Deblended-Data Reconstruction Using a Closed-Loop Approach for Time-Lapse Seismic Monitoring*

Tomohide Ishiyama[2], Mohammed Y. Ali[2], Gerrit Blacquire[3], and Shotaro Nakayama[1]

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[1]Technical Division, INPEX, Tokyo, Japan
[2]Khalifa University of Science and Technology, Petroleum Institute, Abu Dhabi, United Arab Emirates (tishiyama@pi.ac.ae)
[3]Delft University of Technology, Delft, Netherlands

Abstract

In this paper, we introduce a method of deblended-data reconstruction. Using this method, we expect to ensure high repeatability in time-lapse seismic monitoring, even if we use best practices in the industry today for the monitor surveys, such as blended-acquisition methods, rather than legacy ones used for the baseline survey. For deblended-data reconstruction, we use the properties of blended signal introduced by blending codes in acquisition: the coherency of blended signal versus the incoherency of blending noise in the pseudo-deblended domain. This process can be posed as an inverse problem with quantifying the coherency and its solutions by selecting optimal metrics of the coherency. To solve the inverse problem, we consider an optimization scheme using a so-called closed-loop approach, where the deblended data are iteratively estimated. The general concept of deblended-data reconstruction includes all shot-generated-wavefields separation, regularization and interpolation, and both at the source and receiver side. For this concept, we face challenges to reconstruct deblended data from complicated blended data, such as spatially and/or temporally, blended and/or non-uniformly sampled data at the source and/or receiver side. At the time of writing this abstract, we have obtained reasonable results even under the challenging situation. We expect to obtain and present more successful results in the conference. It should be noted that our method is highly applicable to time-lapse seismic monitoring. Using this method, we can reconstruct from blended data on an irregular observed grid of a monitor survey into corresponding deblended data on a fine and regular nominal grid, which is adaptable for the baseline survey. This significantly reduces the repeatability problem because reconstructing deblended data is much more realistic and reliable than positioning sources and receivers exactly as the baseline survey. Therefore, we could acquire blended data and reconstruct deblended data without any problems but with the benefit of blending to acquire a large amount of data in an economical way. For time-lapse seismic monitoring, many studies have been carried out for the detectability, but relatively few for the repeatability. Therefore, our method should have significant impact in oil and gas fields where expectation to time-lapse seismic monitoring is increasing in order to achieve their business objectives.

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Deblended-data reconstruction using a closed-loop approach for time-lapse seismic monitoring

Tomohide Ishiyama, Mohammed Ali,
Khalifa University of Science and Technology, Petroleum Institute;
Gerrit Blacquire, Delft University of Technology;
Shotaro Nakayama, Inpex Corporation

INPEX Group JODCO

PI
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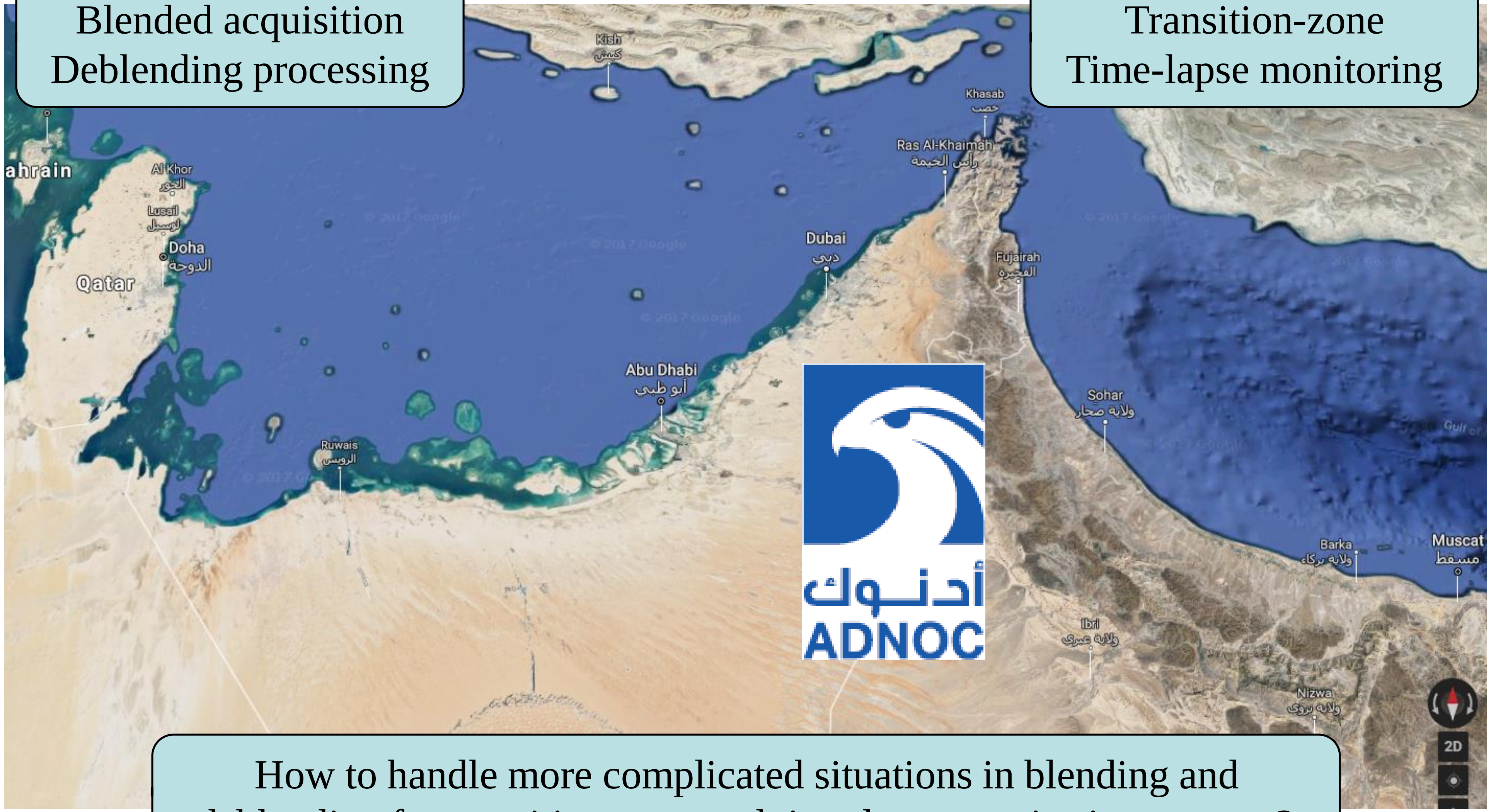
Seismic trend in Abu Dhabi

