Randomization & *repeatability* in *time*-lapse marine acquisition

Haneet Wason, Felix Oghenekohwo, and Felix J. Herrmann

SLIM
University of British Columbia

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with help from Curt da Silva & Ernie Esser

 

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Motivation

Seemingly *innocent* remark by Craig J. Beasley at SBGf meeting:

"Should we repeat in randomized marine acquisition?"

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Disclaimer

Assumptions:

- you are a *believer* in *randomized* acquisition & *sparse* recovery
- *seismic* data & *time*-lapse signal *both* permit *sparse* representations
- there are *no* calibration *errors but* there can be *additive* noise
- *degree* repetition refers to *percentage* of a *survey* that is repeated *exactly*

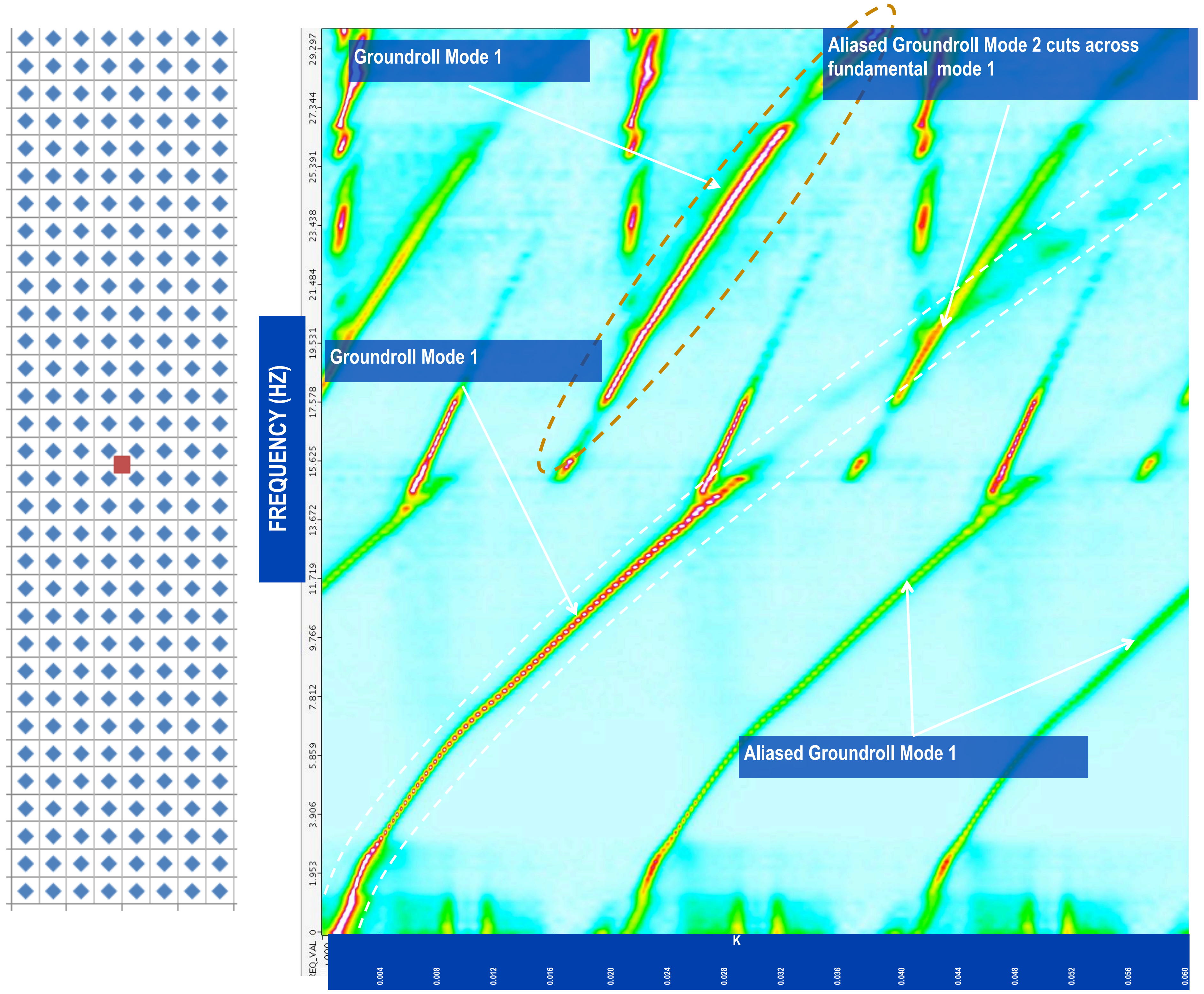
All observations are based on *synthetic* ocean bottom data...

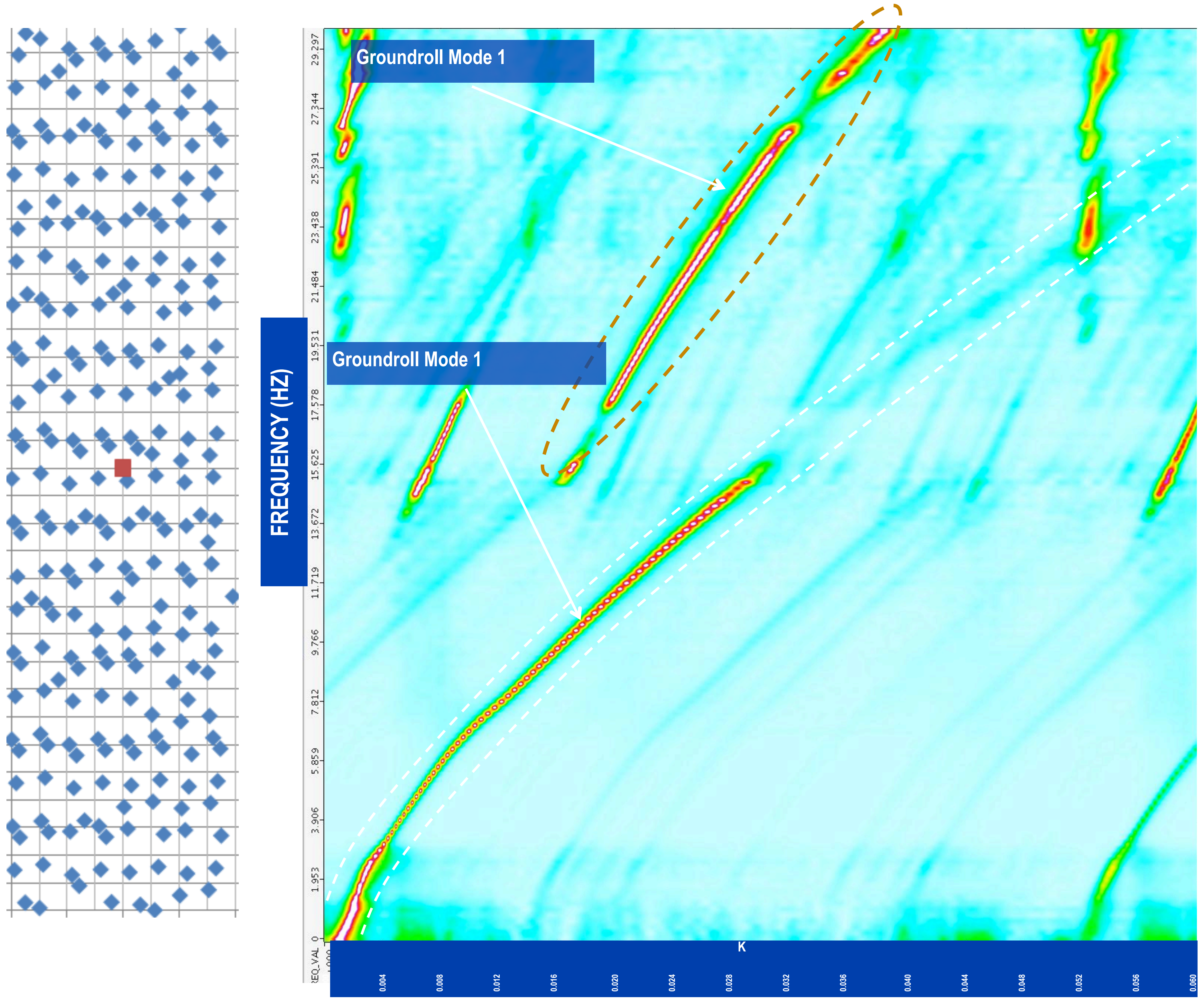
Moldoveanu, N., & Quigley, J. (2011, May). Random Sampling for Seismic Acquisition. In *73rd EAGE Conference & Exhibition*.

Randomized sampling
– examples from industry (WesternGeco)

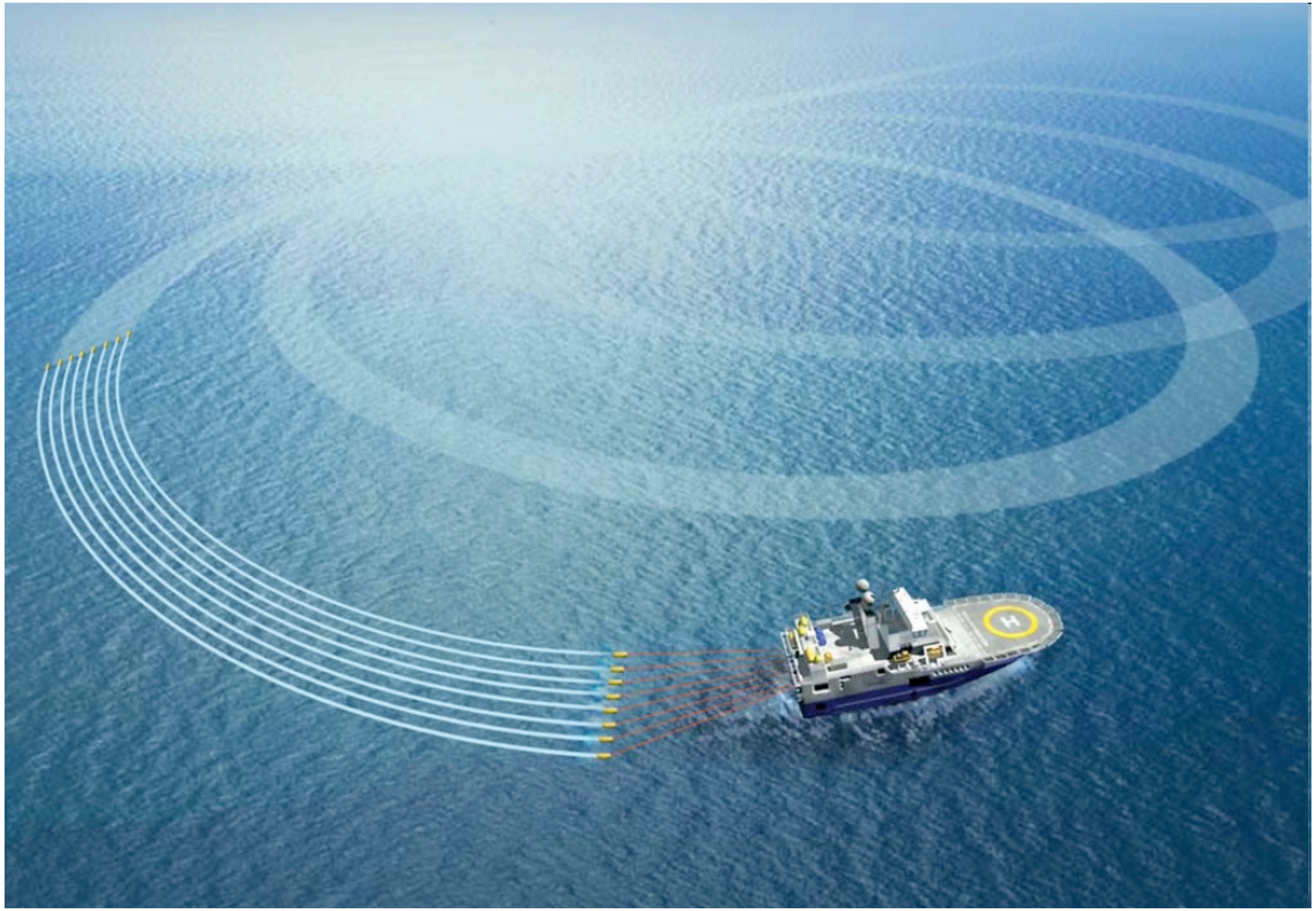
Random *source* locations

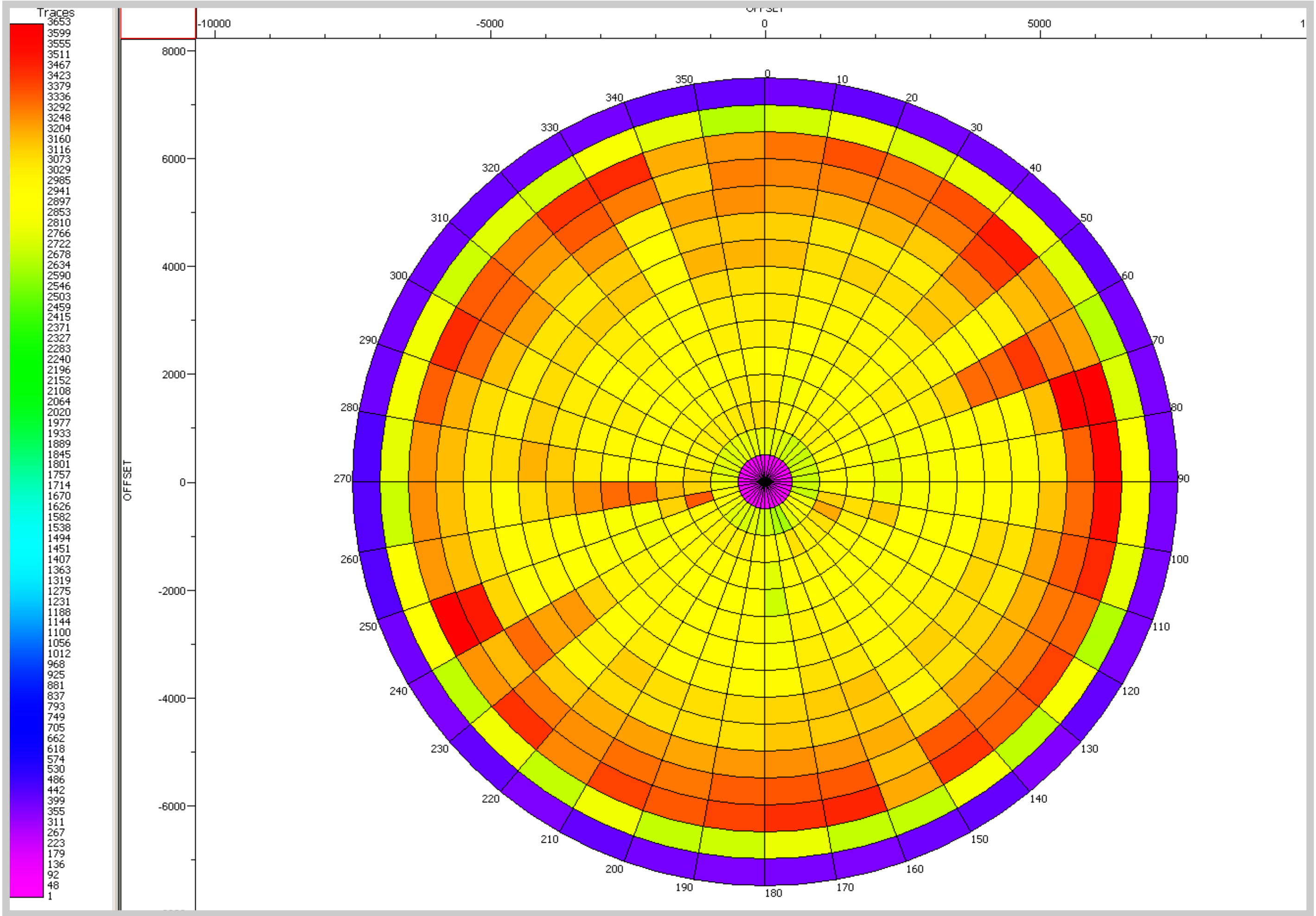
(thanks Nick Moldoveanu)

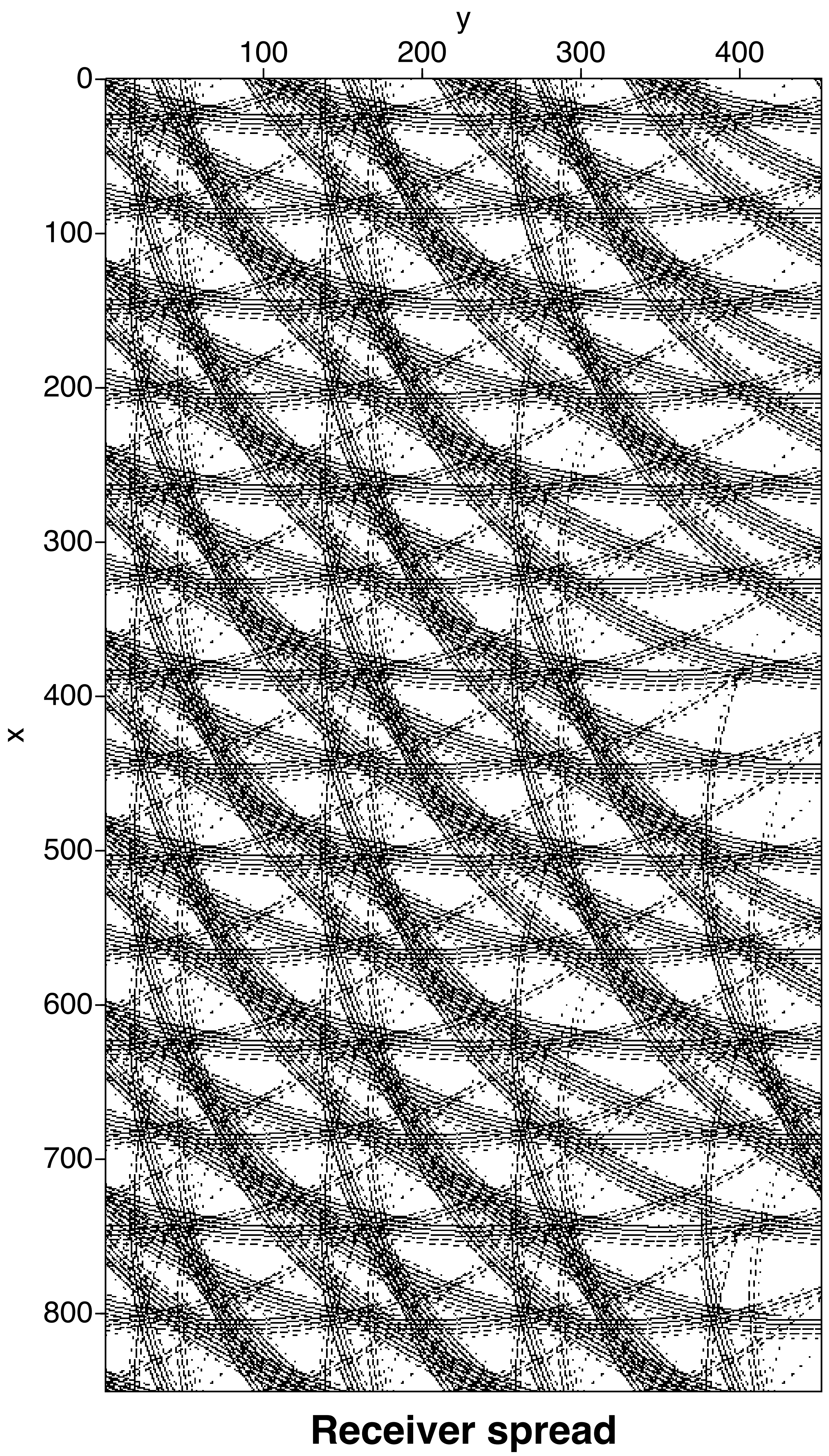




Coil sampling
– examples from industry (WesternGeco)





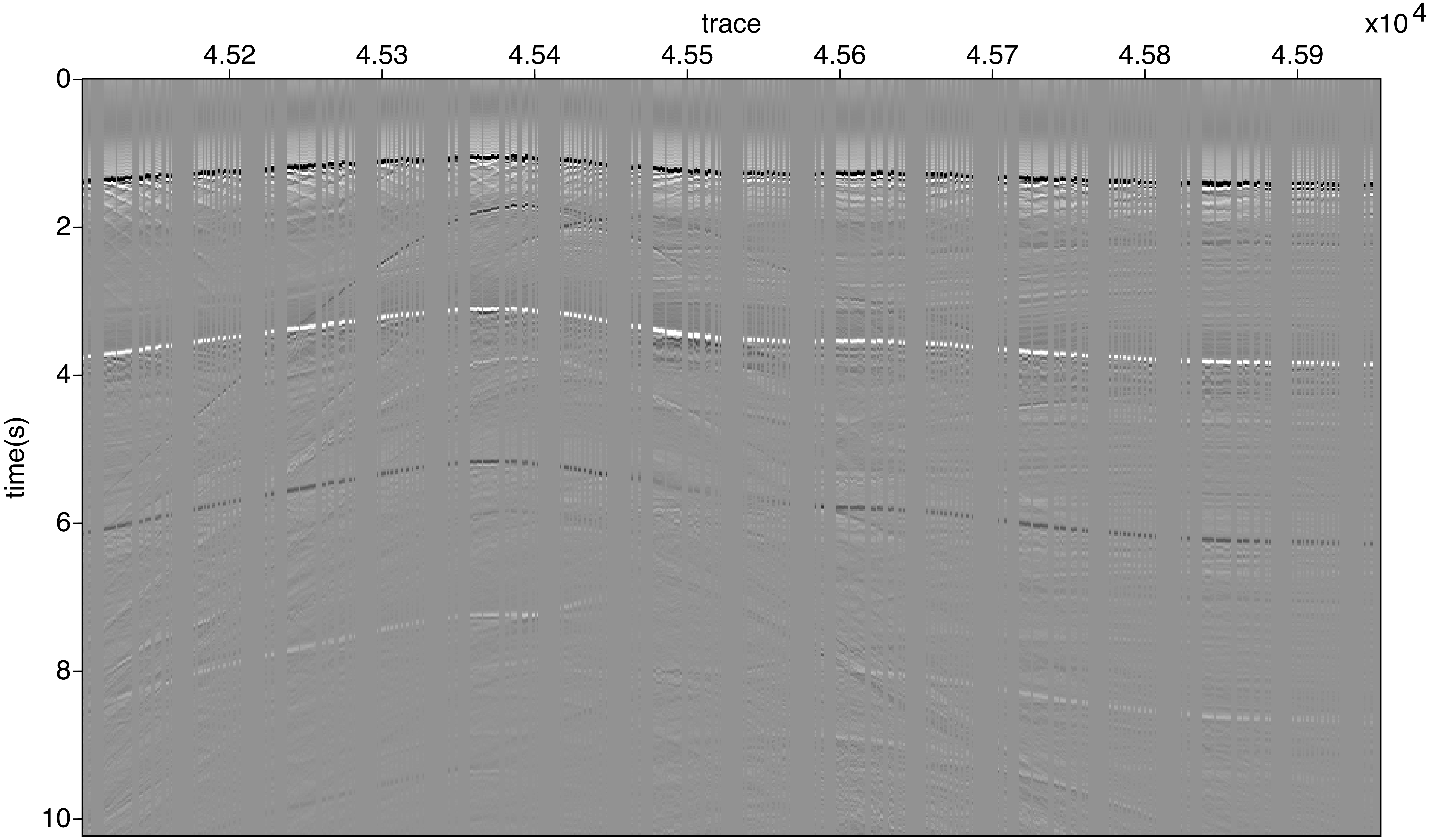


34 % of samples

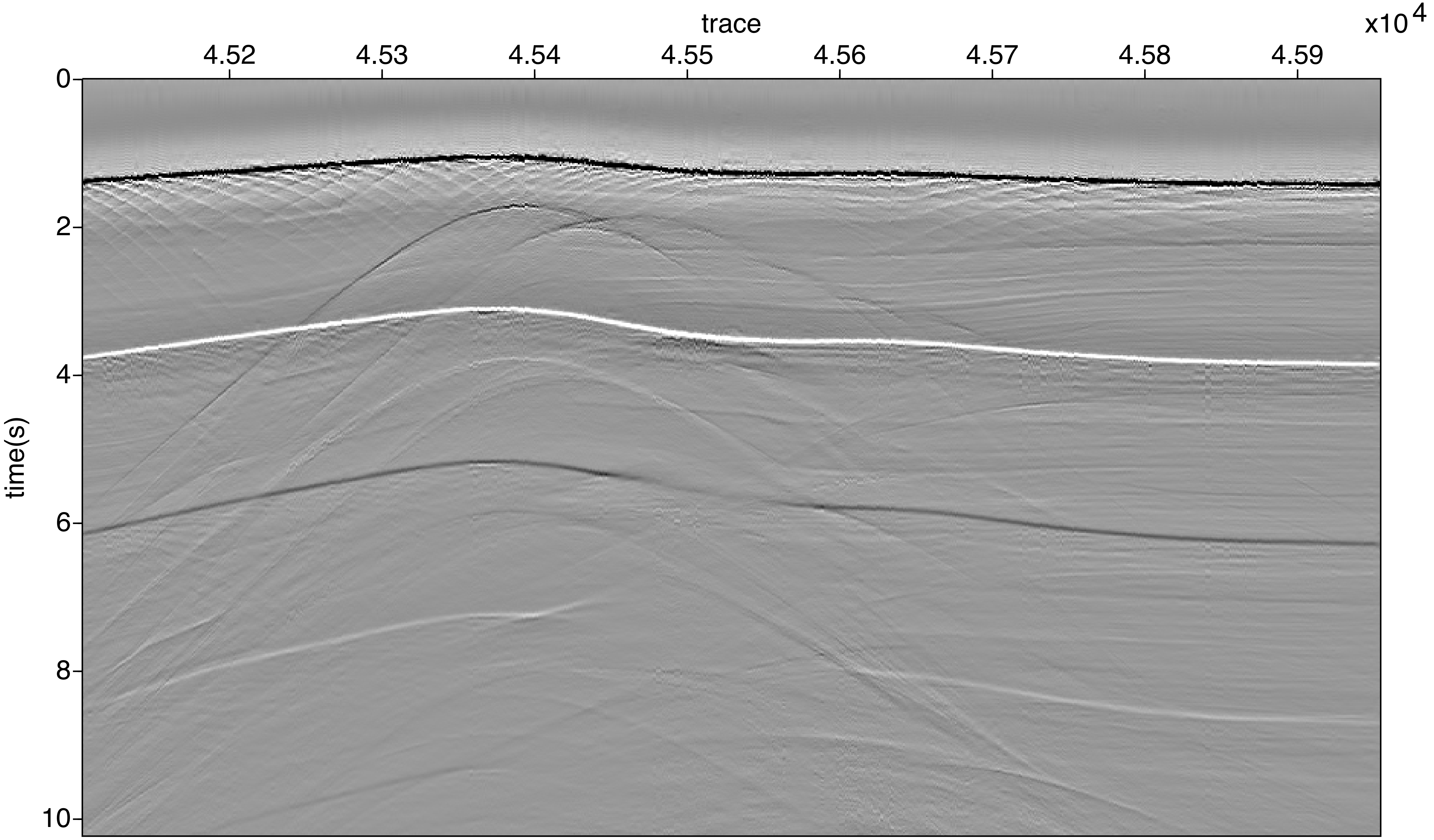
Courtesy Nick Moldoveanu

Challenge

```
Starting SPGl1 recovery...

 ================================================================================
 SPGL1_SLIM v. 46  (Tue, 14 Jun 2011) based on v.1017
 ================================================================================
 No. rows                : 103672320      No. columns          : 1459253760
 Initial tau             : 0.00e+00      Two-norm of b        : 3.92e+05
 Optimality tol          : 1.00e-04      Target objective     : 0.00e+00
 Basis pursuit tol       : 1.00e-06      Maximum iterations   :      110

  Iter      Objective   Relative Gap  Rel Error      gNorm   stepG    nnzX    nnzG            tau
     0  3.9236638e+05  0.0000000e+00   1.00e+00  6.903e+03     0.0       0       0  2.2303101e+07
     1  3.9219958e+05  1.9364118e+00   1.00e+00  6.677e+03    -0.3       2       0
     2  3.4192692e+05  2.1884194e+00   1.00e+00  5.147e+03     0.0   14452       0
     3  3.2859582e+05  4.1722491e-01   1.00e+00  1.373e+03     0.0   48295       0

   108  1.5609476e+03  1.6347854e+04   1.00e+00  7.335e+00     0.0  356264726       0
   109  1.5850938e+03  9.3198454e+04   1.00e+00  4.283e+01     0.0  346355398       0
   110  1.5641524e+03  6.9308202e+04   1.00e+00  3.104e+01     0.0  345144021       0

 ERROR EXIT -- Too many iterations

 Products with A      :      125        Total time   (secs) :  34838.7
 Products with A'     :      112        Project time (secs) :  2875.2
 Newton iterations    :       26        Mat-vec time (secs) :  25882.1
 Line search its      :       23        Subspace iterations :       0
```



Input data



Interpolation with 2D Curvelet

Mosher, C. C., Keskula, E., Kaplan, S. T., Keys, R. G., Li, C., Ata, E. Z., ... & Sood, S. (2012, November). Compressive Seismic Imaging. In *2012 SEG Annual Meeting*. Society of Exploration Geophysicists.

