Time *jittered* ocean bottom seismic acquisition

Haneet Wason, and Felix J. Herrmann*

SLIM
University of British Columbia

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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

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Motivation

- Is there a way to circumvent the Nyquist-related acquisition/processing costs?
- Design seismic acquisition within the *compressed sensing* framework
- 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 ...

Motivation

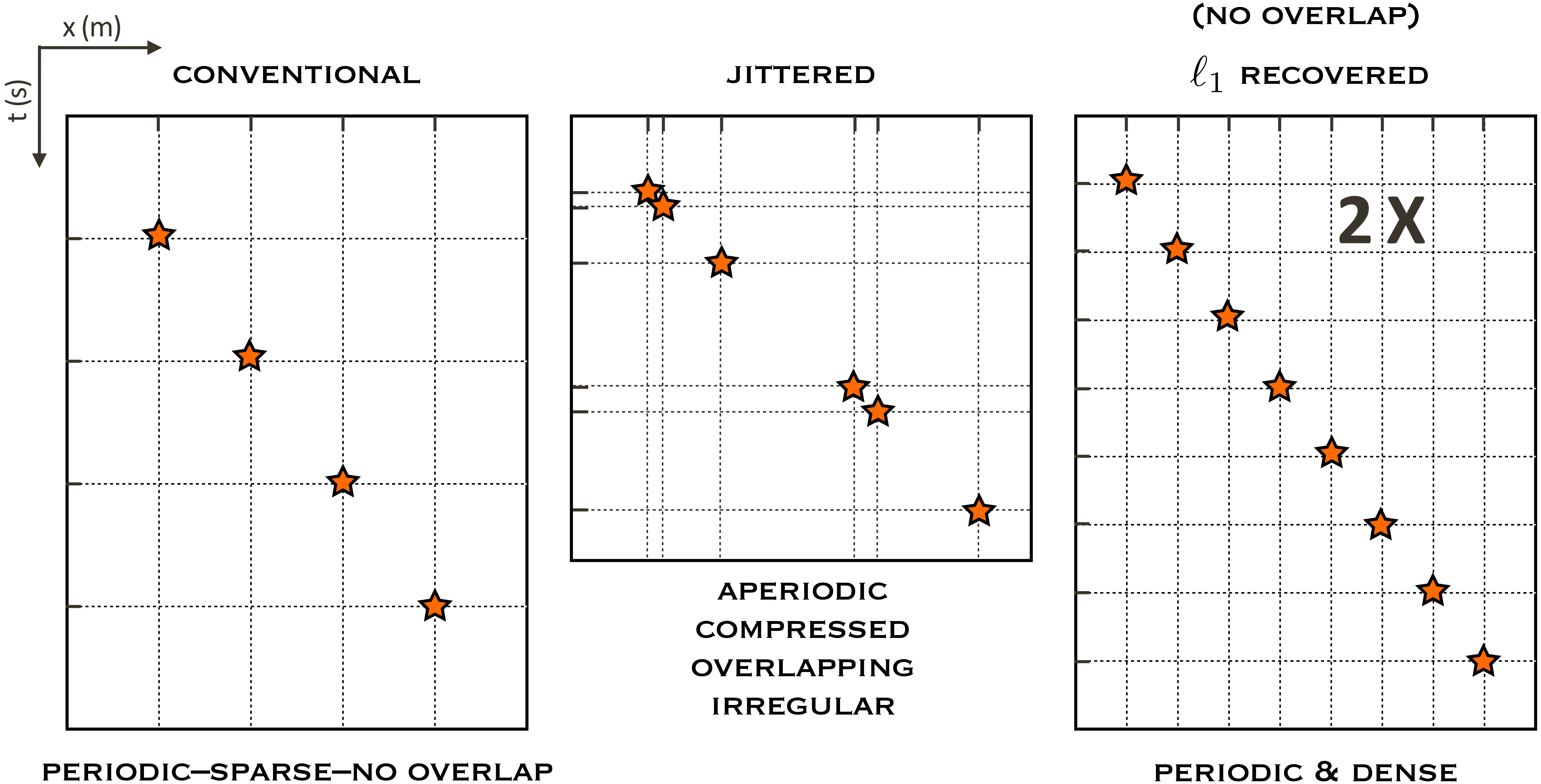
... want more for less

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

How is this possible?

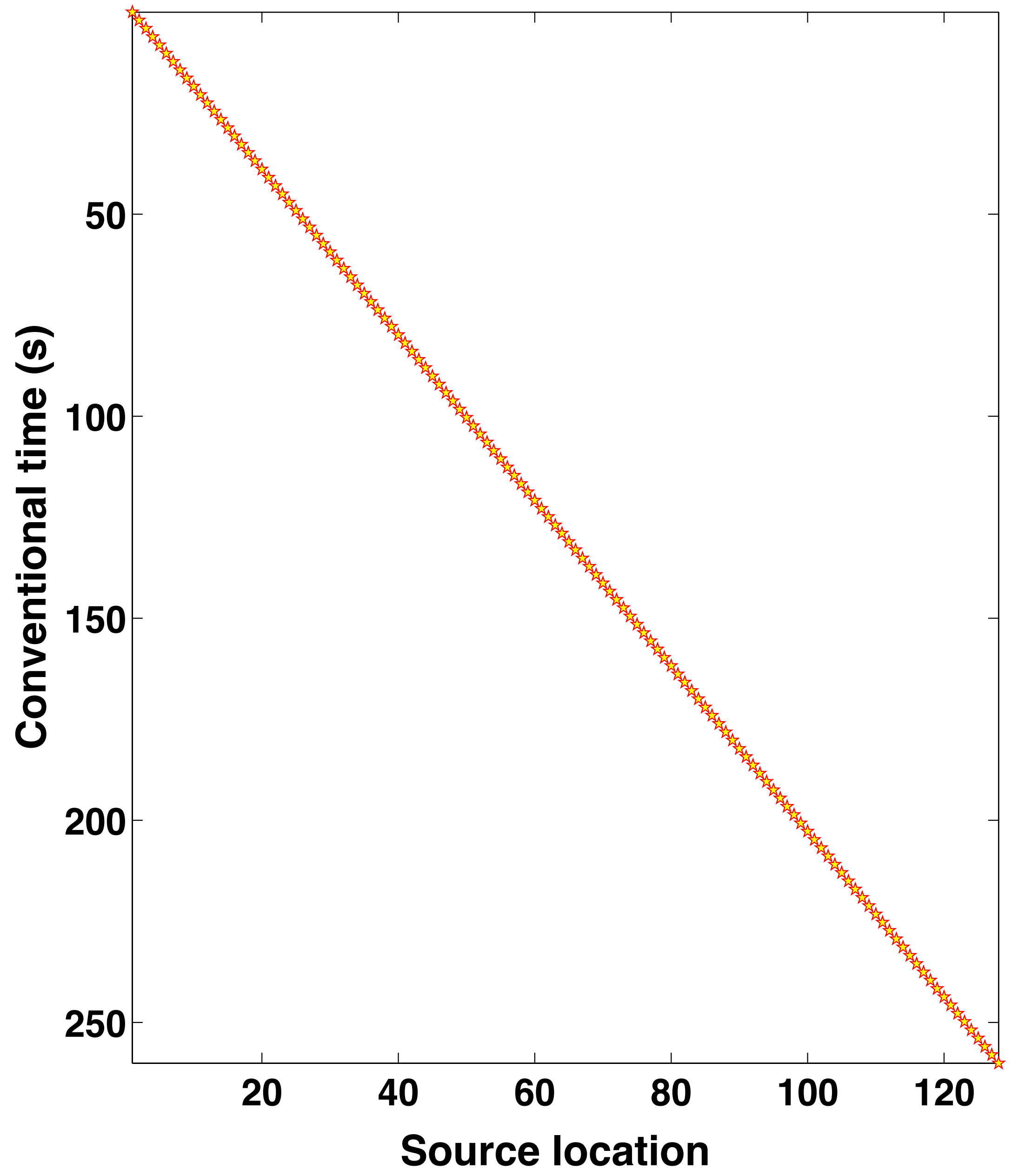
- (multi) vessel acquisition w/ *jittered* sampling & "blending" *via* compressed *randomized intershot* firing times
- sparsity-promoting recovery using ℓ_1 constraints ("deblending")

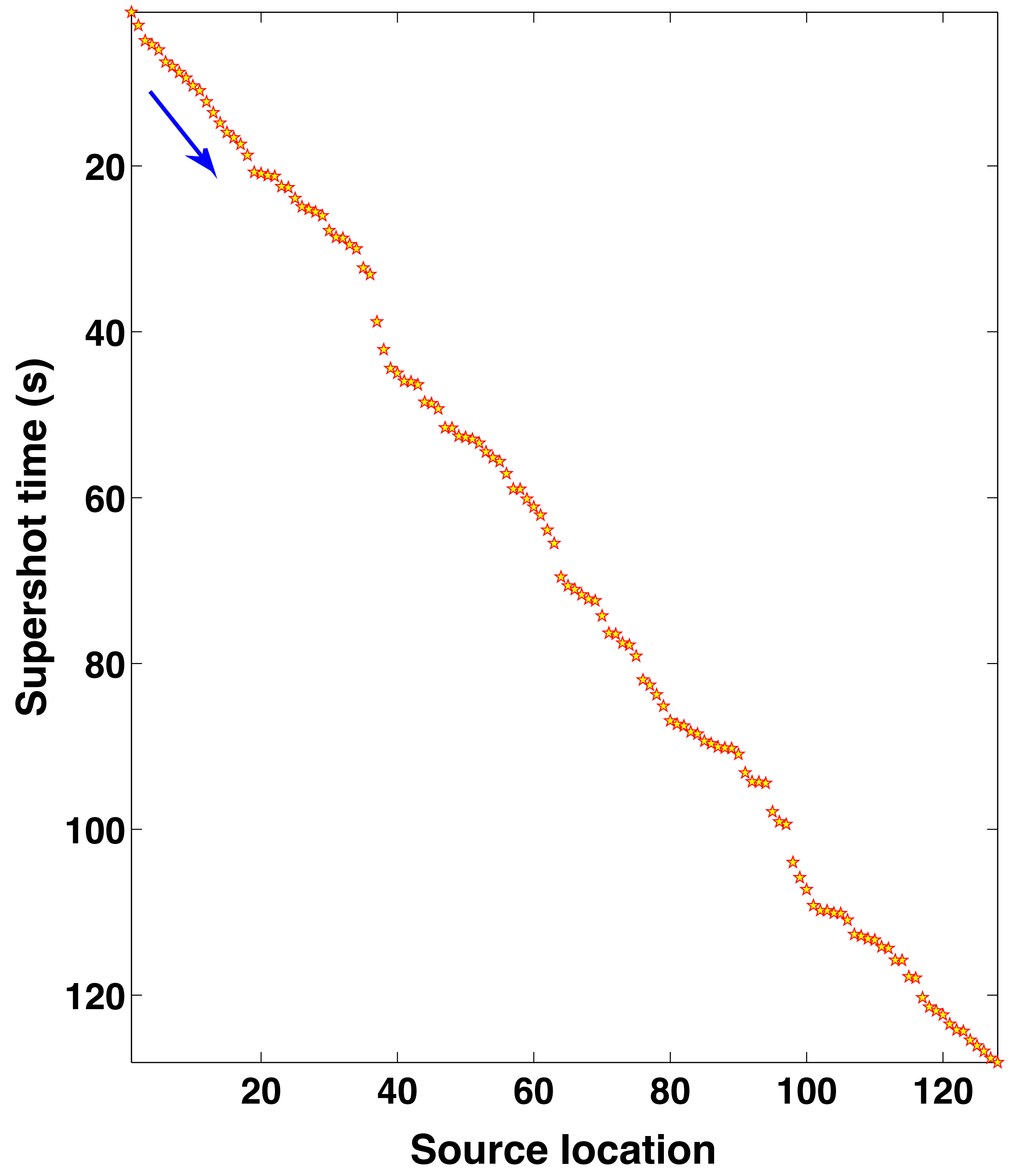
More for less



Conventional vs. *jittered* sources
[EAGE 2012]

Speed of source vessel
Constant

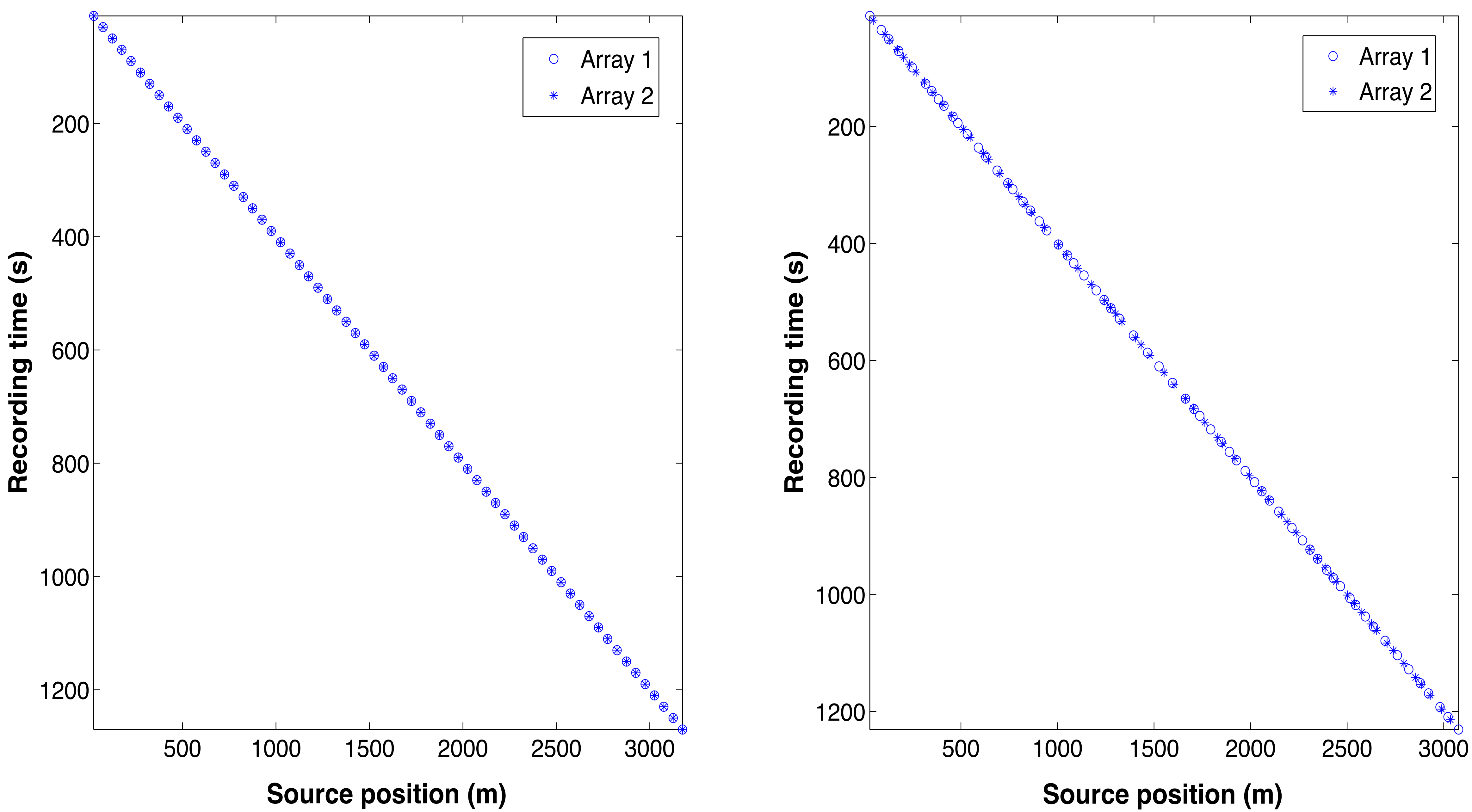




Conventional vs. *jittered* sources

[EAGE 2013]

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



Outline

- Problem statement & recovery strategy
- Design of *jittered*, ocean bottom cable acquisition
  - jitter in *time* ⇒ jittered in *space* (*shot* locations)
- Experimental results of *sparsity*-promoting processing
  - wavefield *recovery* via "*deblending*" & *interpolation* from (coarse) *jittered* 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 *constant* 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!*)

On going work - move *off the grid* (use *non-uniform* grid)

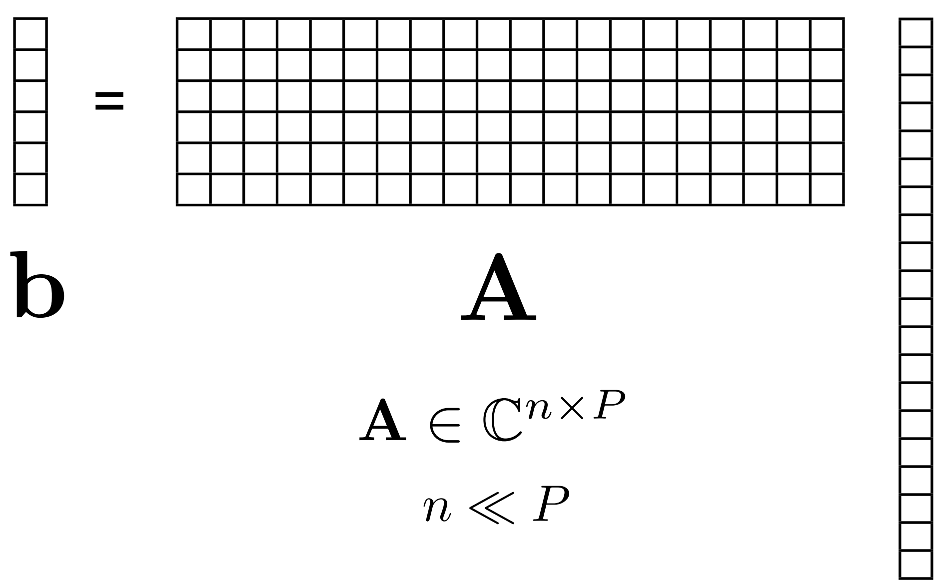
[Hennenfent et.al., 2010]