Blended acquisition
Deblending processing

Transition-zone
Time-lapse monitoring

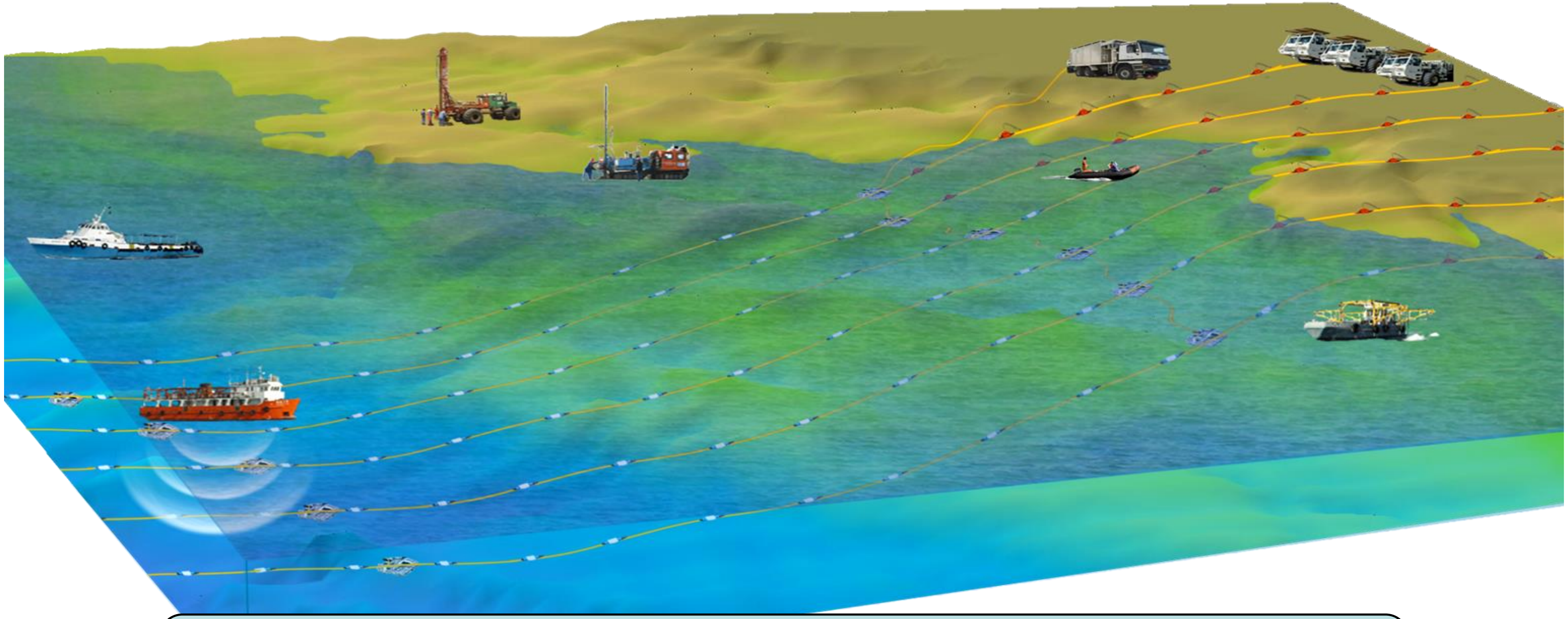


How to handle more complicated situations in blending and deblending for transition-zone and time-lapse monitoring surveys?