Randomized undersampling

– examples from industry (ConocoPhilips)

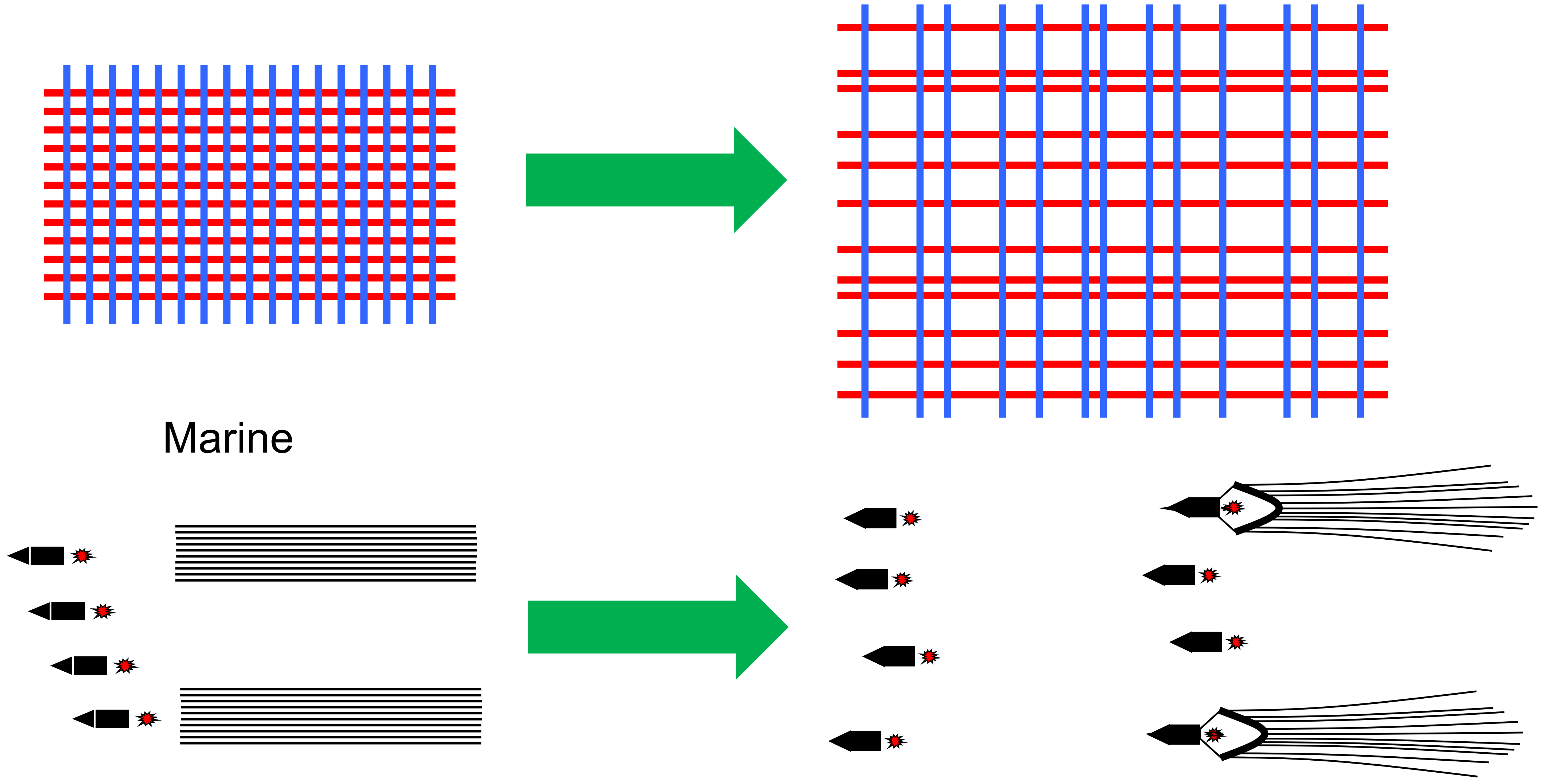
Deliberate & natural randomness in acquisition

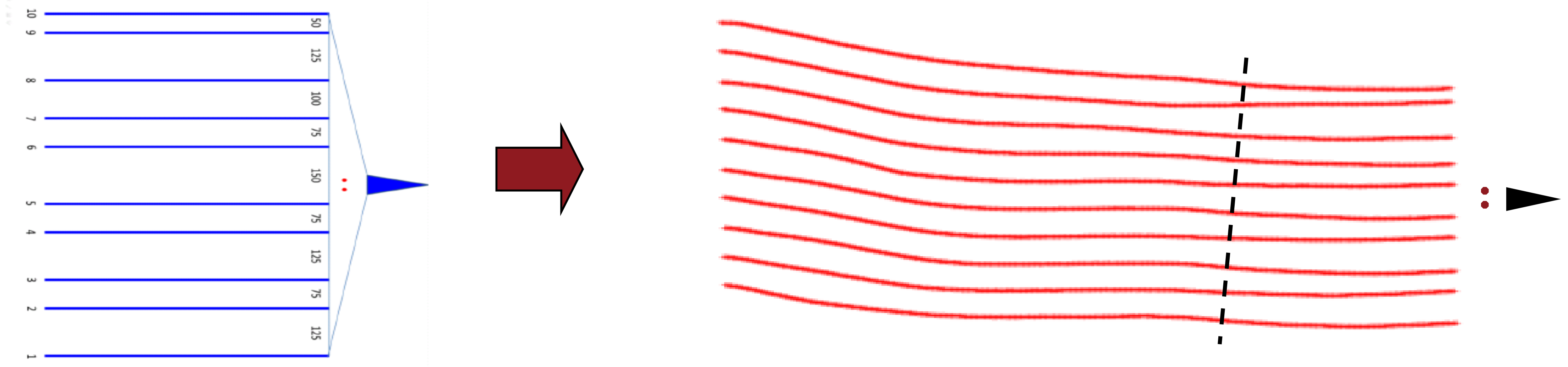
(thanks to Chuck Mosher)

Compressive Sensing = Acquisition Efficiency

Land / Node

Marine





Designed

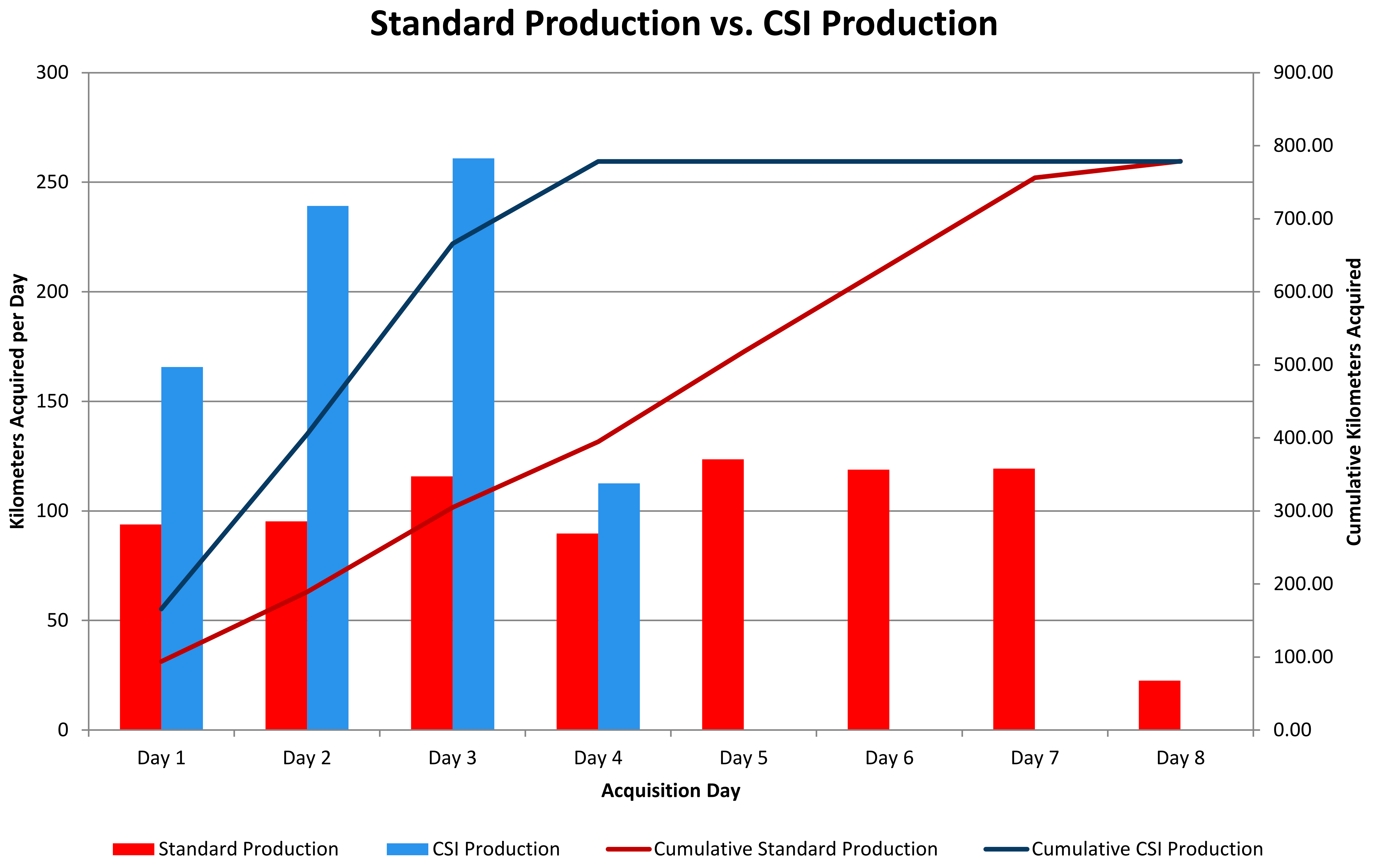
Actually Acquired

Bottom line

– examples from industry (ConocoPhilips)

Economics

(thanks to Chuck Mosher)



Felix J. Herrmann, Michael P. Friedlander, and Ozgur Yilmaz, "Fighting the Curse of Dimensionality: Compressive Sensing in Exploration Seismology", *Signal Processing Magazine, IEEE*, vol. 29, p. 88-100, 2012
Felix J. Herrmann, "Randomized sampling and sparsity: Getting more information from fewer samples", *Geophysics*, vol. 75, p. WB173-WB187, 2010

Compressive sensing *paradigm*

Find **representations that reveal** ***structure***

- *transform*-domain *sparsity* (e.g., Fourier, curvelets, etc.)

Sample **to** ***break*** **the** ***structure***

- *randomized* acquisition (e.g., *jittered* sampling, time *dithering*, *encoding*, etc.)
- destroy *sparsity*

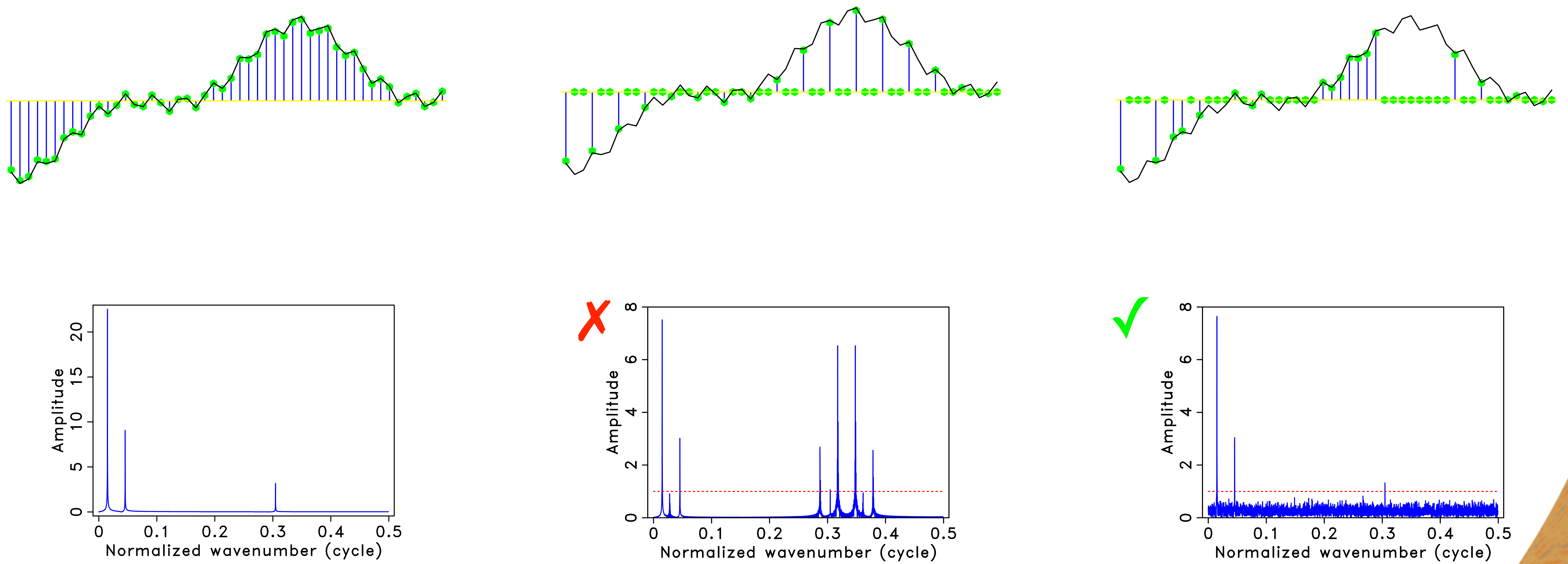
Recover ***structure*** **by promoting**

- *sparsity* via *one*-norm *minimization*

Felix J. Herrmann and Gilles Hennenfent, "Non-parametric seismic data recovery with curvelet frames", *GJI*, vol. 173, p. 233-248, 2008.
Gilles Hennenfent and Felix J. Herrmann, "Simply denoise: wavefield reconstruction via jittered undersampling", *Geophysics*, vol. 73, p. V19-V28, 2008.
Felix J. Herrmann, "Randomized sampling and sparsity: Getting more information from fewer samples", *Geophysics*, vol. 75, p. WB173-WB187, 2010.

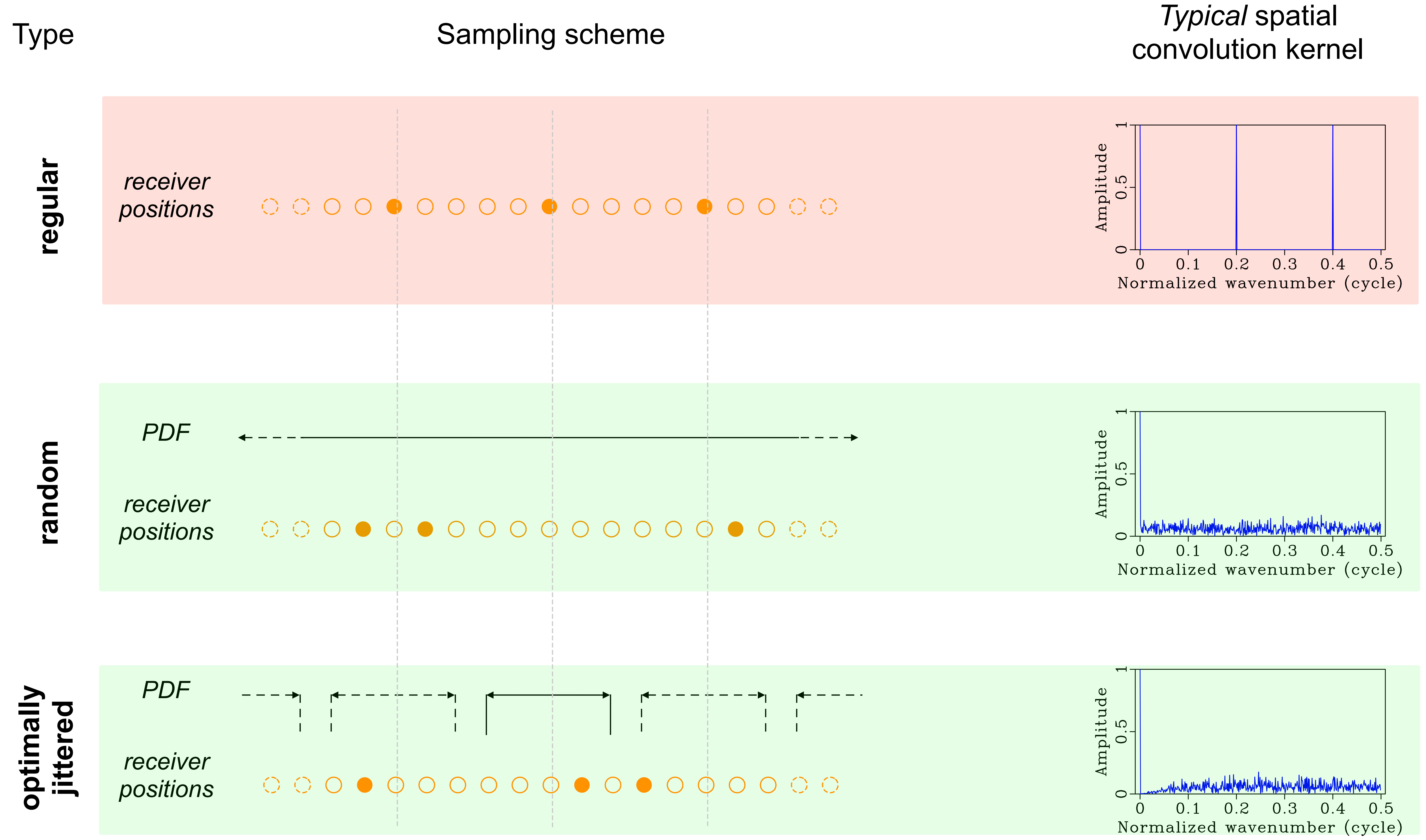
Golden oldies

– sparse time-harmonic signals

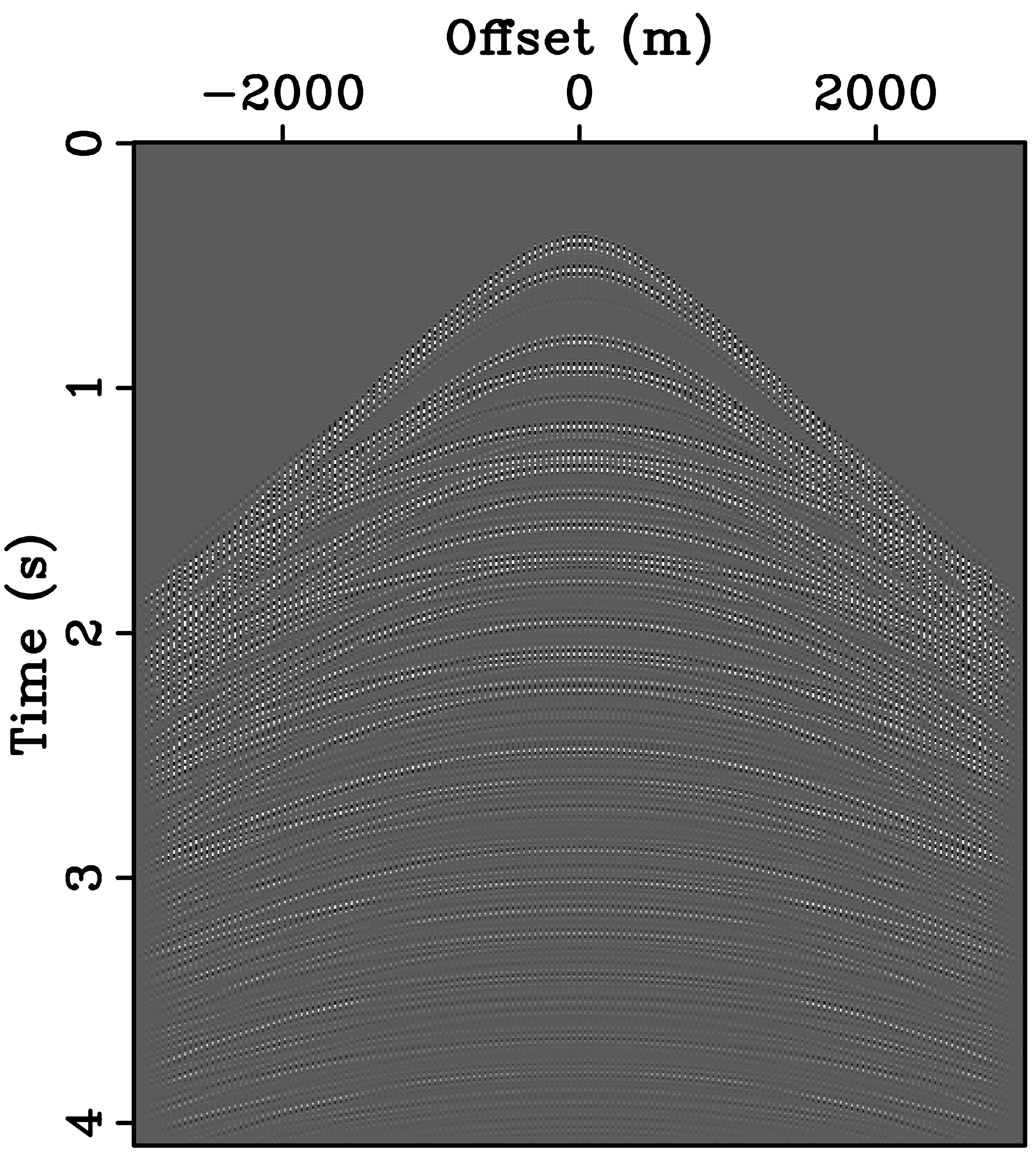


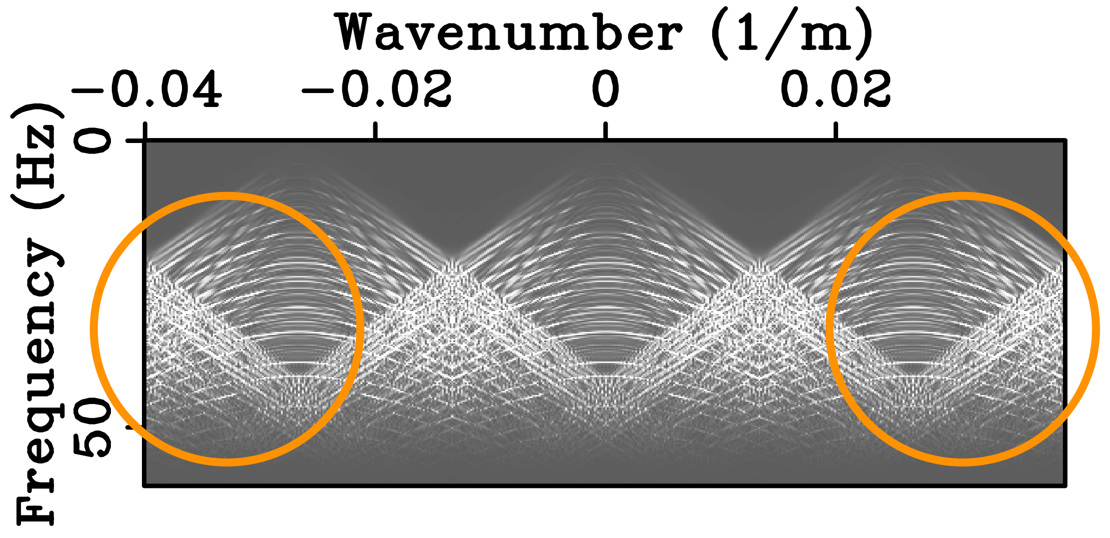
Gilles Hennenfent and Felix J. Herrmann, “Simply denoise: wavefield reconstruction via jittered undersampling”, *Geophysics*, vol. 73, p. V19-V28, 2008.