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

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

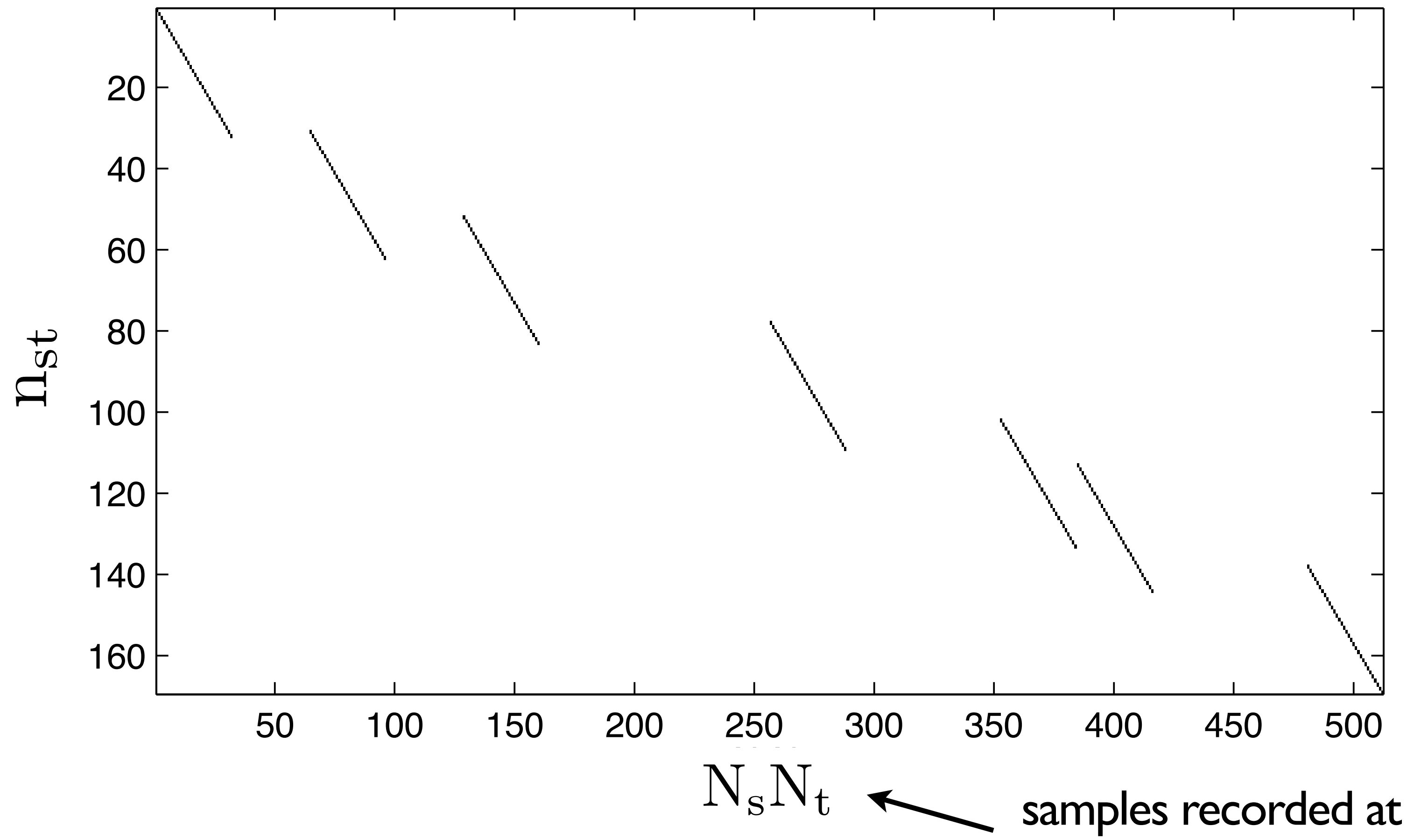
$$\mathbf{A} = \mathbf{R}\mathbf{M}\mathbf{S}^{\mathbf{H}}$$

sampling matrix ($\mathbf{RM}$)

transform matrix ($\mathbf{S}^{\mathbf{H}}$)

Sampling matrix

For a seismic line with N_s sources, N_r receivers, and N_t time samples, the sampling matrix is



samples recorded at each receiver during *jittered* acquisition

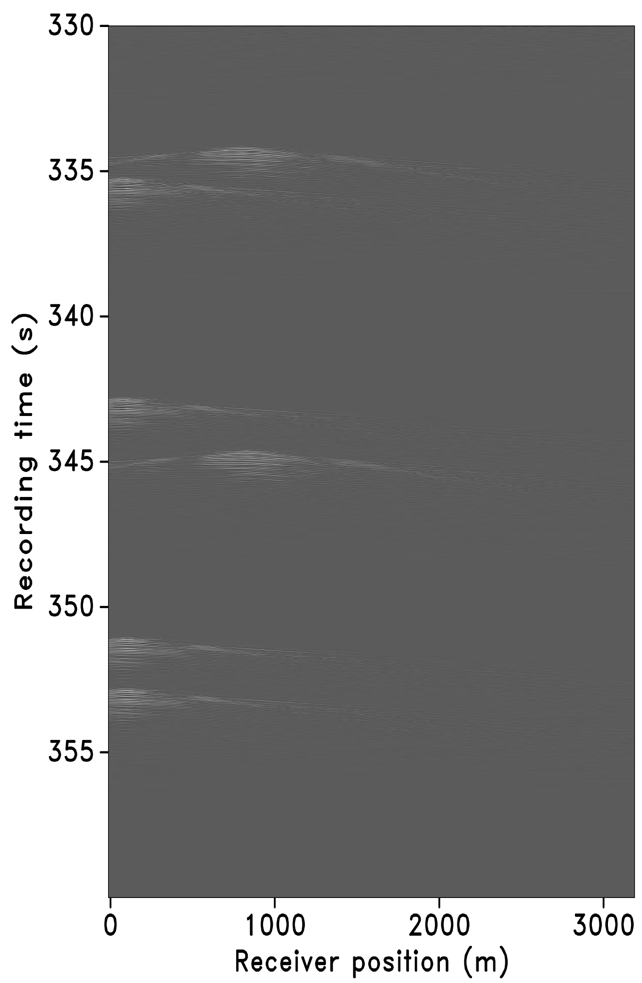
samples recorded at each receiver during *conventional* acquisition

$$\mathbf{RM}$$

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

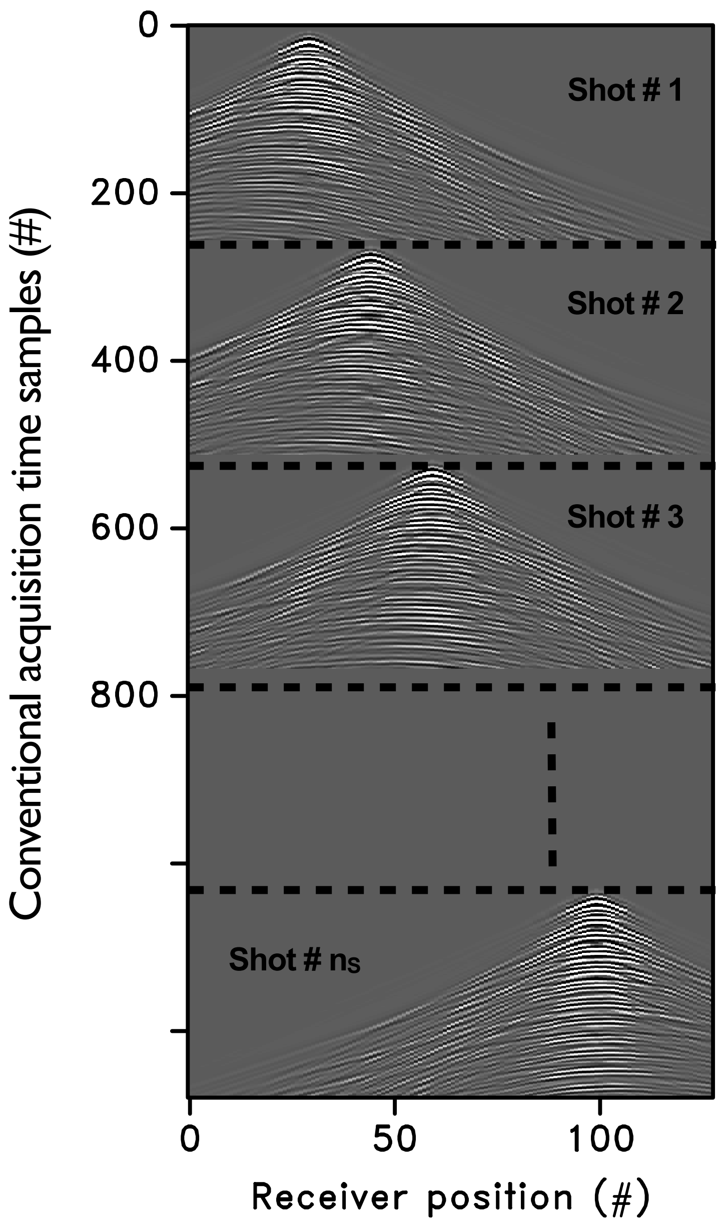
would like to have
(*all* shots *w/o overlaps*
between shot records)

b



= **RM**

d



Sparse recovery

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

Sparsity-promoting program:

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

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

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

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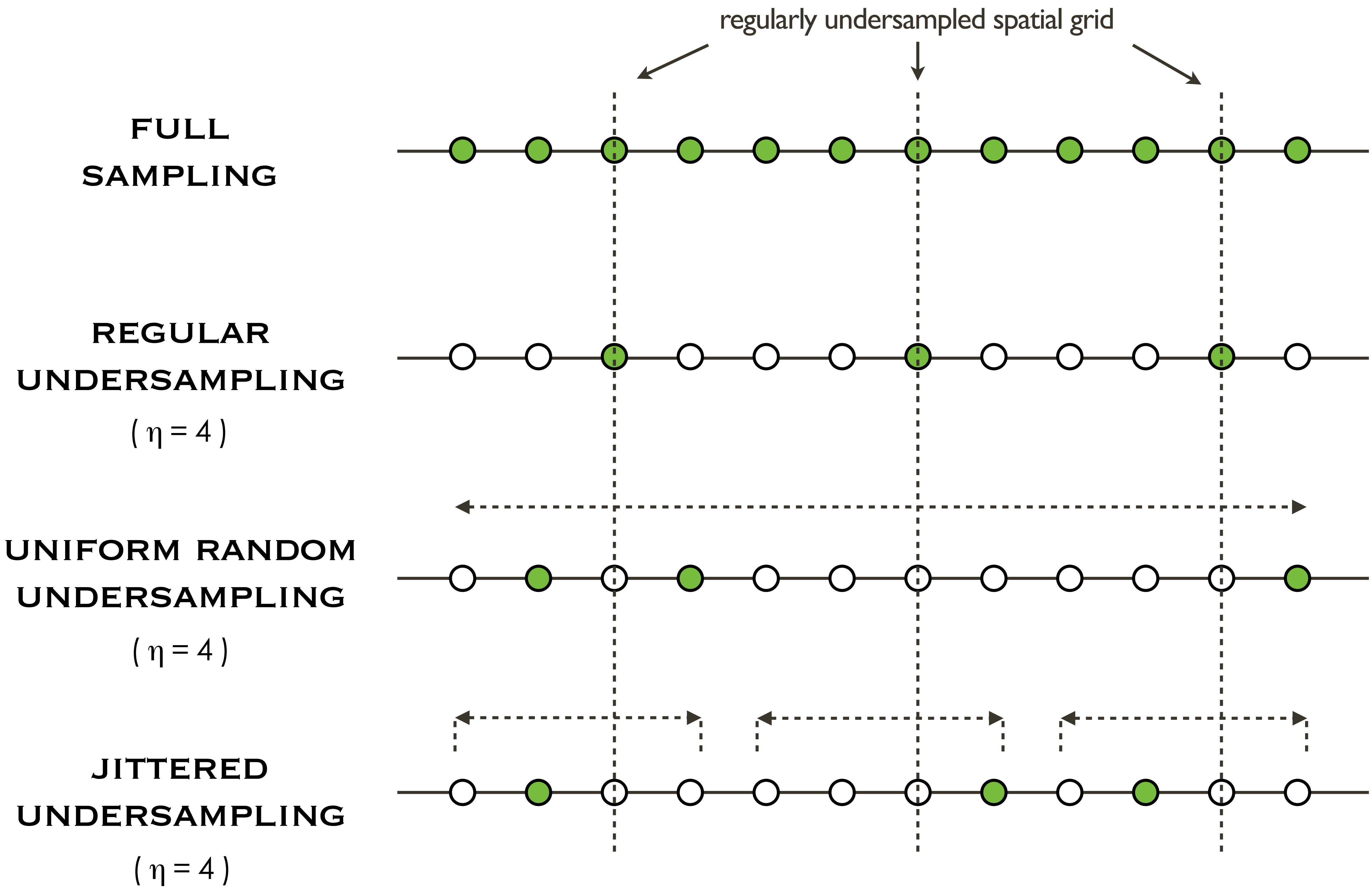
[Hennenfent et.al., 2008]

Sampling schemes



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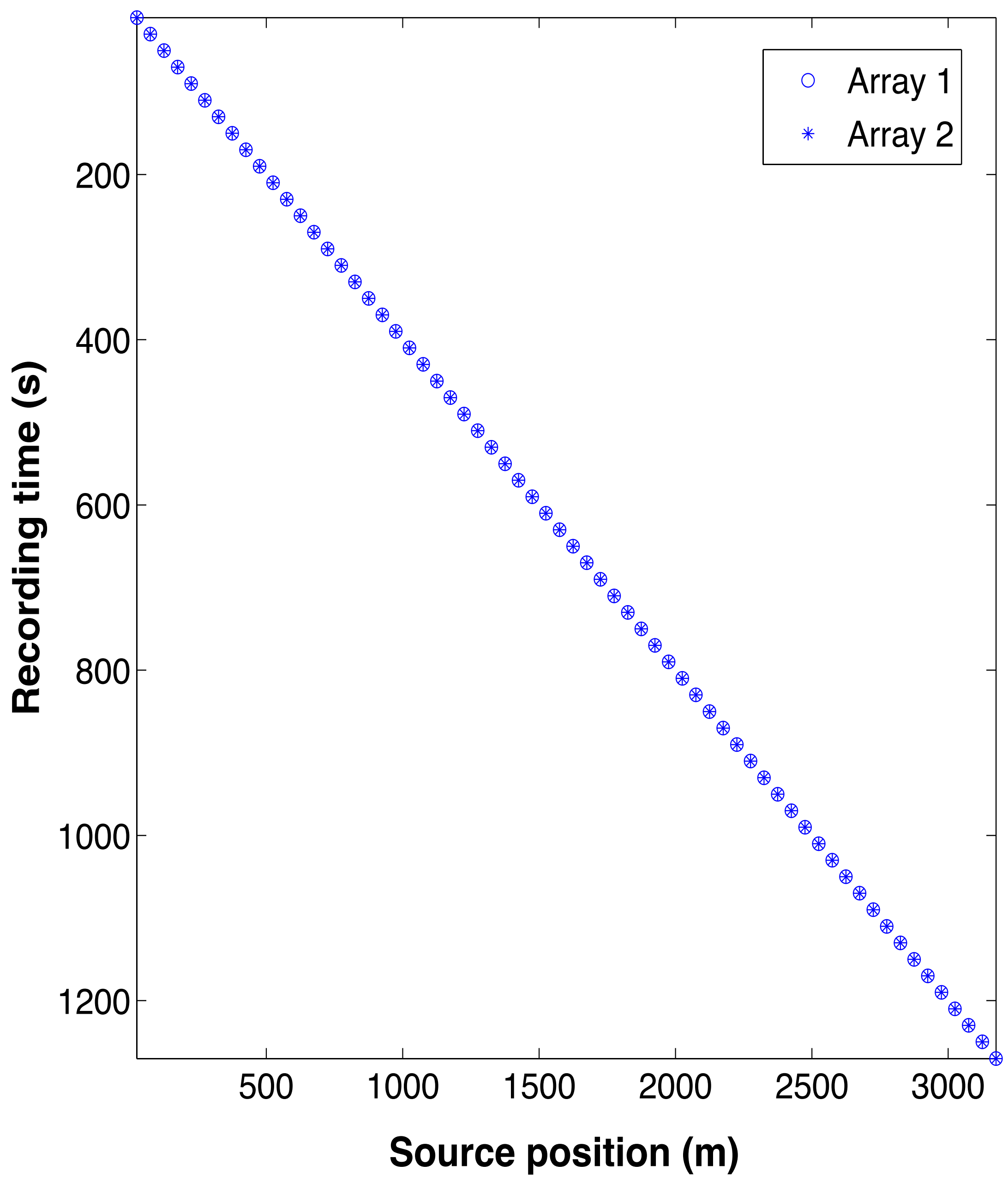
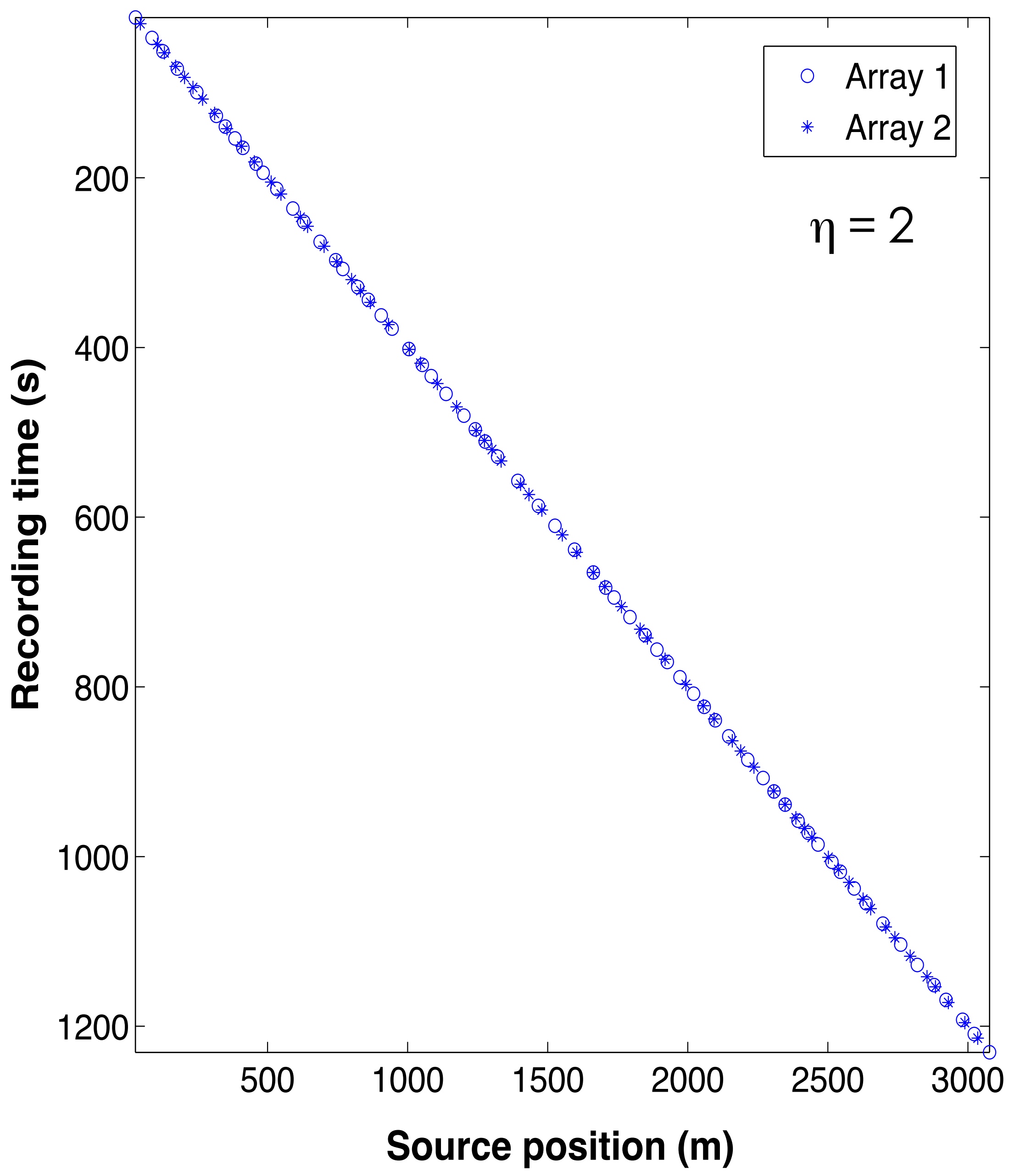
Conventional vs. *jittered* sources

