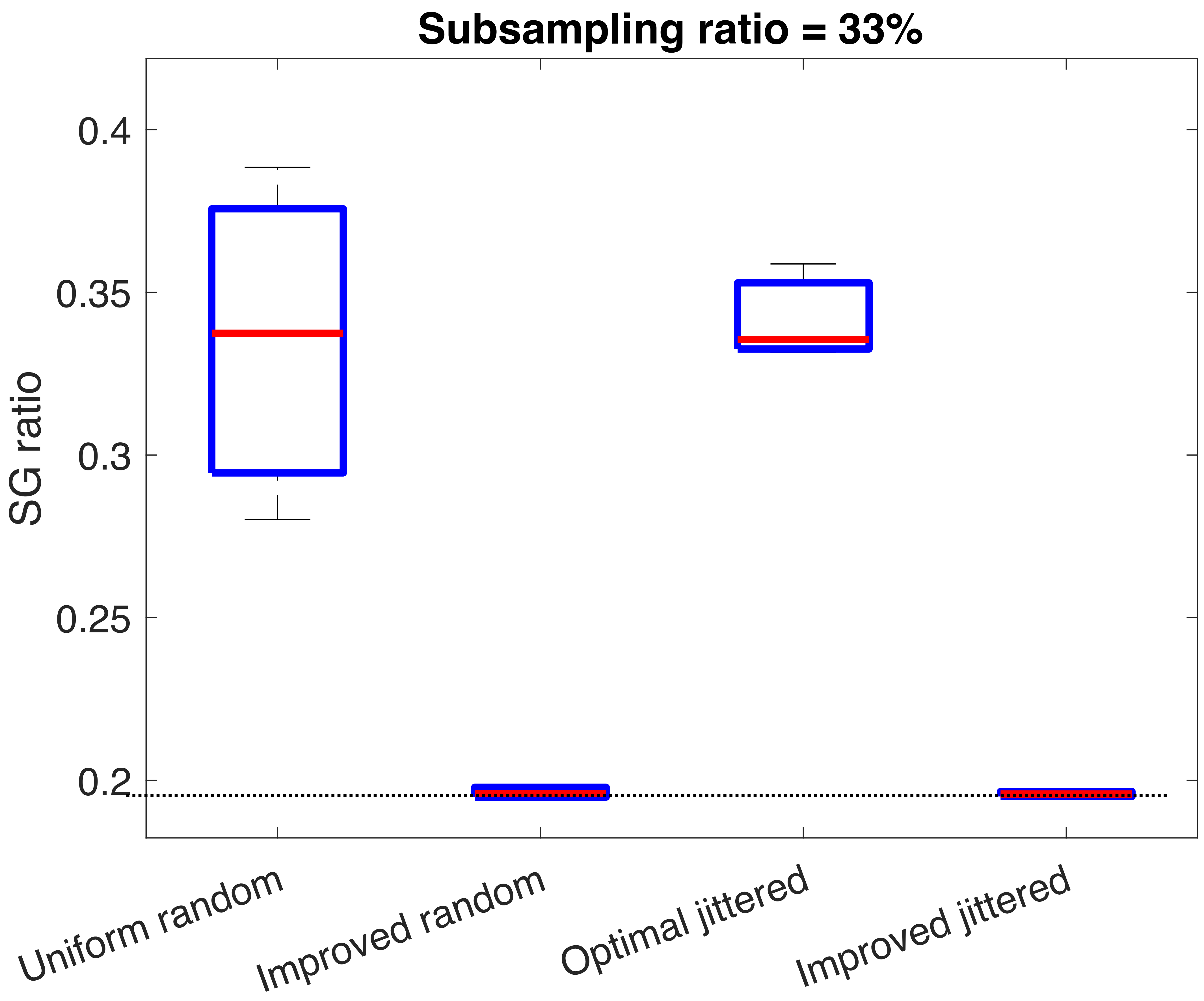
Improved jittered mask w/ proposed method

