Dense shot-sampling via **time-jittered** marine sources

Felix J. Herrmann, Tim Lin*, and Haneet Wason

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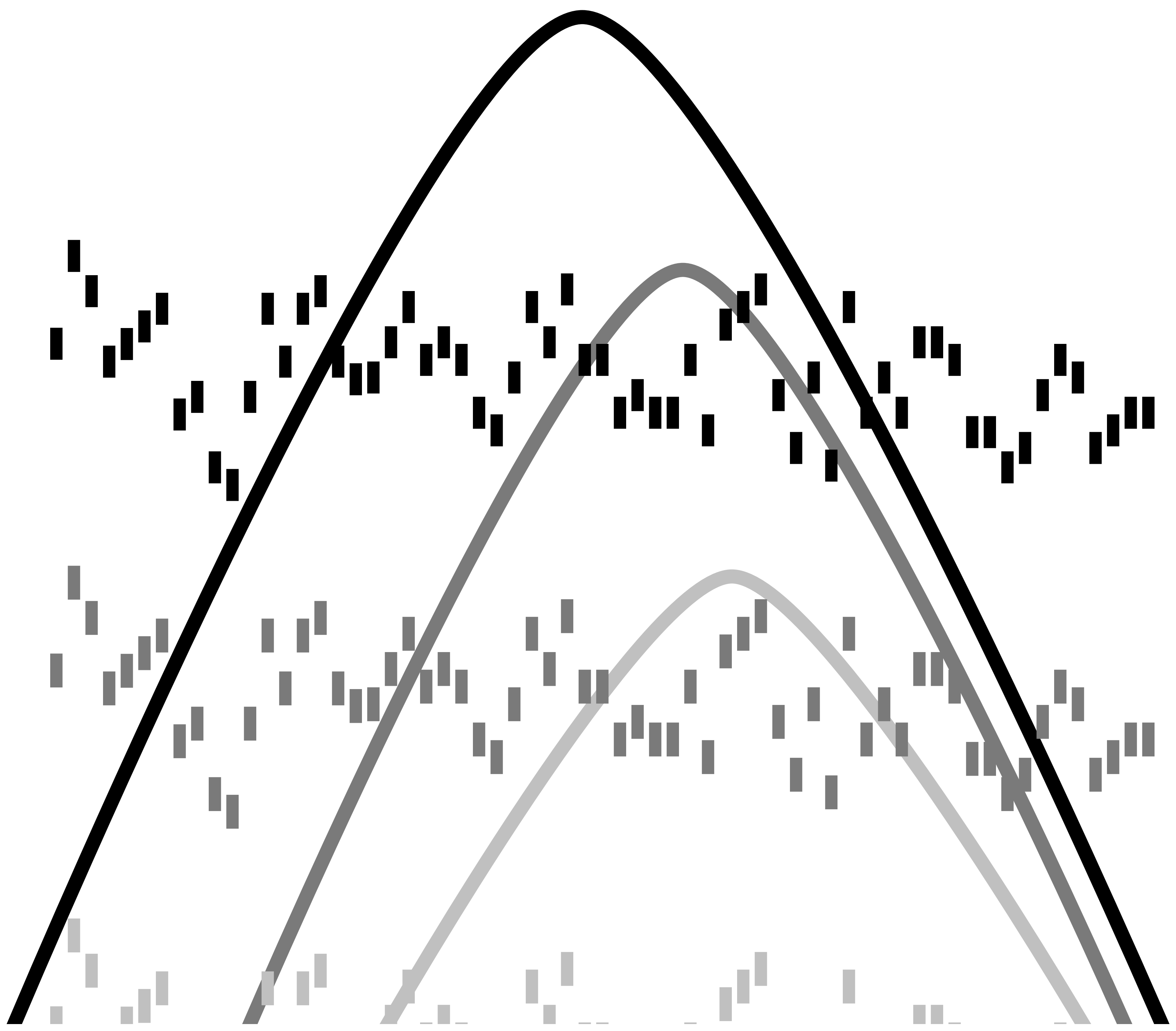
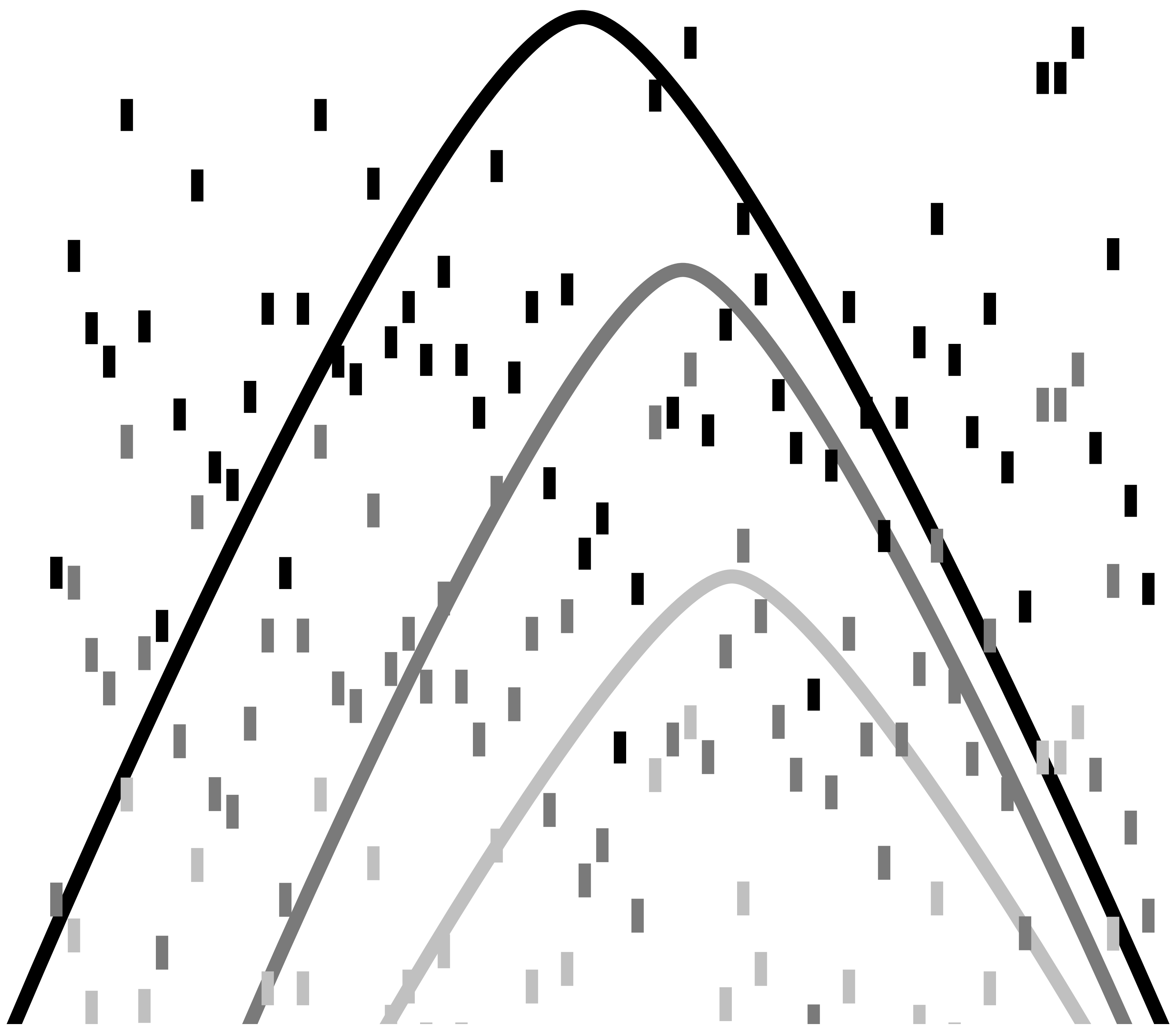
Shot-time randomness: “low” vs “high” variability



low variability

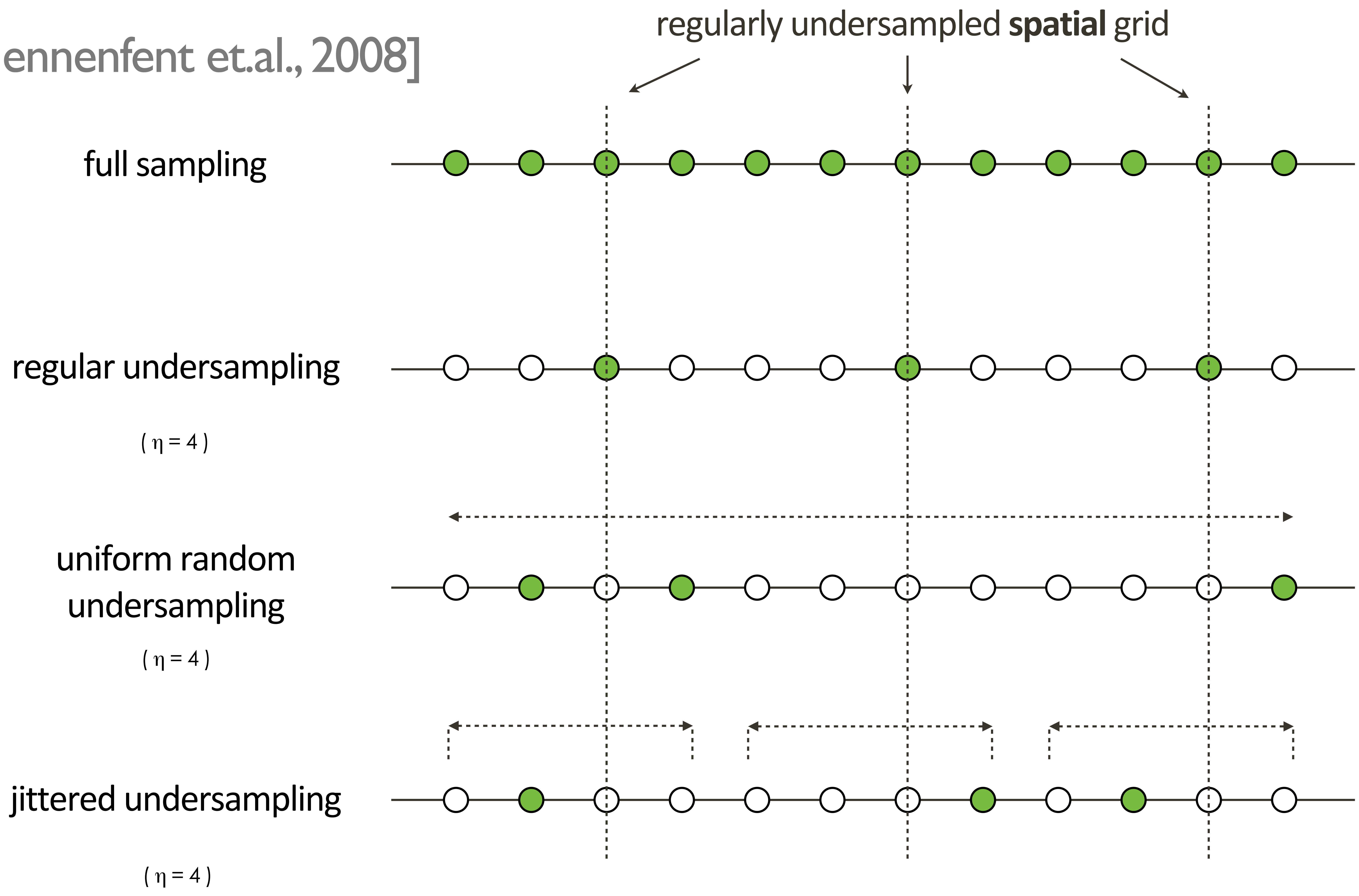
Shot-time randomness: “low” vs “high” variability



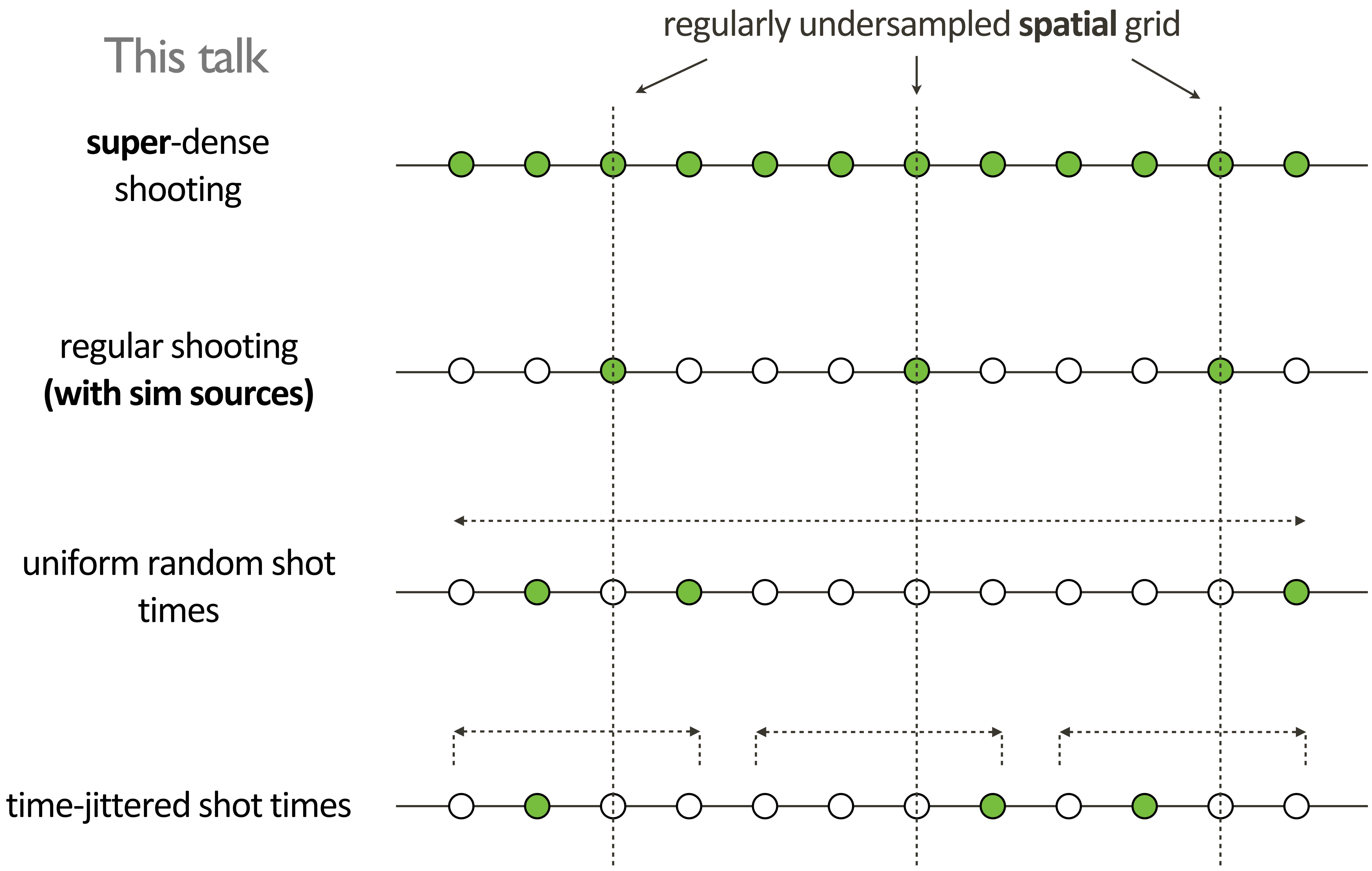
high variability,
easier to separate,
better low-frequency
recovery(?)

Spatial grid for sampling schemes

[Hennenfent et.al., 2008]



Spatial grid for sampling schemes



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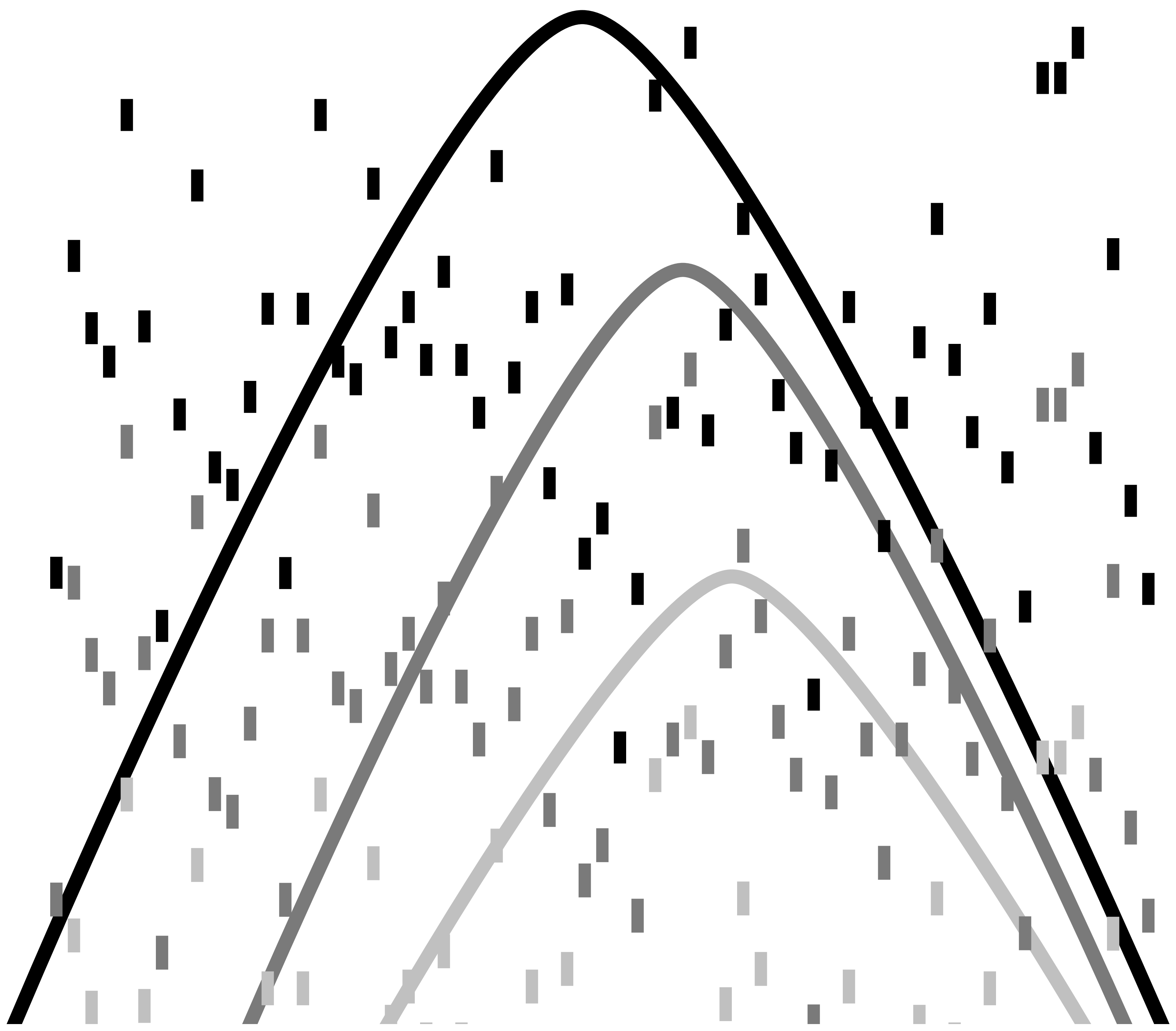