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

shot interval: **50** m



shot interval: **25** m



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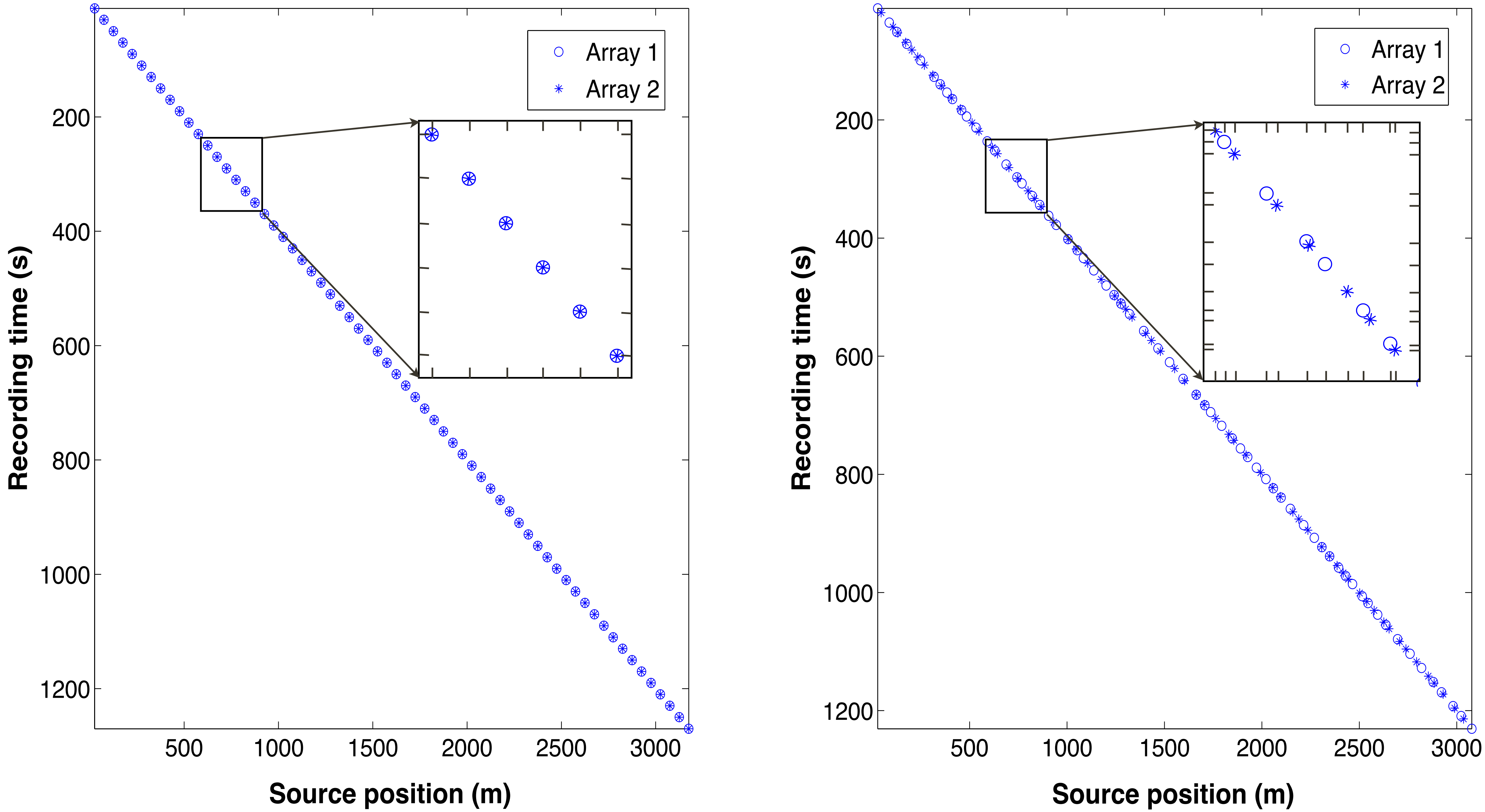

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Simultaneous source acquisition & deblending

- *A new look at simultaneous sources* by Beasley et. al., '98, '08
- *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 - *jittered sampling & overlap*

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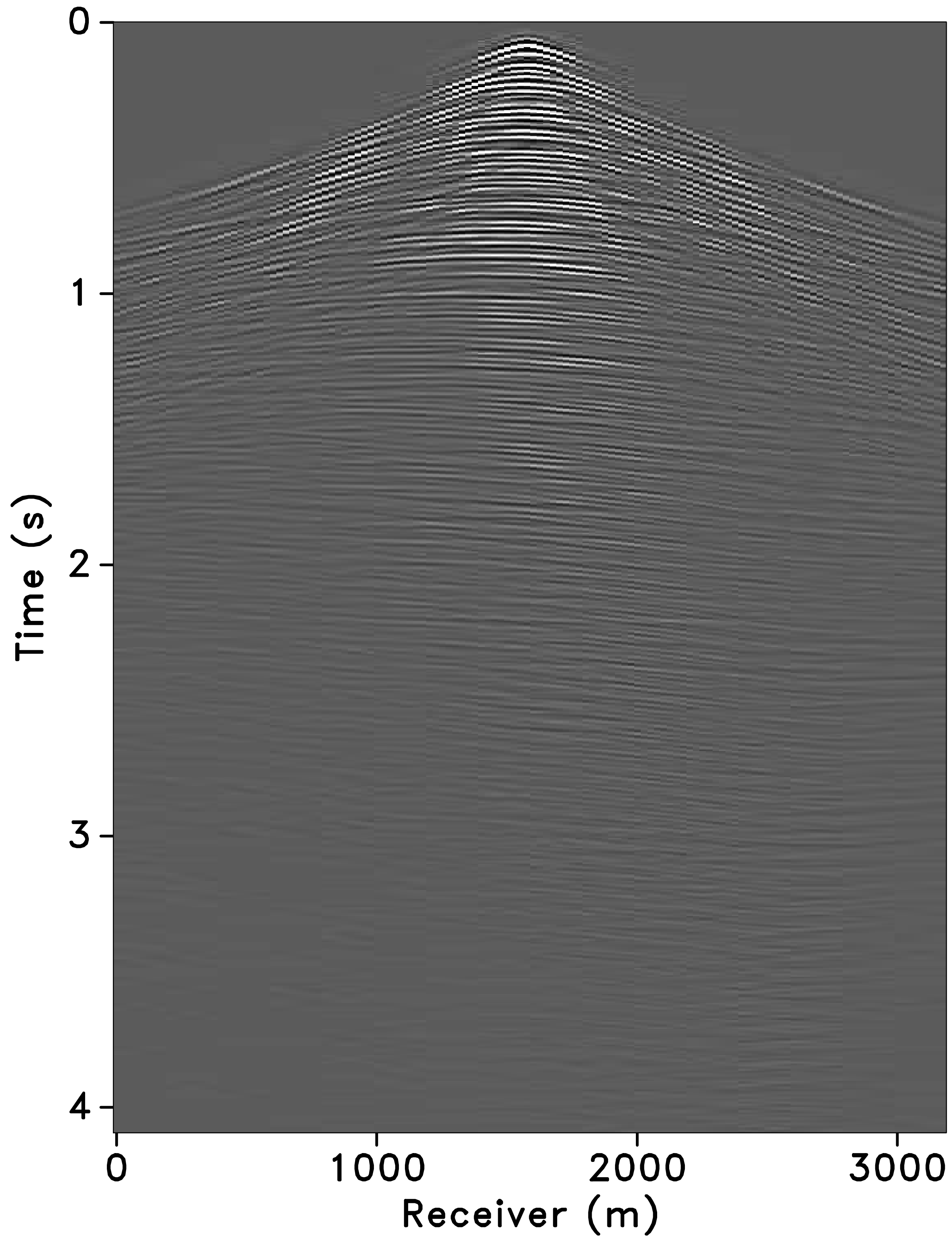


Gulf of Suez

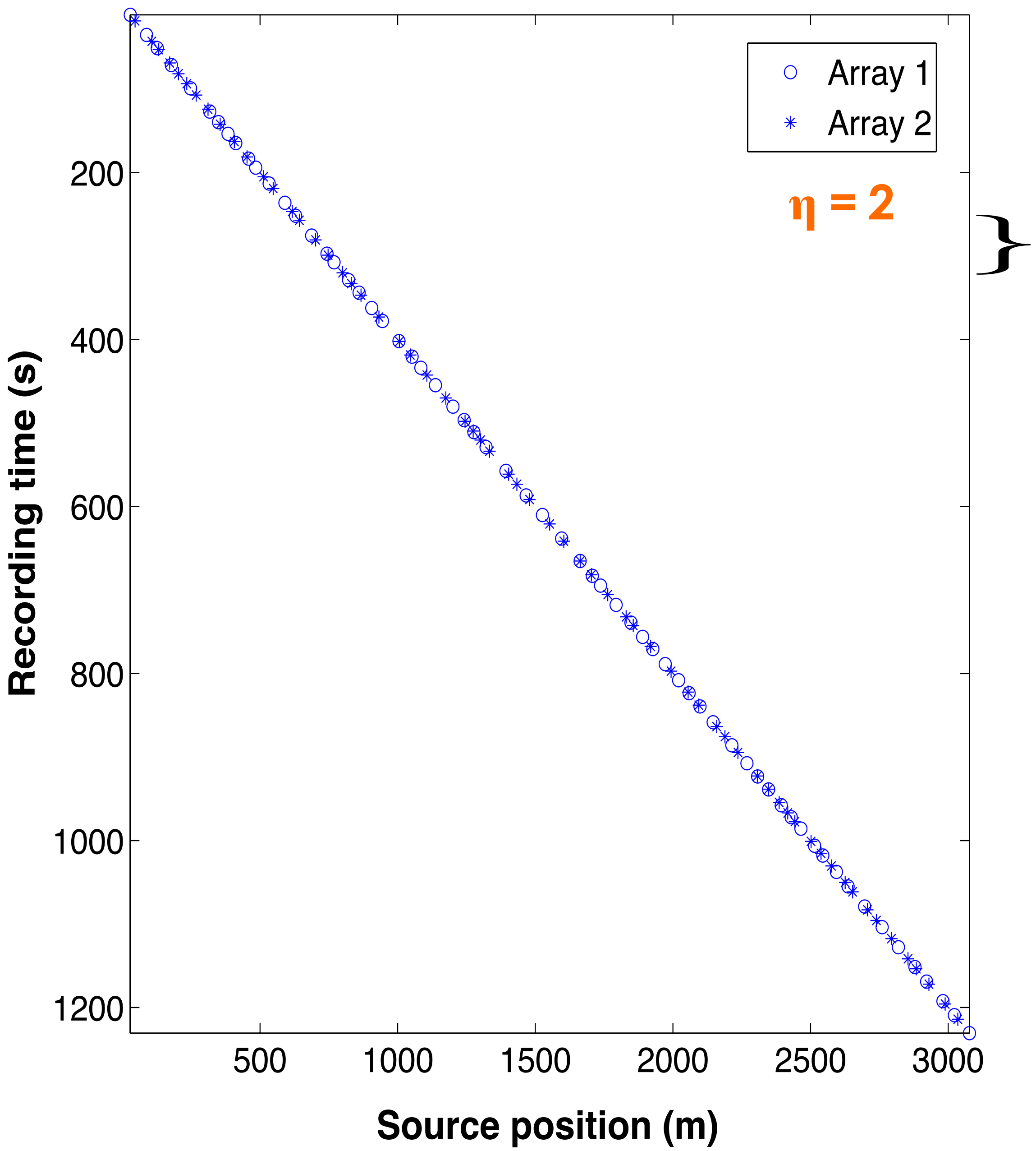
1024 time samples
128 sources
128 receivers

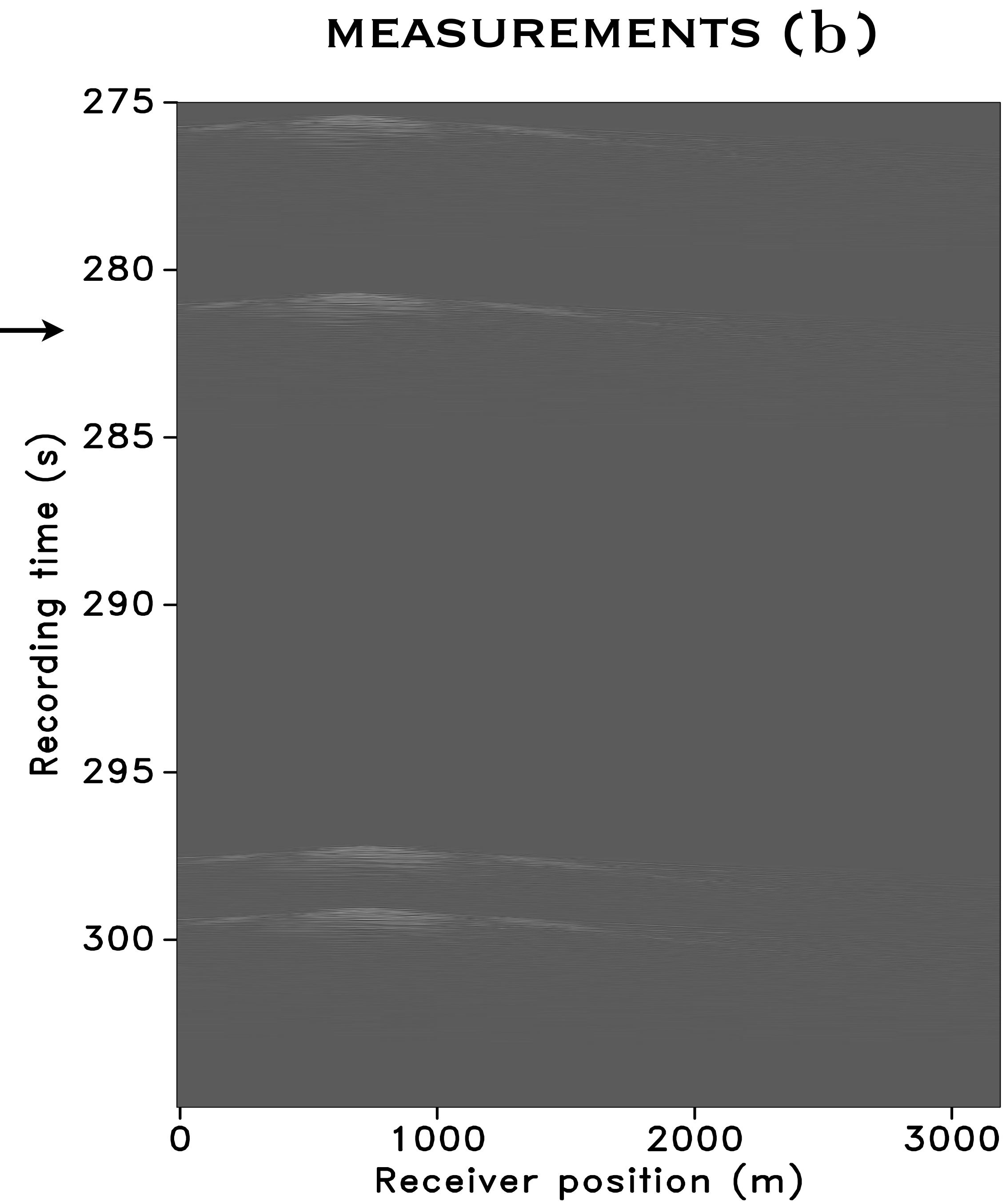
Shot interval: **25 m**
Receiver/group interval: **25 m**

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]