Seismic trend in Abu Dhabi

Blended acquisition
Deblending processing

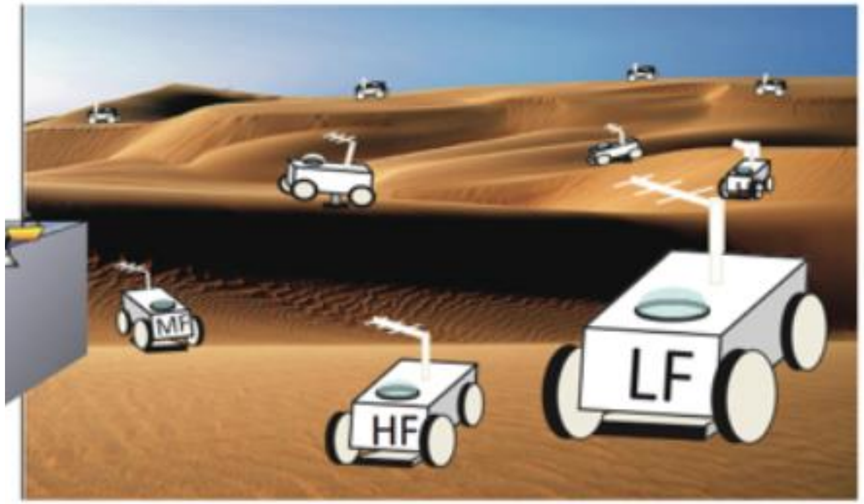
Transition-zone
Time-lapse monitoring



Establish generalized blending and deblending models!
Establish a method of deblending using these models!

Contents

- Theory and method
- Examples
- Conclusions



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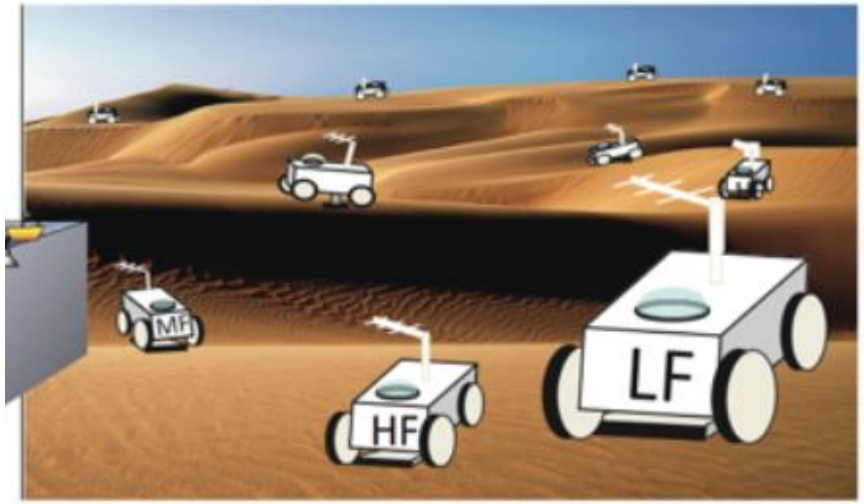
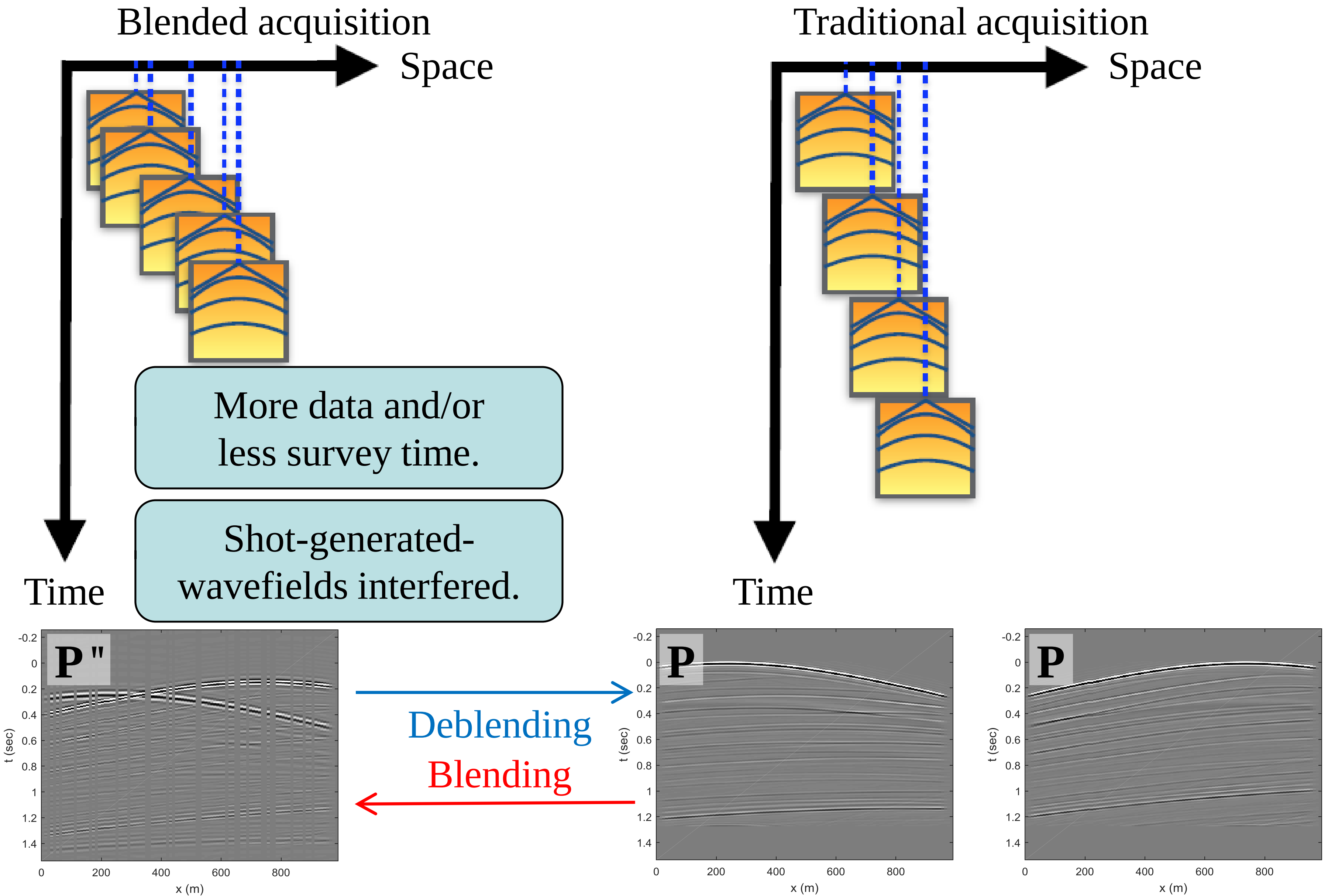