Jittered sampling

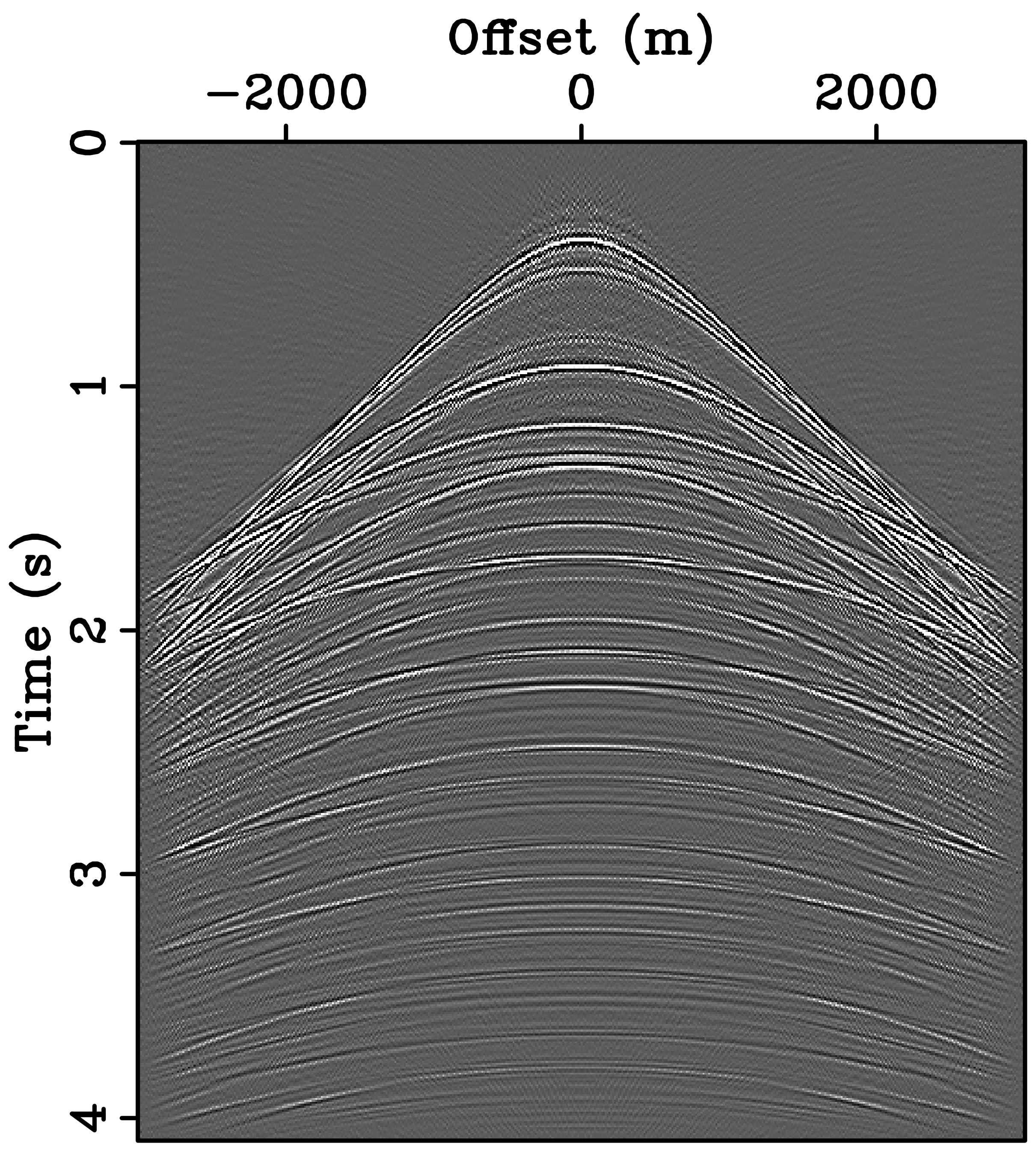


Periodic sampling

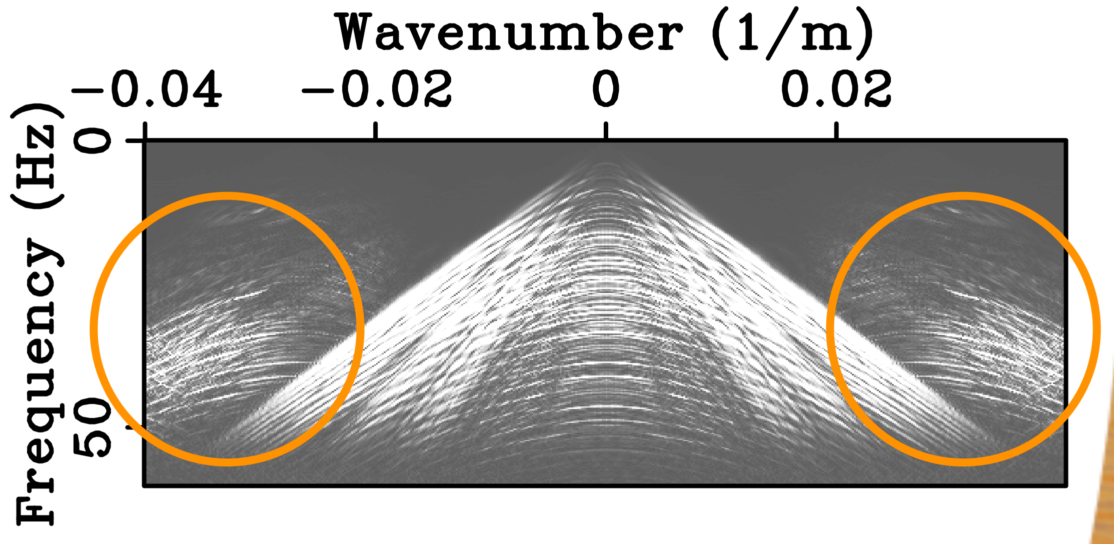




***3-fold under*sampled**

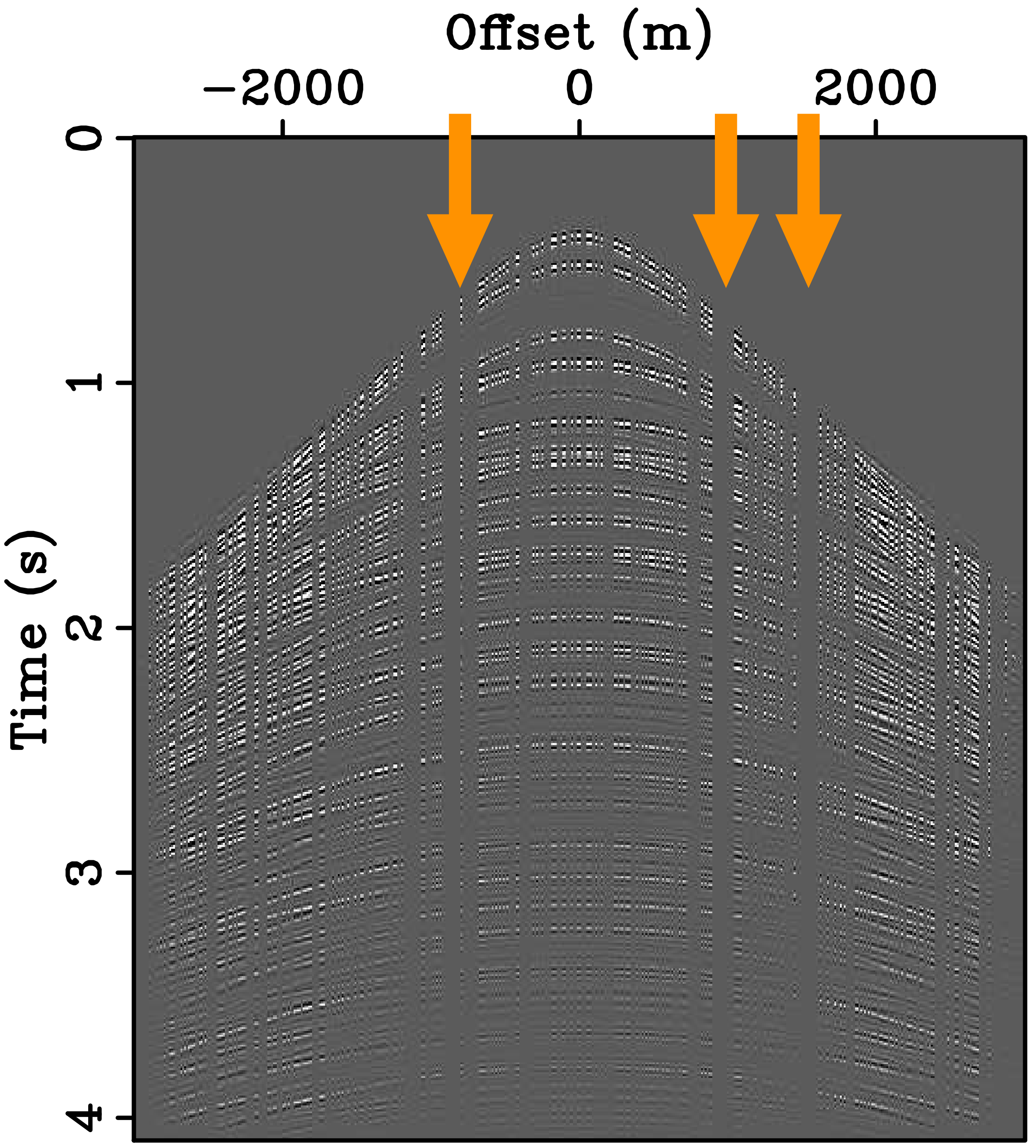


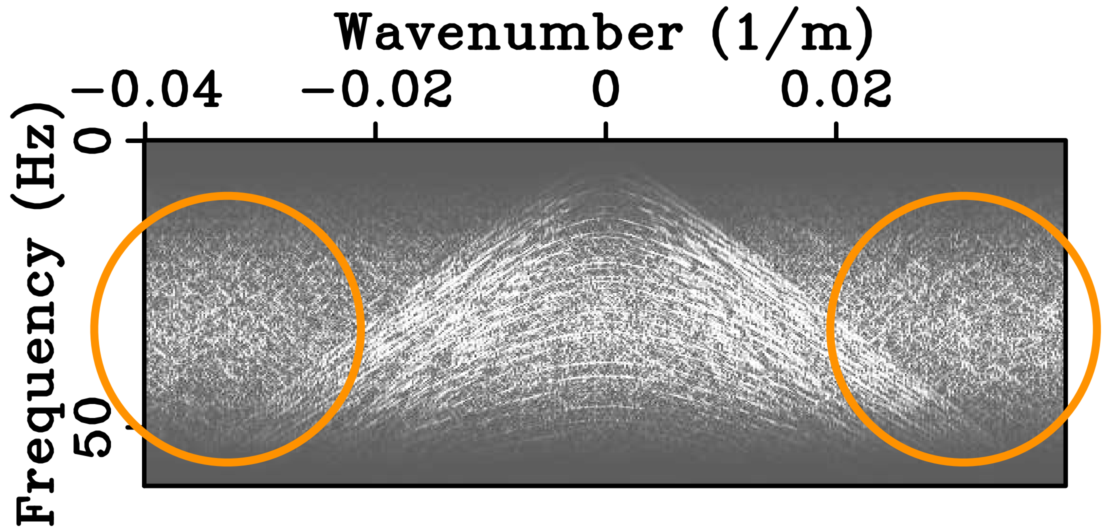
SNR = 6.92 dB

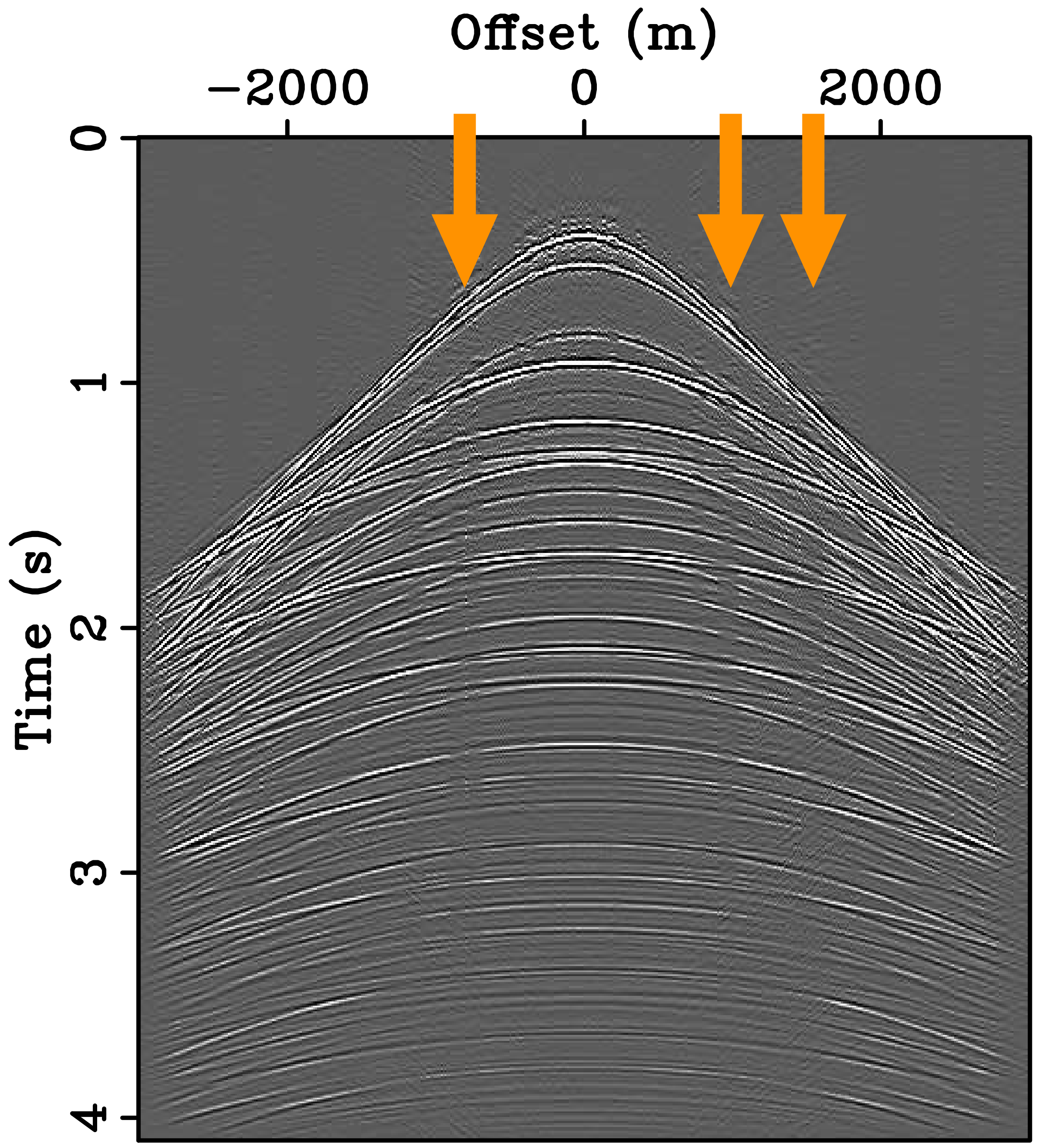


recovered

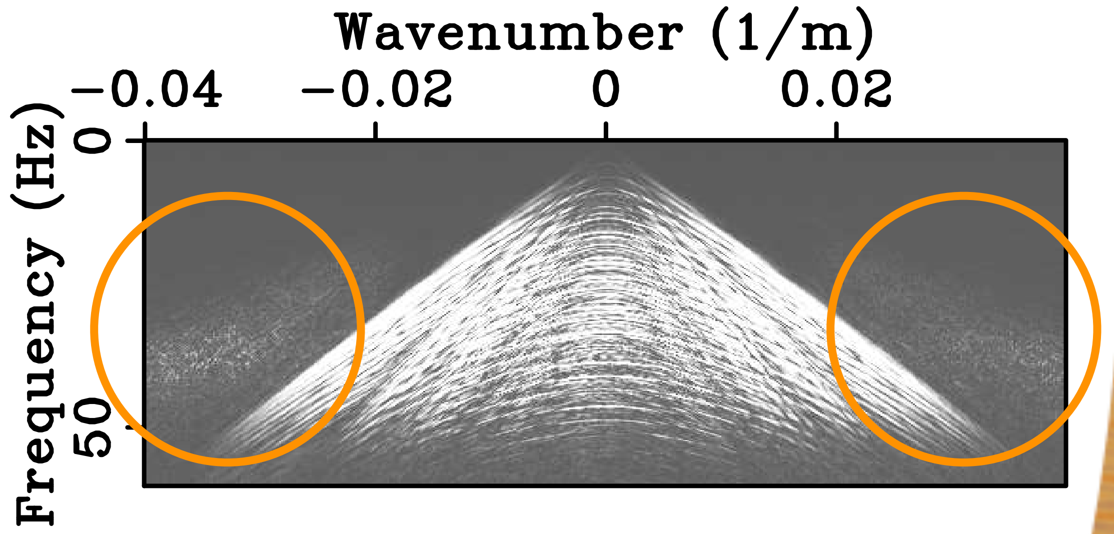
Uniform random sampling







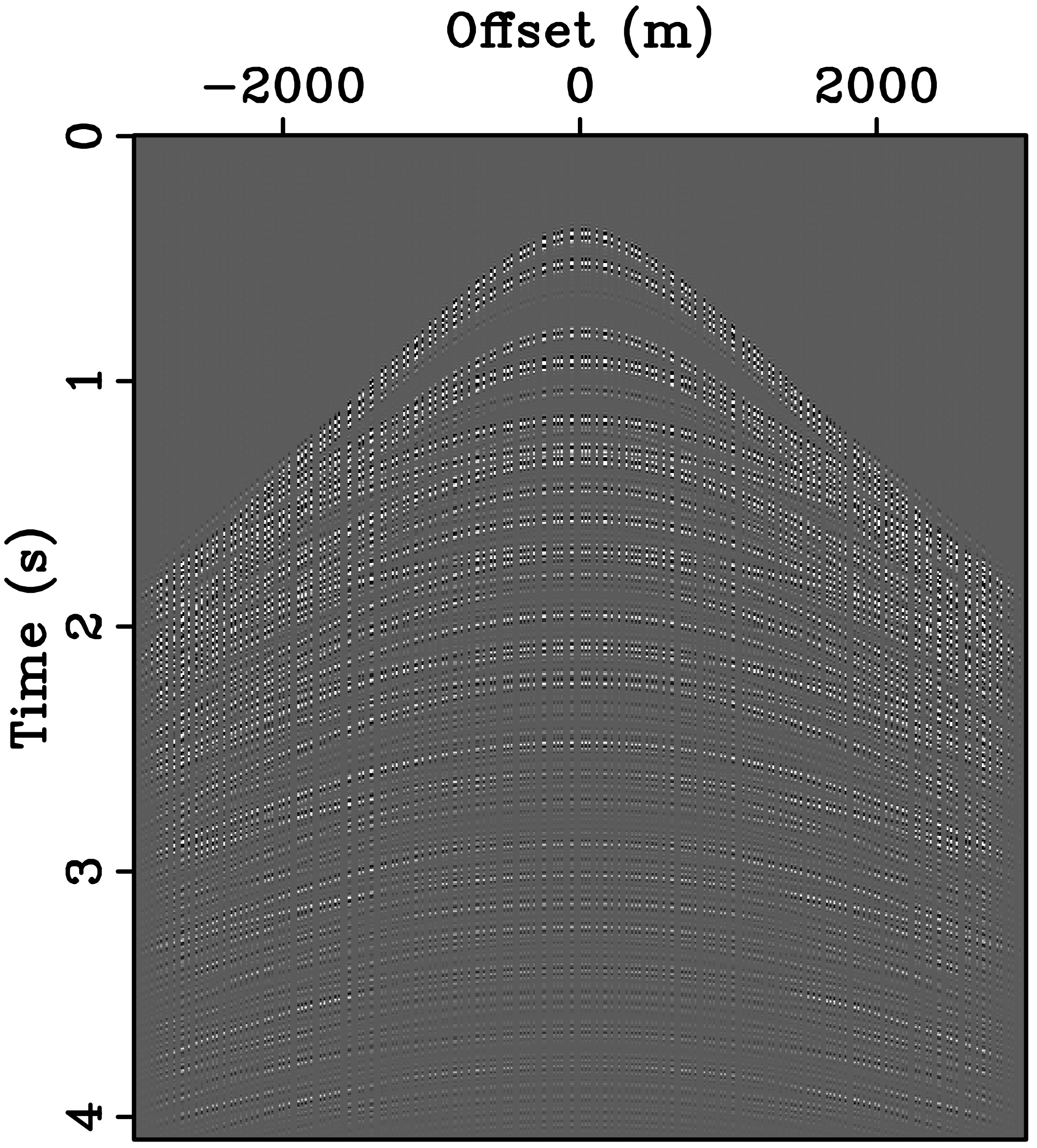
SNR = 9.72 dB

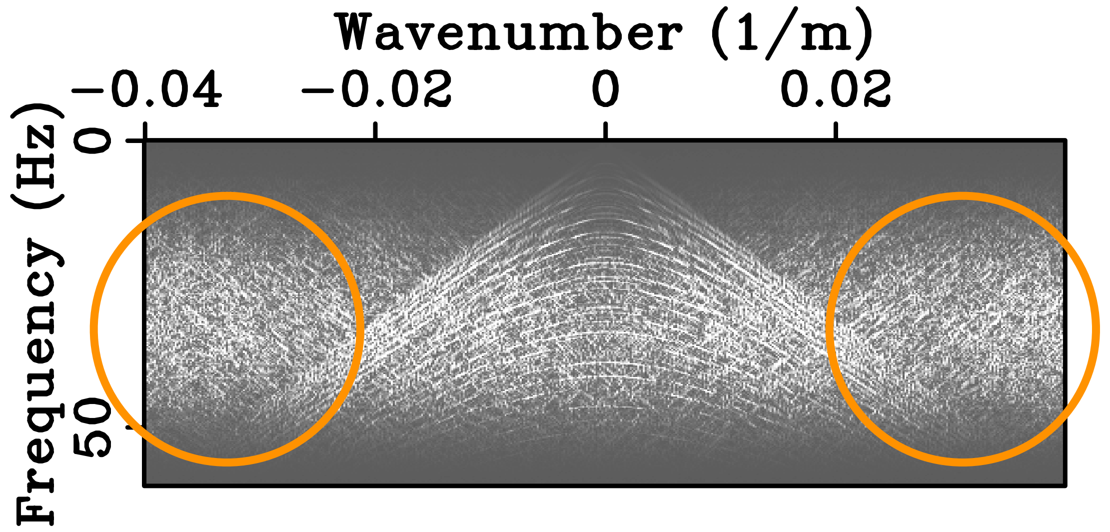


***3-fold under*sampled**

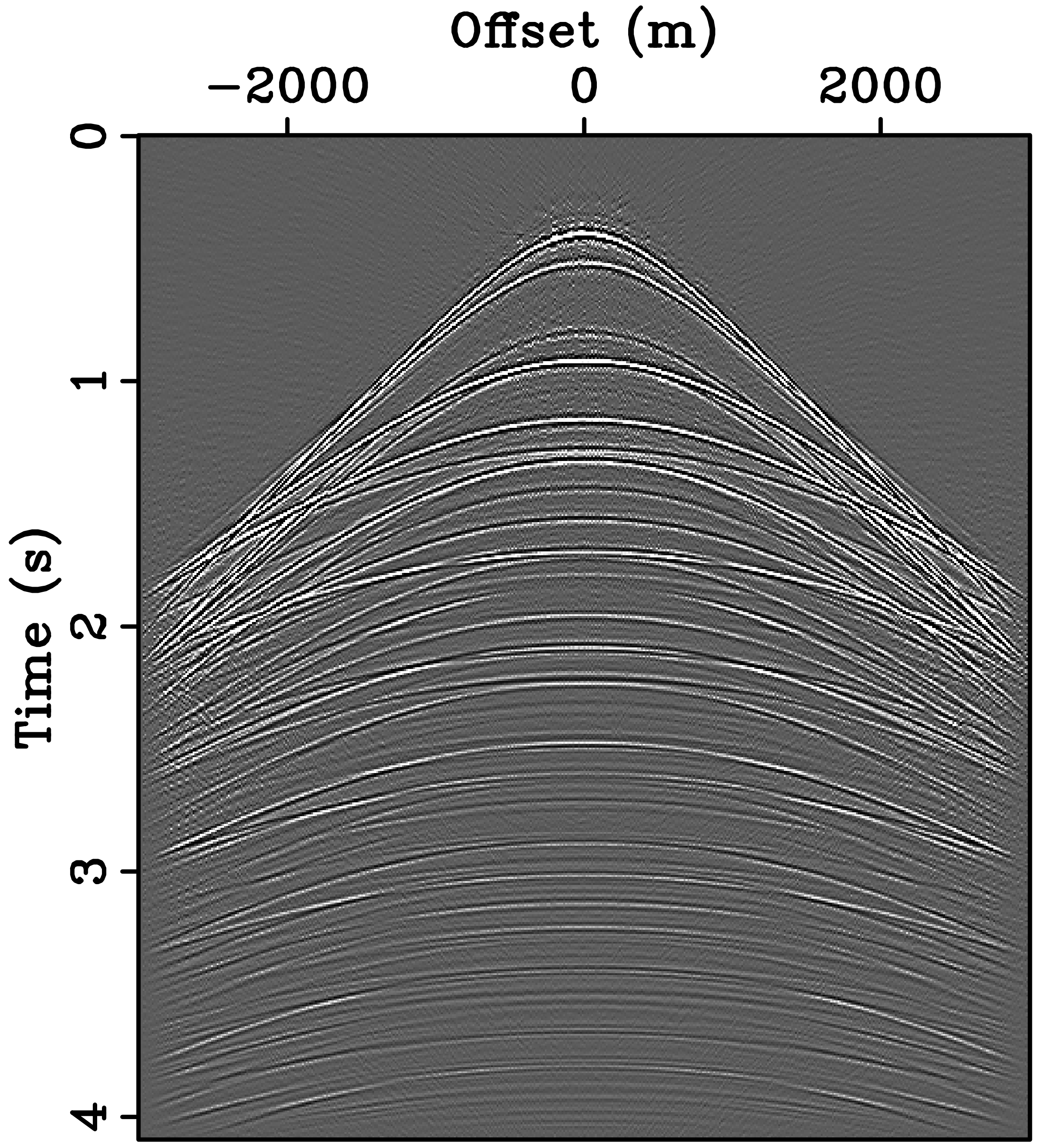
recovered

Jittered sampling

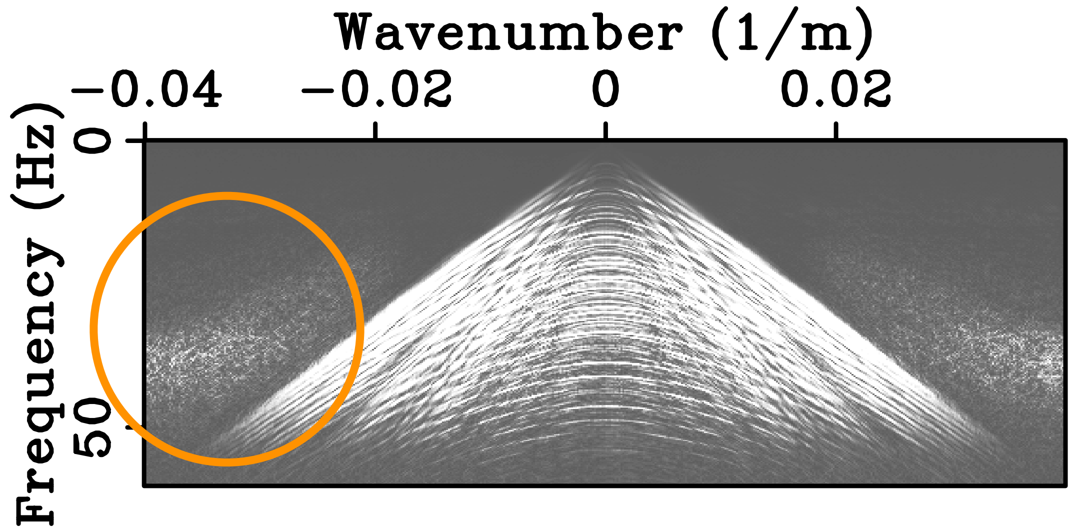




*3-fold under*sampled



SNR = 10.42 dB



recovered

Time-*jittered* marine acquisition

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Objective

***Shorten* marine acquisition *times* & *increase* source sample *density*.**

Question:

Does increased *variability* of *firing* times improve recovery?

Regular vs. *jittered* locations

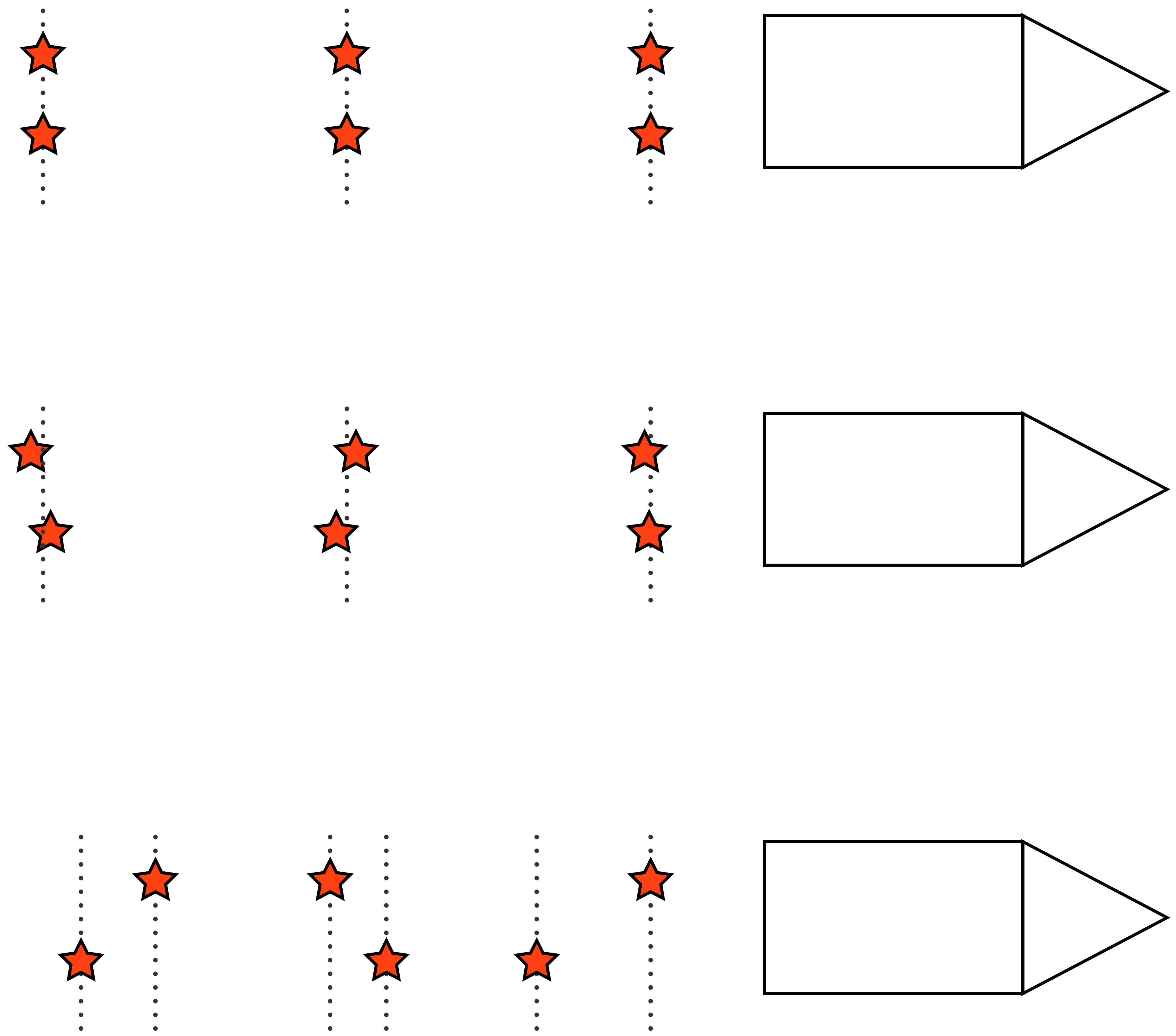
regularly sampled spatial grid

almost regularly sampled spatial grid

(low variability)

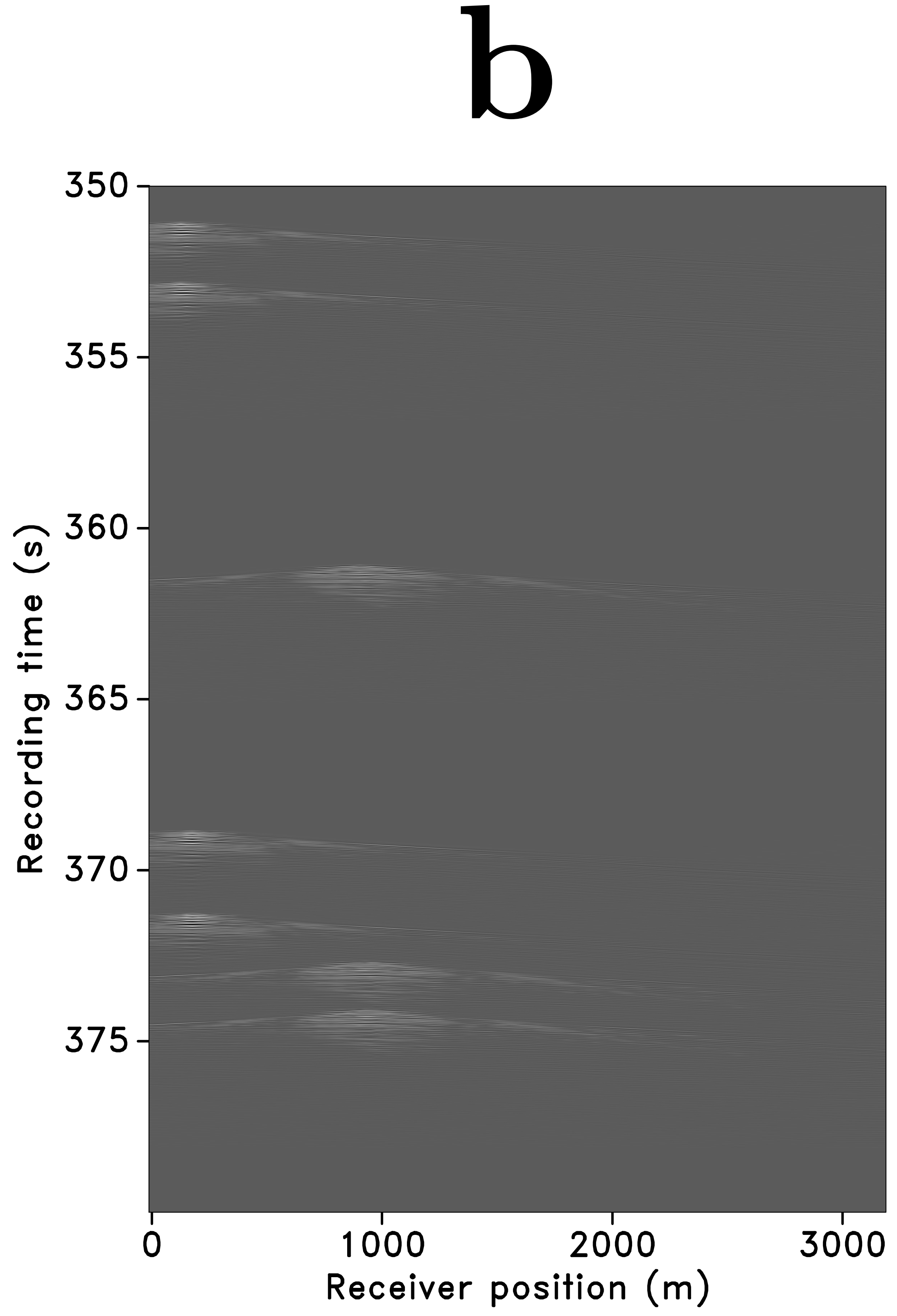
irregularly sampled spatial grid

(high variability)

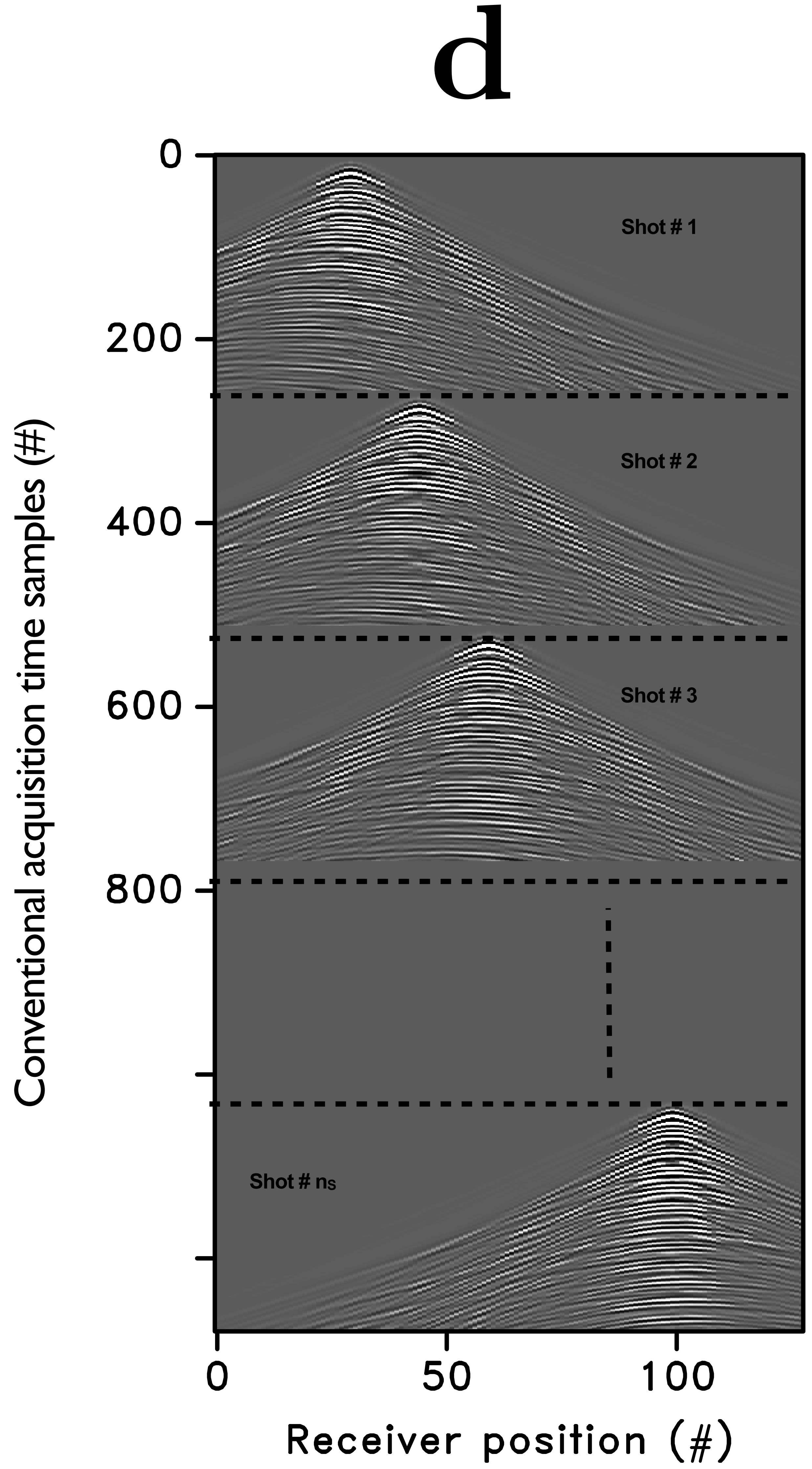


acquire in the field on *irregular* grid (*subsampled* shots *w/ overlap* between shot records)