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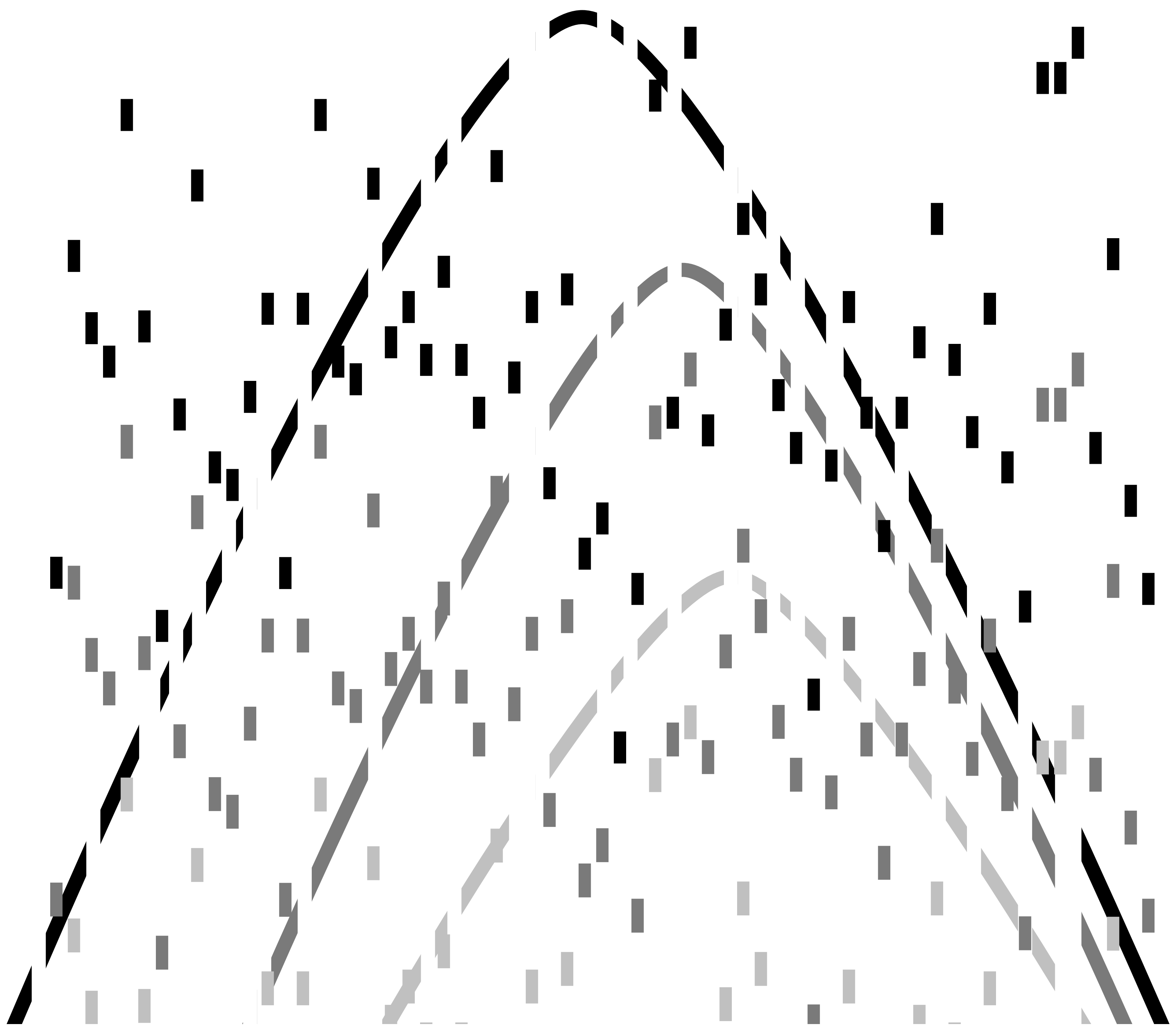
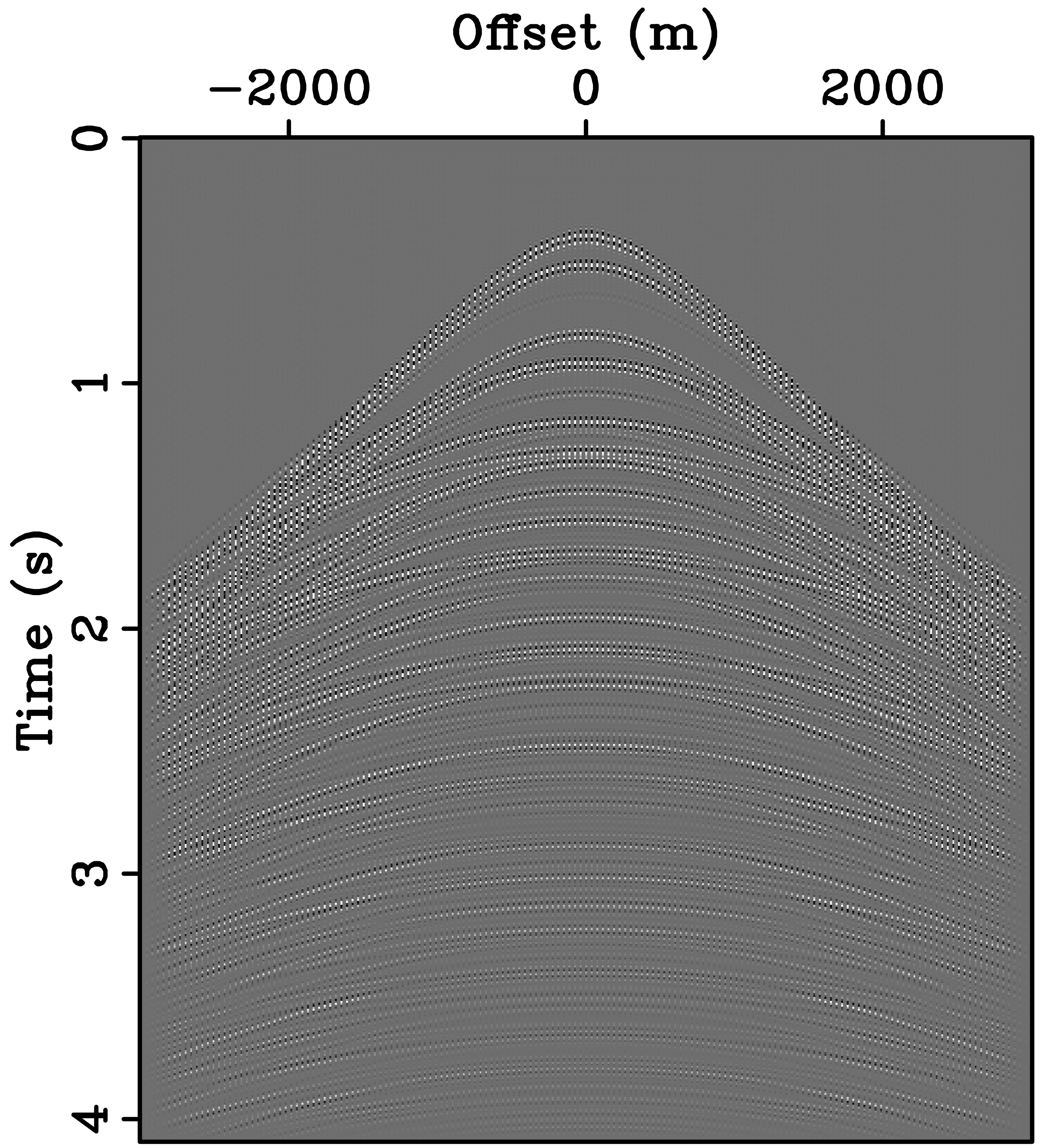
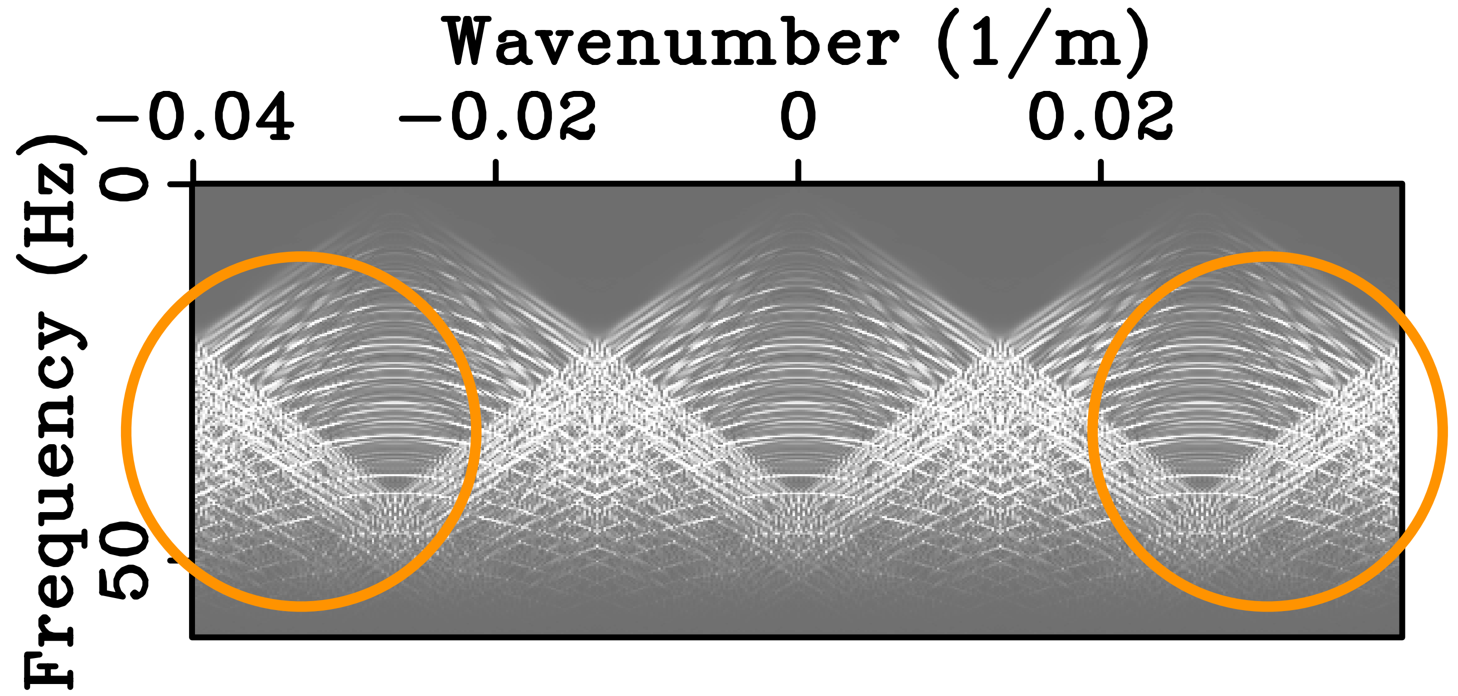


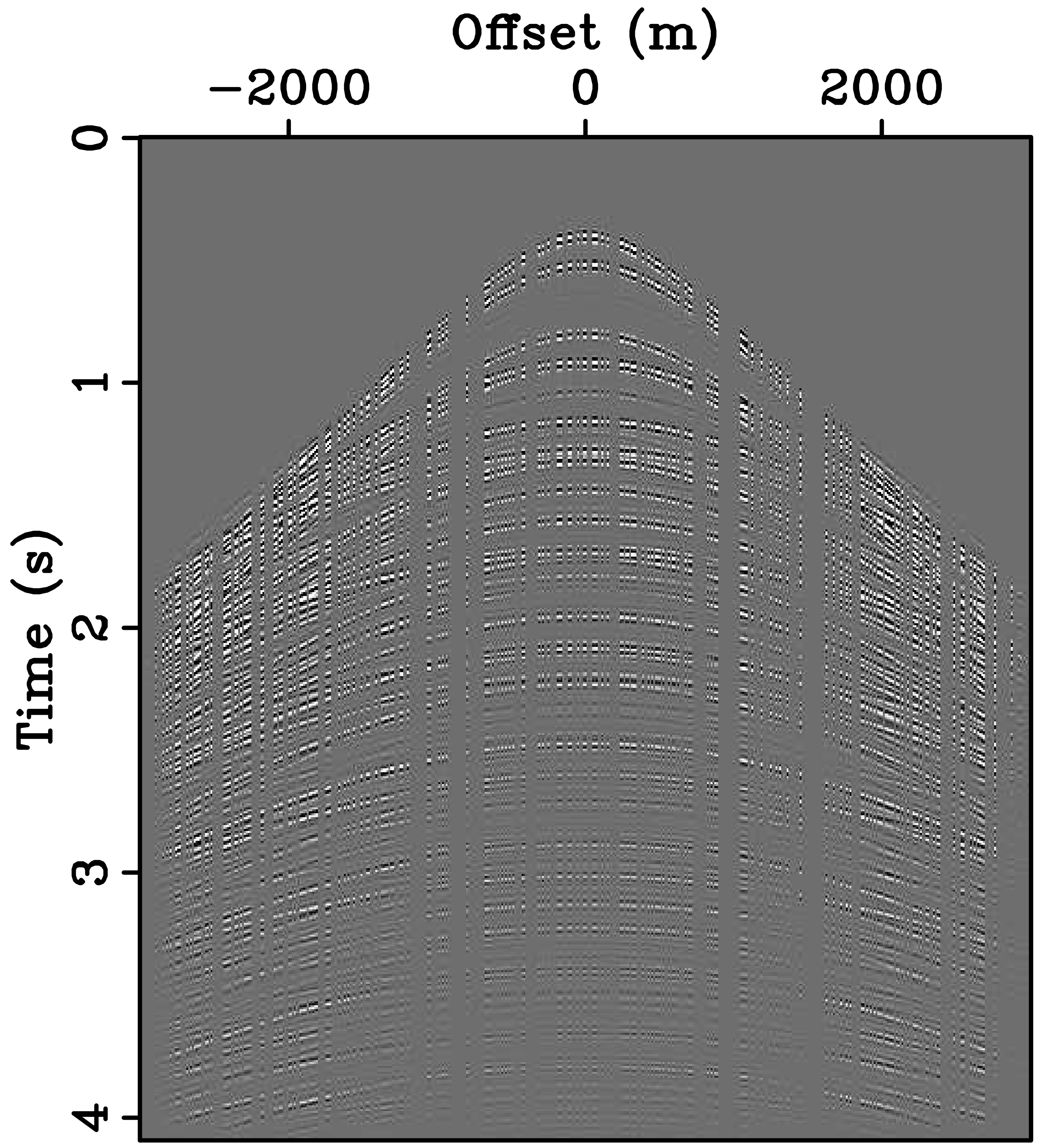
high variability
leads to
source separation
+
regularization
+
interpolation

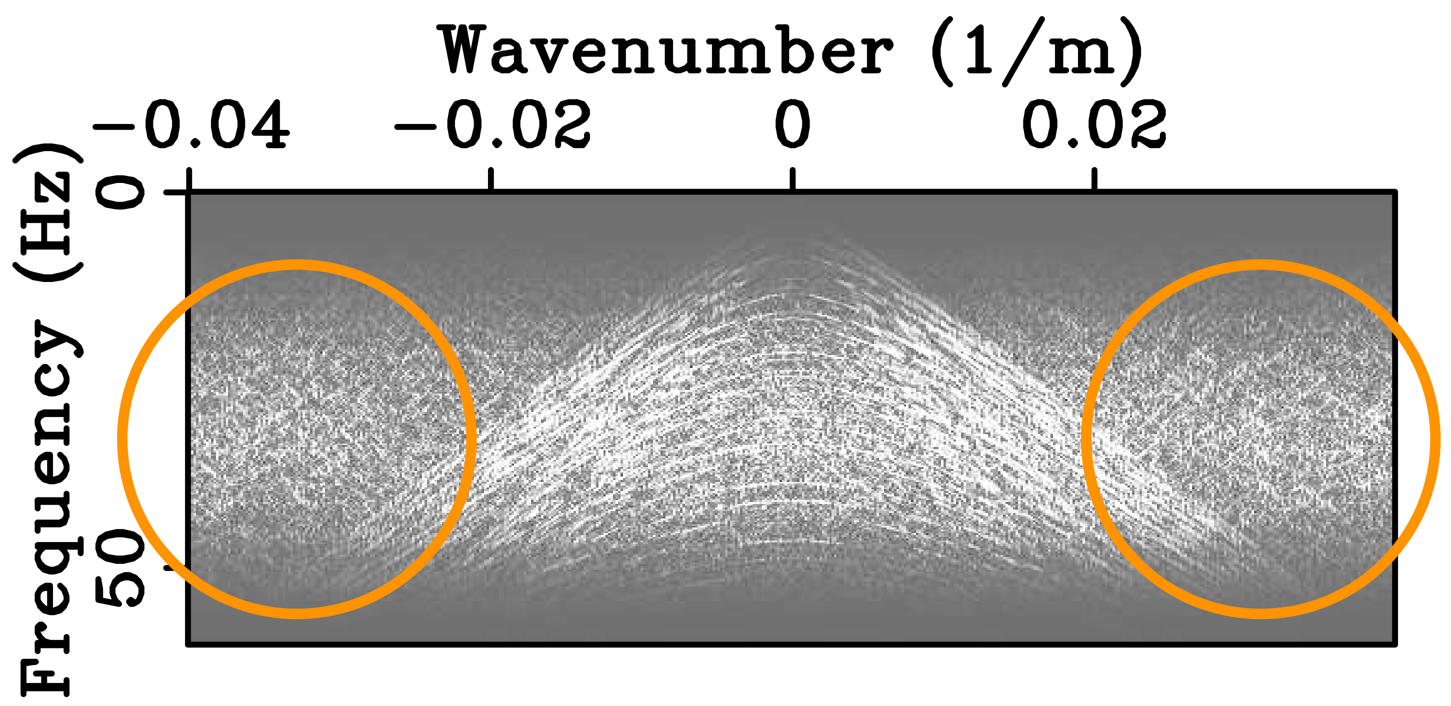
Regular 3-fold undersampling





Random 3-fold undersampling (discreet)





Shot time variability leads to shot irregularity, necessitates regularization + interpolation

(but not necessarily a bad thing)

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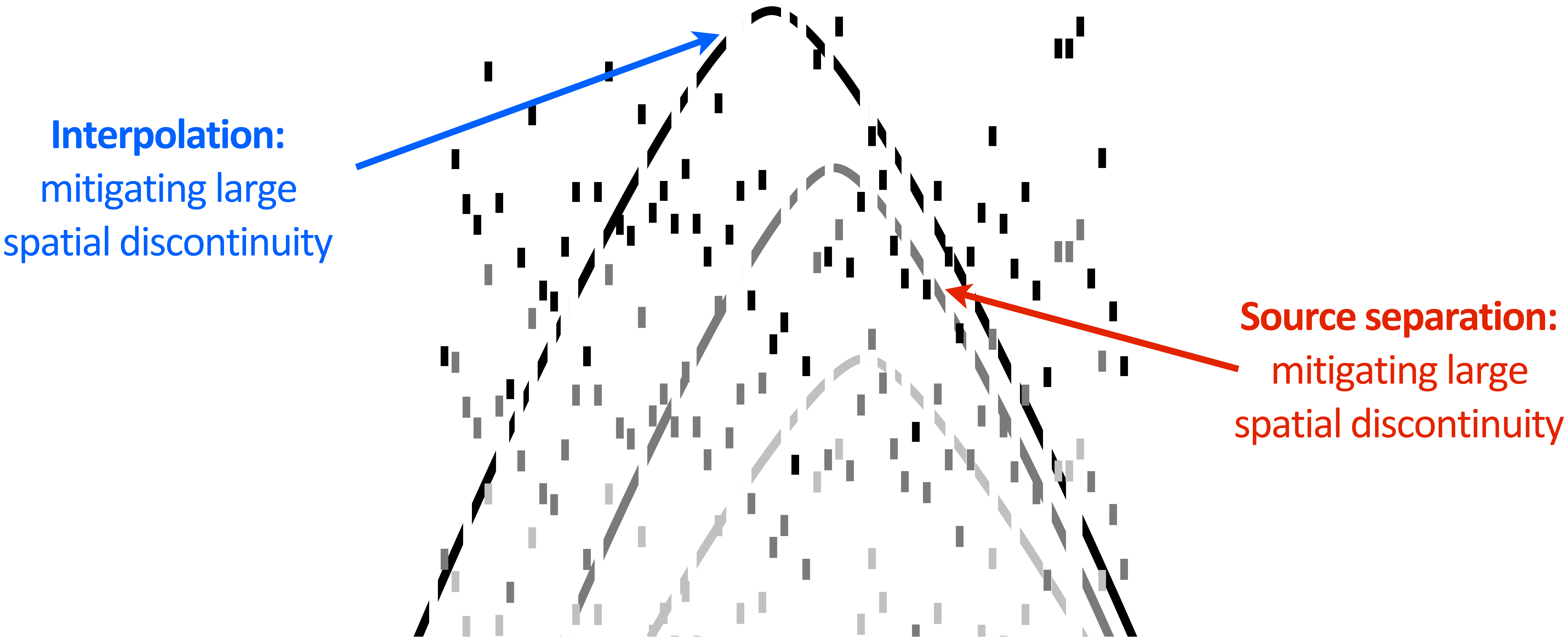
(but not necessarily a bad thing, if you take it into account)

Shot-time randomness: “low” vs “high” variability



Source separation as sparse inversion

$$\mathbf{x} = \mathbf{D}\mathbf{z}$$ (assume **x** is not sparse, but **z** is)

$$\tilde{\mathbf{x}} = \mathbf{D} \cdot \underset{\mathbf{z}}{\operatorname{argmin}} \|\mathbf{z}\|_1 \text{ subject to } \mathbf{y} = \mathbf{\Gamma}\mathbf{D}\mathbf{z}$$

- 1-norm measure of sparsity
- $\mathbf{y}$ is sim src data
- $\mathbf{\Gamma}$ is “blending” operator
- $\tilde{\mathbf{x}}$ is an estimated source separated wavefield
- $\mathbf{D}$ is a transform domain synthesis (coefficients -> wavefield)
- $\mathbf{z}$ is *a* choice of curvelet coefficients for $\mathbf{x}$

Interpolation as sparse inversion

$$\mathbf{x} = \mathbf{D}\mathbf{z}$$ (assume **x** is not sparse, but **z** is)

$$\tilde{\mathbf{x}} = \mathbf{D} \cdot \underset{\mathbf{z}}{\operatorname{argmin}} \|\mathbf{z}\|_1 \text{ subject to } \mathbf{y} = \mathbf{A}\mathbf{D}\mathbf{z}$$

- 1-norm measure of sparsity
- $\mathbf{y}$ is data with missing traces
- $\mathbf{A}$ is trace mask (match data at observed trace positions)
- $\tilde{\mathbf{x}}$ is an estimated interpolated wavefield
- $\mathbf{D}$ is a transform domain synthesis (coefficients -> wavefield)
- $\mathbf{z}$ is *a* choice of curvelet coefficients for $\mathbf{x}$

