Time-jittered ocean bottom seismic acquisition

Haneet Wason and Felix J. Herrmann

SLIM
University of British Columbia

Challenges

- Need for full sampling
  - wave-equation based inversion (RTM & FWI)
  - SRME/EPSI or related techniques
- Full azimuthal coverage
  - multiple source vessels
  - simultaneous/blended acquisition
- Deblending or wavefield reconstruction
  - recover unblended data from blended data
  - challenging to recover weak late events

Motivation

Rethink marine acquisition (OBC, OBN)

- sources (and receivers) at *random* locations
- exploit *natural* variations in the acquisition (e.g., cable feathering)
- as long as you know where sources were afterwards... *it is fine!*

Want more for less ...

- *shorter* survey times
- *increased* spatial sampling

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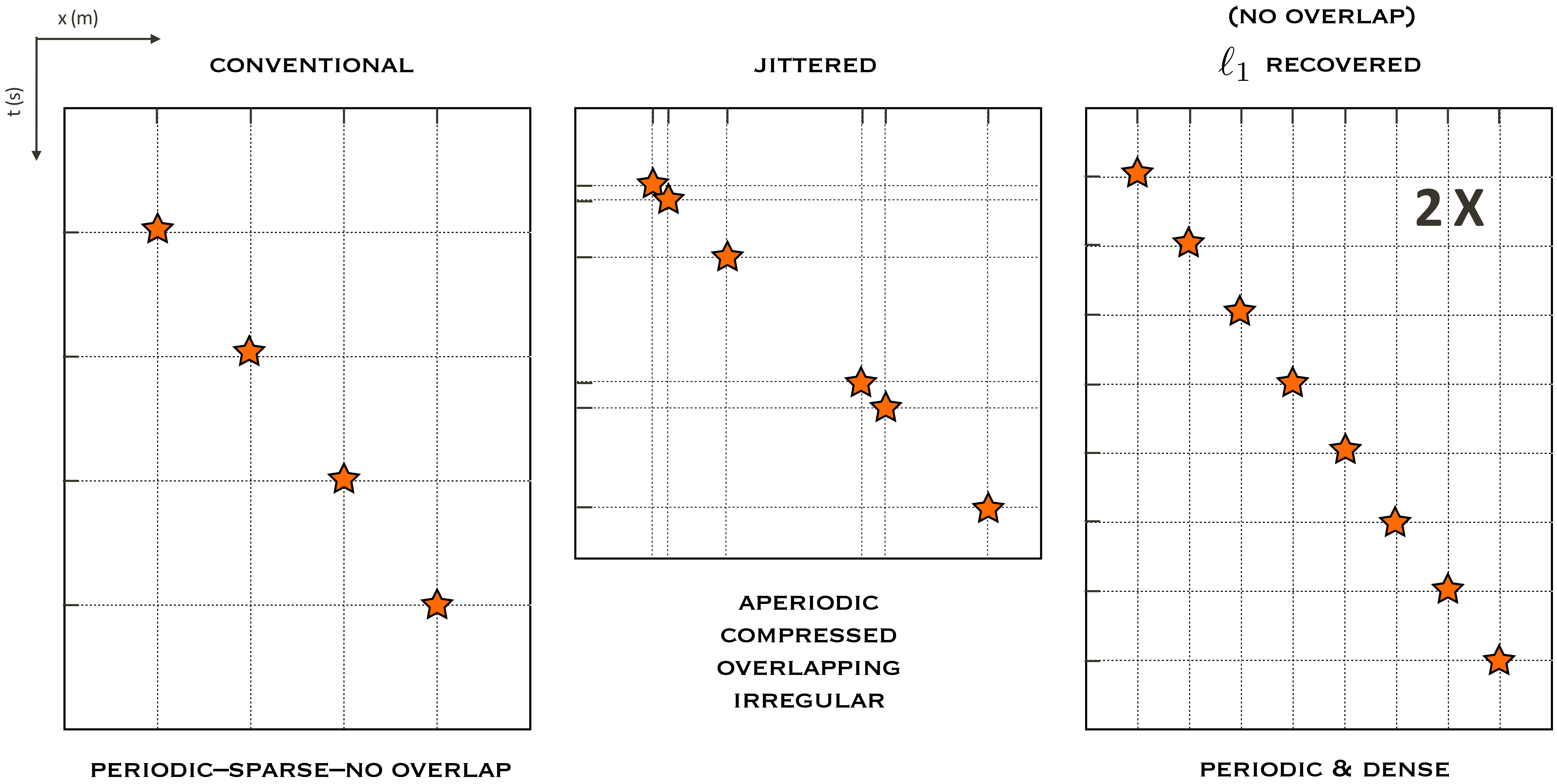
How is this possible?

- (multi) vessel acquisition w/ *jittered* sampling & "blending" *via compressed randomized intershot* firing times
- *sparsity*-promoting recovery using ℓ_1 constraints ("deblending")

More for less



Outline

- Measurement model & recovery strategy
- Design of *jittered*, ocean bottom acquisition
  - jitter in *time* $\Rightarrow$ jittered in *space* (*shot* locations)
- Experimental results of *sparsity*-promoting processing
  - wavefield *recovery* via "*deblending*" & *interpolation* from (coarse) *jittered/irregular* to (fine) *regular* sampling grid

Compressed Sensing

Successful sampling & reconstruction scheme

- exploit *structure* via *sparsifying* transform
- *subsampling* – decreases sparsity
- large scale *optimization* – look for *sparsest* solution

Time-jittered acquisition

Compress inter-shot times

- *random jitter* in *time* $\Longrightarrow$ *jitter* in *space* for a given speed
- *discrete* jittering - start by being *on the grid*
- maximum (acquisition) gap *effectively* controlled

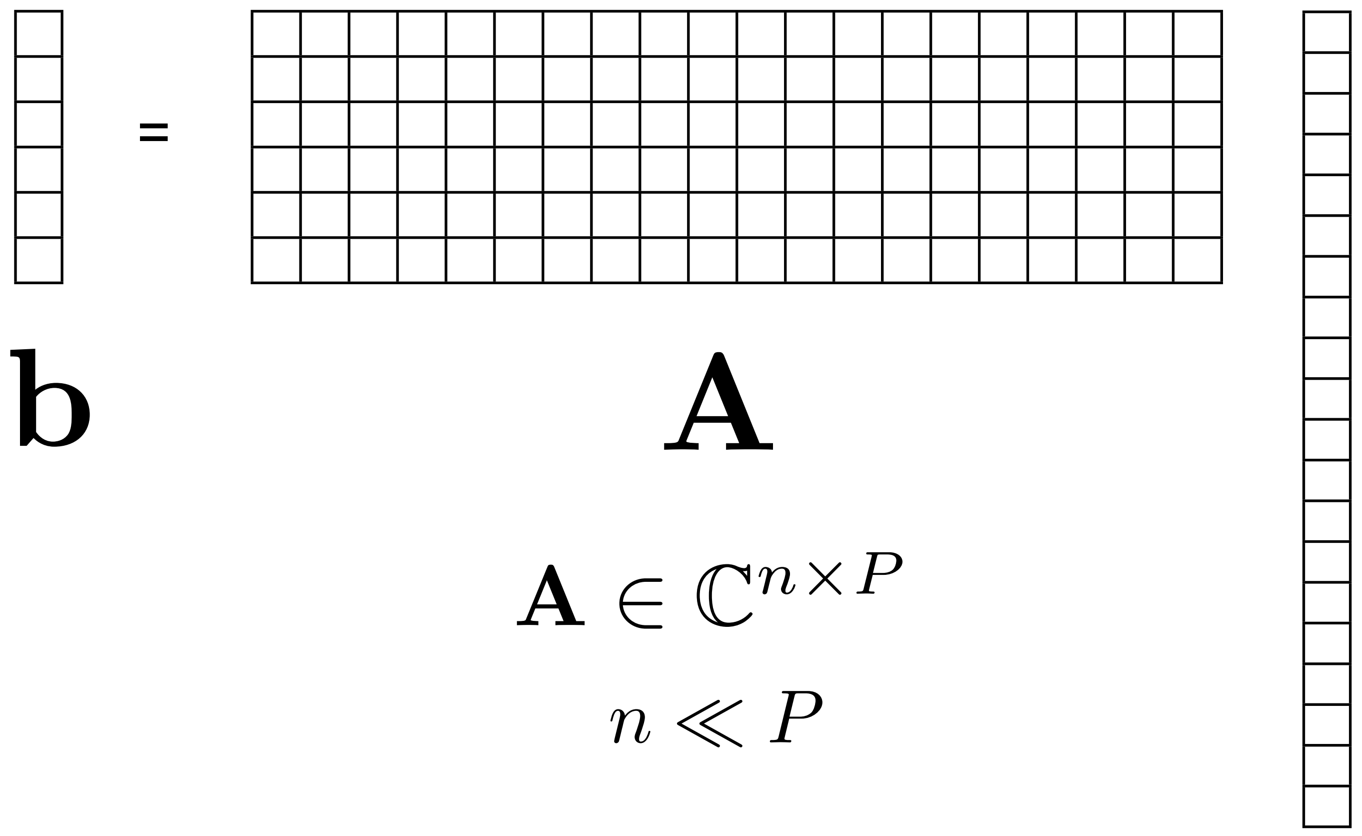
Challenges: recover *fully* sampled data from *jittered* data *and* remove overlaps (*but no fear..... sparse recovery is here!*)

Recent work - use *non-uniform* grid [Hennenfent et.al., 2010]

Measurement model

Solve an *underdetermined* system of *linear* equations:

data (measurements /observations) →



$\mathbf{b} \in \mathbb{C}^n$

$\mathbf{b}$ $\mathbf{A}$

$\mathbf{A} \in \mathbb{C}^{n \times P}$

$n \ll P$

$\mathbf{x_0}$ ← unknown

$\mathbf{x_0} \in \mathbb{C}^P$

$$\mathbf{A} = \underbrace{\mathbf{RM}}\mathbf{S^H}$$

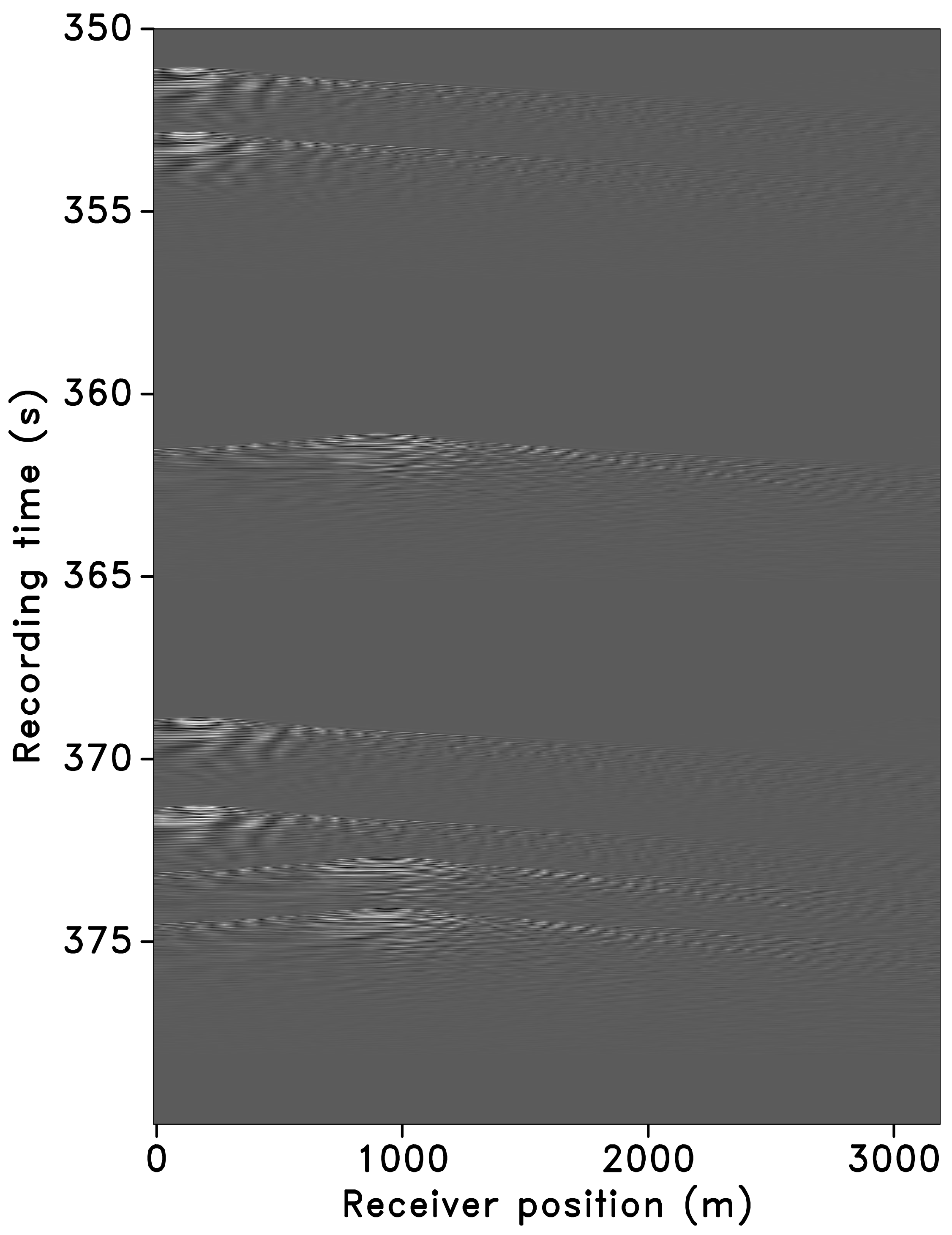
sampling matrix

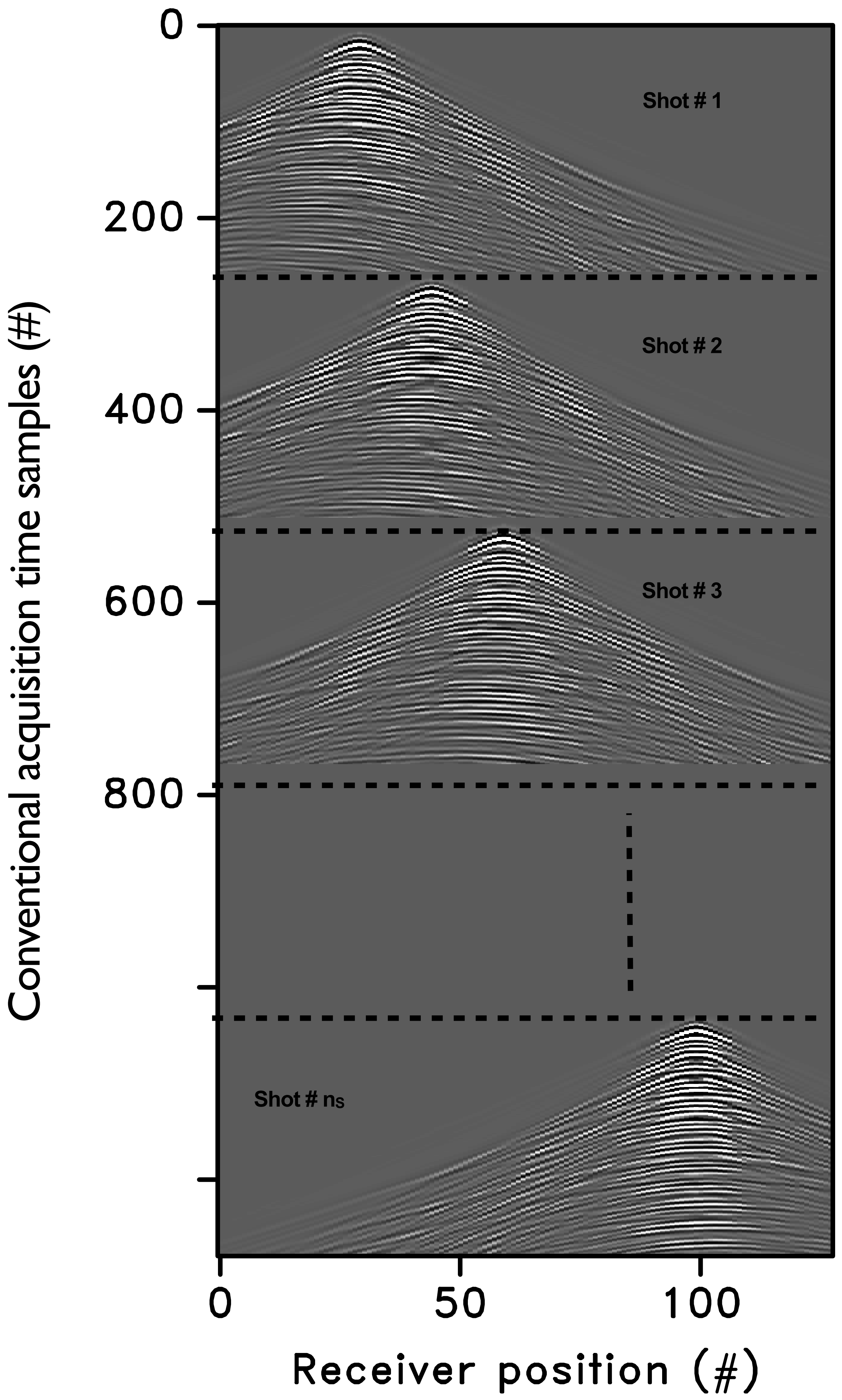
transform matrix

acquire in the field on *irregular* grid (*subsampled* shots *w/ overlap* between shot records)

would like to have on *regular* grid (*all* shots *w/o overlaps* between shot records)

$$\mathbf{b} = \mathbf{RM}\,\mathbf{d}$$





Sparsity-promoting recovery

Exploit *curvelet*-domain *sparsity* of seismic data

Sparsity-promoting program:

$$\tilde{\mathbf{x}} = \underbrace{\arg\min_{\mathbf{x}} \|\mathbf{x}\|_1}_{\text{support detection}} \quad \text{subject to} \quad \underbrace{\mathbf{A}\mathbf{x} = \mathbf{b}}_{\text{data-consistent amplitude recovery}}$$

Sparsity-promoting solver: $\mathbf{SPG}\ell_1$ [van den Berg and Friedlander, 2008]

Recover *single*-source *prestack* data volume: $\tilde{\mathbf{d}} = \mathbf{S^H}\tilde{\mathbf{x}}$