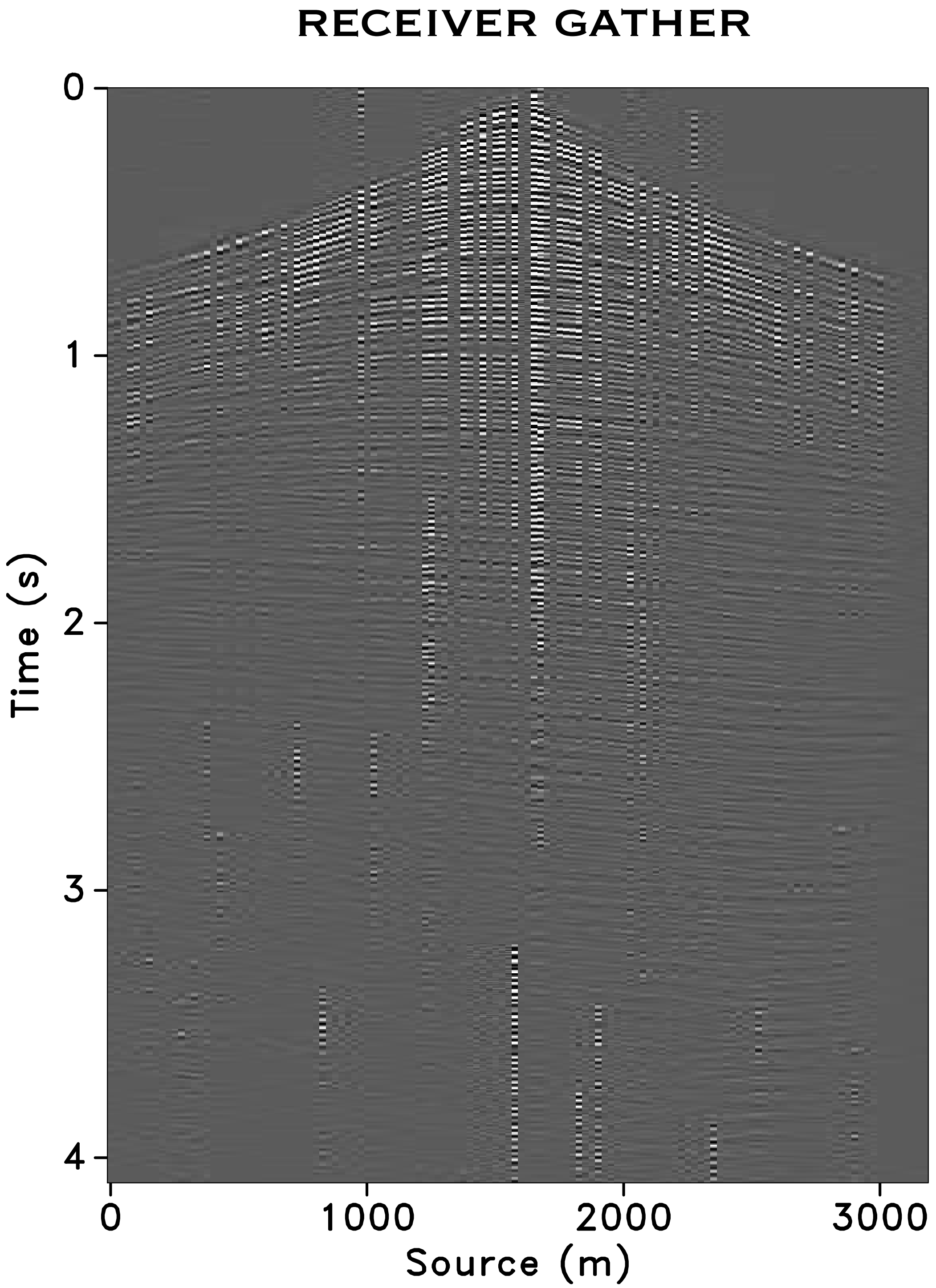
Recovery

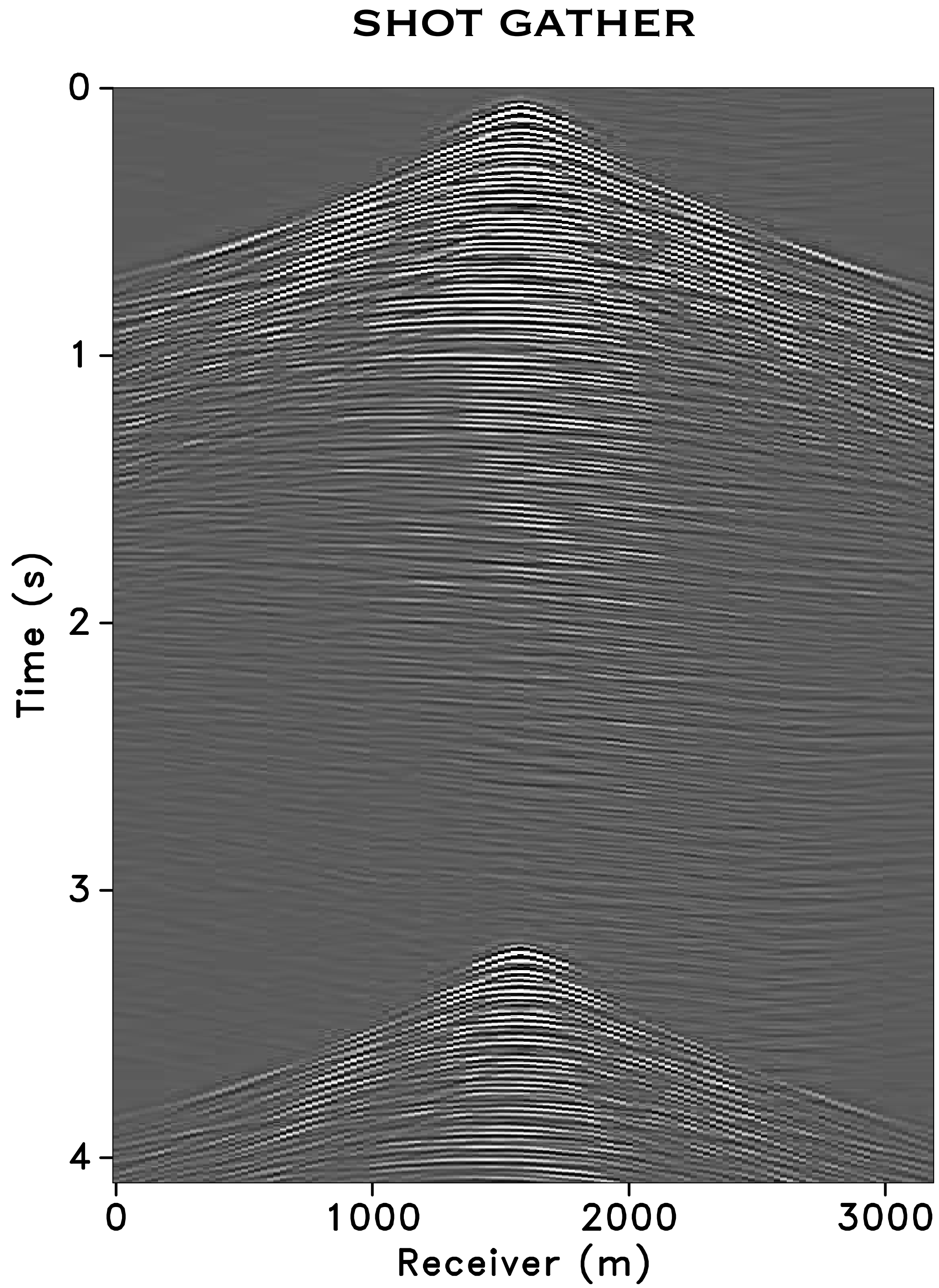
[“Deblending” + Interpolation from (coarse) *jittered* grid to (fine) *regular* grid]

Conventional processing	**Curvelet-domain sparsity-promotion**
Apply the adjoint of the sampling operator + Median filtering in the midpoint-offset domain	Solve an optimization problem (e.g., one-norm minimization)

Conventional processing

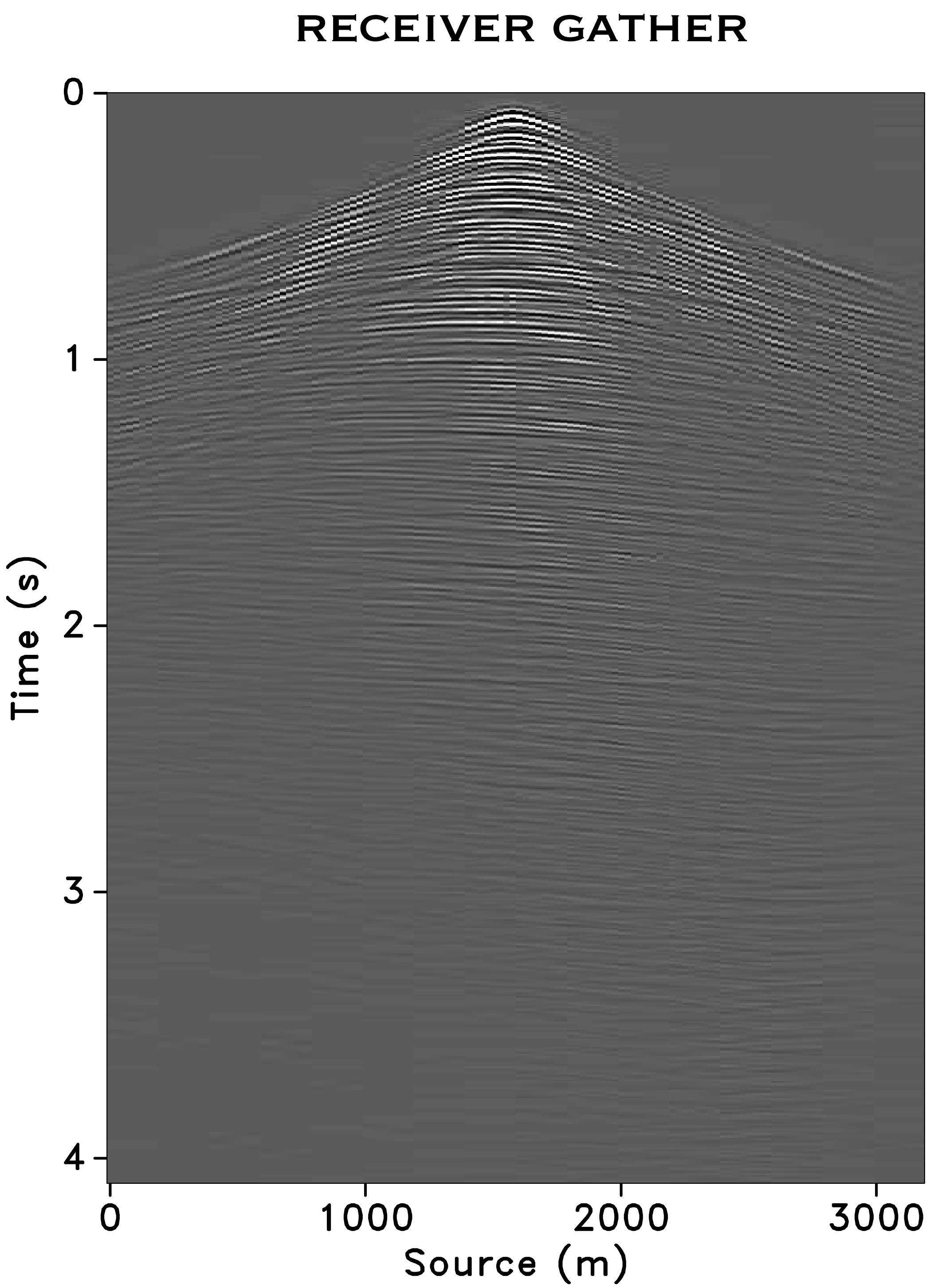
[adjoint applied: $(\mathbf{RM})^{\mathbf{H}}\mathbf{b}$]

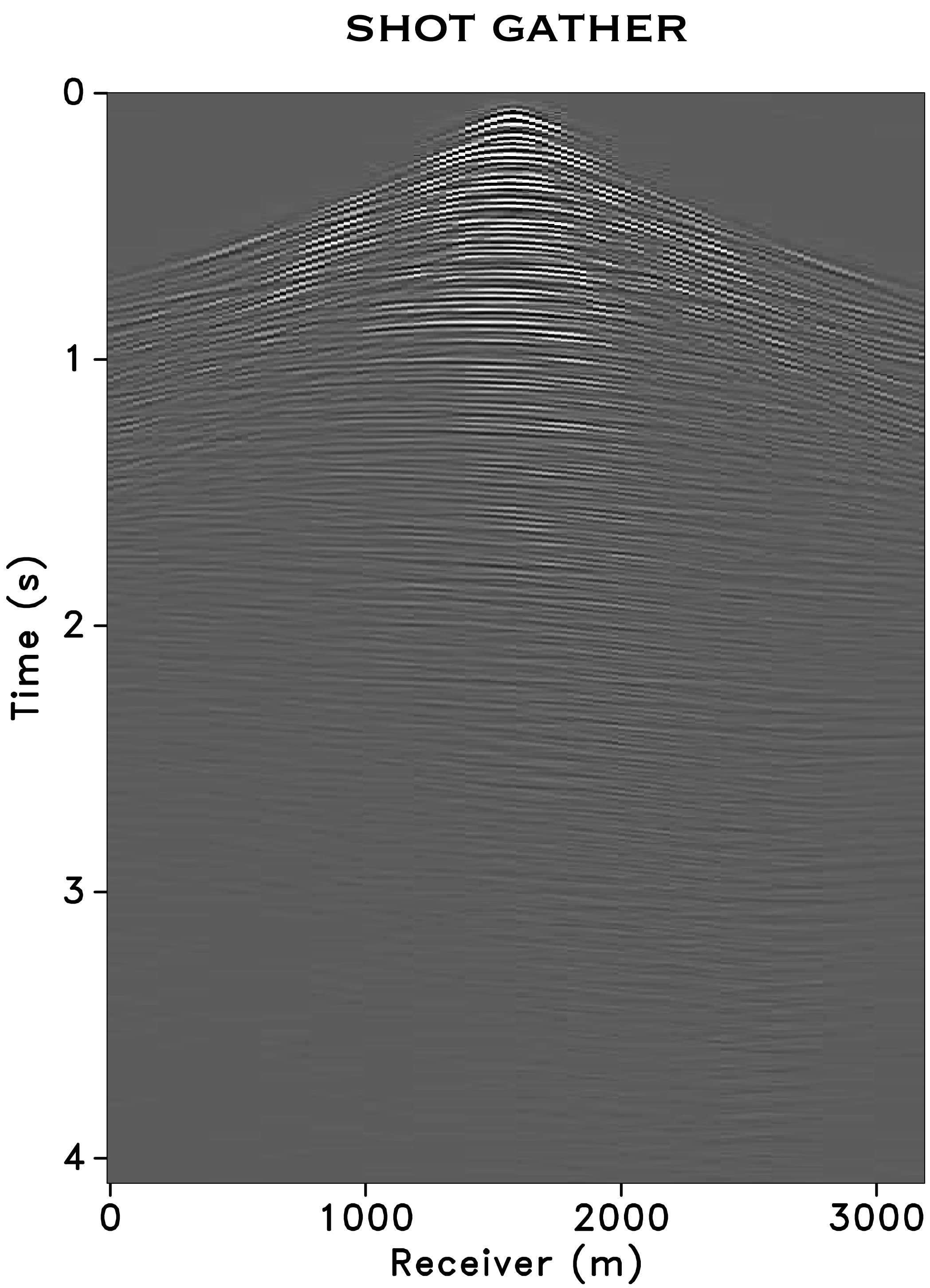




Sparsity-promoting recovery (14.6 dB)

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

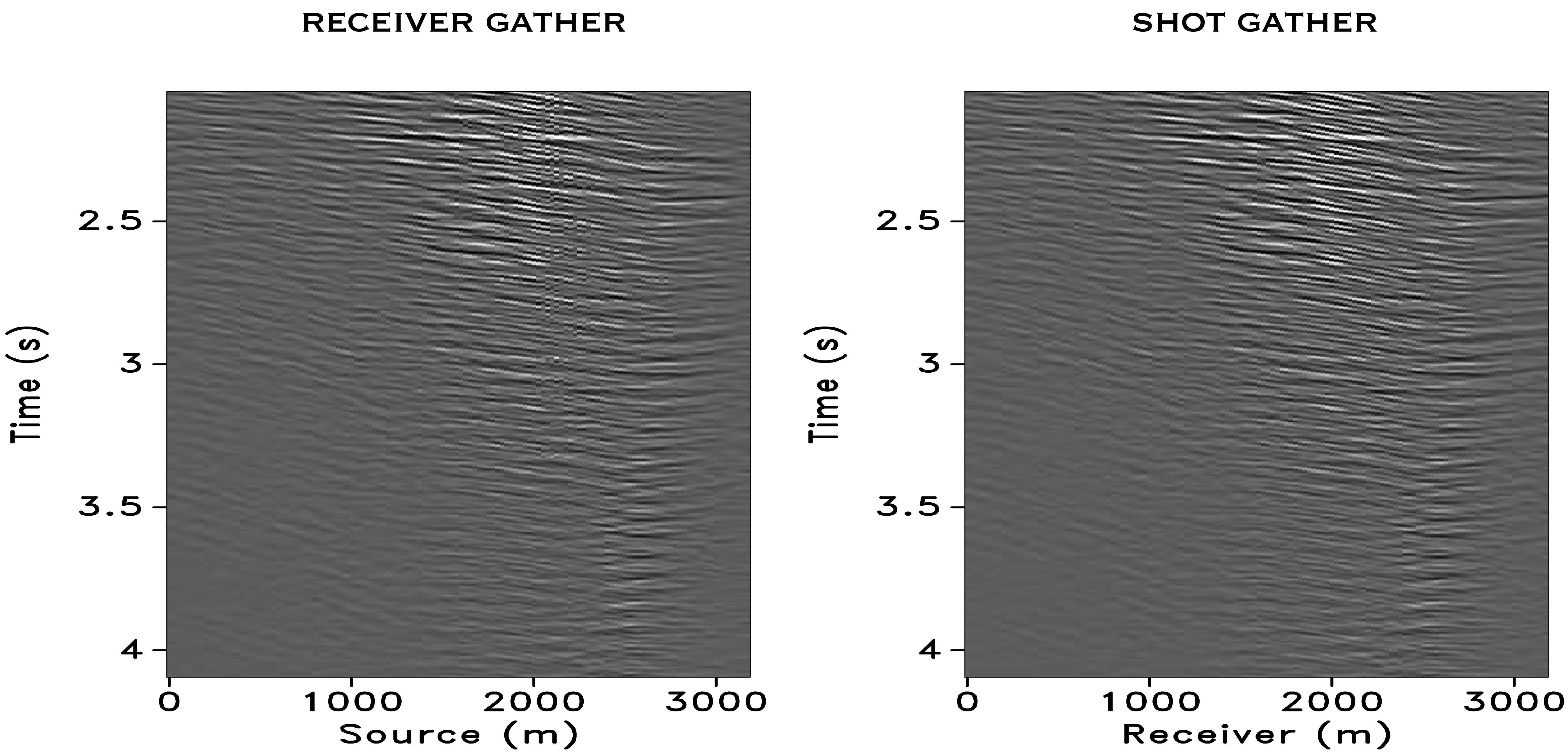




Sparsity-promoting recovery (14.6 dB)

