Estimating 4D *differences* in time-lapse using *randomized* sampling techniques

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Current challenges in 4D

- *Repeatability* of 4D seismic experiments
  - effort spent to repeat baseline and monitor surveys
  - processing decisions - should we apply similar or different processing to both data?
  - how do processing decisions depend on the data and the 4D signal?
- *Detectability* of 4D signal
  - very weak signals pose a challenge - hard to detect
  - 4D noise level impact on the signal quality

Motivation

- Need for repeatability ?
  - effort spent to repeat baseline and monitor surveys
  - processing decisions - should we apply similar or different processing to both data?
  - how do processing decisions depend on the data and the 4D signal?
- Resolution of 4D signals
  - how can we better *detect* and *improve* the signal-to-noise ratios of 4D signals ?
- Would like to *reduce* the acquisition *cost* of a 4D project

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Big Question ???

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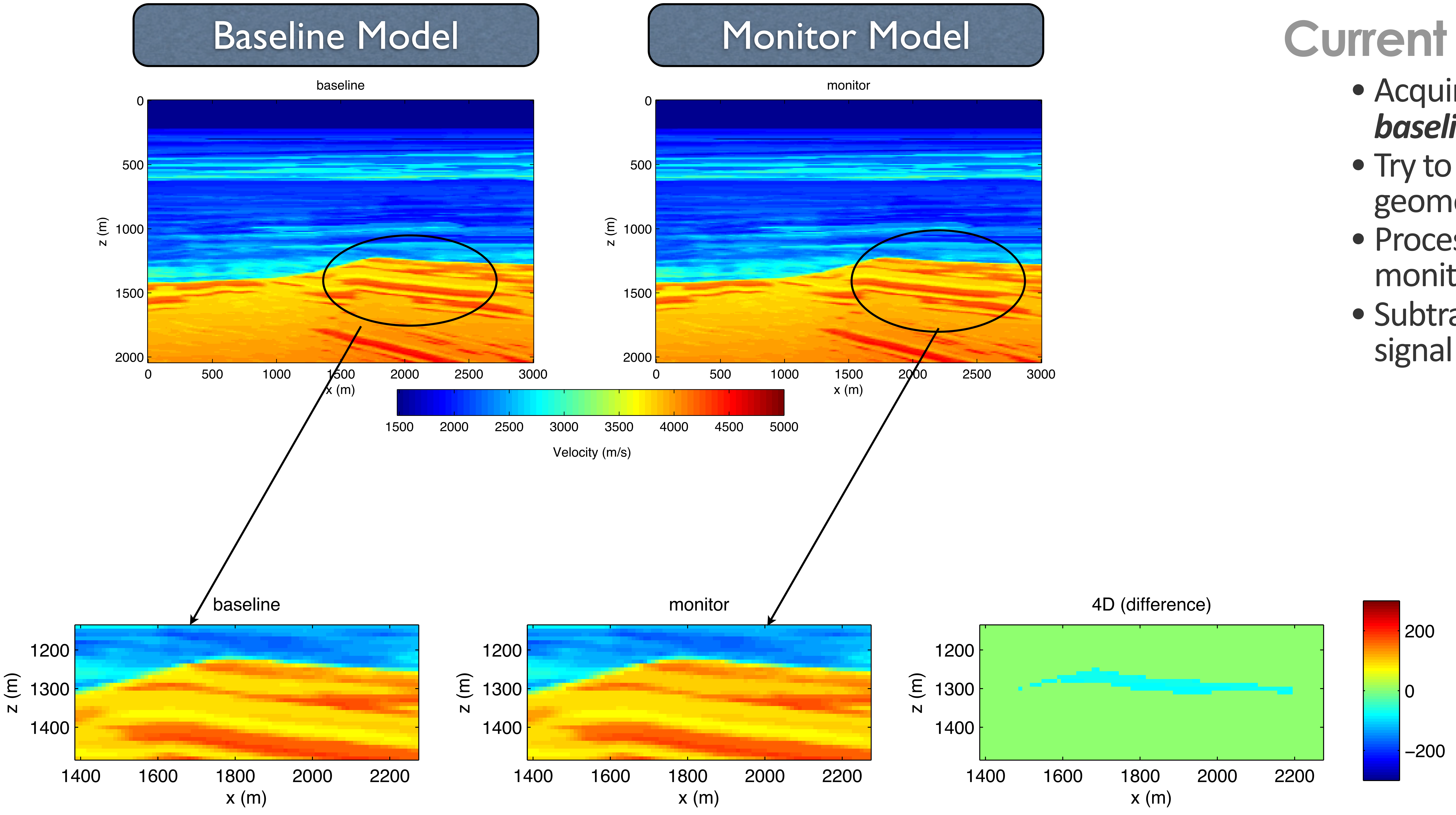
Big Question ???

- Should we perform **randomized** acquisition for a 4D project ?
- Should we **repeat** the acquisition or not ?
- What is the net effect on the 4D signal?



Current Practice

- Acquire data for ***baseline***
- Try to **repeat** acquisition geometry for ***monitor***
- Process baseline and monitor data
- Subtract to observe 4D signal

Conventional acquisition

Sequential shot acquisition

Baseline

Repeatability in Geometry

Sequential shot acquisition

Monitor

Proposed acquisition

Acquisition with Randomized Missing Shots

Baseline

Repeatability in Randomness?

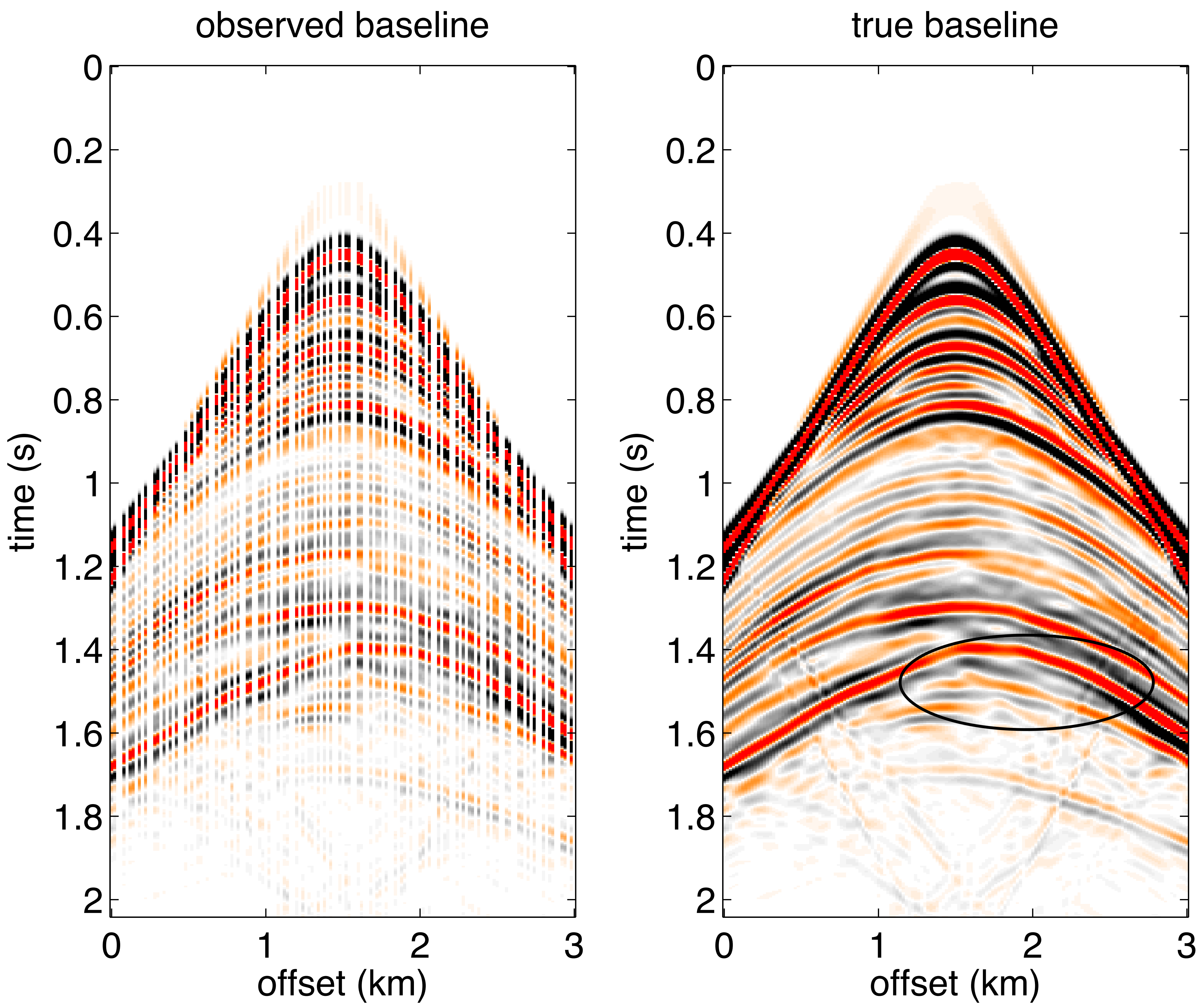
Acquisition with *DIFFERENT* Randomized Missing Shots

Monitor

Numerical Experiment

For Baseline model

- (**Proposed Setup**) randomized acquisition with missing shots
  - we require the fully and coarsely sampled data on a regular grid
  - apply Compressed Sensing (CS)