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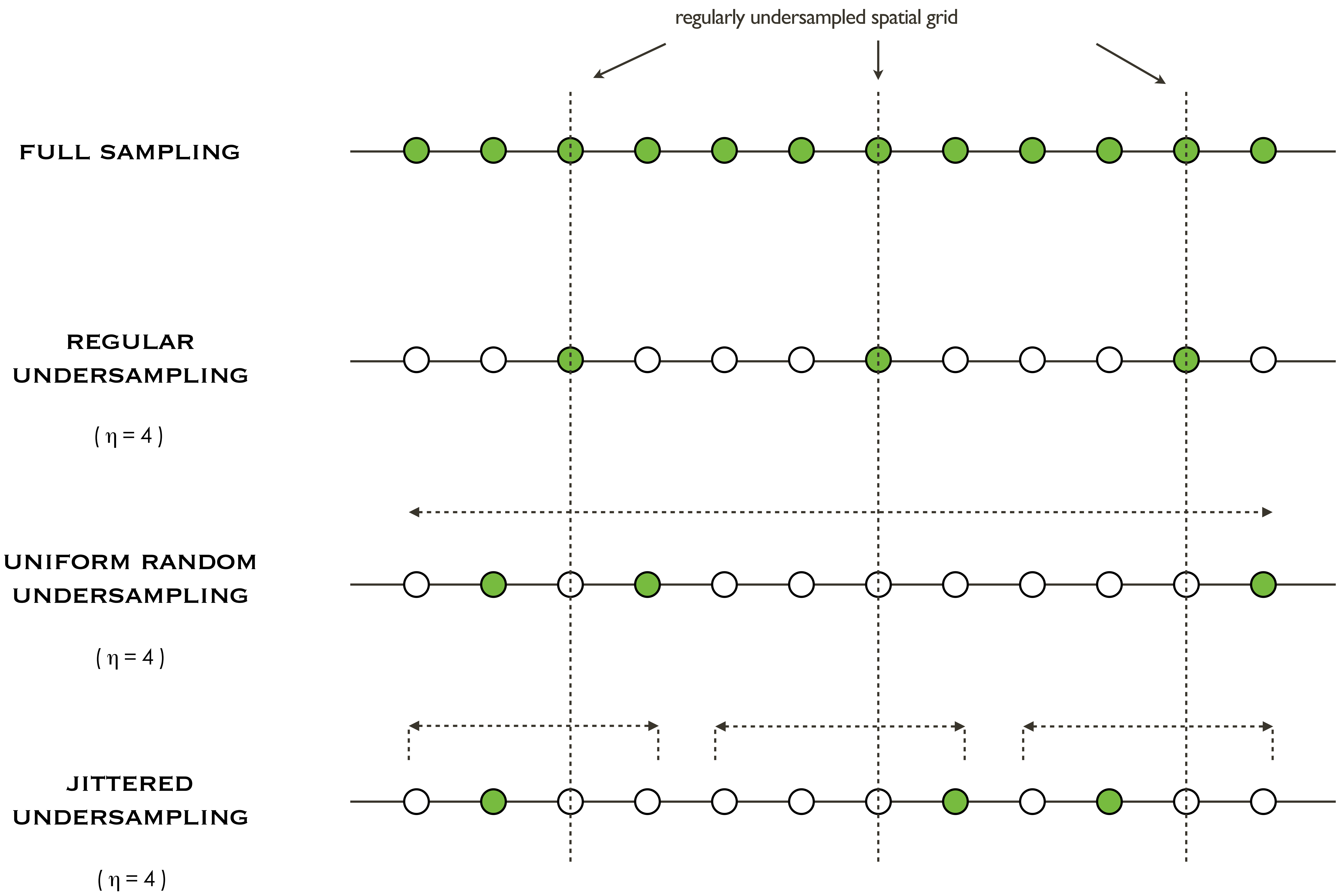
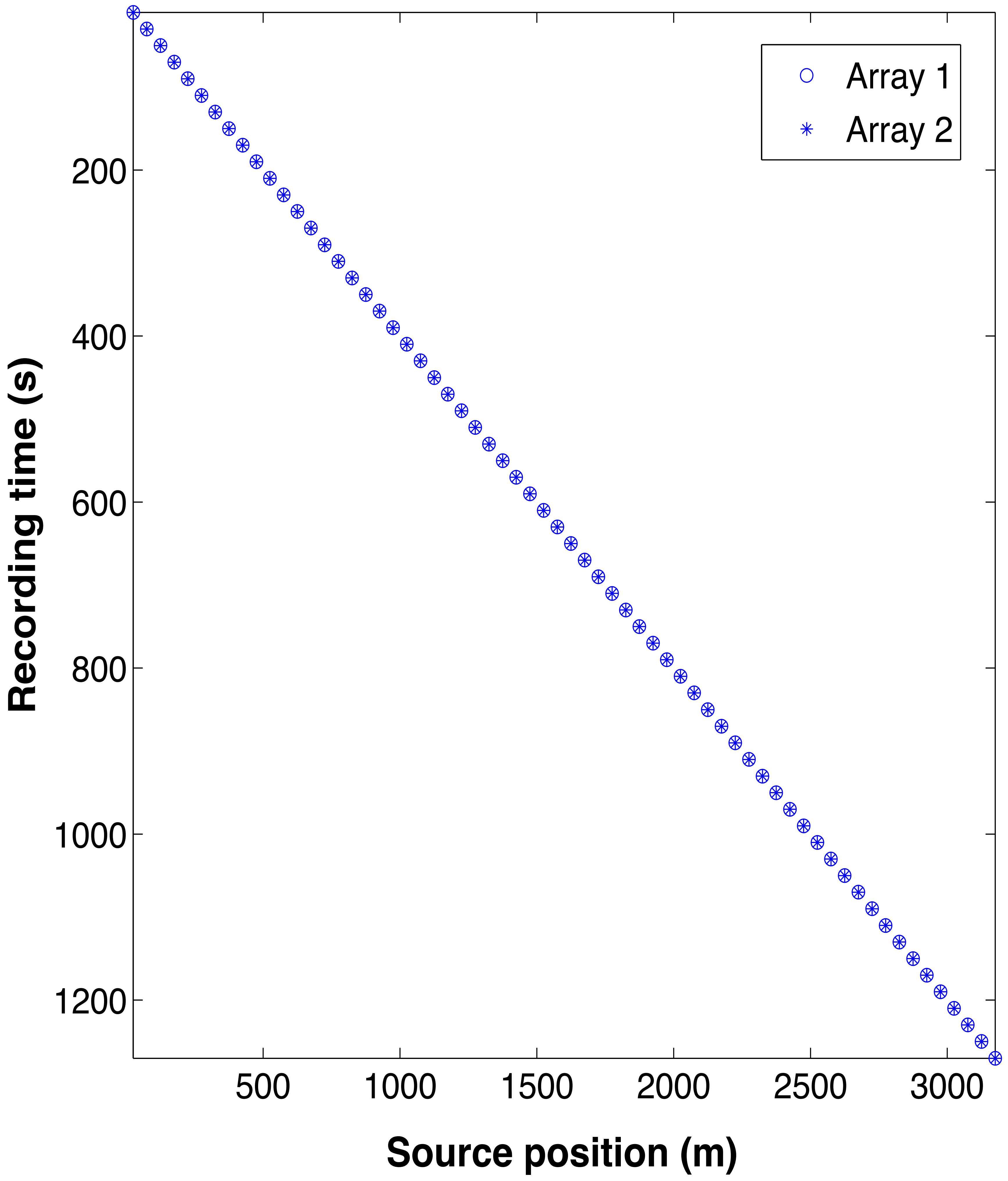
Sampling schemes

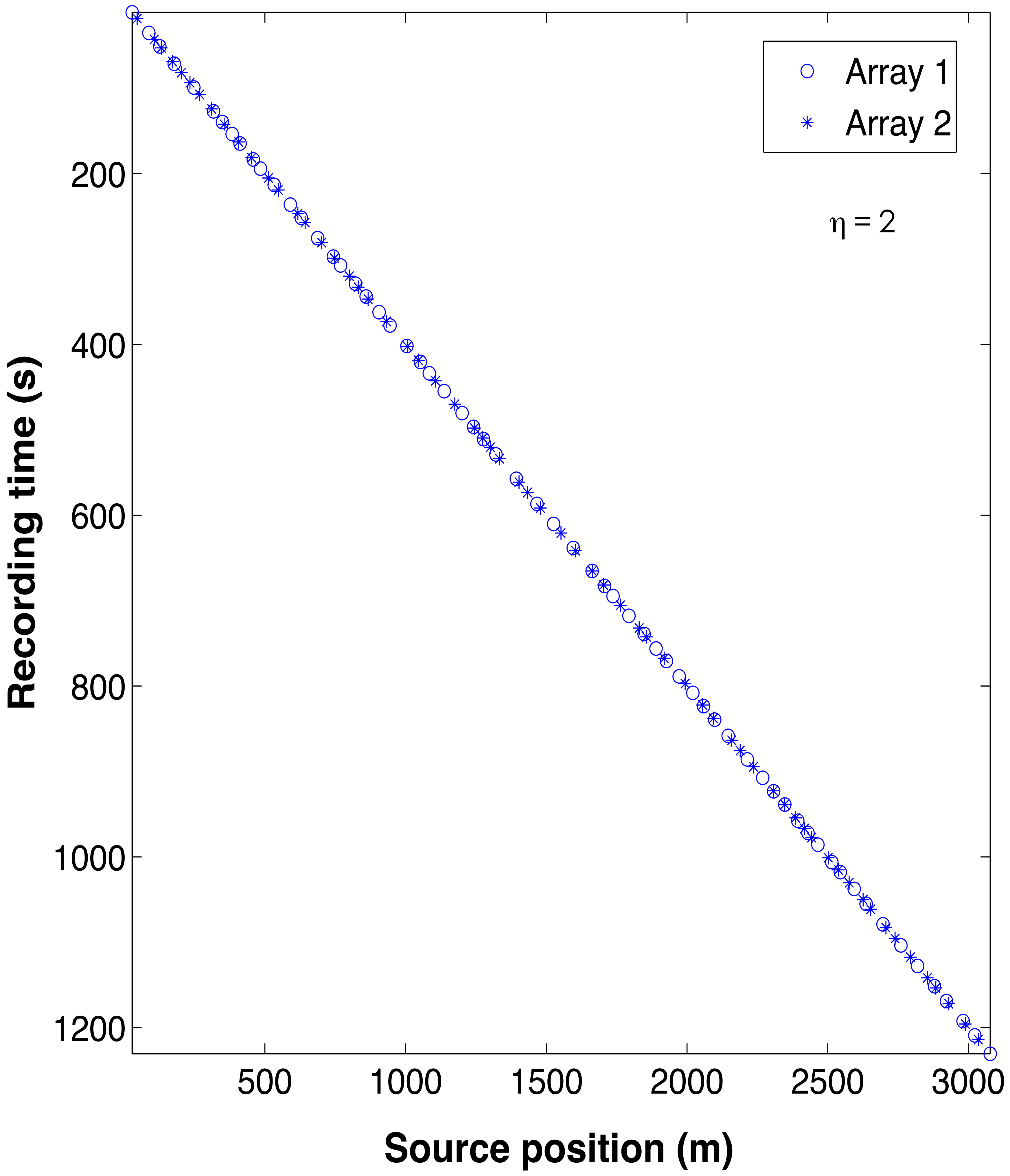


[Hennenfent et.al., 2008]