Src sep + Interp as sparse inversion

$$\mathbf{x} = \mathbf{D}\mathbf{z}$$ (assume **x** is not sparse, but **z** is)

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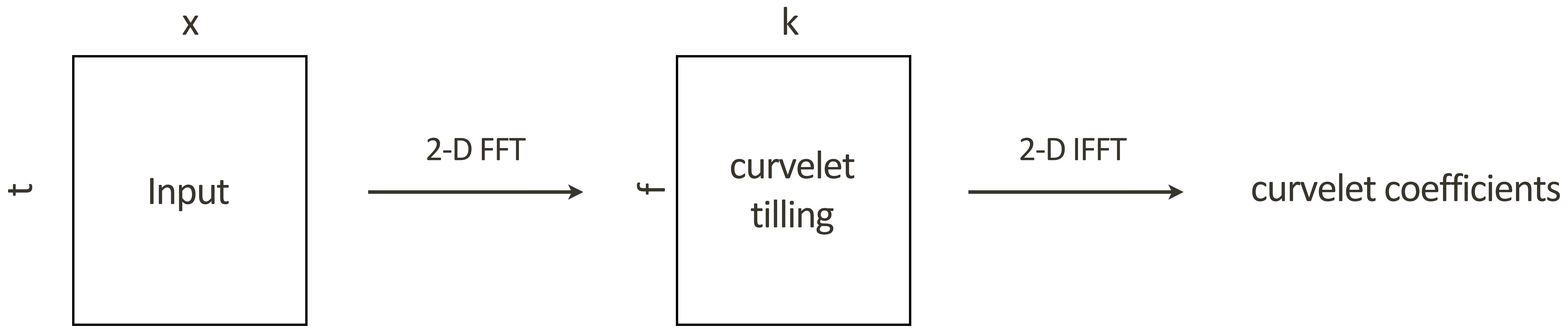
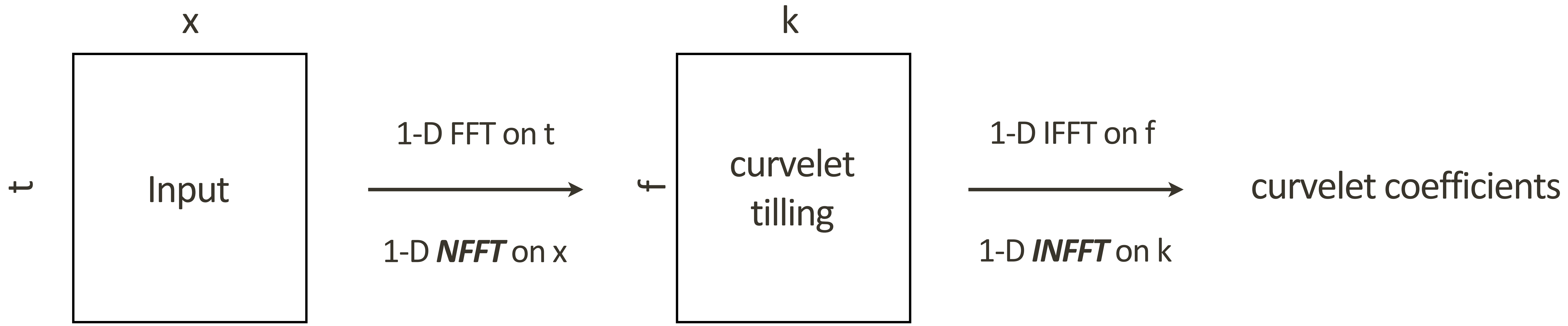
Dealing with irregular shot locations

FDCT vs. NFDCT

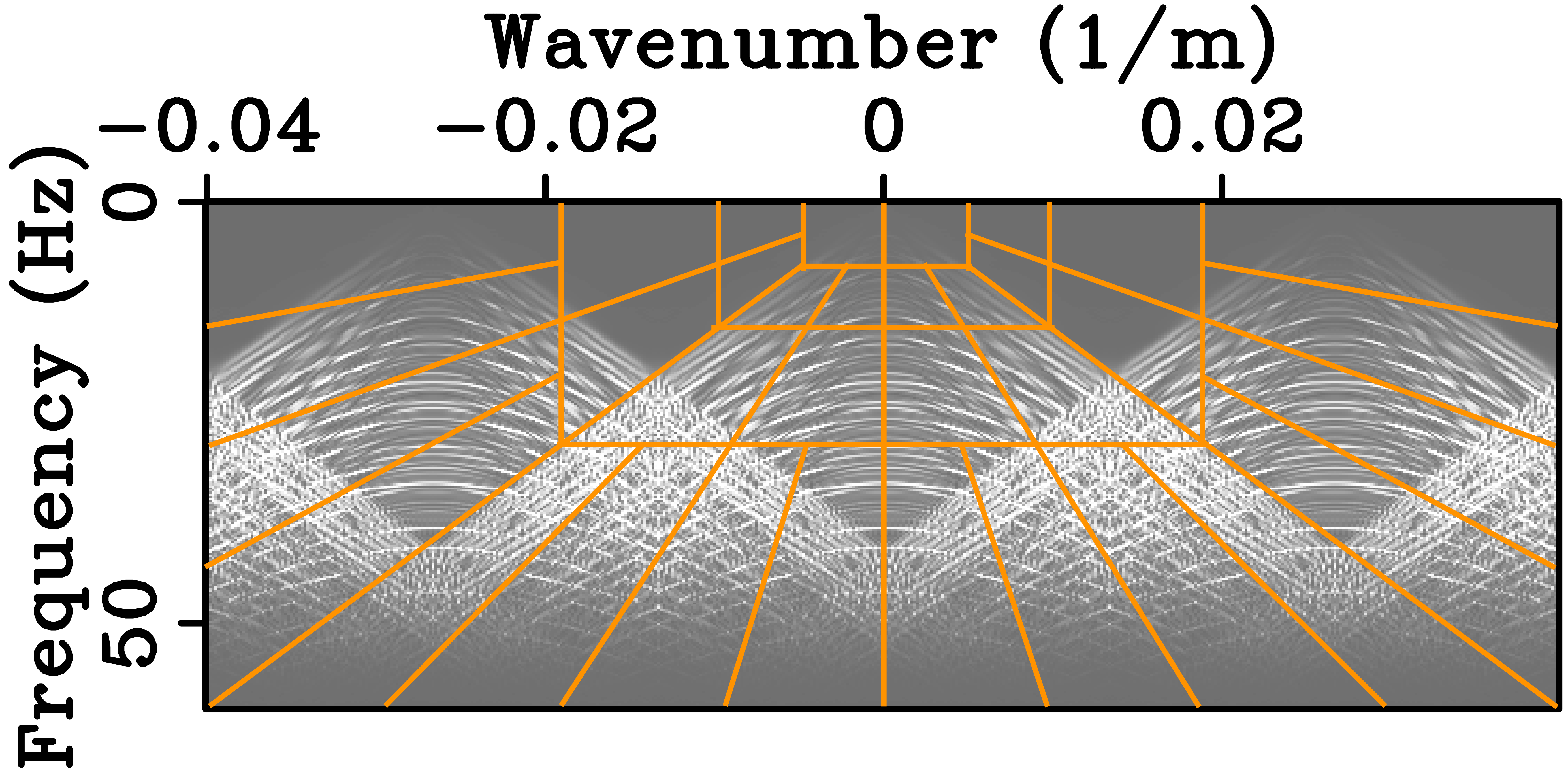
fast discrete curvelet transform



non-equispaced fast discrete curvelet transform

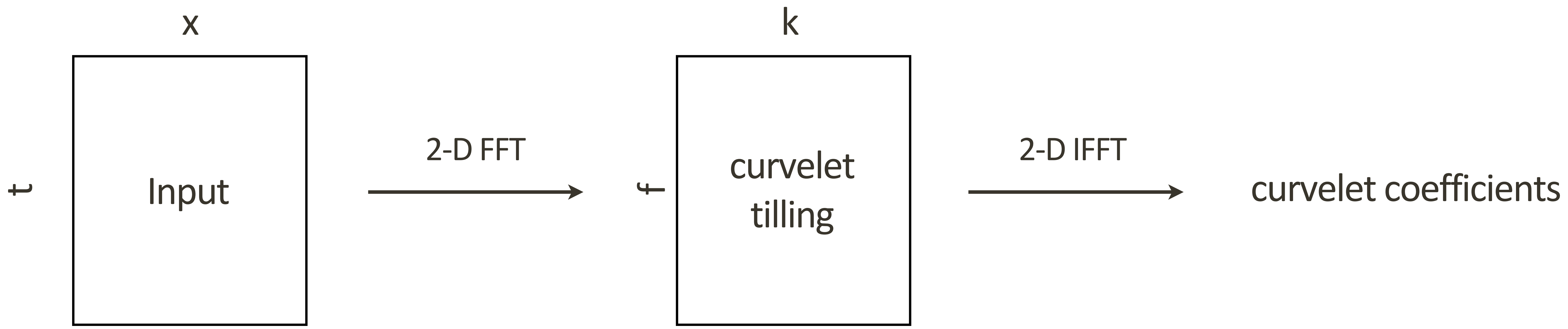


Curvelet tiling



FDCT vs. NFDCT

fast discrete curvelet transform



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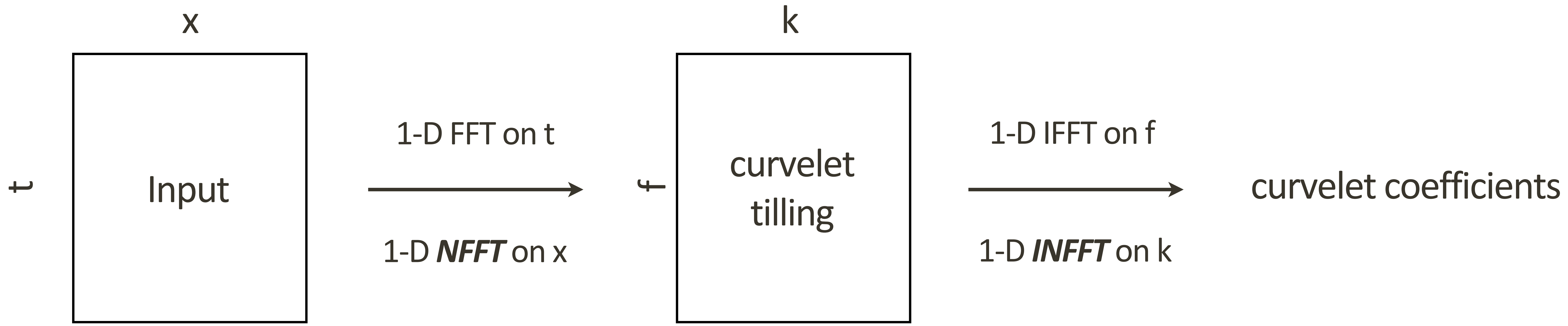
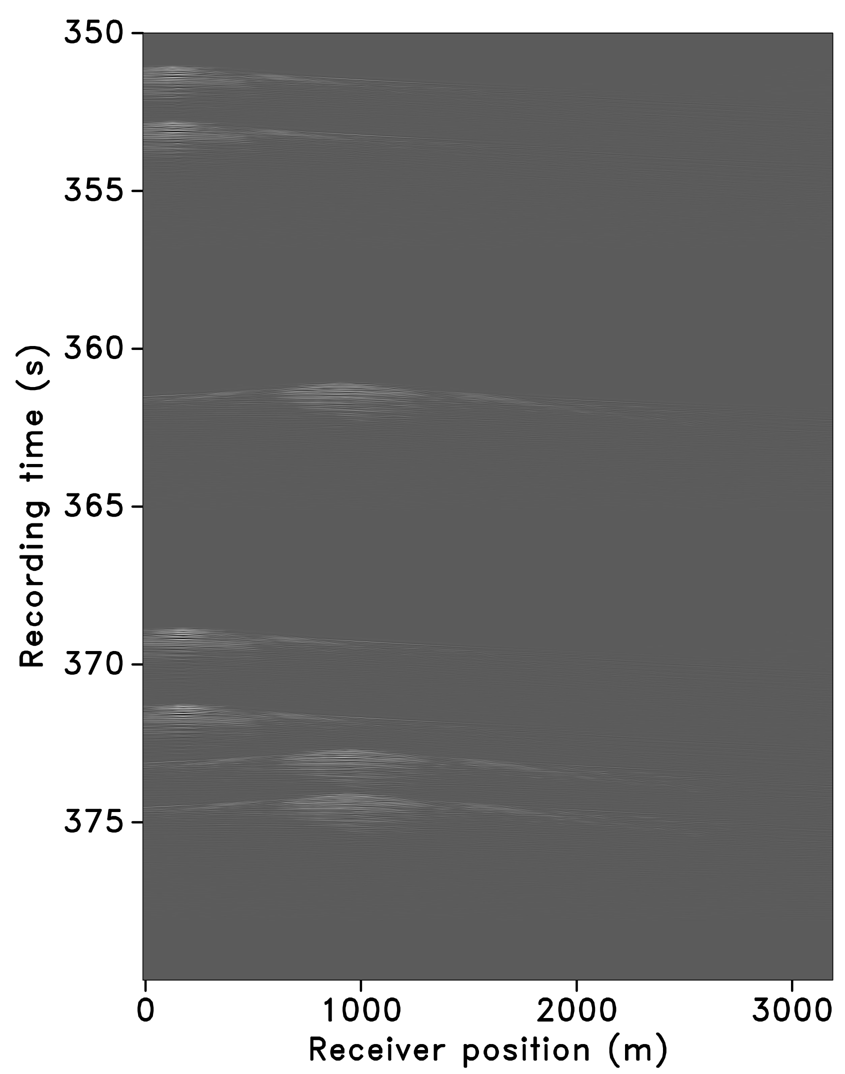


Forward mapping of the inversion

$$\mathbf{x} = \mathbf{D}\mathbf{z} \quad \text{(assume } \mathbf{x} \text{ is not sparse, but } \mathbf{z} \text{ is)}$$

$$\tilde{\mathbf{x}} = \mathbf{D} \cdot \underset{\mathbf{z}}{\operatorname{argmin}} \|\mathbf{z}\|_1 \text{ subject to } \mathbf{y} = \mathbf{\Gamma}\mathbf{A}\mathbf{D}\mathbf{z}$$



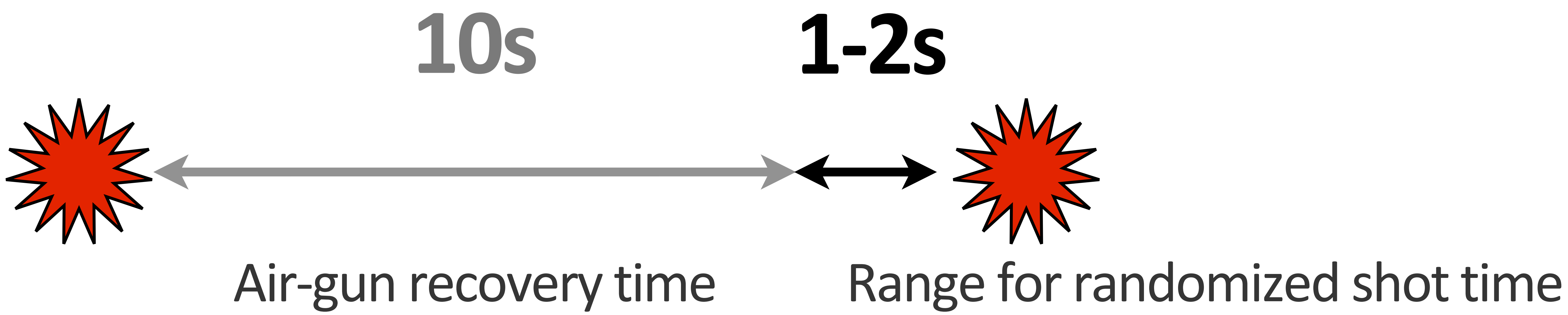
$\mathbf{\Gamma}$ — "Blending" operator

$\mathbf{A}$ — "Regularization" operator (time FFT + spatial nFFT)

$\mathbf{D}$ — "Sparsity transform" operator (Curvelet tiling in FK)

Design of highly variable time-jittered source firing times

Design of time-jittered shot times (low variation)



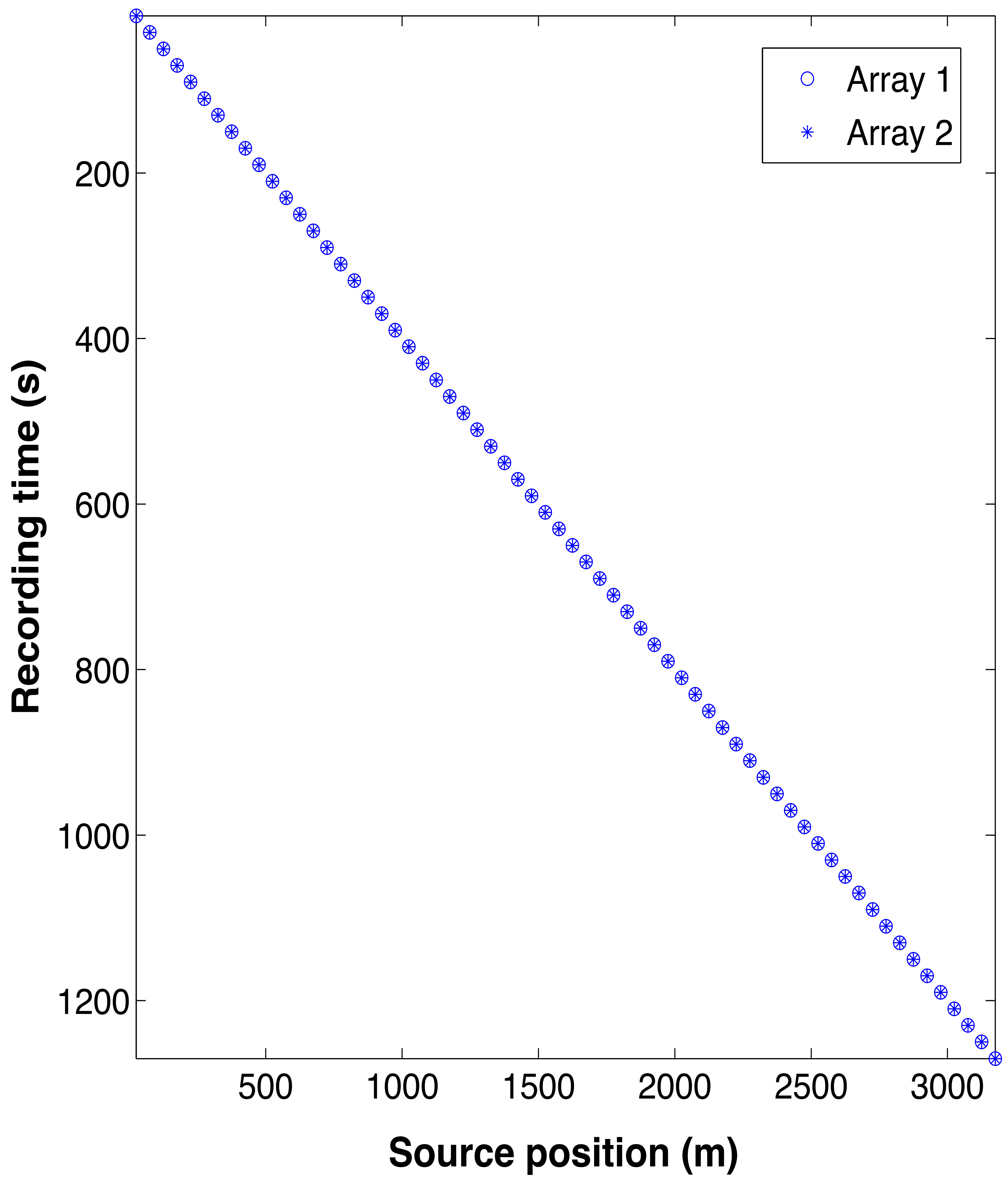
Design of time-jittered shot times (this talk)