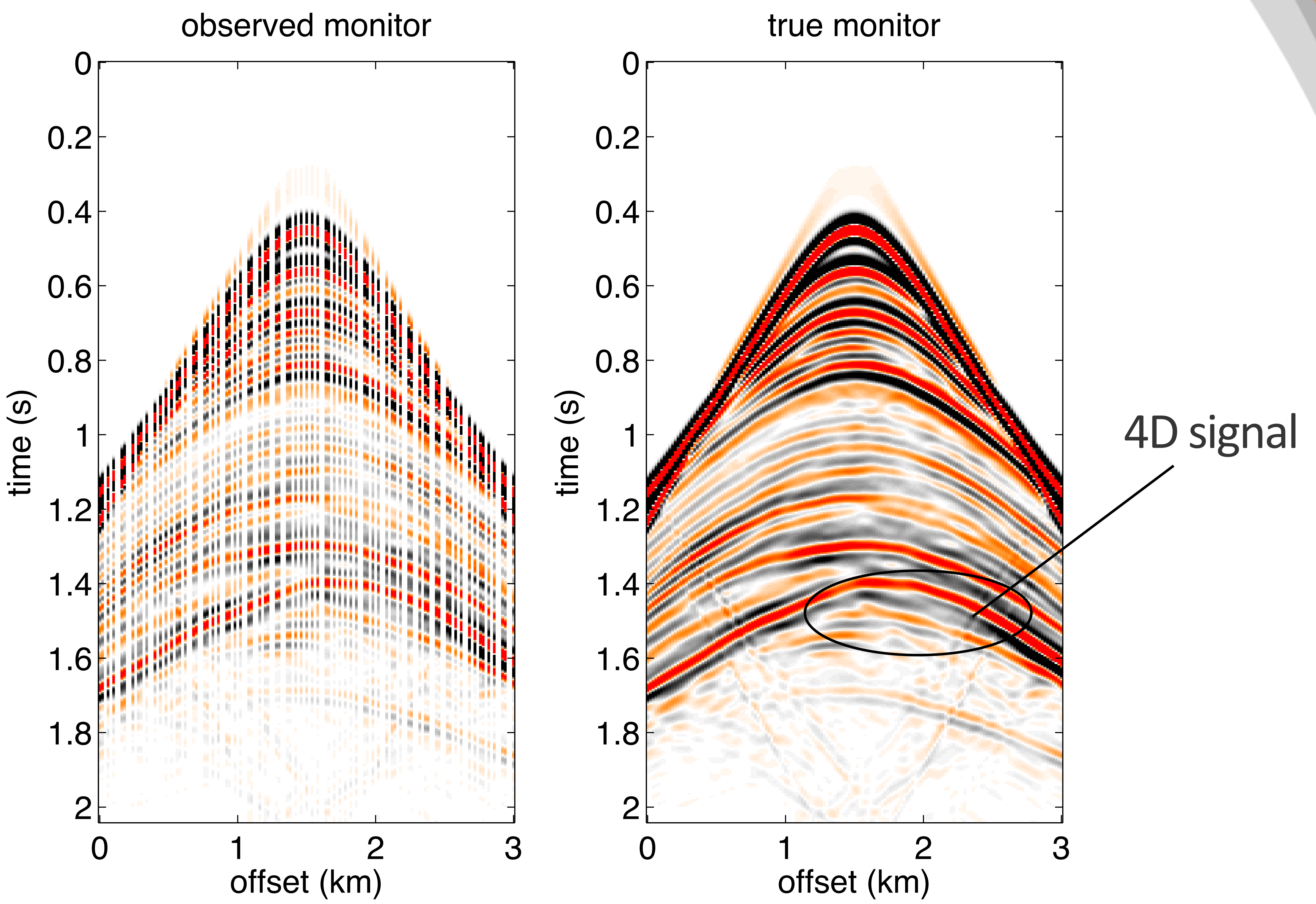
Numerical Experiment

For Baseline model

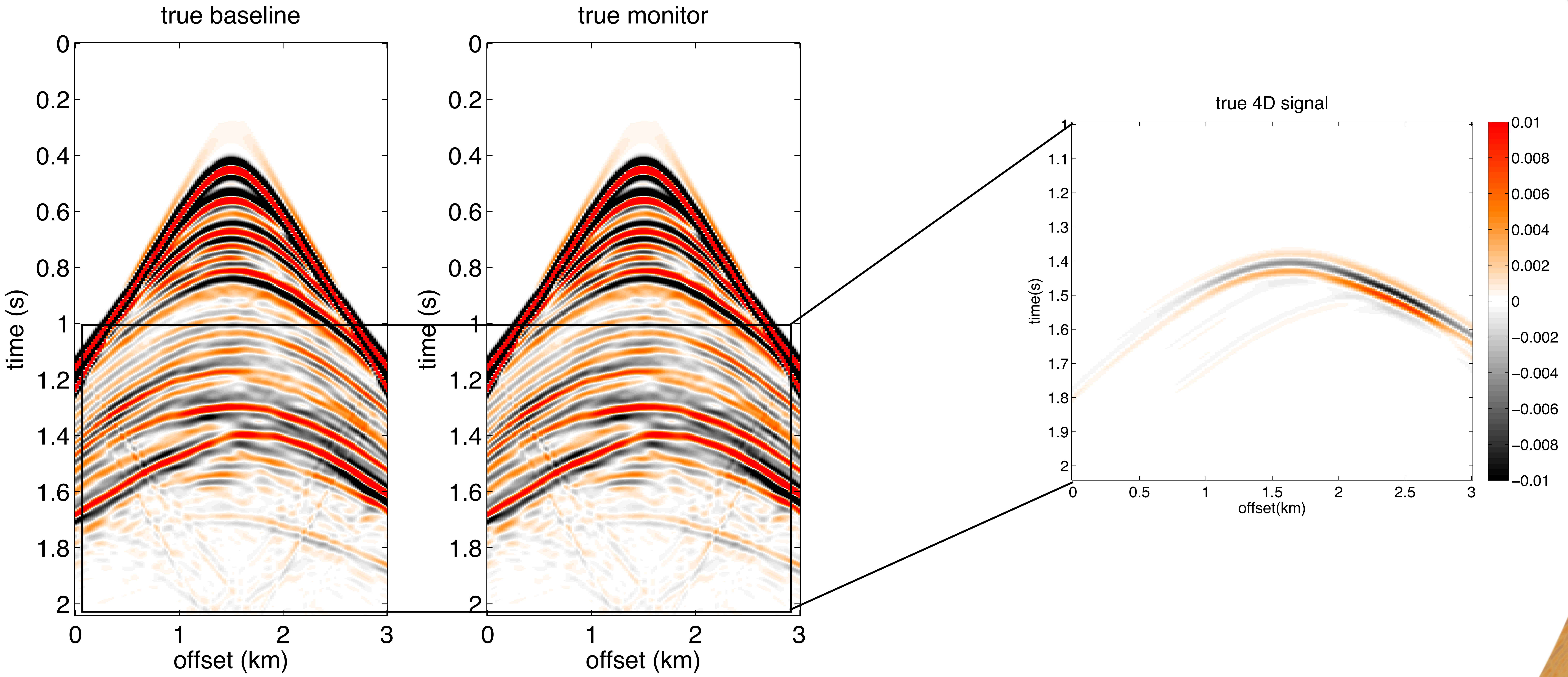
- (**Proposed Setup**) randomized acquisition with missing shots
  - we require the fully and coarsely sampled data on a regular grid
  - apply Compressed Sensing (CS)

For Monitor

- use a ***different*** randomized acquisition geometry ?
  - we require the fully and coarsely sampled data on a regular grid
  - apply CS



100% Repeated Seismic = Same Acquisition Geometry Regularly and Densely Sampled



CS in 4D – first approach

In general

$$\mathbf{A} = \mathbf{RMS}^*$$

Sparsifying transform

Restriction

Measurement matrix

$$\mathbf{y} = \mathbf{Ax}$$

observed data

Unknown vector (sparse representation of data)

Solve $$\tilde{\mathbf{x}} = \arg\min_{\mathbf{x}} \|\mathbf{x}\|_1 \quad \text{s.t.} \quad \mathbf{y} = \mathbf{Ax}$$

In 4D

$$\text{let } \mathbf{M} \text{ be the identity basis}$$

$$\mathbf{A}_1 = \mathbf{R}_1\mathbf{MS}^* \quad \text{and} \quad \mathbf{A}_2 = \mathbf{R}_2\mathbf{MS}^*$$

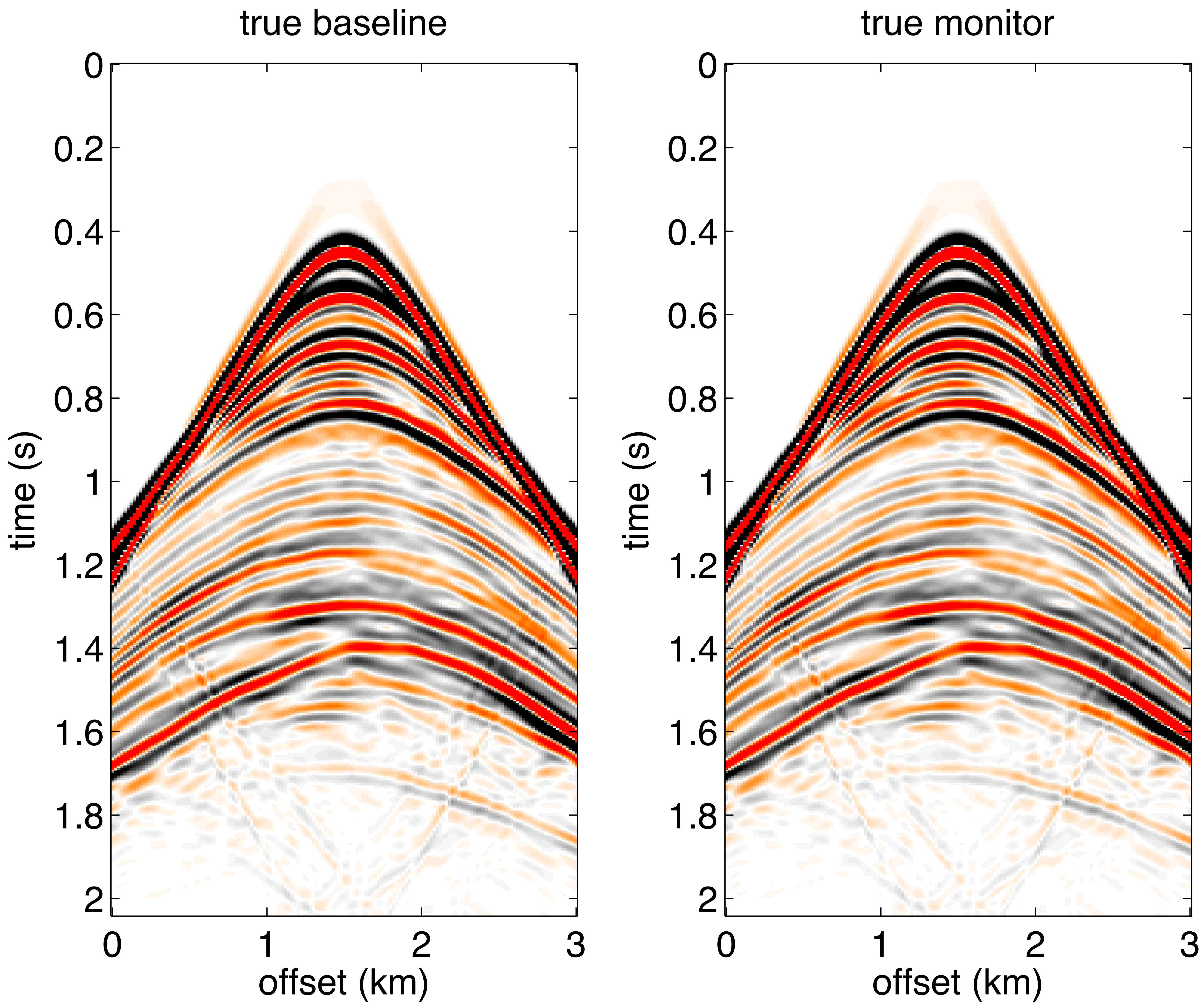
measure $$\mathbf{y}_1 = \mathbf{A}_1\mathbf{x}_1 \quad \text{and} \quad \mathbf{y}_2 = \mathbf{A}_2\mathbf{x}_2$$