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

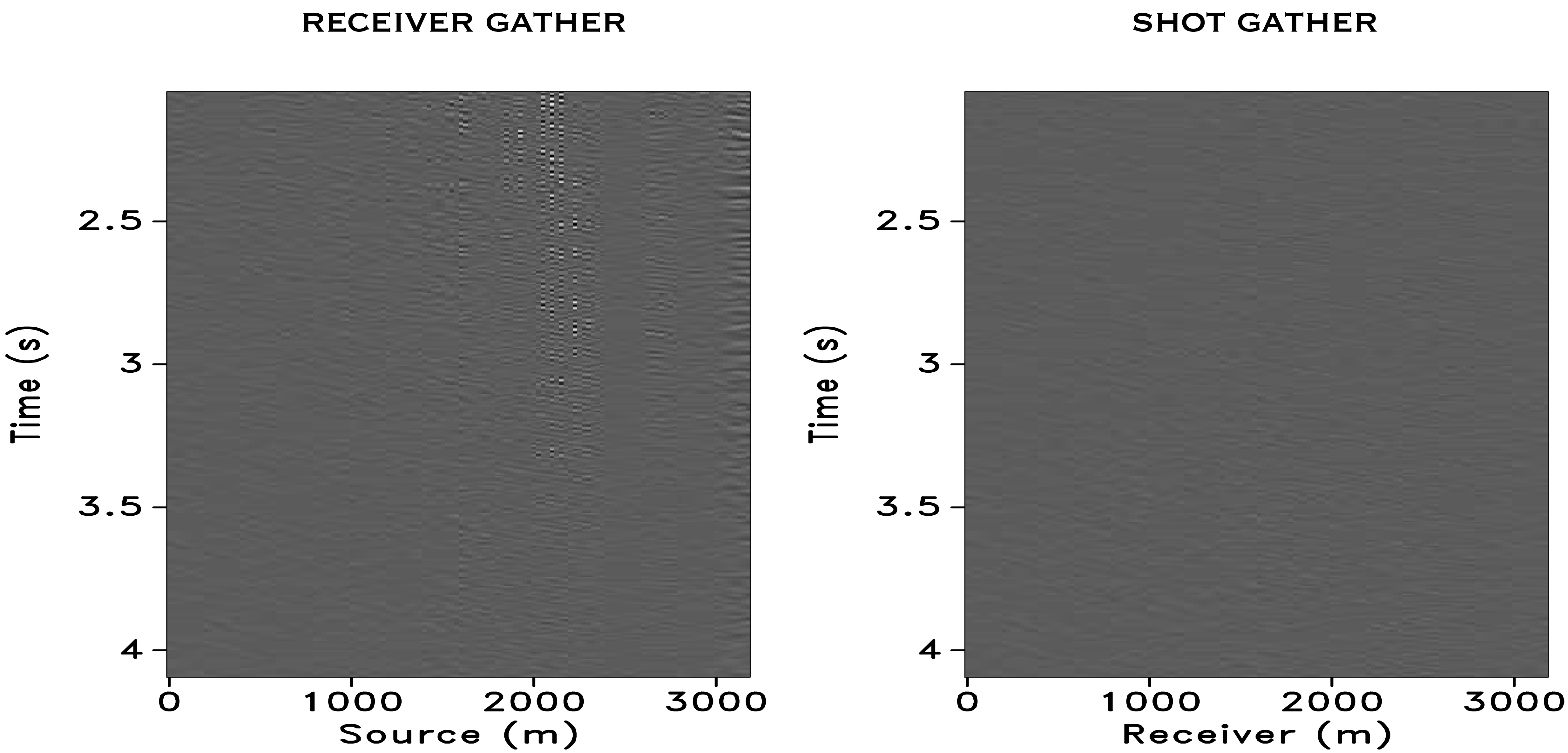
** recovered weak late events*



Sparsity-promoting recovery (14.6 dB)

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

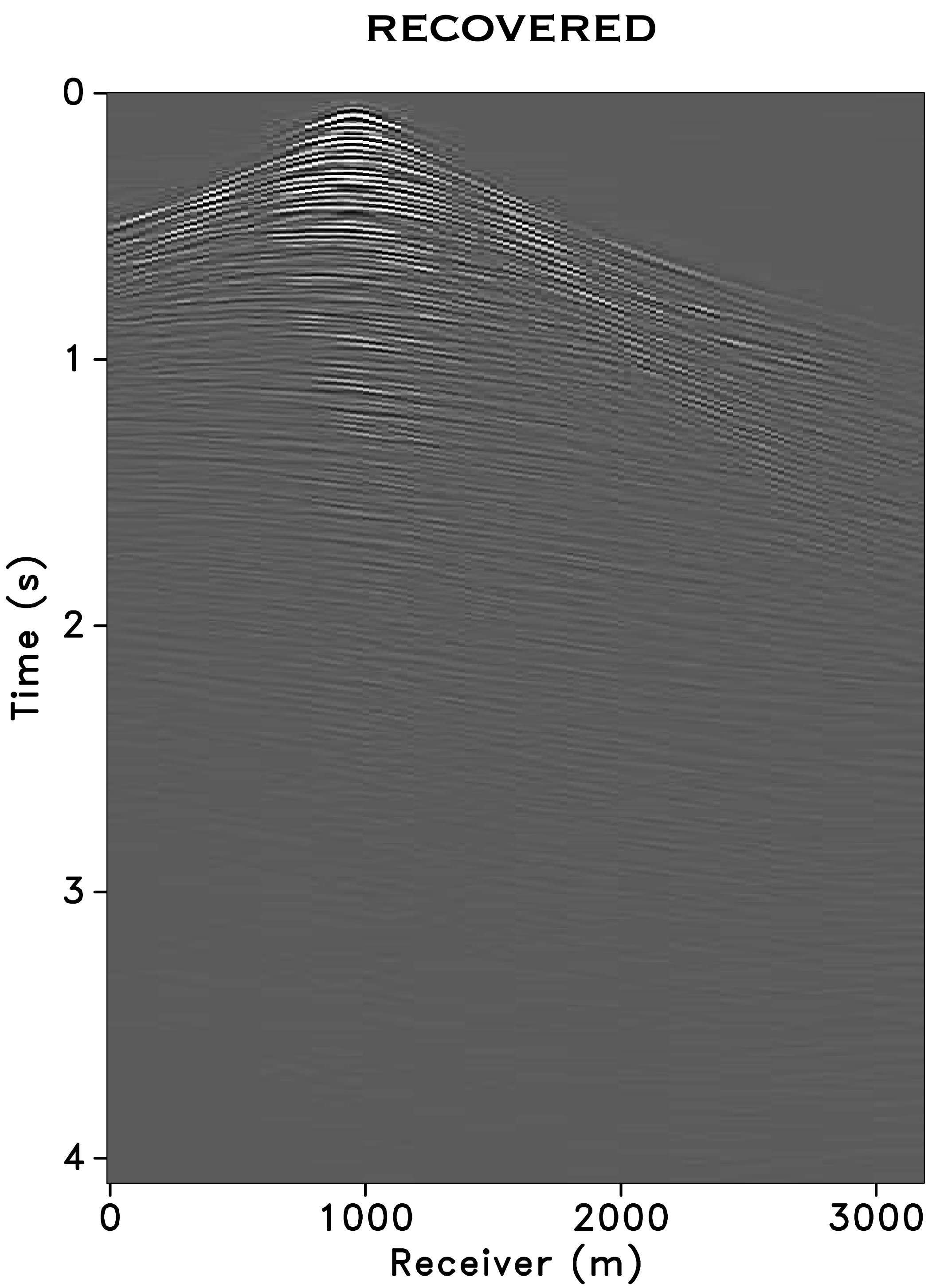
*** residual**

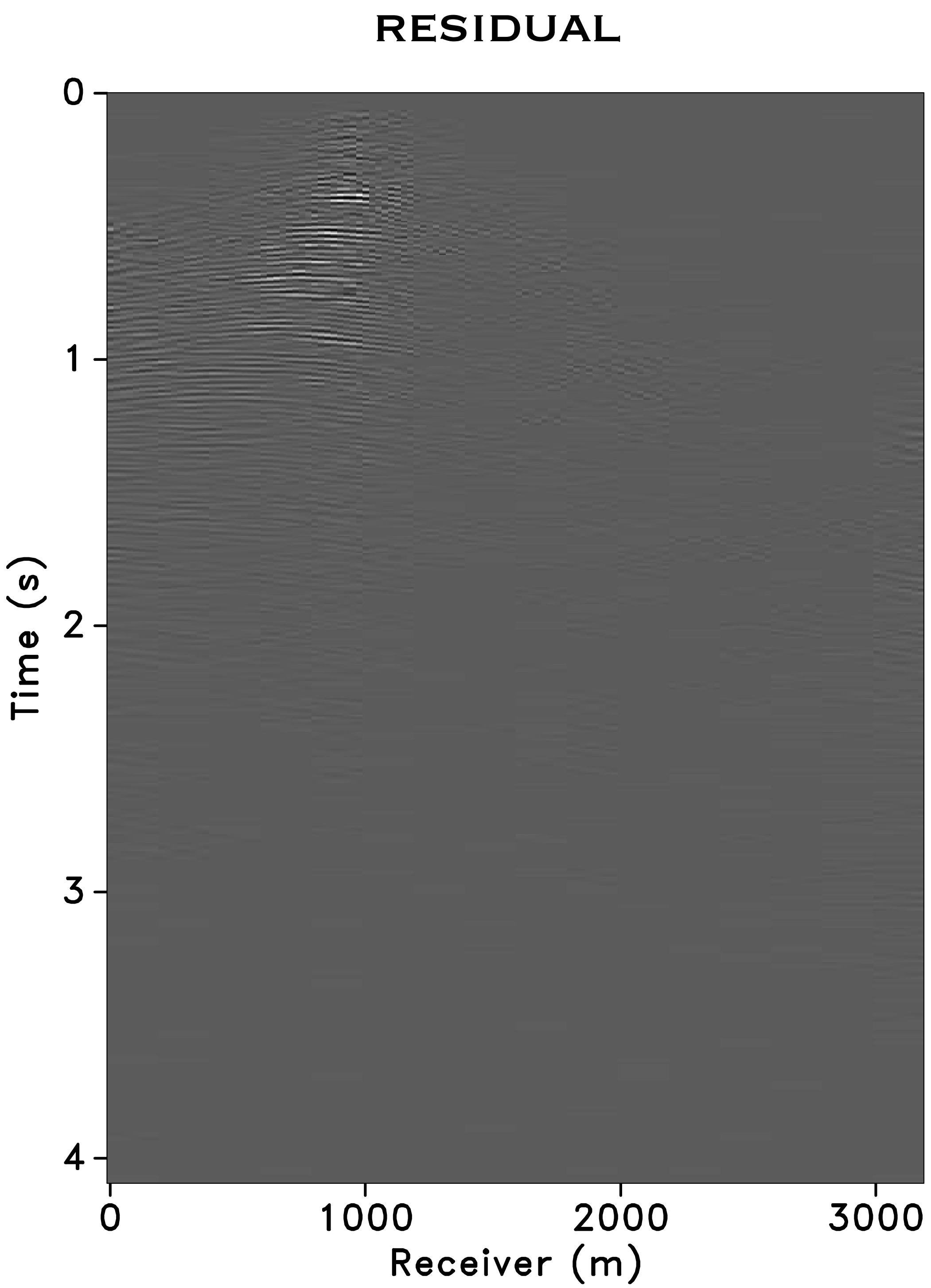


Sparsity-promoting recovery (14.6 dB)

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

** shot location where none of the airguns fired*





Performance

Improvement spatial sampling ratio

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

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

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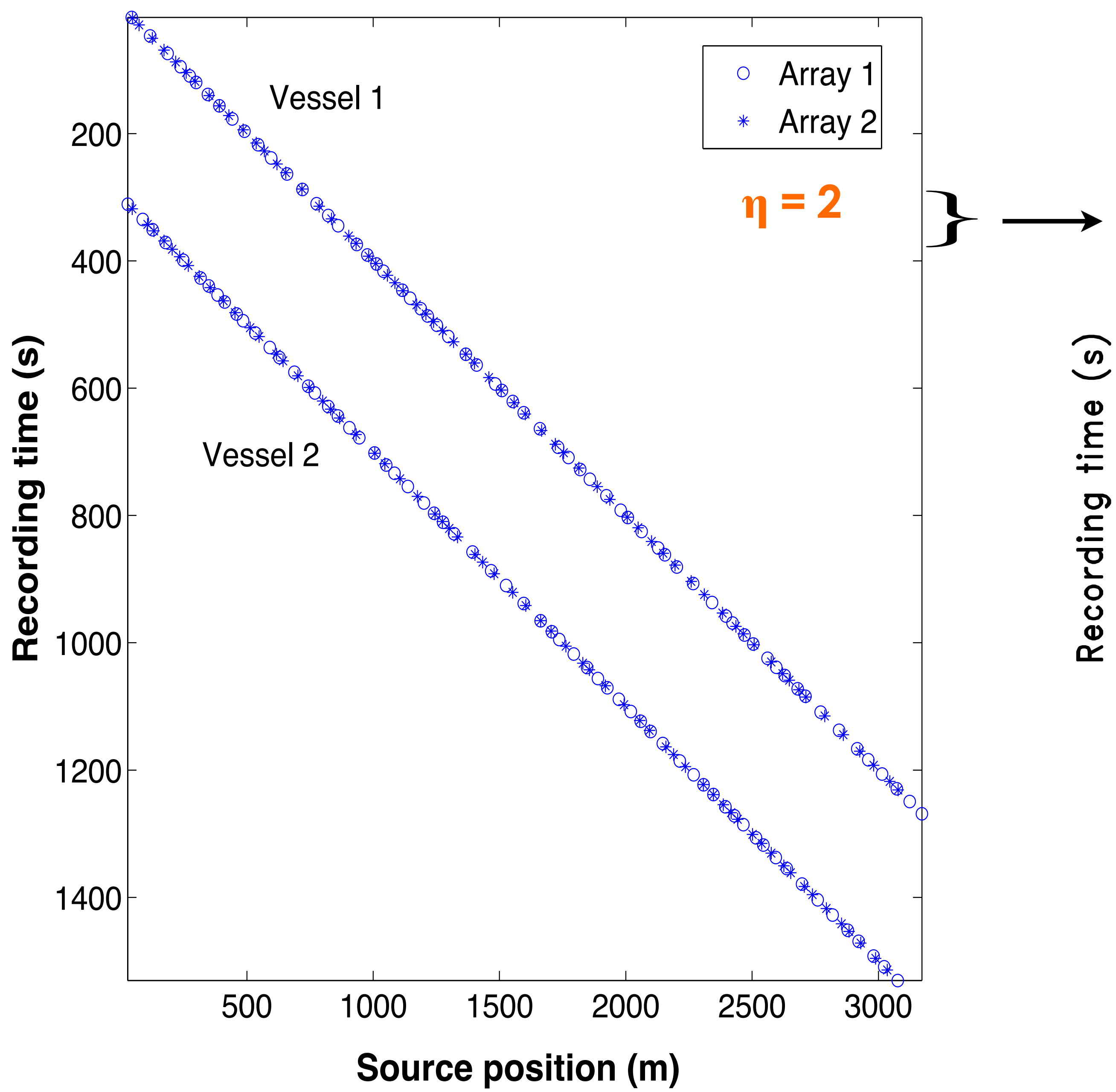
Multiple source vessels

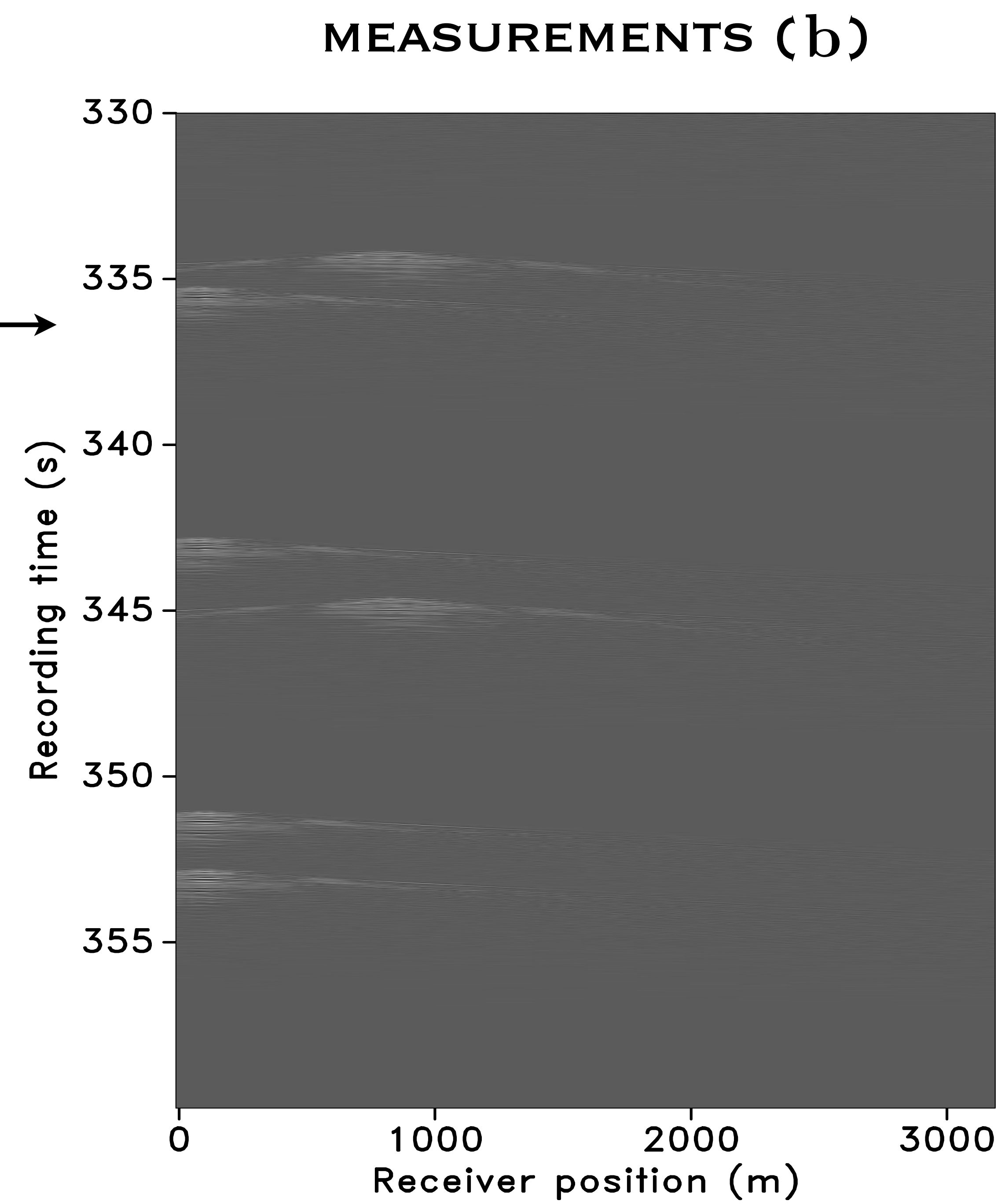
- *improves* recovery – *shorter* times lead to better *spatial* sampling at the expense of *more* overlap
- better *azimuthal* coverage