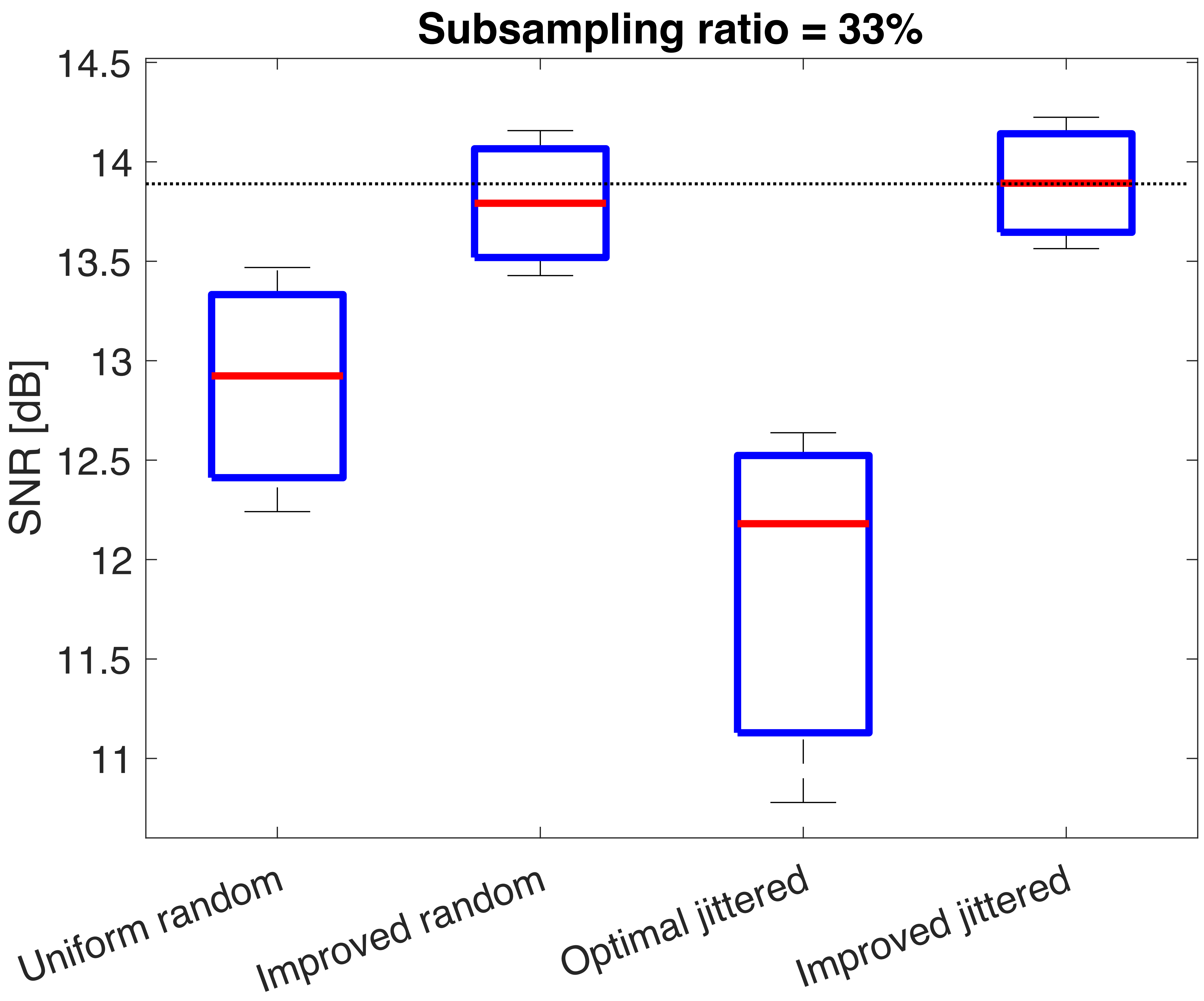


SNR comparison
W/ 10 independent tests



SG ratio comparison vs. SNR comparison
W/ 10 independent tests





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Stylized example
w/ unequal source/receiver dimension (300×150)

Experiment 3

Optimal SG ratio w/ simulated annealing

Mask dimension: 300×150

Subsampling ratio: $20\,\%$

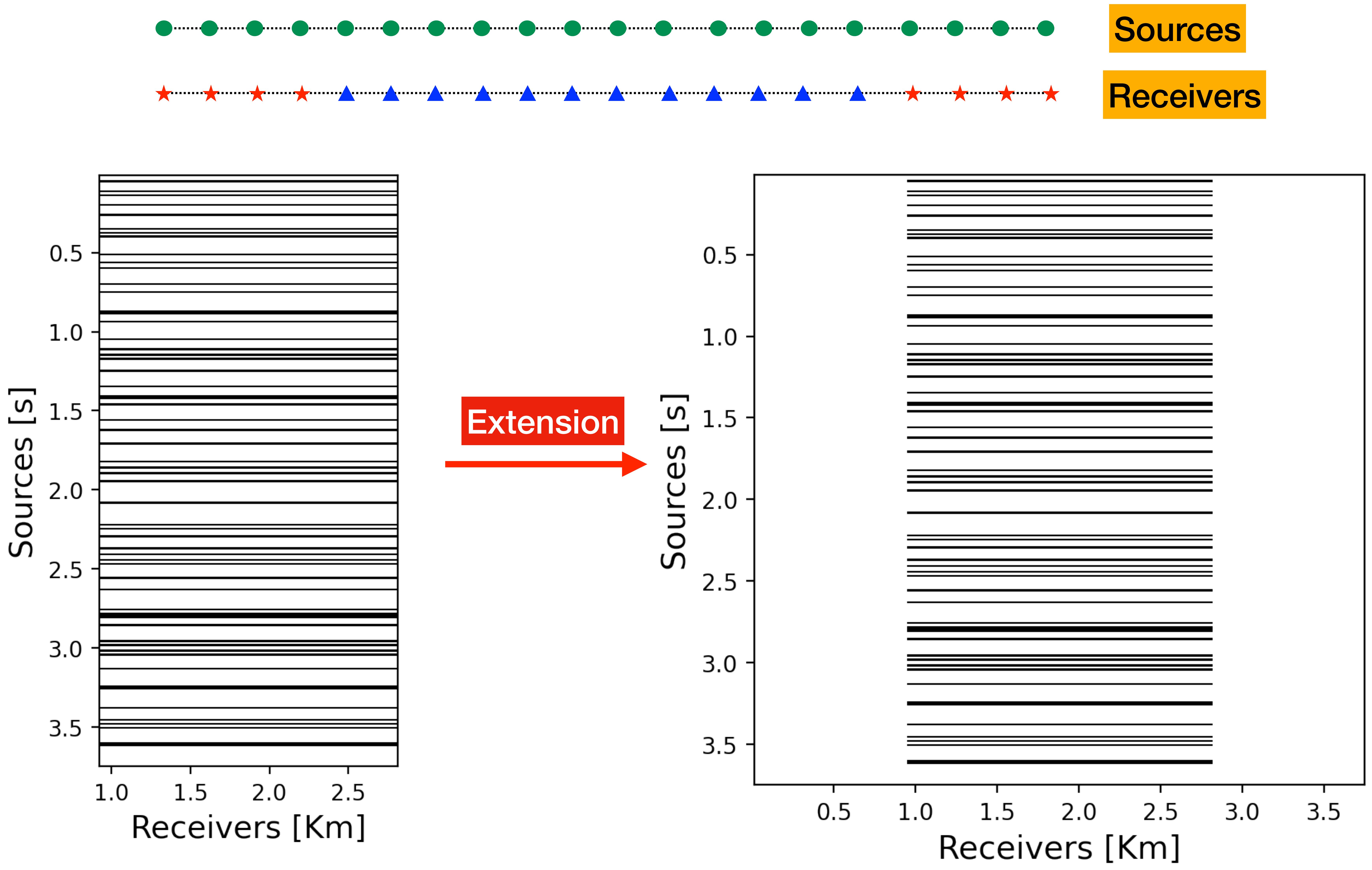
Source & receiver sampling interval: 12.5 m

Decrease SG ratio of given initial subsampling masks:

- uniform random subsampling
- optimal jittered subsampling

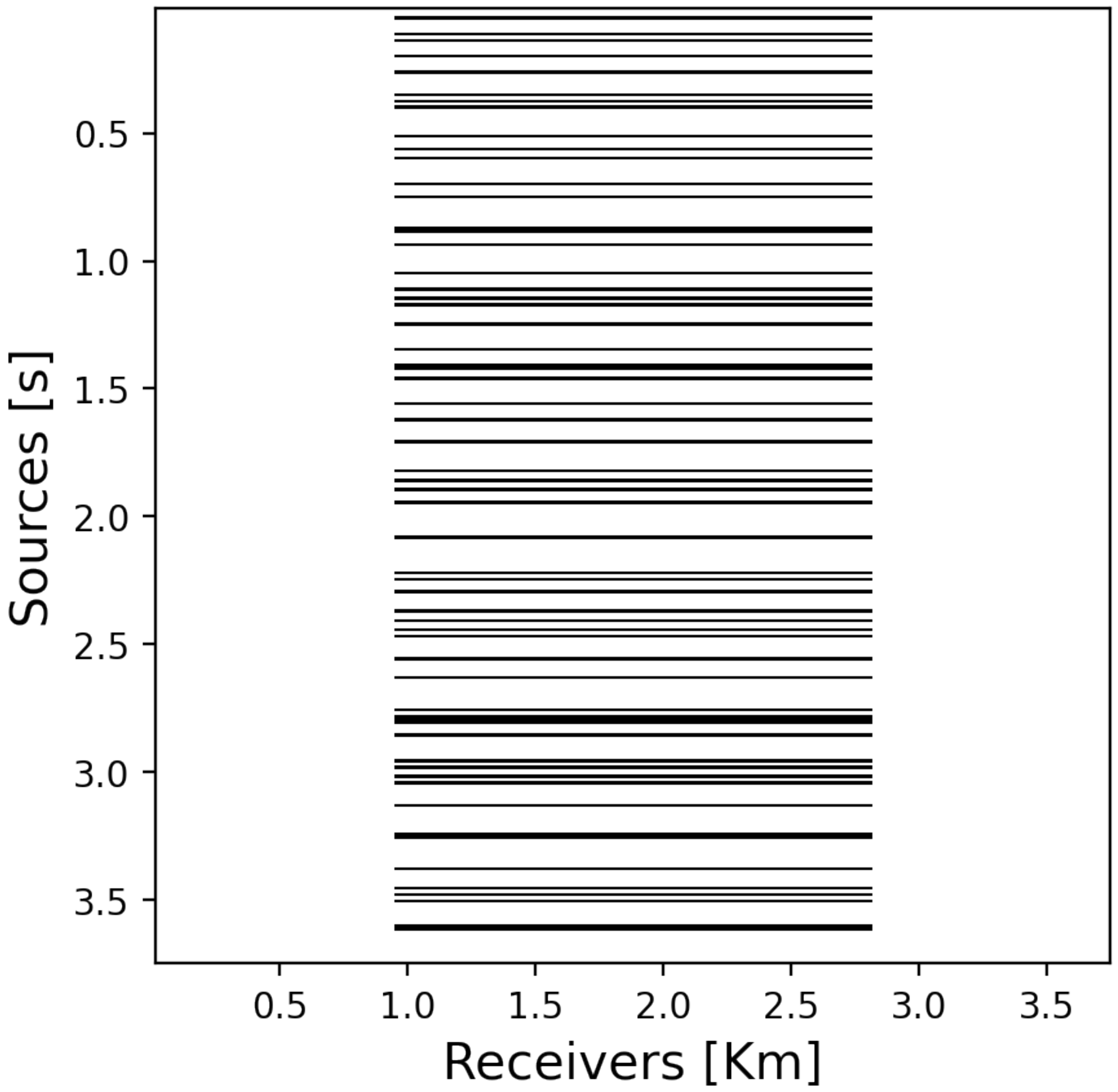
Subsampled mask in source-receiver domain