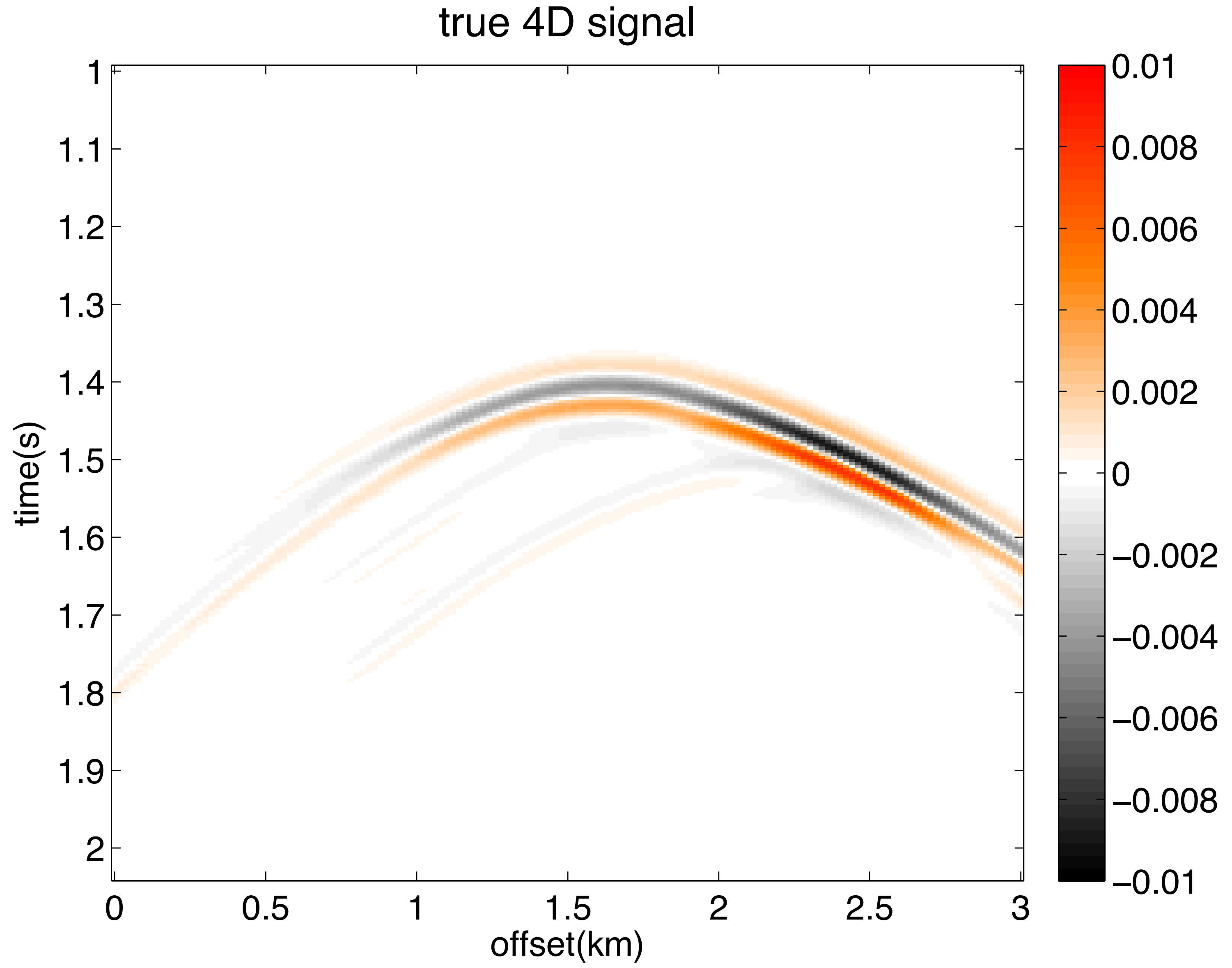
True 4D signal : $\mathbf{S}^*(\mathbf{x}_1 - \mathbf{x}_2)$ (baseline - monitor)

Estimated 4D signal : $\mathbf{S}^*(\tilde{\mathbf{x}_1} - \tilde{\mathbf{x}_2})$

- observe random measurements for ***baseline***
- observe a *different* random set of measurements for **monitor**
- reconstruct for each independently by using the sparsity recovery algorithm
- 4D signal is the difference of the reconstructed signals

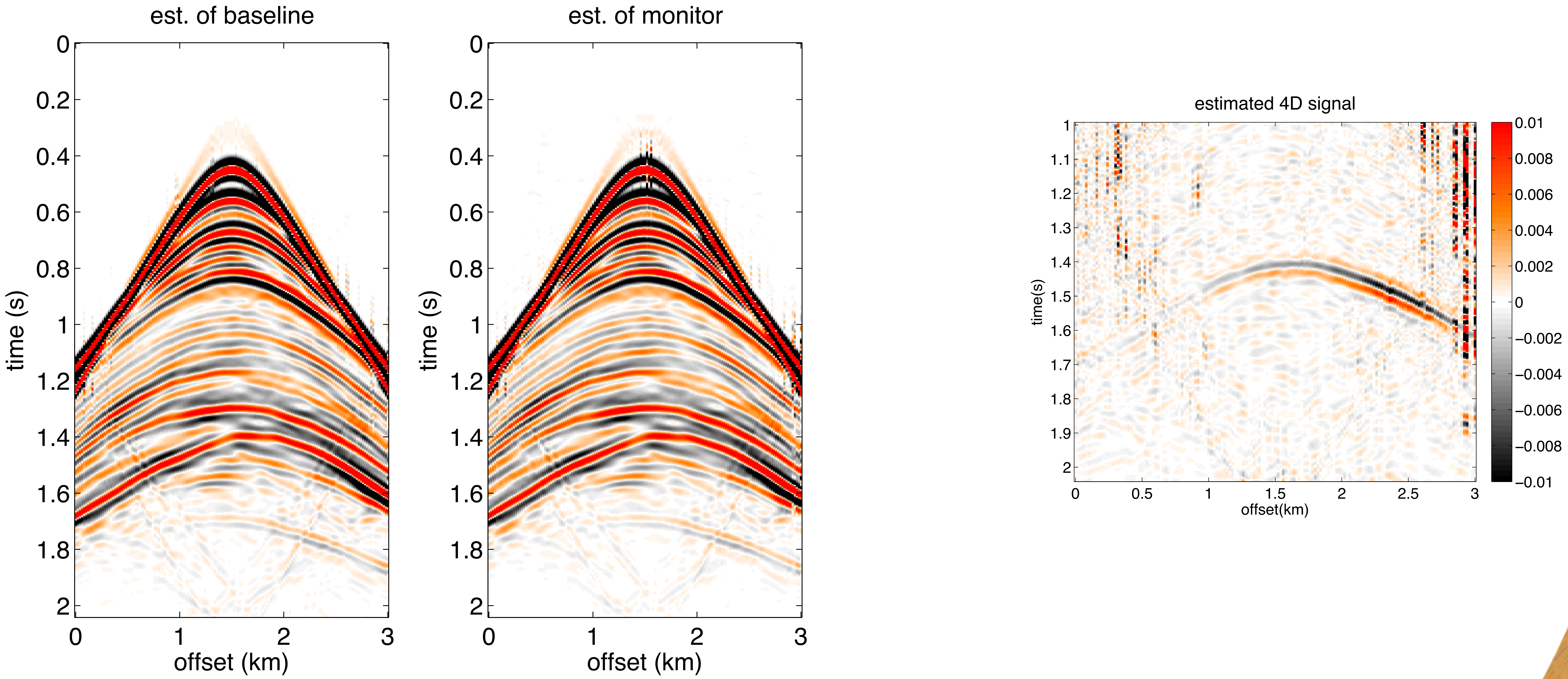
SAME Geometry – regularly & densely sampled – IDEAL but *UNREALISTIC* CASE