Blending and deblending



Generalized-blending model

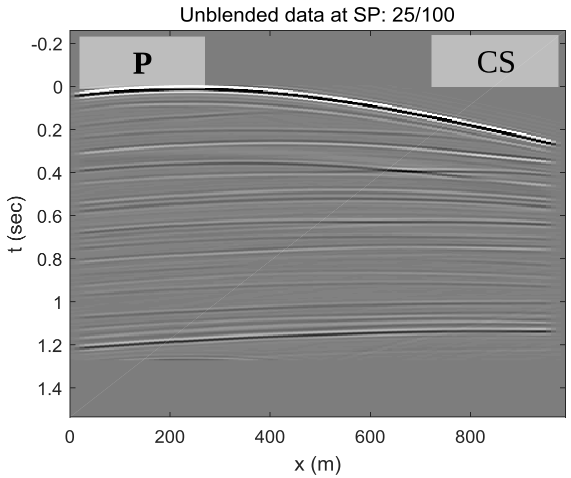
$$\mathbf{P''} = \mathbf{\Gamma}_D \mathbf{P} \mathbf{\Gamma}_S$$

Generalized blending

P'' : Blended data
P : Unblended data
$\mathbf{\Gamma}_D$: Blending operator (receiver side)
$\mathbf{\Gamma}_S$: Blending operator (source side)

Generalized-blending model

P



CS : Common-source domain
CR : Common-receiver domain

Generalized-blending model

$$\mathbf{P}\boldsymbol{\Gamma}_S$$

- Generalized-blending operator at the source side working for source encoding:
  - Incoherent shooting (random time shifts and spatial distribution of source units in the blended-source array)
  - Inhomogeneous shooting (mono-frequency-source units in the dispersed-source array, or DSA)
  - Signature stamping (popcorn shooting, sweeping, etc.)
  - Non-uniform and under sampling … etc.

Generalized-blending model

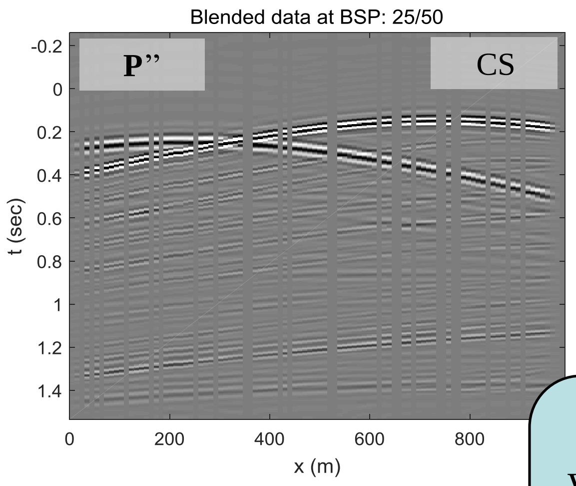
$$\Gamma_D \mathbf{P} \Gamma_S$$

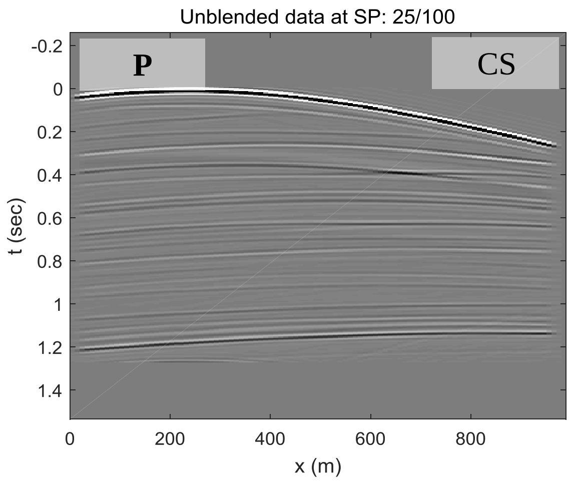
- Generalized-blending operator at the receiver side working for receiver encoding:
  - Non-uniform and under sampling … etc.
  - ➢ Incoherent and inhomogeneous sensing can be theoretically included, but may not be practical in the acquisition operations.

Generalized-blending model

$$\mathbf{P''} = \mathbf{\Gamma}_D \mathbf{P} \mathbf{\Gamma}_S$$

Generalized blending





Shot-generated-wavefields interfered, frequency-banded, non-uniformly and under sampled.