Conventional vs. *jittered* sources

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





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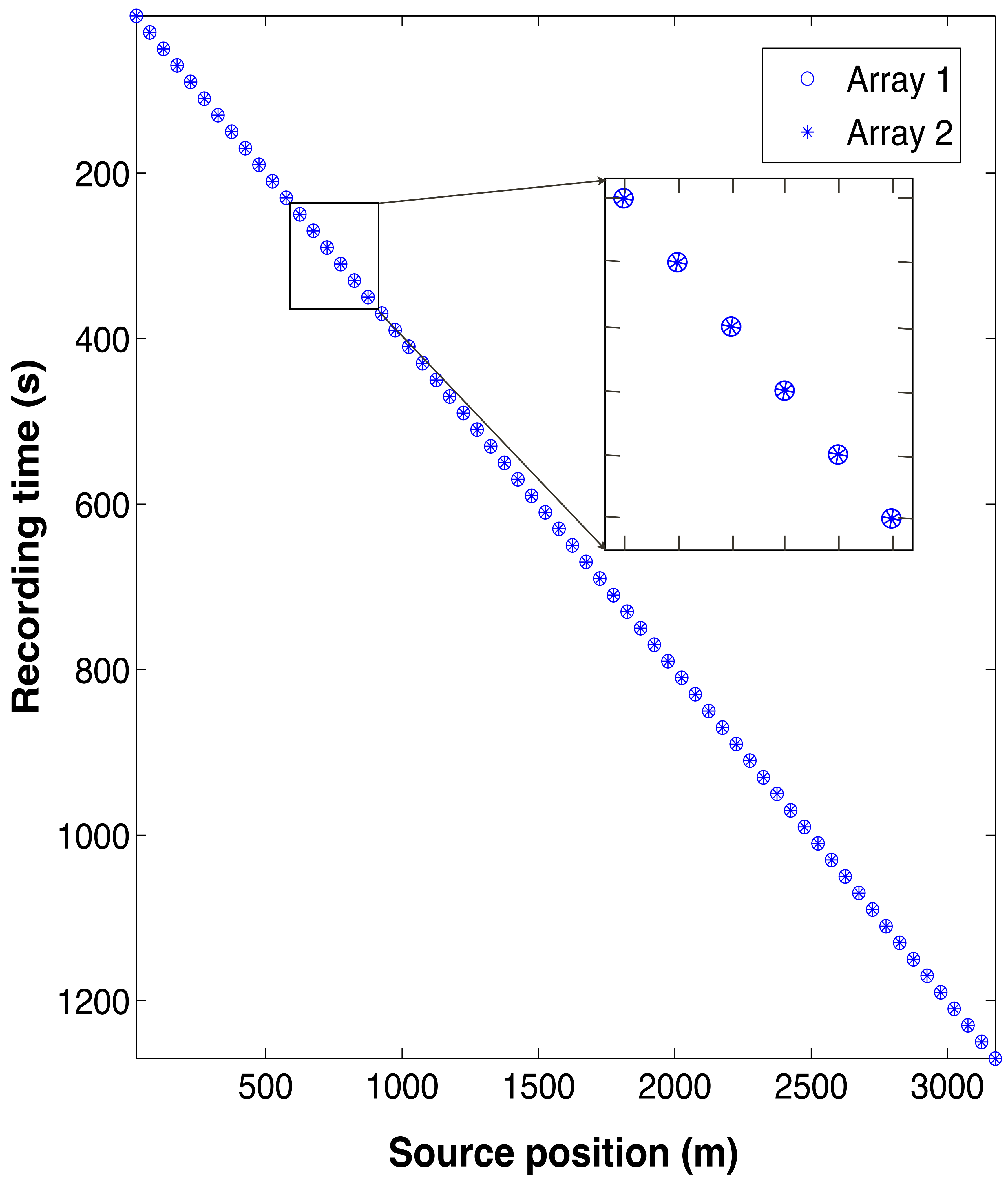
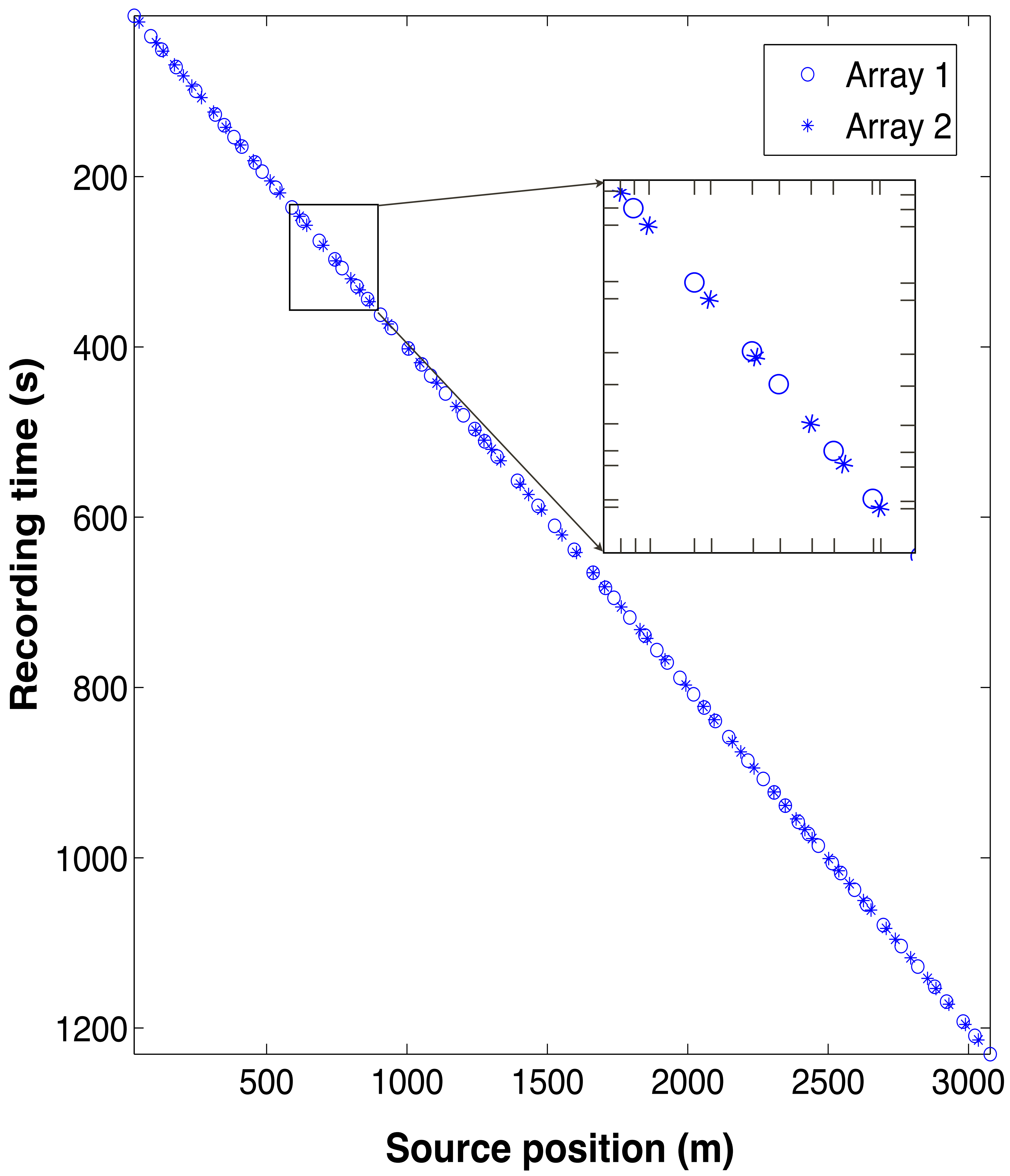
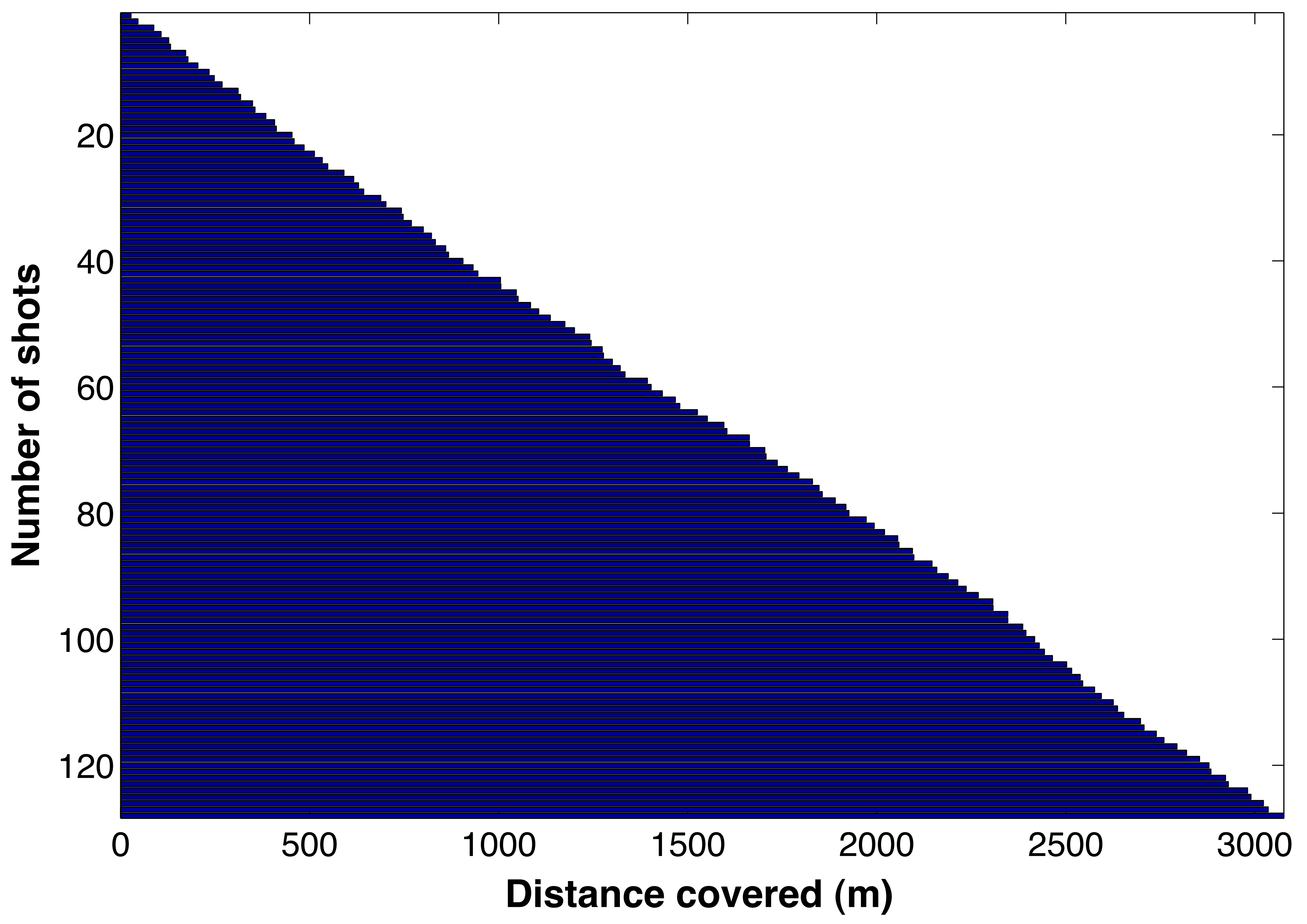
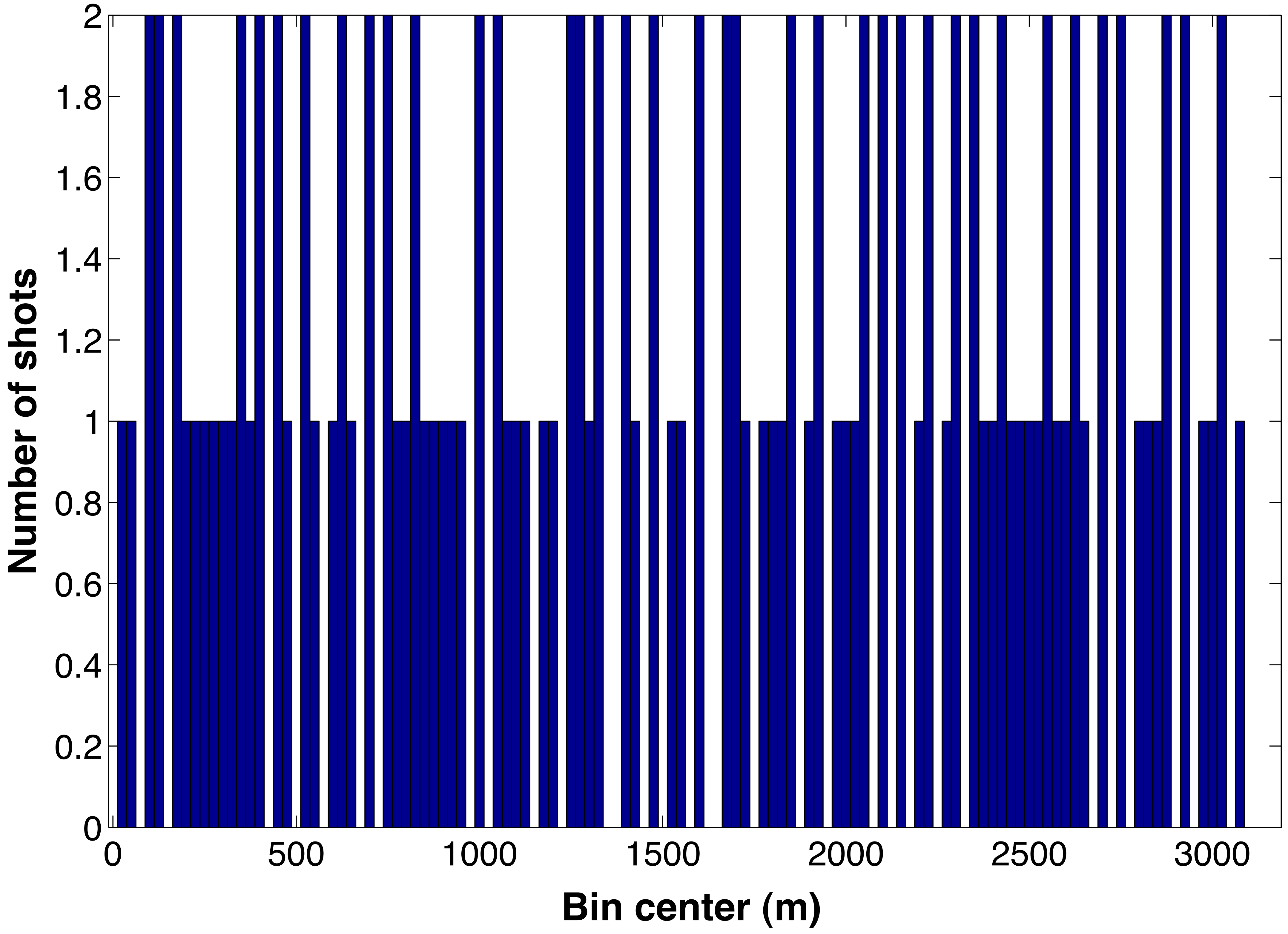




Significant spatial jittering





Simultaneous source acquisition & deblending

- *A new look at simultaneous sources* by Beasley et. al., '98, '08
- *High quality separation of simultaneous sources by sparse inversion* by Abma et. al., '13
- *Changing the mindset in seismic data acquisition* by Berkhout, '08
- *Utilizing dispersed source arrays in blended acquisition* by Berkhout et. al., '12
- *Random sampling: a new strategy for marine acquisition* by Moldoveanu, '10
- *Multi-vessel coil shooting acquisition* by Moldoveanu, '10
- *Simultaneous source separation by sparse radon transform* by Akerberg et. al., '08
- *Simultaneous source separation using dithered sources* by Moore et. al., '08
- *Simultaneous source separation via multi-directional vector-median filter* by Huo et. al., '09
- *Separation of blended data by iterative estimation and subtraction of blending interference noise* by Mahdad et. al., '11

Our approach

Combination of

- multiple-source *time-jittered* acquisition
  - *random jitter* in time $\Longrightarrow$ *jitter* in *space* for a constant speed (*favours* recovery compared to *periodic* sampling)
  - shorter acquisition times
- *sparsity*-promoting processing
  - *data* is *sparse* in *curvelets*
  - *optimization*: use ℓ_1 *constraints*

Address two challenges - *overlap* and *jittered sampling* (*regularize* & *interpolate*)

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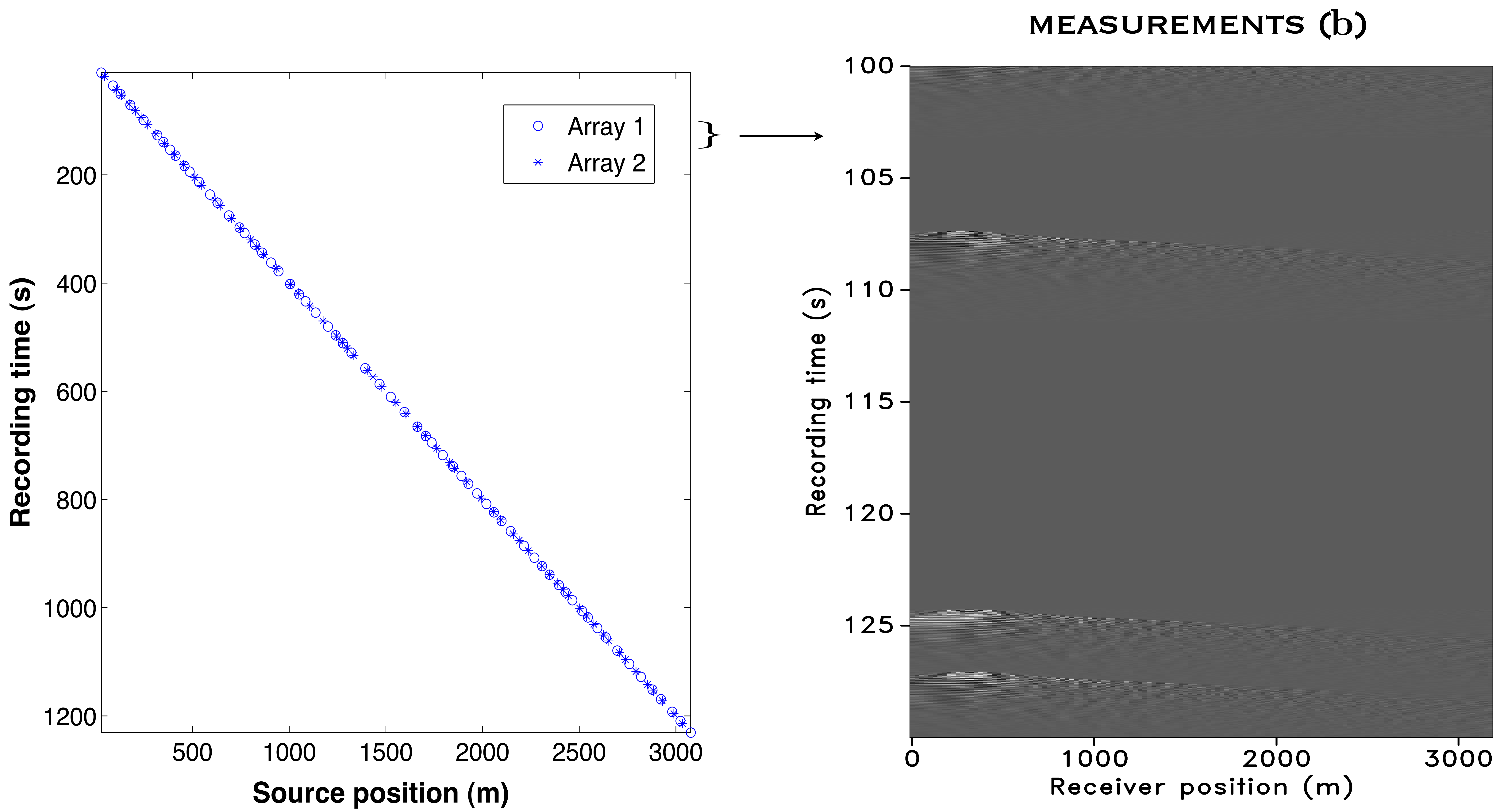
Time-jittered OBC acquisition

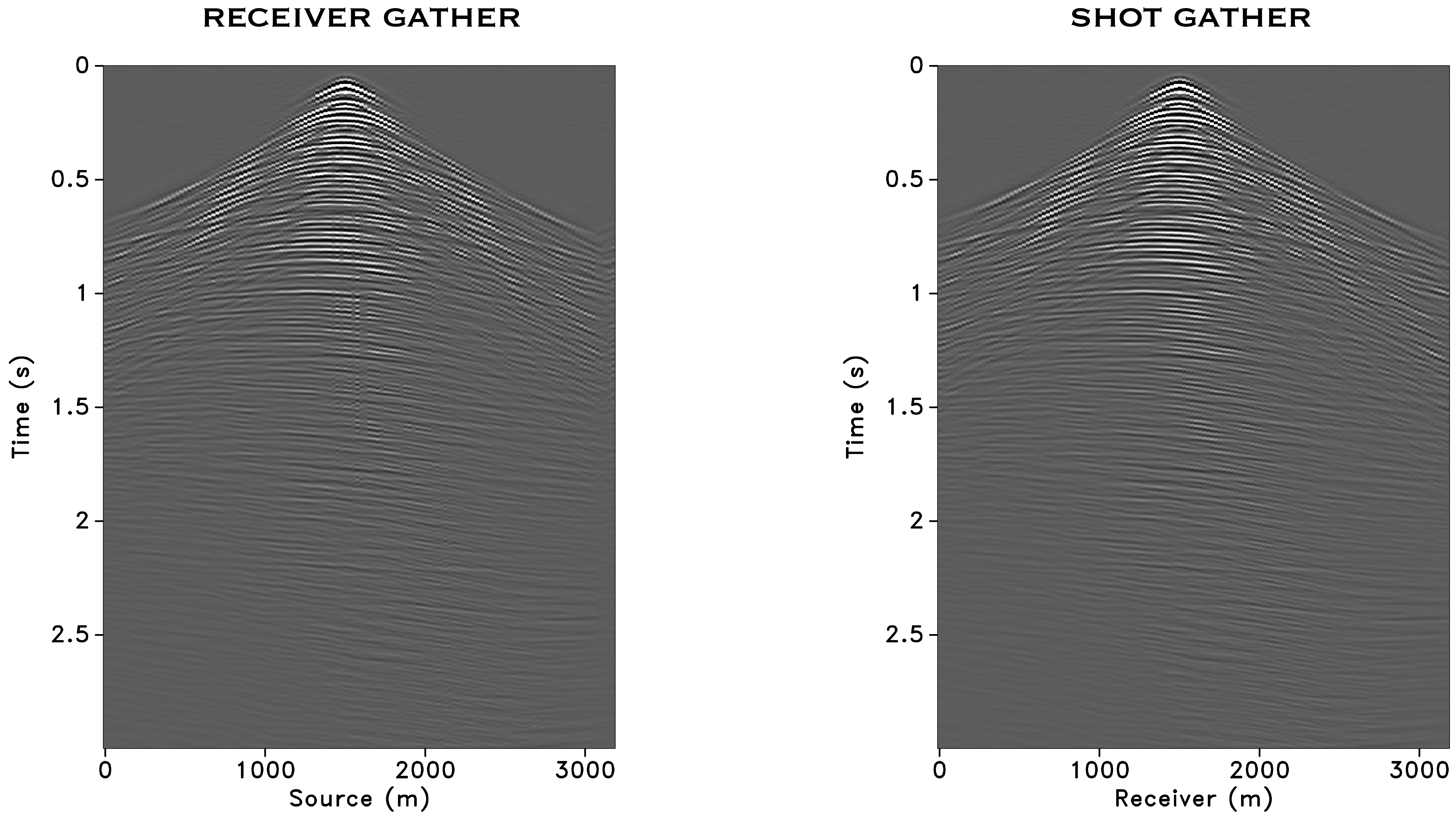
[1 source vessel, speed = 5 knots, underlying grid: 25 m]

[no. of *jittered* source locations is *half* the number of sources in *ideal* periodic survey w/o overlap]



Sparsity-promoting recovery *on the grid* (14.2 dB)