Time-jittered OBC acquisition

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

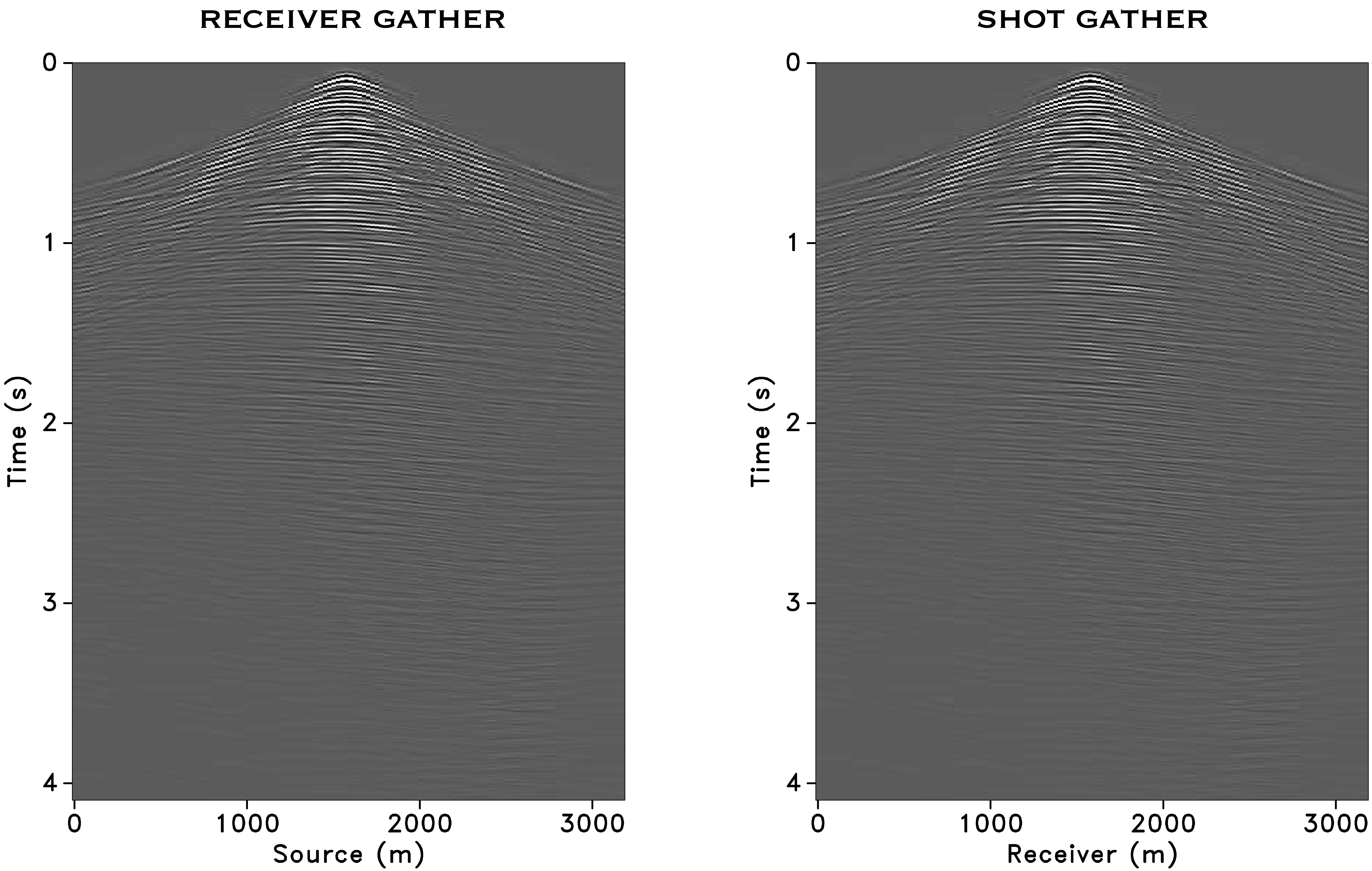
[no. of *jittered* source locations is *half* the number of sources in *ideal* periodic survey w/o overlap]





Sparsity-promoting recovery (20.8 dB)

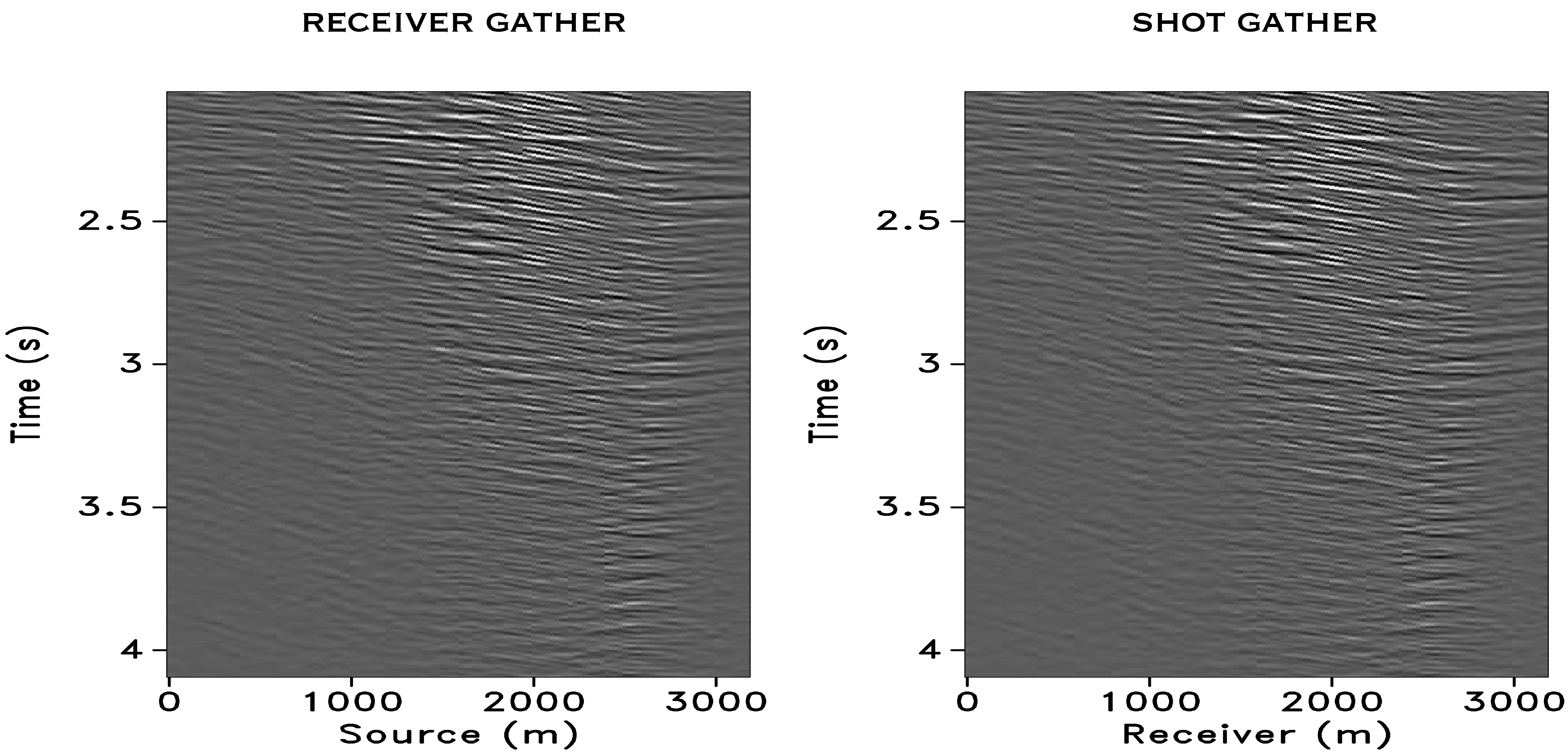
[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]



Sparsity-promoting recovery (20.8 dB)

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

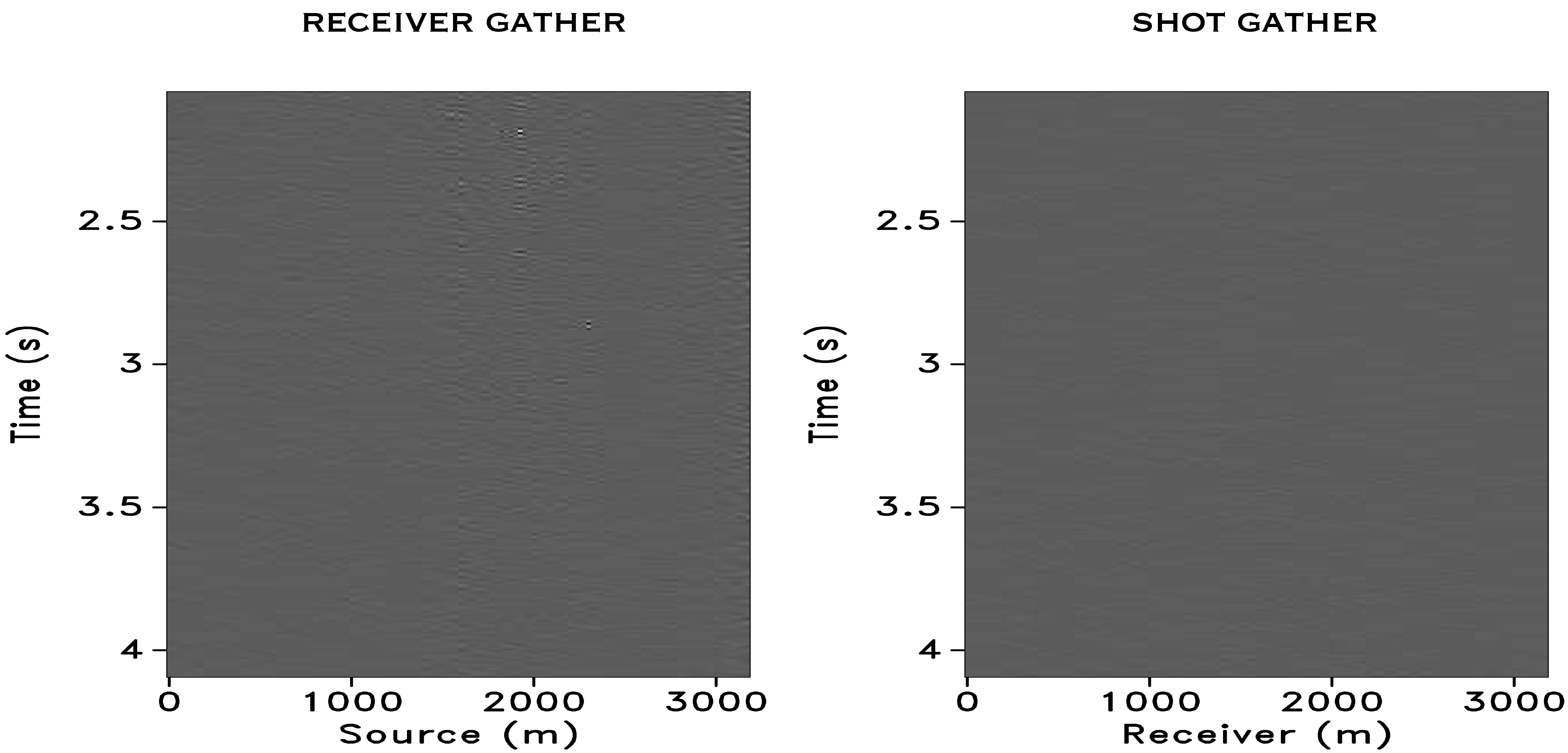
** recovered weak late events*



Sparsity-promoting recovery (20.8 dB)