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

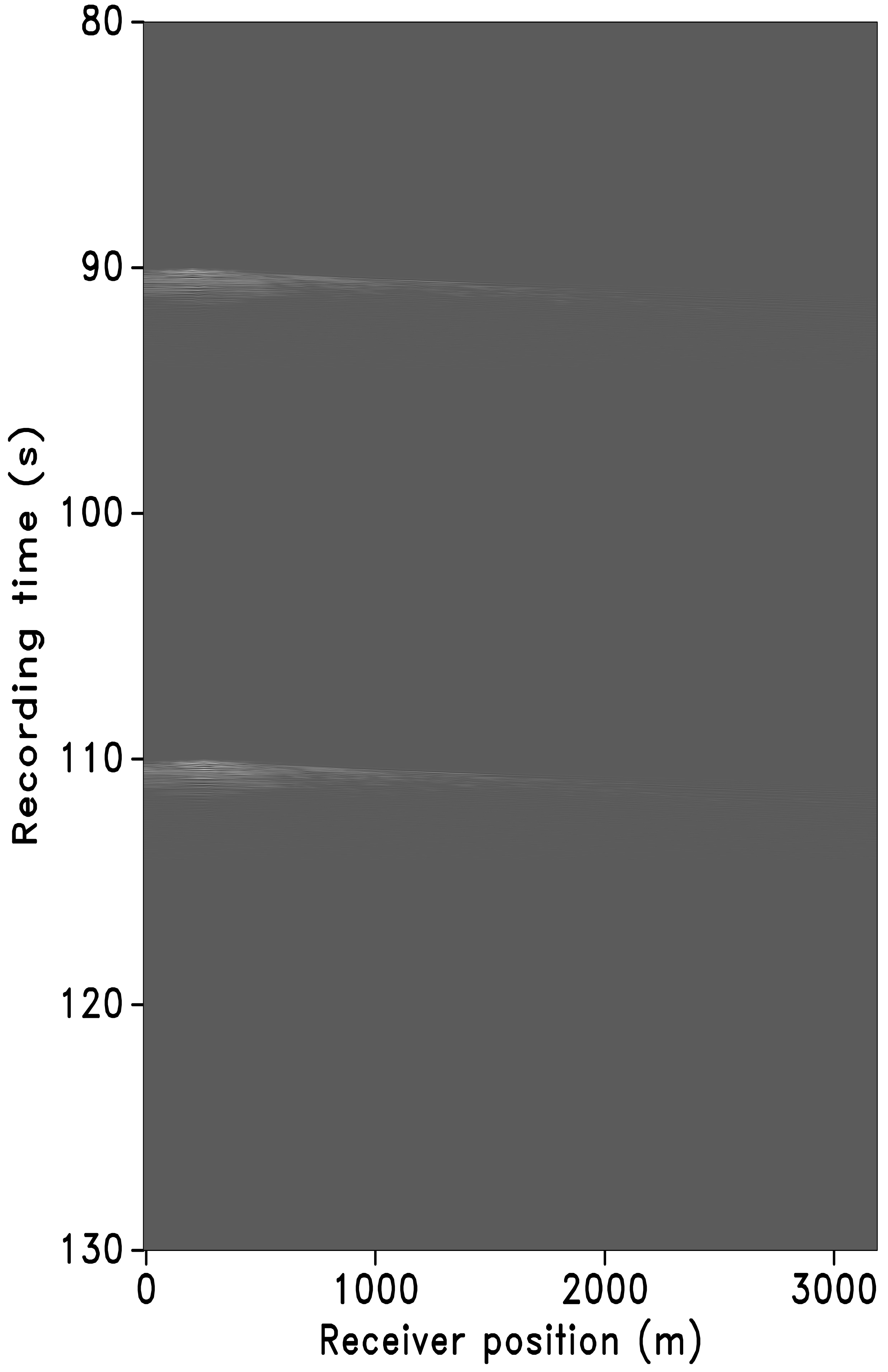


= M

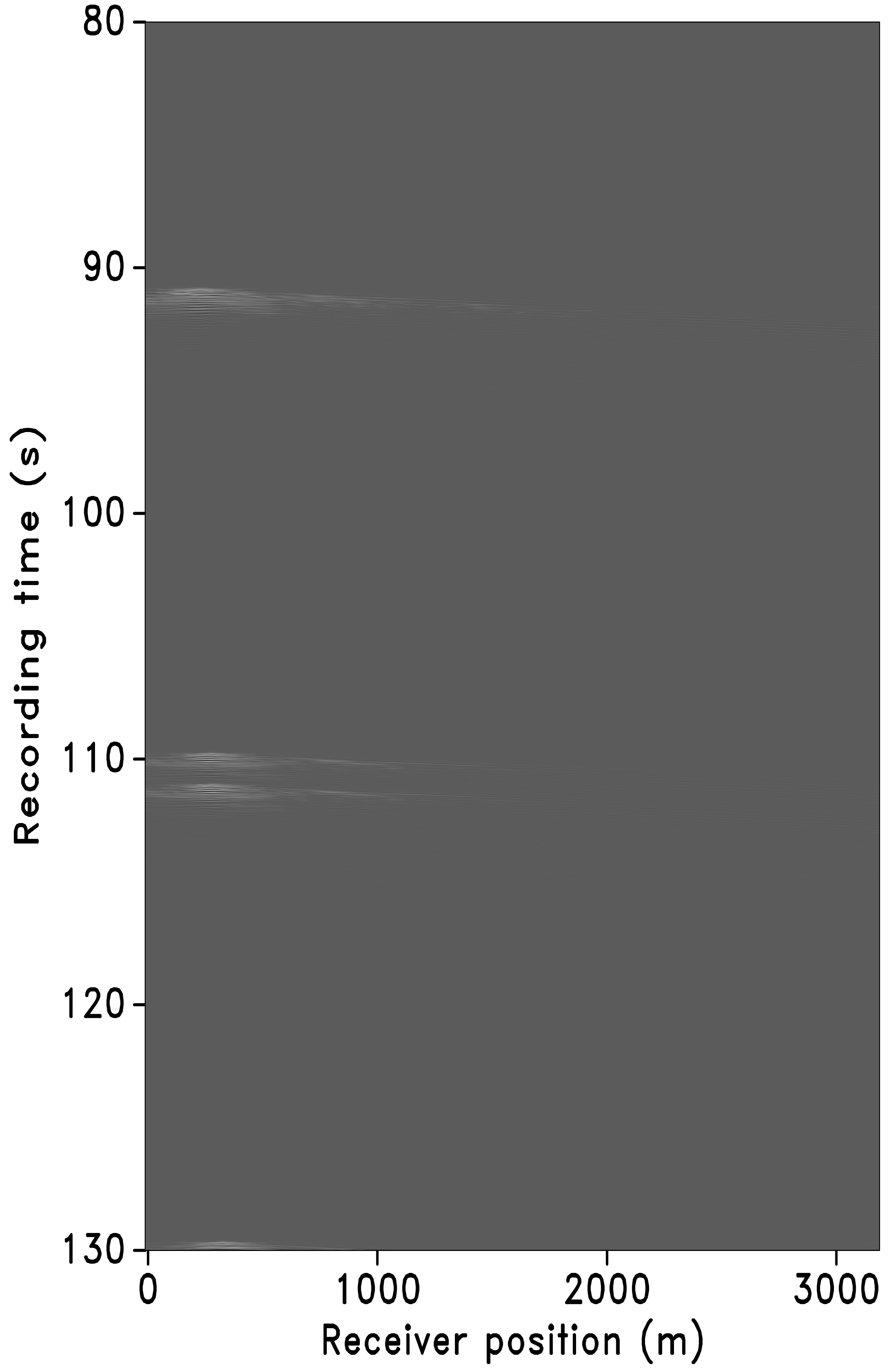


Measurements

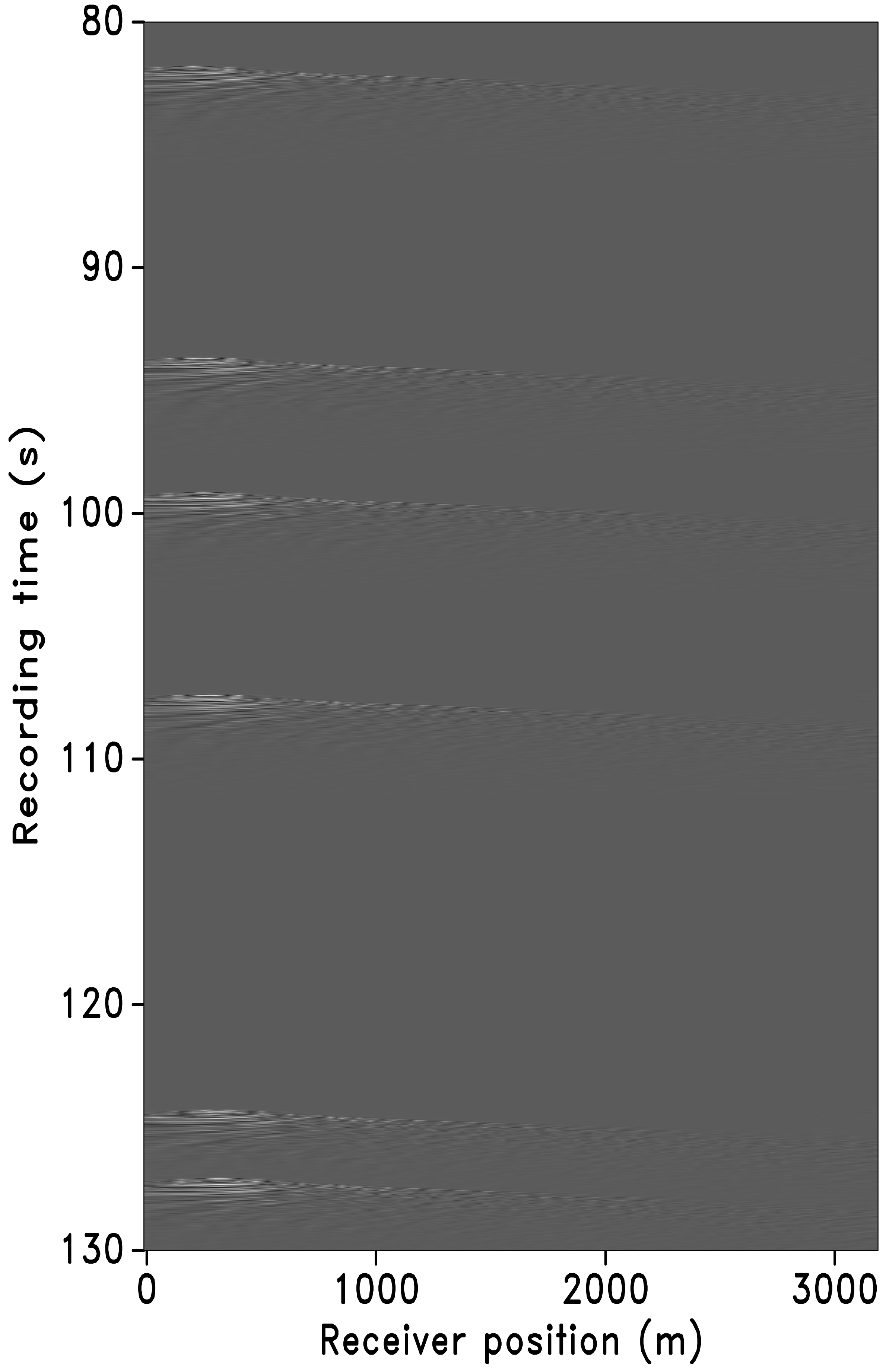
periodic



***low* variability**



***high* variability**



Sparsity-promoting recovery

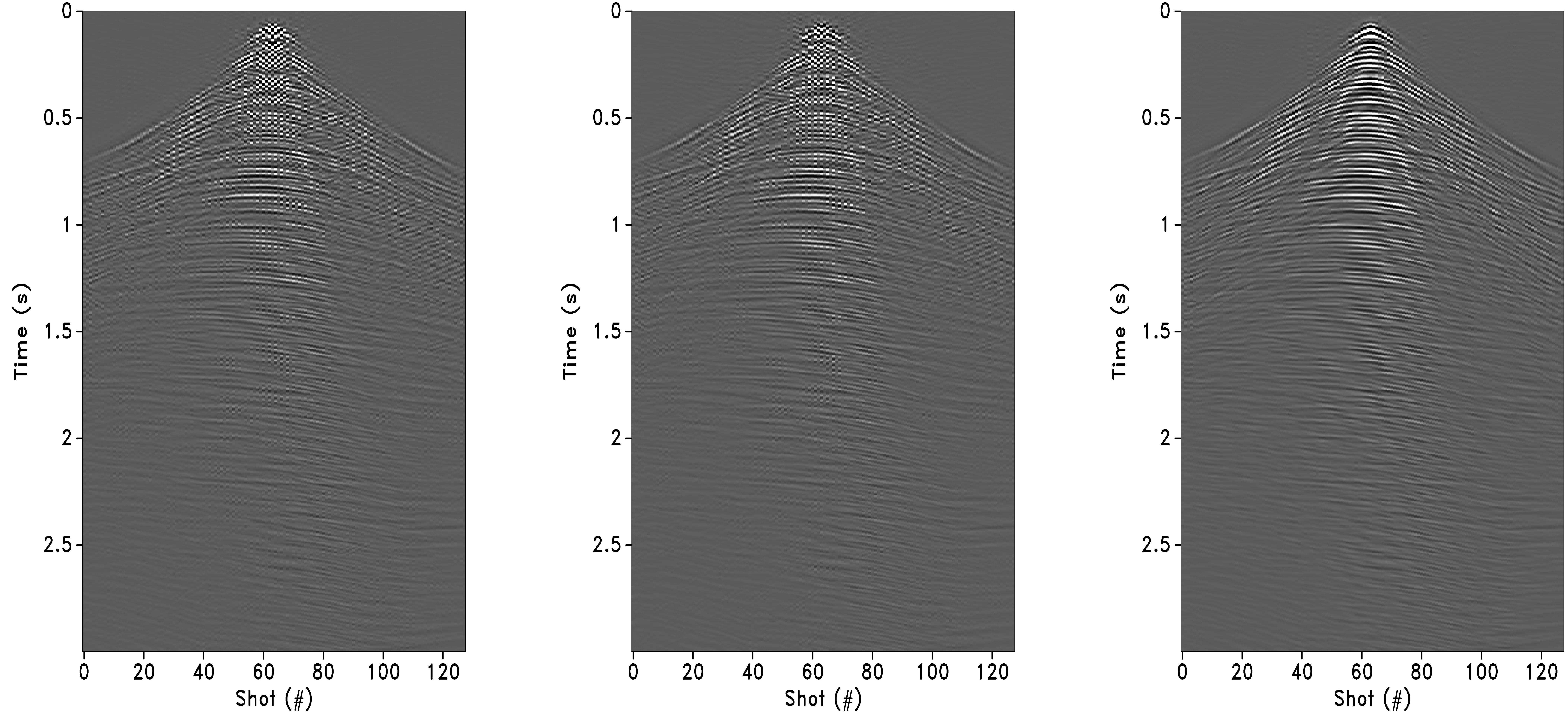
$$\tilde{\mathbf{x}} = \arg\min_{\mathbf{x}} \underbrace{\|\mathbf{x}\|_1}_{\text{support detection}} \quad \text{subject to} \quad \underbrace{\mathbf{A}\mathbf{x} = \mathbf{b}}_{\text{data-consistent amplitude recovery}}$$

recovered data: $\tilde{\mathbf{d}} = \mathbf{S}^H \tilde{\mathbf{x}}$

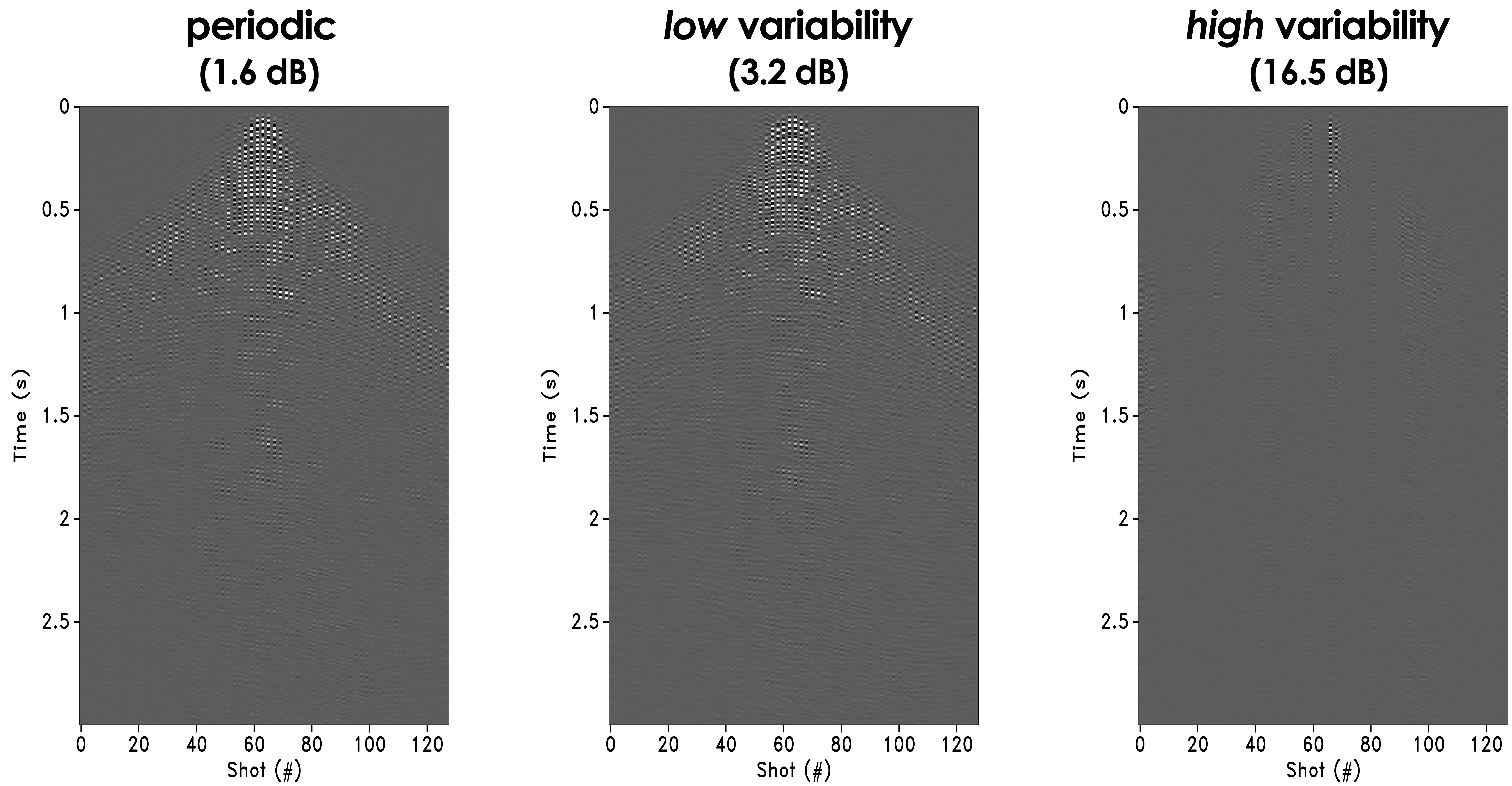
$\mathbf{S^H}$	a *transform* domain *synthesis*
$\mathbf{A}$	measurement operator : $\mathbf{MS^H}$, $\mathbf{M}$ is a blending operator
$\mathbf{b}$	blended data
$\tilde{\mathbf{x}}$	estimated curvelet coefficients for source separated wavefield

Recovery ["deblending" from 50 m grid to 25 m grid]

periodic	*low* variability	*high* variability
(1.6 dB)	(3.2 dB)	(16.5 dB)



Difference [“deblending” from 50 m grid to 25 m grid]



Haneet Wason and Felix J. Herrmann, "Time-jittered ocean bottom seismic acquisition", *SEG*, 2013
Hassan Mansour, Haneet Wason, Tim T.Y. Lin, and Felix J. Herrmann, "Randomized marine acquisition with compressive sampling matrices", *Geophysical Prospecting*, vol. 60, p. 648-662, 2012

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Observations

Recoveries entail *joint* interpolations & deblendings/source separations

Question:

Does increased *variability* of firing times improve curvelet recovery?

✓ yes, but only for ocean bottom acquisition – towed arrays are more challenging

Randomized time-*lapse* seismic

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Objective

Acquire *high*-fidelity *wide*-azimuth *long*-offset *time*-lapse

Questions:

Process/recover *independently* or *jointly* – to exploit *common* features of *surveys*?

Should we *repeat* the *surveys* when doing *randomized under*sampling?

Haneet Wason, Felix Oghenekohwo, and Felix J. Herrmann, "**Randomization and repeatability in time-lapse marine acquisition**". 2014.
Felix Oghenekohwo, Ernie Esser, and Felix J. Herrmann, "**Time-lapse seismic without repetition: reaping the benefits from randomized sampling and joint recovery**", in *EAGE*, 2014.

Time-lapse seismic

Current acquisition *paradigm*:

- *repeat* **expensive** *dense* acquisitions & *"independent"* processing
- compute *differences* between *baseline* & *monitor* survey(s)
- *hampered* by *practical* challenges to ensure *repetition*

New compressive sampling paradigm:

- **cheap** *sub*sampled acquisition, e.g. via time-*jittered* marine *under*sampling
- may offer *possibility* to *relax* insistence on *repeatability*
- *exploits* insights from *distributed* compressive sensing

Dror Baron , Marco F. Duarte , Shriram Sarvotham , Michael B. Wakin , Richard G. Baraniuk. An Information-Theoretic Approach to Distributed Compressed Sensing (2005)

Distributed compressive sensing
– *joint* recovery model (JRM)

vintages

$$\mathbf{x}_1 = \mathbf{z}_0 + \mathbf{z}_1$$
$$\mathbf{x}_2 = \mathbf{z}_0 + \mathbf{z}_2$$

differences

common component

$$\overbrace{\begin{bmatrix} \mathbf{A}_1 & \mathbf{A}_1 & \mathbf{0} \\ \mathbf{A}_2 & \mathbf{0} & \mathbf{A}_2 \end{bmatrix}}^{\mathbf{A}} \overbrace{\begin{bmatrix} \mathbf{z}_0 \\ \mathbf{z}_1 \\ \mathbf{z}_2 \end{bmatrix}}^{\mathbf{z}} = \overbrace{\begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \end{bmatrix}}^{\mathbf{b}}$$

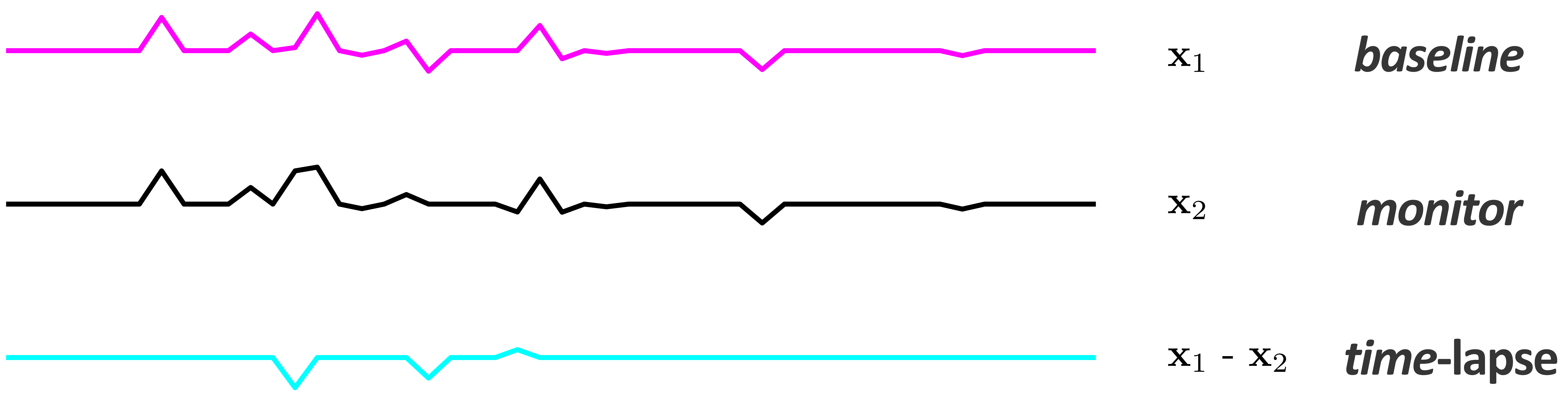
baseline

monitor

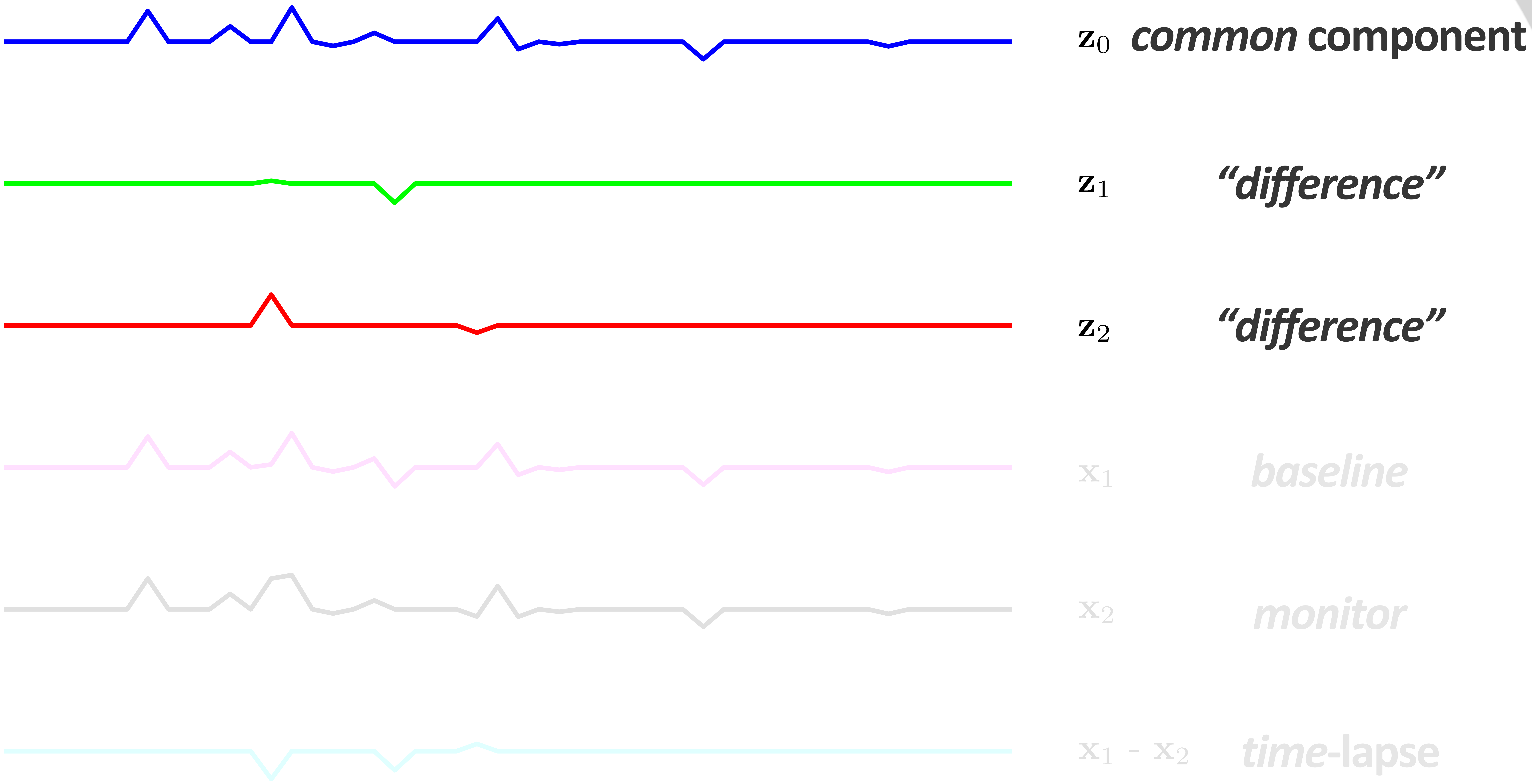
Key idea:

- use the fact that *different* vintages *share* common information
- invert for *common* components & *differences* w.r.t. the *common* components with *sparse* recovery

Sparse baseline, monitor & time-lapse signals

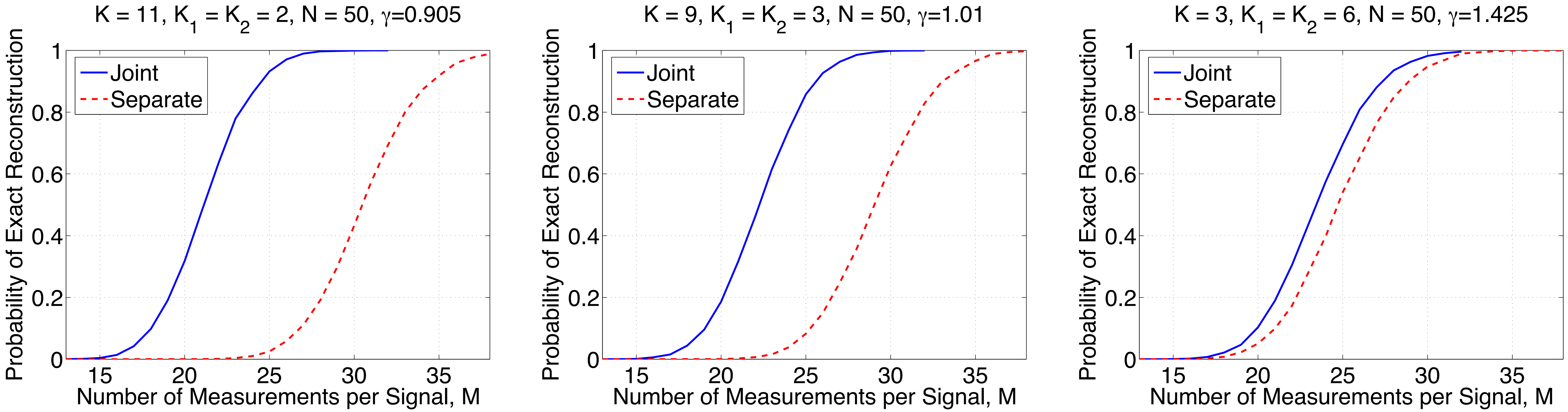


Sparse Joint Recovery Model (JRM)



Sparse recovery
– w/ & w/o JRM (1000 experiments)

$$\tilde{\mathbf{z}} = \arg\min_{\mathbf{z}} \|\mathbf{z}\|_1 \quad \text{subject to} \quad \mathbf{A}\mathbf{z} = \mathbf{b}$$



decreasing *common* sparsity

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Observations

***Joint* recovery model (JRM):**

- improves *recovery* results for *both* vintages *significantly* compared to *independent* recovery strategy (IRS)
- when there is *common* sparsity
- quality *decreases* for *decreasing* common *sparsity*

Is this the *end* of the *story* for *time*-lapse where we are interested in *differences* between the *vintages…?*