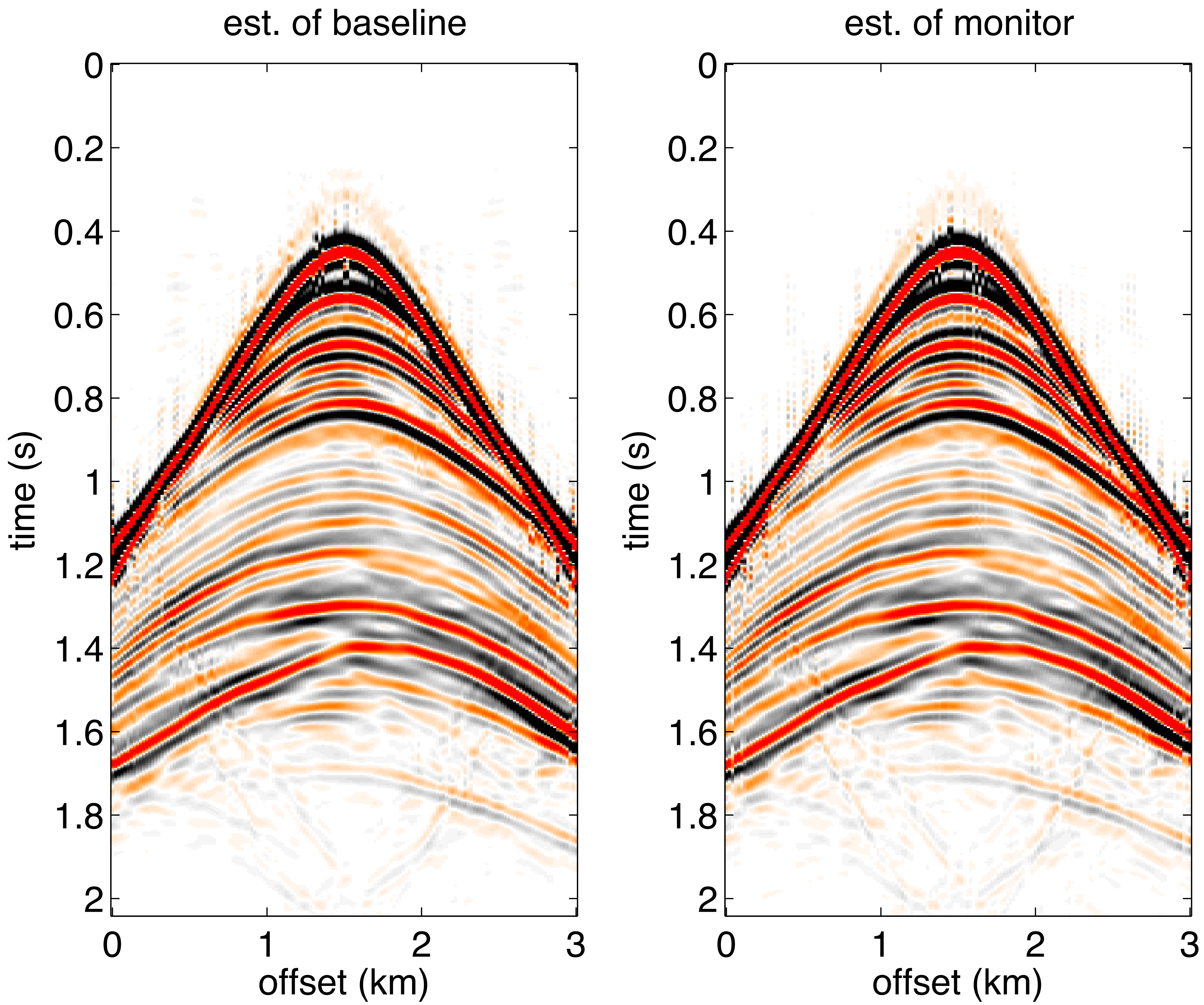
Result: 25% *INDEPENDENT* missing shots from each *vintage*

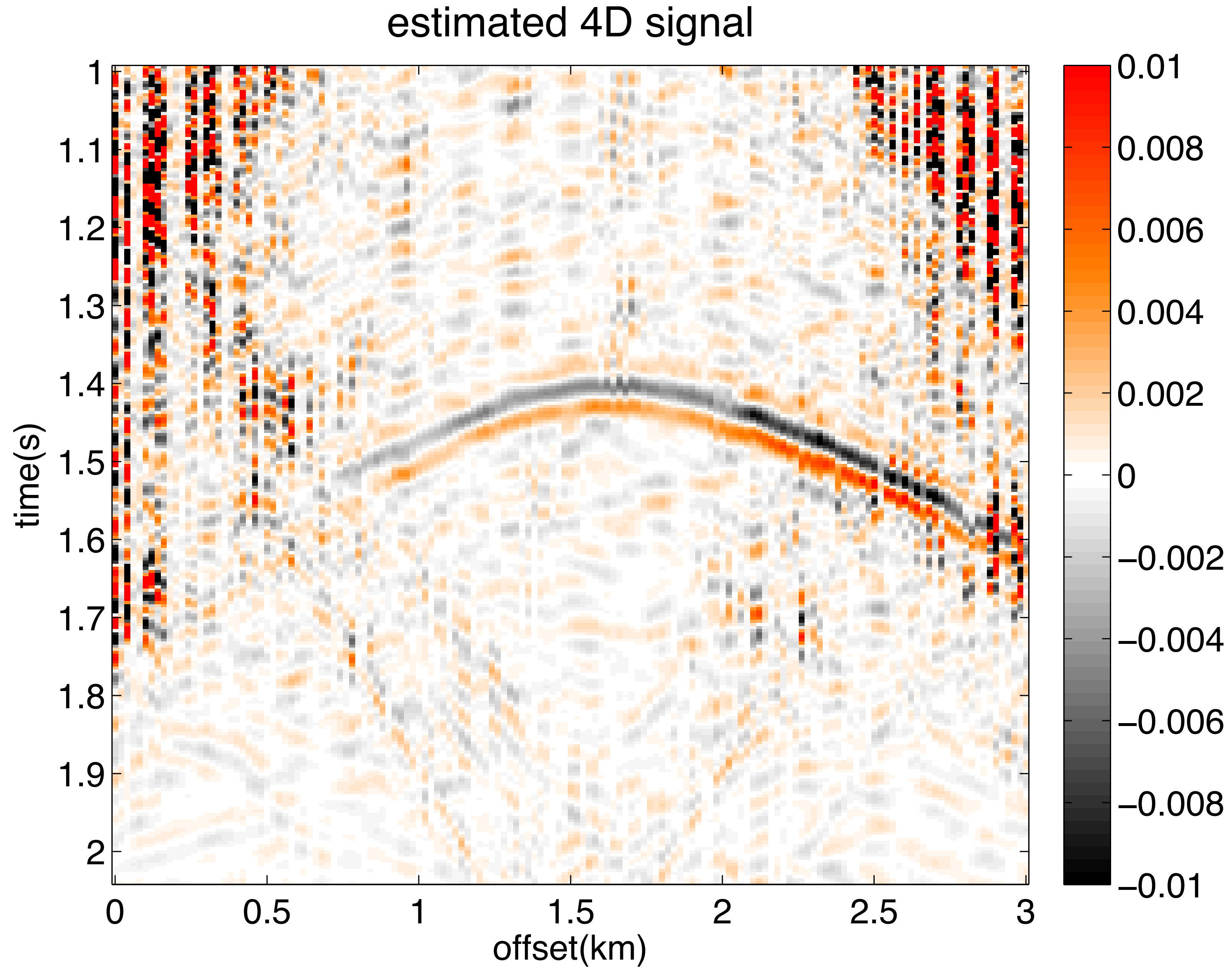
Result: OK



Result: 40% *INDEPENDENT* missing shots from each *vintage*

Result: Not OK





Motivation

- *Time*-lapse wavefields are compressible in the curvelet domain
- They have a lot of *information* in *common*

- Can we *exploit* this common **shared** information to make more *efficient* use of measurements?
- Can we use a model that *jointly* represents the wavefields.

Joint reconstruction model (JRM)

- Reconstruction of two or more signals
- *Each* of the signal is *compressible*
- The *joint* representation of the signals is *compressible*

$$\mathbf{A}_1 = \mathbf{R}_1\mathbf{M}\mathbf{S}^* \quad \text{and} \quad \mathbf{A}_2 = \mathbf{R}_2\mathbf{M}\mathbf{S}^*$$

$$\mathbf{y}_1 = \mathbf{A}_1\mathbf{x}_1 \quad \text{and} \quad \mathbf{y}_2 = \mathbf{A}_2\mathbf{x}_2$$

Rewrite

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

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

$\mathbf{z}_1$, $\mathbf{z}_2$ → ***unique* part**

$\mathbf{z}_0$ → ***common* shared support**

An Information-Theoretic Approach to Distributed Compressed Sensing (2005)

by Dror Baron , Marco F. Duarte , Shriram Sarvotham , Michael B. Wakin , Richard G. Baraniuk