Generalized-deblending model

$$\boldsymbol{\Gamma}_D^H \mathbf{P}'' \boldsymbol{\Gamma}_S^H = \langle \mathbf{P} \rangle$$

→ Generalized deblending

P” : Blended data
<**P**> : Deblended data
<▪> : ‘Estimated’
$\boldsymbol{\Gamma}_D$: Blending operator (receiver side)
$\boldsymbol{\Gamma}_S$: Blending operator (source side)
$\cdot^H$: ‘Hermitian’, or ‘pseudo-inversed’

An inverse problem to solve from **P”** to <**P**>…

Generalized-deblending model

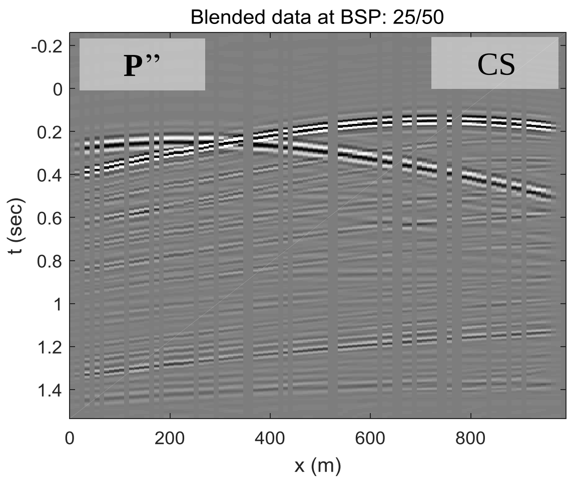
$$\text{where} \quad \left\| \mathbf{P''} - \langle \mathbf{P''} \rangle \right\| \quad \text{is min.}$$

P” : Blended data
<**P”**> : Re-blended data

… such that the residual can be minimized.

Generalized-deblending model

P’’



Generalized-deblending model

$$\boldsymbol{\Gamma}_D^H \mathbf{P}'' \boldsymbol{\Gamma}_S^H$$

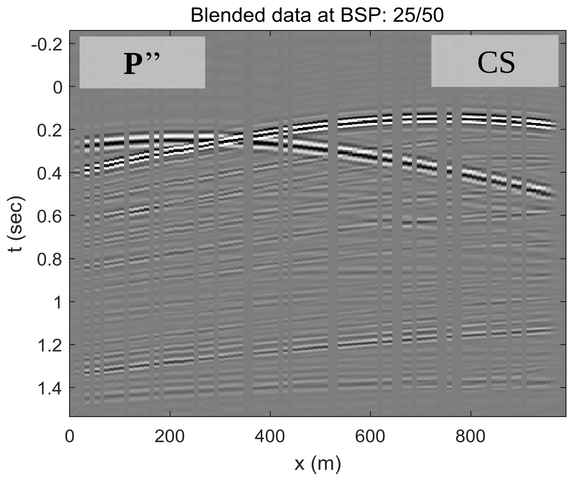
- Generalized-deblending operators both at the source and receiver sides working for data reconstruction:
  - Wave-fields separation
  - Full-frequency balancing
  - Designature
  - Regularization and interpolation

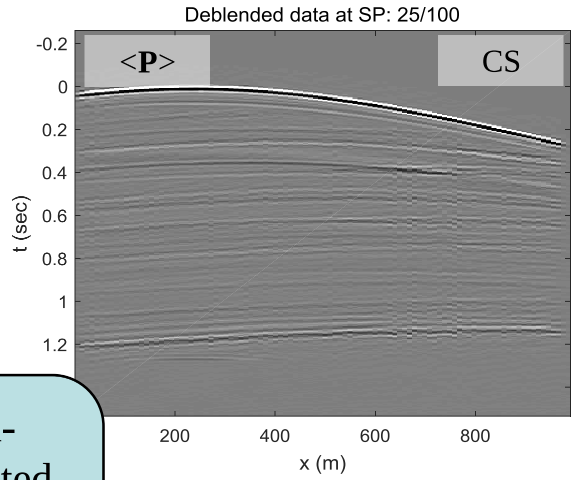
… etc.

Generalized-deblending model

$$\mathbf{\Gamma}_D^{\,H}\mathbf{P}''\mathbf{\Gamma}_S^{\,H} = \langle\mathbf{P}\rangle$$