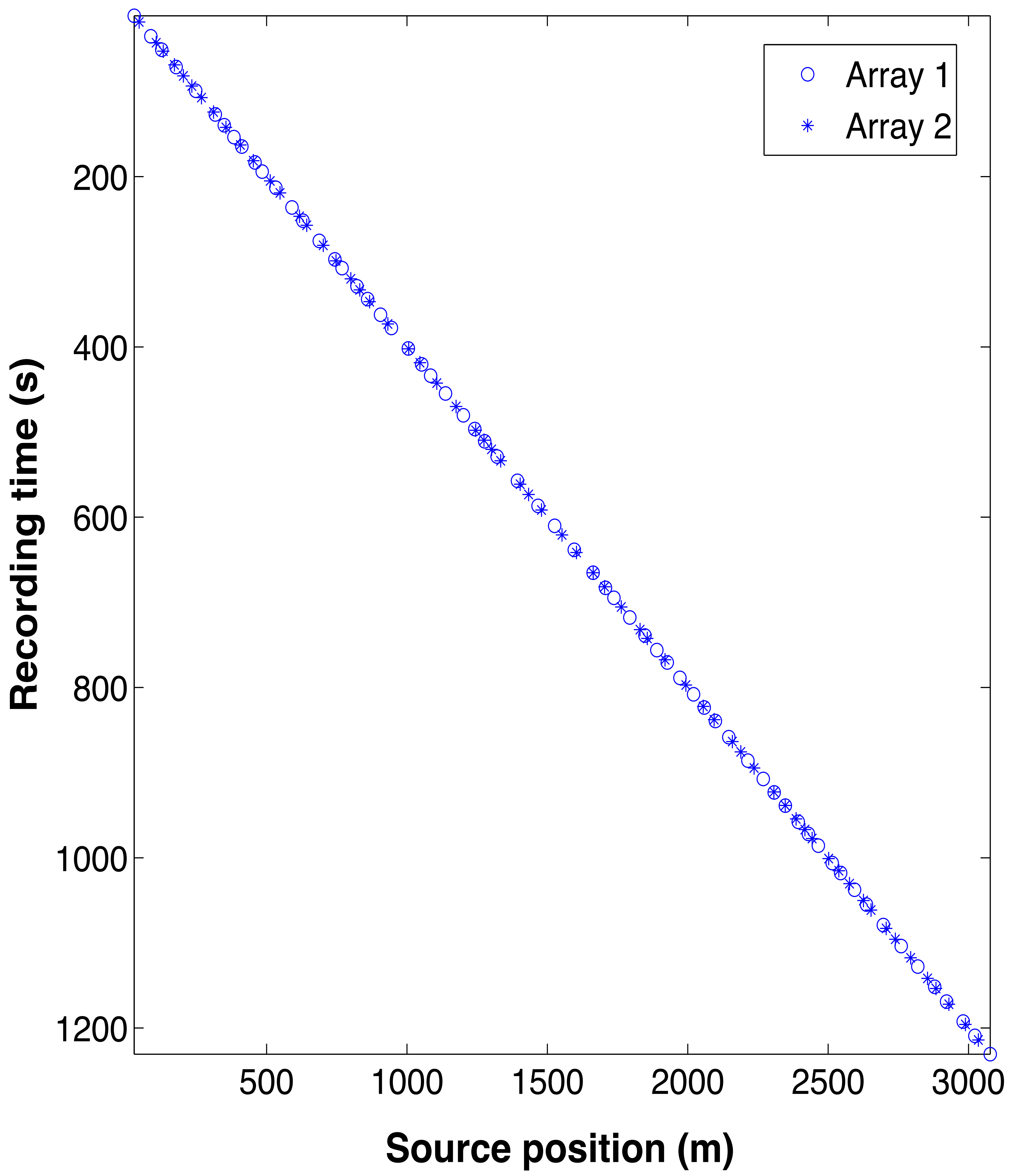
Design of time-jittered shot times (this talk)

Assume boat speed 2.5m/s (5 knots)

Regular vs. Randomized locations

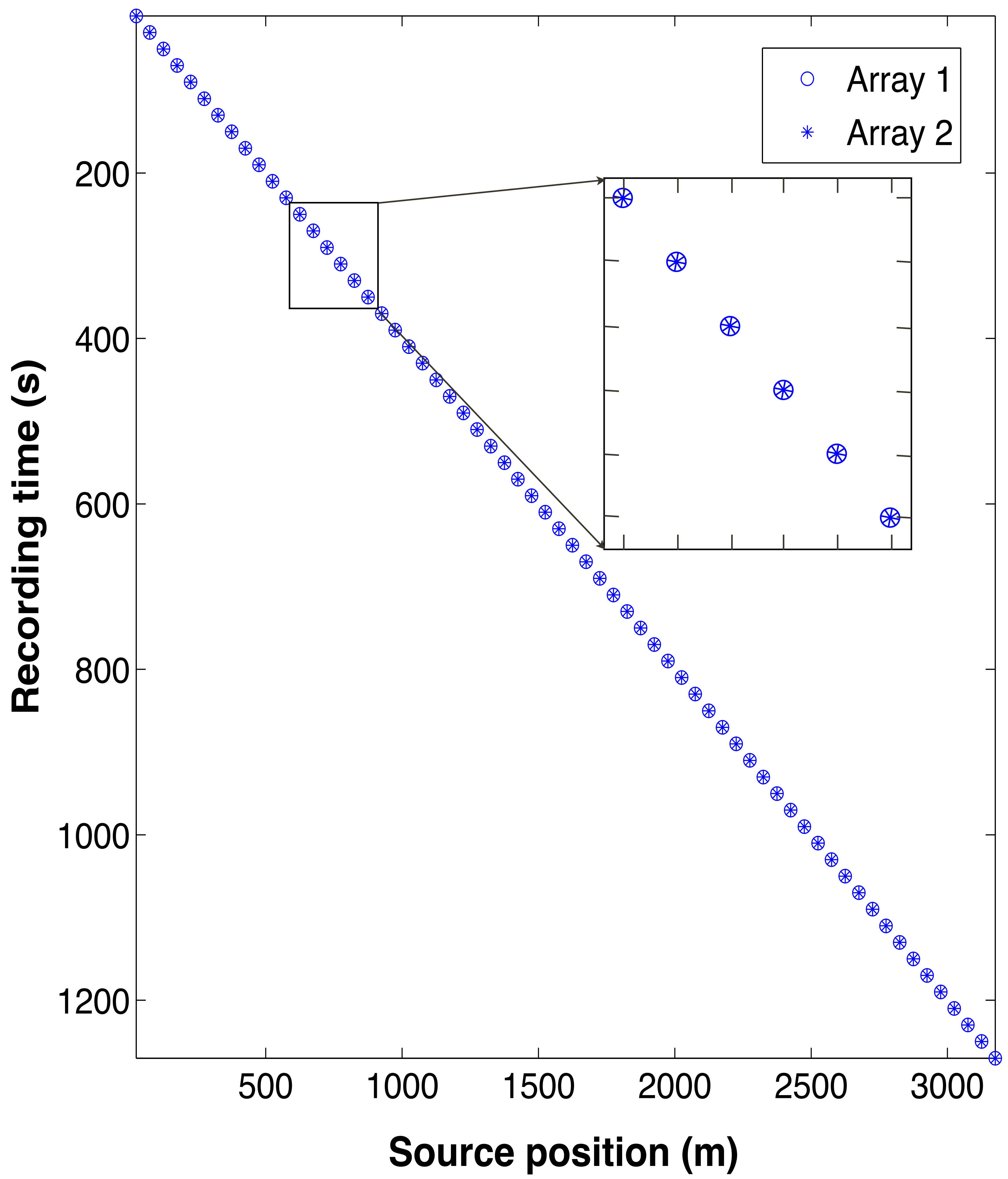
[Speed of source vessel = 5 knots ≈ 2.5 m/s]

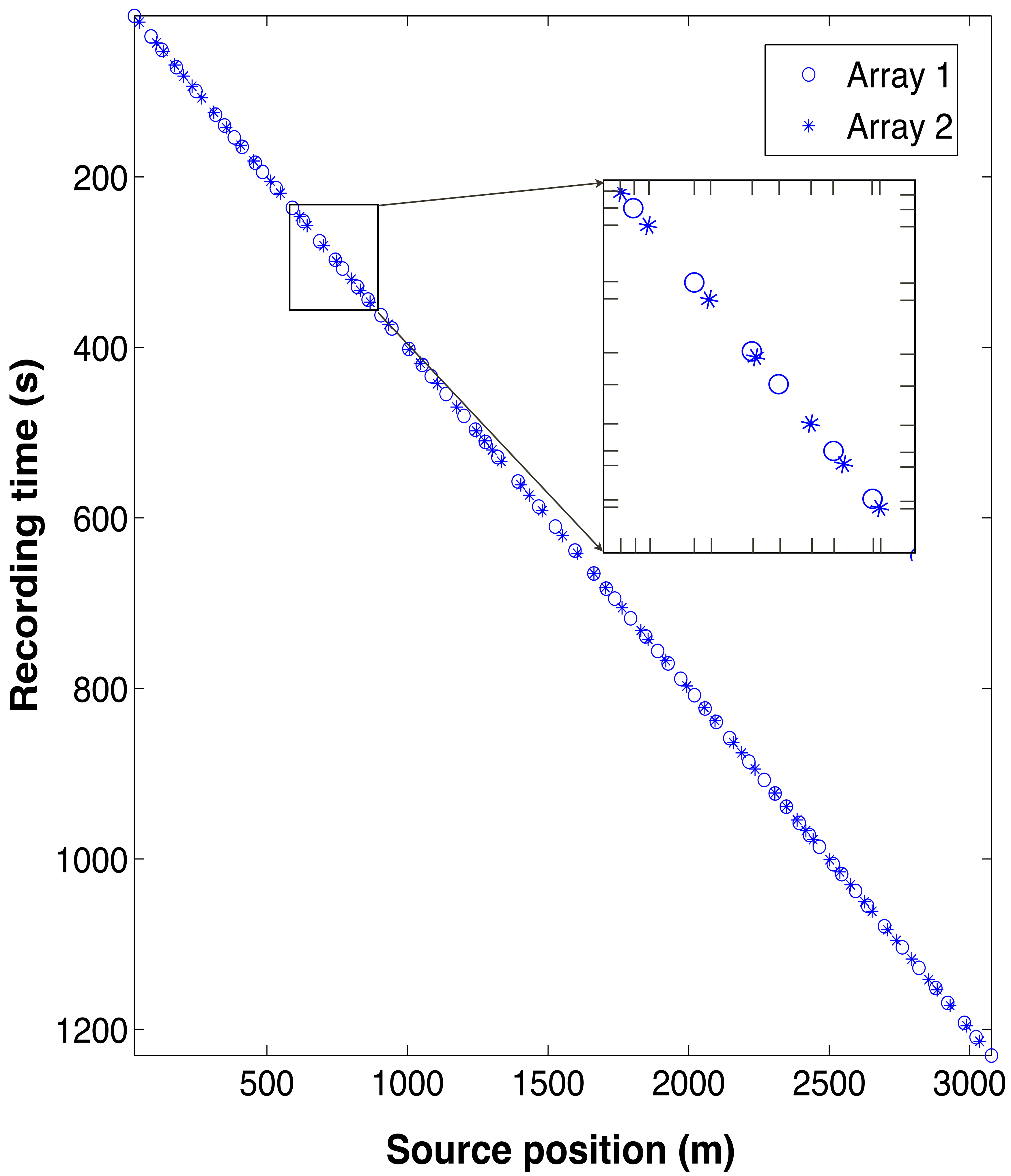




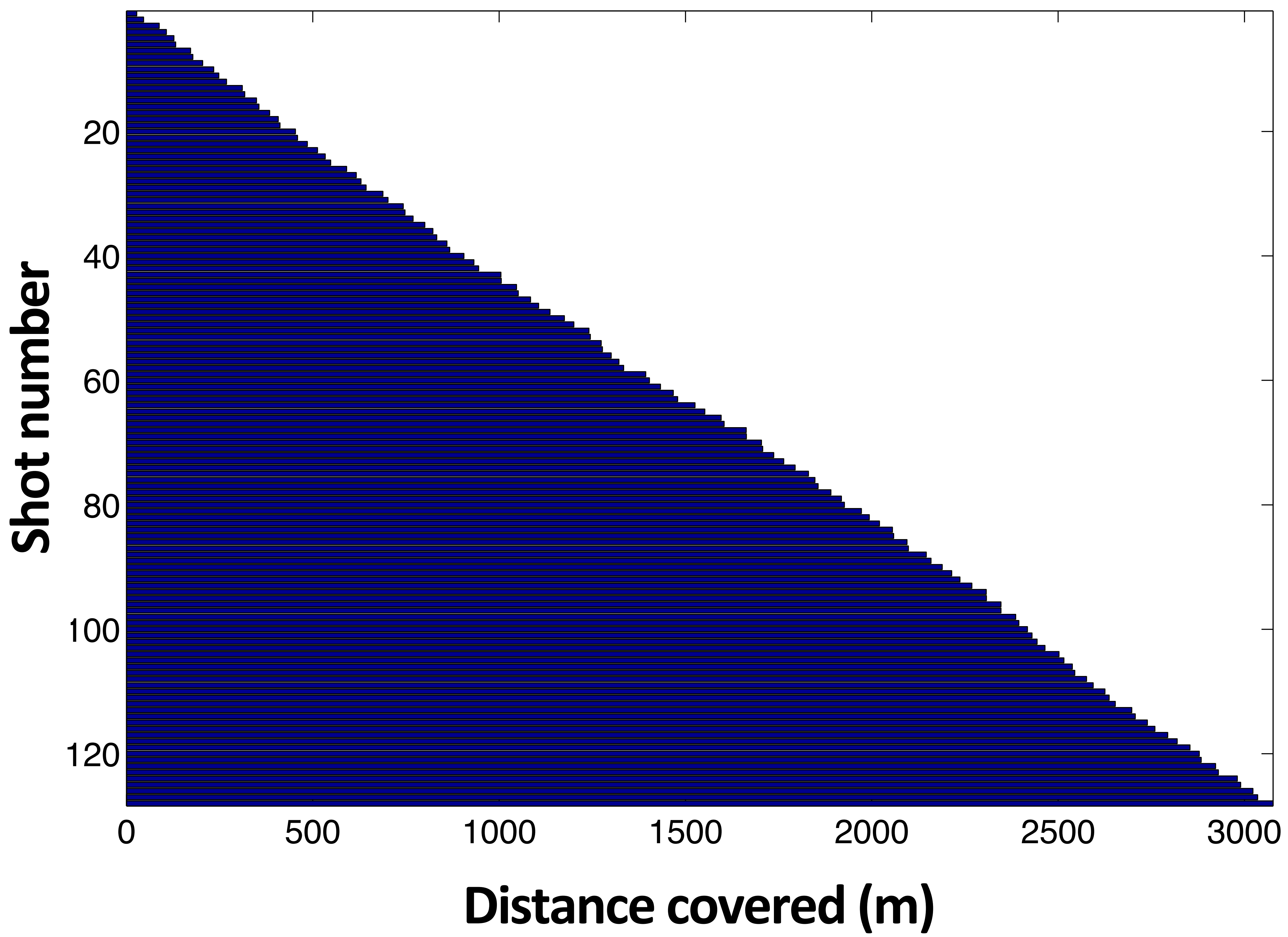
Regular vs. Randomized locations

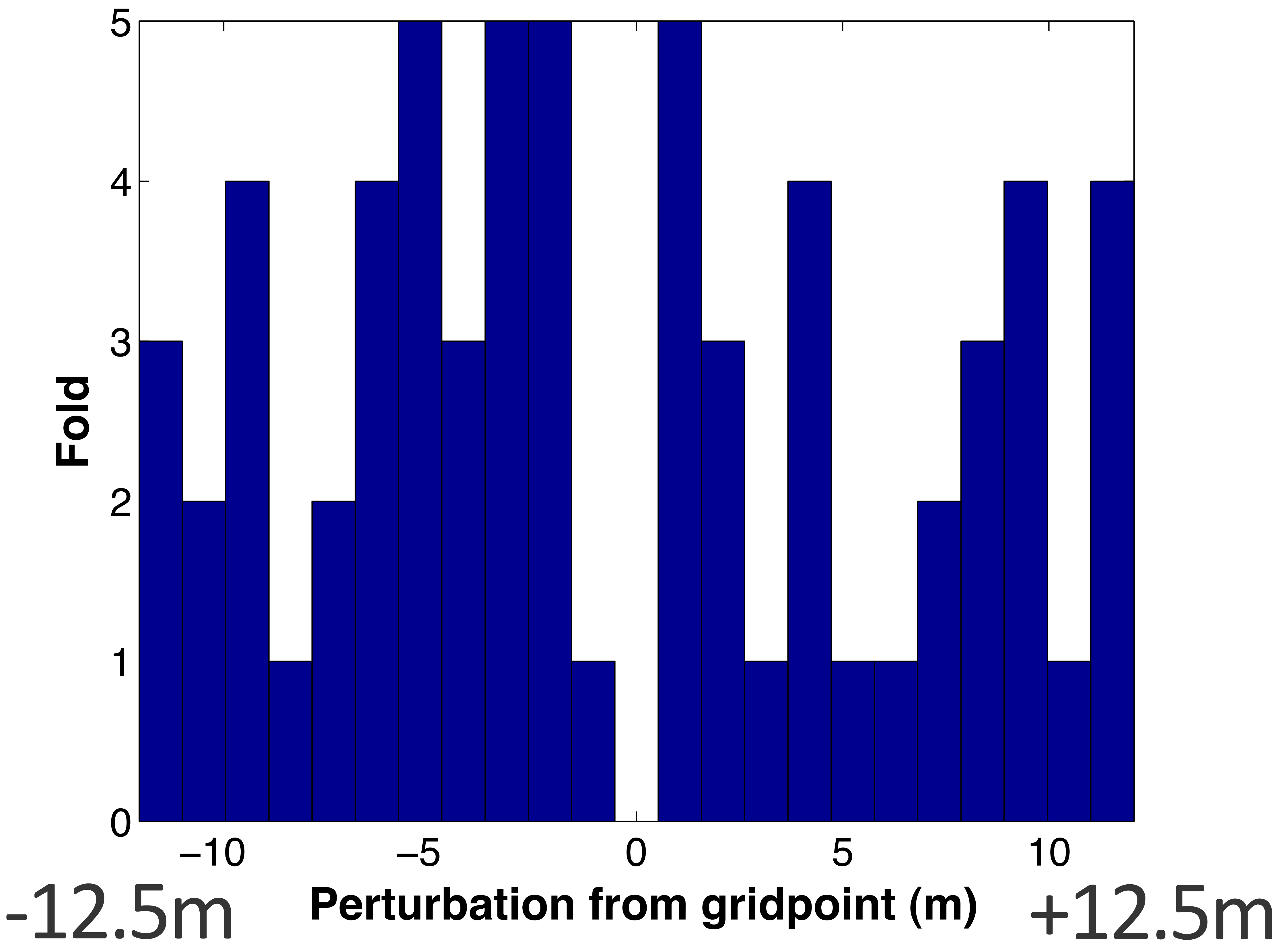
[Speed of source vessel = 5 knots ≈ 2.5 m/s]