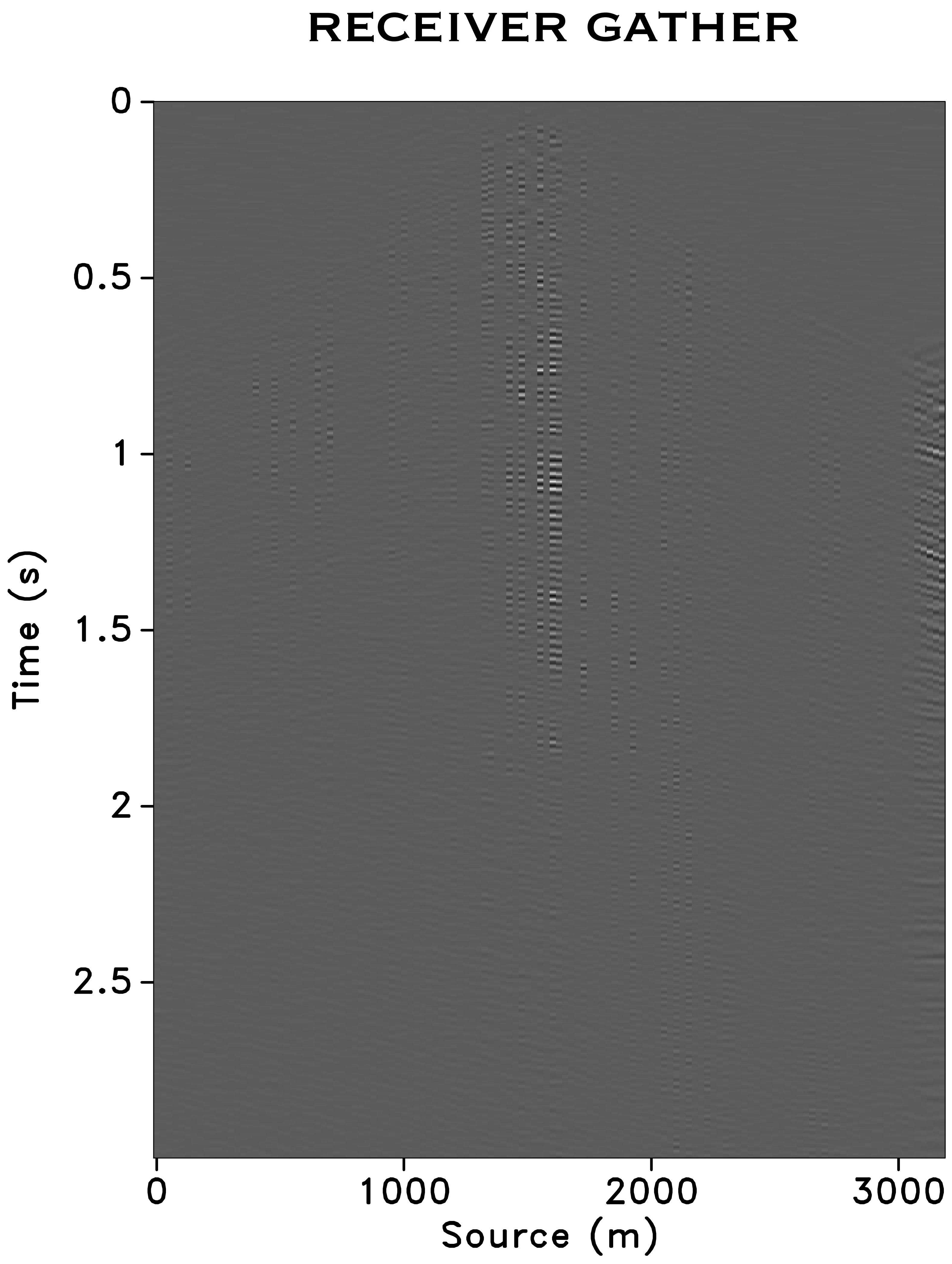
[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]

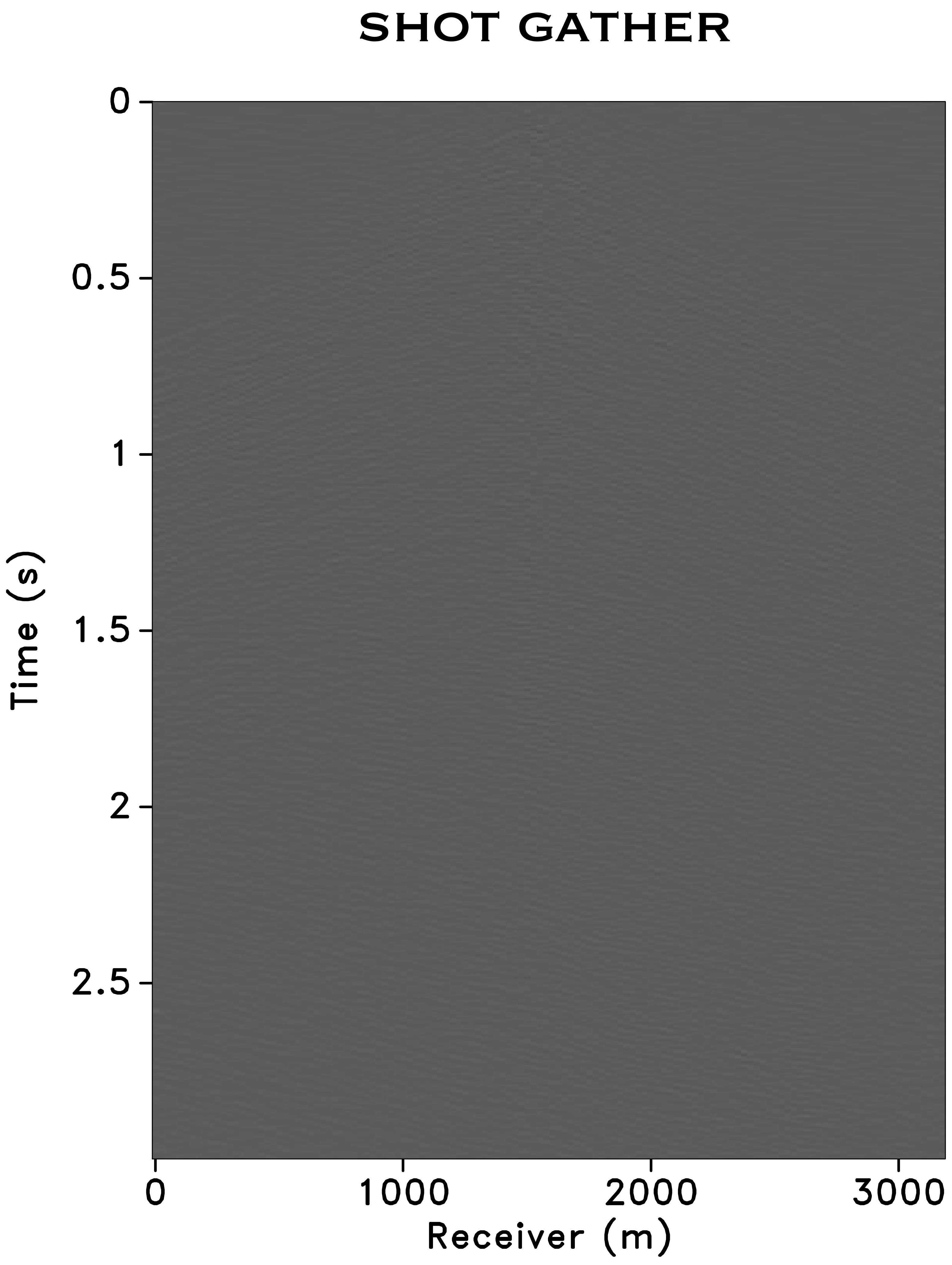


Sparsity-promoting recovery *on the grid* (14.2 dB)

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

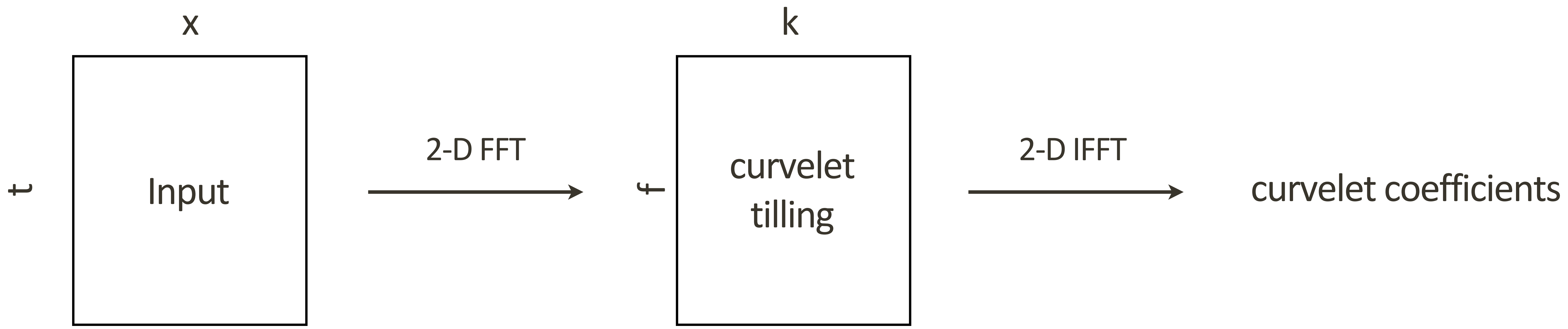
(difference)



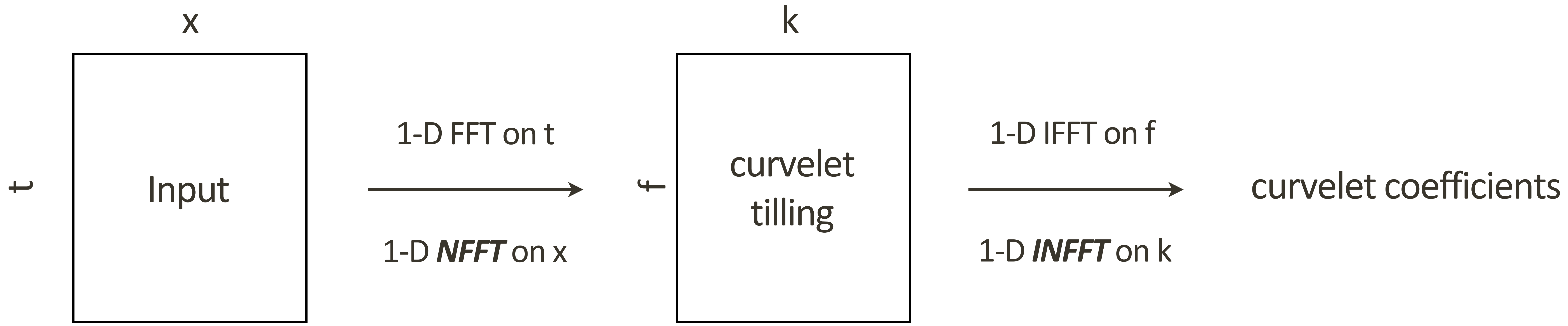


FDCT vs. NFDCT

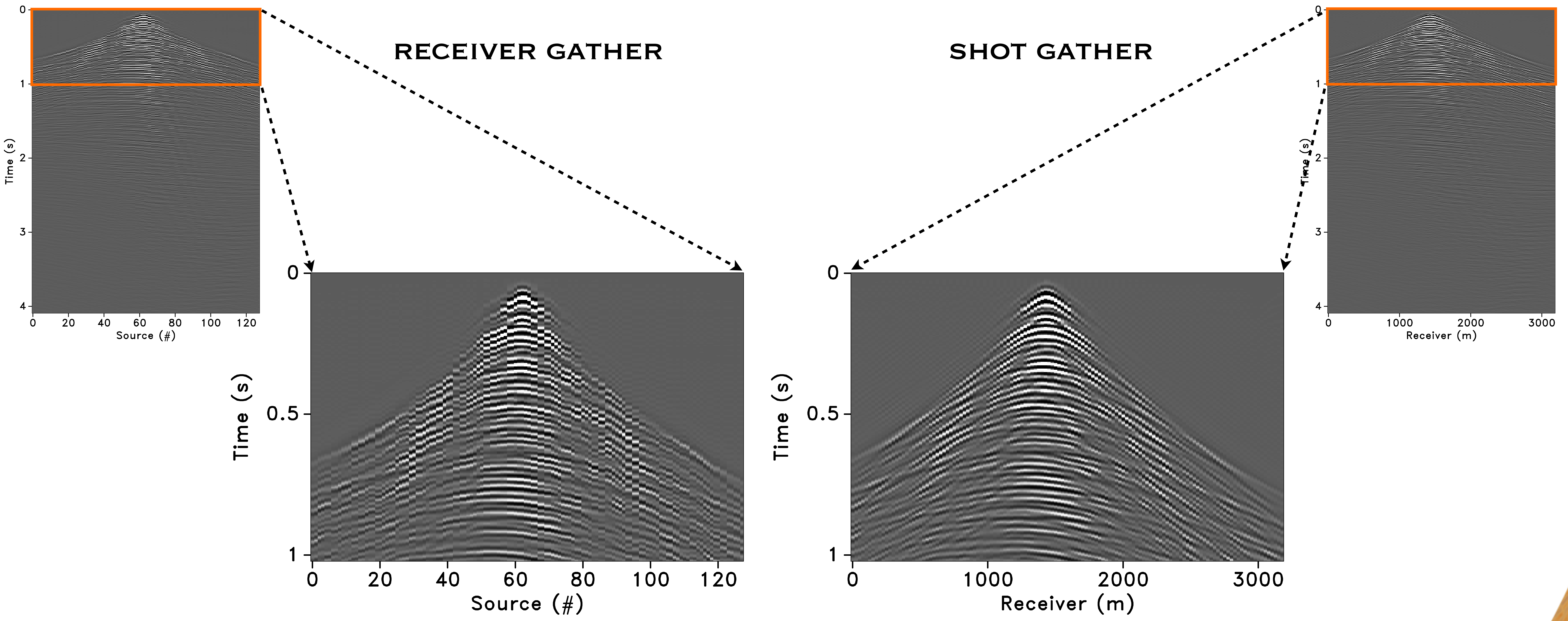
FAST DISCRETE CURVELET TRANSFORM



NON-EQUISPACED FAST DISCRETE CURVELET TRANSFORM

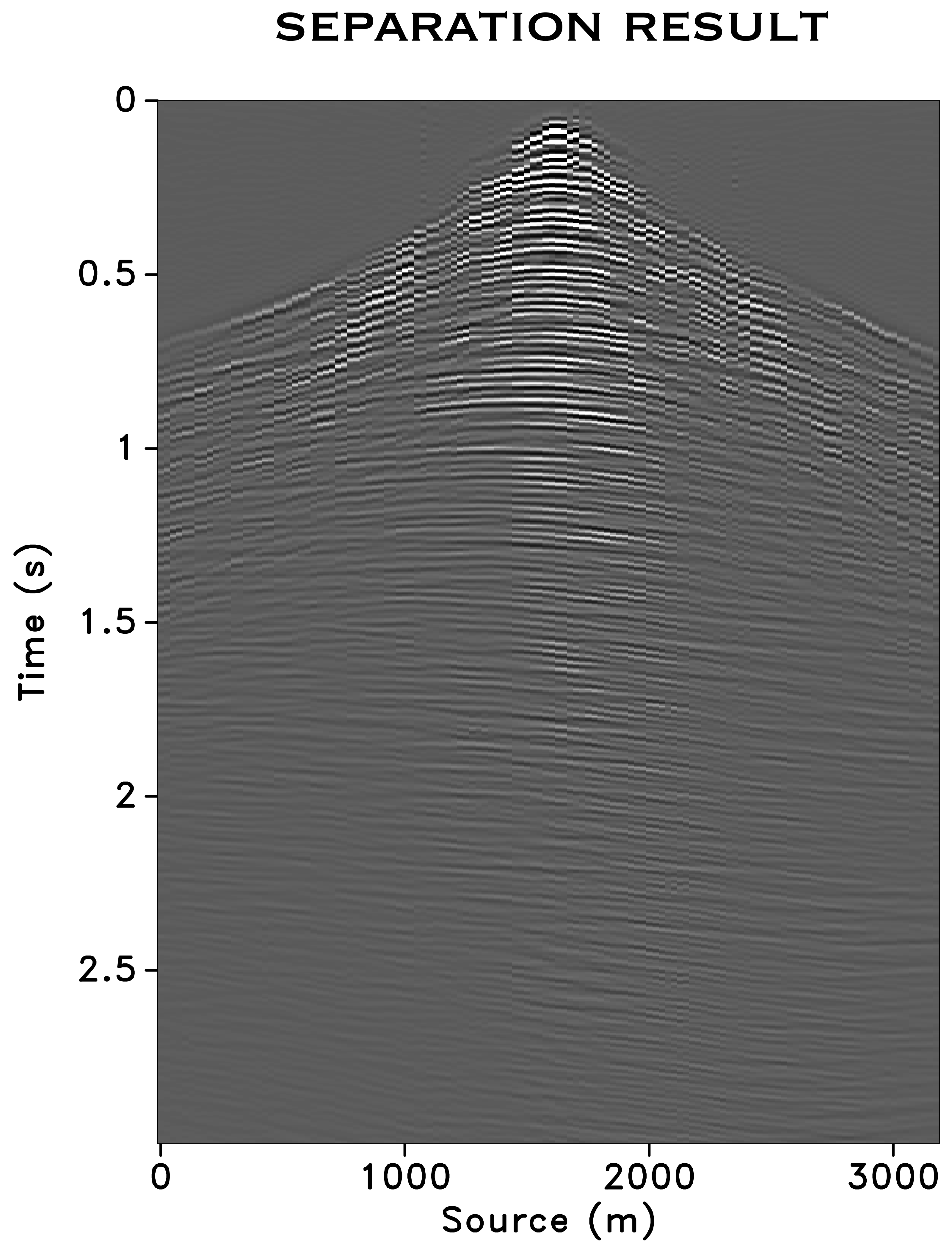


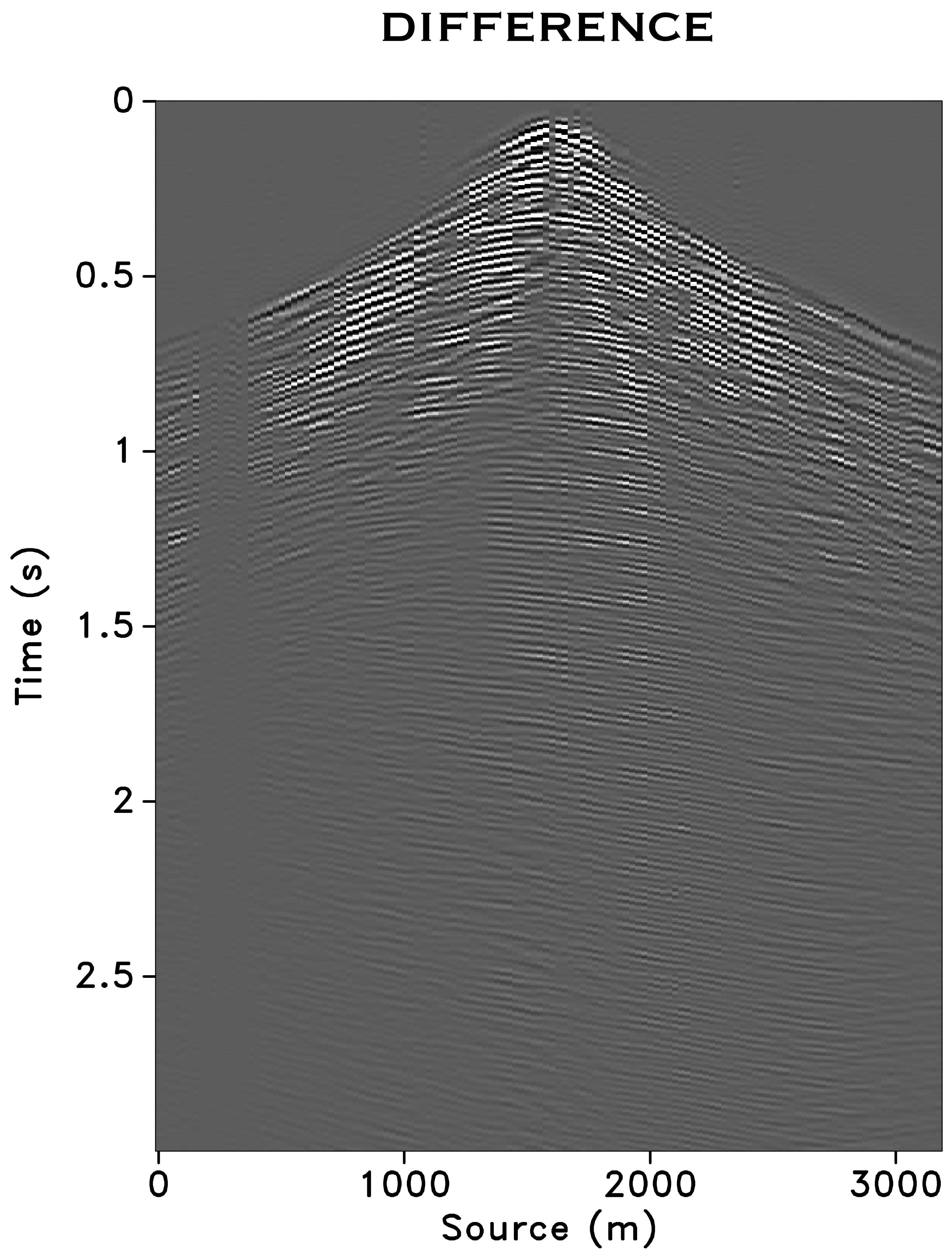
NFFT-generated data



Recovery with *FDCT* ('*binning*')