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

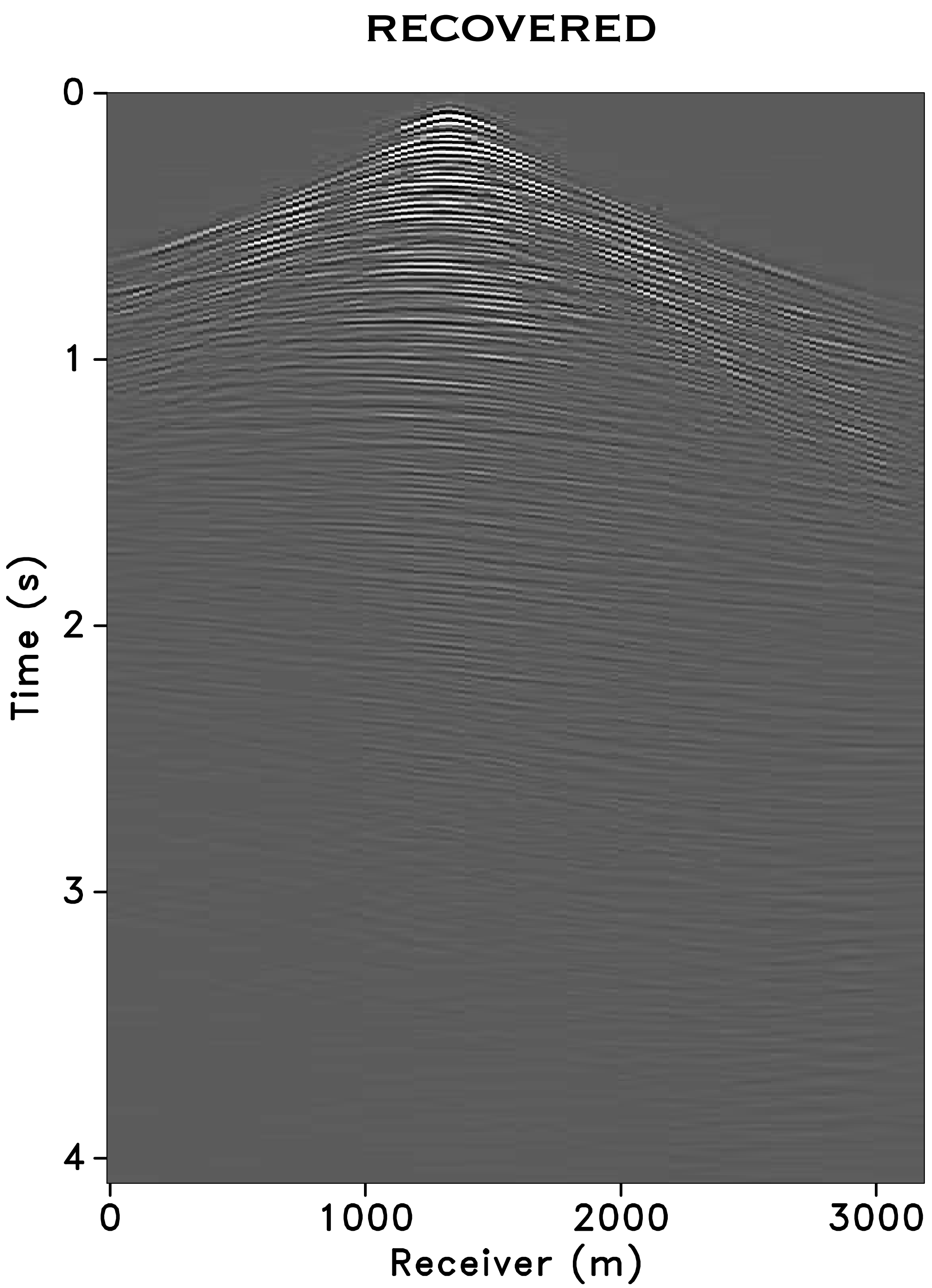
** residual*

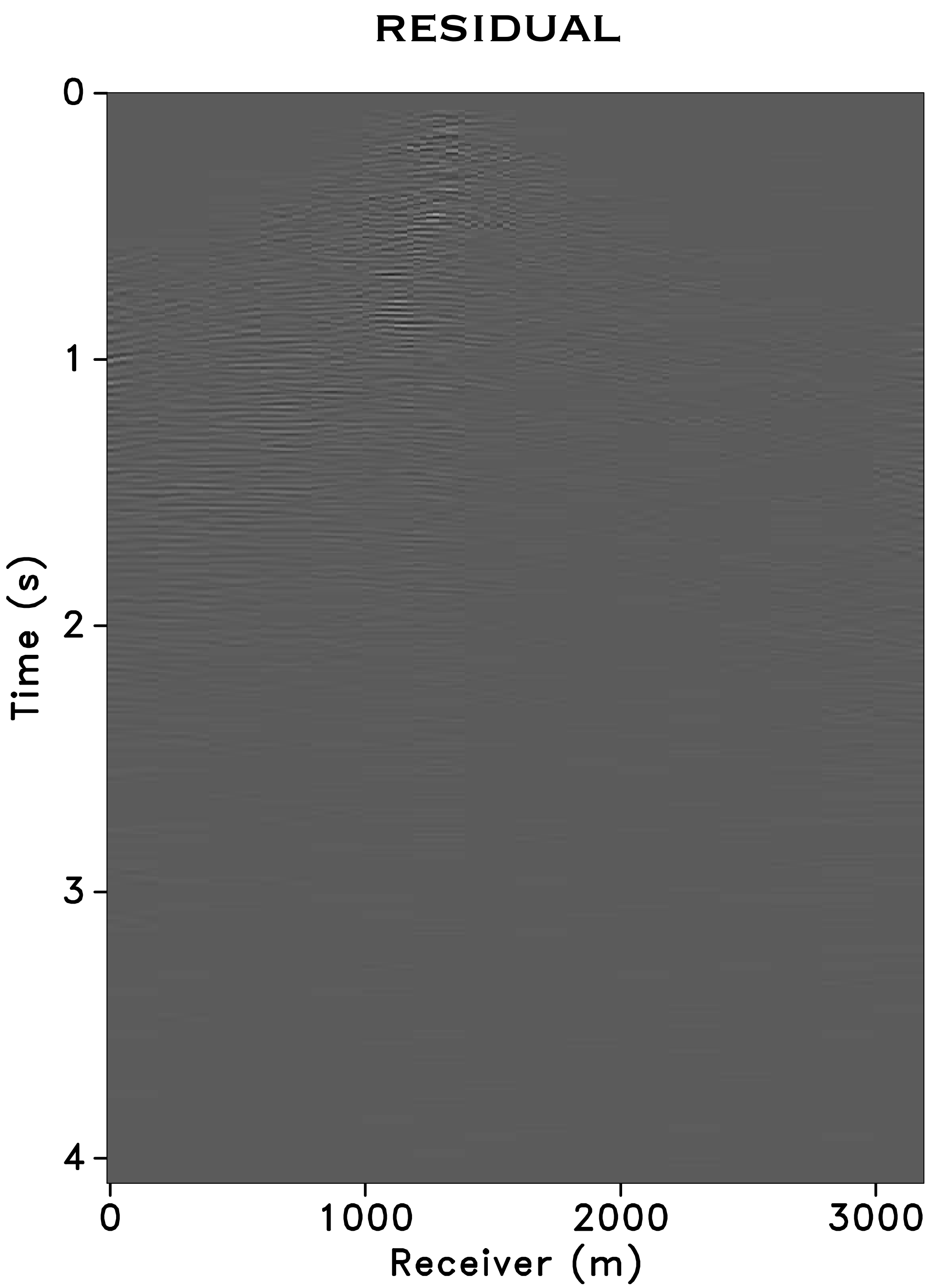


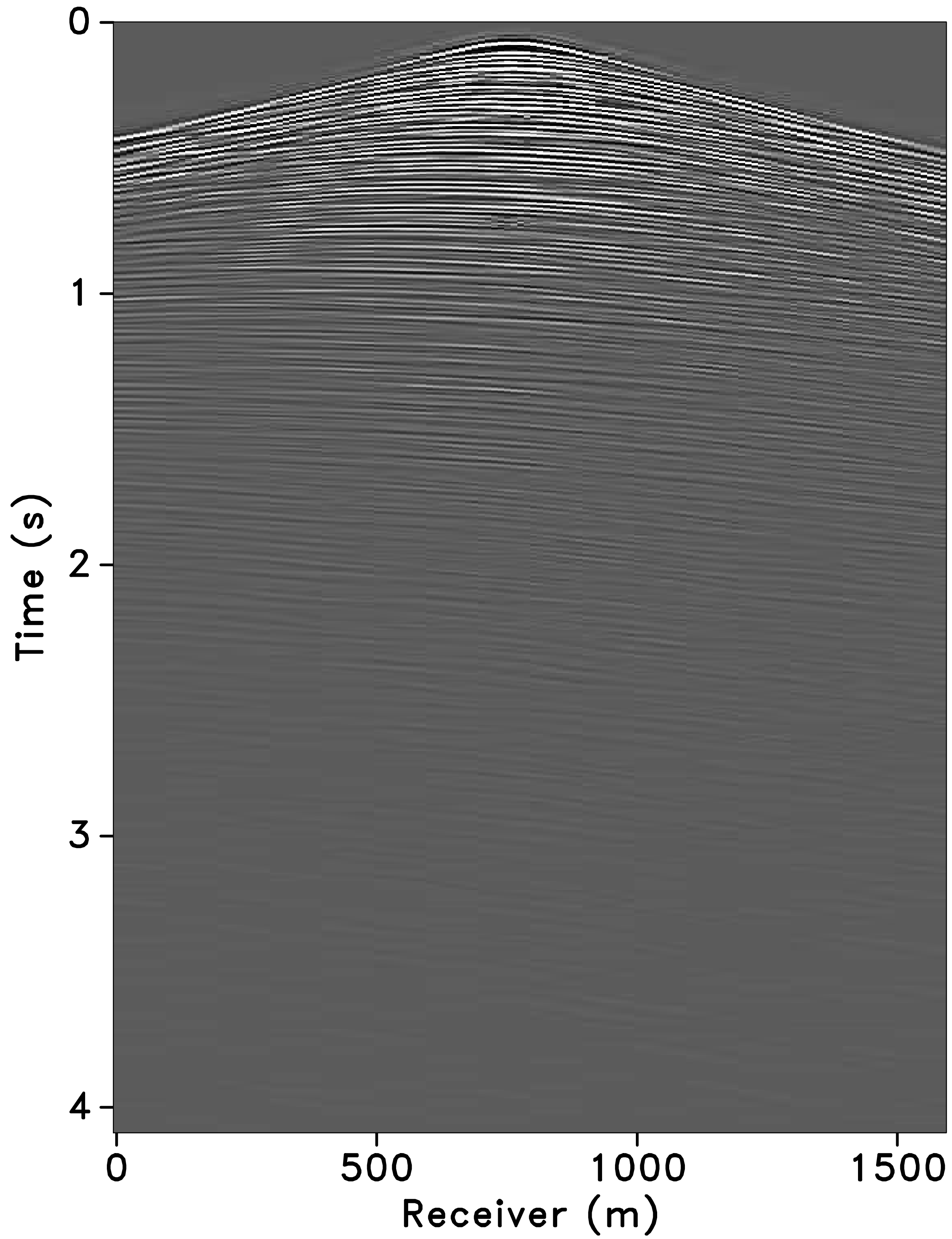
Sparsity-promoting recovery (20.8 dB)

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

** shot location where none of the airguns fired*







Gulf of Suez

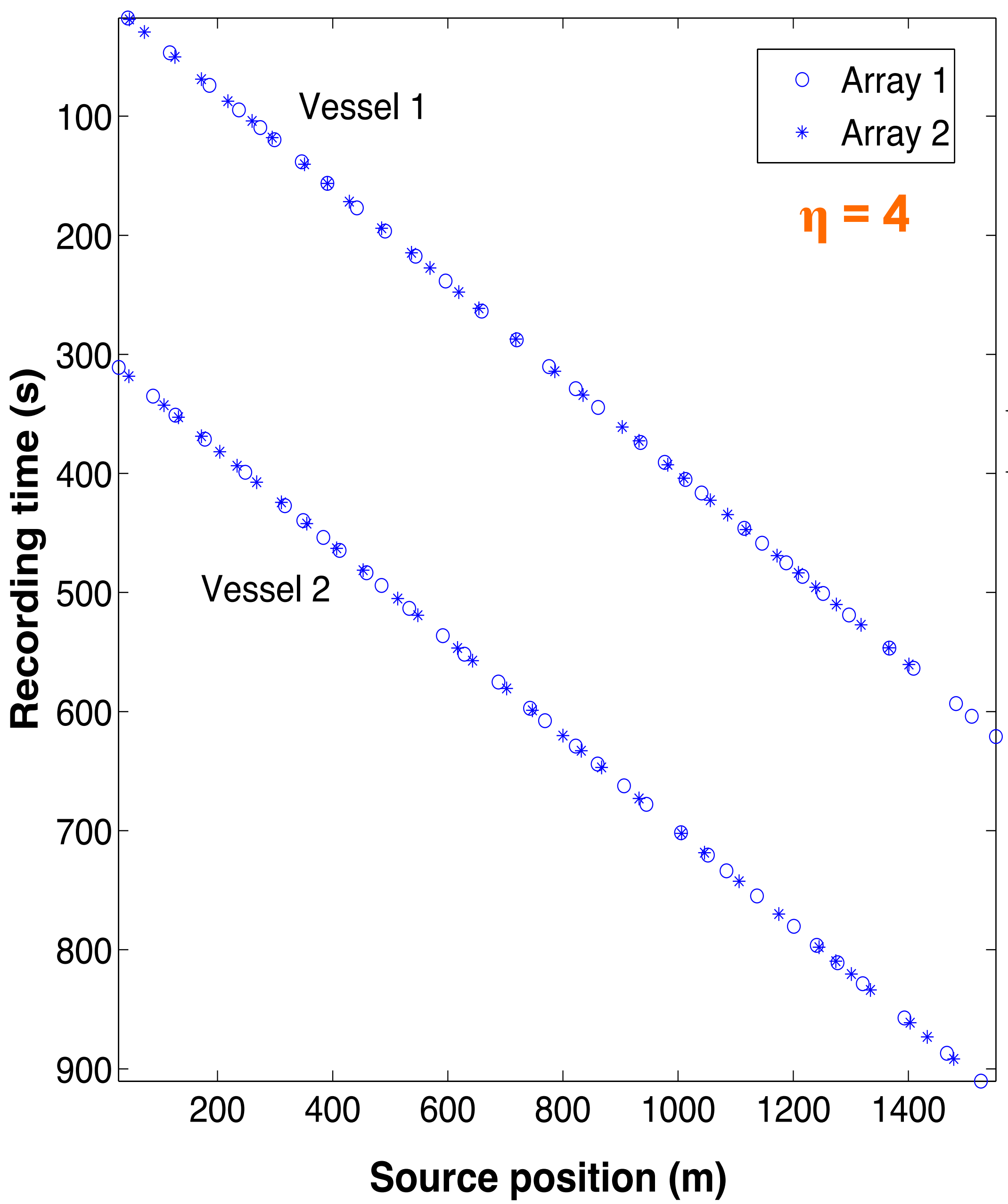
1024 time samples
128 sources
128 receivers

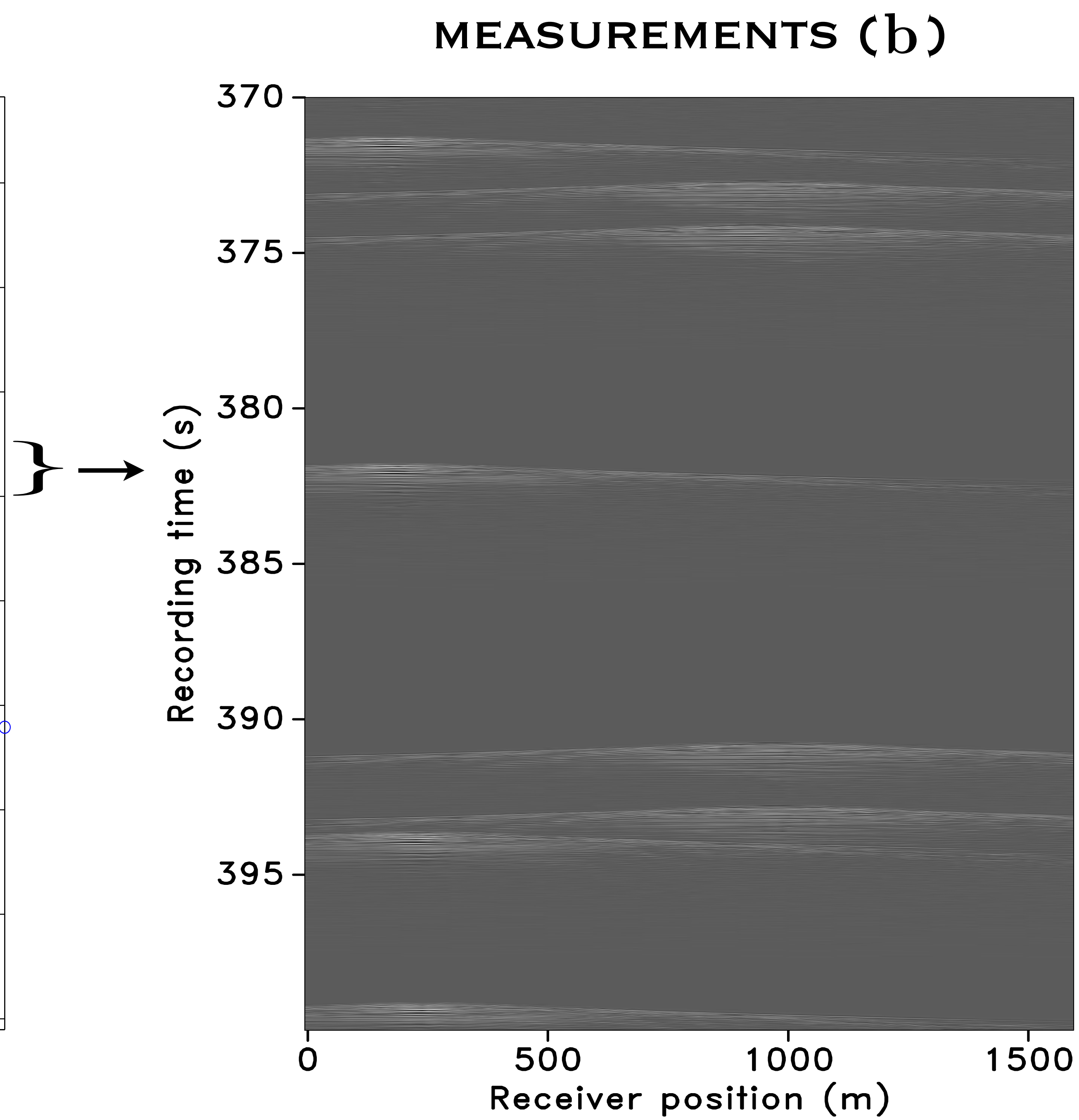
Shot interval: **12.5 m**
Receiver/group interval: **12.5 m**

Time-jittered OBC acquisition

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

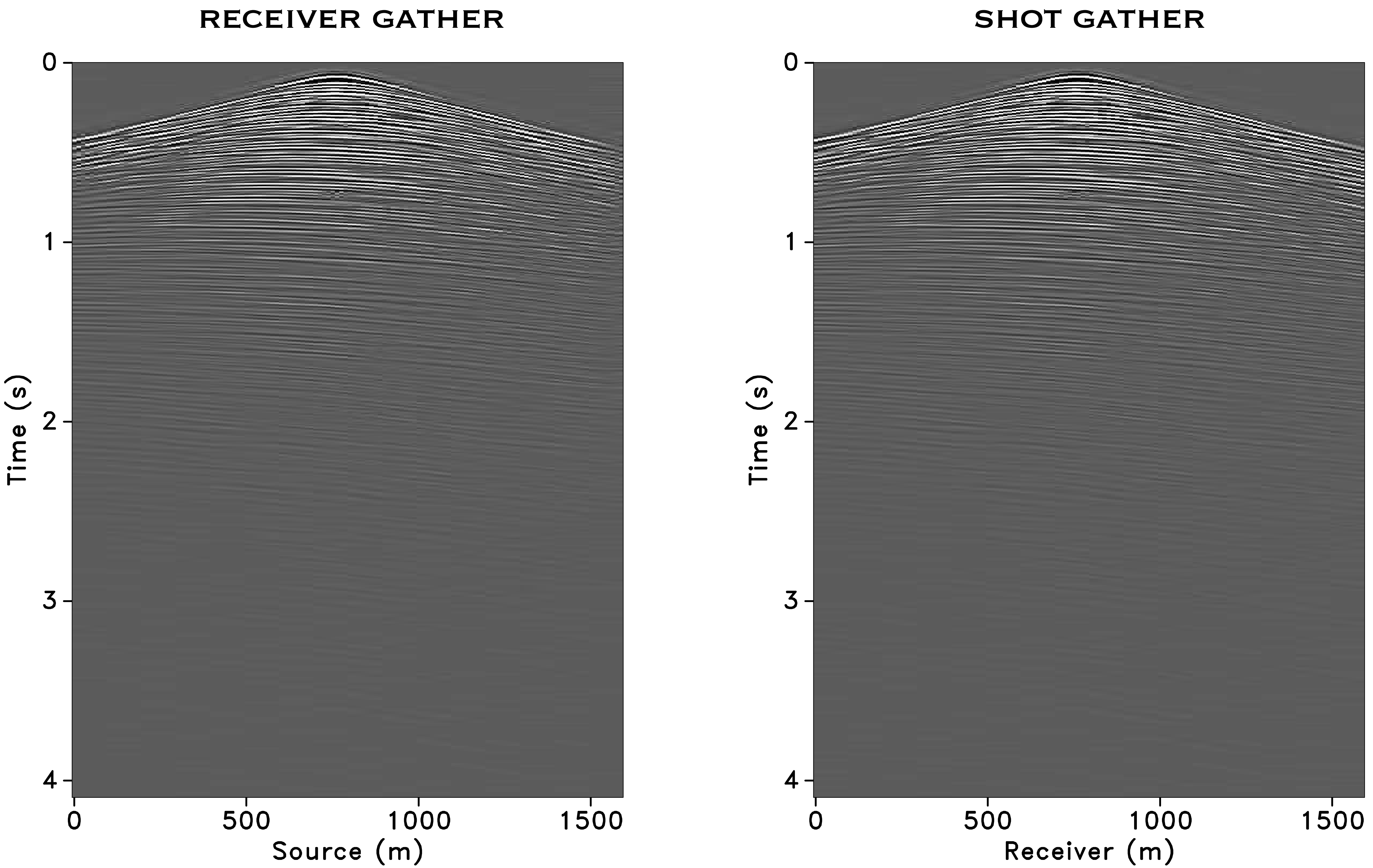
[no. of *jittered* source locations is *one-fourth* the number of sources in *ideal* periodic survey w/o overlap]





Sparsity-promoting recovery (15.4 dB)