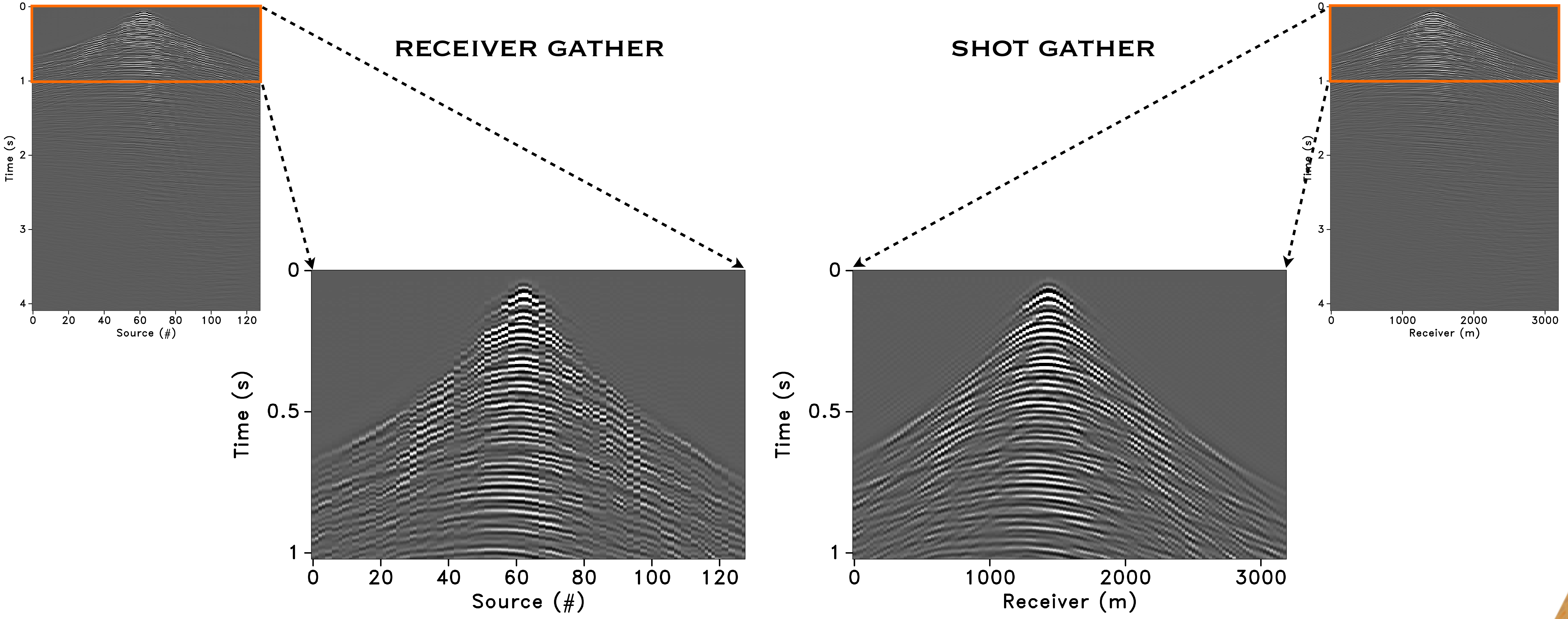


Significant spatial jittering





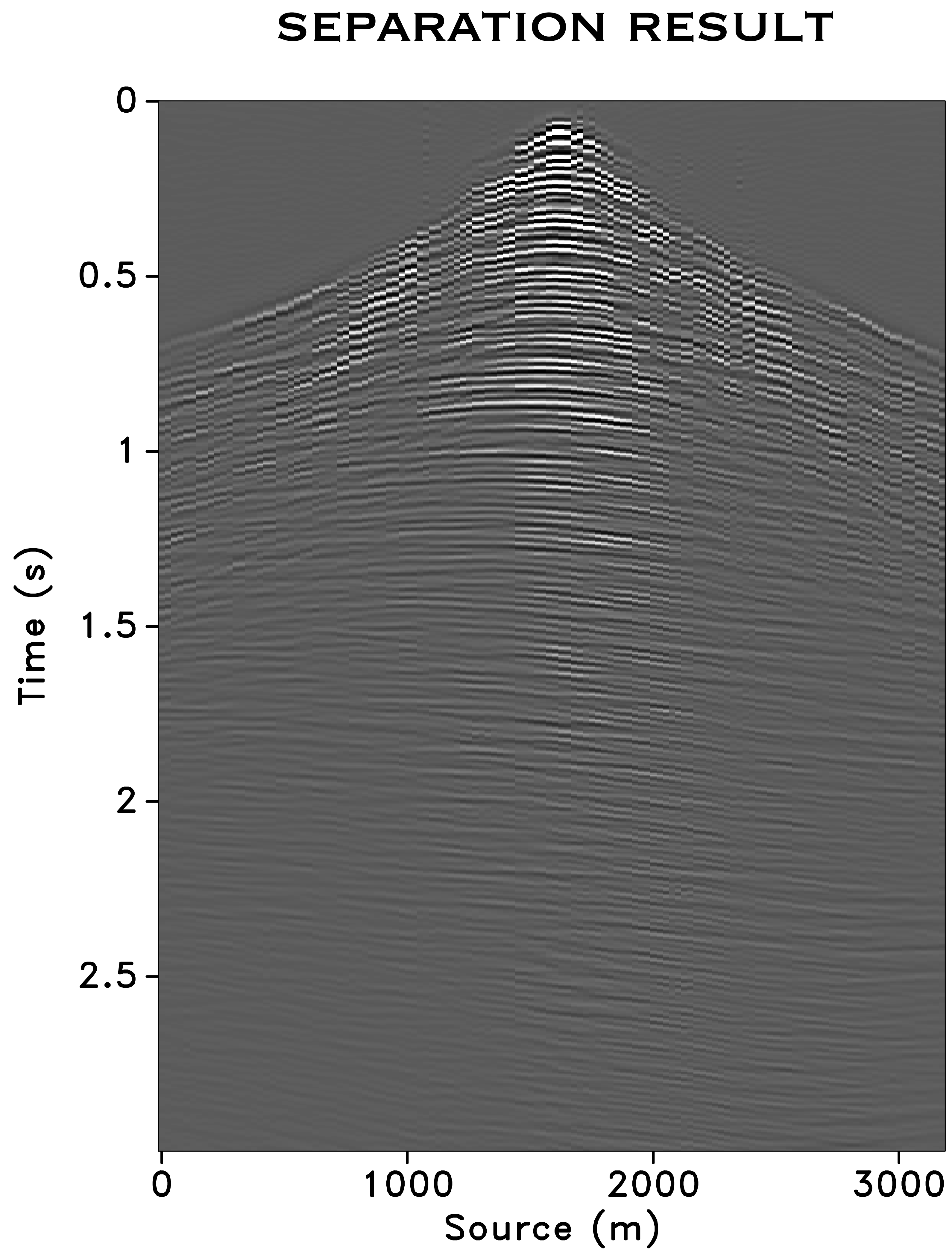
Irregular traces

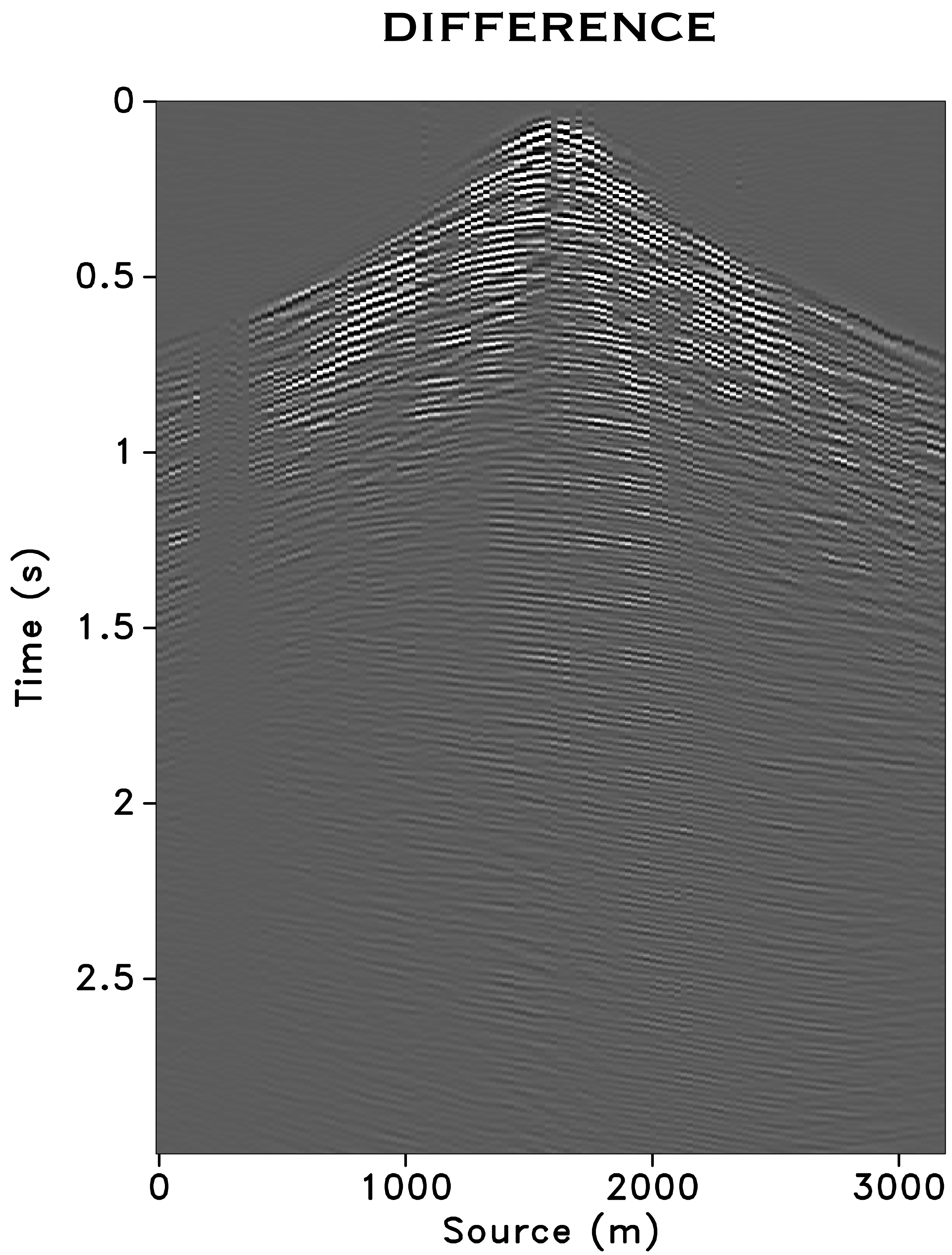


Numerical examples

Recovery with *FDCT* (‘*binning*’)

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





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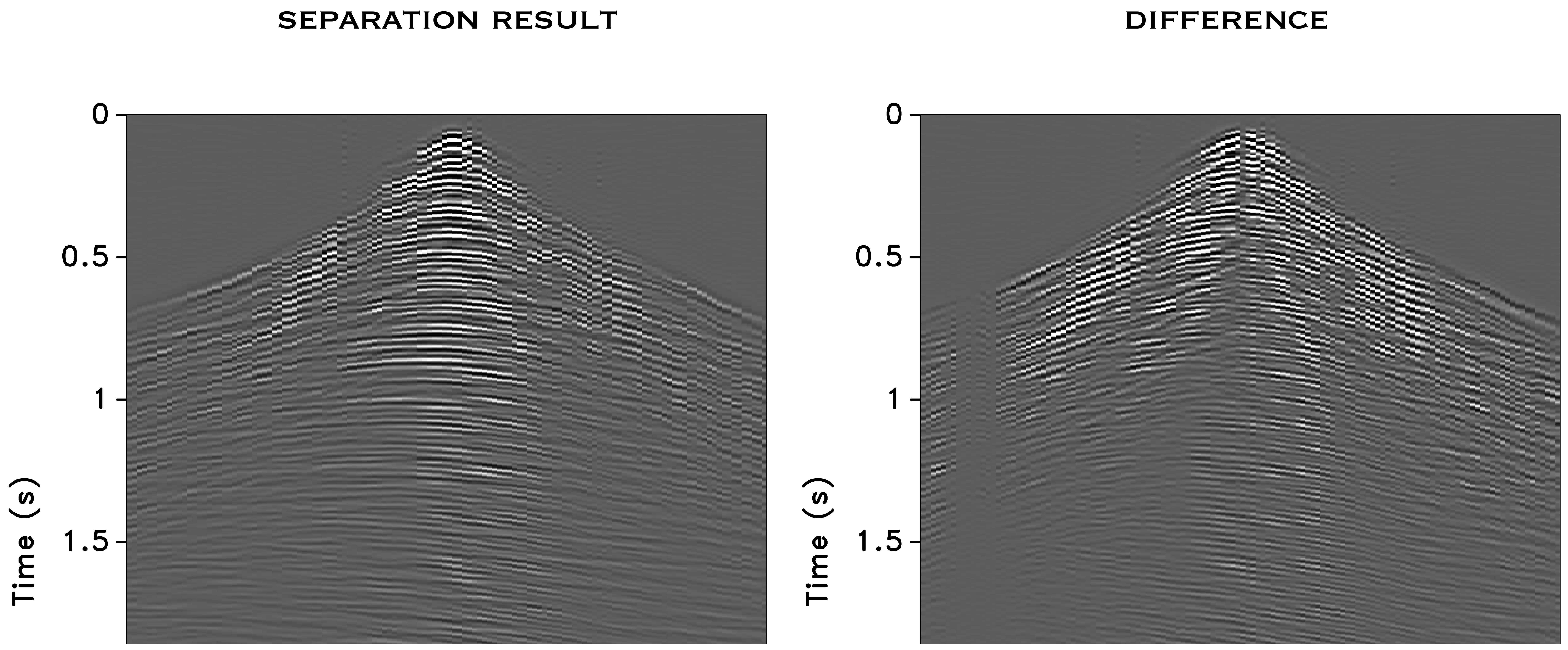
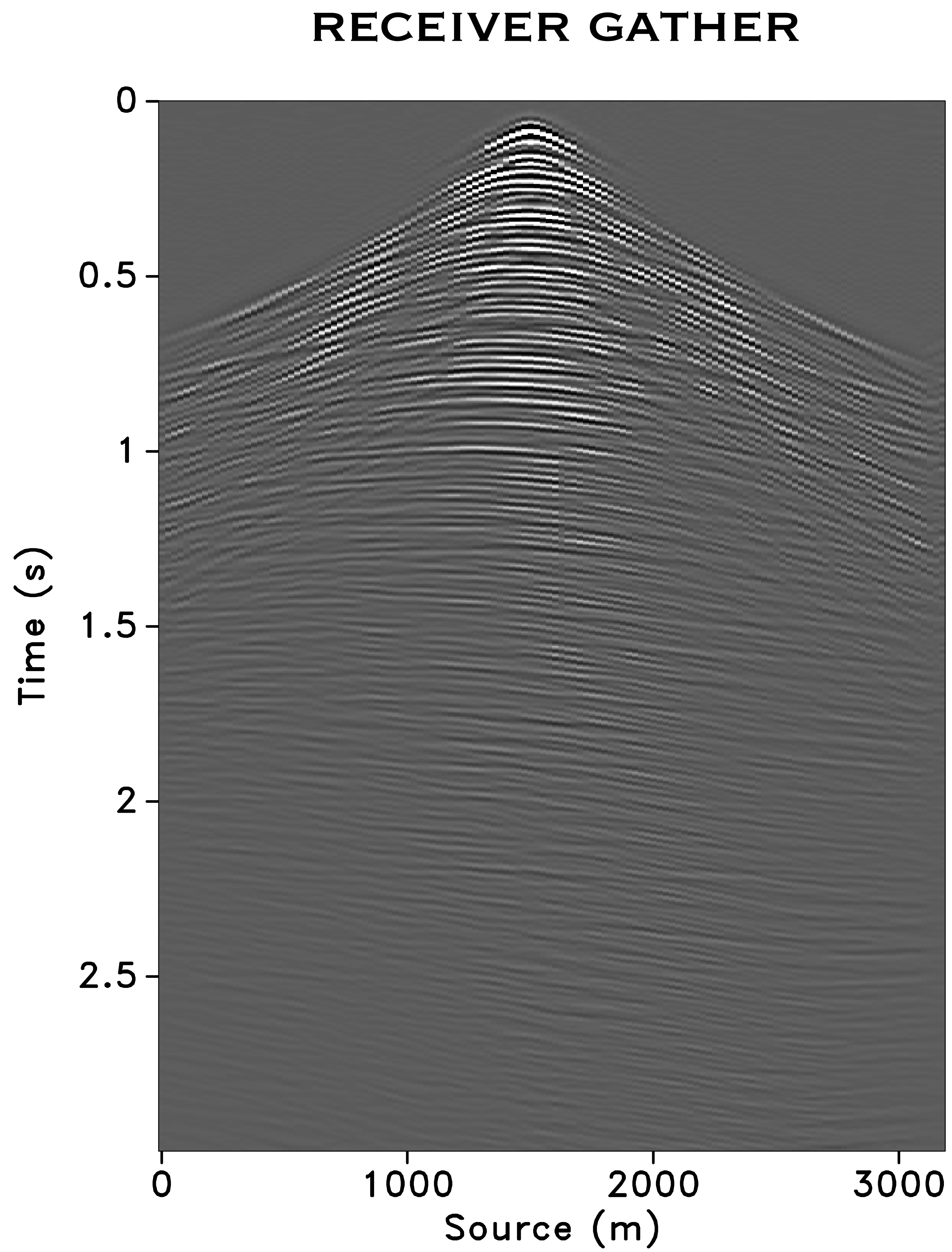
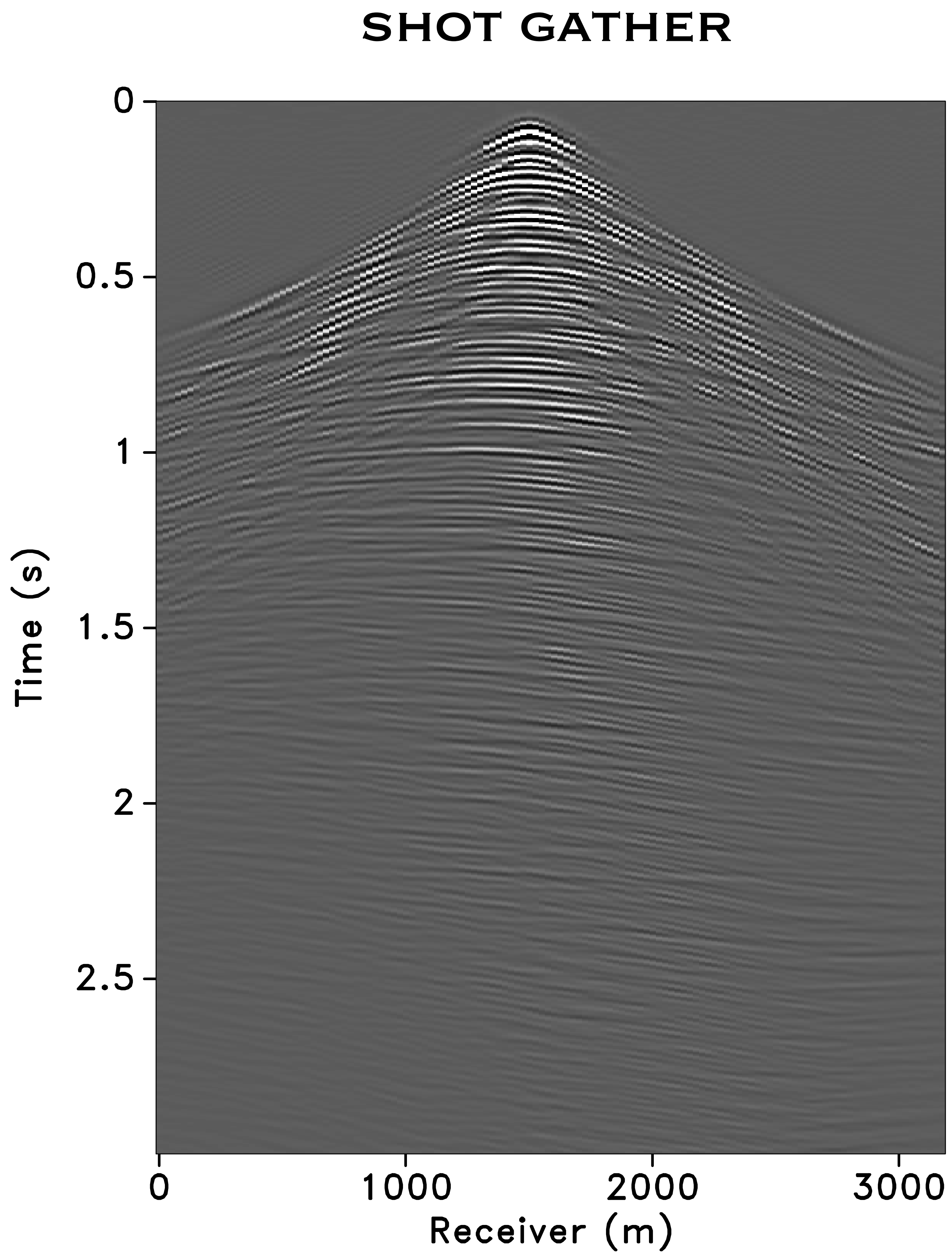
[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]



Sparsity-promoting recovery on *irregular* grid with *NFDCT* (17.6 dB)