Generalized deblending

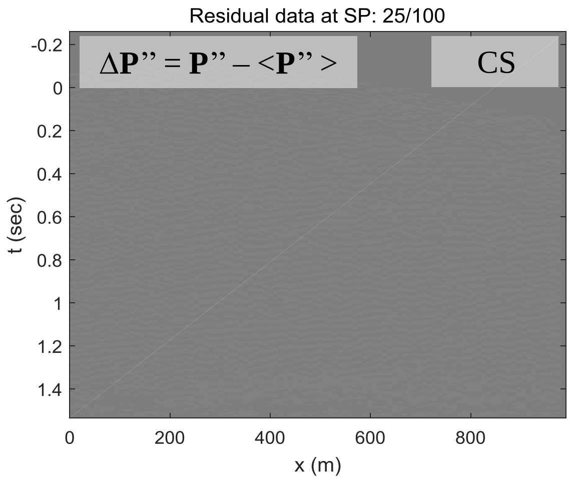




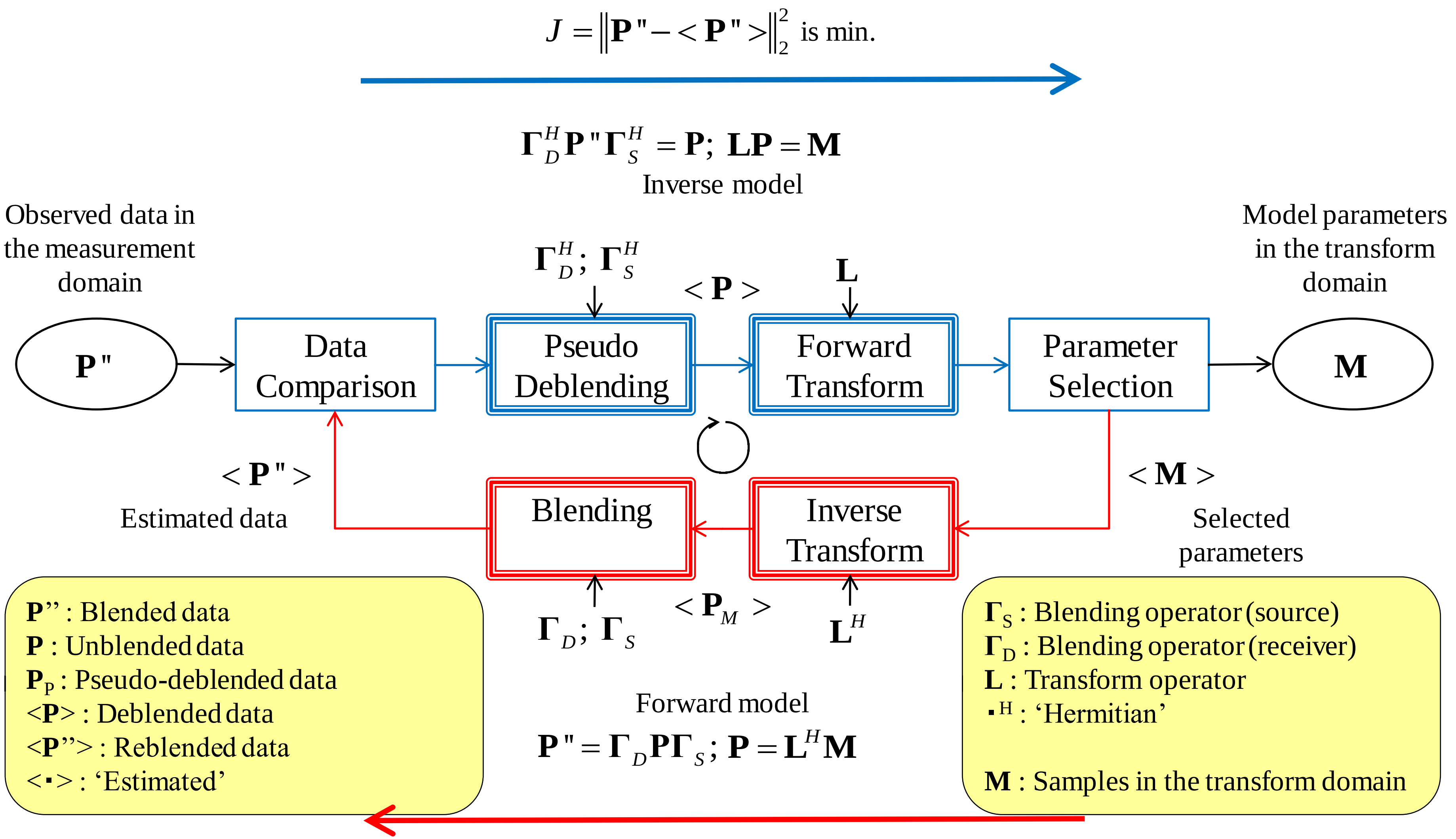
Shot-generated-wavefields separated, full-frequency-balanced, regularized and interpolated.

Generalized-deblending model

$$\text{where} \quad \left\| \mathbf{P}'' - \langle \mathbf{P}'' \rangle \right\| \quad \text{is min.}$$



Deblended-data reconstruction



An inversion solver to solve from **P”** to <**M**>, thus <**P**>.

Deblended-data reconstruction

- Closed-loop approach
  - The transformed domain of a 3-D Fourier domain (the $k_D k_S$-f domain).
  - The parameters selected by a regularization-term algorithm of sparse inversion to minimize the objective function: $J = \|\mathbf{P}'' - \langle \mathbf{P}'' \rangle\|_2^2 + \mu F(\mathbf{m})$.
  - The estimated data updated by applying a scale to the residual and adding it to the previous one.

Blended signal is more sparsely compressed in the $k_D k_S$-f domain, rather than in a conventional Fourier domain.