Subsampling ratio = $20\ \%$

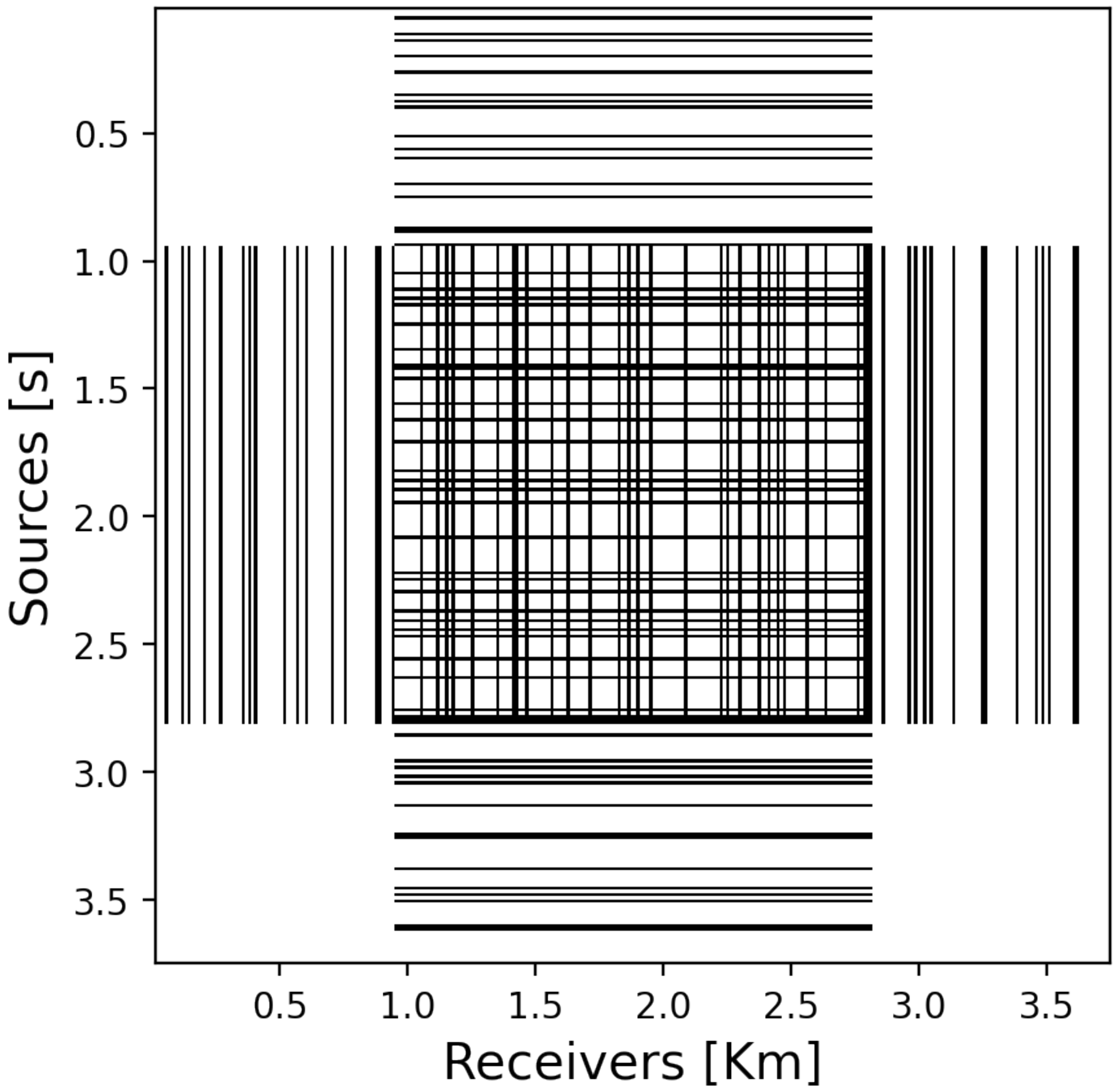


Subsampled mask in source-receiver domain

Subsampling ratio = $20\,\%$

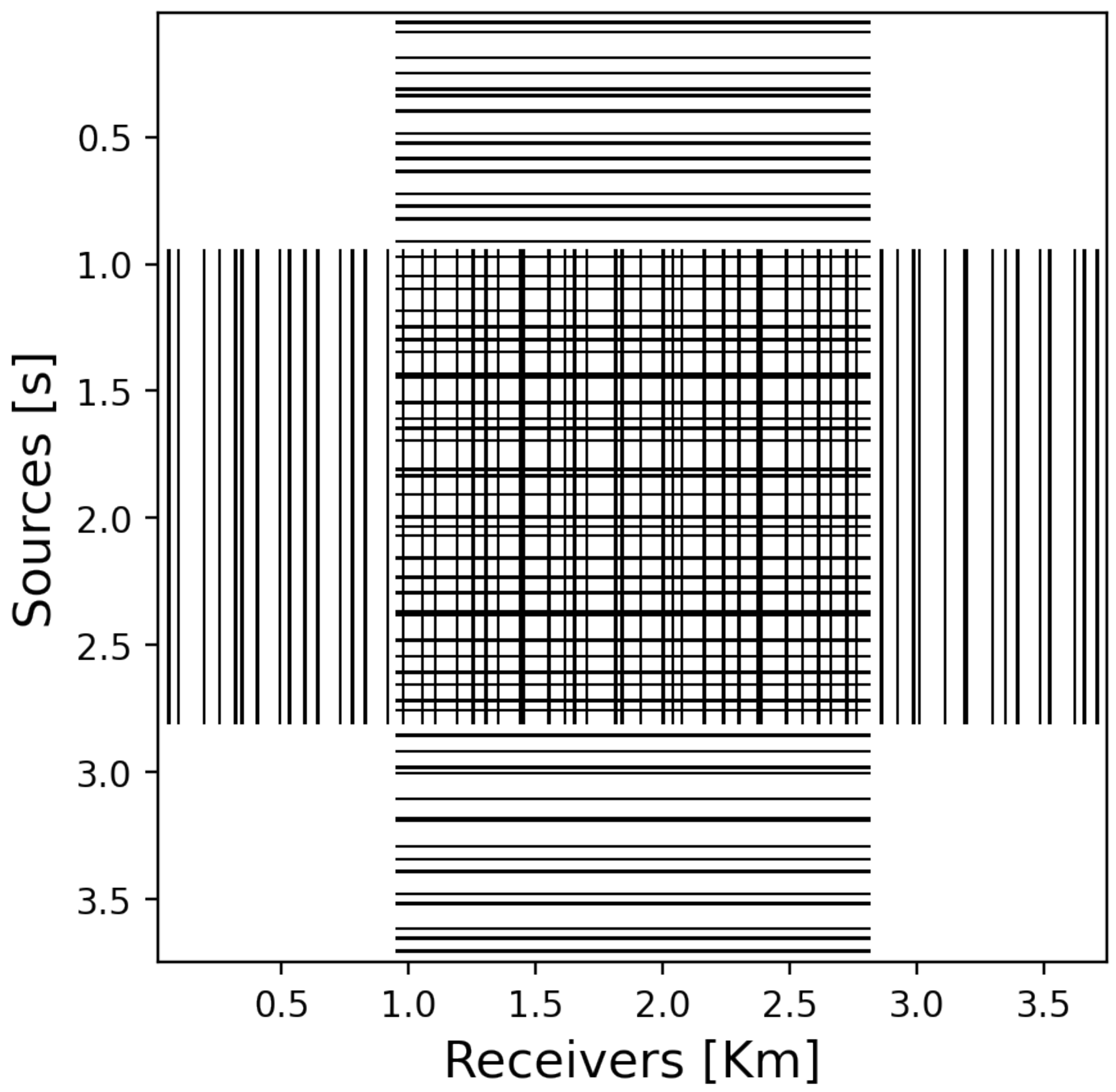