Time-lapse
– w/ & w/o *repetition*

In an *ideal* world $(\mathbf{A}_1 = \mathbf{A}_2)$

- JRM *simplifies* to recovering the *difference* from $(\mathbf{b}_2 - \mathbf{b}_1) = \mathbf{A}_1(\mathbf{x}_2 - \mathbf{x}_1)$
- expect *good* recovery when *difference* is *sparse*
- ***but*** relies on "*exact*" repeatability…

In the *real* world $(\mathbf{A}_1 \neq \mathbf{A}_2)$

- no absolute *control* on *surveys*
- *calibration* errors
- noise…

To *repeat* or *not* repeat that's the question…

Stylized experiments

Conduct *many* CS experiments to compare

- *joint* vs *independent* recovery
- recovery w/ the *same*, *partly* or *completely* independent $\mathbf{A}_1,\ \mathbf{A}_2$

for *baseline* & *monitor* surveys that

- *share* a *common* sparse component & have sparse *time*-lapse components
- are *randomly* acquired w/ *different* numbers of *samples*

Stylized experiment setup

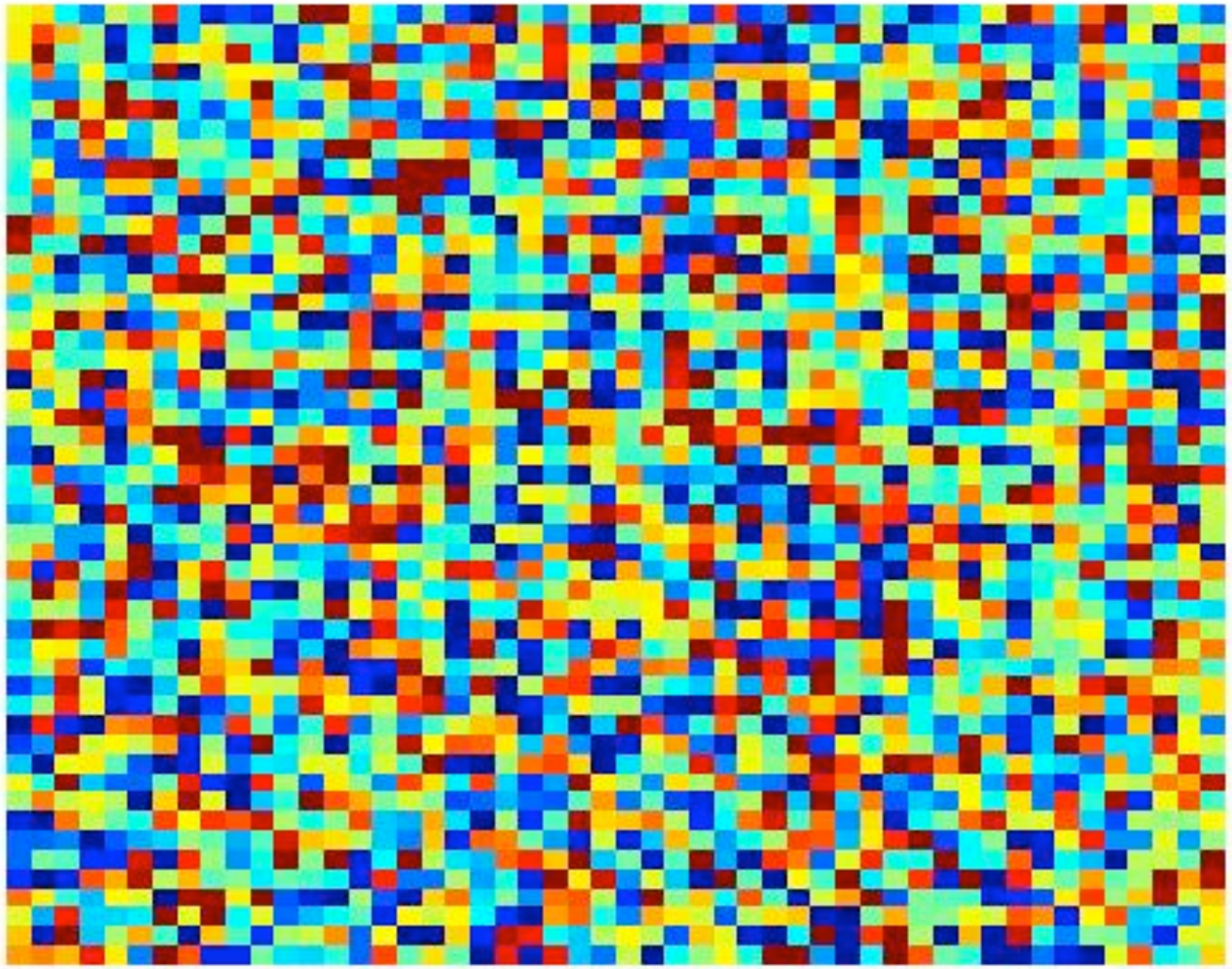
***Time*-lapse signal:**

$$
\begin{aligned}
N &= 50 && \text{(is the total length of the time-lapse signal)} \\
K &= 11 && \text{(is the number of non-zeros in the common part of } x_1 \text{ and } x_2\text{)} \\
K_1, K_2 &= 2 && \text{(is the number of non-zeros which is not common to } x_1 \text{ and } x_2\text{)}
\end{aligned}
$$

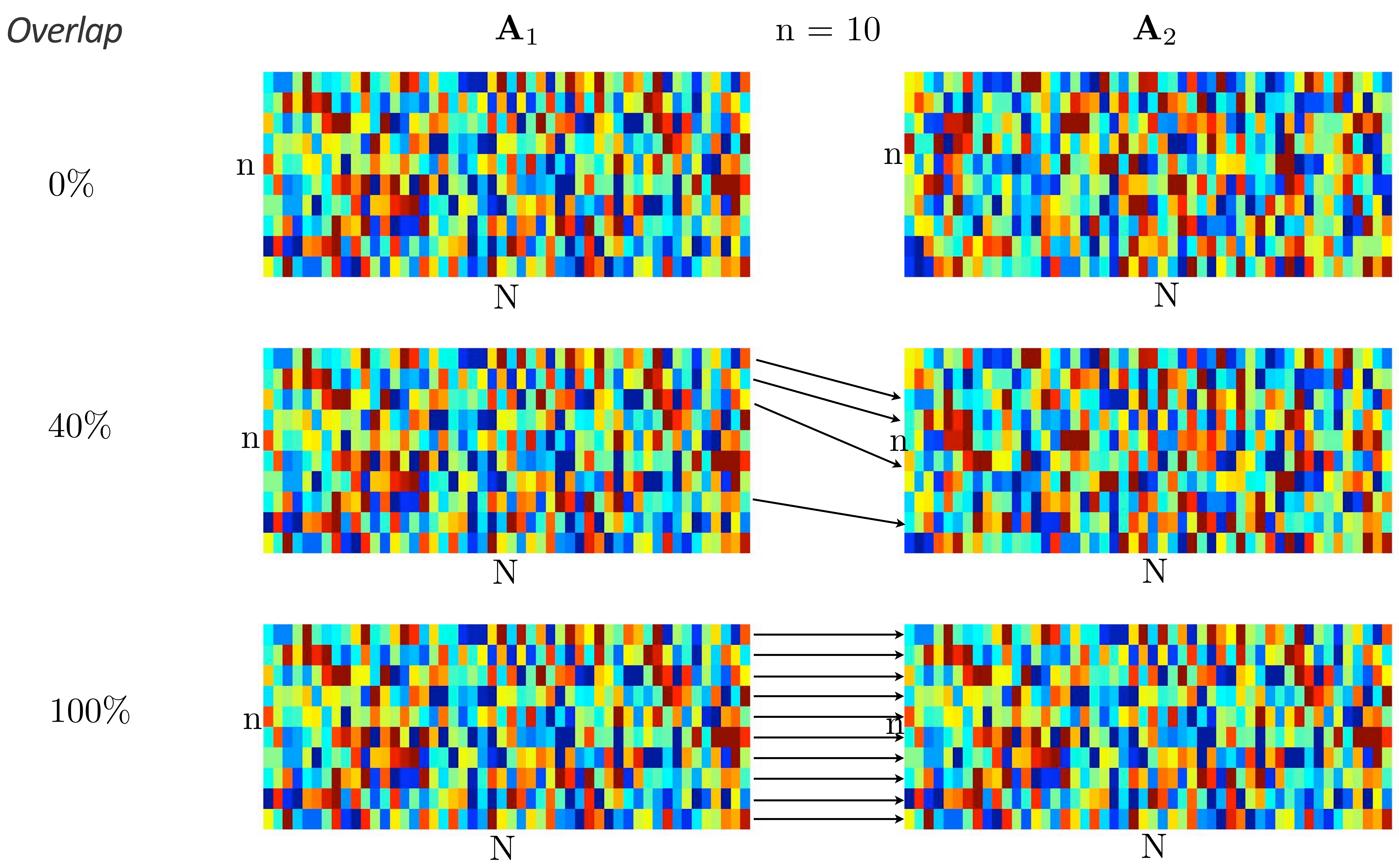
***Randomized under*samples:**

- rows from a Gaussian matrix
- $n = \{5, 10, 15, 20, 25, 30, 35, 40\}$
- $\{0, 20, 40, 60, 80, 100\}\,\%$ overlap

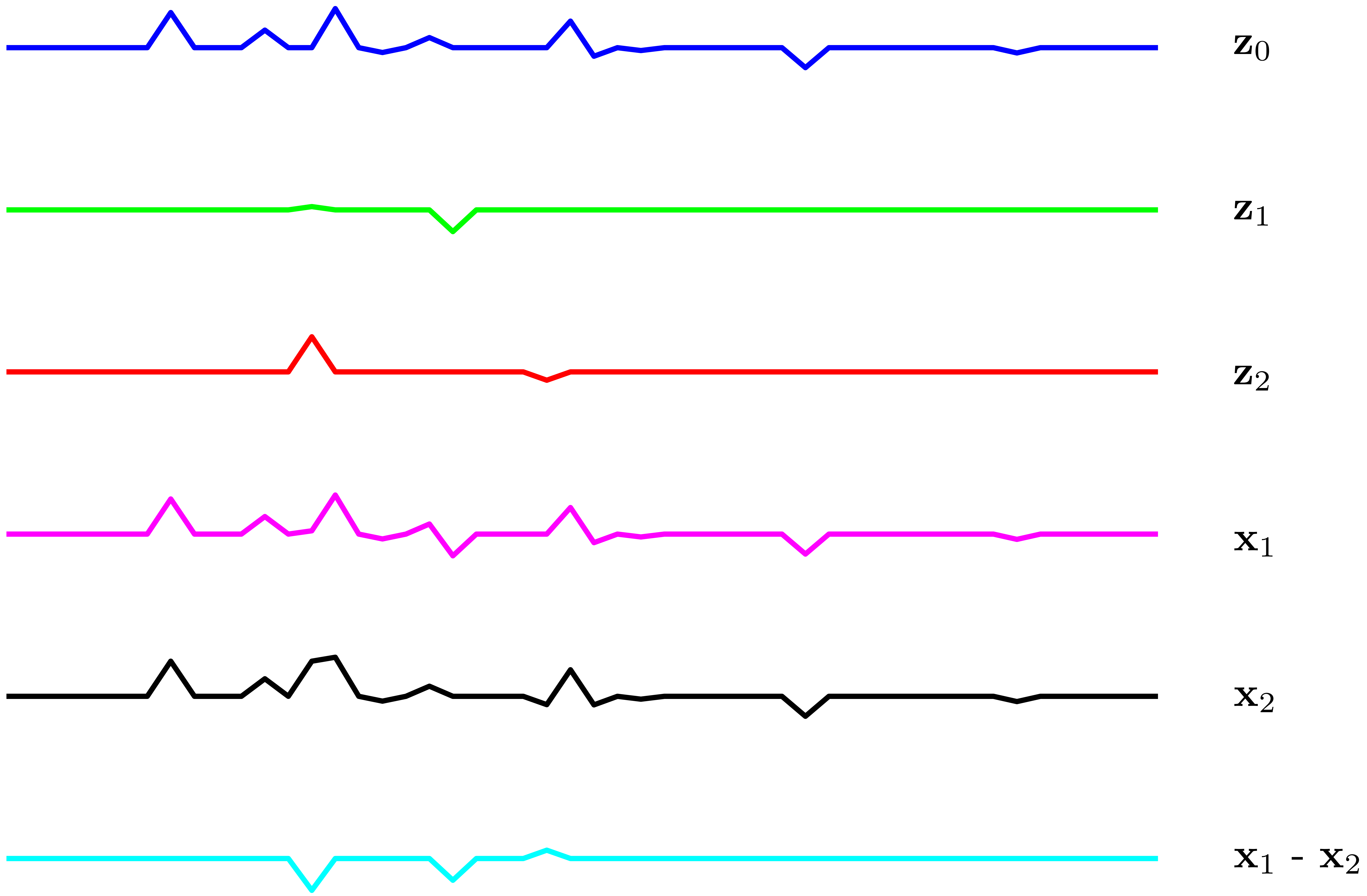
Underlying *Gaussian* sensing matrix



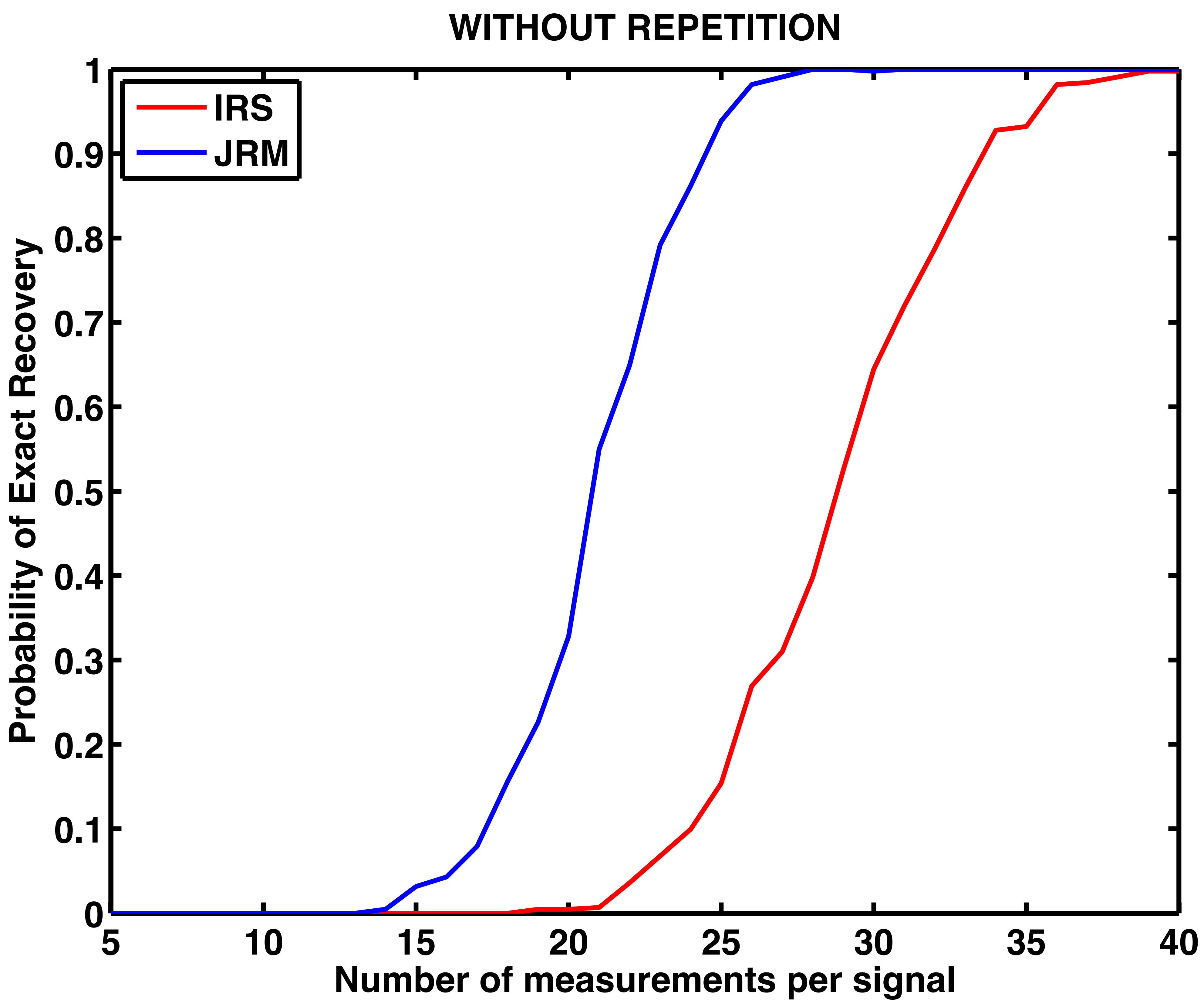
Randomized sensing matrices w/ *varying* overlap



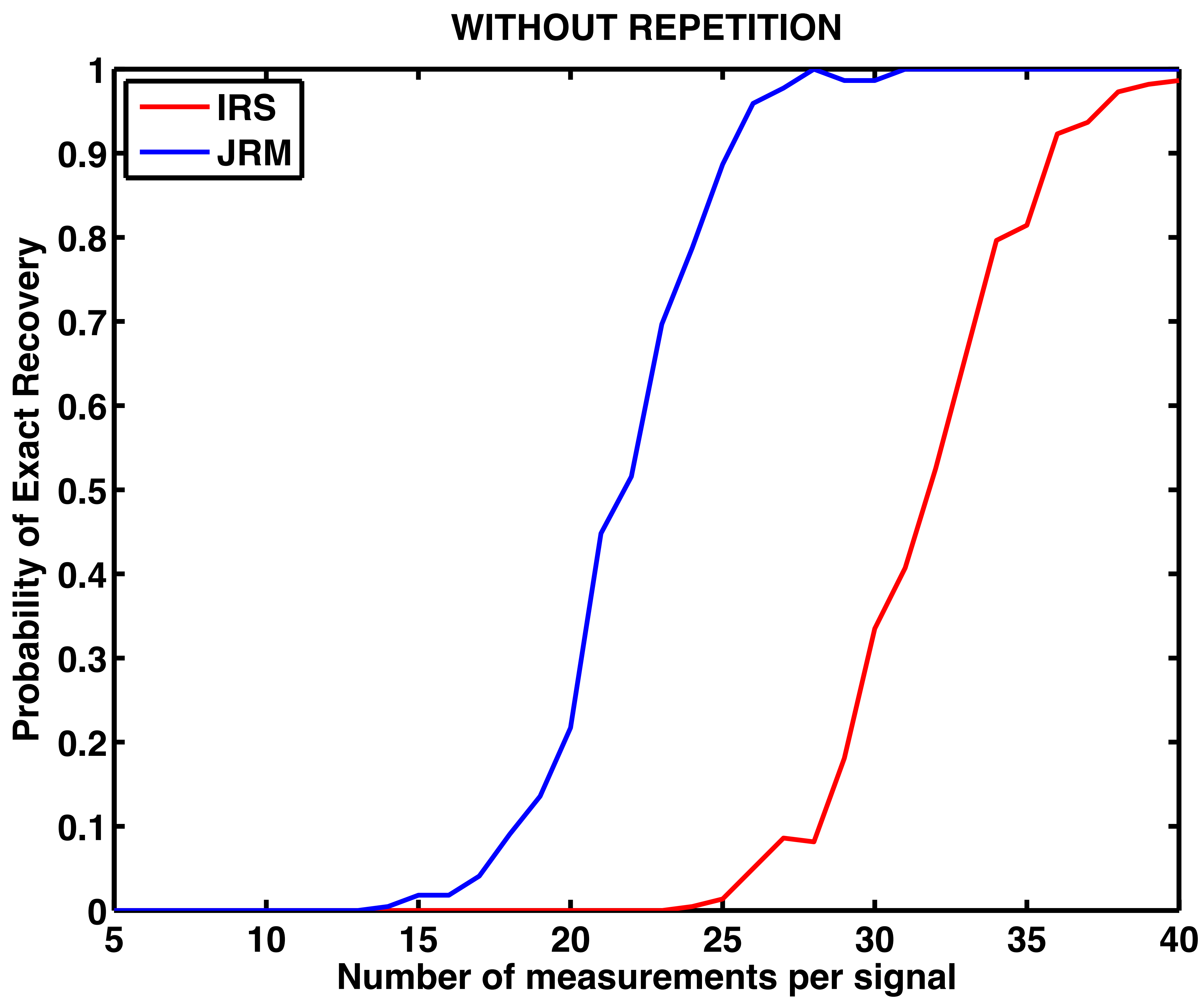
Random *sparse* vectors
– 250 experiments



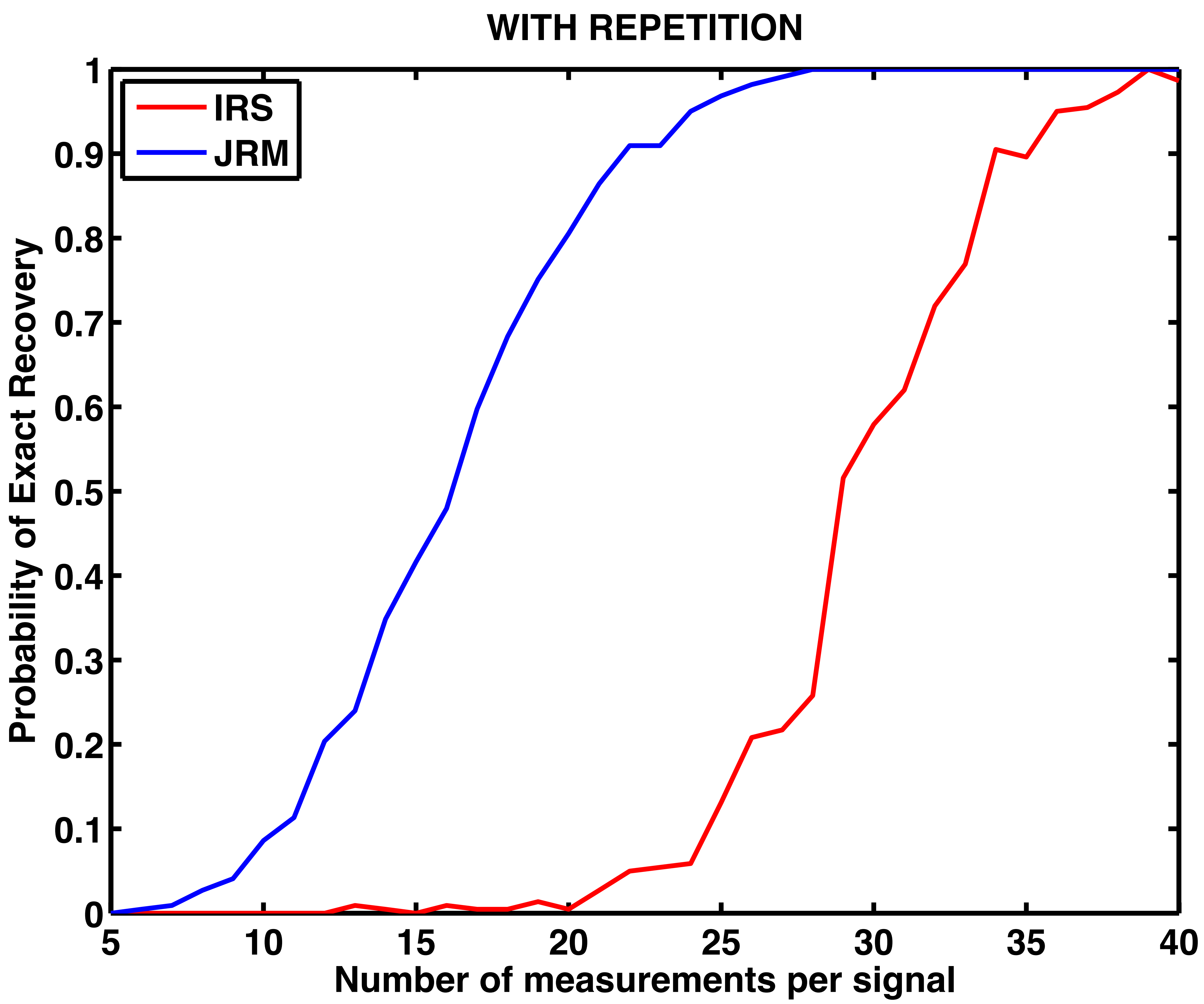
Recovery probability of *vintages*
– w/o repetition



Recovery probability of *time*-lapse *difference*
– w/o repetition



Recovery probability of *time*-lapse *difference*
– w/ repetition



Observations

Recovery of *vintages* themselves *improves* **without** *repetition*

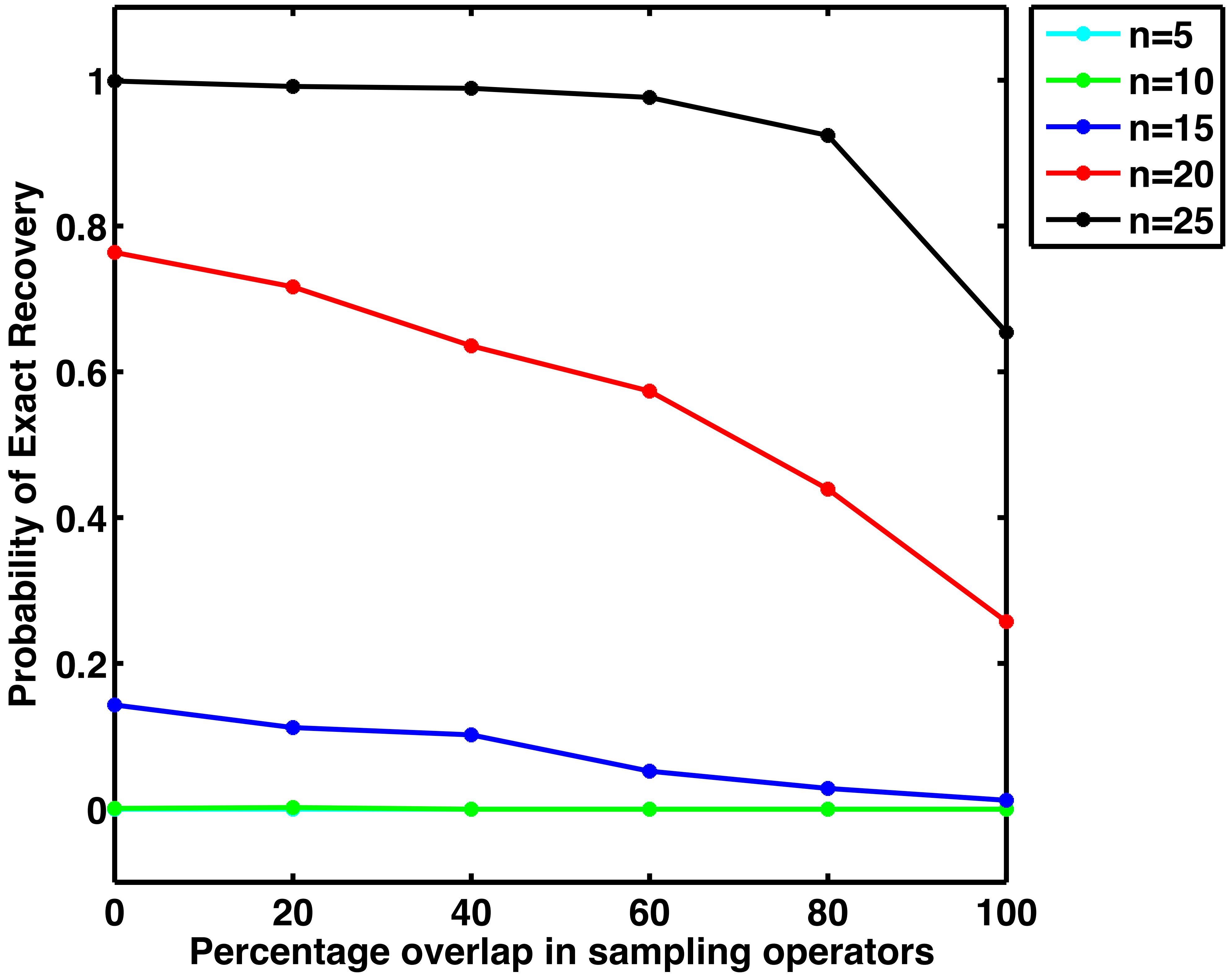
Recovery of *difference improves* **with** *repetition* because

- *difference* is *sparse* compared to *sparsity* of *vintages*
- does ***not*** recover the *vintages* themselves… *dangerous*

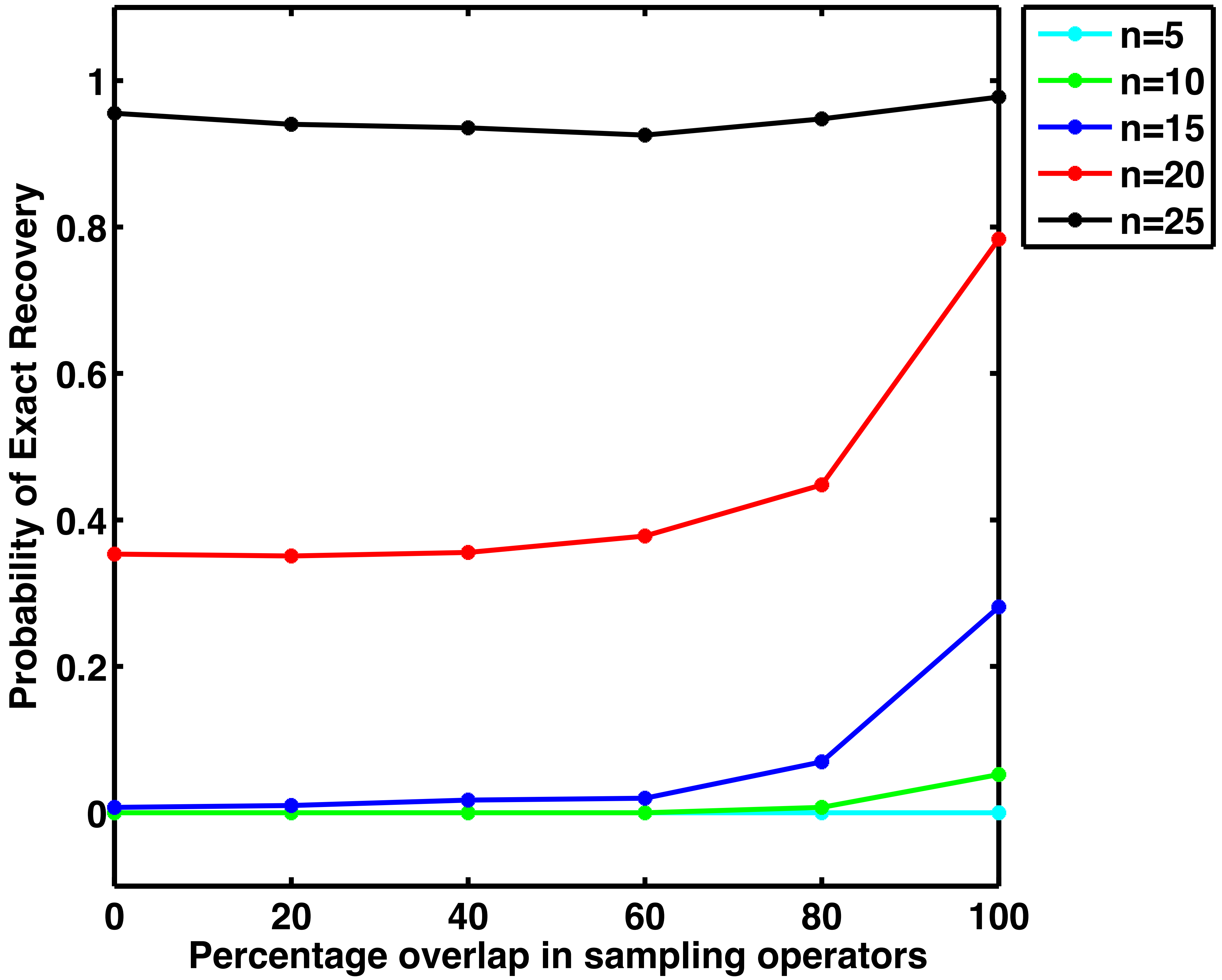
Do the acquisitions really have to overlap?