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





Recovery with *FDCT* (*'binning'*)

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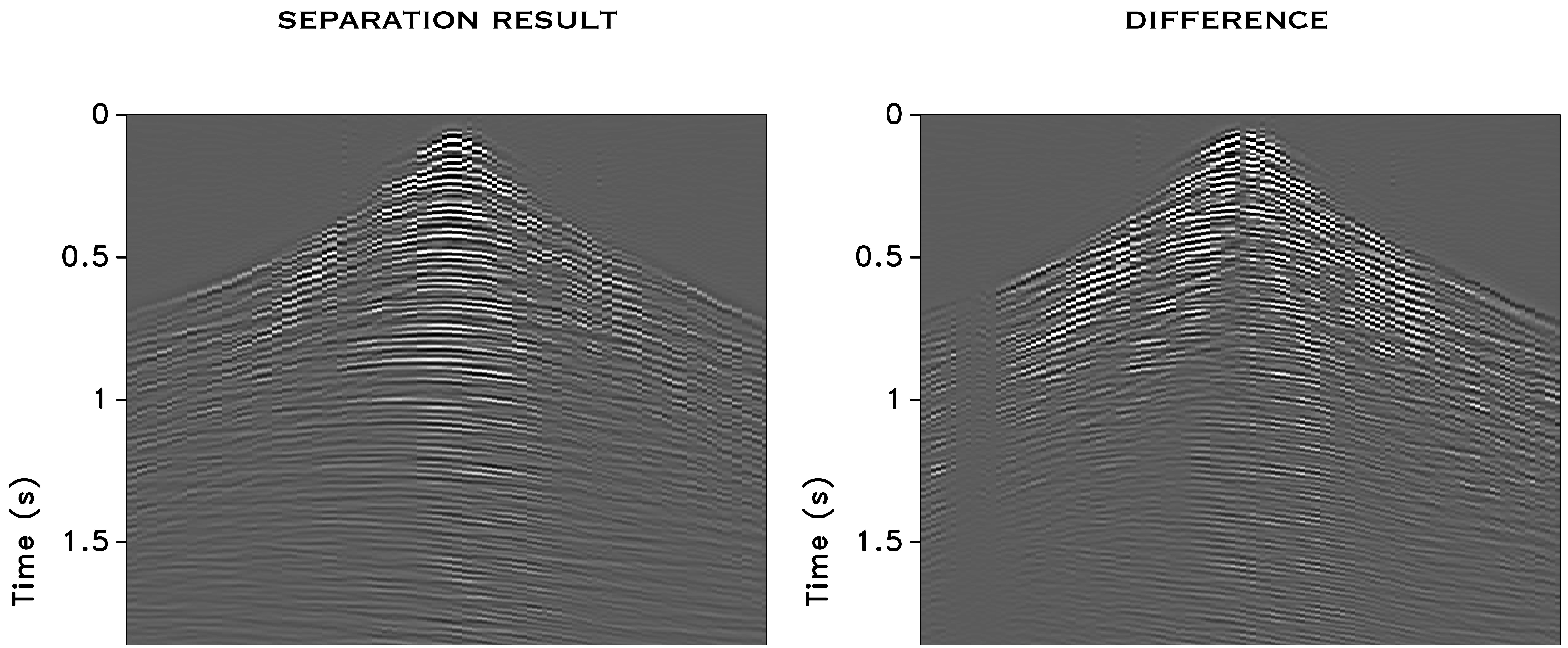
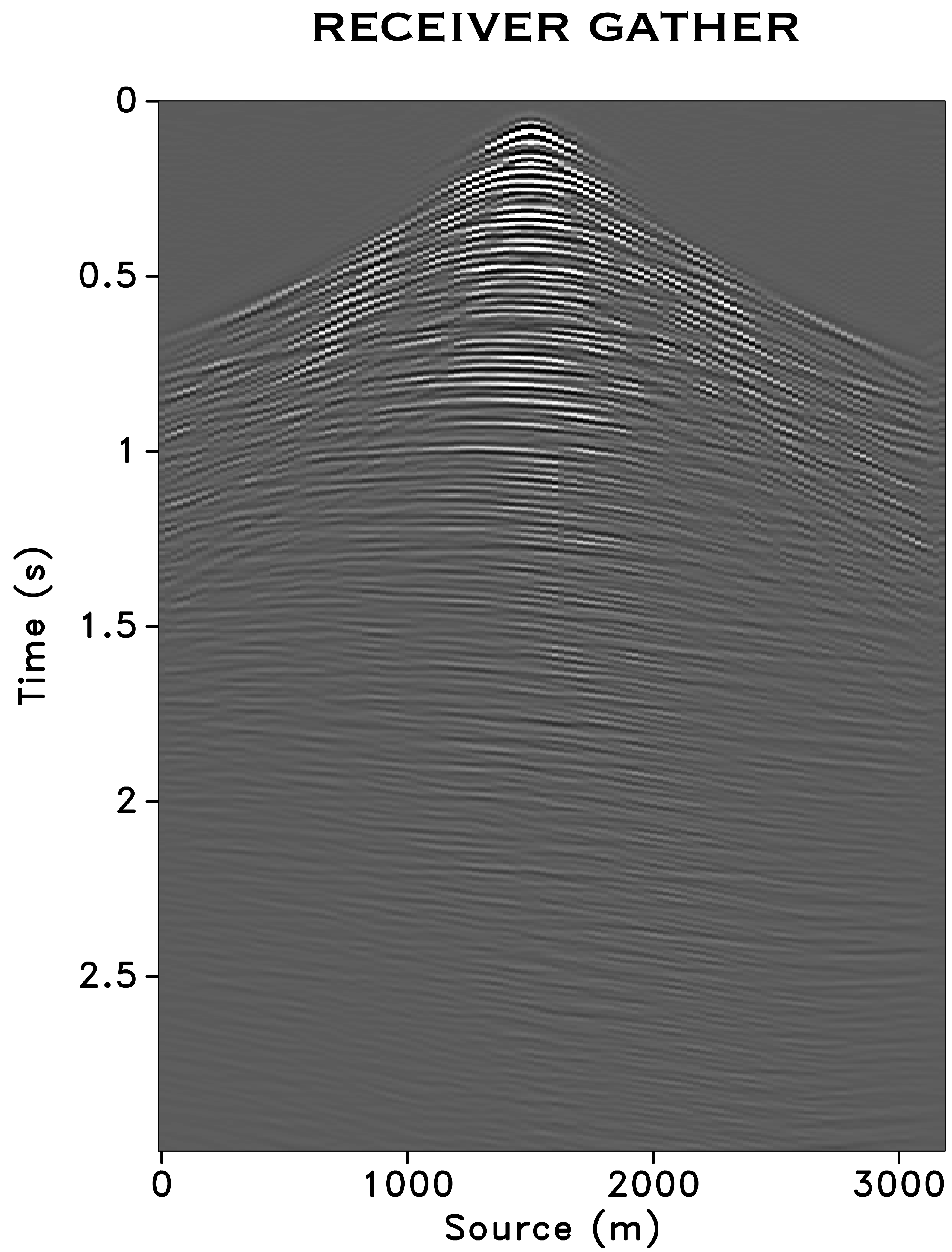
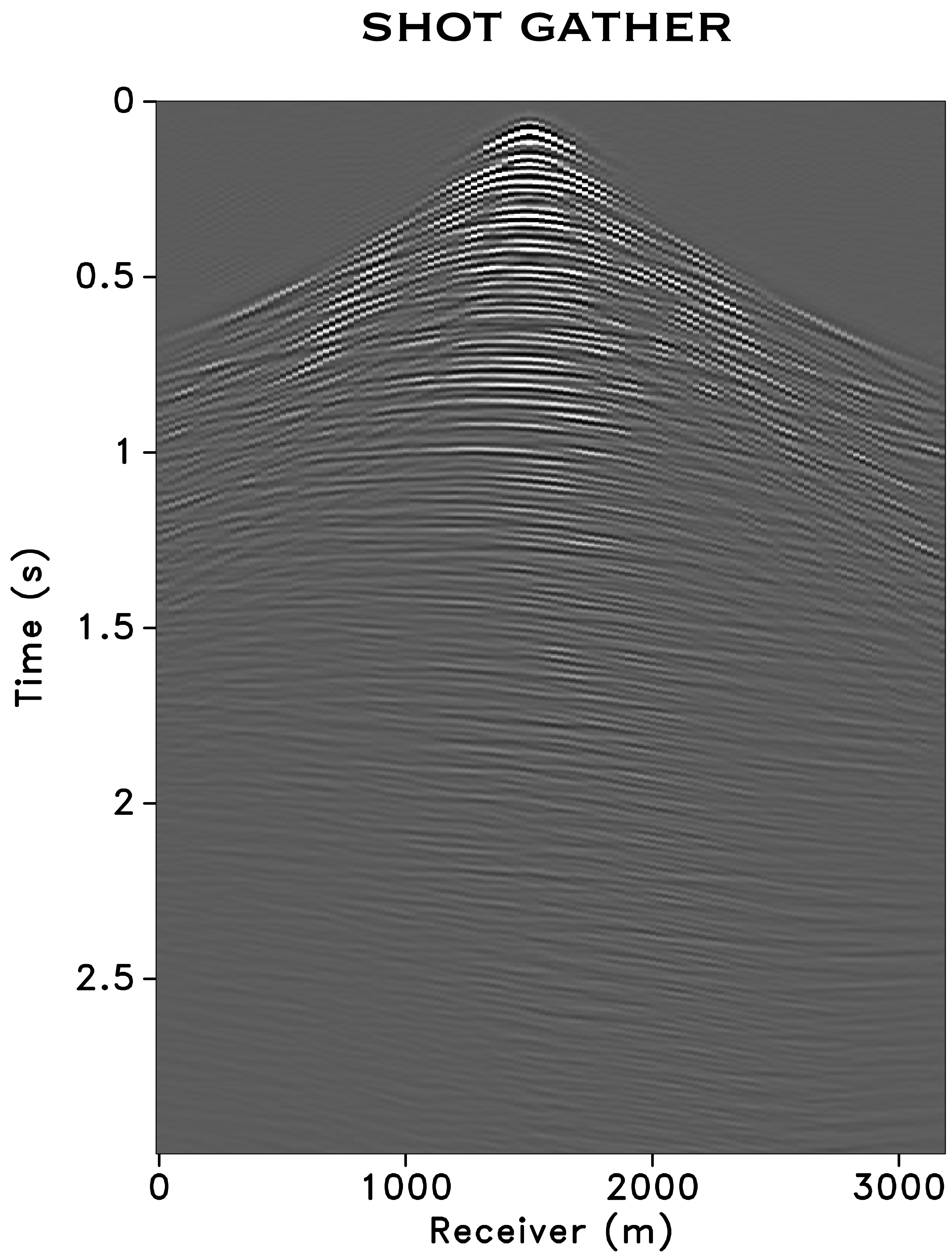


Sparsity-promoting recovery on *irregular* grid with *NFDCT* (17.6 dB)

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





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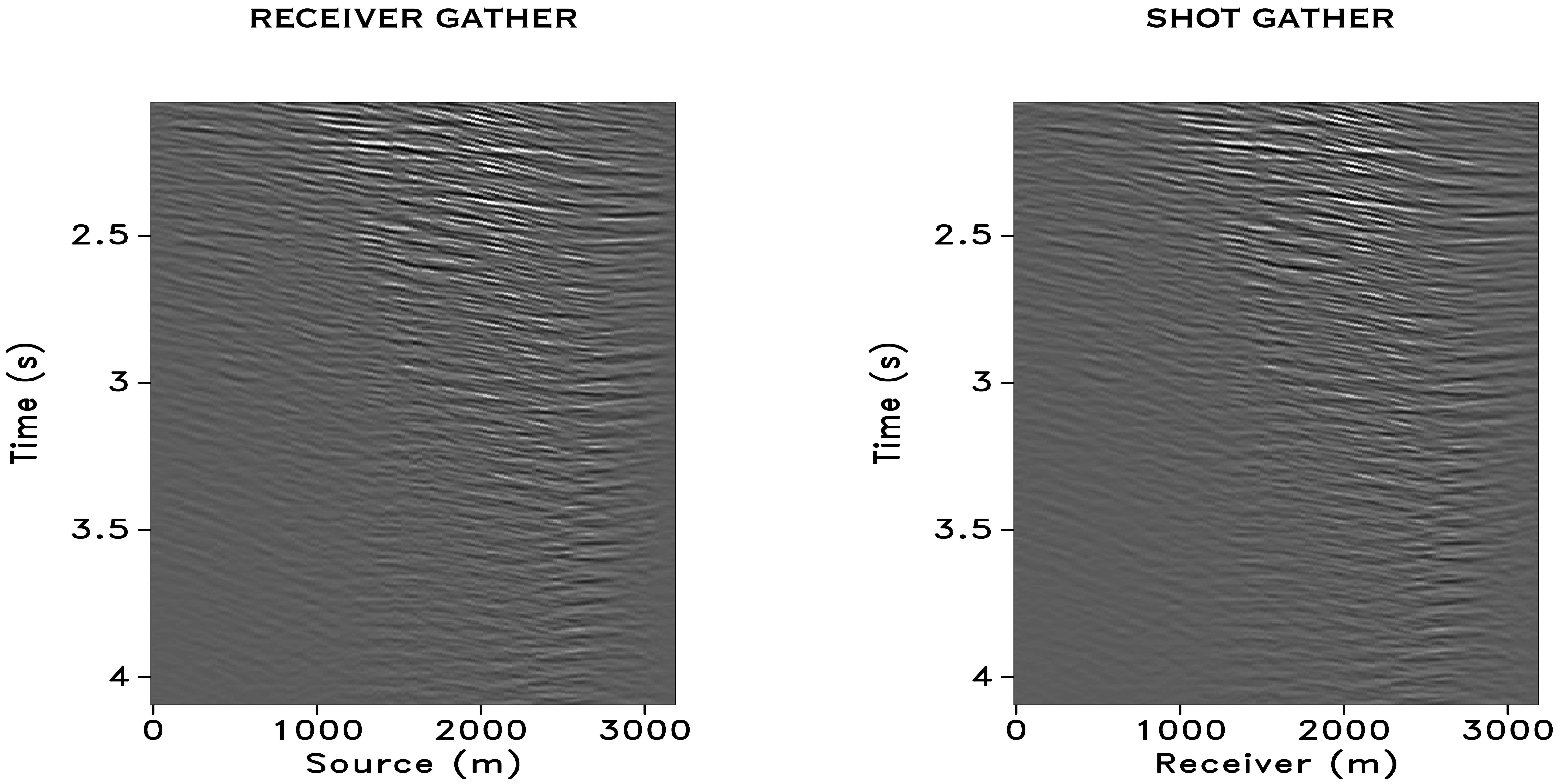