Joint reconstruction model

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

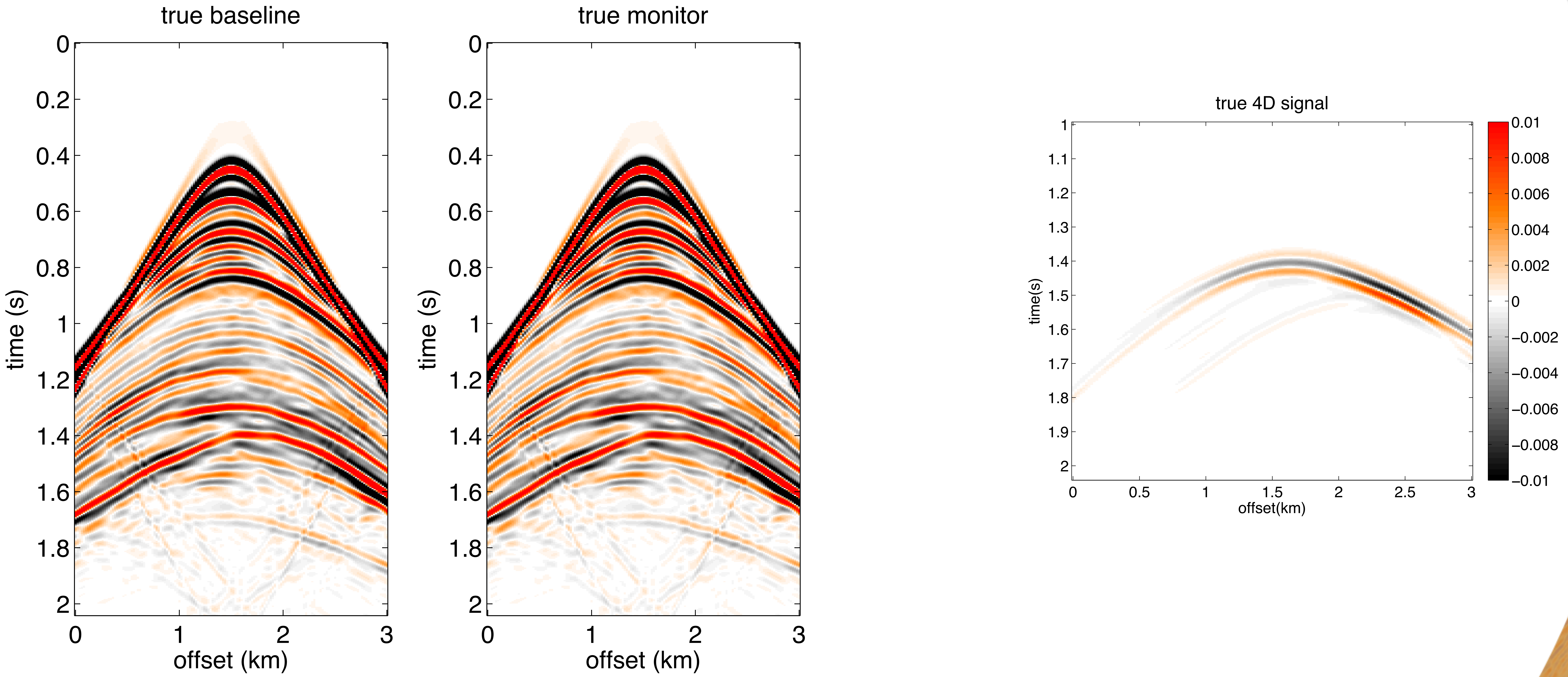
$$\overbrace{\begin{bmatrix} \mathbf{A}_1 & \mathbf{A}_1 & \mathbf{0} \\ \mathbf{A}_2 & \mathbf{0} & \mathbf{A}_2 \end{bmatrix}}^{\mathbf{A}} \overbrace{\begin{bmatrix} \mathbf{z}_0 \\ \mathbf{z}_1 \\ \mathbf{z}_2 \end{bmatrix}}^{\mathbf{z}} = \overbrace{\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix}}^{\mathbf{y}}$$

$$\tilde{\mathbf{z}} = \arg\min_{\mathbf{z}} \|\mathbf{z}\|_1 \quad \text{s.t.} \quad \mathbf{y} = \mathbf{A}\mathbf{z}$$

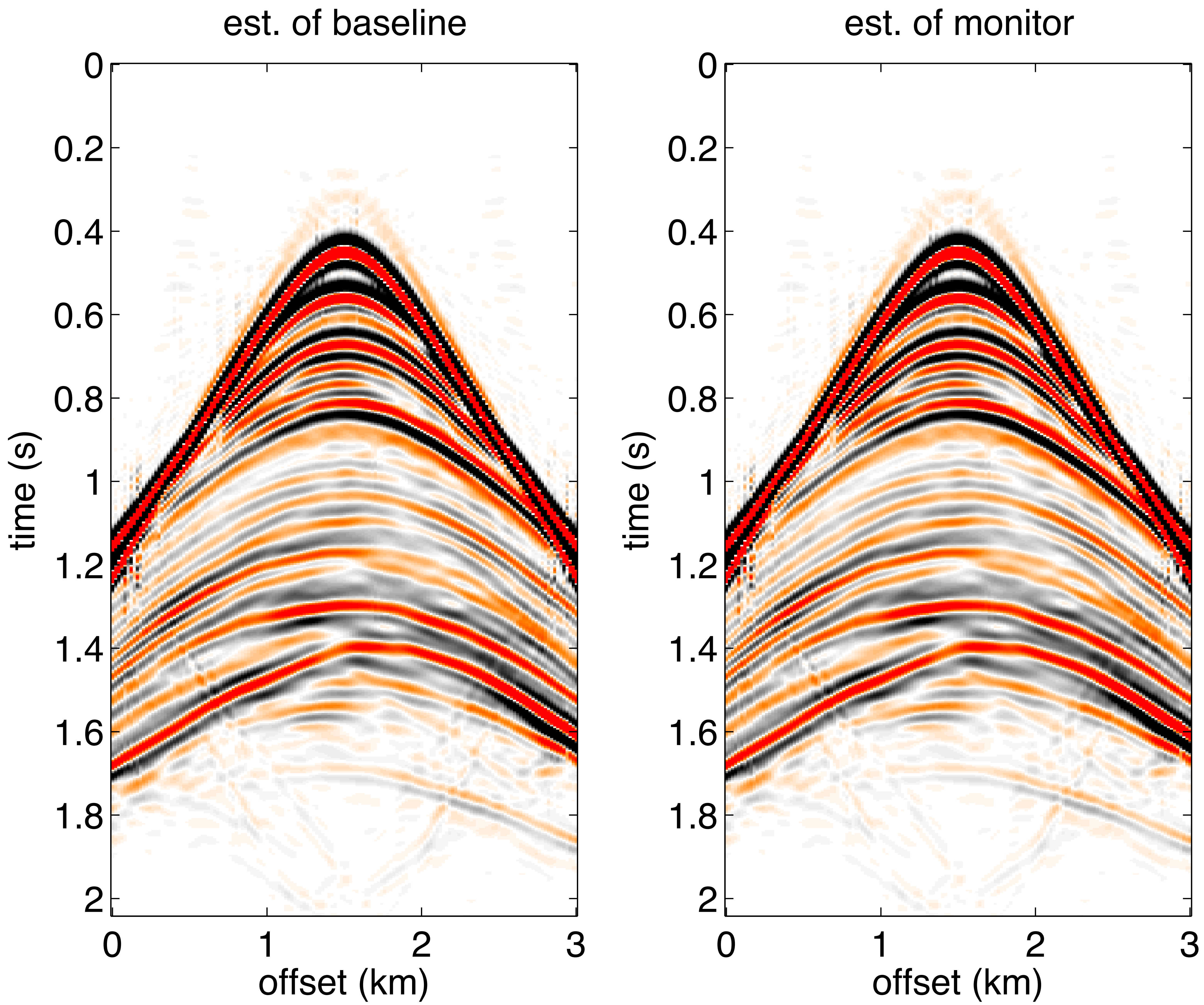
$$\tilde{\mathbf{z}} = \begin{bmatrix} \tilde{\mathbf{z}_0} \\ \tilde{\mathbf{z}_1} \\ \tilde{\mathbf{z}_2} \end{bmatrix} \qquad \tilde{\mathbf{x}_1} = \tilde{\mathbf{z}_0} + \tilde{\mathbf{z}_1}, \quad \tilde{\mathbf{x}_2} = \tilde{\mathbf{z}_0} + \tilde{\mathbf{z}_2}$$

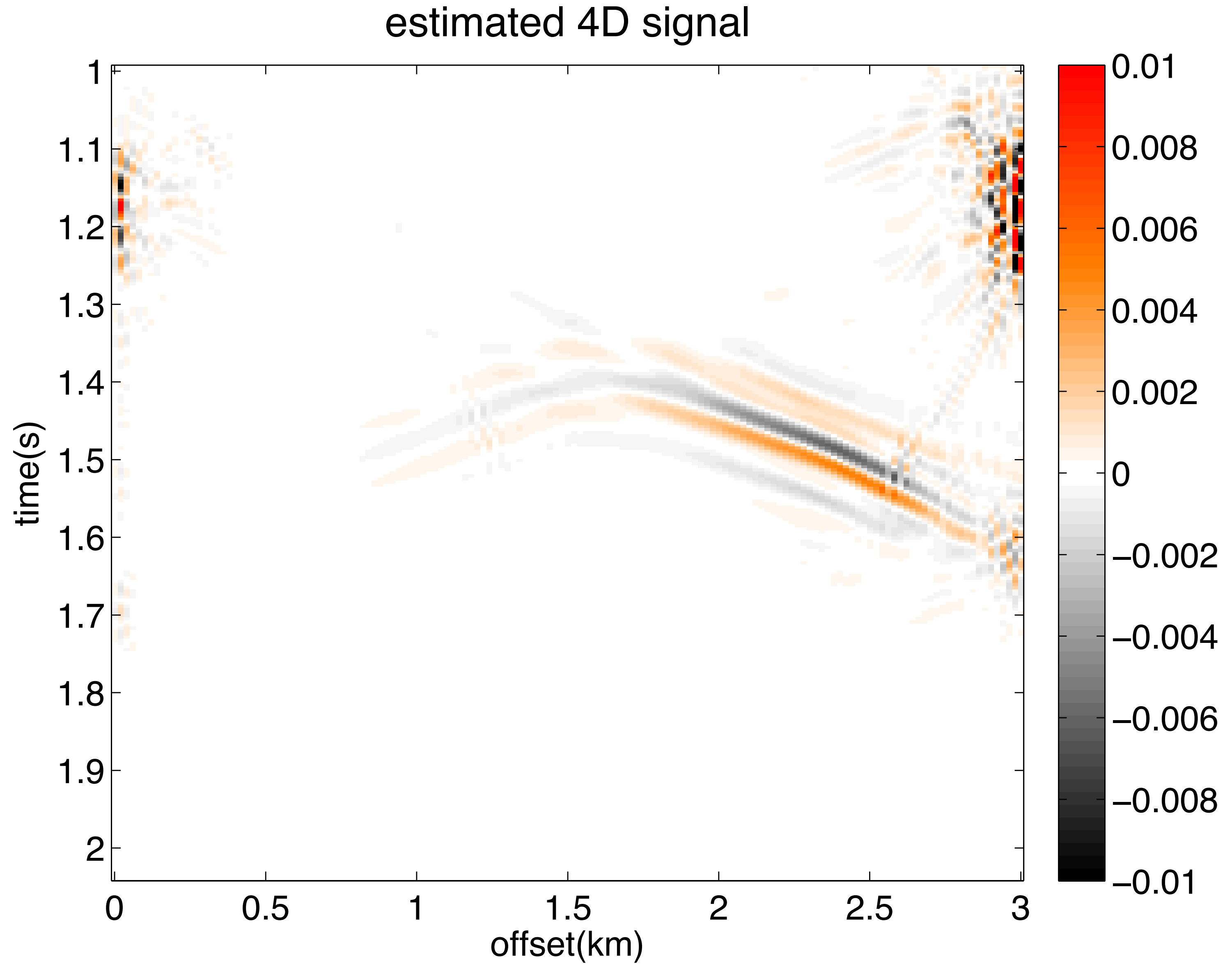
Estimated 4D signal : $\mathbf{S}^* \left(\tilde{\mathbf{x}_1} - \tilde{\mathbf{x}_2}\right)$