Recovery probabilities
– *varying* degrees of *repetition*

vintages



time-lapse



Observations

Recovery w/ *joint*-recovery model is ***always*** *superior*

- recovery *quality* of vintages *decreases* when *repeating* time-lapse experiments

When *joint* recovery *fails:*

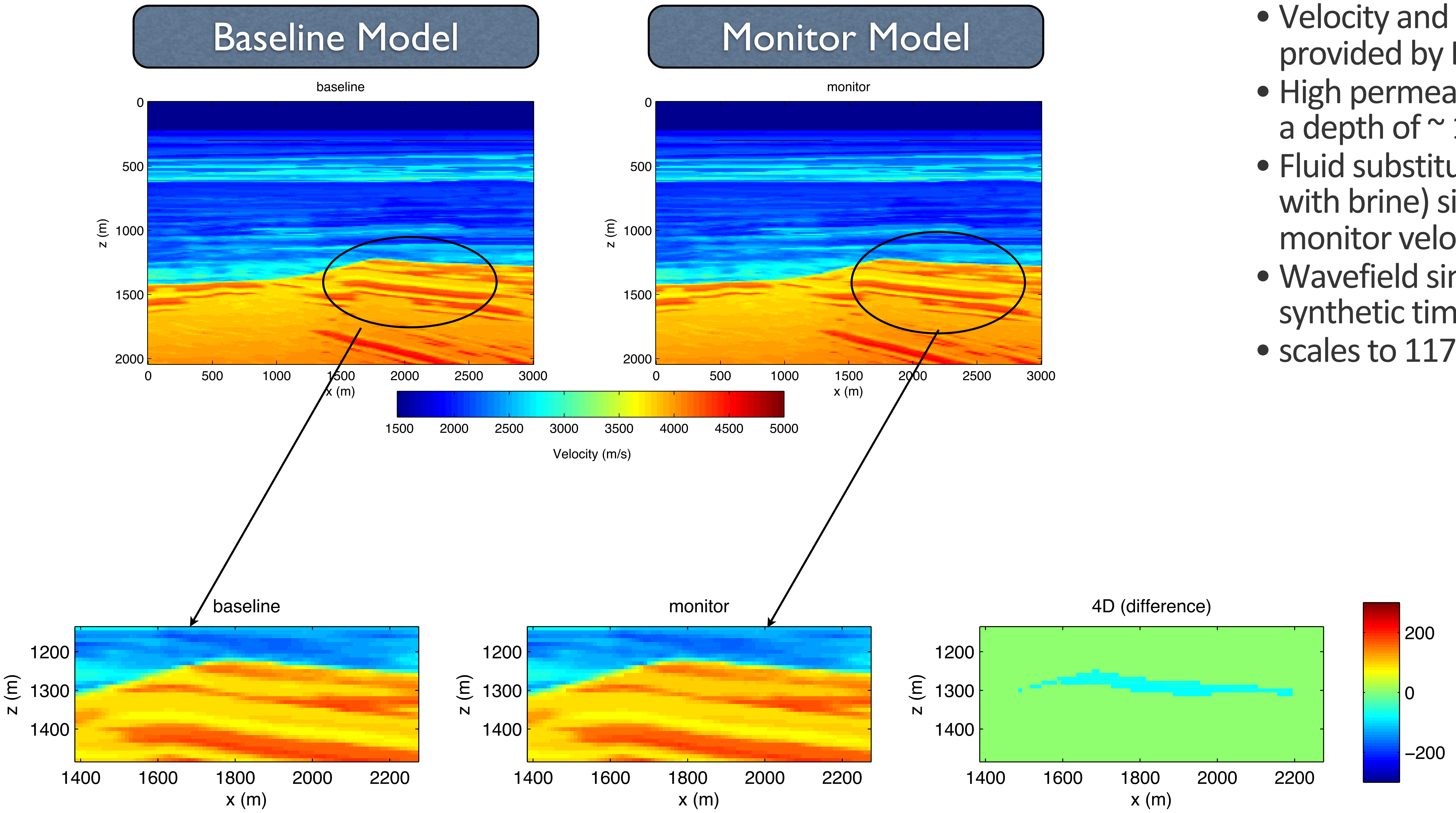
- *repetition* is *required* to obtain *time*-lapse signal
- *degree* of repetition needs to *increase* for *increased* subsampling

When *joint* recovery *succeeds:*

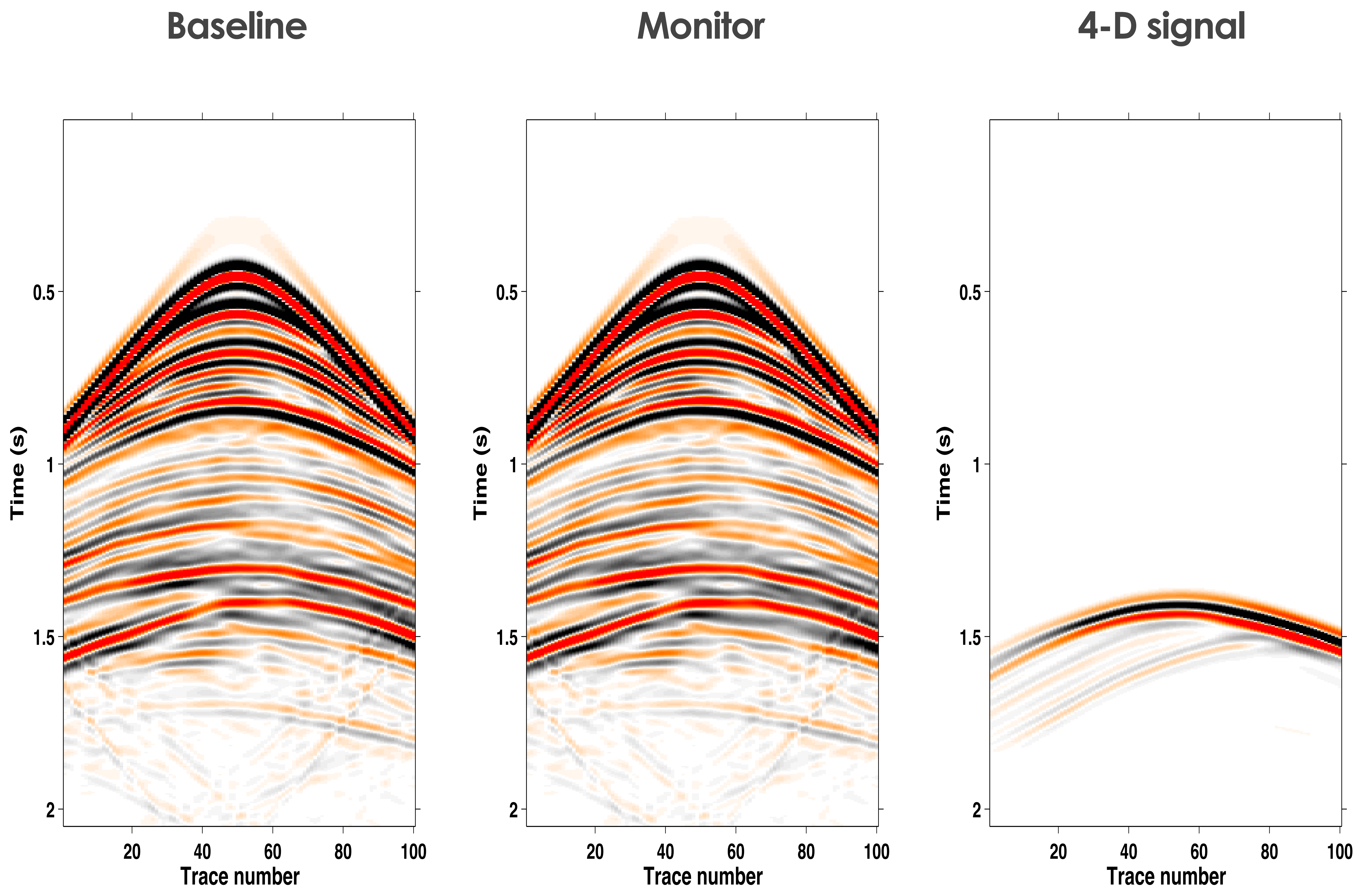
- *repetition* is **not** *required*
- *recovery* quality *time*-lapse does *not strongly* depend on *degree* of *repeatability*

Method

- Velocity and density model provided by BG, taken as baseline
- High permeability zone identified at a depth of ~ 1300m
- Fluid substitution (gas/oil replaced with brine) simulated to derive monitor velocity model
- Wavefield simulation to generate synthetic time-lapse data
- scales to 11733300 x 114882048



Simulated original data
– time-domain finite differences



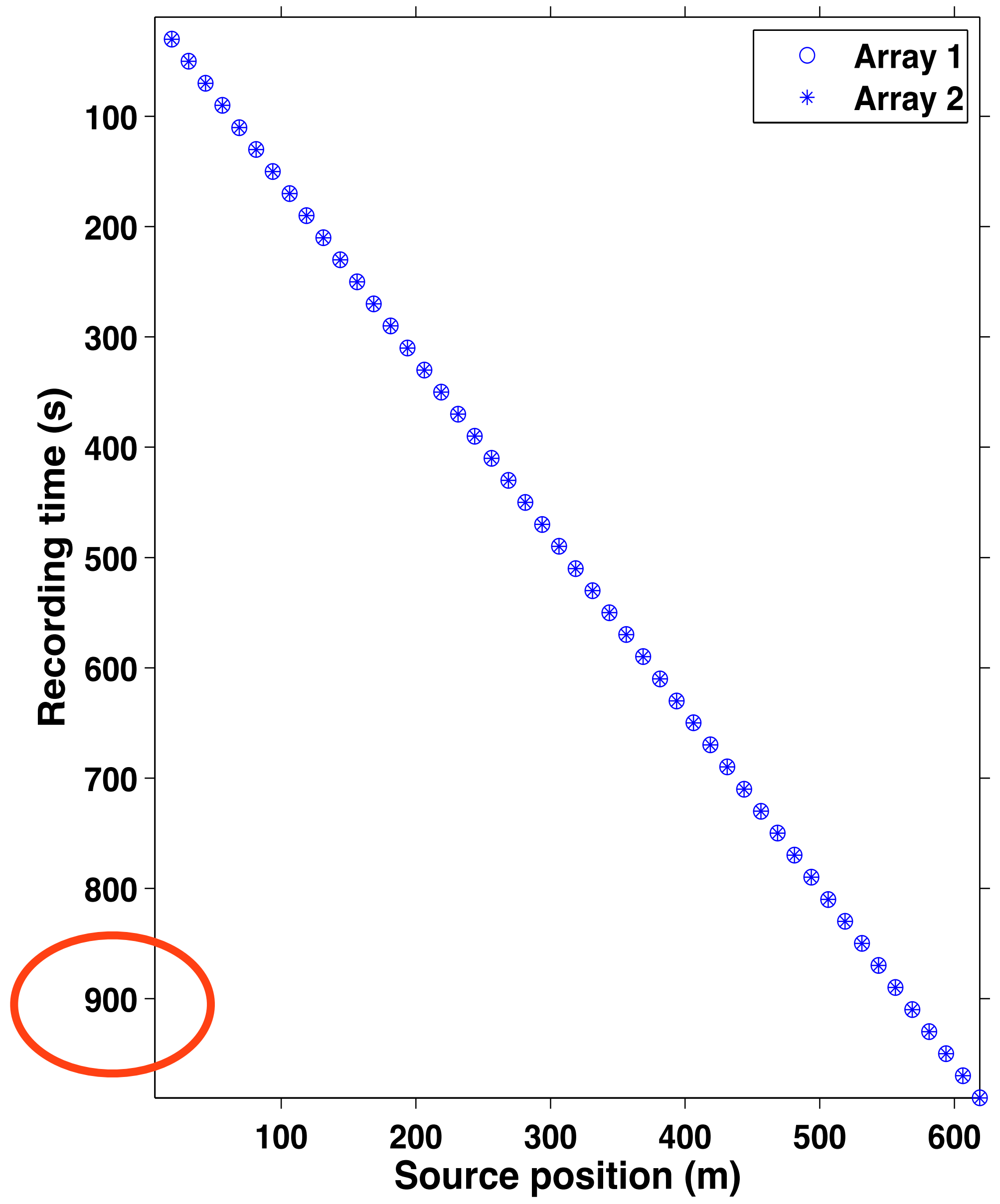
time samples: **512**
receivers: **100**
sources: **100**

sampling
time: **4.0 ms**
receiver: **25.0 m**
source: **25.0 m**

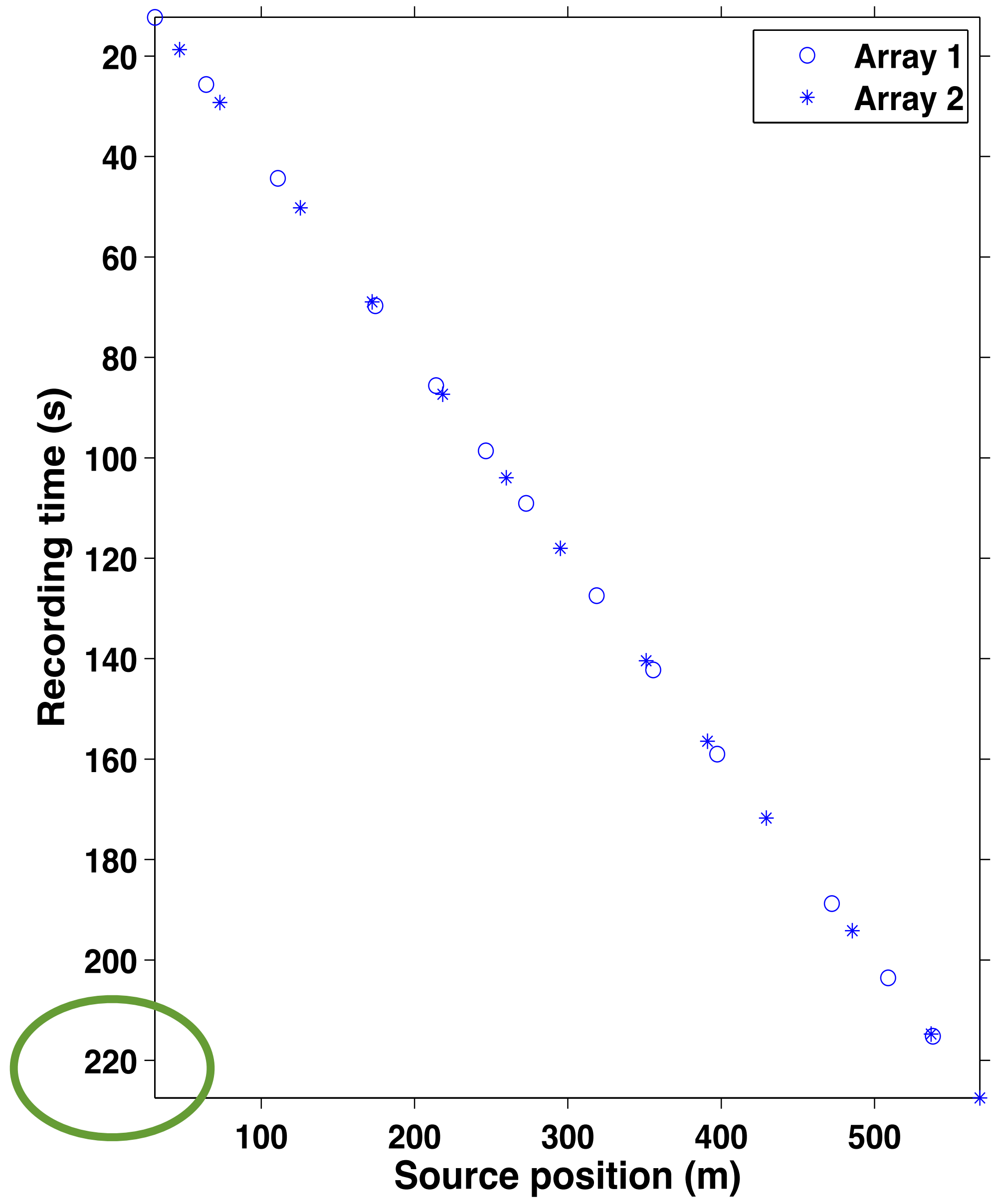
Conventional vs. *time-jittered* sources

– *undersampling* ratio = 4, 2 source arrays

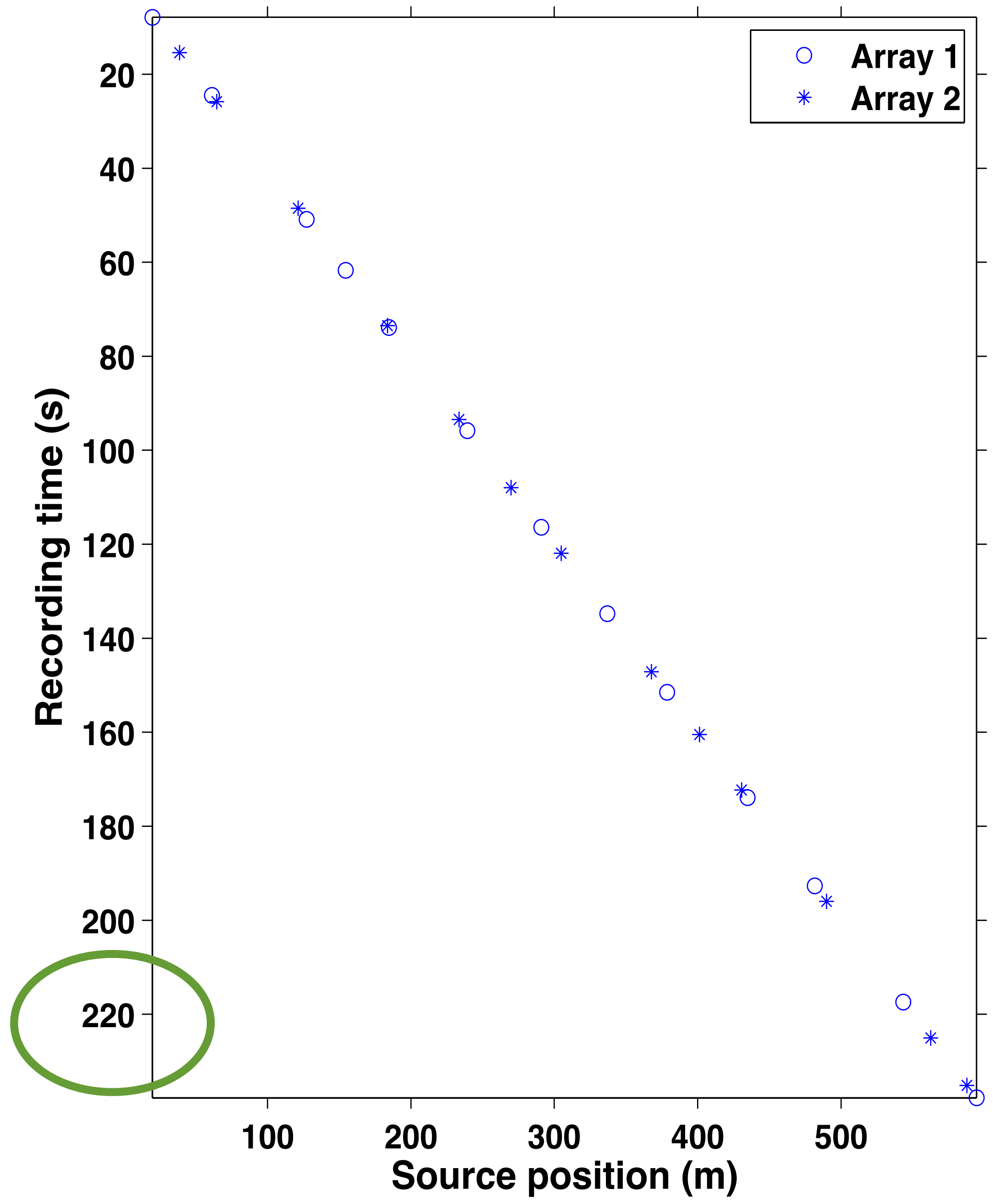
conventional



jittered acquisition 1 (for baseline)



jittered acquisition 2 (for monitor)



"unblended" **shot gathers**
number of shots = **100** (per array)
shot record length: 10.0 s
spatial sampling: **6.25 m**
vessel speed: **0.625 m/s**
recording time = 100 x 10.0 = **1000.0 s**

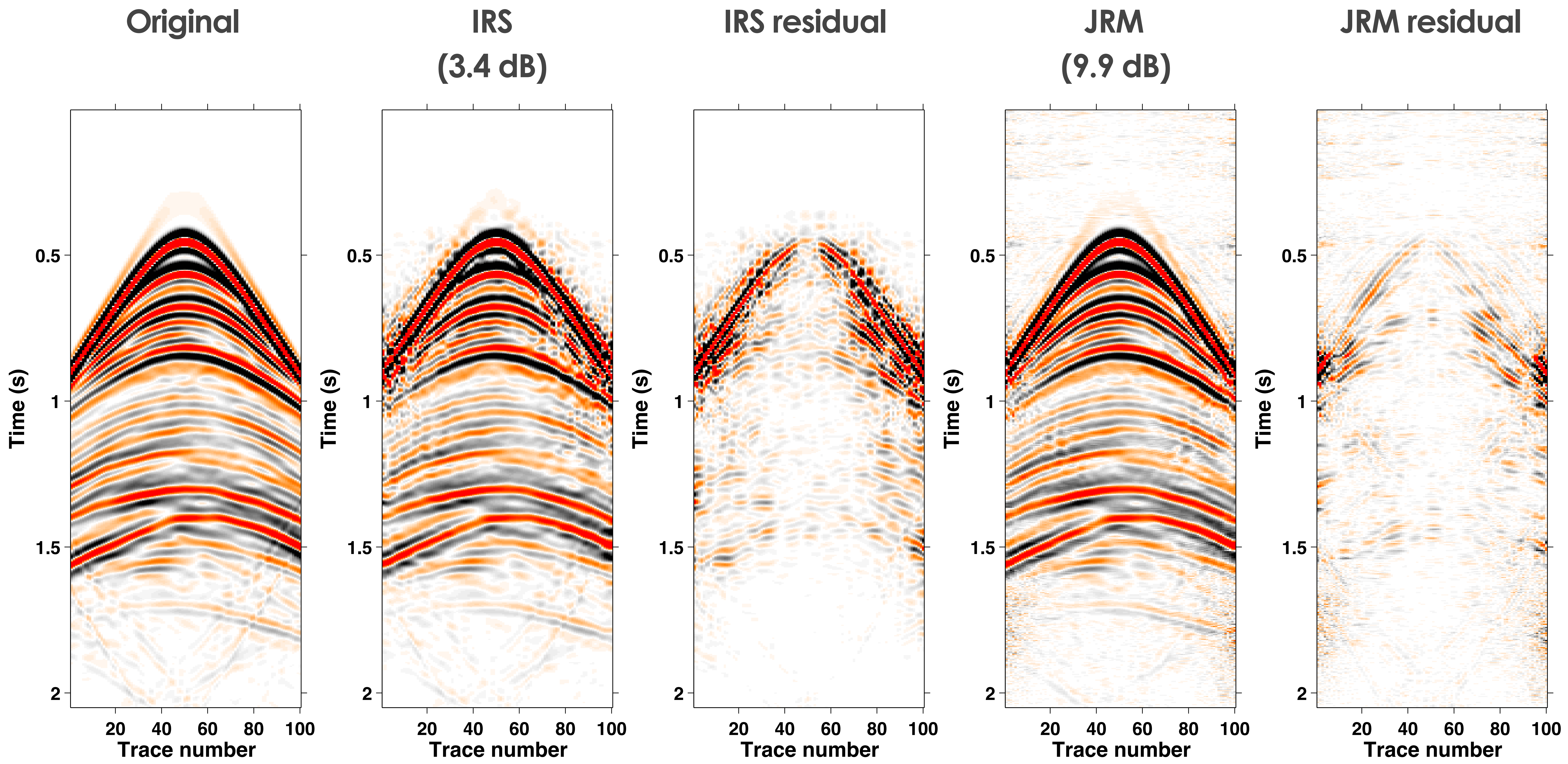
[BLENDING & UNDERSAMPLING]
spatial undersampling factor = 4

spatial sampling ***increase*** factor = 4
[DEBLENDING & INTERPOLATION]

"blended" **shot gathers**
number of shots = 100/4 = **25** (12-13 per array)
spatial sampling: **50.0 m (*jittered*)**
vessel speed: **2.50 m/s**
recording time ≈ 1000.0 s/4 = **250.0 s**