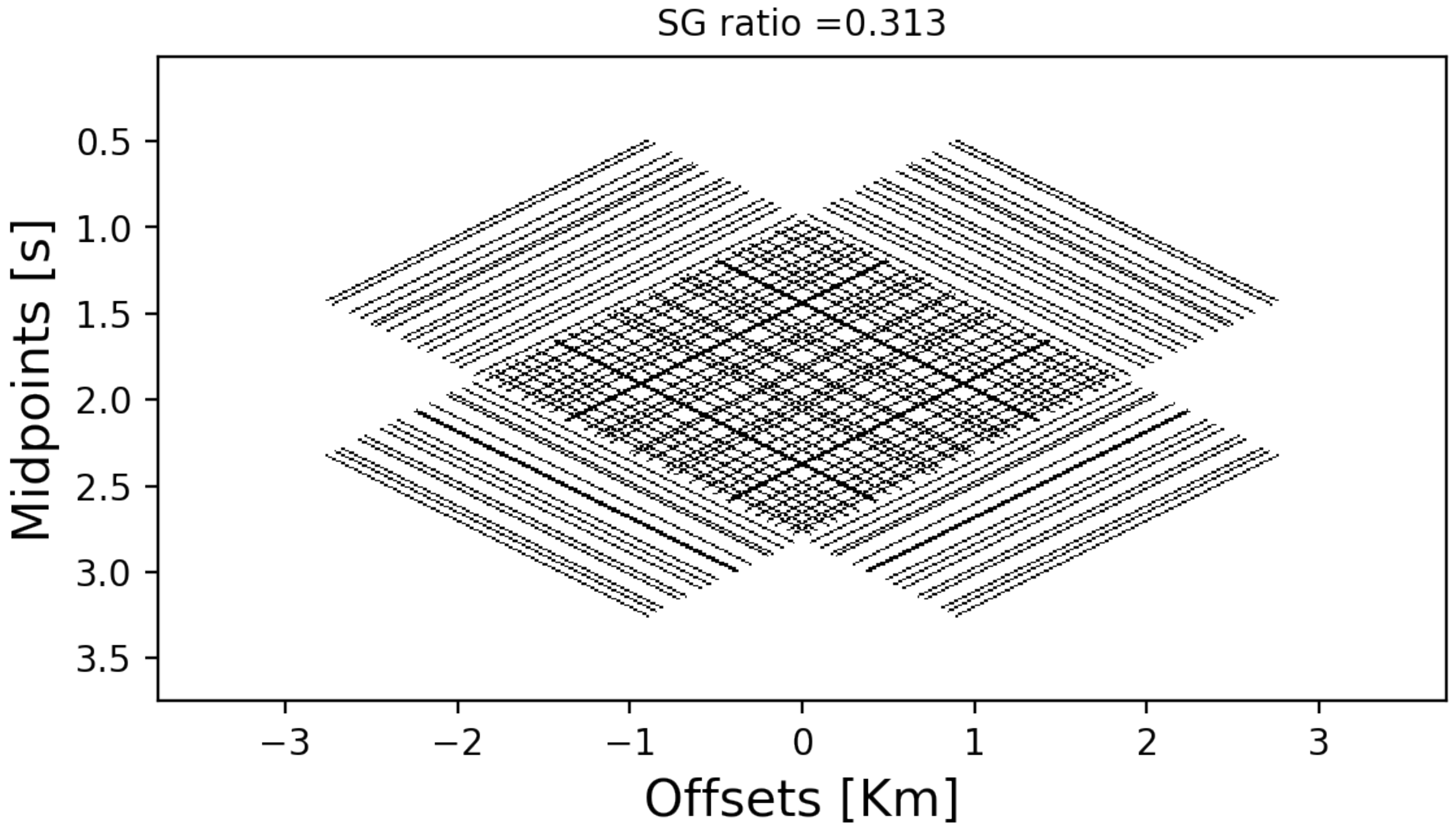
Reciprocity



Uniform random mask

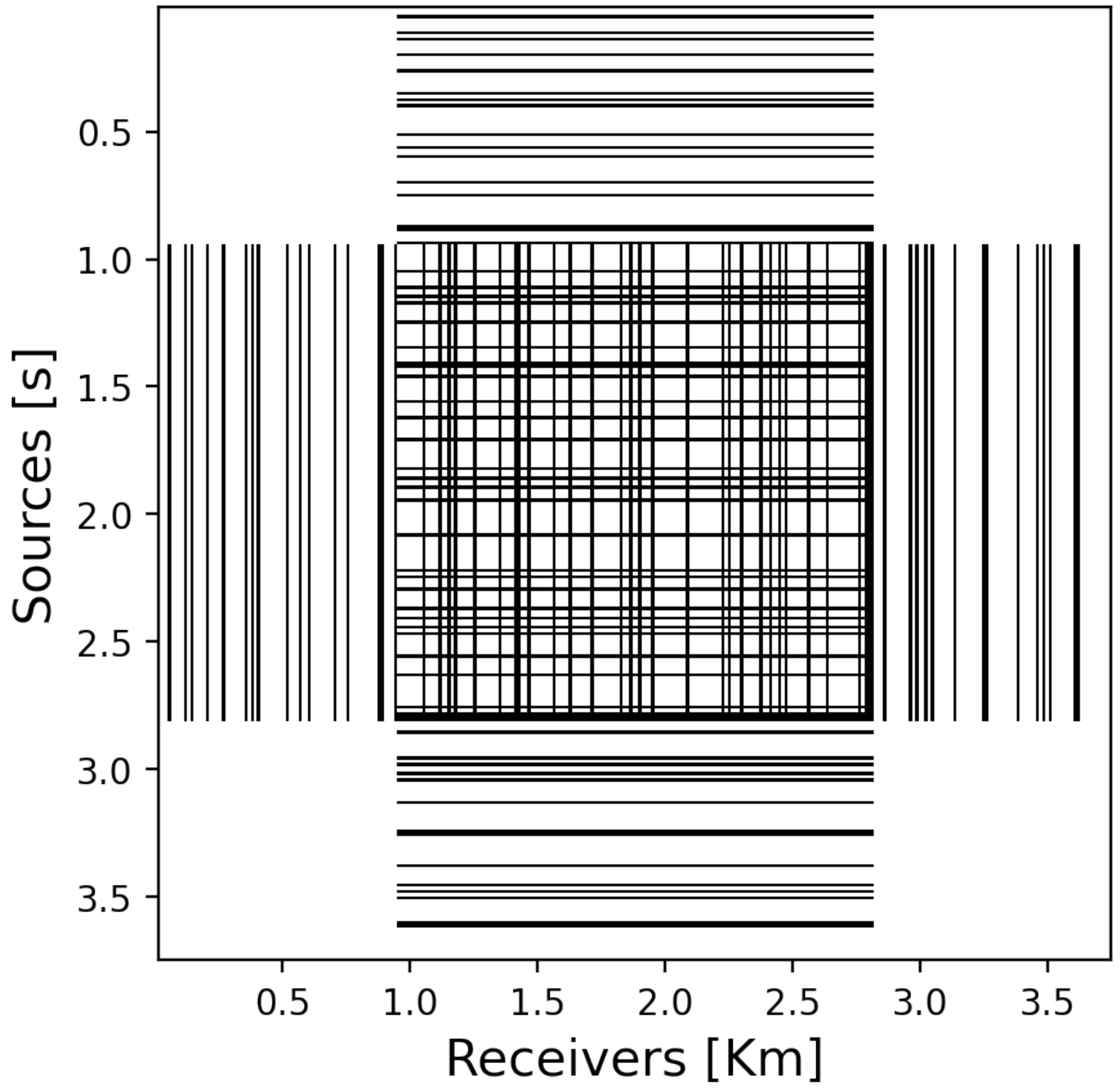
Initial state (input) of the optimal method