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





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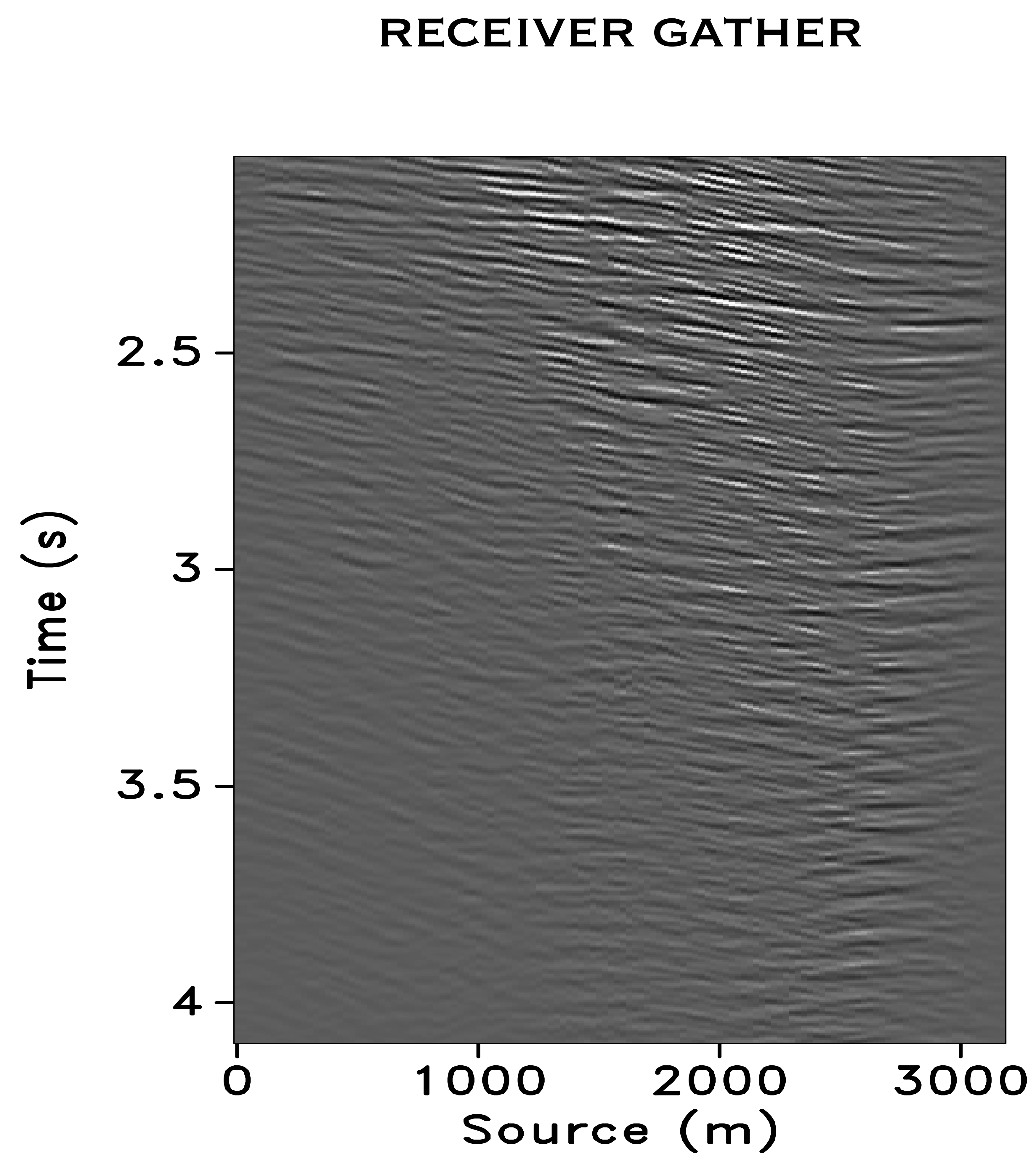
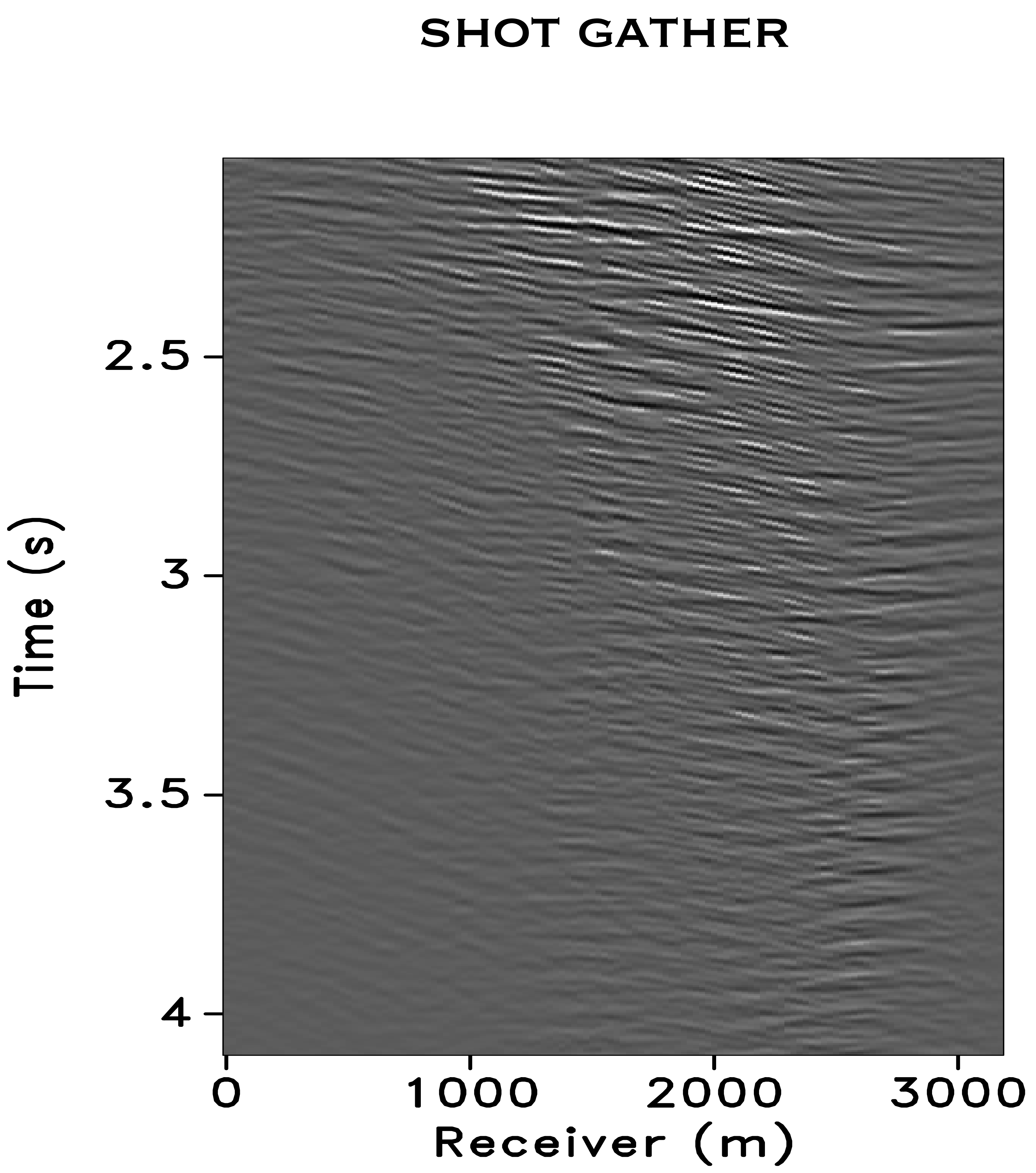
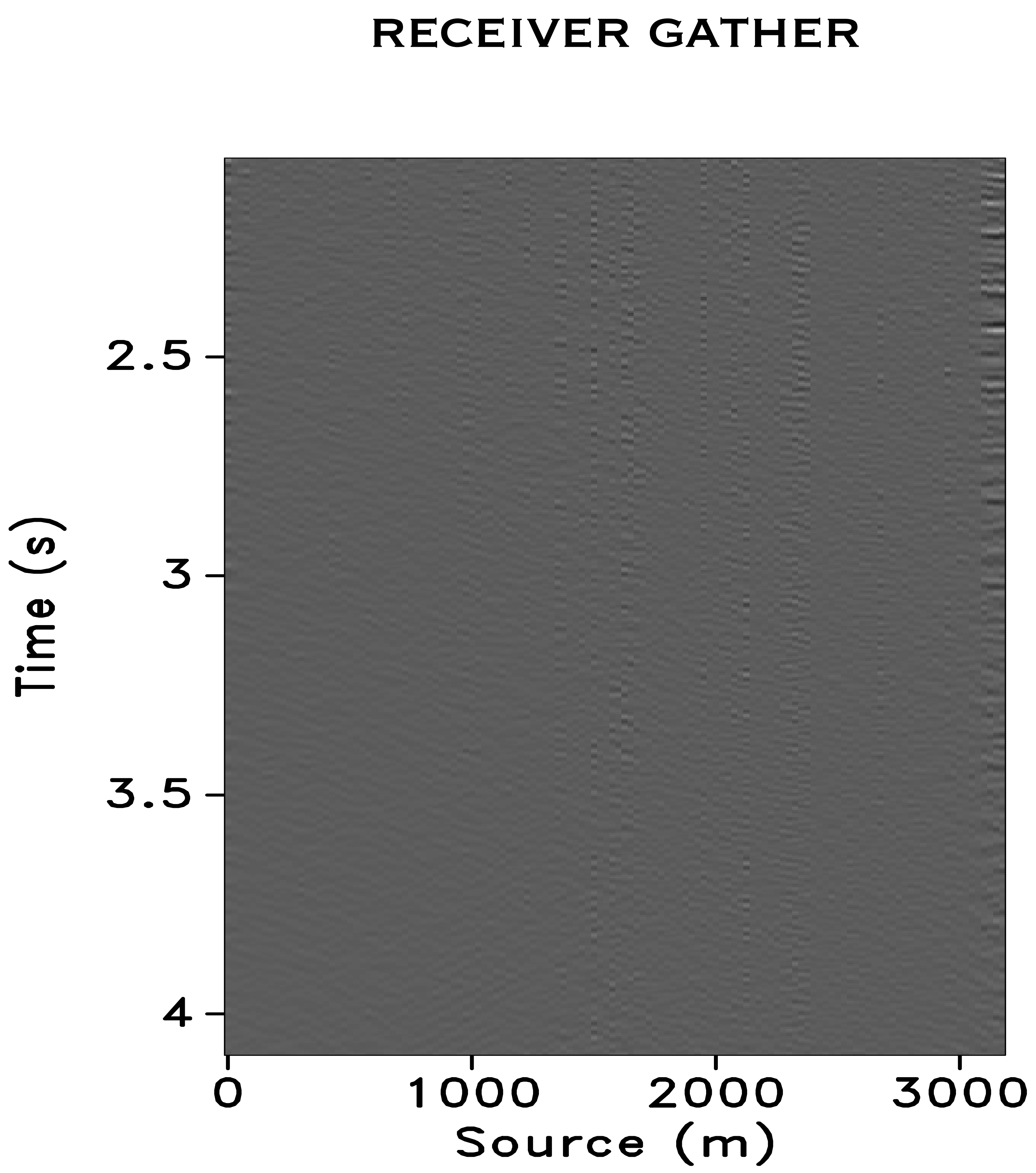
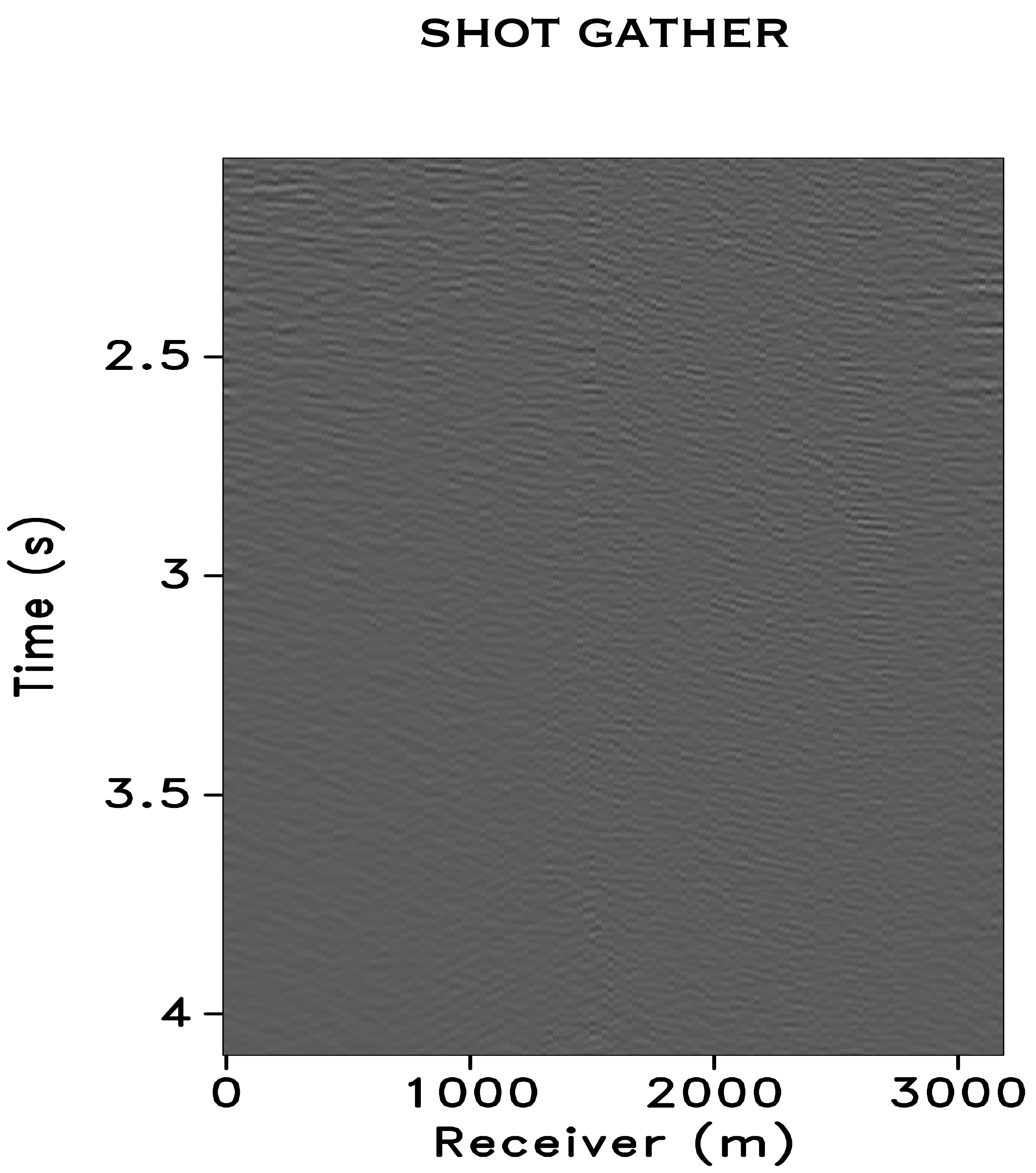




Sparsity-promoting recovery on *irregular* grid with *NFDCT* (17.6 dB)

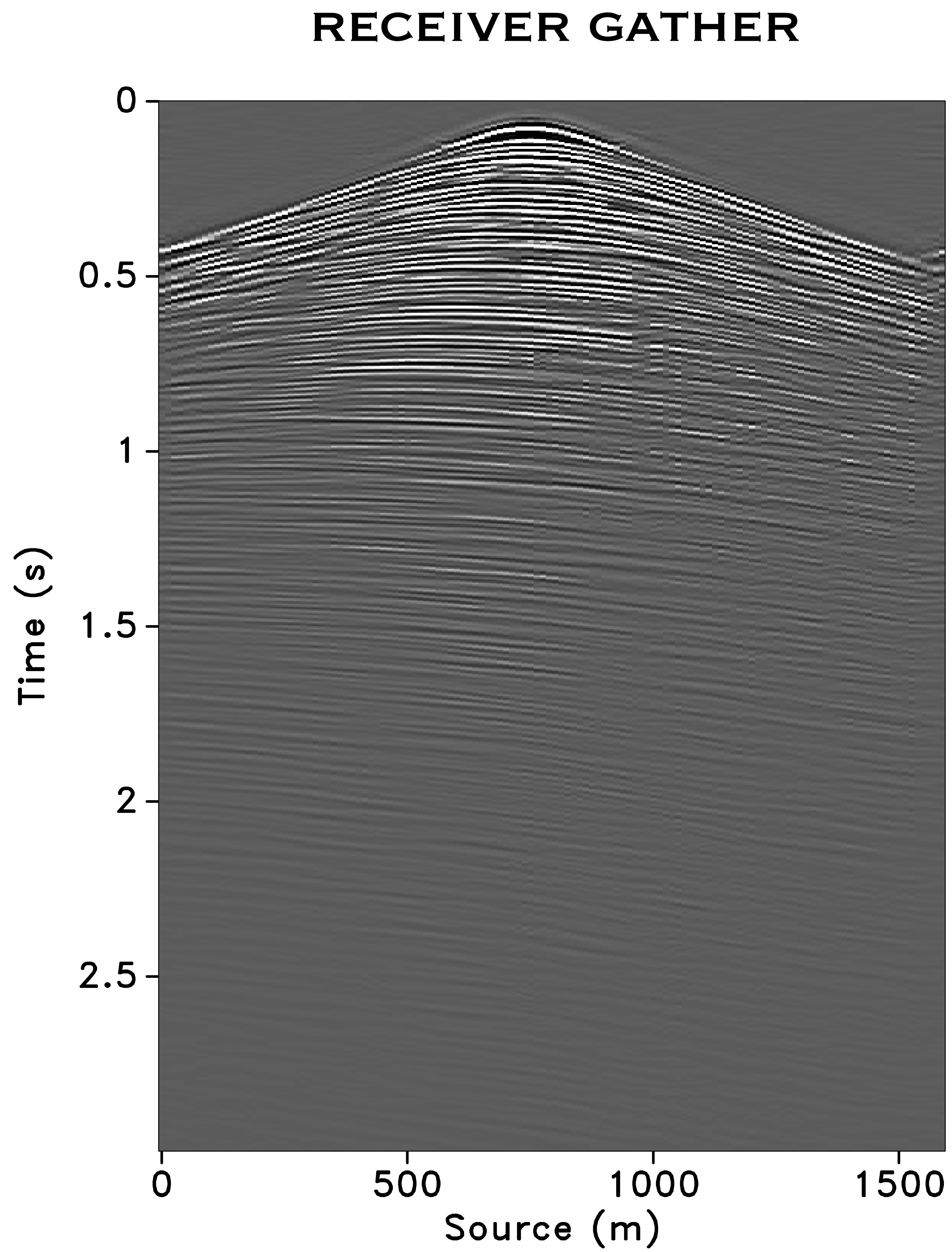
[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid] (difference)

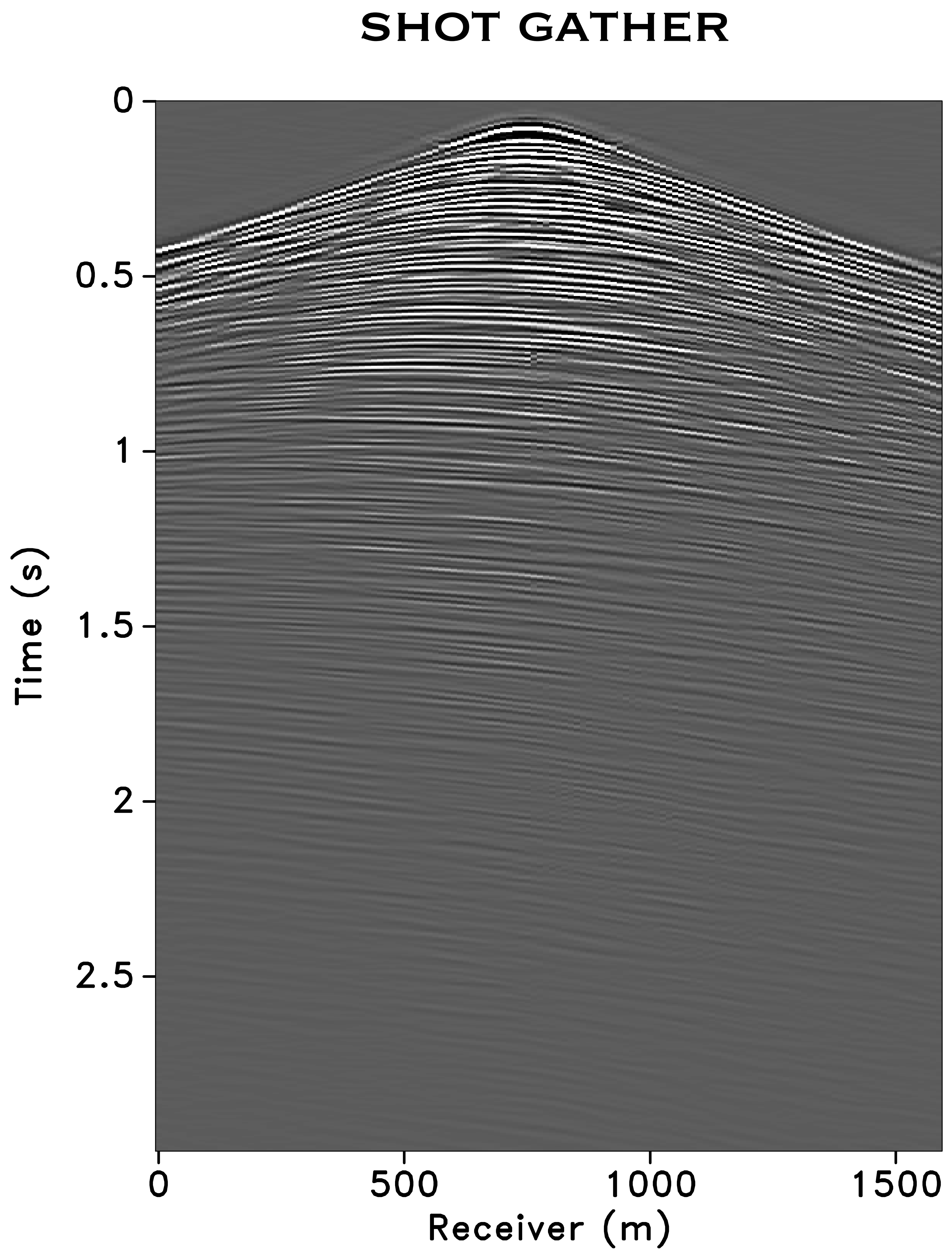




Sparsity-promoting recovery on *irregular* grid with *NFDCT* (12.7 dB)