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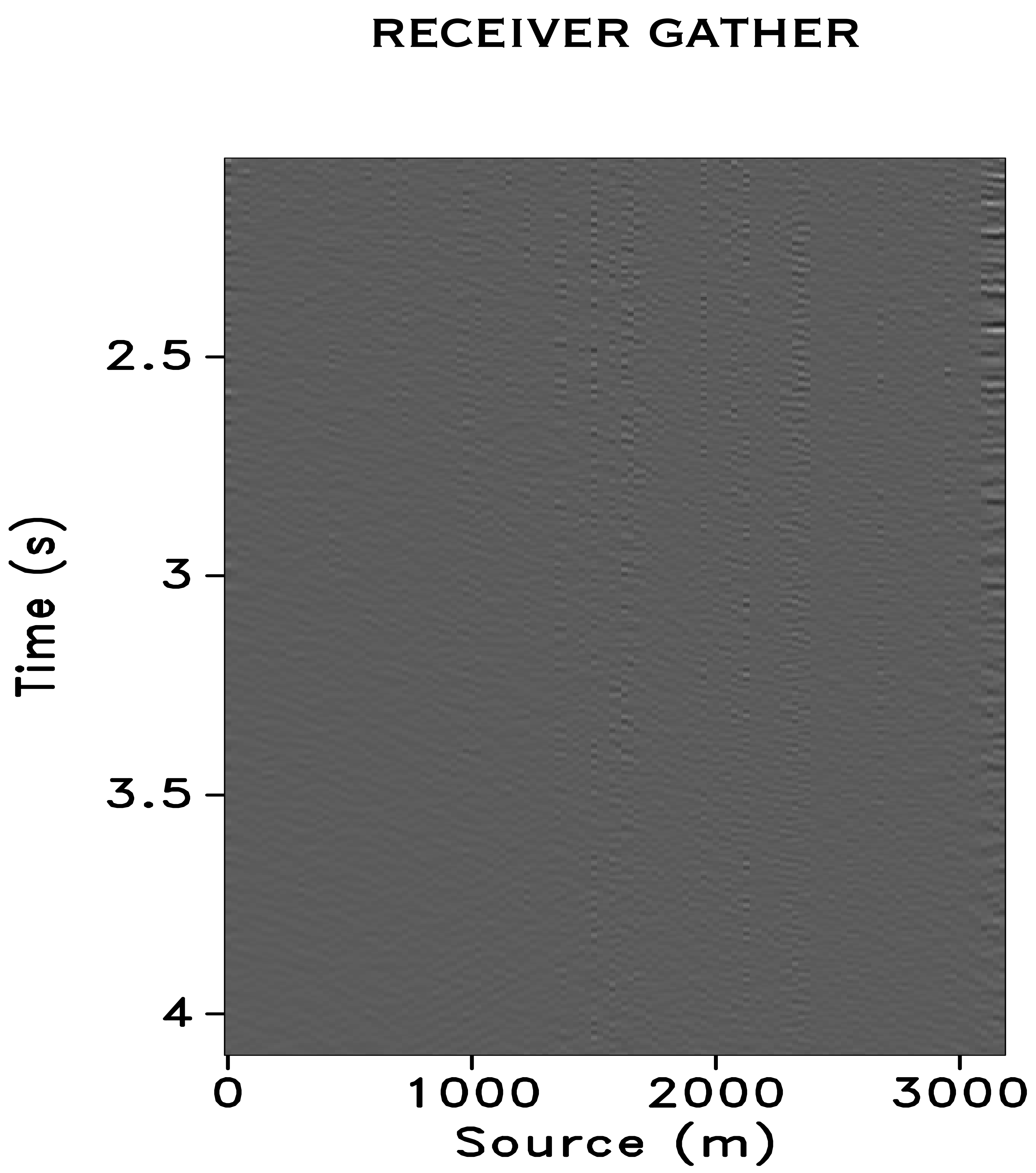
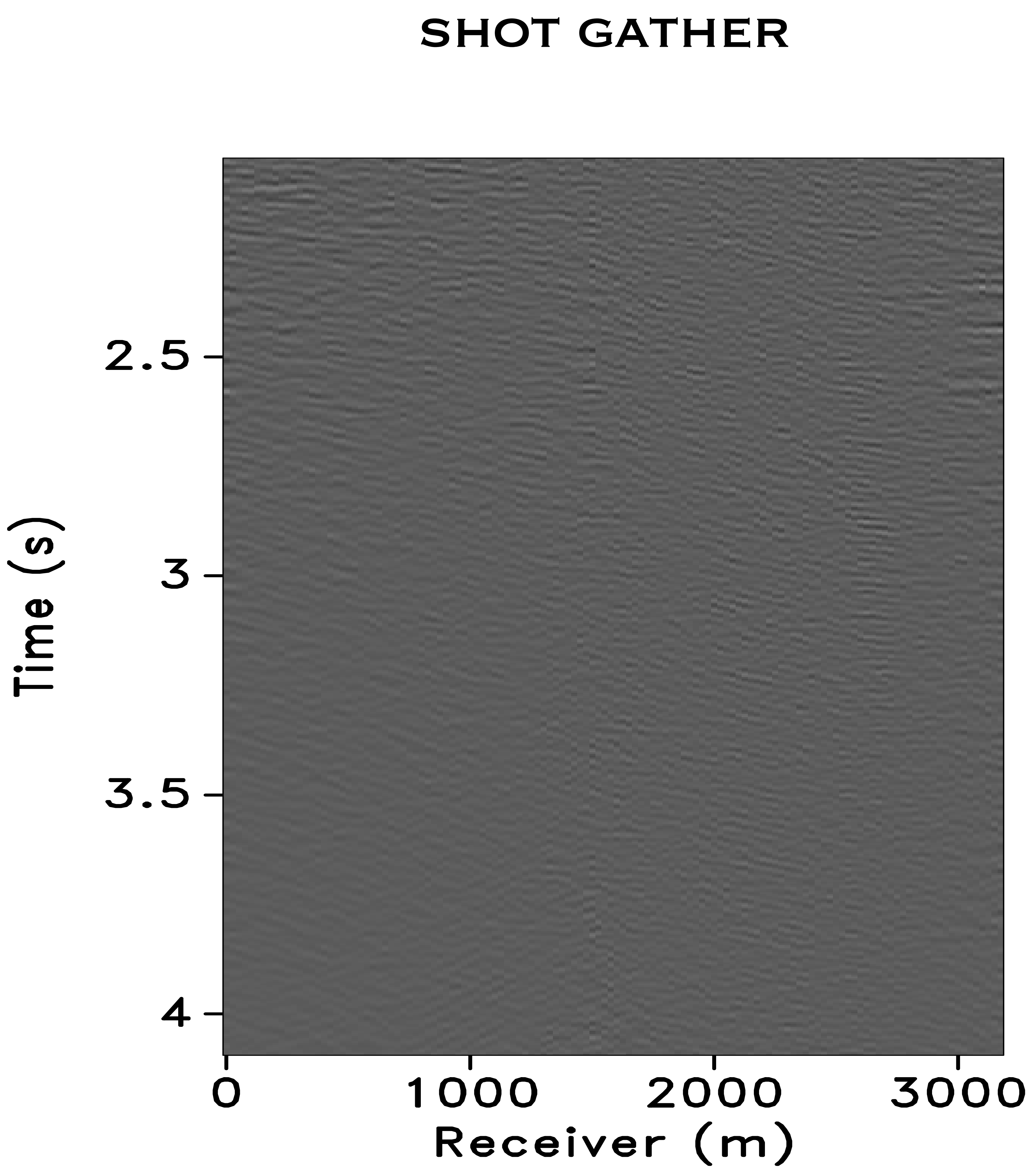




Performance

Improvement spatial sampling ratio

$$= \frac{\text{no. of spatial grid points recovered from jittered sampling via sparse recovery}}{\text{no. of spatial grid points in conventional sampling}}$$

$$= \frac{128}{64} = 2$$

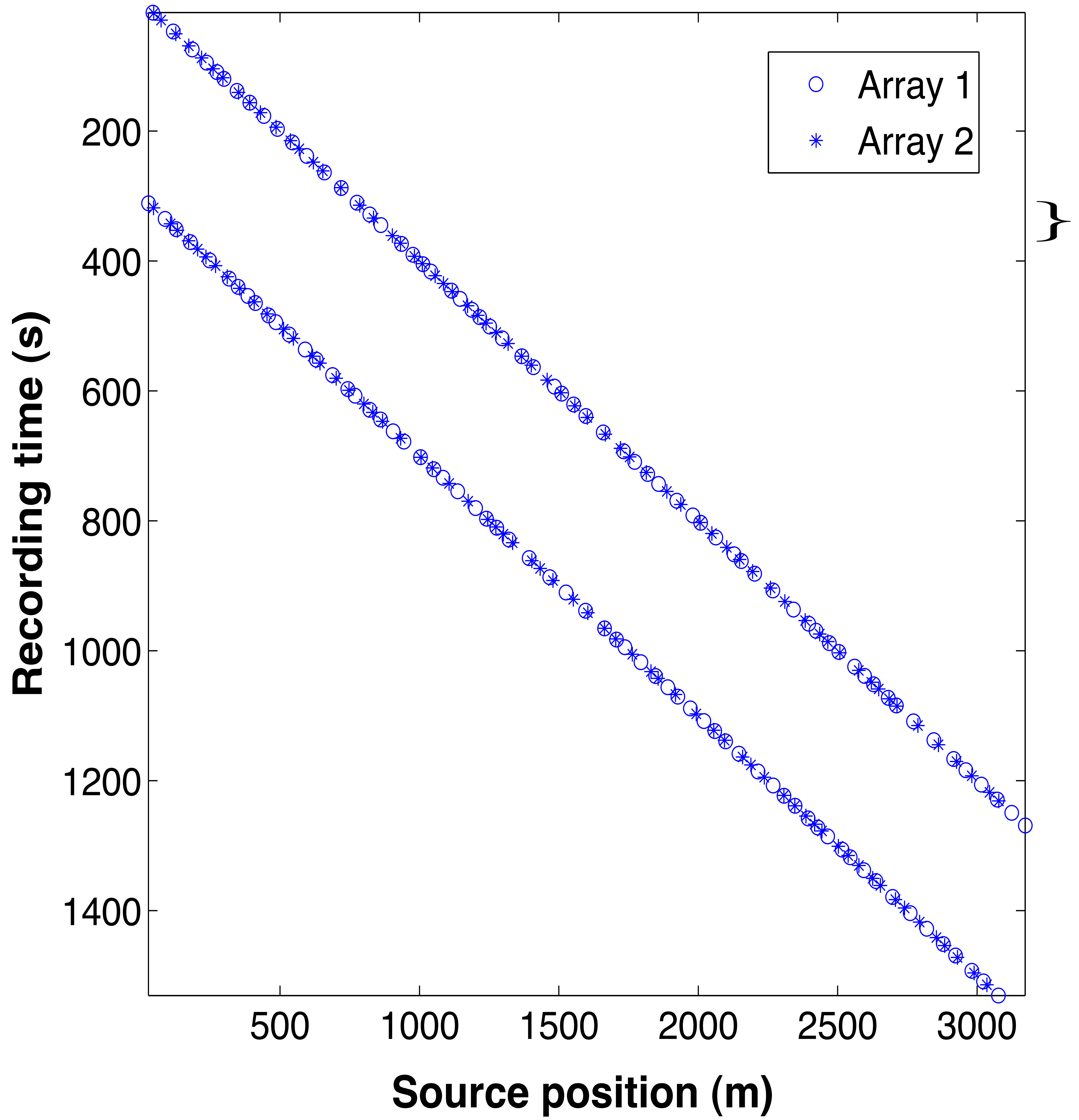
Multiple source vessels

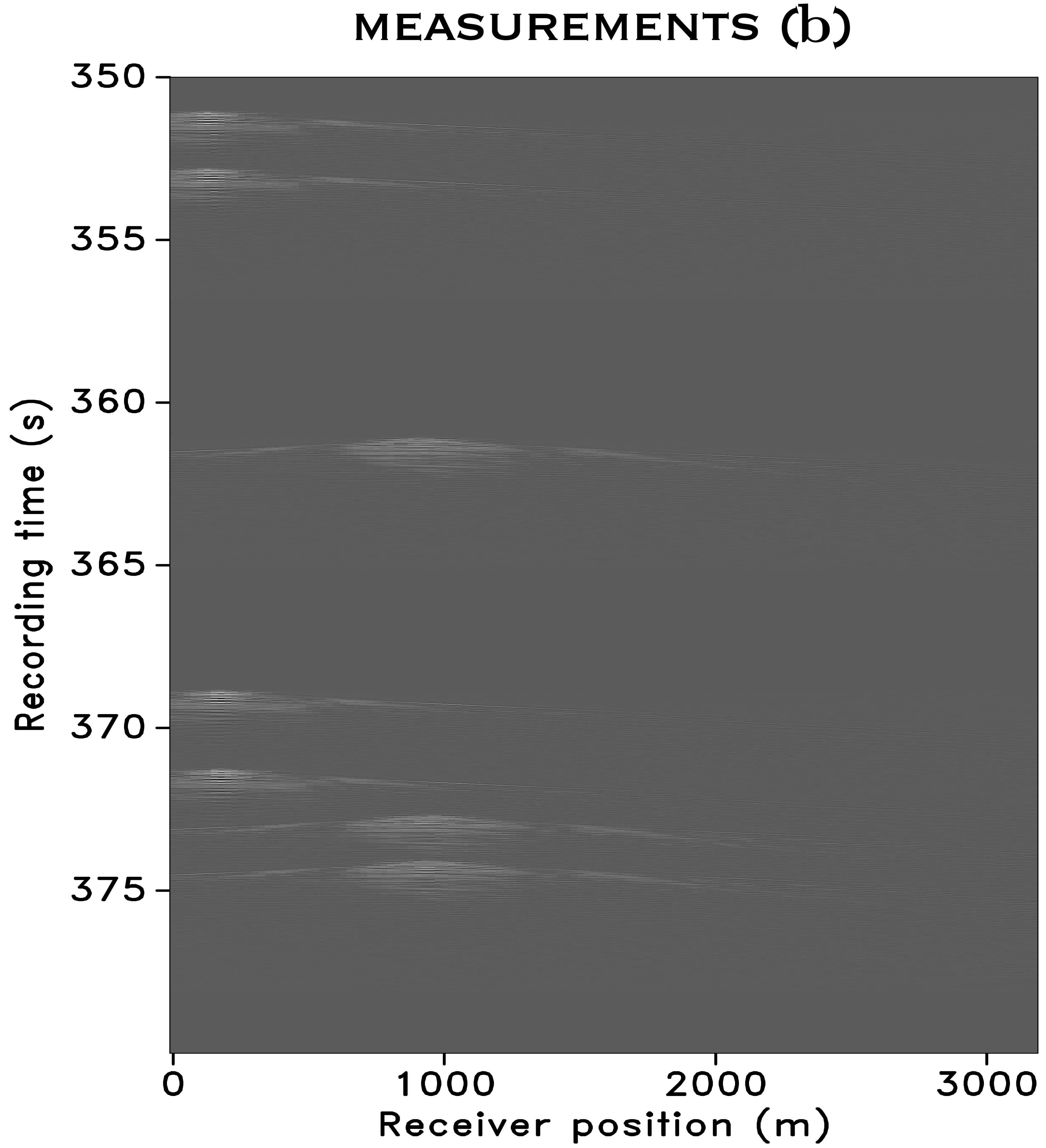
- *improves* recovery – *shorter* times lead to better *spatial* sampling at the expense of *more* overlap
- better *azimuthal* coverage

Time-jittered OBC acquisition

[2 source vessels, speed = 5 knots, underlying grid: 25 m]

[no. of *jittered* source locations is *half* the number of sources in *ideal* periodic survey w/o overlap]

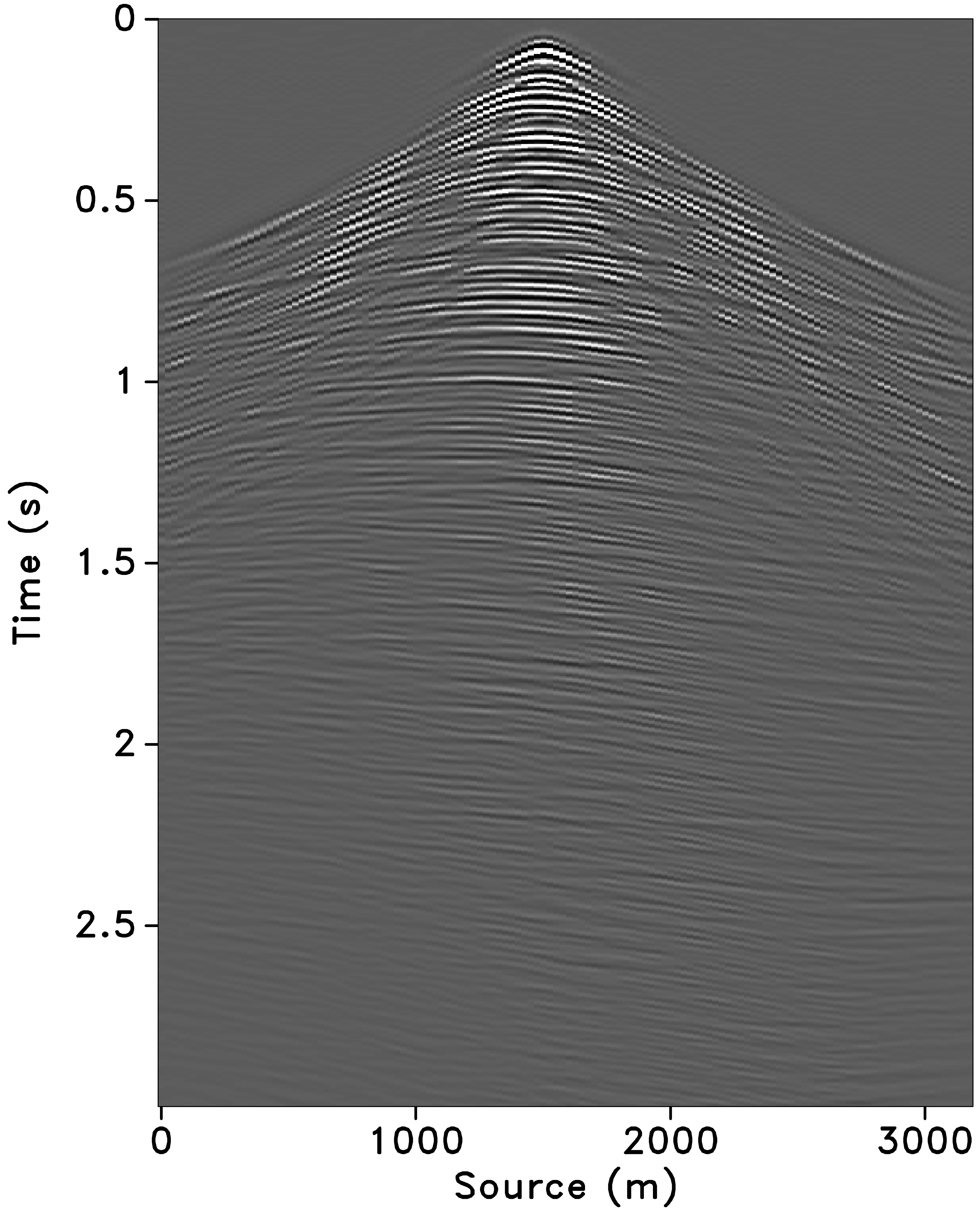




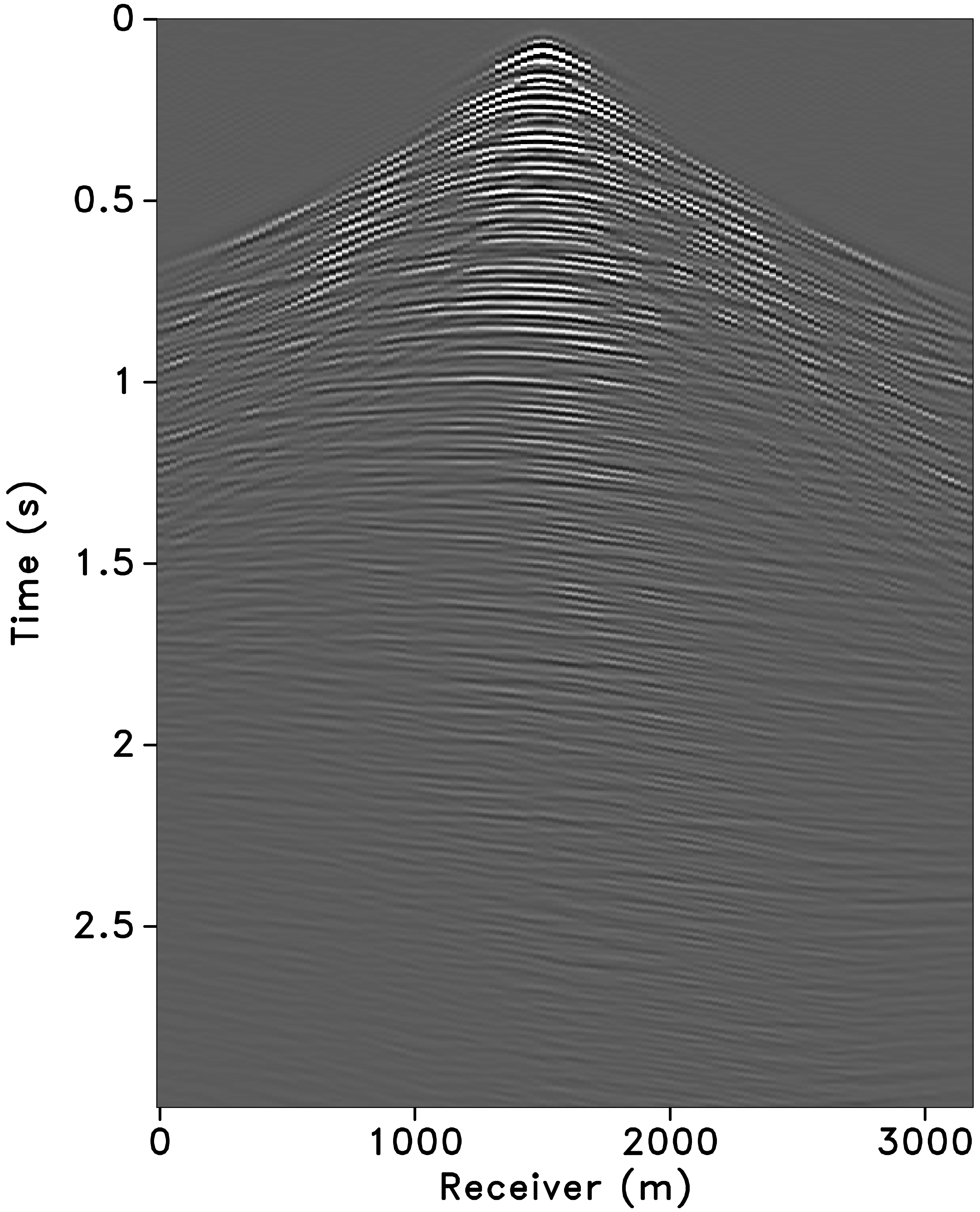
Sparsity-promoting recovery on *irregular* grid with *NFDCT* (21.5 dB)