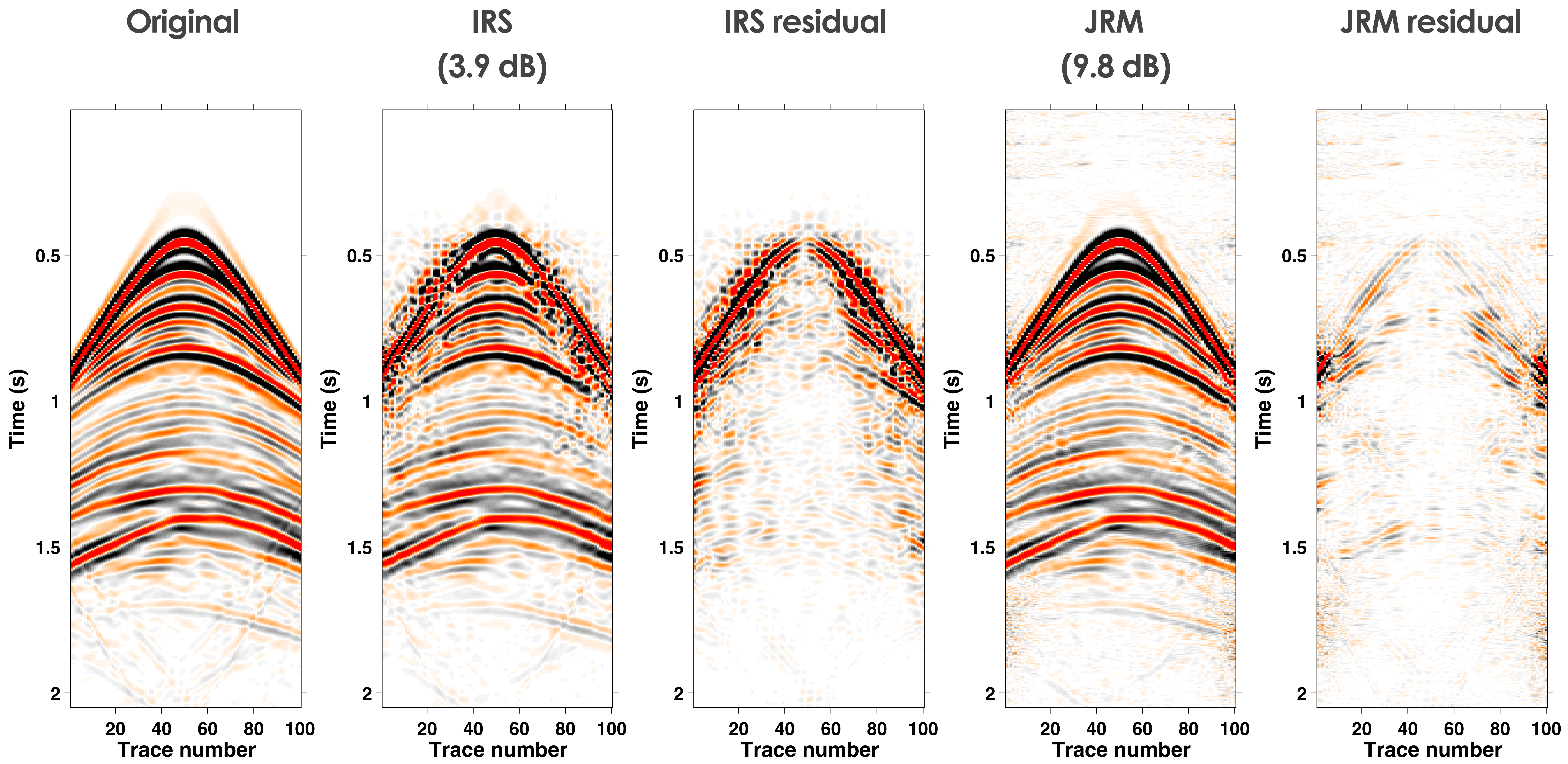
Baseline recovery

–"*small*" overlap (25%) in *acquisition* matrices



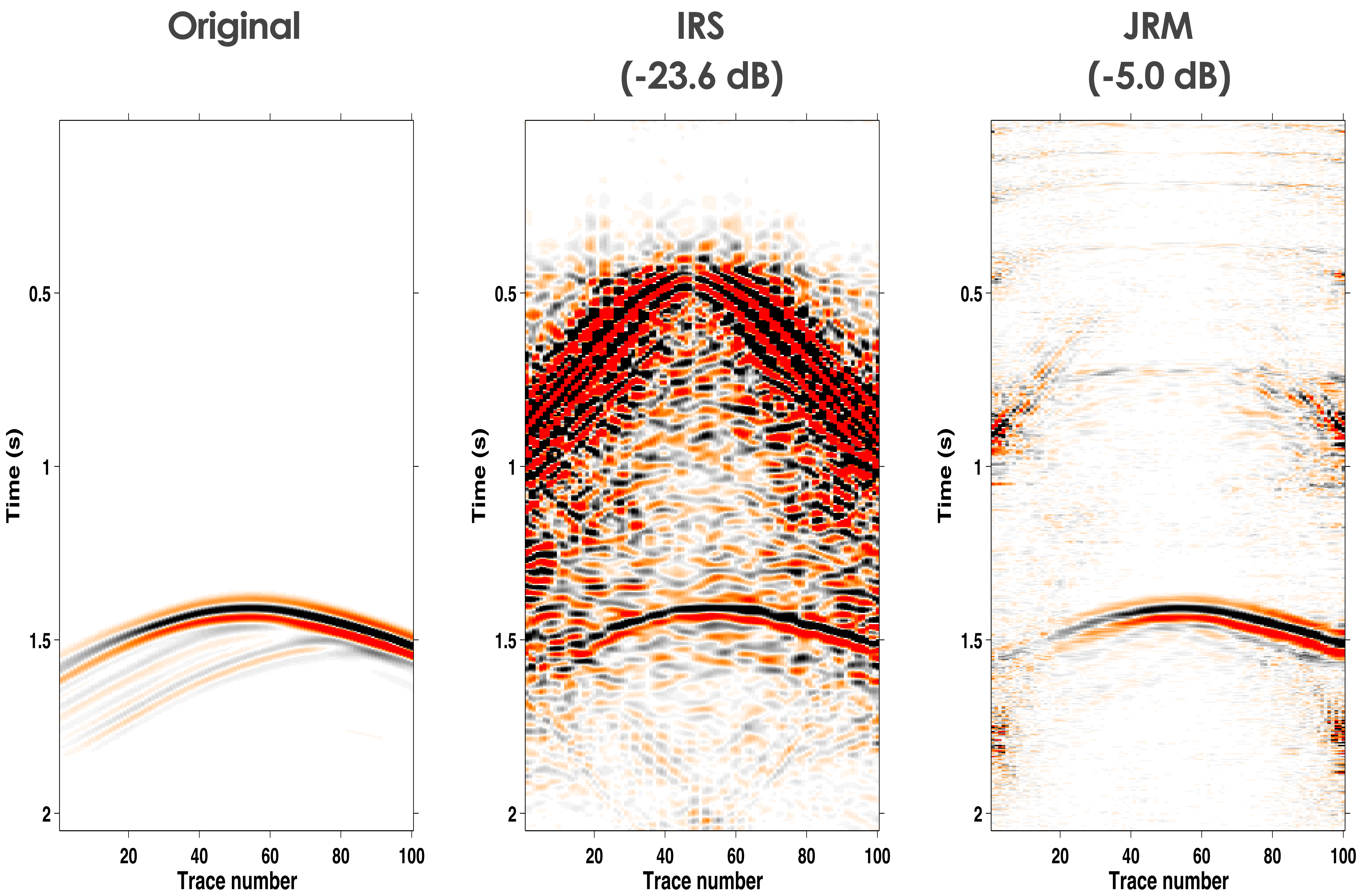
Monitor recovery

–“*small*” overlap (25%) in *acquisition* matrices

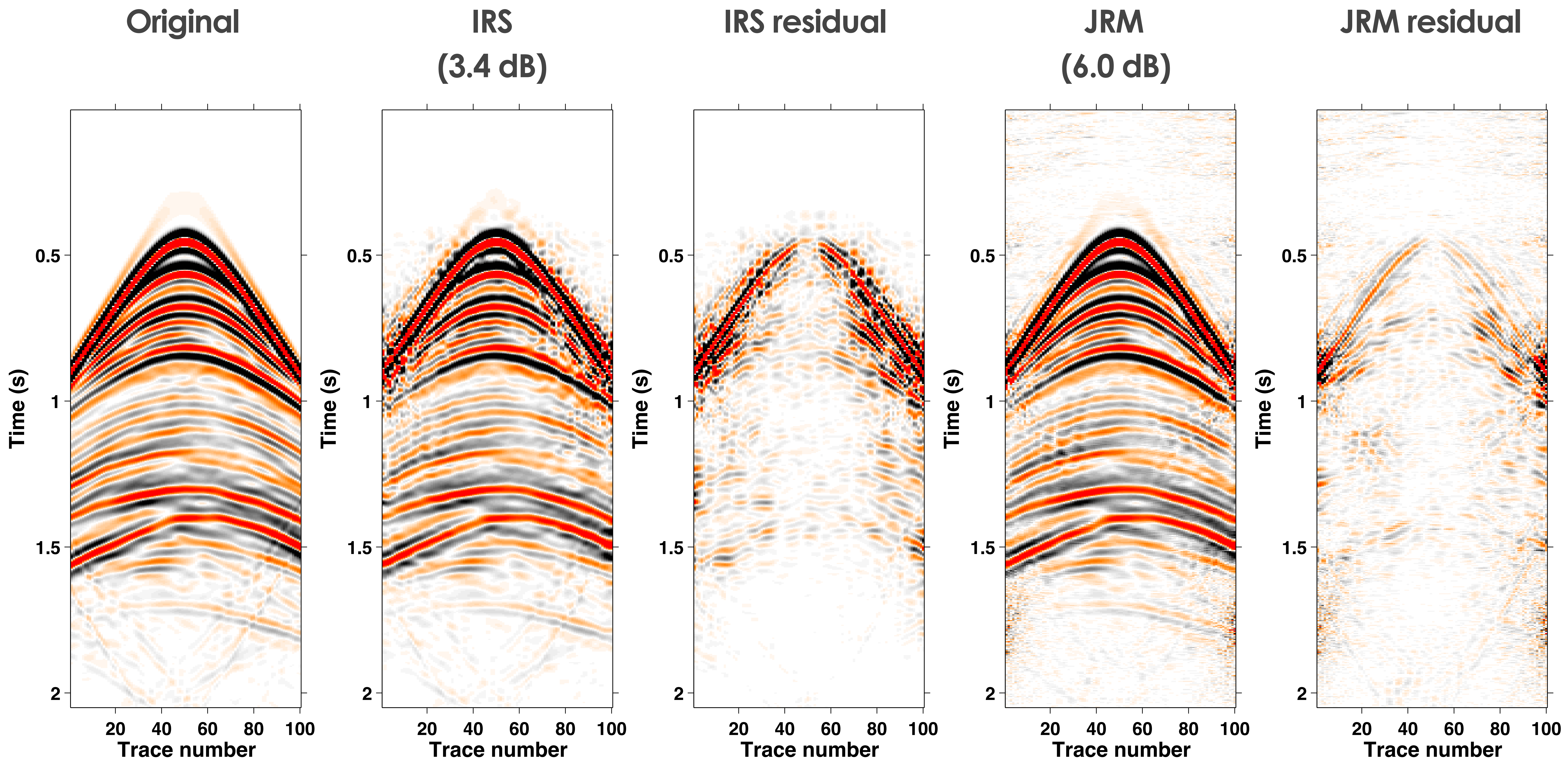


4-D recovery

– “*small*” overlap (25%) in *acquisition* matrices

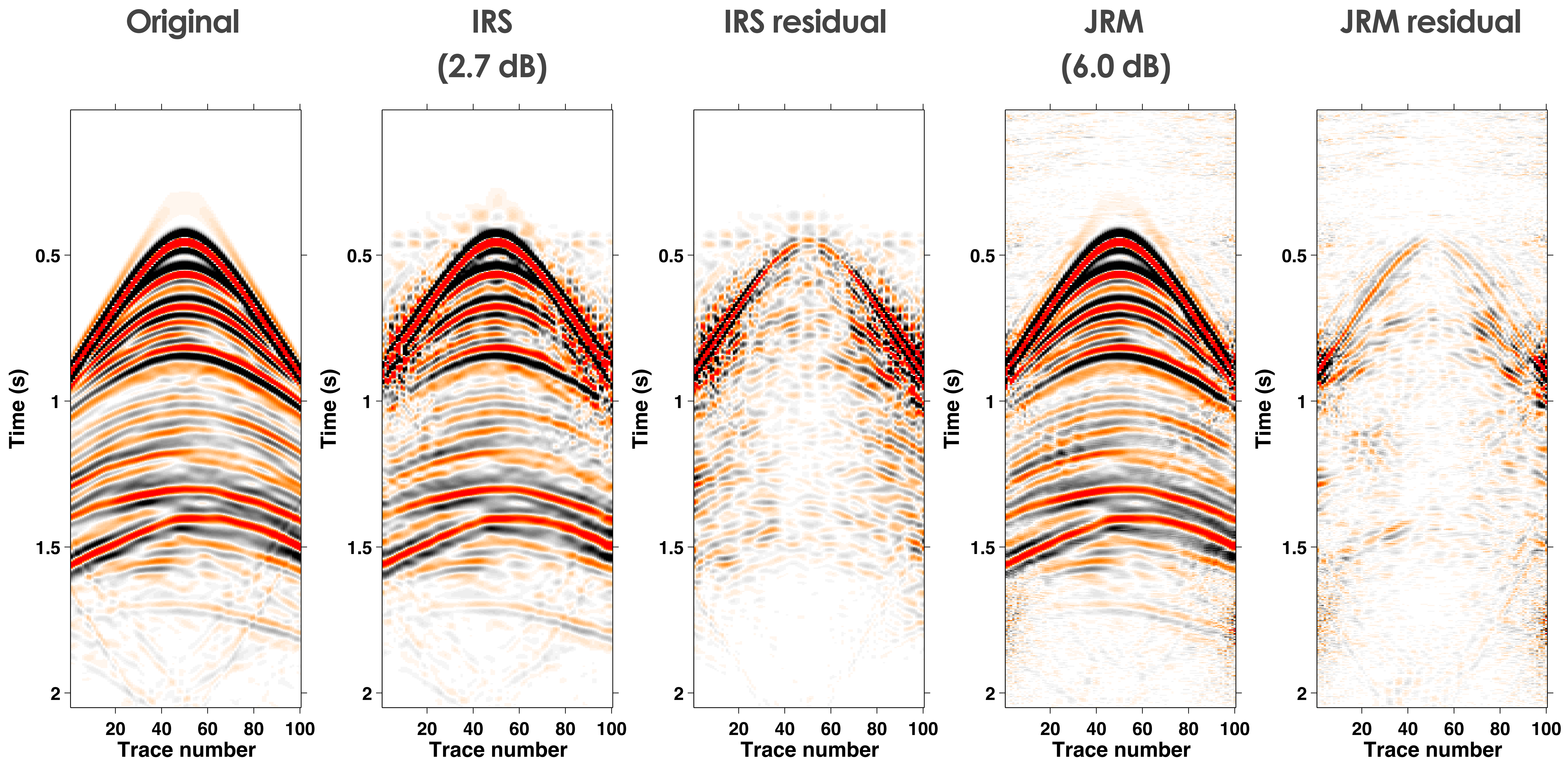


Baseline recovery
–"*large*" overlap (50%) in *acquisition* matrices



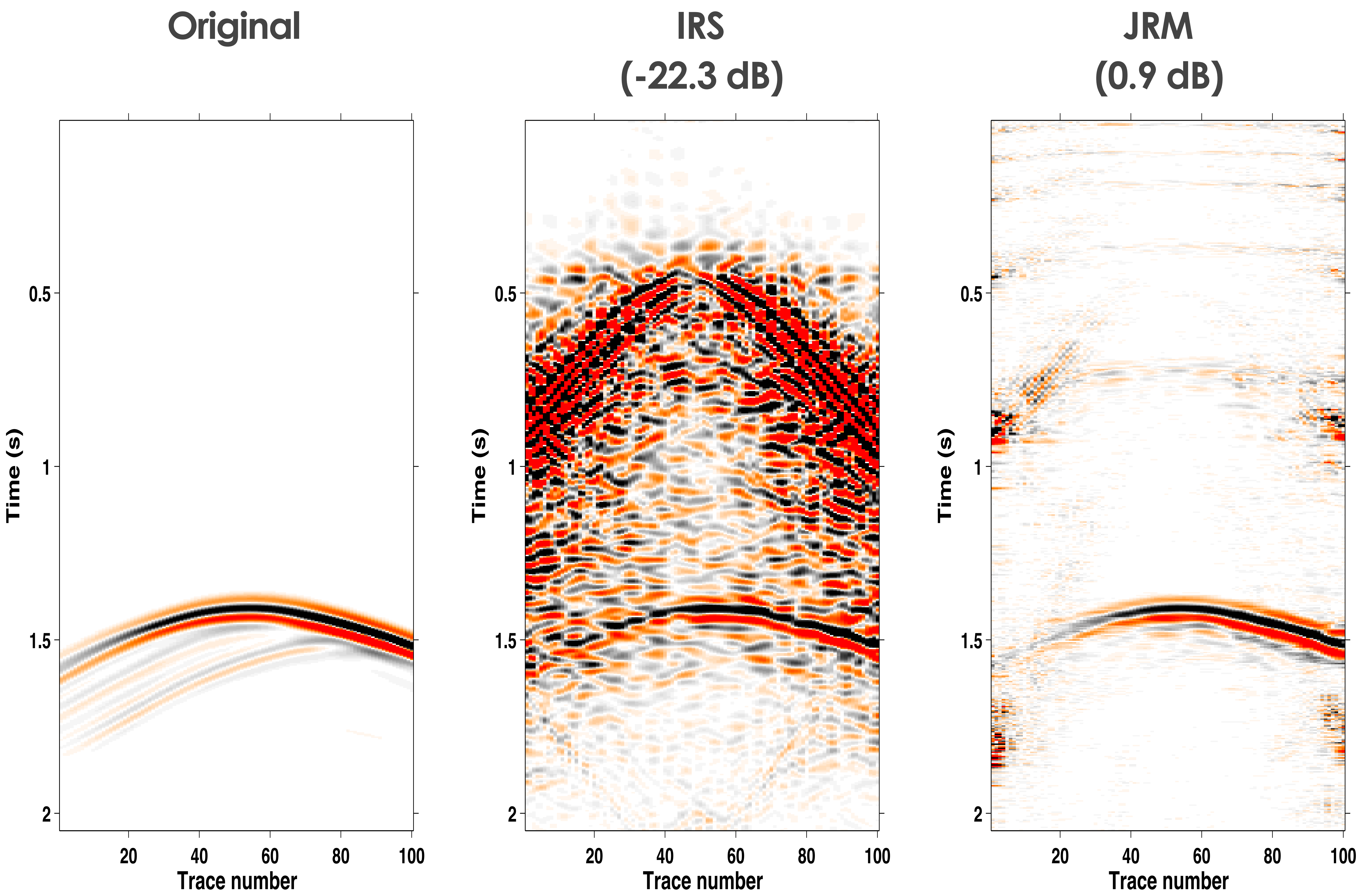
Monitor recovery

–"*large*" overlap (50%) in *acquisition* matrices



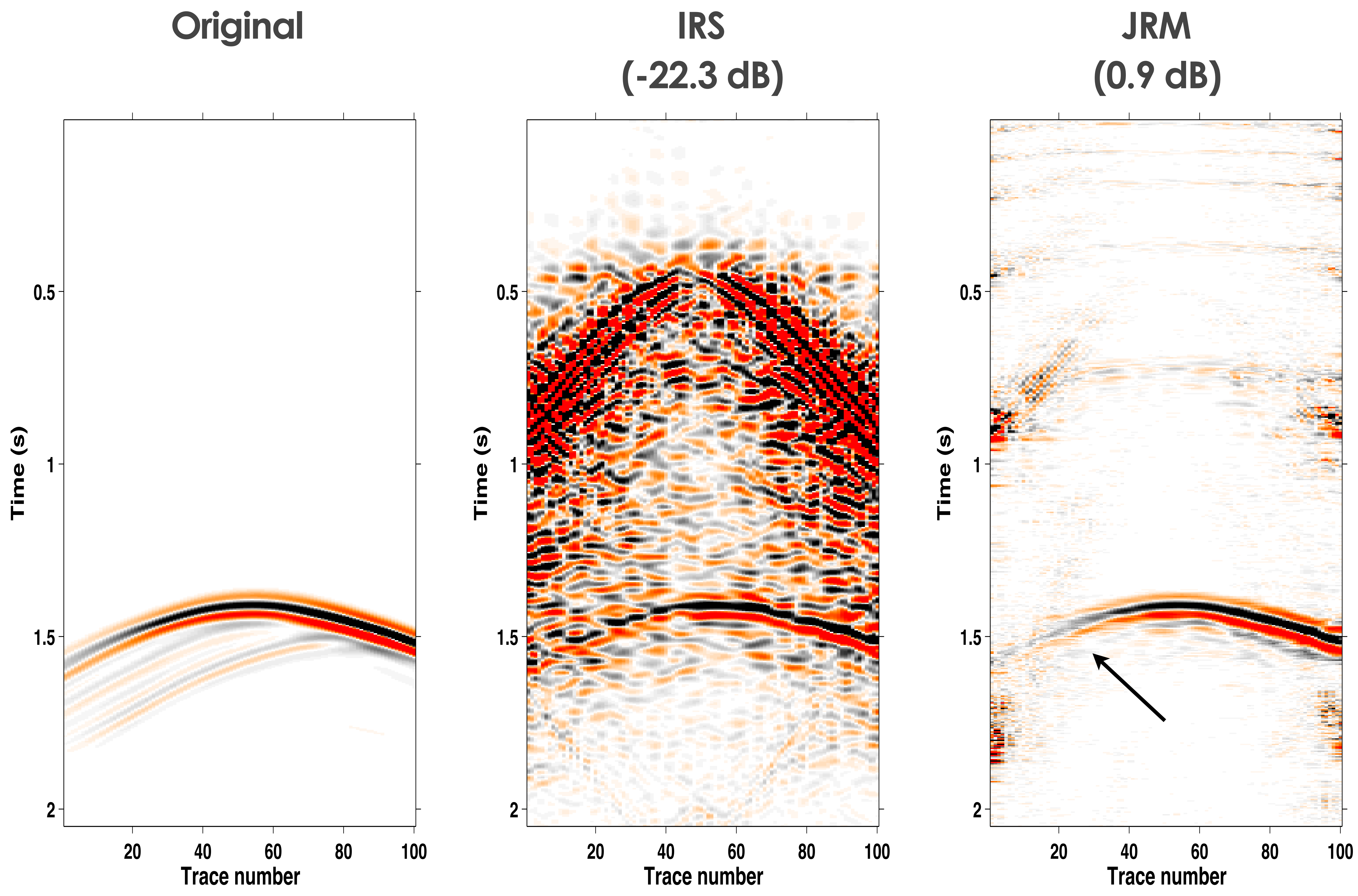
4-D recovery

–"*large*" overlap (50%) in *acquisition* matrices

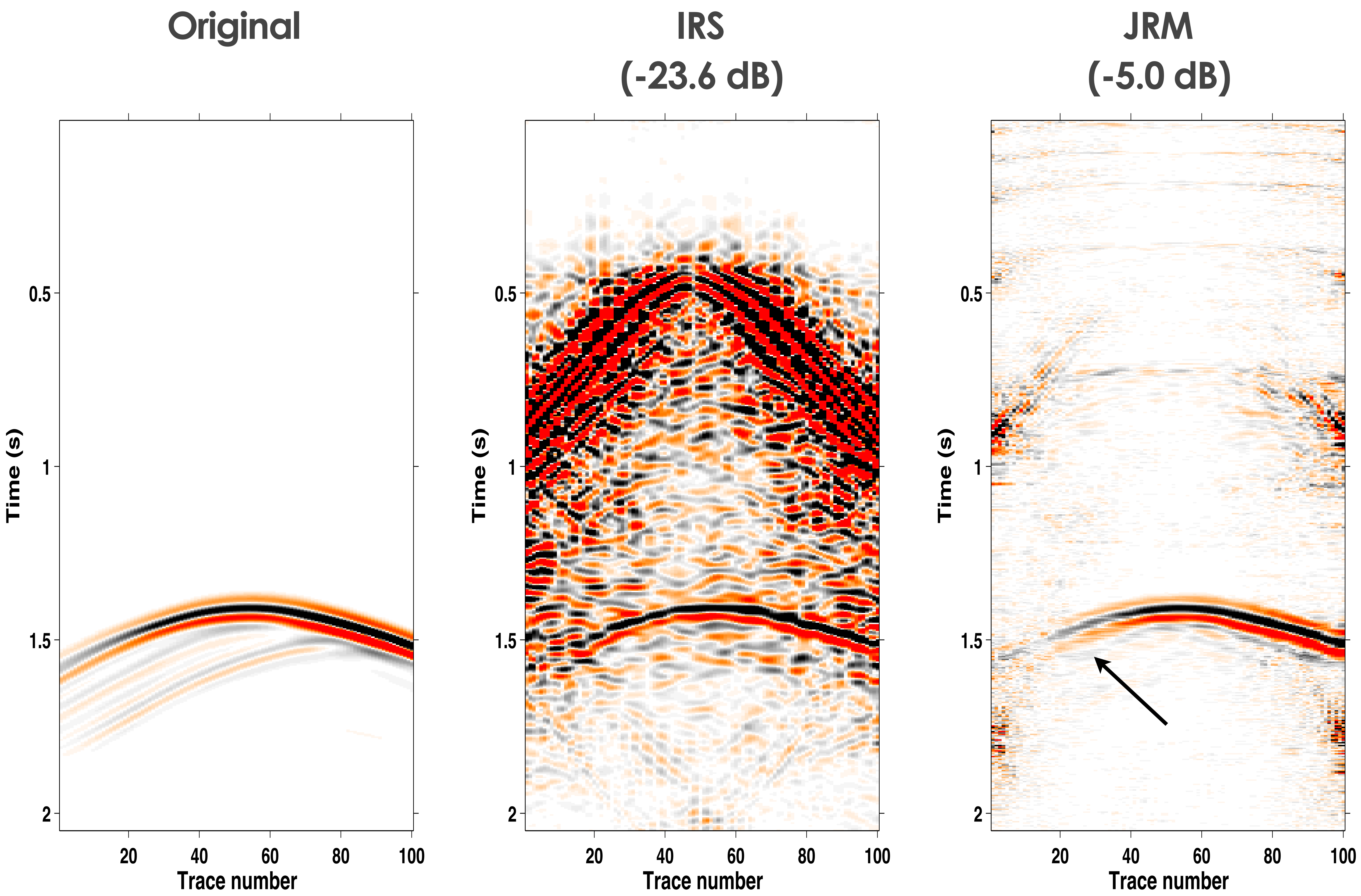


4-D recovery

–"*large*" overlap (50%) in *acquisition* matrices



4-D recovery
–"*small*" overlap (25%) in *acquisition* matrices



Observations

Stylized synthetics give *fundamental* insights when recovering 4-D seismic

Seismic synthetics are somewhat *inconclusive* but show that we do ***not*** necessarily have to insist on full *repetition* depending on the *recovery* of the *vintages*

Approach is *trivially* extendable to *multiple* vintages & *image* space

Questions:

Process/recover *independently* or *jointly* to exploit *common* features of *surveys*?

- ✓ process *jointly* leads to *improved* recovery of ***both*** *vintages* & *time*-lapse

Should we *repeat* the *surveys* when doing *randomized under*sampling?

- ✓ no, as long as one samples *sufficiently* to recover ***both*** *vintages* jointly
- ✓ yes, if recovery of vintages *fails* and *one* has a *high* degree of *repetition* then the *only* hope is to recover the *difference*, *not* recommended

Recommendations

The *Joint Recovery Model always* give *superior* results

- avoid *independent* recovery/processing *not* to miss *shared* structure
- while *large* degrees of *repetition* may allow for *recovery* of *sparse time-lapse* there is ***no*** guaranteed *recovery* of the *vintages* themselves

Aim for guaranteed *recovery* of the *vintages* instead

- *improves* recovery of *vintages* for *lower* degrees of *repetition*
- while *recovery* quality of *time*-lapse remains more or less the *same*

Lower *sub*sampling rates instead of increasing *degree*s of *repetition!*

Acknowledgements

We need 4-D data!

Thank you for your attention !

https://www.slim.eos.ubc.ca/

SINBAD

NSERC CRSNG

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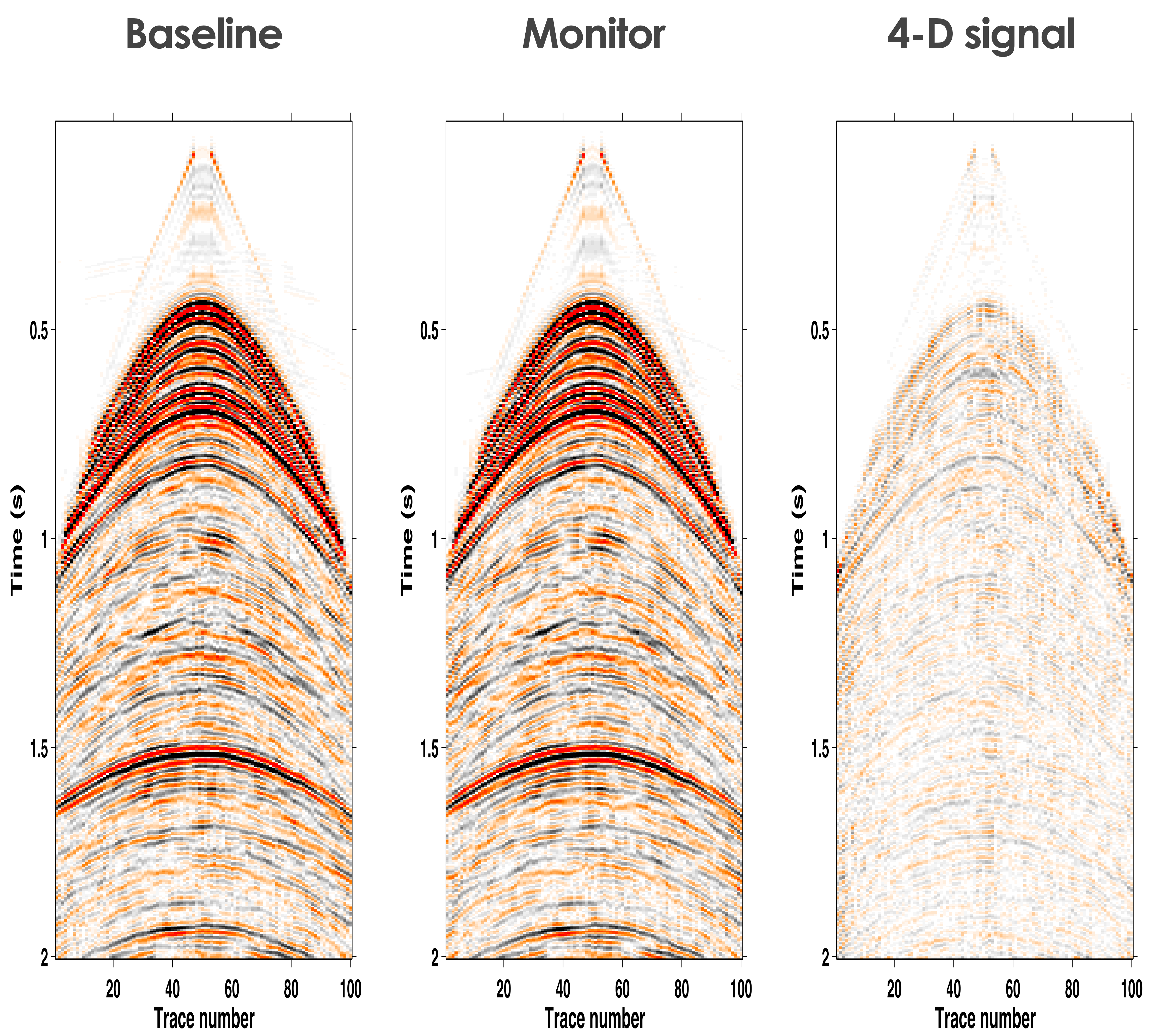
Real field-data example (from SEG abstract)

Original data

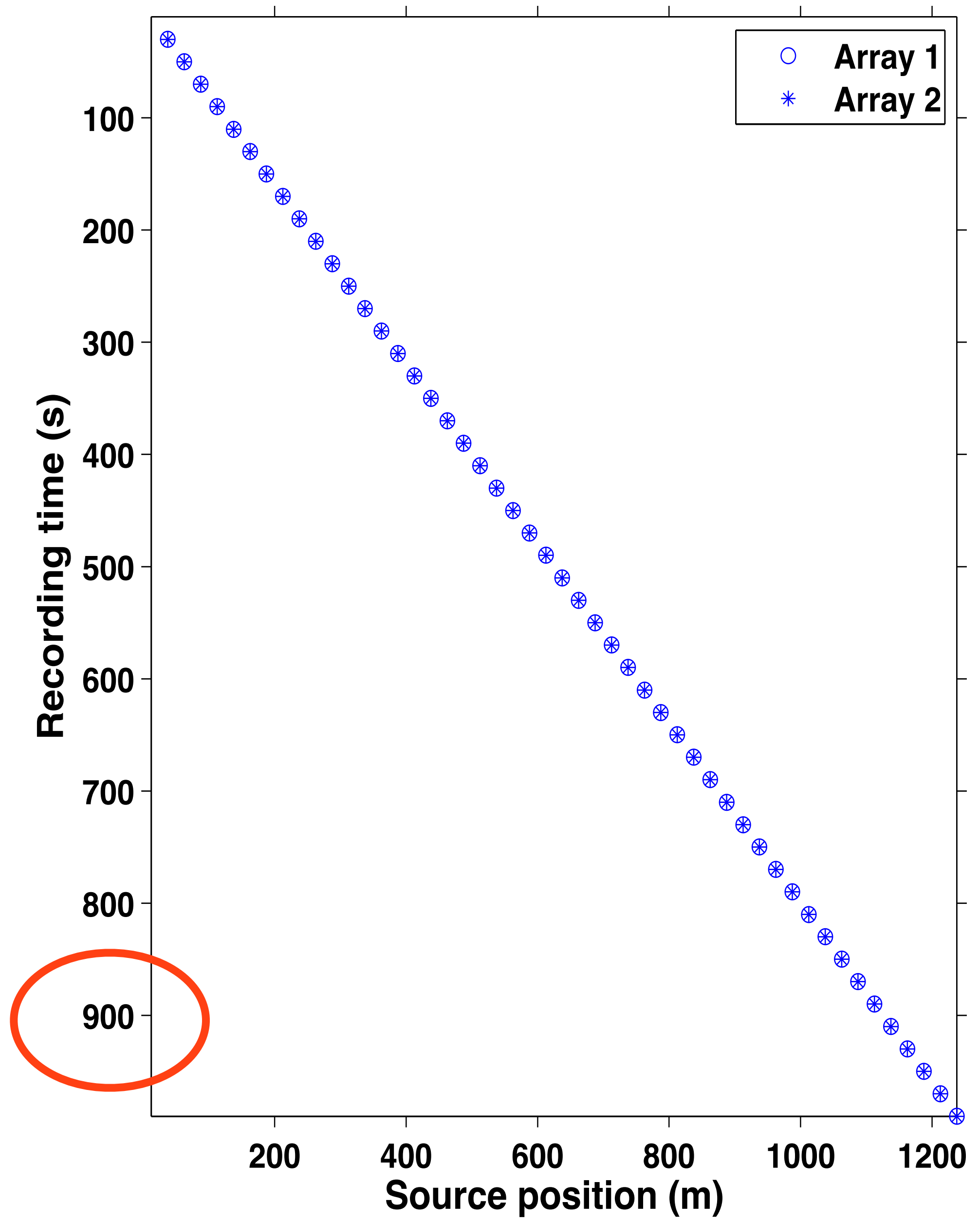


time samples: **501**
receivers: **100**
sources: **100**

sampling
time: **4.0 ms**
receiver: **25.0 m**
source: **25.0 m**

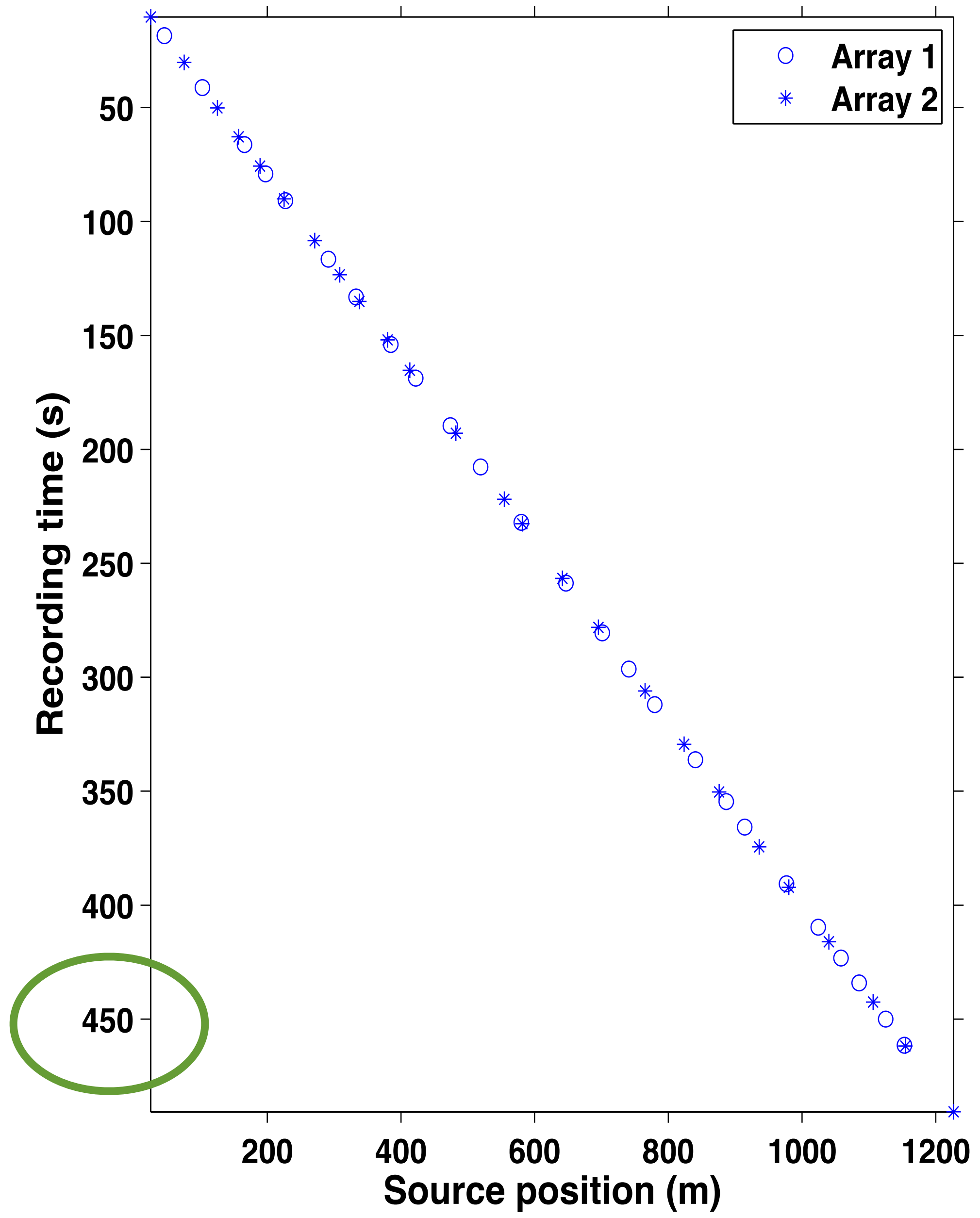
Conventional vs. *time-jittered* sources

conventional



***"unblended"* shot gathers**
number of shots = **100** (per array)
shot record length: 10.0 s
spatial sampling: **12.5 m**
vessel speed: **1.25 m/s**
recording time = 100 x 10.0 = **1000.0 s**