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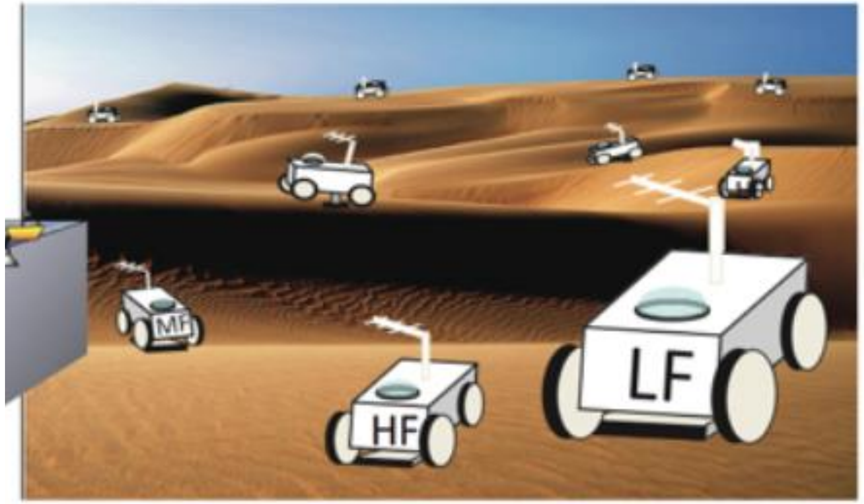
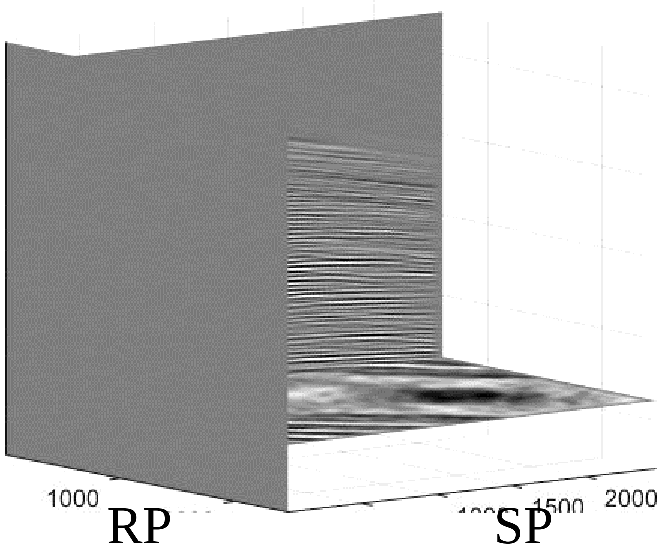
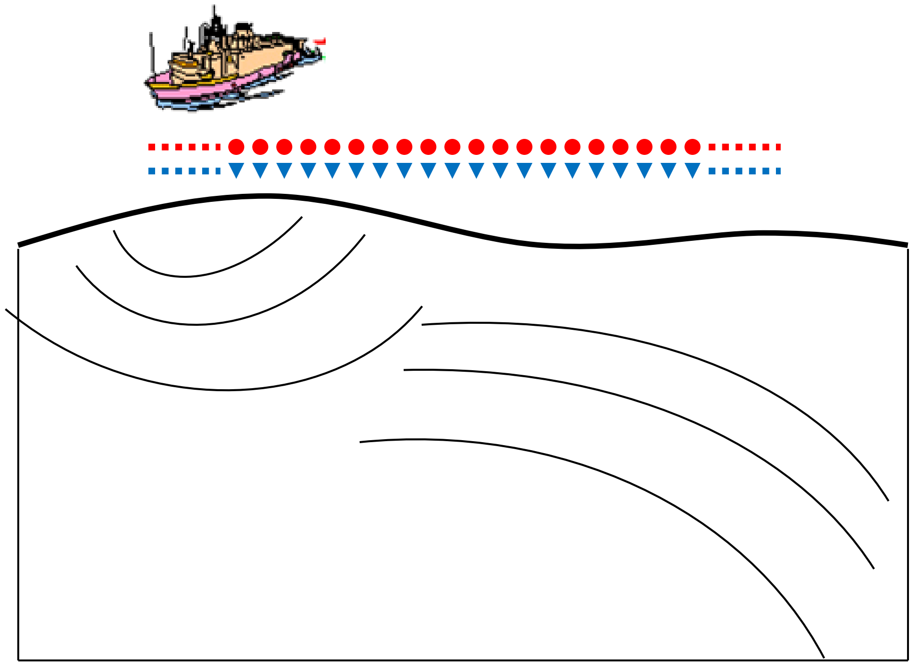


Unblended-data preparation

- Unblended data **P** acquired offshore Abu Dhabi
  - 100 sources and 100 receivers
  - Spatial sampling intervals of Δx_S = 25 m and Δx_D = 25 m
  - Spatial sampling apertures of X_S = 2500 m and X_D = 2500 m