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

RECEIVER GATHER



SHOT GATHER



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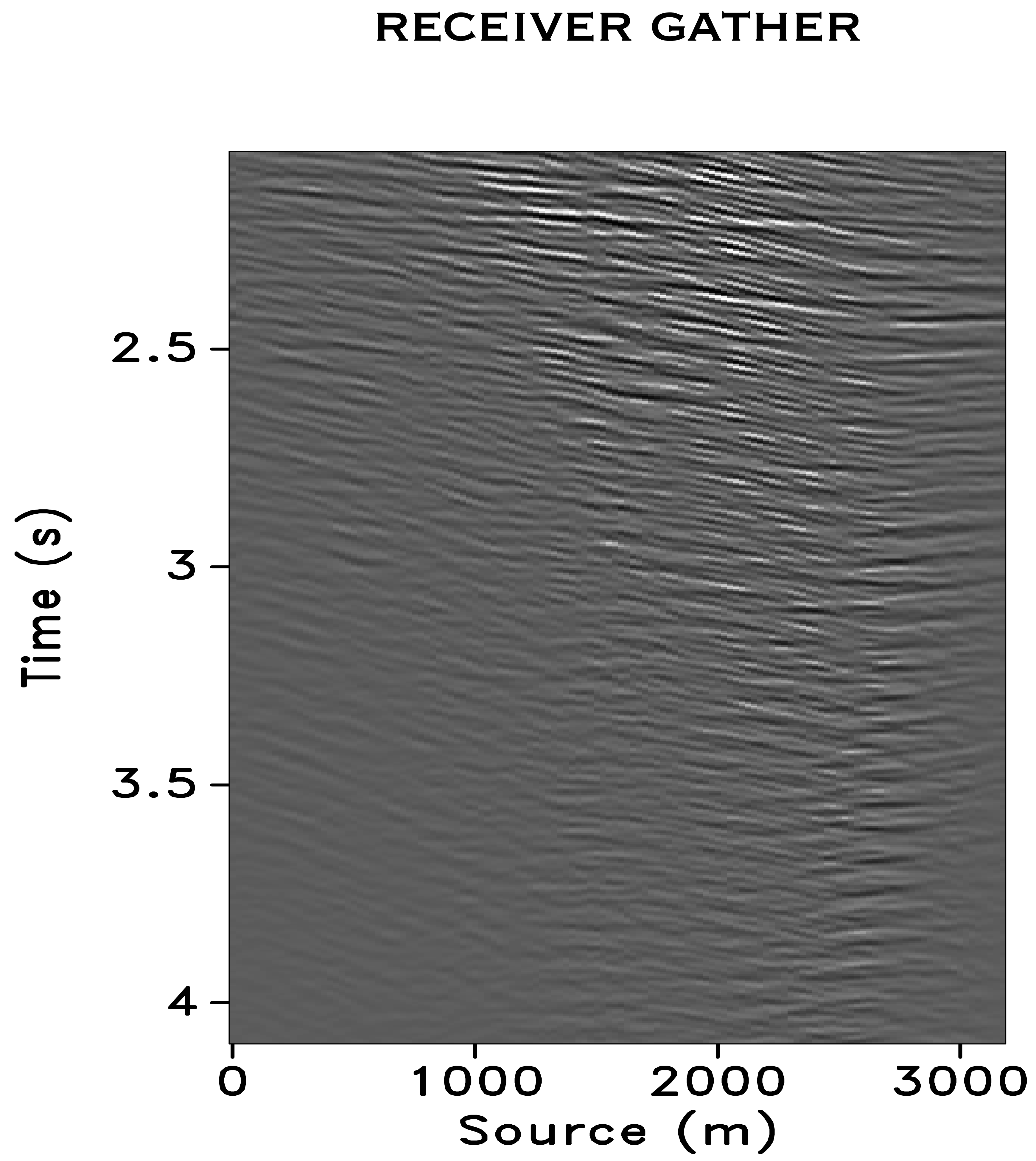

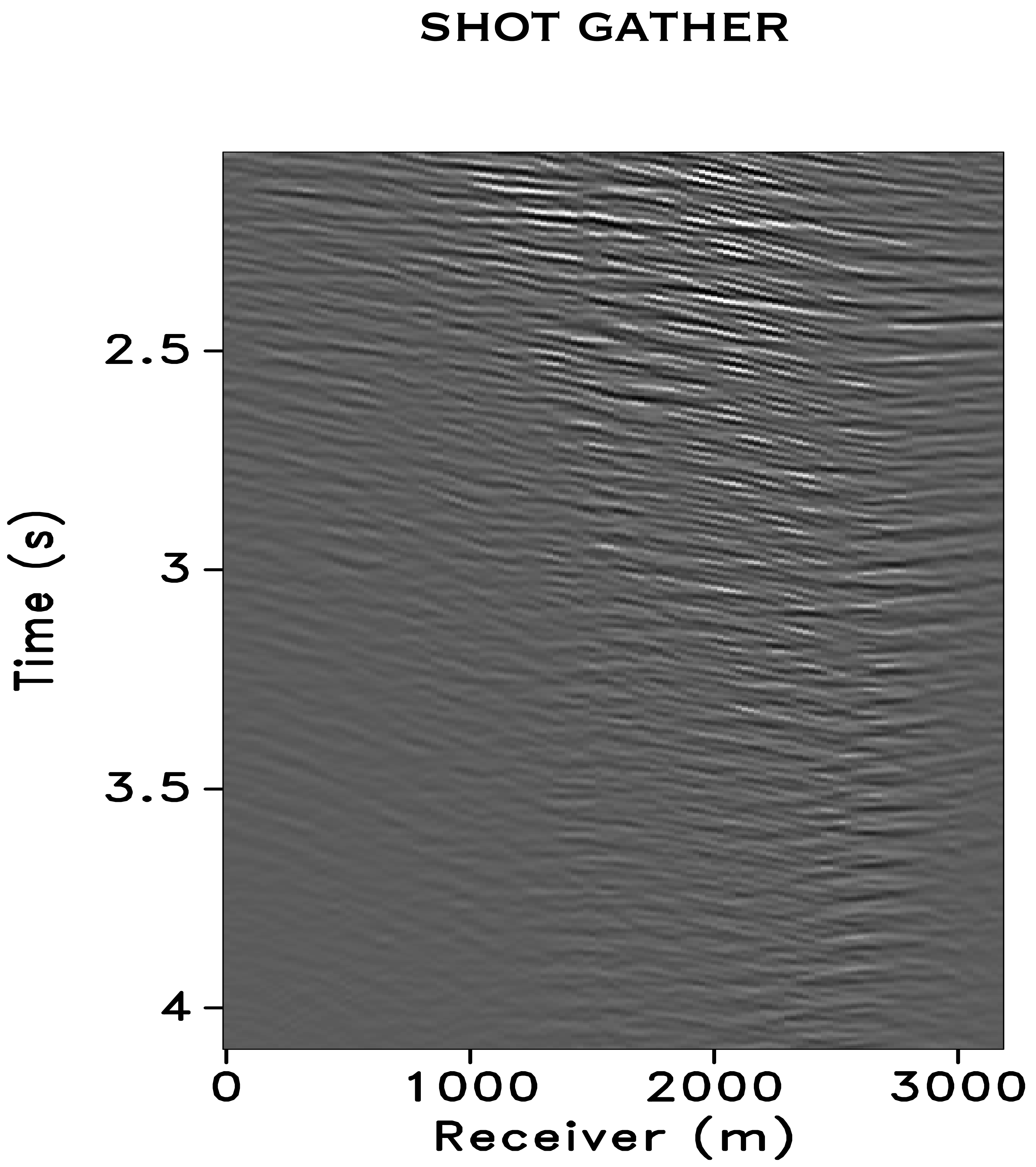

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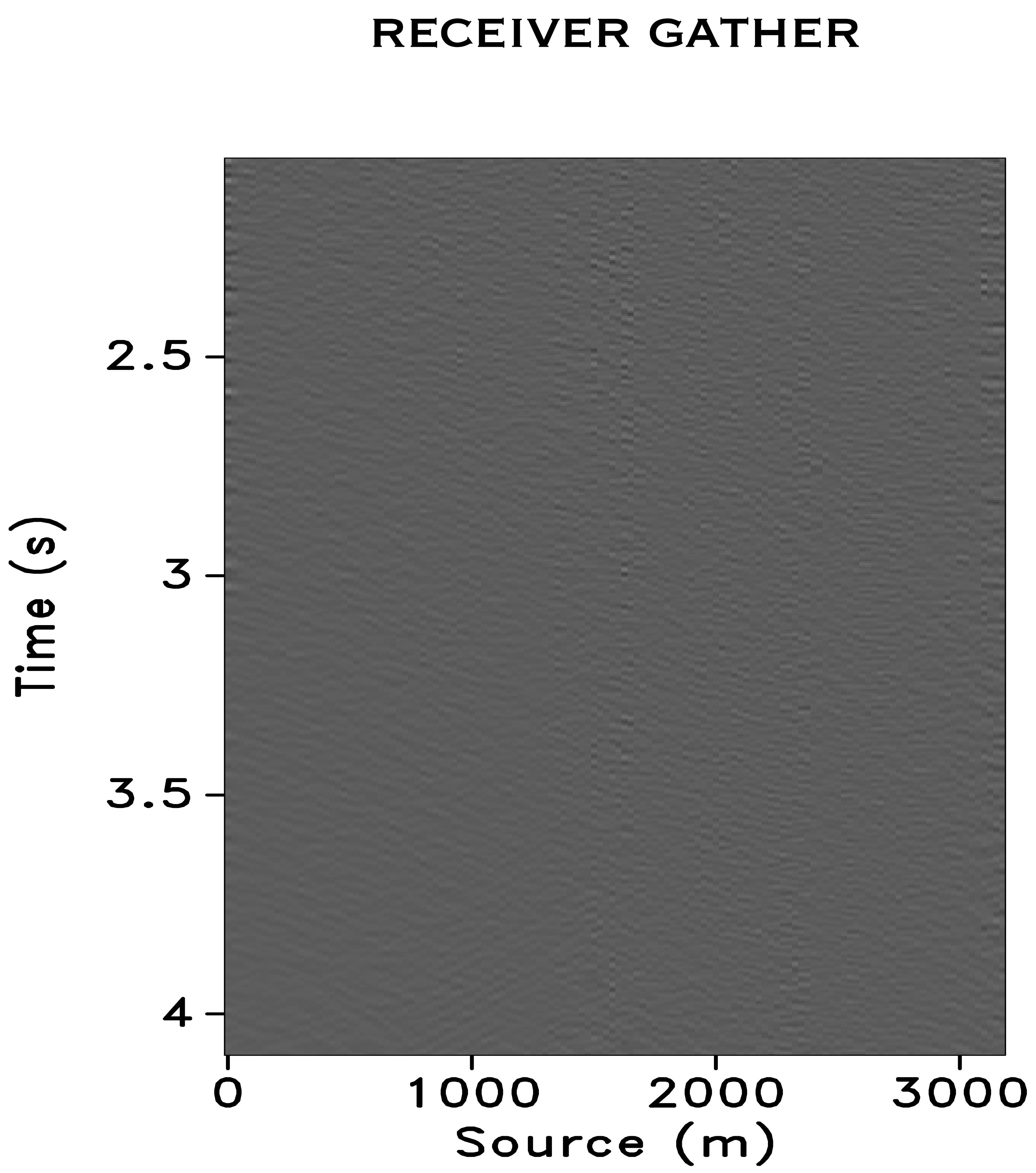
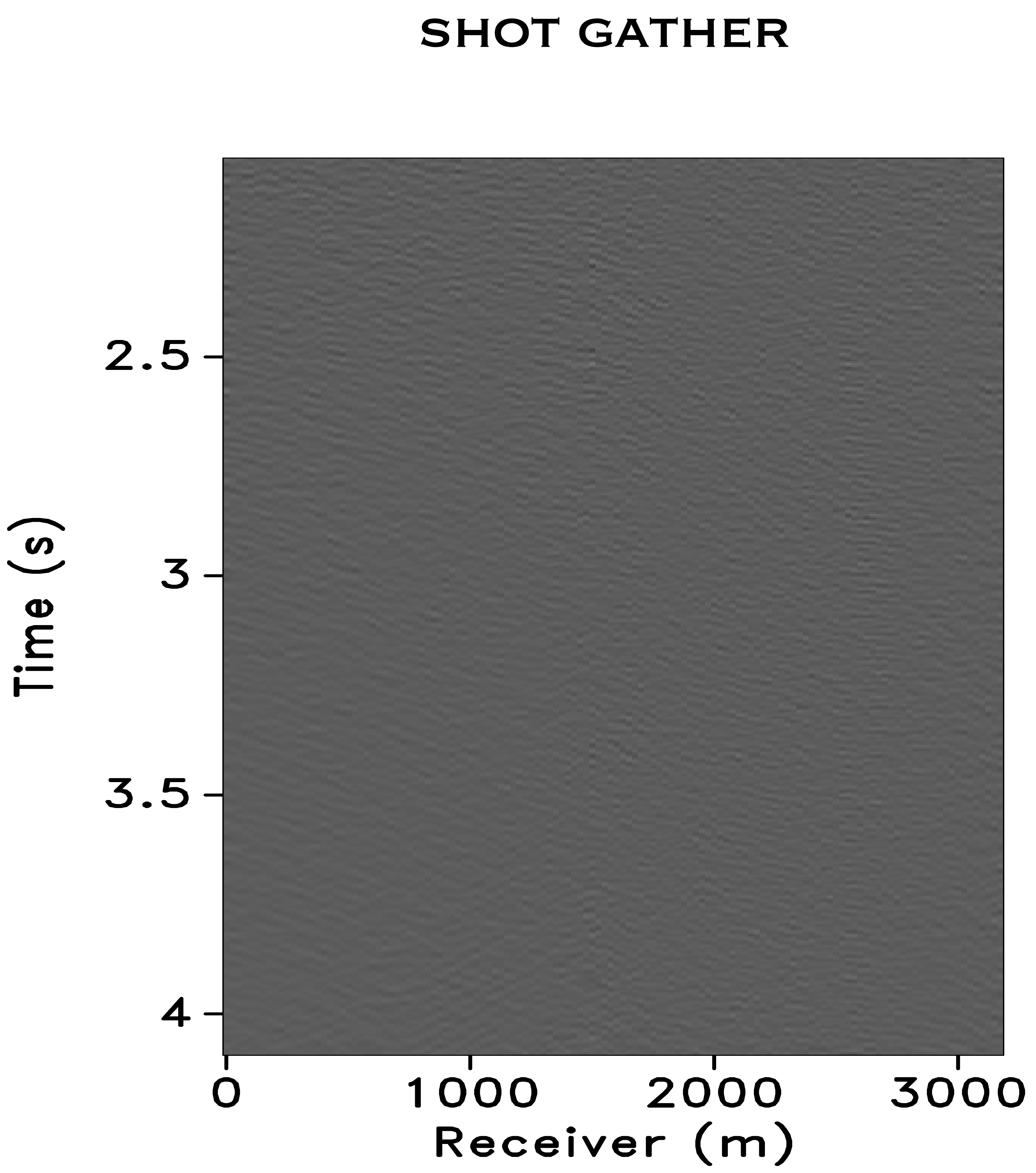
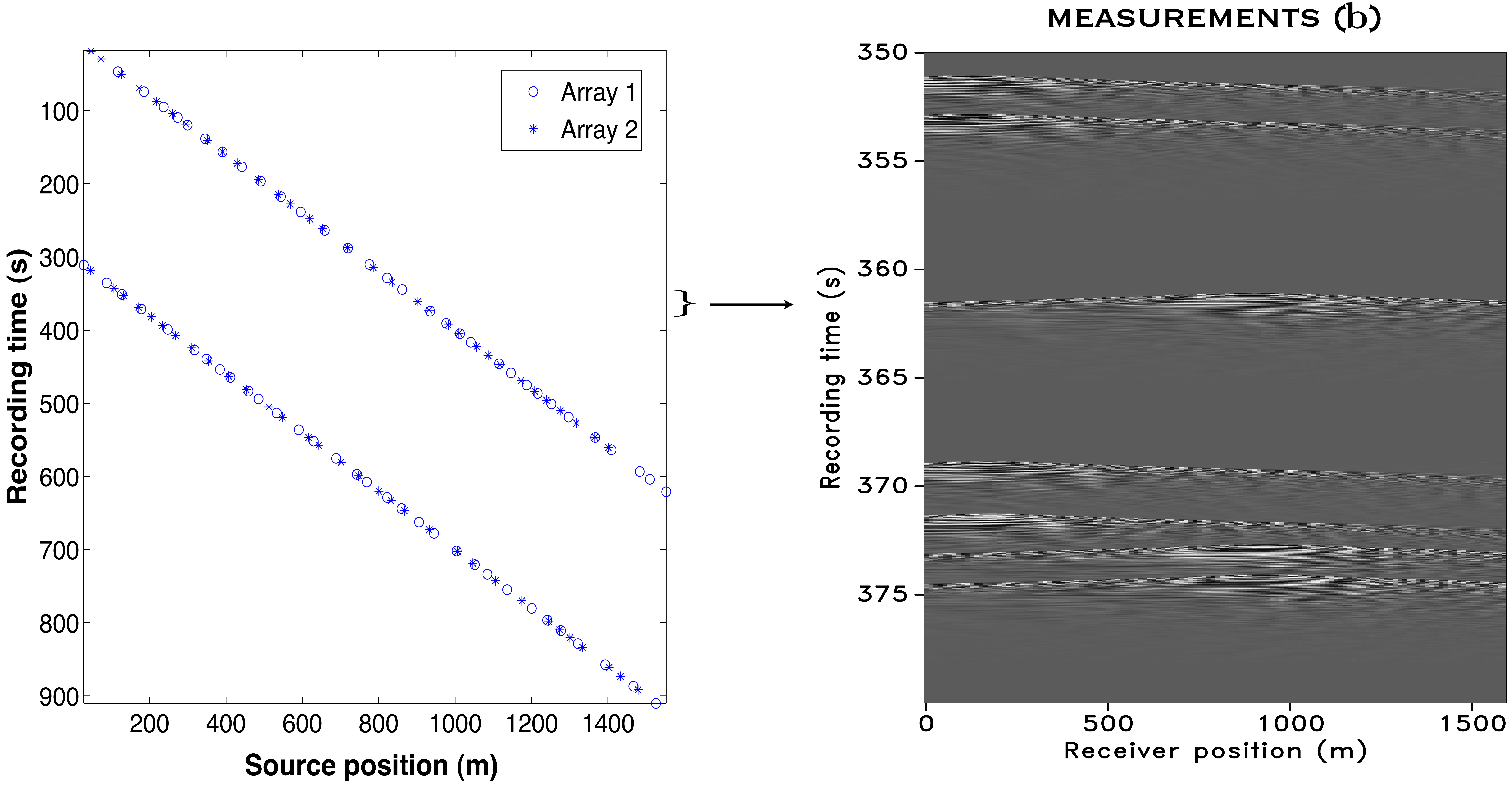