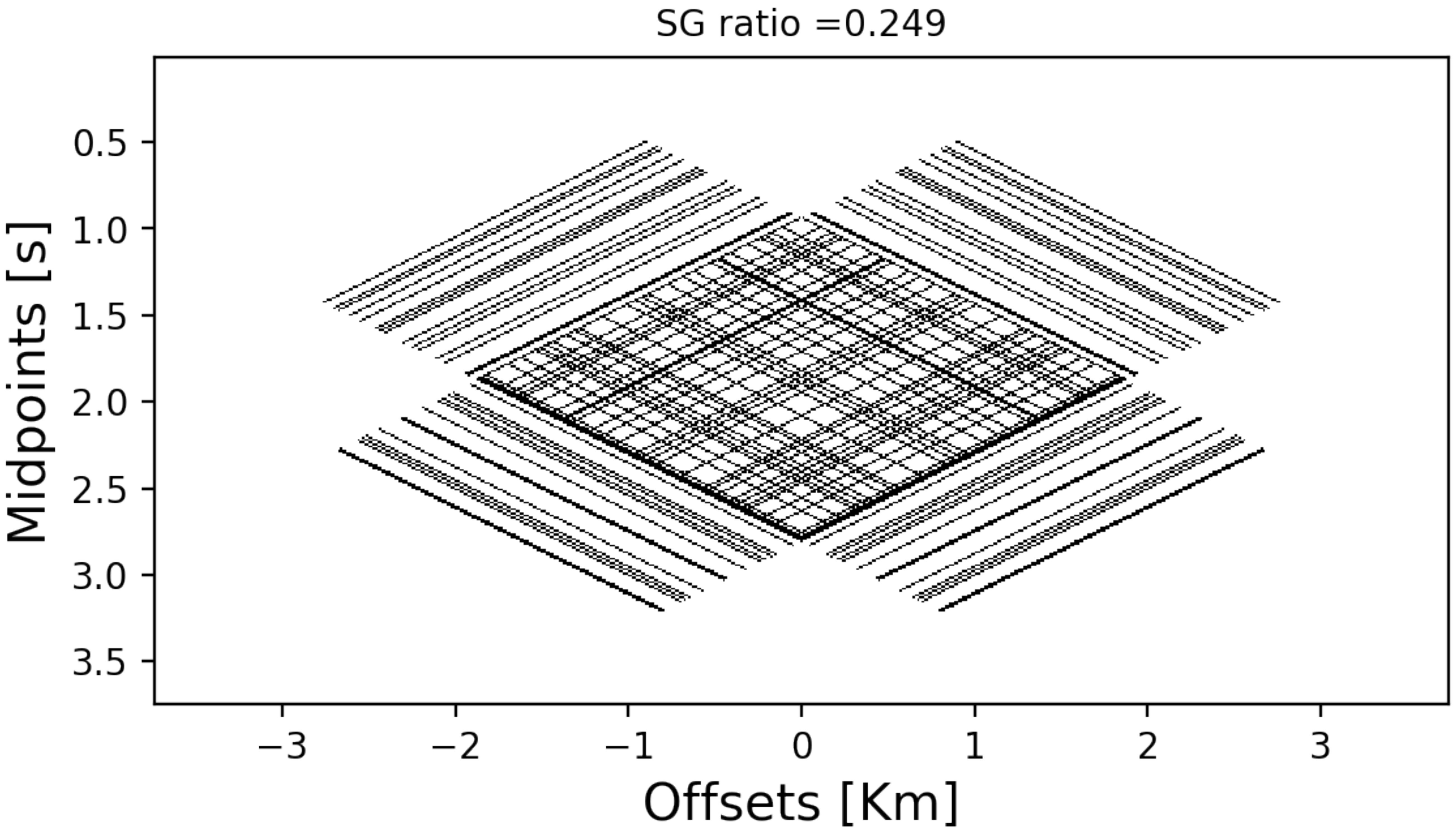




Improved random mask

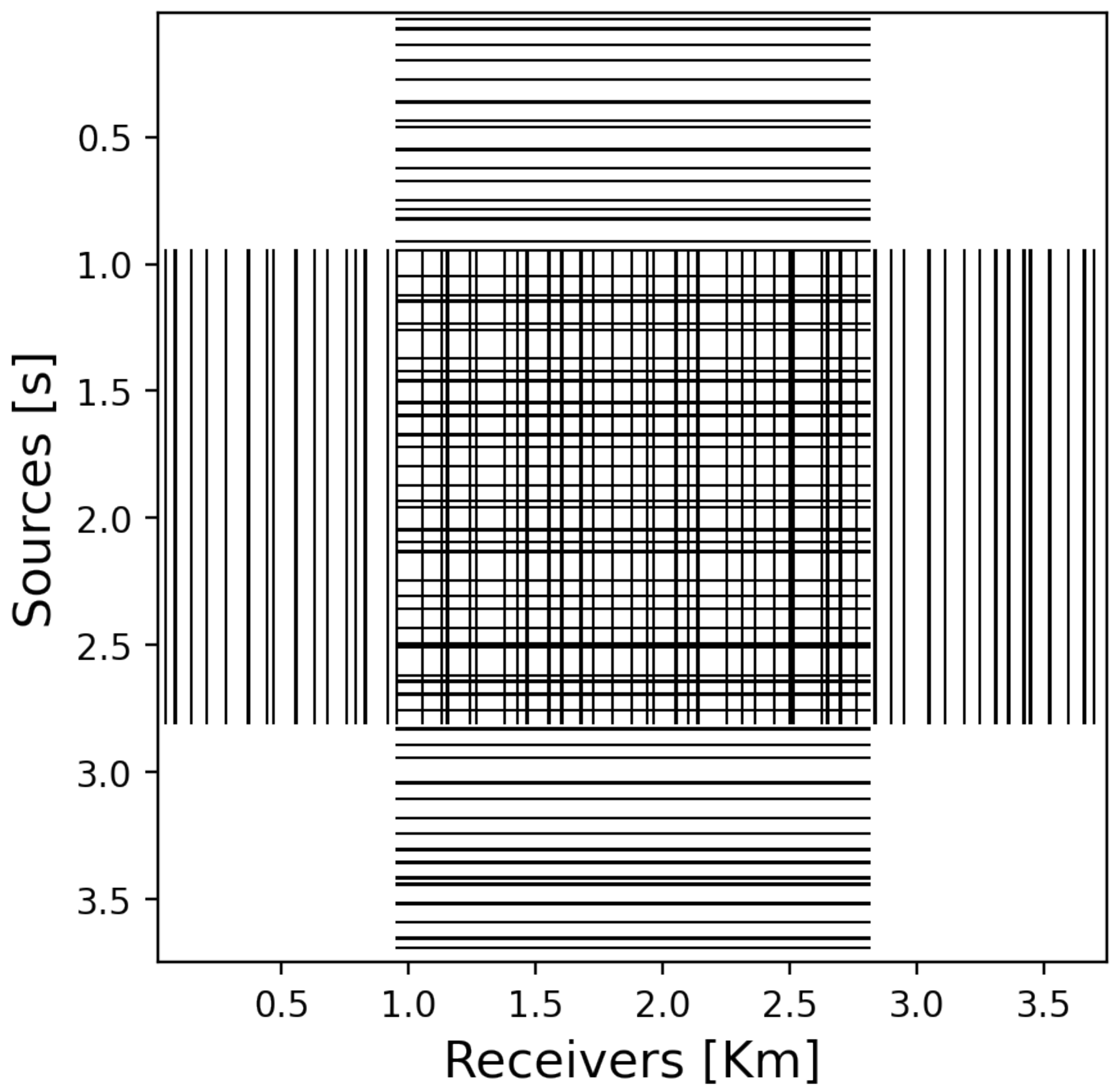
Output of the optimal method w/ SA algorithm