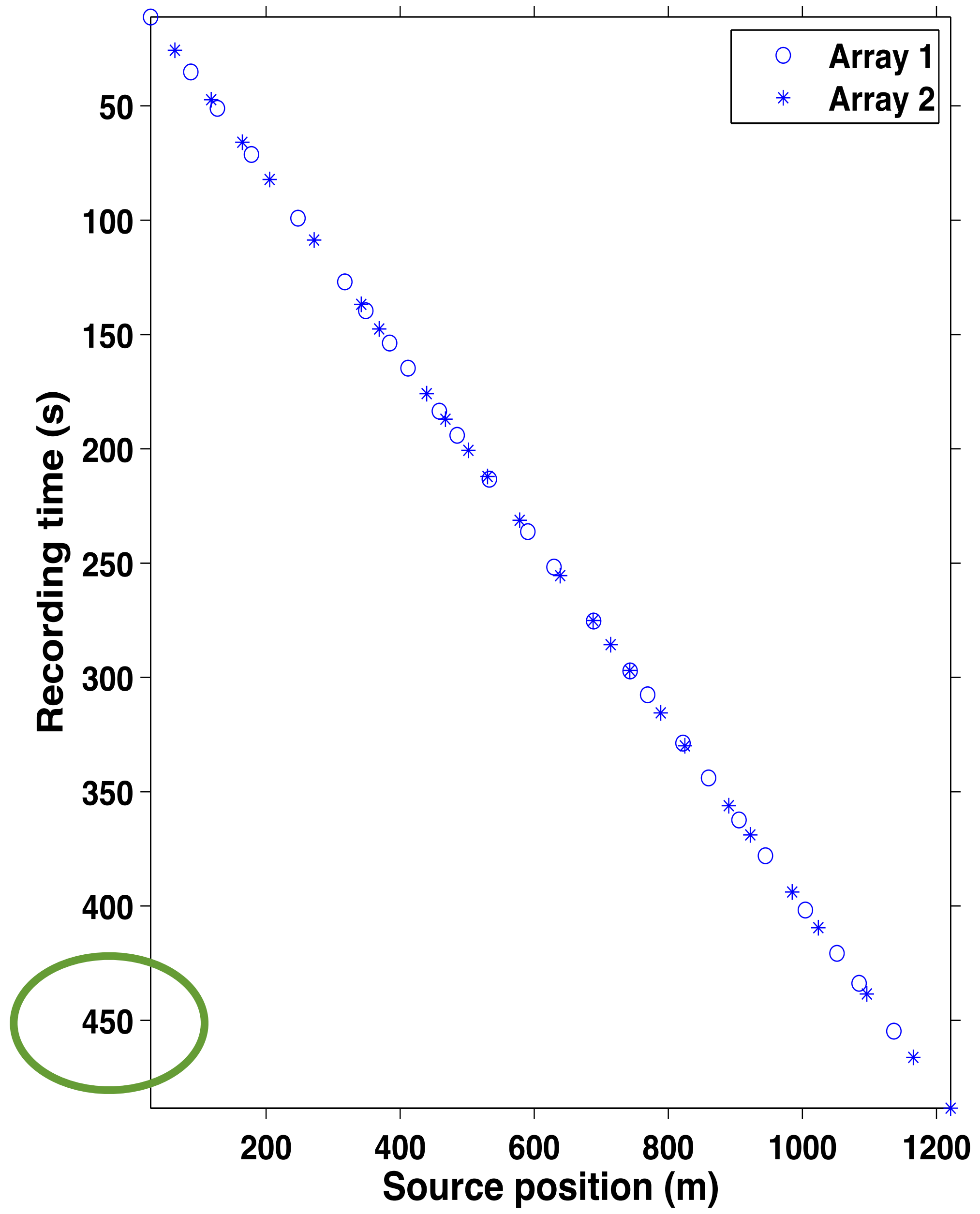
jittered acquisition 1 (for baseline)



[BLENDING & UNDERSAMPLING]
spatial undersampling factor = **2**

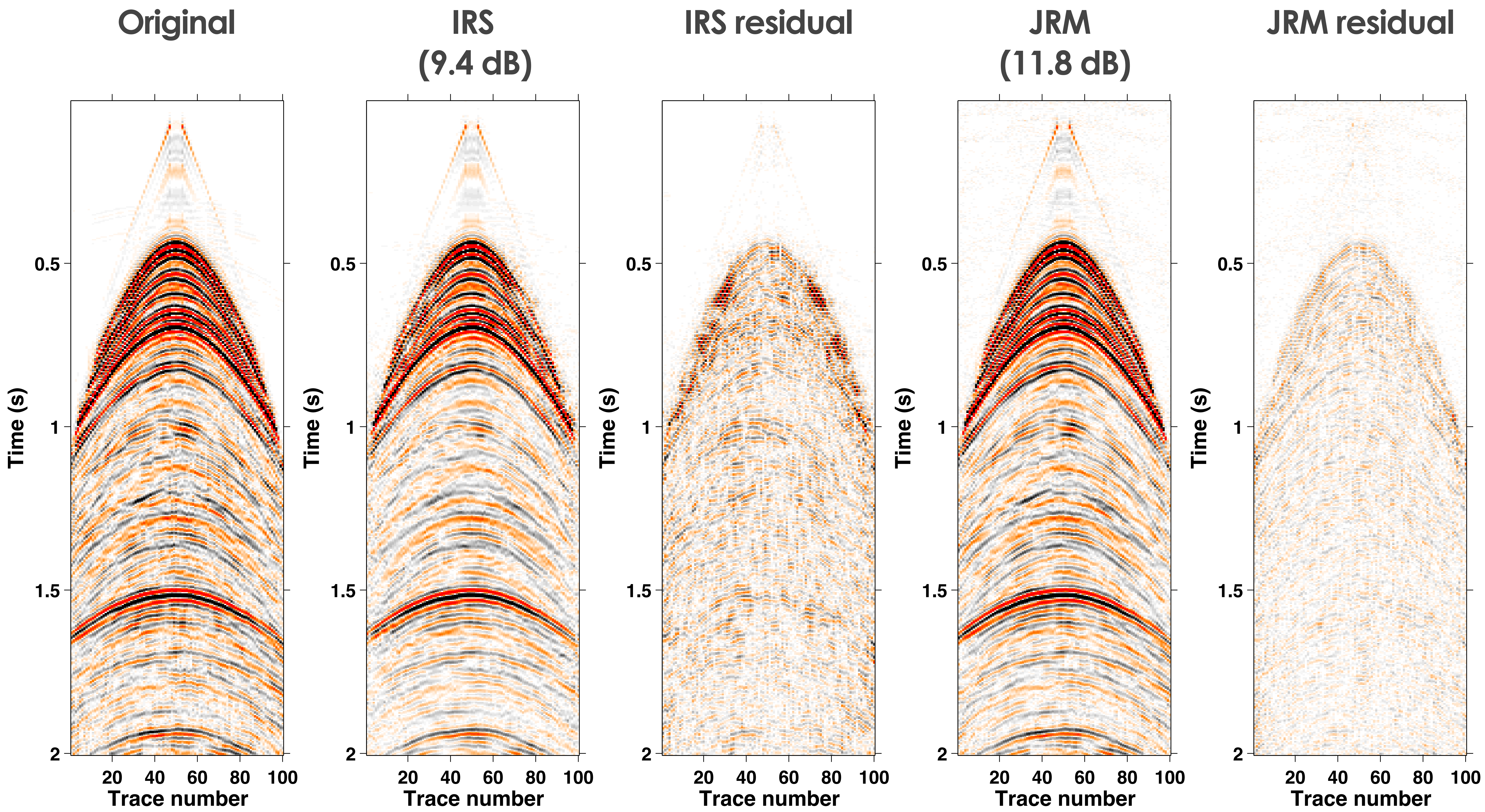
spatial sampling ***increase*** factor = **2**
[DEBLENDING & INTERPOLATION]

jittered acquisition 2 (for monitor)

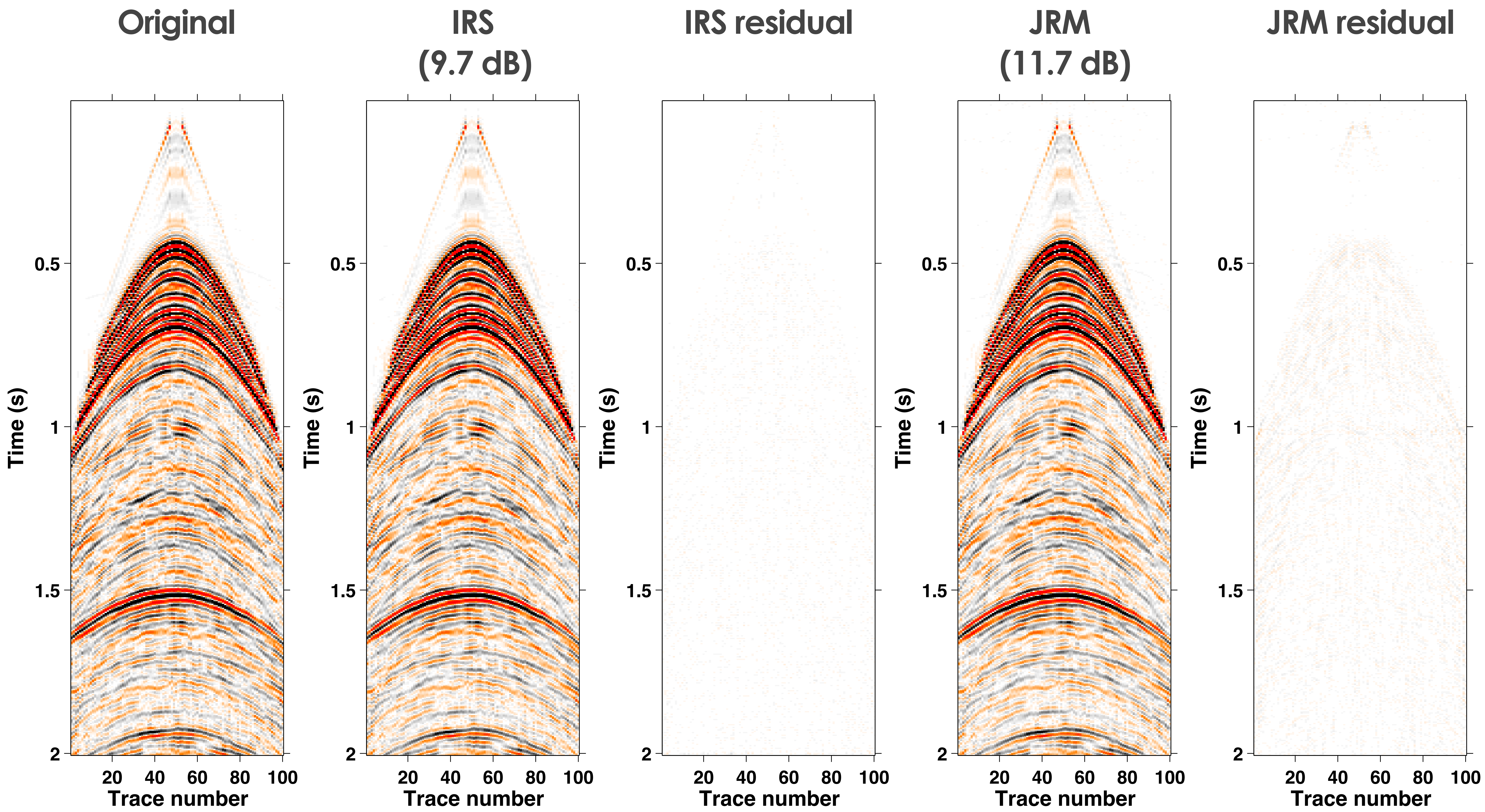


***"blended"* shot gathers**
number of shots = 100/2 = **50** (25 per array)
spatial sampling: **50.0 m (*jittered*)**
vessel speed: **2.50 m/s**
recording time ≈ 1000.0 s/2 = **500.0 s**

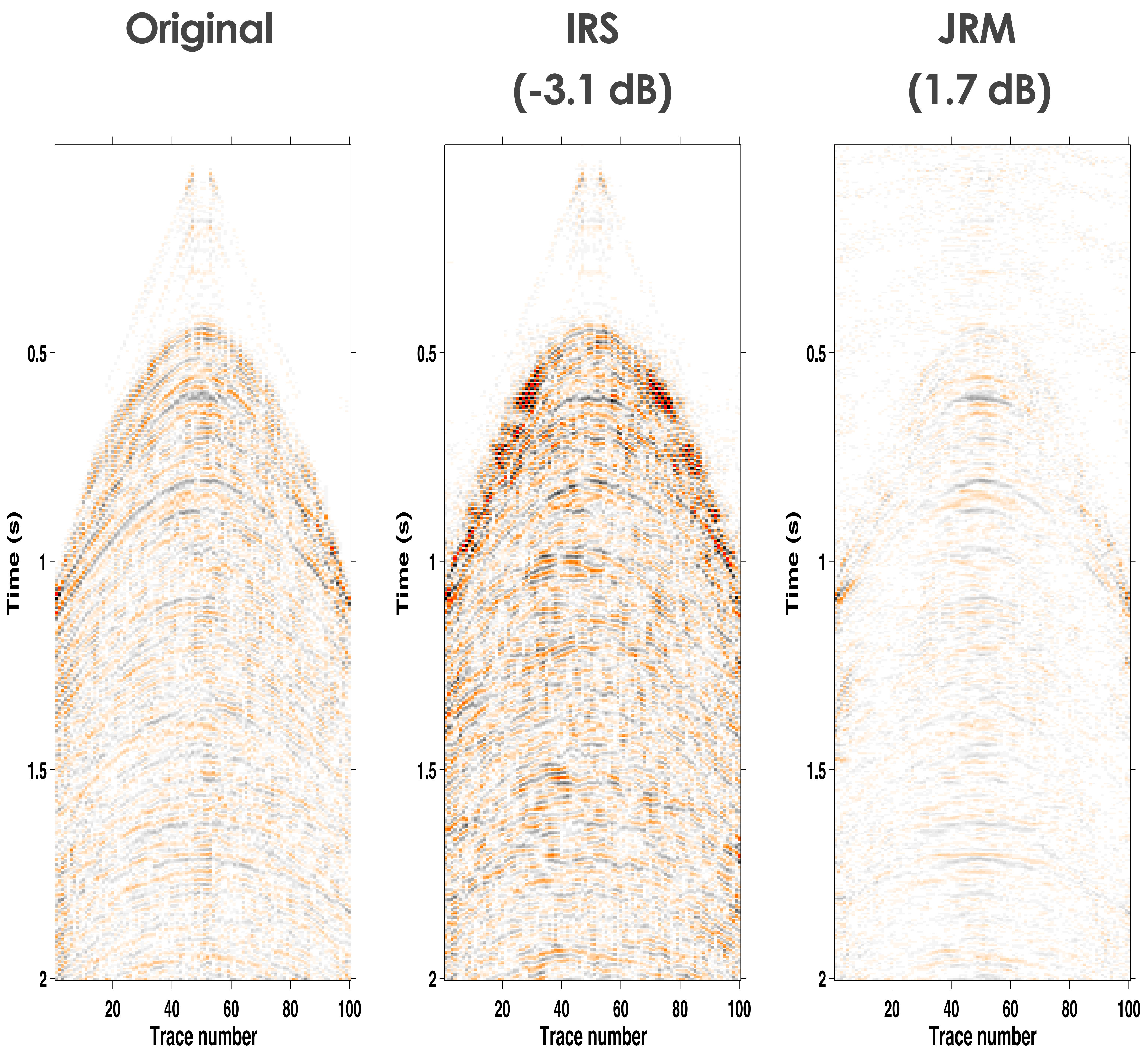
Baseline recovery



Monitor recovery

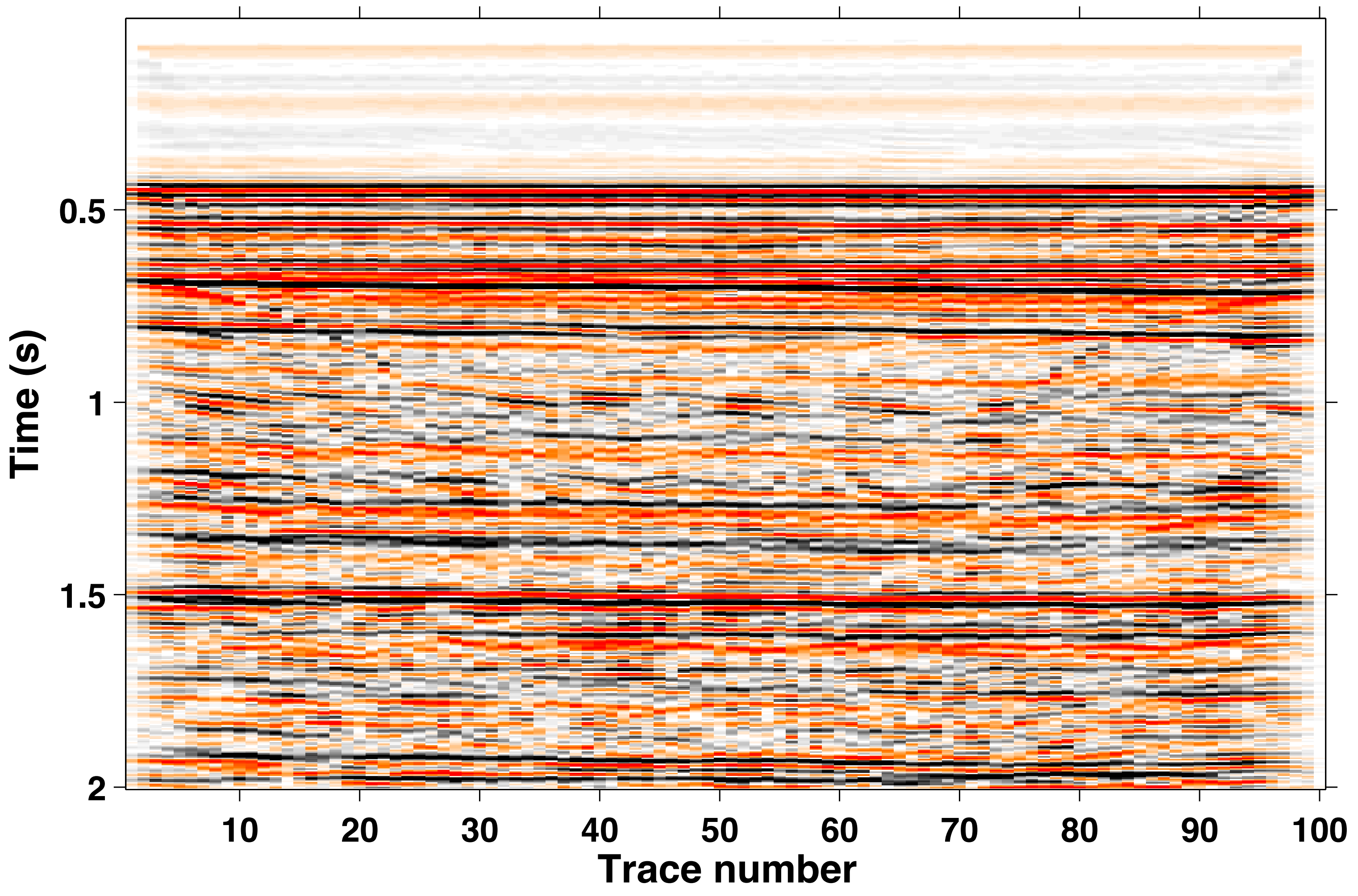


4-D signal recovery

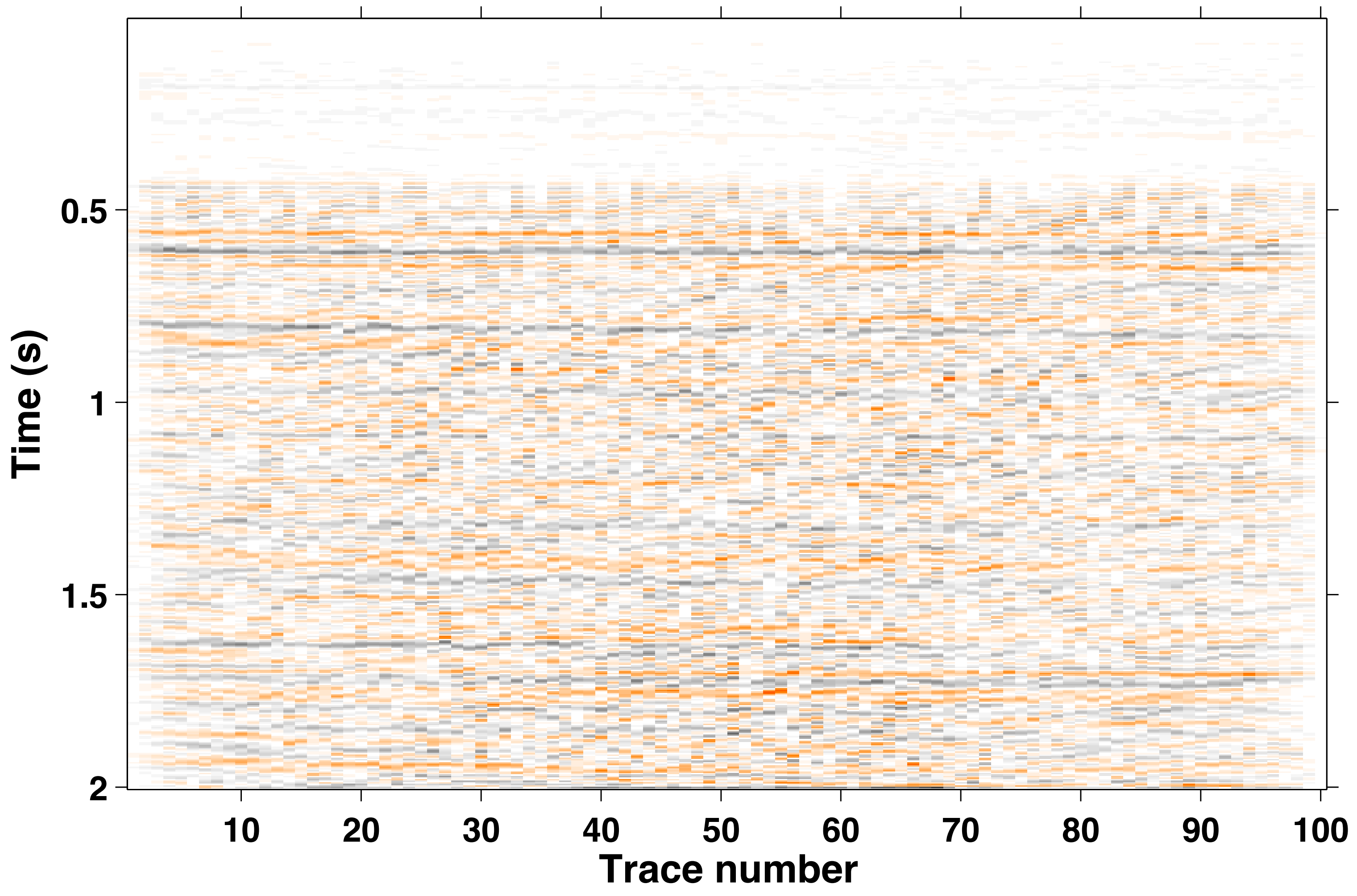


Stacked sections

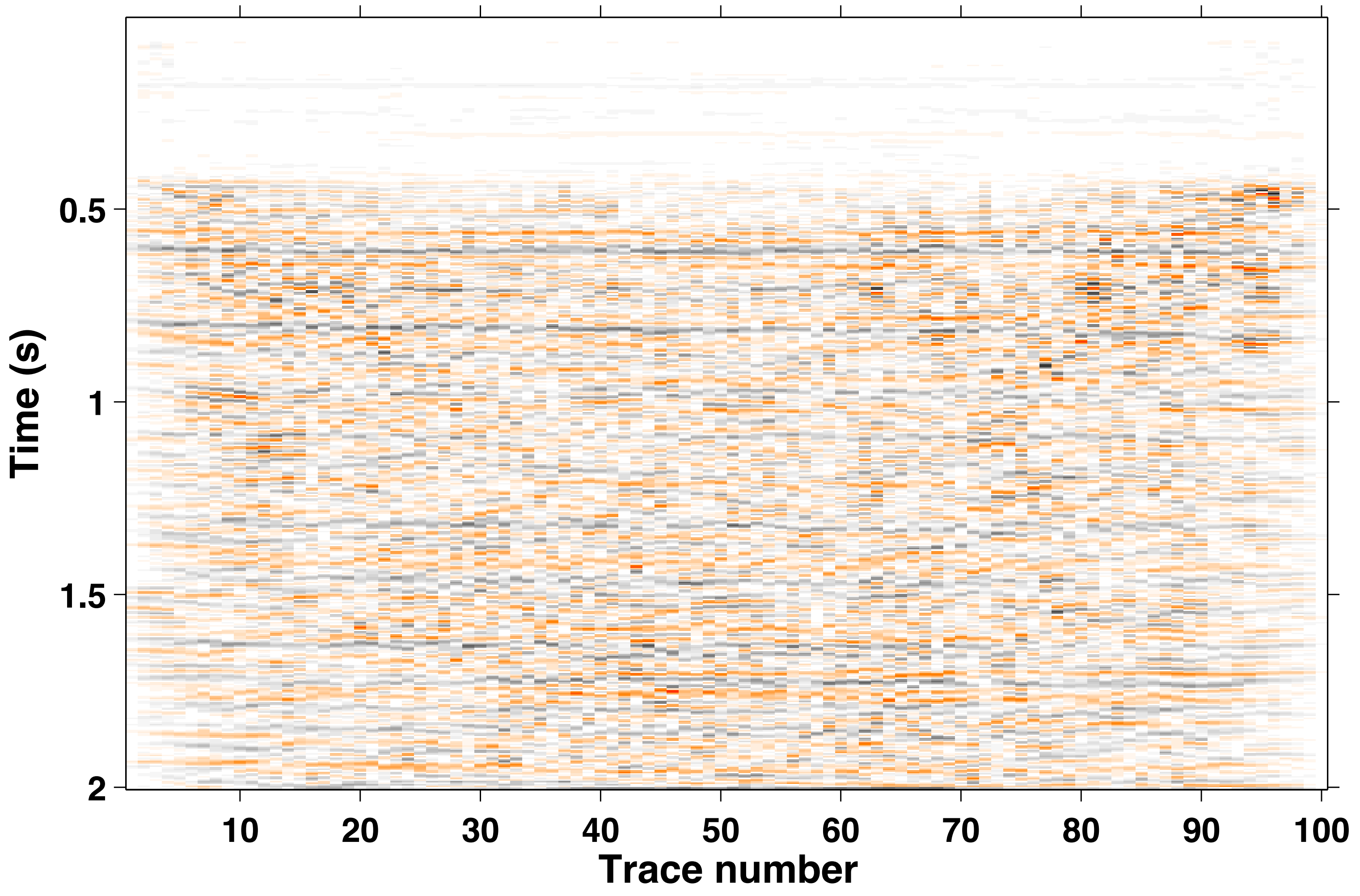
Original baseline



Original 4-D



IRS recovered 4-D



JRM recovered 4-D