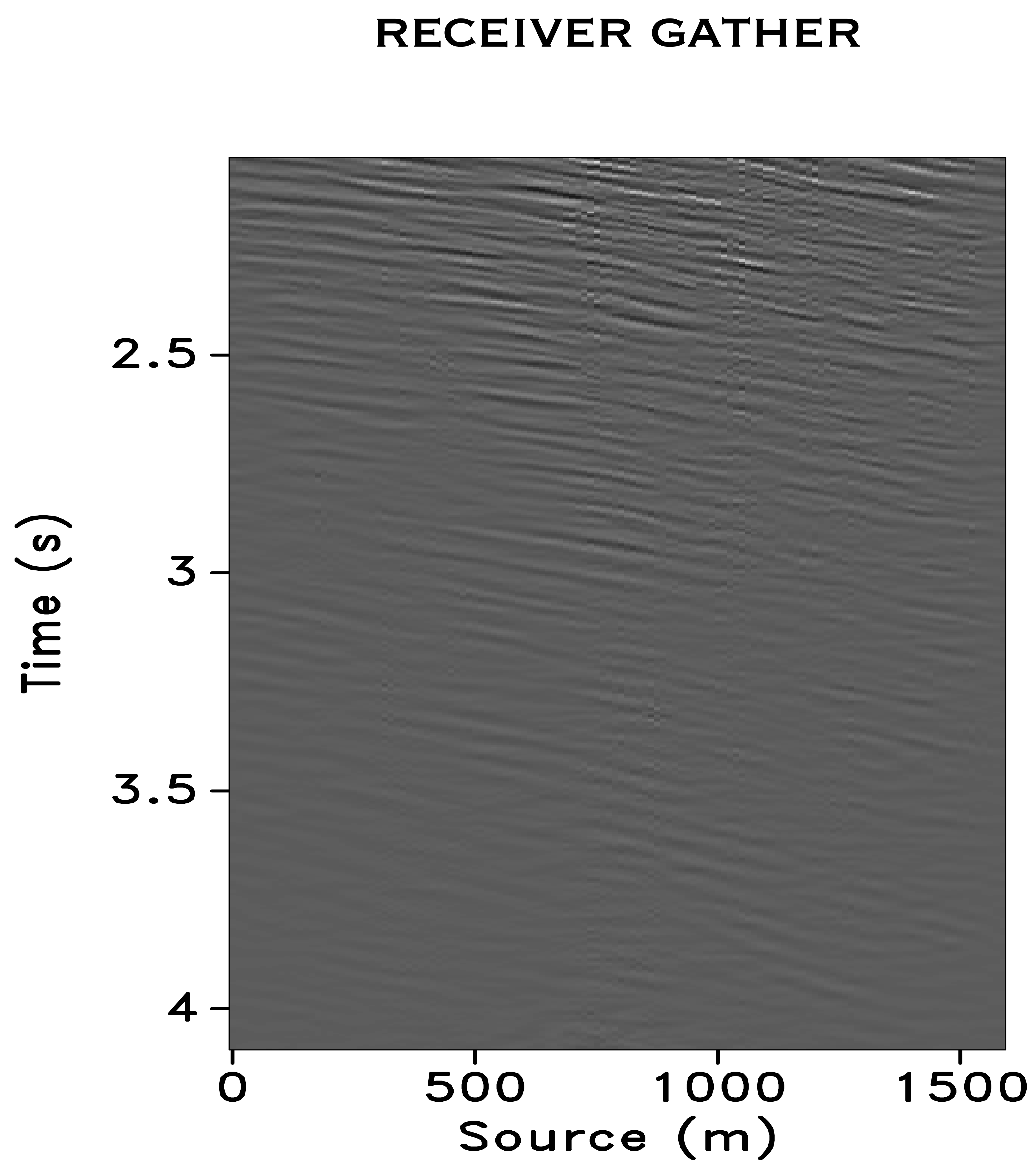
[“deblending” + interpolation from *jittered* 50m grid to *regular* 12.5m grid]

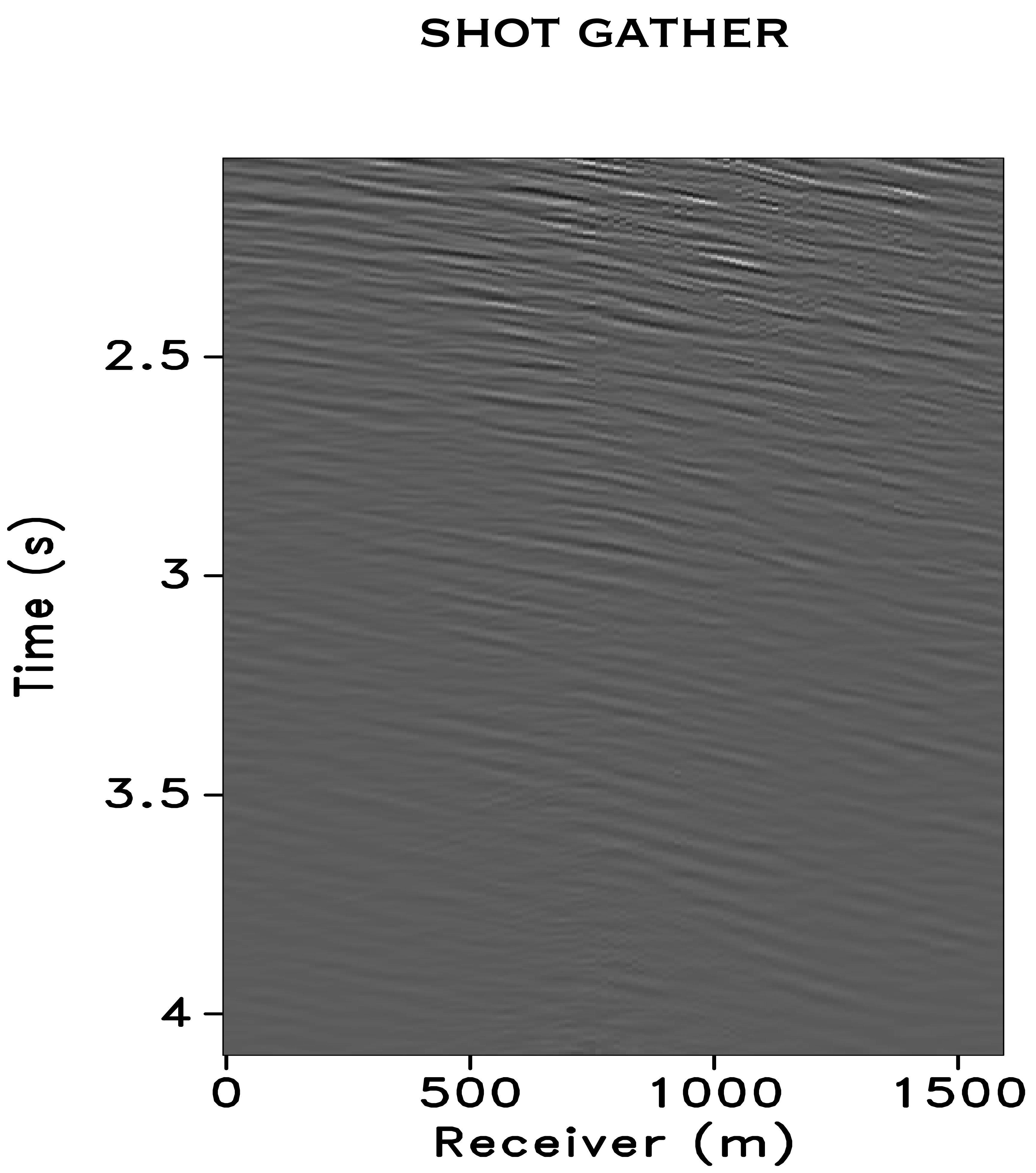




Sparsity-promoting recovery on *irregular* grid with *NFDCT* (12.7 dB)

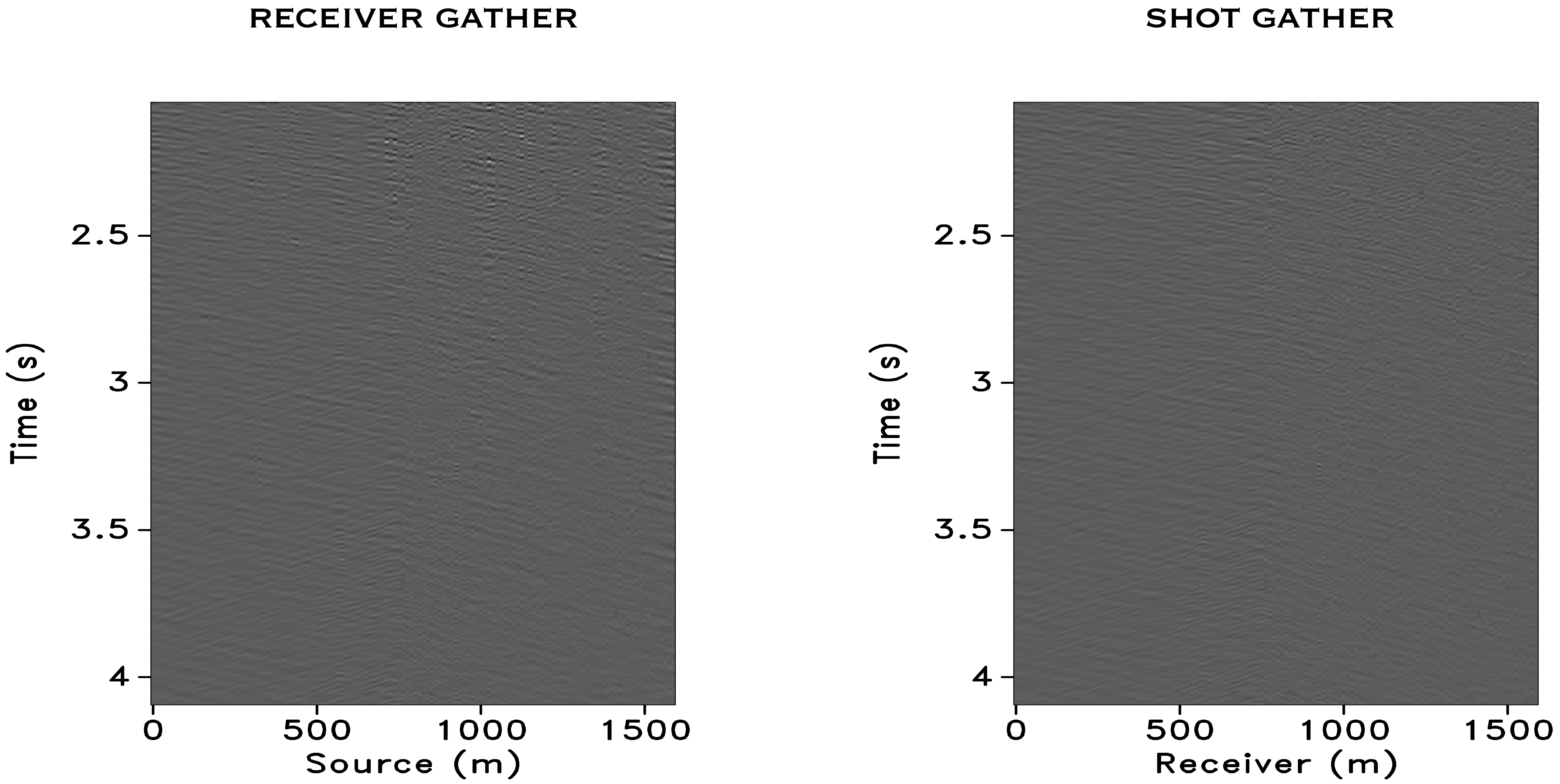
[“deblending” + interpolation from *jittered* 50m grid to *regular* 12.5m grid]





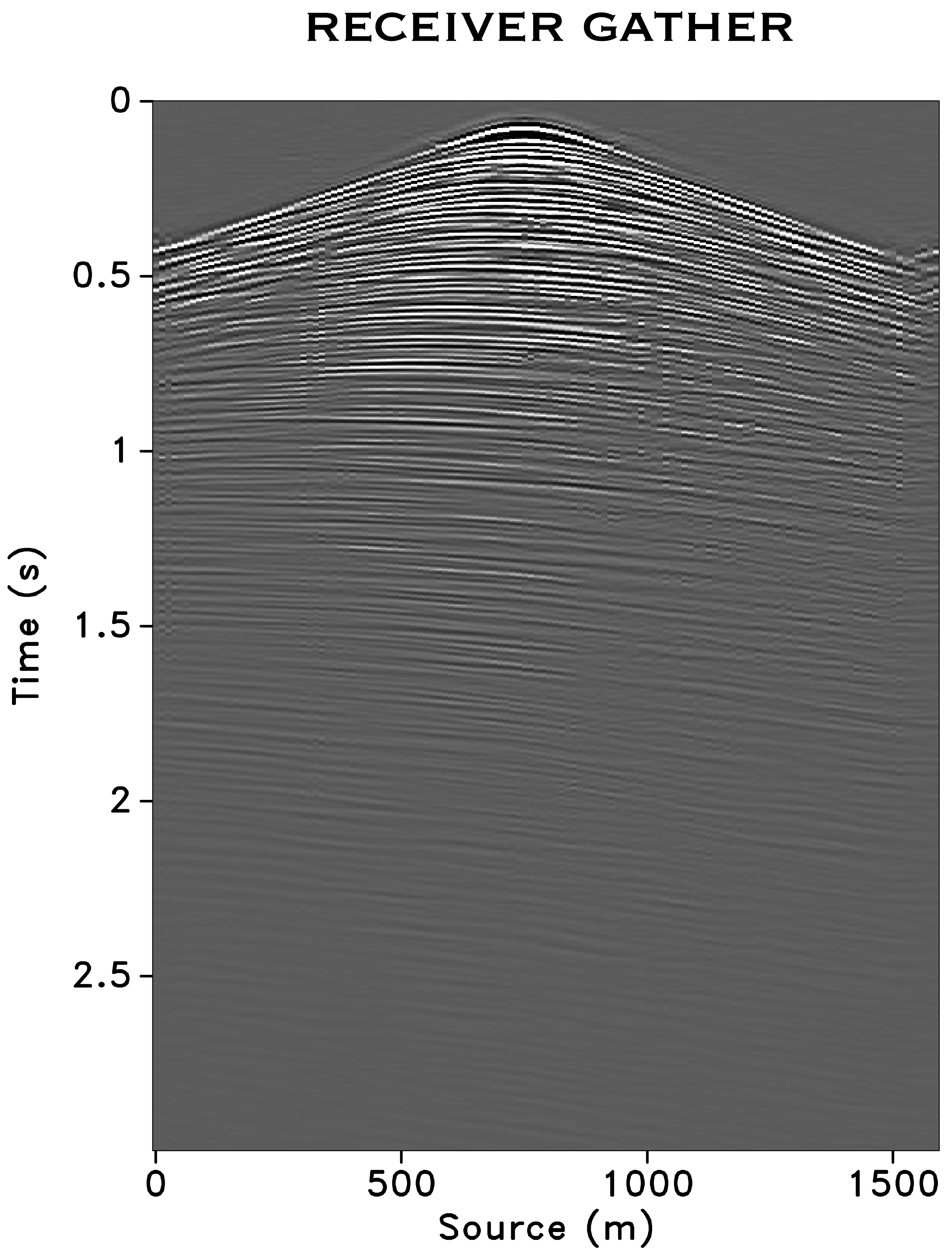
Sparsity-promoting recovery on *irregular* grid with *NFDCT* (12.7 dB)

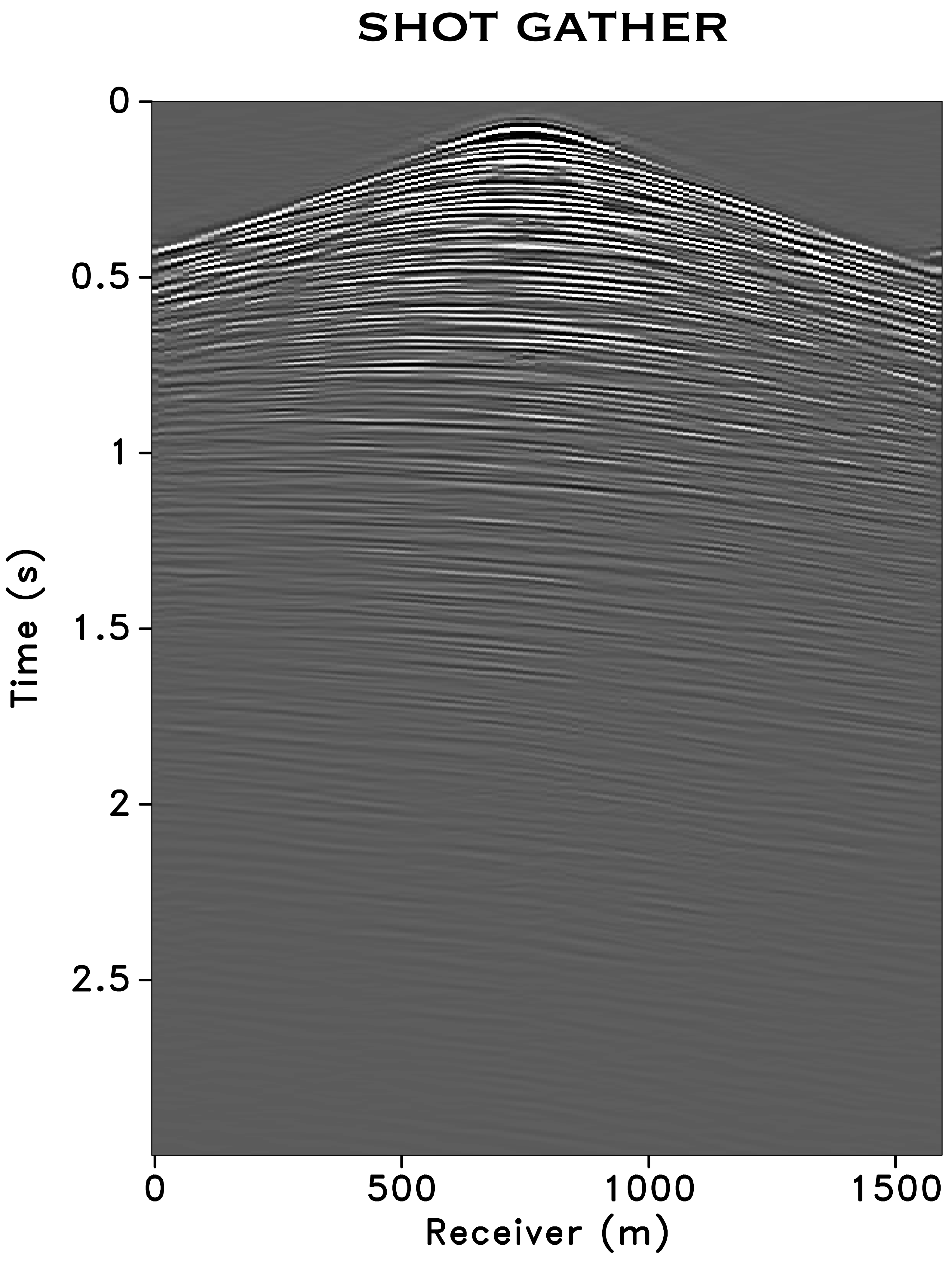
[“deblending” + interpolation from *jittered* 50m grid to *regular* 12.5m grid] (difference)



Sparsity-promoting recovery *on the 12.5m grid* (11.1 dB)