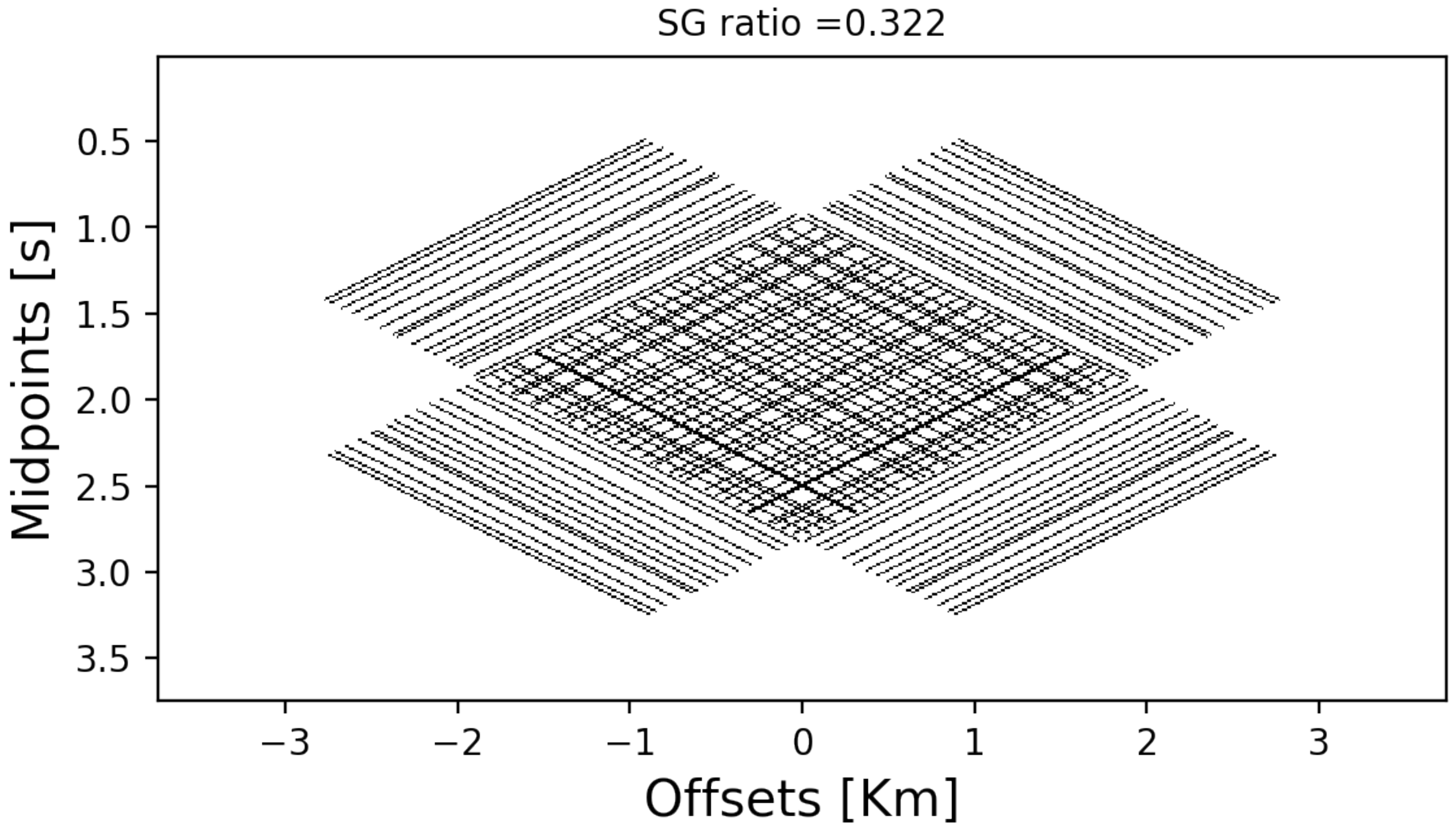




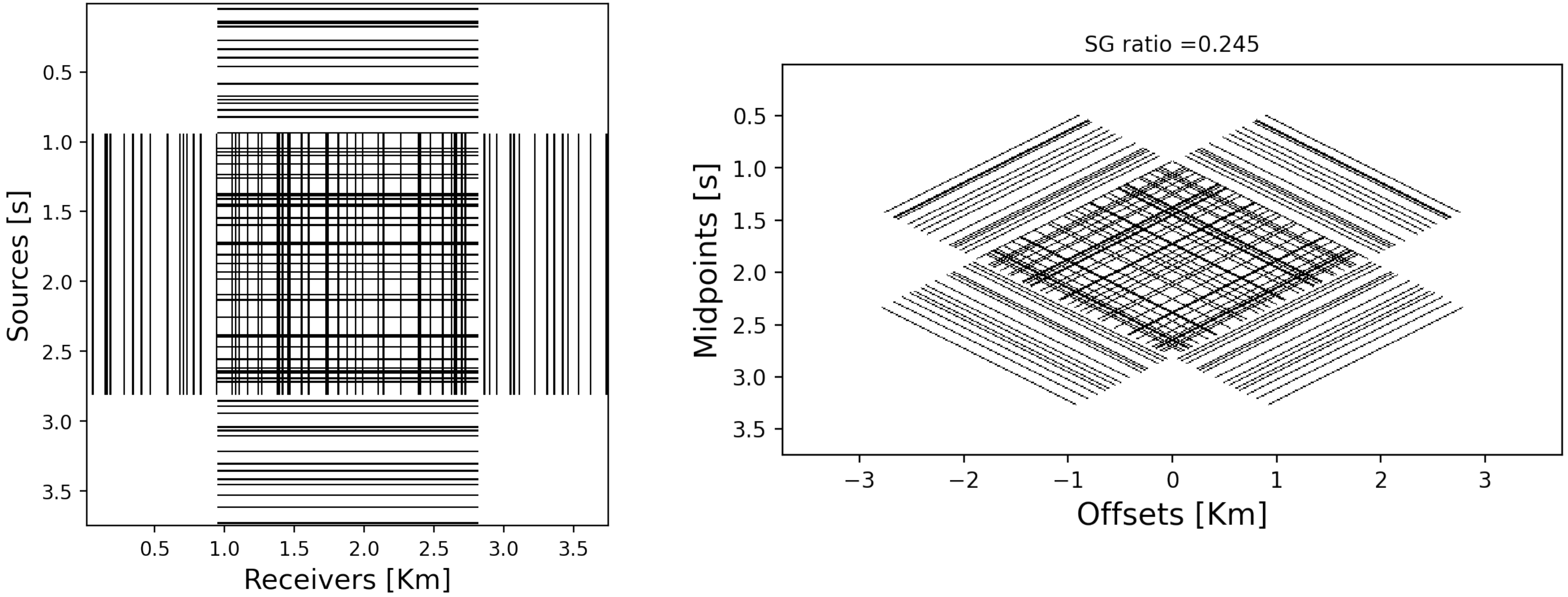
Optimal jittered mask

Initial state (input) of the optimal method

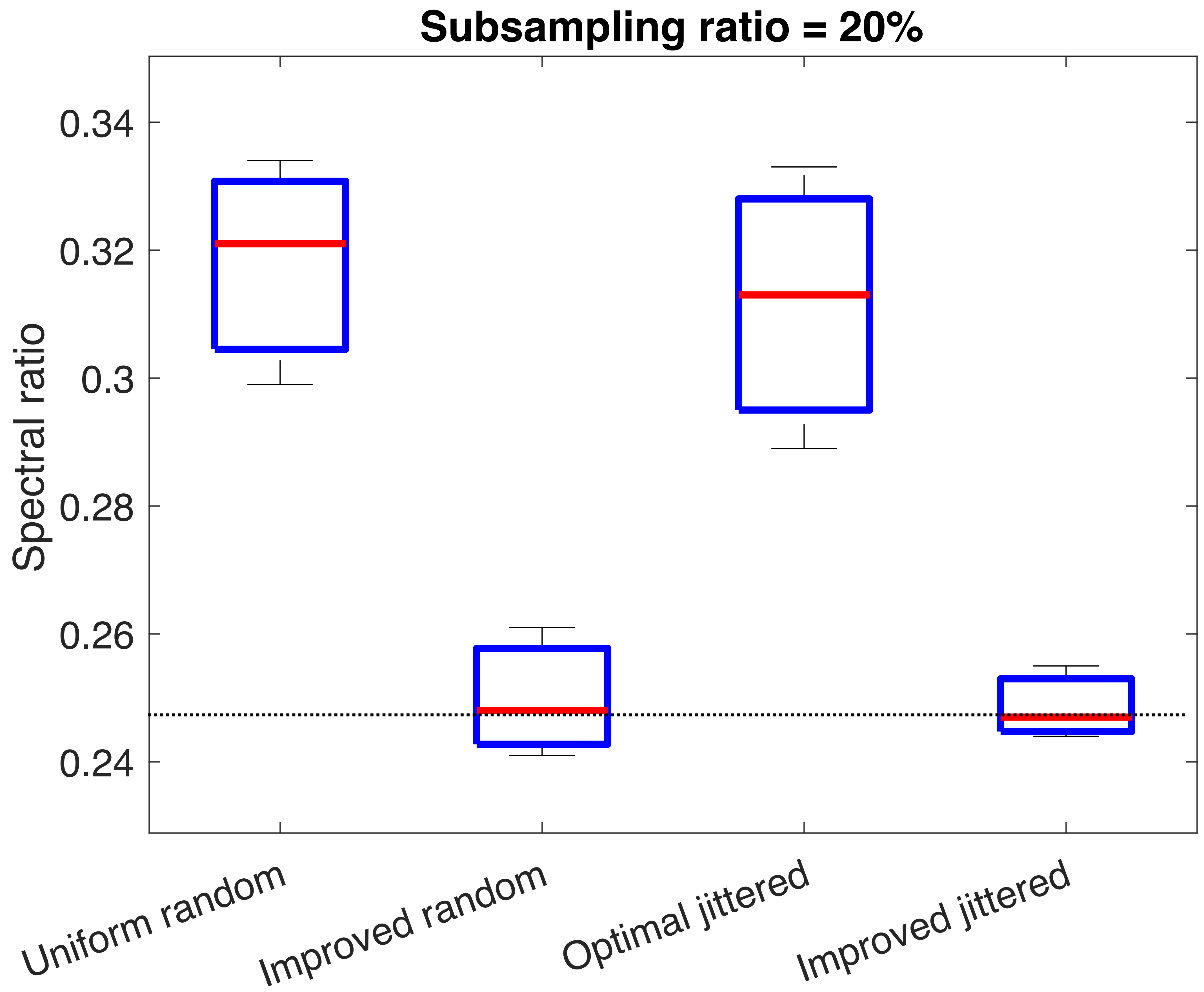




Improved jittered mask
Output of the optimal method w/ SA algorithm



SG ratio comparison
W/ 10 independent tests



Conclusion & future works

Improved seismic survey design w/o expensive wavefield reconstruction

Proposed optimization scheme that finds subsampling masks w/ small SG ratio

Optimized masks improve wavefield reconstruction

Test reconstruction quality w/ unequal source/receiver dimension

3D seismic data survey design

Thank you for your attention!