Time-jittered OBC acquisition

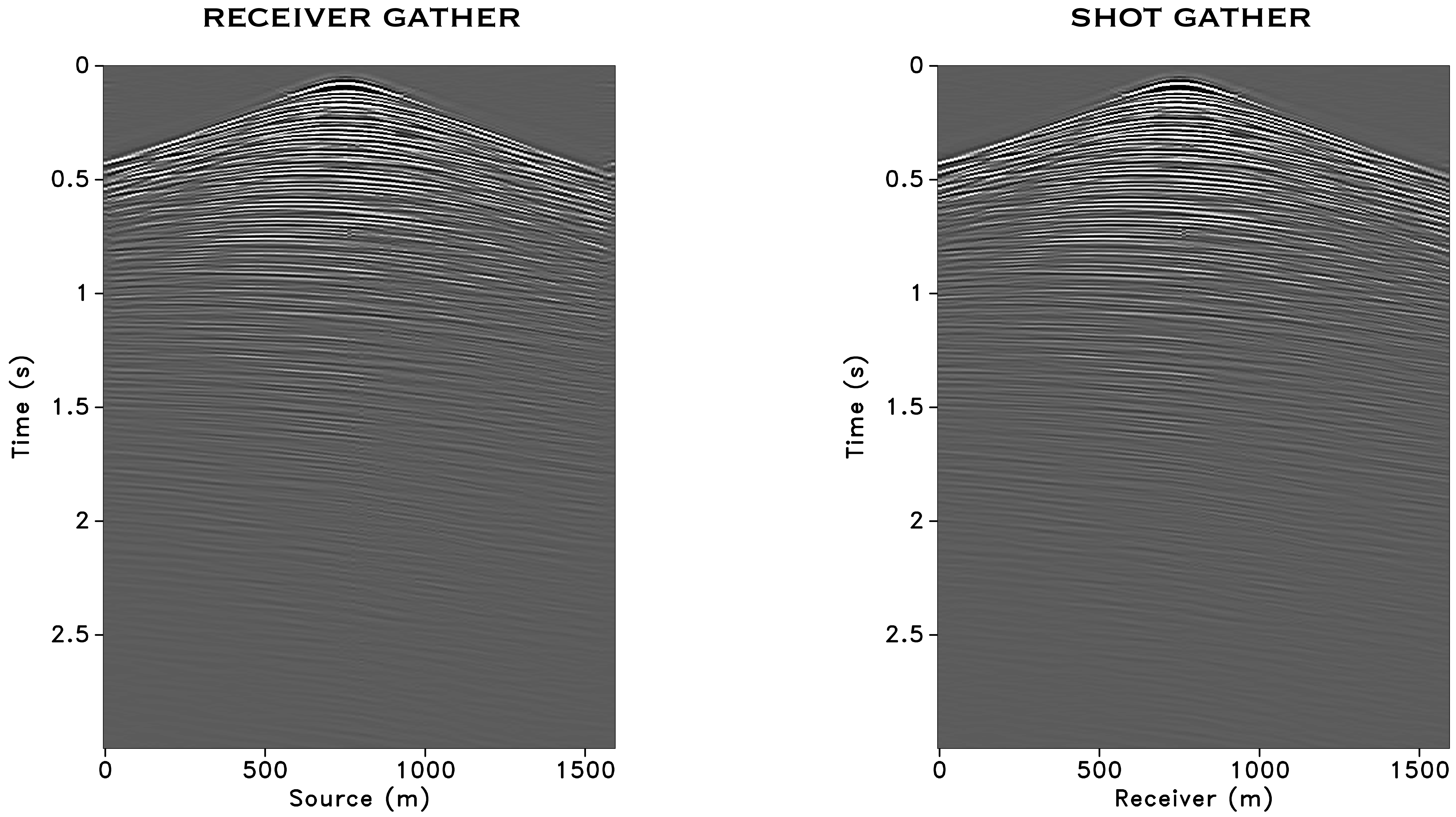
[2 source vessels, speed = 5 knots, underlying grid: 12.5 m]

[no. of *jittered* source locations is *one-fourth* the number of sources in *ideal* periodic survey w/o overlap]



Sparsity-promoting recovery on *irregular* grid with *NFDCT* (16.8 dB)

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



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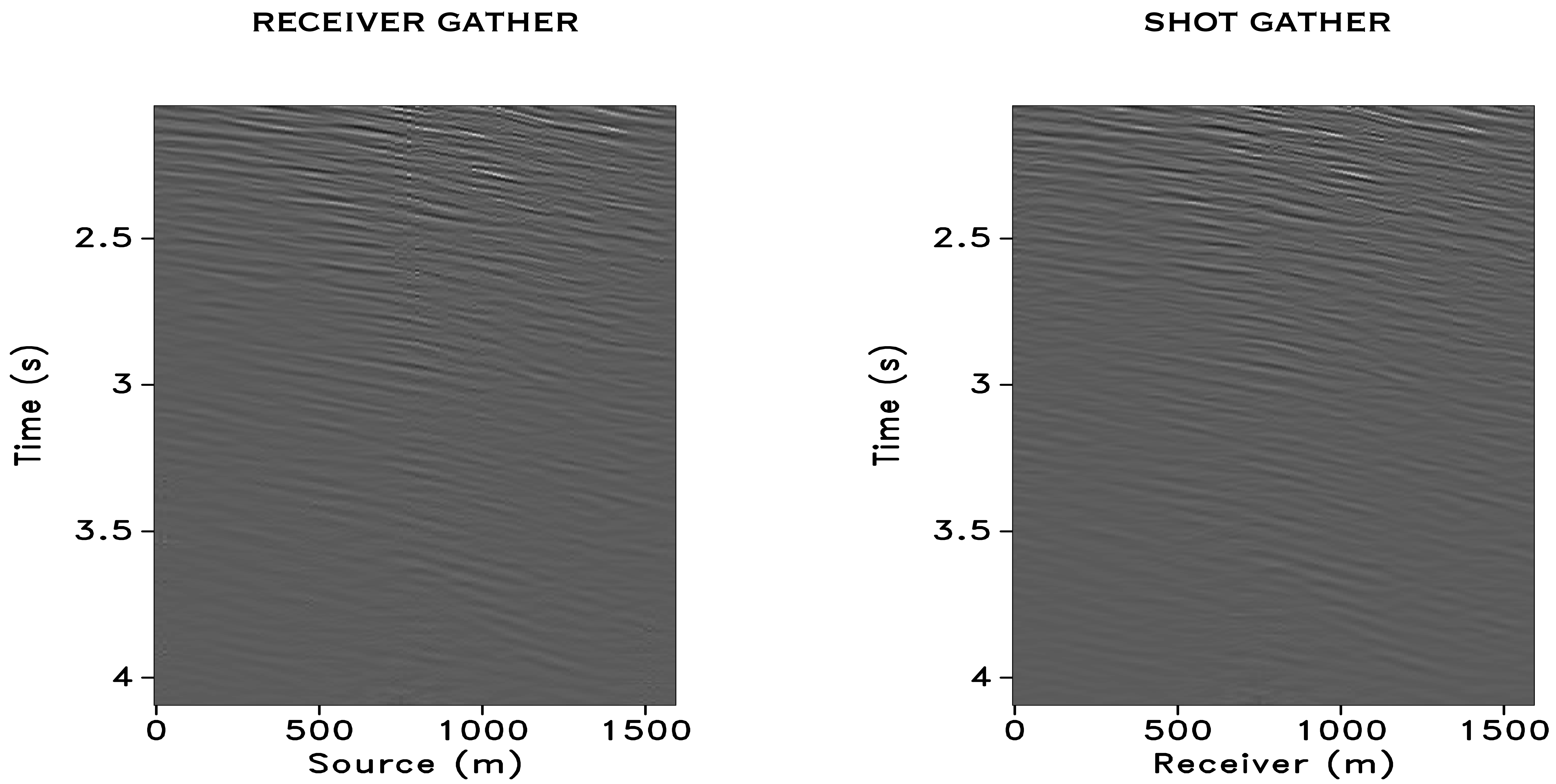

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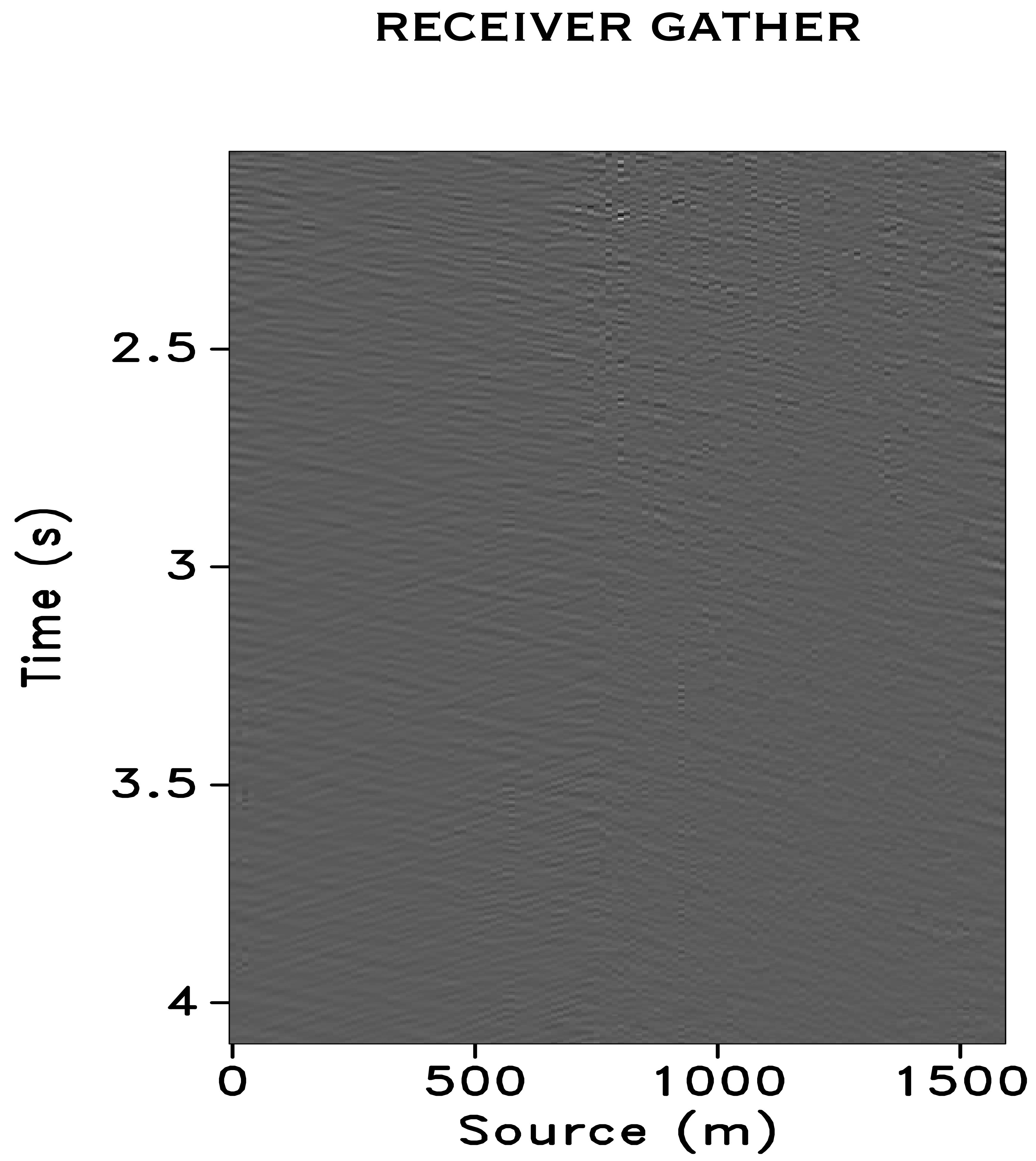

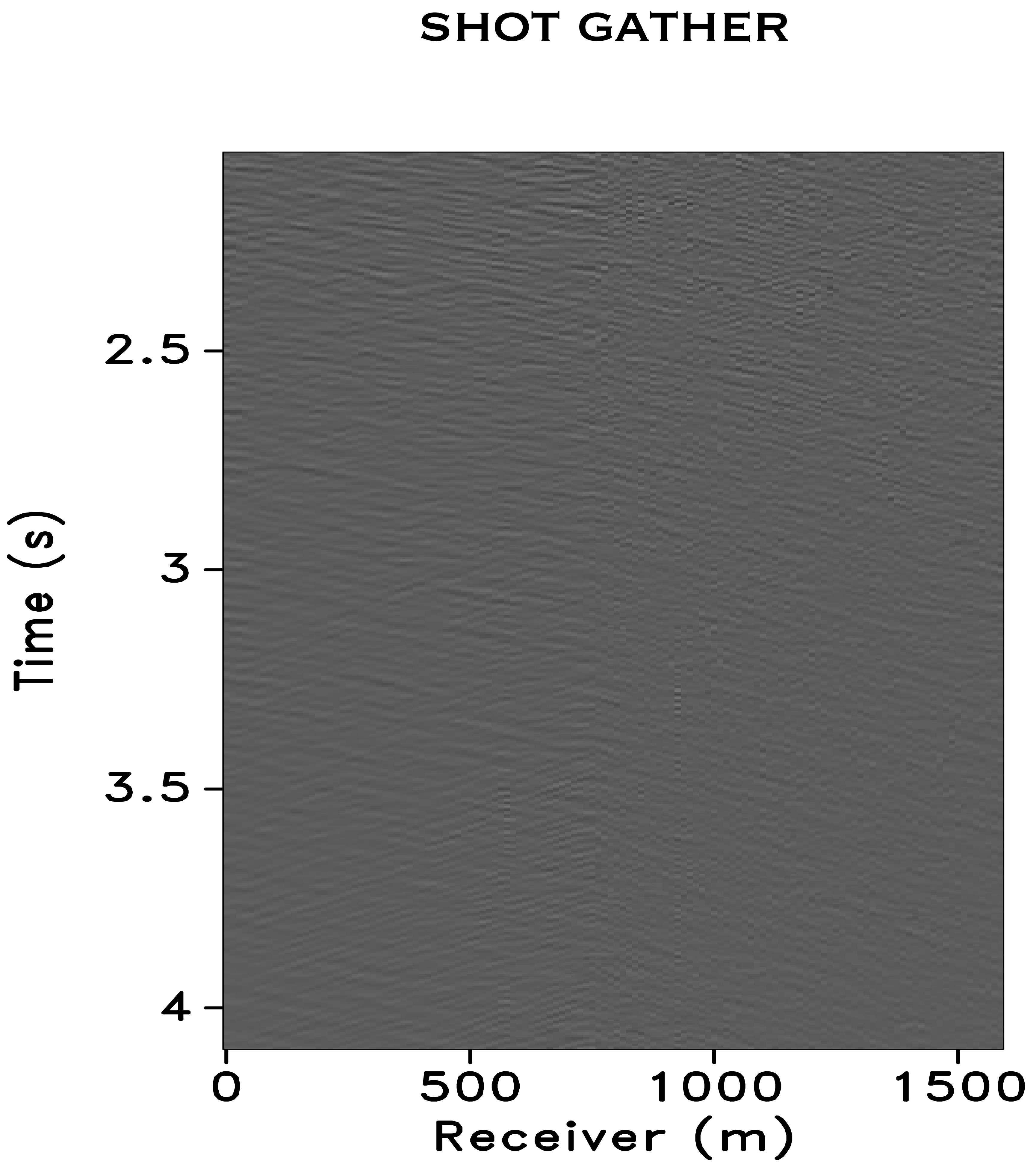

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$$= \frac{128}{32} = 4$$

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Summary

	deblend + interpolate (jittered (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

Observations

- *Time-jittered* marine acquisition is an instance of *compressed sensing*
- With *sparsity*-promoting recovery we can:
  - *deblend* – recover the wavefield, and
  - *regularize* from a *jittered/irregular* to a *regular* grid
  - *interpolate* from a *coarse jittered* (50m) grid to a *fine regular* grid (25m, 12.5m, and finer)

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Acknowledgements

Thank you!

SINBAD

NSERC CRSNG

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