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

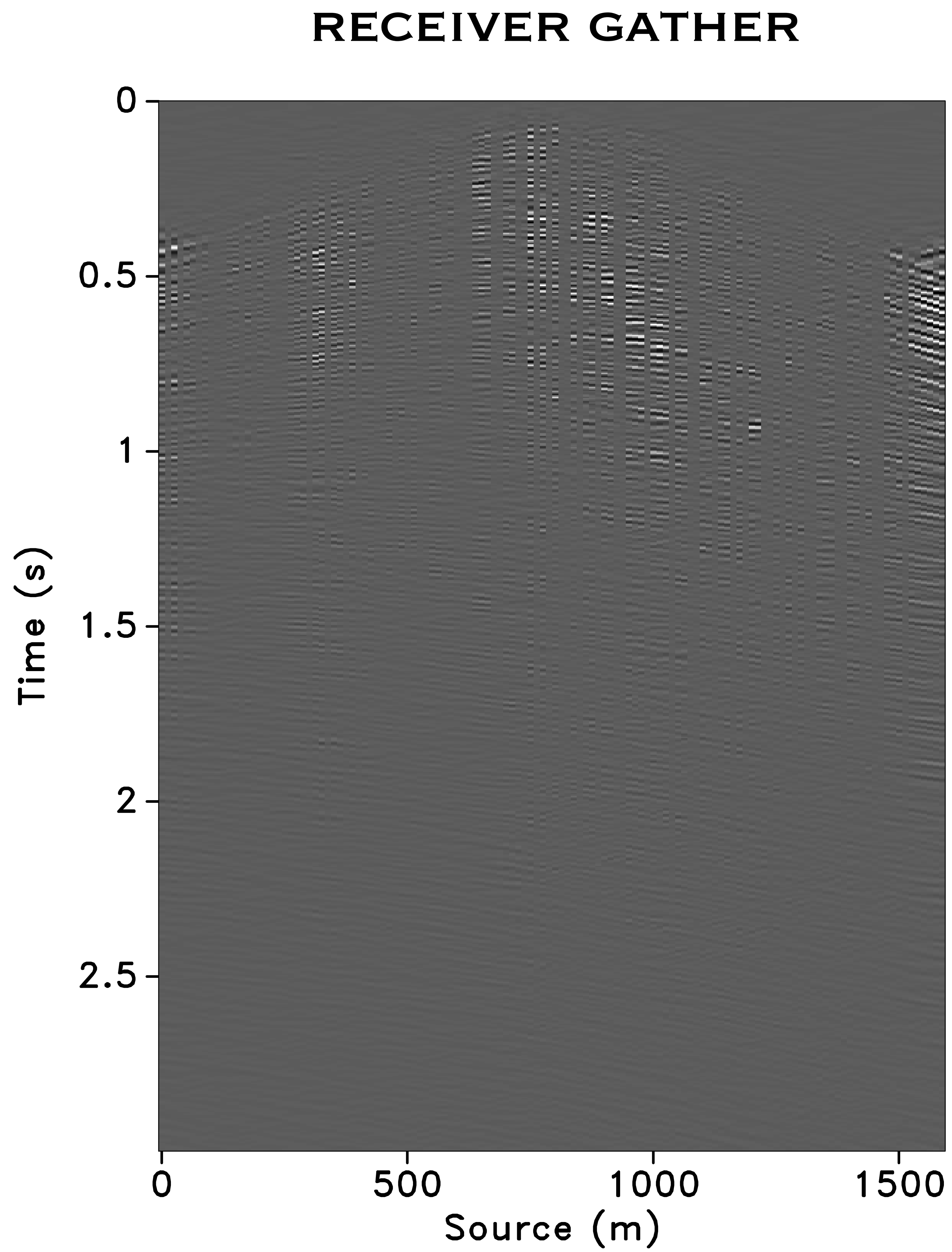


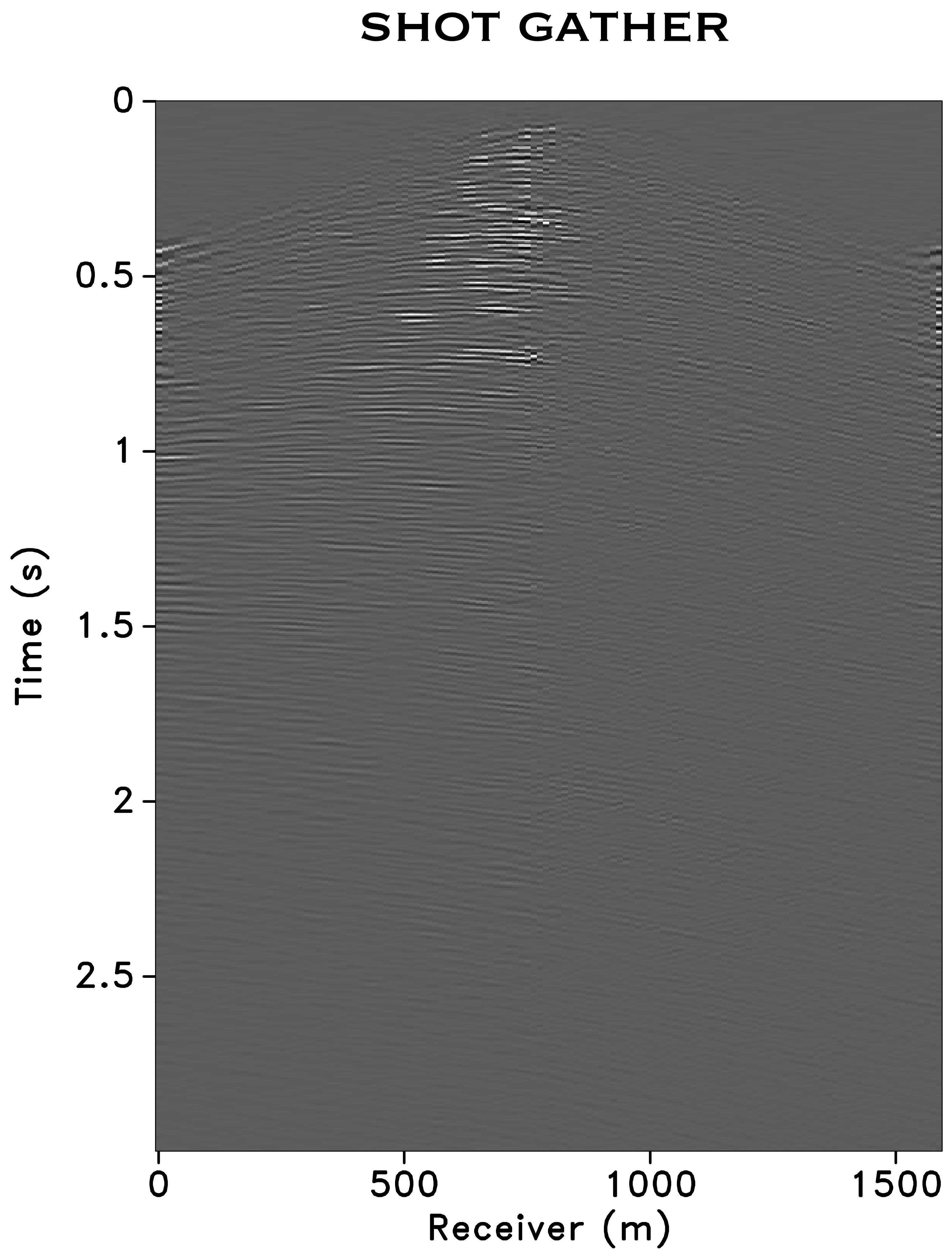


Sparsity-promoting recovery *on the 12.5m grid* (11.1 dB)

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

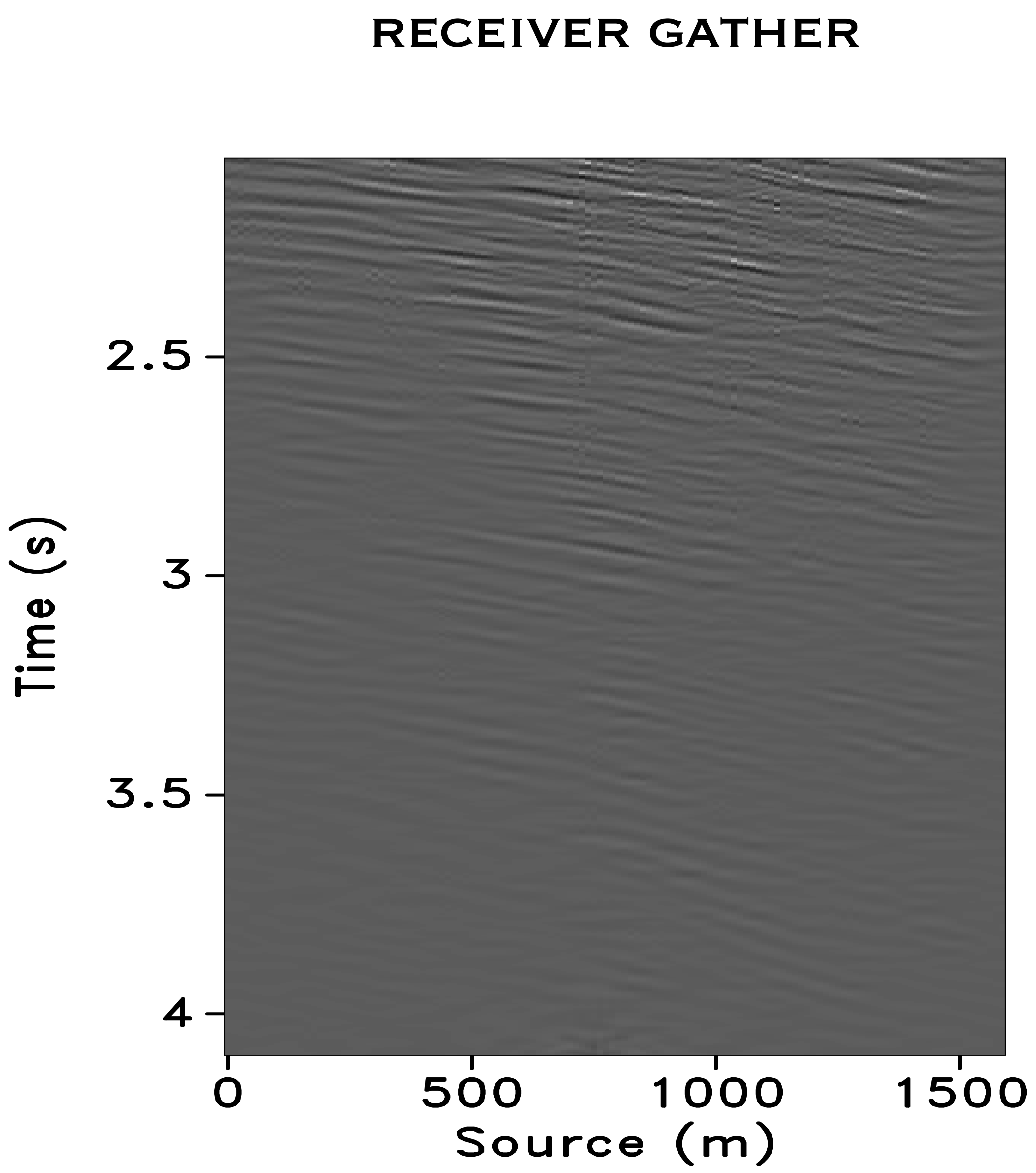
(difference)

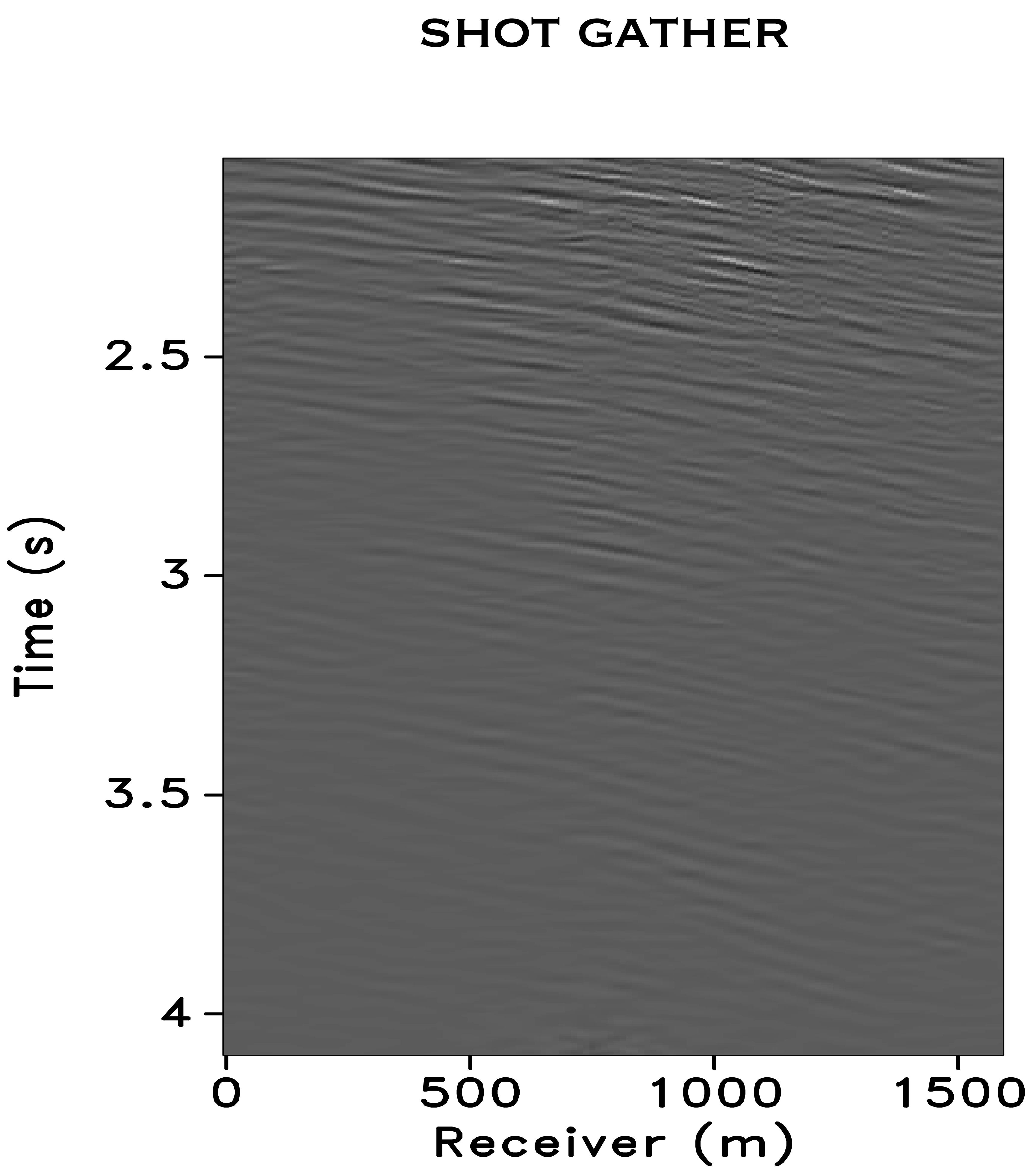




Sparsity-promoting recovery *on the 12.5m grid* (11.1 dB)

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

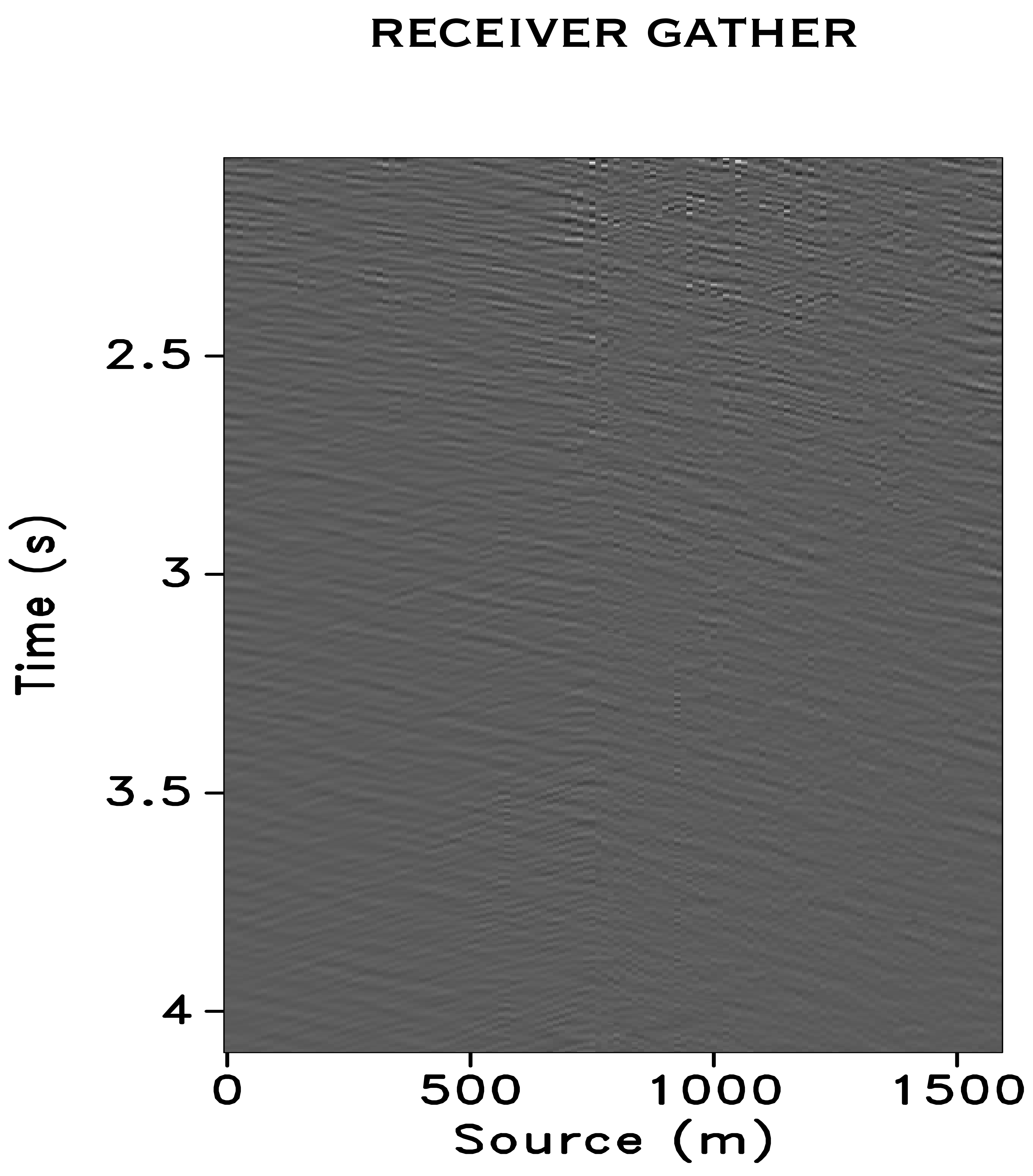


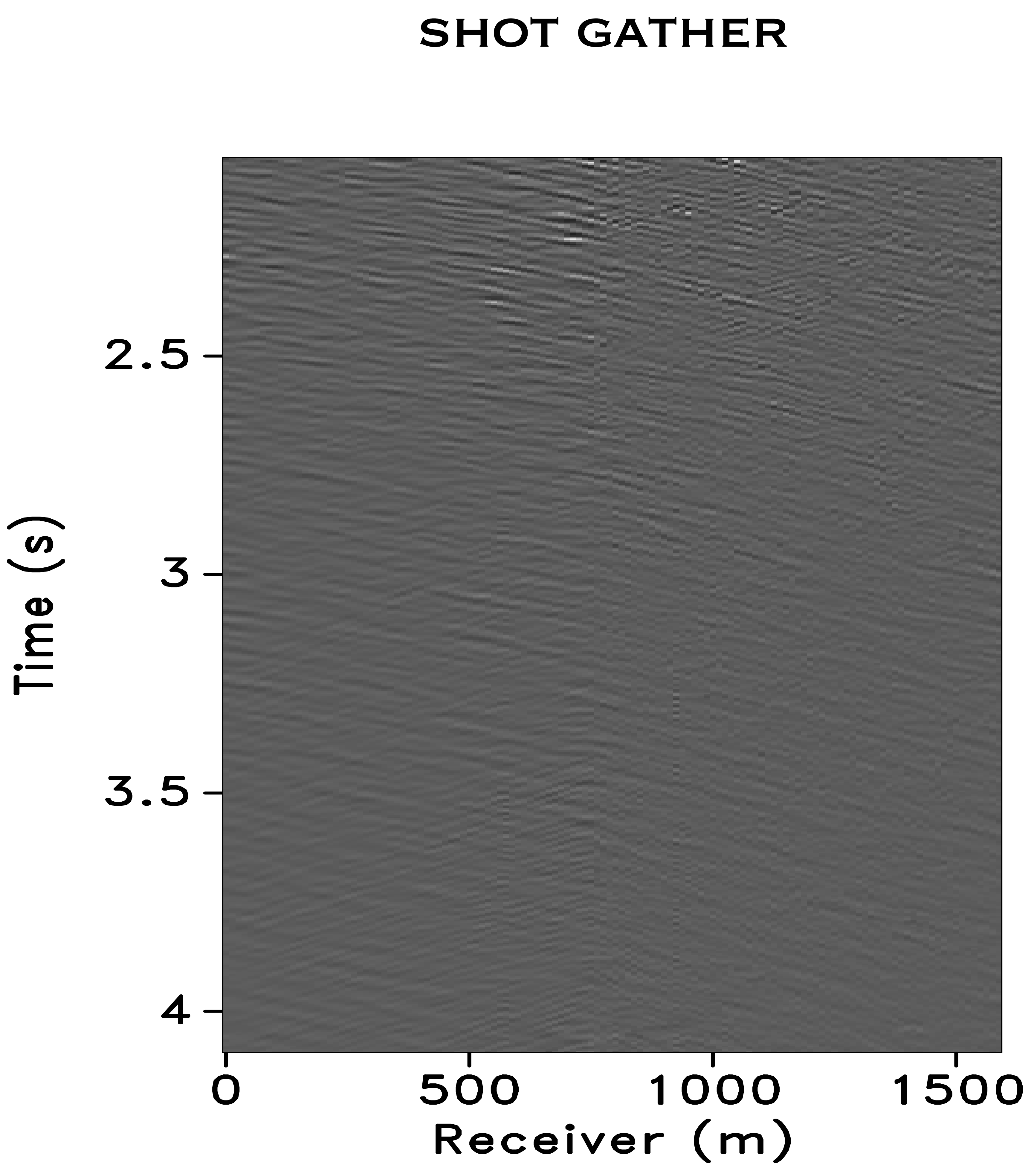


Sparsity-promoting recovery *on the 12.5m grid* (11.1 dB)

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

(difference)





Regular grid, jittered, FDCT recovery

	deblend + interpolate (jittered (m) to regular (m))	sparsity-promoting recovery with ***FDCT*** [SNR (dB)]
1 source vessel (2 airgun arrays)	50 to 25	14.2
	50 to 12.5	11.1
2 source vessels (2 airgun arrays per vessel)	50 to 25	19.7
	50 to 12.5	15.0

Irregular grid, NFDCT recovery

SLIM

	deblend + interpolate (nominal (m) to regular (m))	sparsity-promoting recovery with ***NFDCT*** [SNR (dB)]
1 source vessel (2 airgun arrays)	50 to 25	17.6
	50 to 12.5	12.7
2 source vessels (2 airgun arrays per vessel)	50 to 25	21.5
	50 to 12.5	16.8

Side-by-side

	deblend + interpolate (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	17.6
	50 to 12.5	11.1	12.7
2 source vessels (2 airgun arrays per vessel)	50 to 25	19.7	21.5
	50 to 12.5	15.0	16.8

Summary

Larger variability in shot-time seems desirable

Increased problem with data irregularity as shot-time varies

Irregular data seem more amicable for interpolation (wavenumber diversity, non-coherent aliasing, etc)

Both source separation and trace interpolation can be treated (and work well) as sparse inversion problems

Rather than dealing with them separately, do both together

- sparsity transforms can be better leveraged
- avoid accumulation of errors in separate processing steps

Talk to your reg+interpolation specialists

Acknowledgements

- My colleagues
- Many helpful discussions with industry geophysicists

SINBAD

NSERC CRSNG

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