SAME geometry – regularly & densely sampled – IDEAL CASE

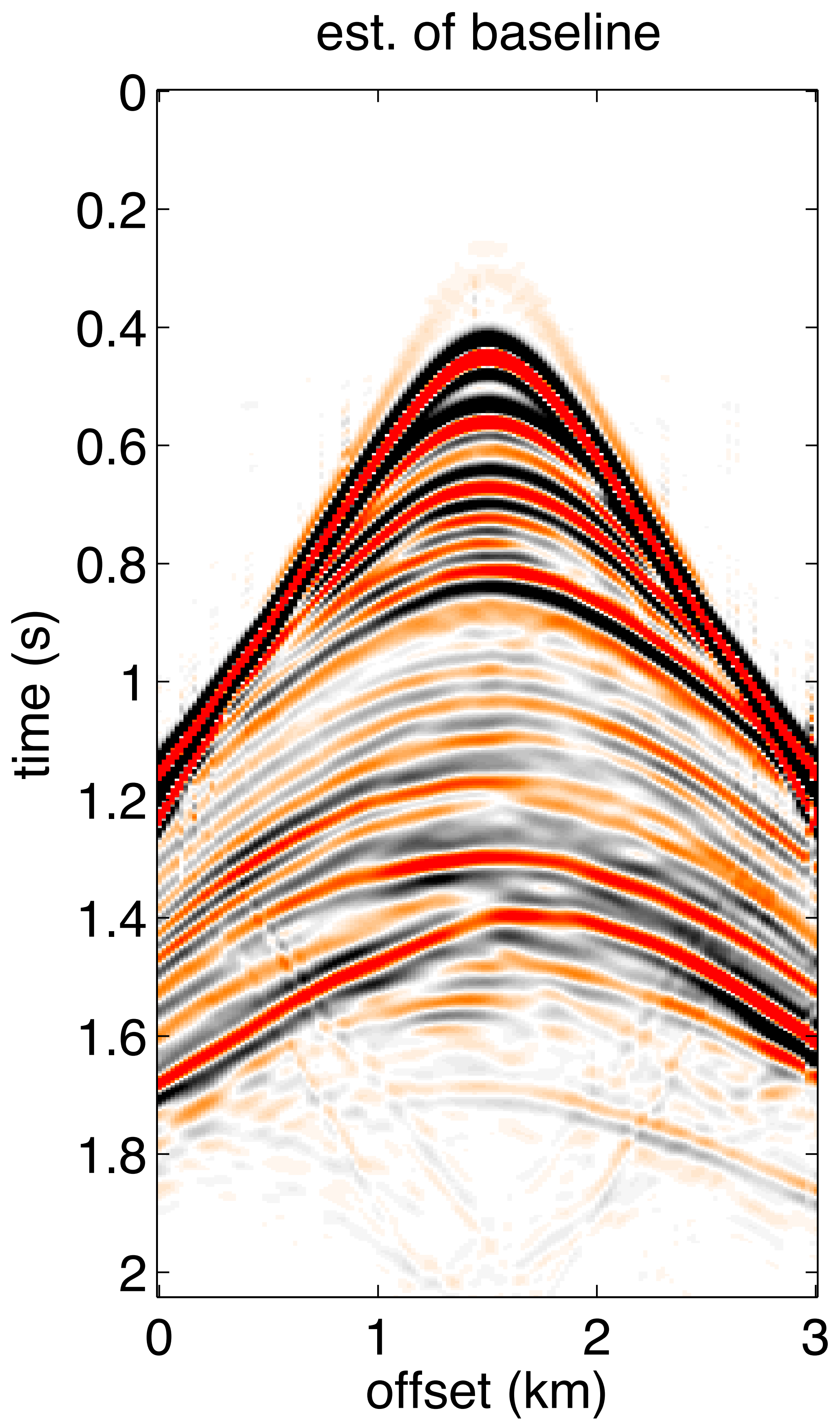


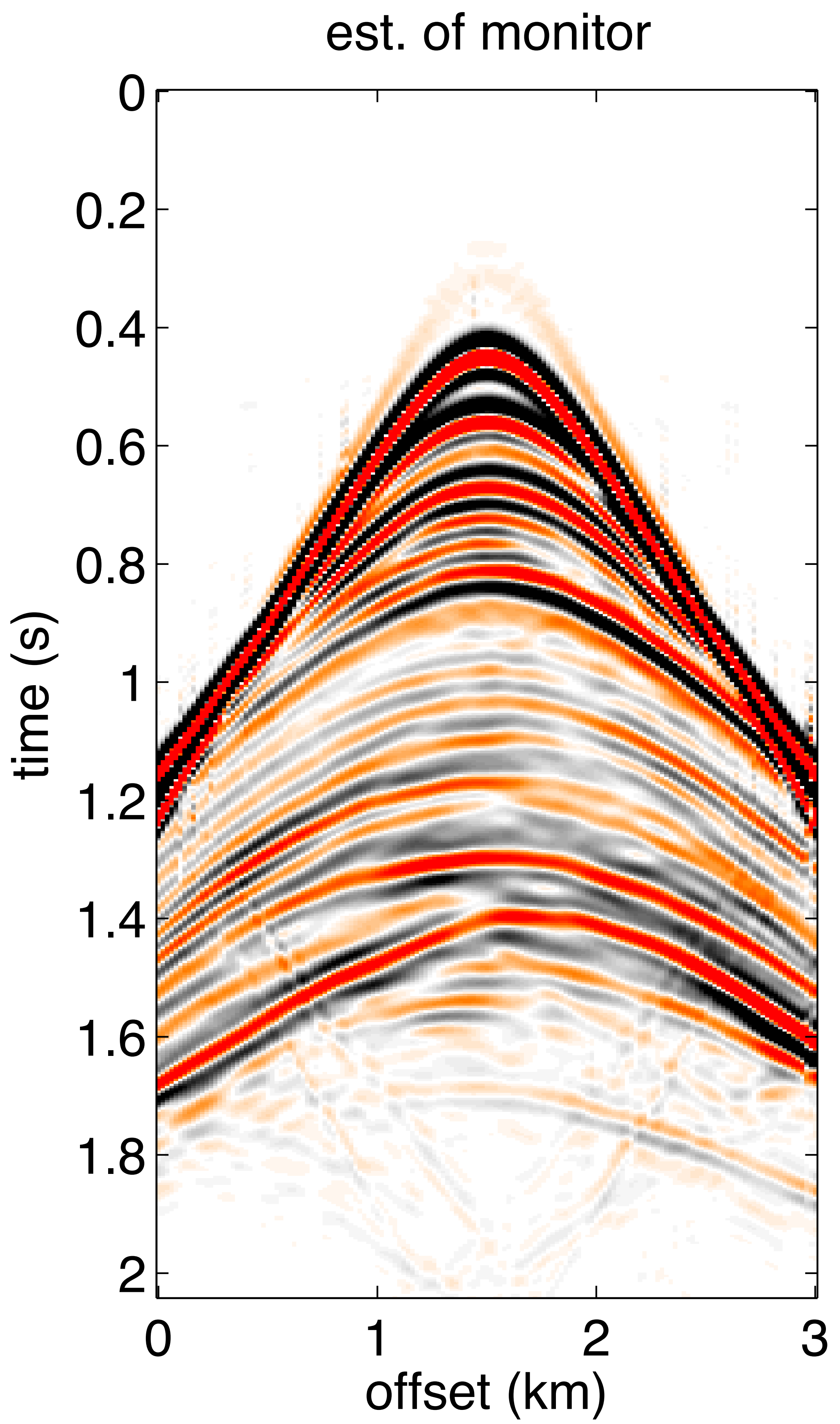
Result: 50% *INDEPENDENT* missing shots from each *vintage* (JRM)