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



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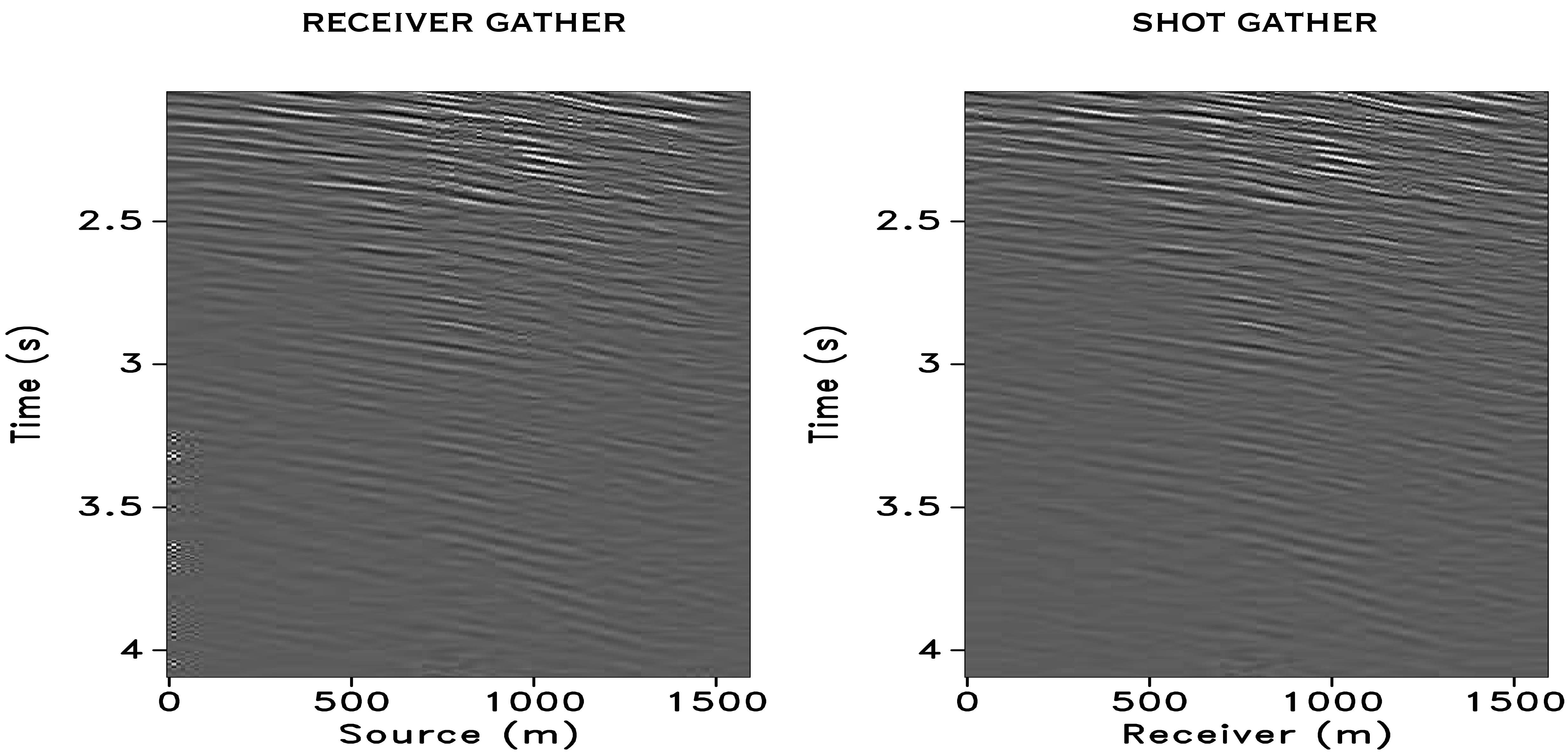

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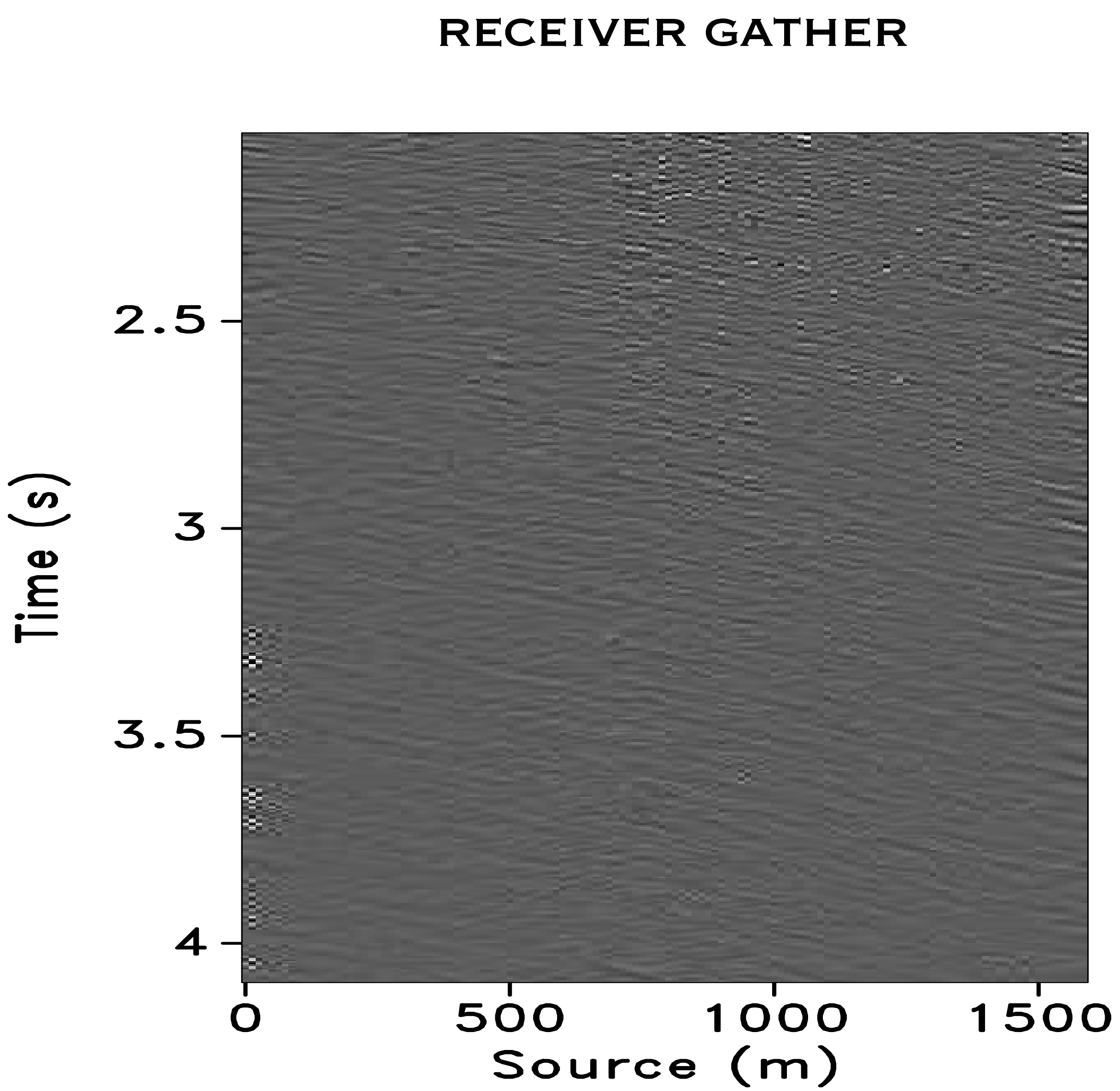

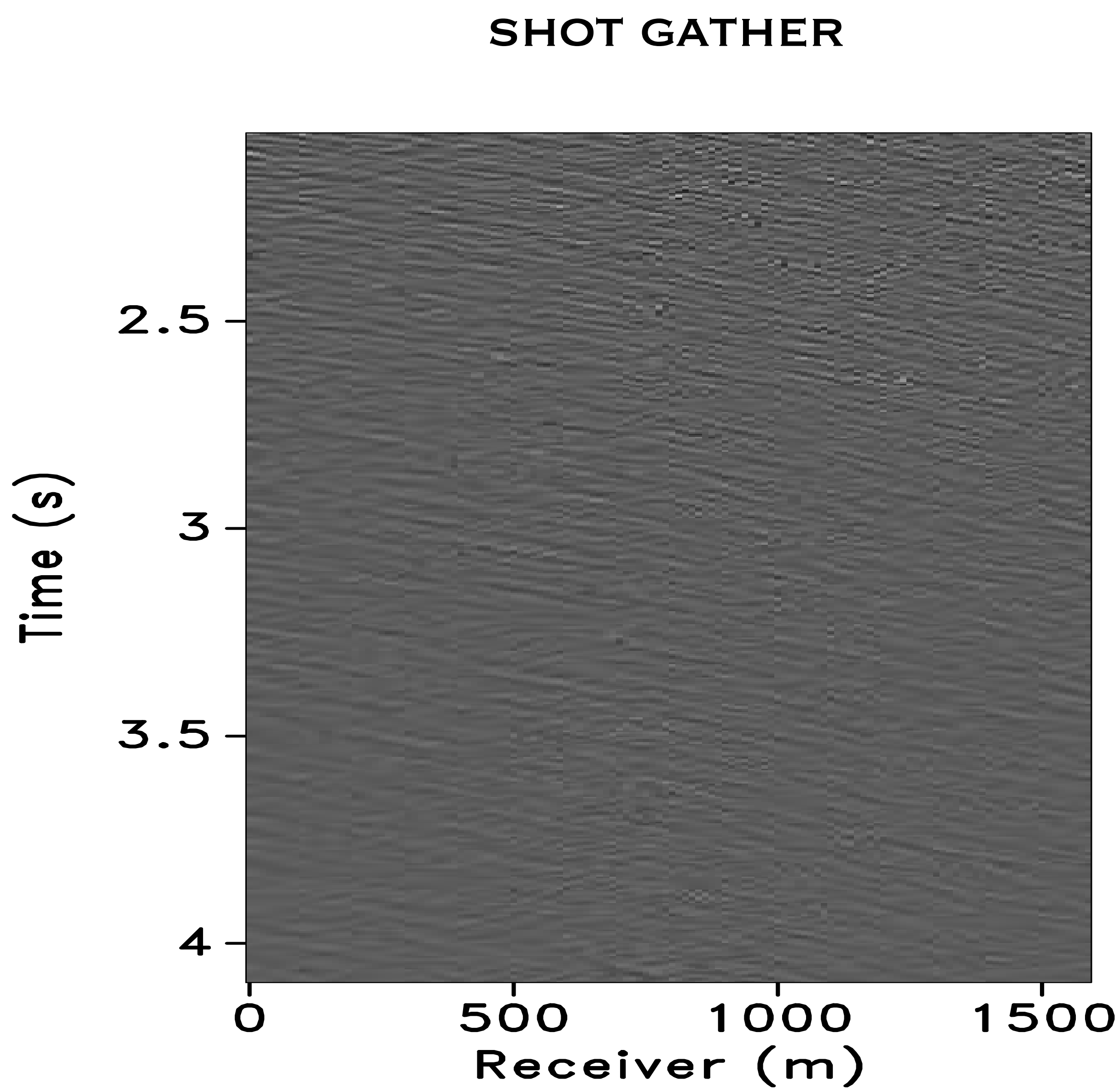

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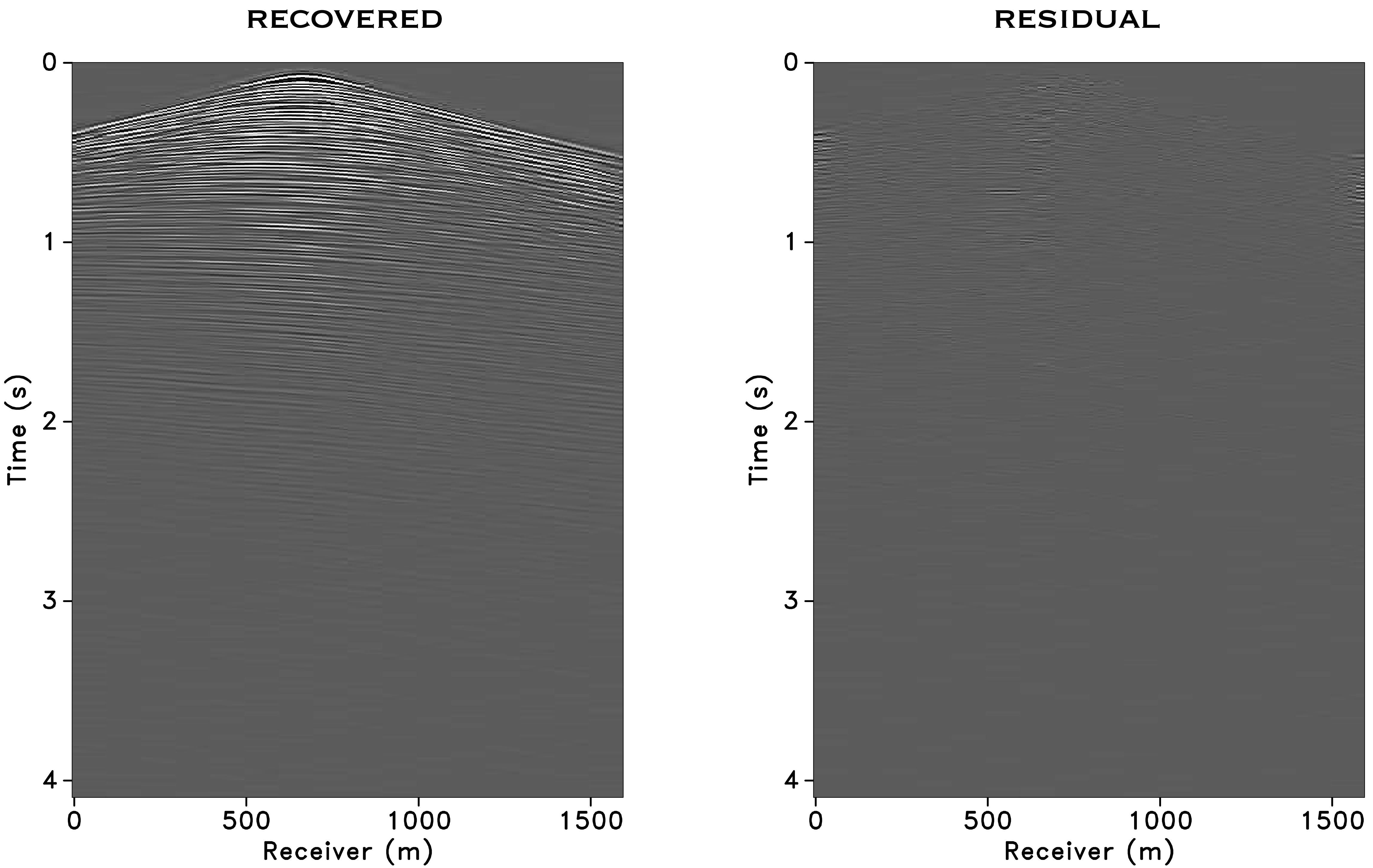

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Performance

Improvement spatial sampling ratio

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

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

Summary

	deblend + interpolate (jittered to regular)	sparsity-promoting recovery [SNR (dB)]
1 source vessel (2 airgun arrays)	50m to 25m	14.6
	50m to 12.5m	11.3
2 source vessels (2 airgun arrays per vessel)	50m to 25m	20.8
	50m to 12.5m	15.4

Observations

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

Observations

- Survey-time ratio, [Berkhout, 2008]

$$\mathrm{STR} = \frac{\text{time of the conventional recording}}{\text{time of the simultaneous recording}}$$

  - shot interval $= 12.5\mathrm{m}$, record length (shot gather) $= 10.0\mathrm{s}$, with no overlap $\implies$ *decreased* speed of the source vessel $= 1.25\mathrm{m/s}$

$$\mathrm{STR} = \frac{1600\mathrm{m}/1.25\mathrm{m/s}}{1600\mathrm{m}/2.5\mathrm{m/s}} = 2$$

Future work

- *Non*-uniform sampling grids
- 3D acquisition – innovative geometries
  - jittered shots *and* receivers
  - ocean bottom nodes

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References

Beasley, C. J., 2008, A new look at marine simultaneous source, *The Leading Edge, 27, 914-917.*
van den Berg, E., and Friedlander, M.P., 2008, Probing the Pareto frontier for basis pursuit solutions, *SIAM Journal on Scientific Computing, 31, 890-912.*
Berkhout, A. J., 2008, Changing the mindset in seismic data acquisition, *The Leading Edge, 27, 924-938.*
Candès, E. J., and L. Demanet, 2005, The curvelet representation of wave propagators is optimally sparse: *Comm. Pure Appl. Math, 58, 1472–1528.*
Candès, E. J., L. Demanet, D. L. Donoho, and L. Ying, 2006, Fast discrete curvelet transforms: *Multiscale Modeling and Simulation, 5, 861–899.*
de Kok, R., and D. Gillespie, 2002, A universal simultaneous shooting technique: 64th EAGE Conference and Exhibition
Donoho, D. L., 2006, Compressed sensing: *IEEE Trans. Inform. Theory, 52, 1289–1306.*
Hennenfent, G., and Felix J. Herrmann, 2008, Simply denoise: wavefield reconstruction via jittered undersampling, *Geophysics, 73, 19-28.*
Hennenfent, G., L. Fenelon, and Felix J. Herrmann, 2010, Nonequispaced curvelet transform for seismic data reconstruction: a sparsity-promoting approach, *Geophysics, 75, WB203-WB210.*
Huo, S., Y. Luo, and P. Kelamis, 2009, Simultaneous sources separation via multi-directional vector-median filter: *SEG Technical Program Expanded Abstracts*, 28, 31–35.
Mahdad, A., P. Doulgeris, and G. Blacquiere, 2011, Separation of blended data by iterative estimation and subtraction of blending interference noise: *Geophysics*, 76, Q9–Q17.
Mansour, H., Haneet Wason, Tim T. Y. Lin, and Felix J. Herrmann, 2012, Randomized marine acquisition with compressive sampling matrices: *Geophysical Prospecting, 60, 648–662.*
Moldoveanu, N., 2010, Random sampling: a new strategy for marine acquisition: *SEG Technical Program Expanded Abstracts*
Moldoveanu, N., and S. Fealy, 2010, Multi-vessel coil shooting acquisition: *Patent Application Publication*, US 20100142317 A1.
Moore, I., 2010, Simultaneous sources - processing and applications: *72nd EAGE Conference and Exhibition*
Stefani, J., G. Hampson, and E. Herkenhoff, 2007, Acquisition using simultaneous sources: *69th EAGE Conference and Exhibition*

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