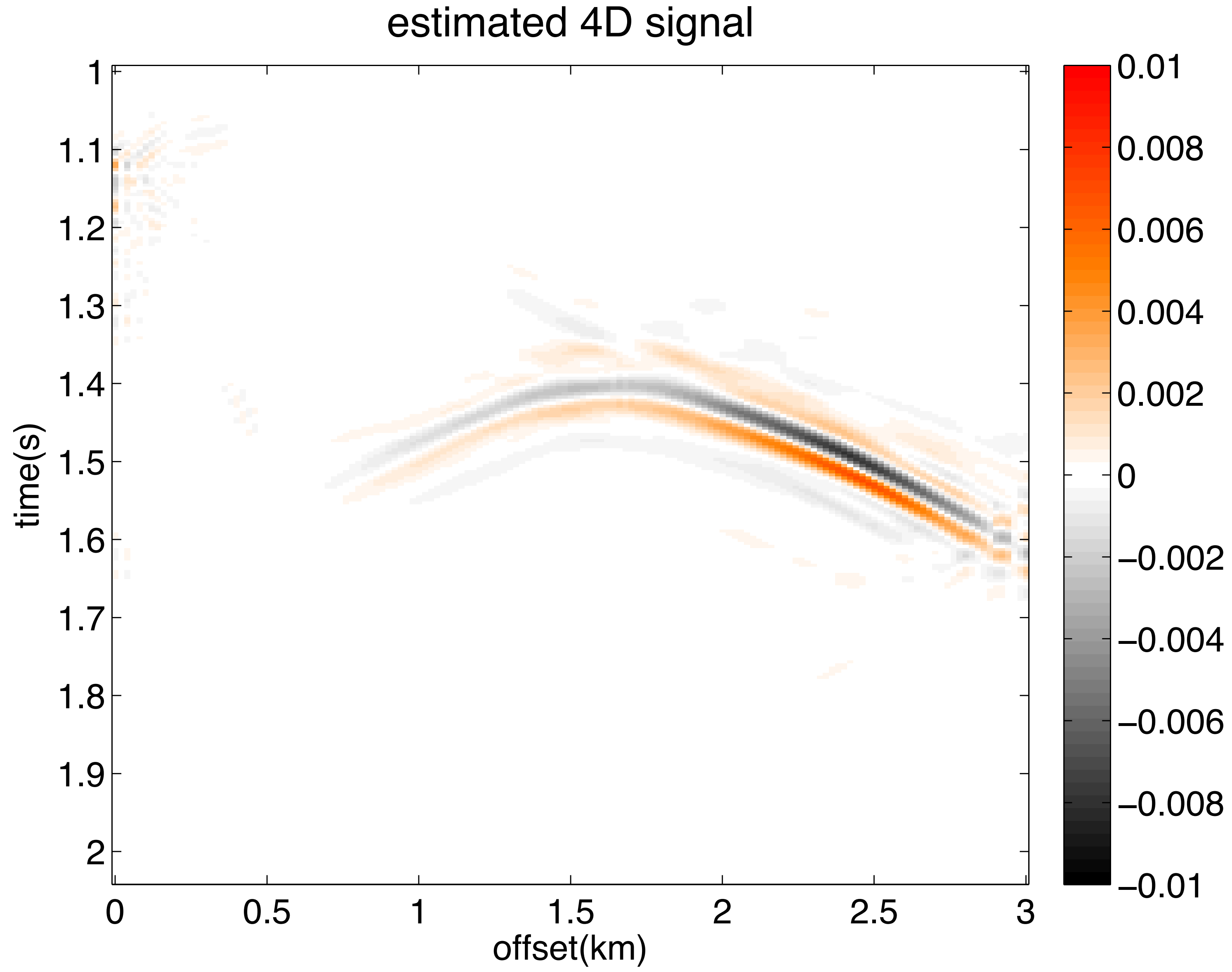




Result: 40% INDEPENDENT missing shots from each *vintage* (JRM)

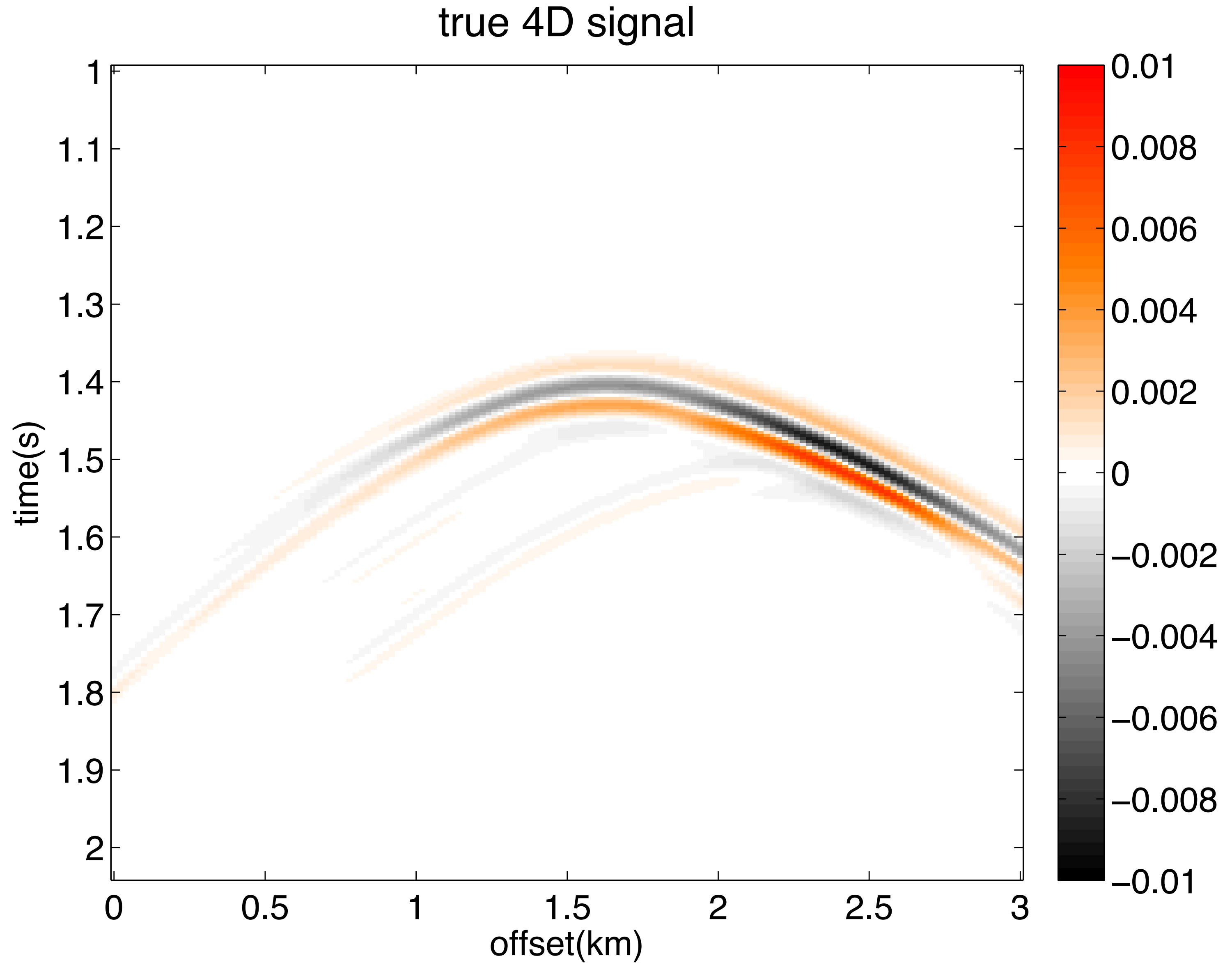






Independent vs *joint* reconstruction

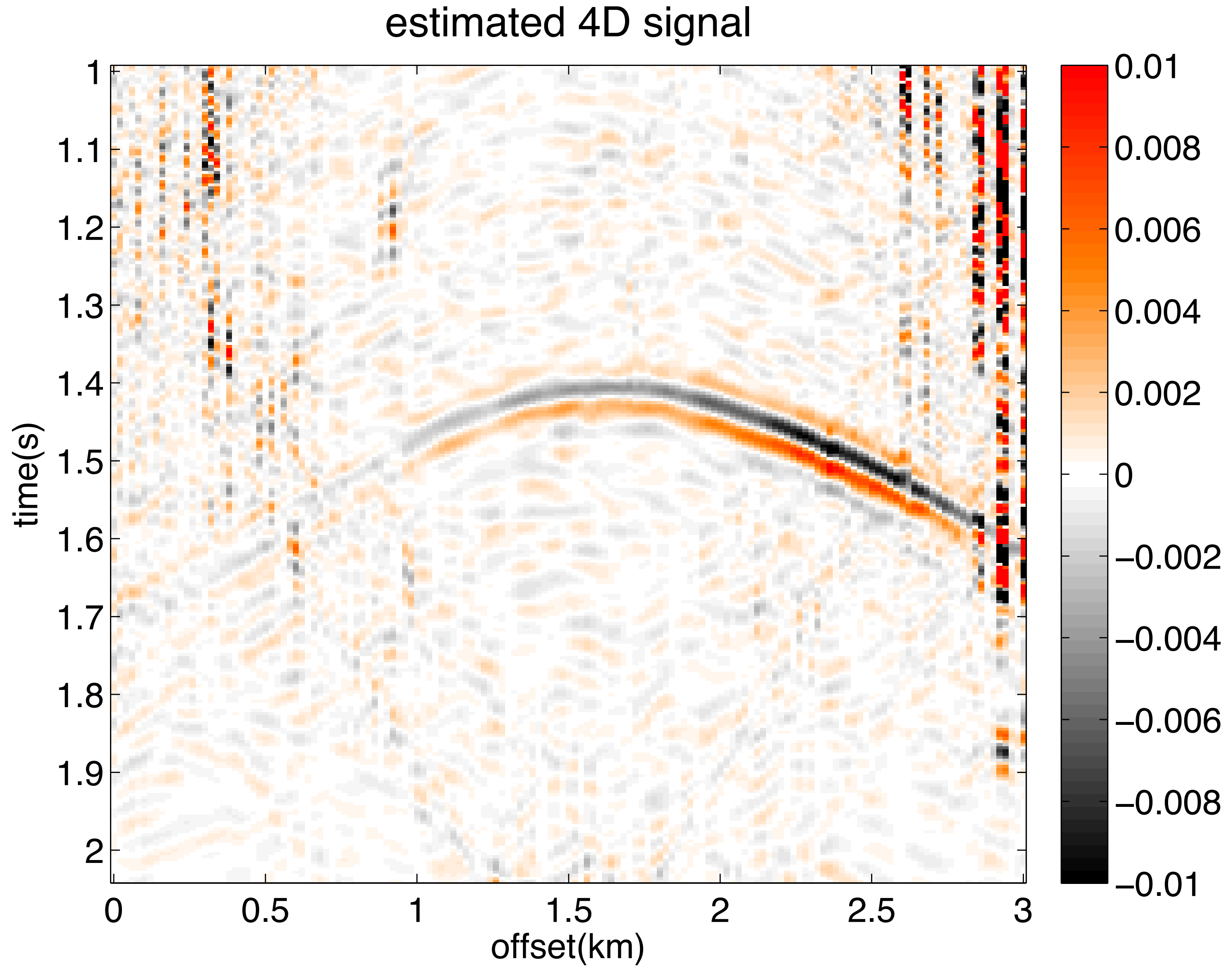
"ideal 4D signal"



"independent CS recovery"

25% missing

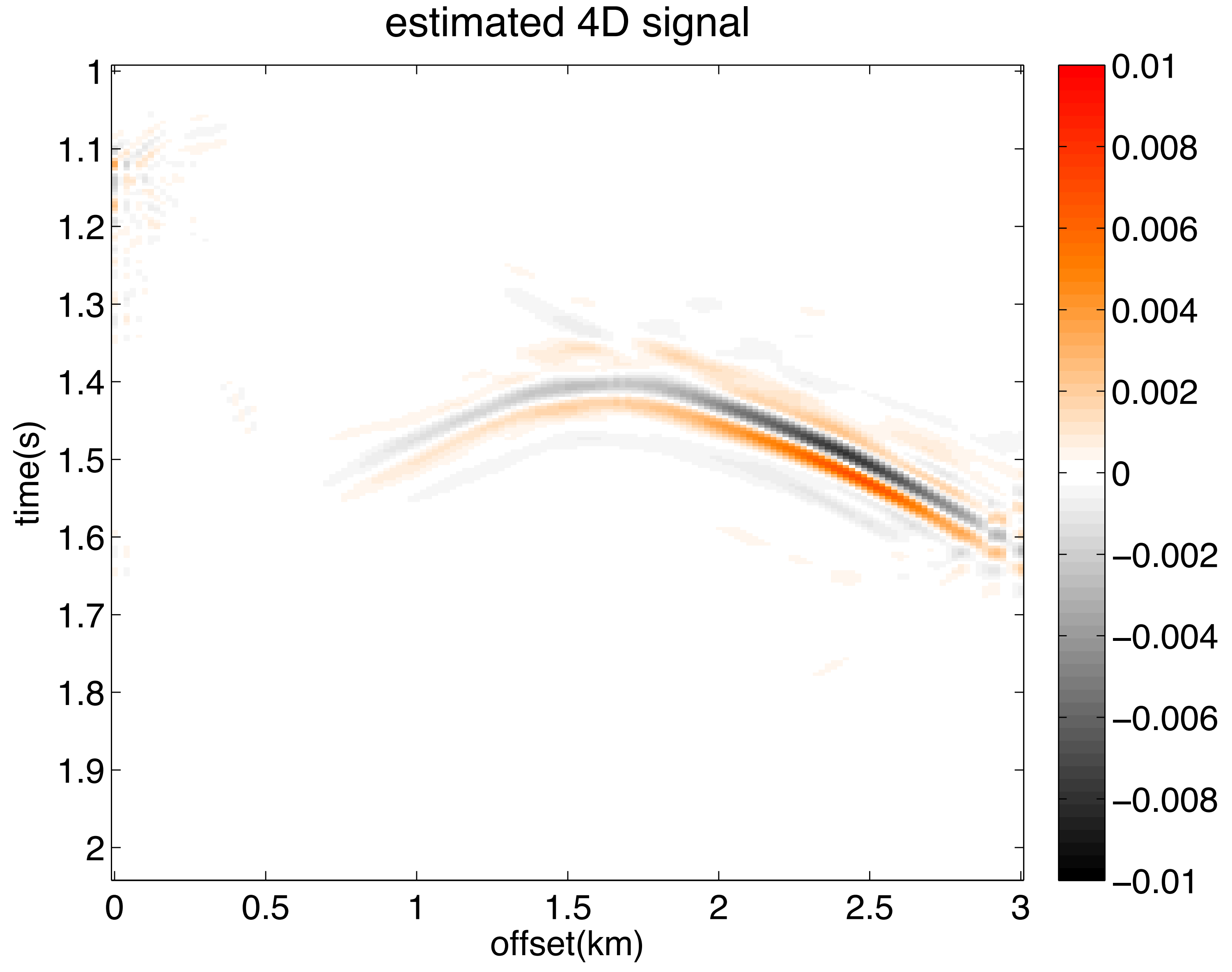
from each vintage



"joint CS recovery"

40% missing

from each vintage



Generalization to more than 2 vintages

- Improvement in reconstruction quality for each signal
- Improved 4D signal reconstruction
- Joint representation enables reconstruction of each wavefield with fewer measurements from each survey

Conclusions

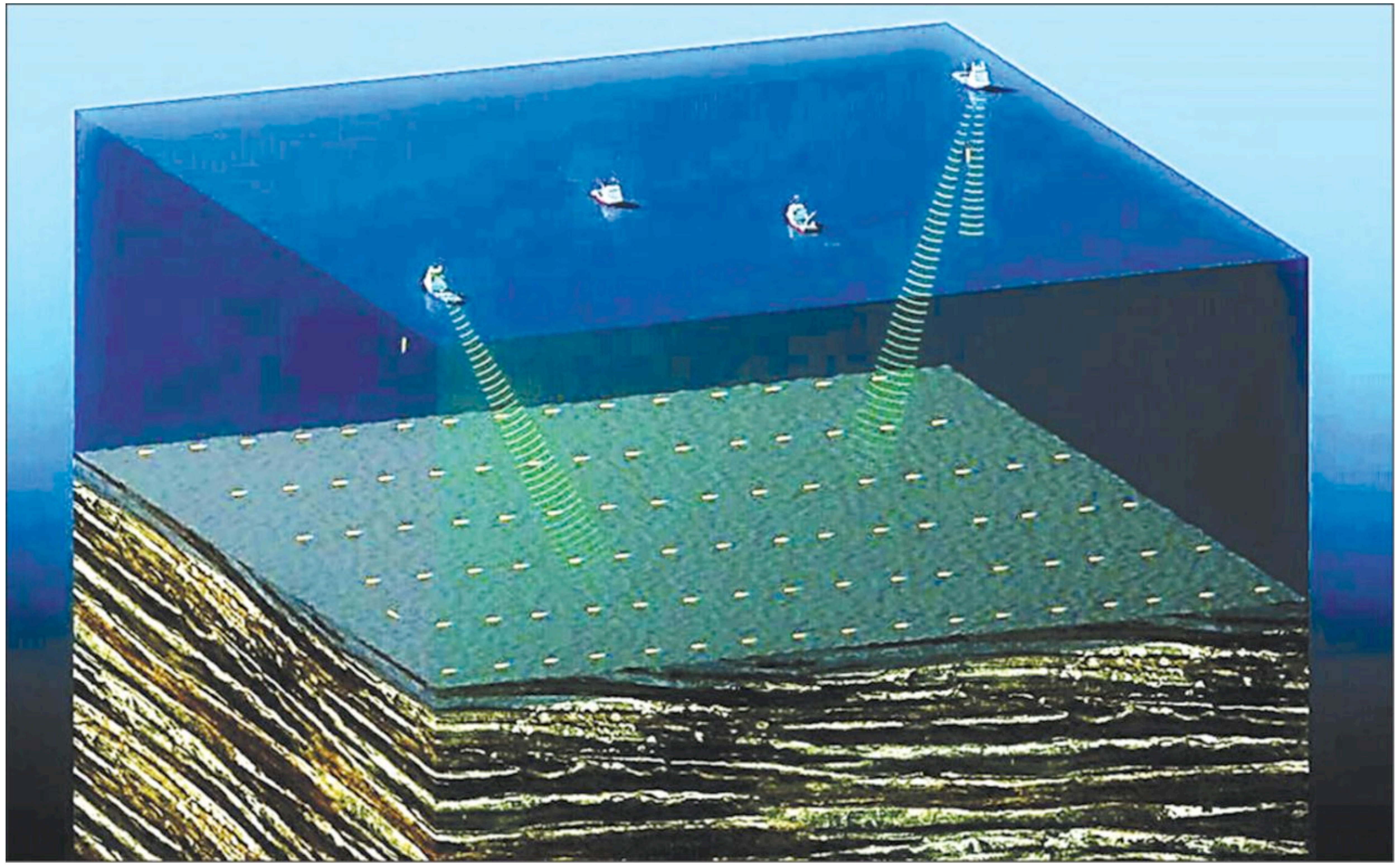
- resolving 4D changes depends on the *subsampling* ratio during *randomized* sampling
- careful planning of 4D project in mind, with *randomized* sampling, can save cost
- we can reconstruct 4D differences accurately without having to take the *same* set of *measurements* - we don't necessarily have to spend efforts *repeating* the surveys

Future Plan

- Detection of *weak* and *strong* 4D changes in *noisy* environments with *high* subsampling *ratios*
- Understand different sampling scenarios
  - we chose the subsampling ratios to be the same
- Incorporate joint reconstruction into wave-equation based inversion
- Extension to other realistic acquisitions including marine

Future Work - where are we going with this?

- Extension to other randomized acquisition scenarios- simultaneous shot acquisition for marine, with OBNs or OBCs



http://tle.geoscienceworld.org/content/32/5/514/

Acknowledgements

- Thanks to the following people
  - Felix Herrmann
  - Haneet Wason
  - Ernie Esser
- And Finally,

Acknowledgements

- Thank you for your attention!

MERCI!!! SIYANBONGA!!! DANKIE!!!!

This work was in part financially supported by the Natural Sciences and Engineering Research Council of Canada Discovery Grant (22R81254) and the Collaborative Research and Development Grant DNOISE II (375142-08). This research was carried out as part of the SINBAD II project with support from the following organizations: BG Group, BGP, BP, CGG, Chevron, ConocoPhillips, ION, Petrobras, PGS, Statoil, Total SA, WesternGeco, and Woodside.