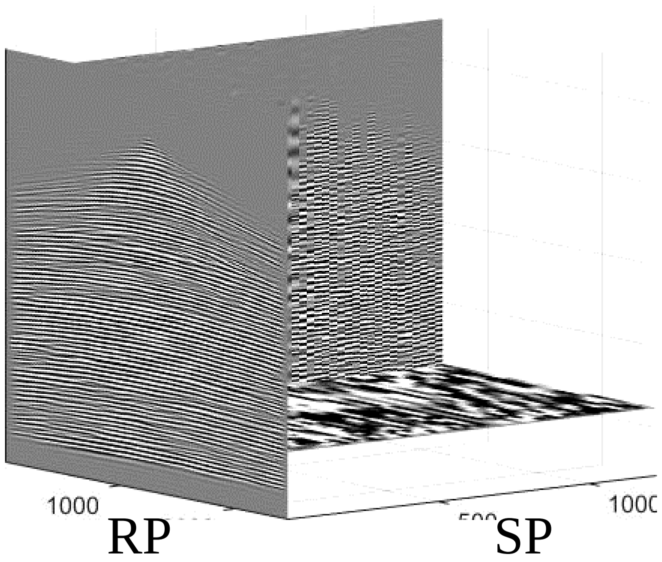


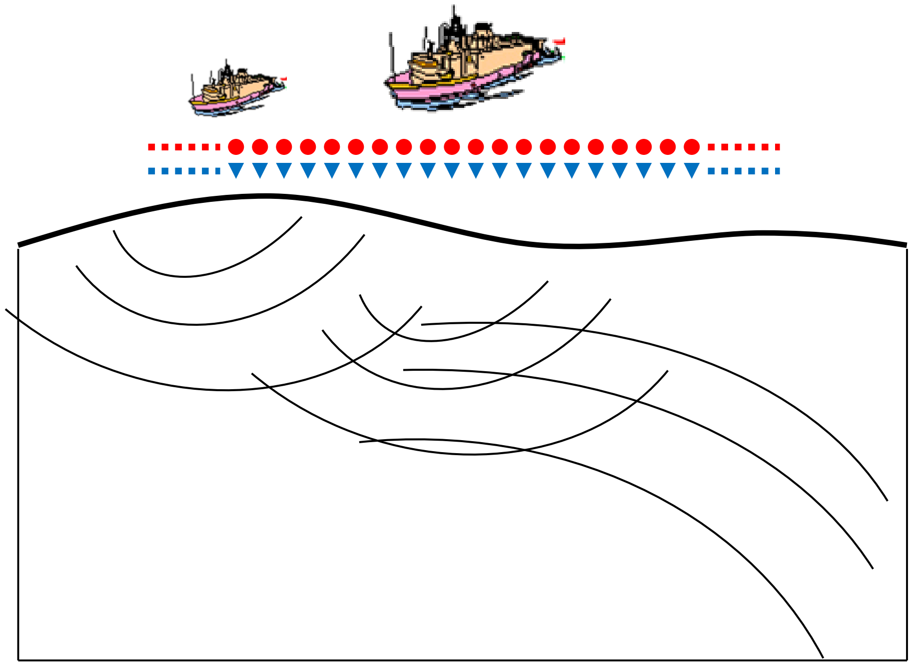
Blended-data generation

- Blended data **P**’’ numerically synthesized
  - Blending fold of 2
  - Max. time shift of 0.256 sec
  - Max. spatial separation of 1250 m
  - Several blending scenarios:
    1. Incoherent shooting at the source side
    - For marine
    2. Inhomogeneous shooting at the source side (i.e. DSA) in addition to scenario 1
    3. Self-inhomogeneous shooting at the source side (i.e. popcorn shooting) in addition to scenario 1
    - For land
    4. Inhomogeneous sweeping at the source side (i.e. DSA) in addition to scenario 1
    - For transition zone (TZ)
    5. Fully generalized case with scenarios 1, 2 and 4, and non-uniform and under sampling both at the source and receiver sides

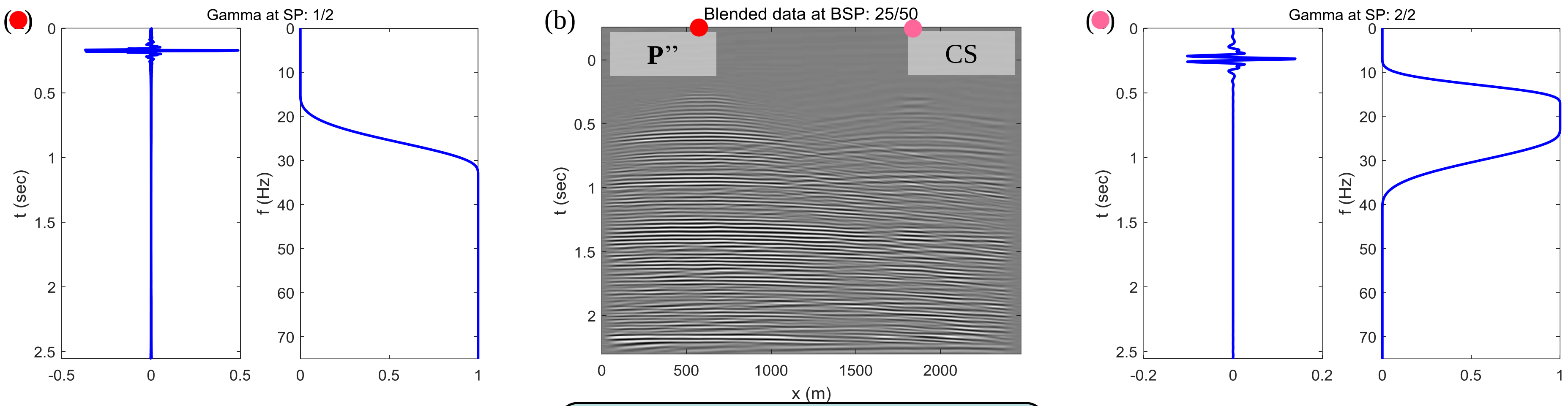
Deblending example 2

- Blended data **P**'' from scenario 2 for marine (input)
  - Inhomogeneous shooting at the source side (3 frequency-banded air-guns in DSA: low, mid and high) in addition to scenario 1.
  - 11 % random distribution of 100 shot points for low of 4-12 Hz; 22 % for mid of 16-24 Hz; 67 % for high of 32-96 Hz.





Deblending example 2

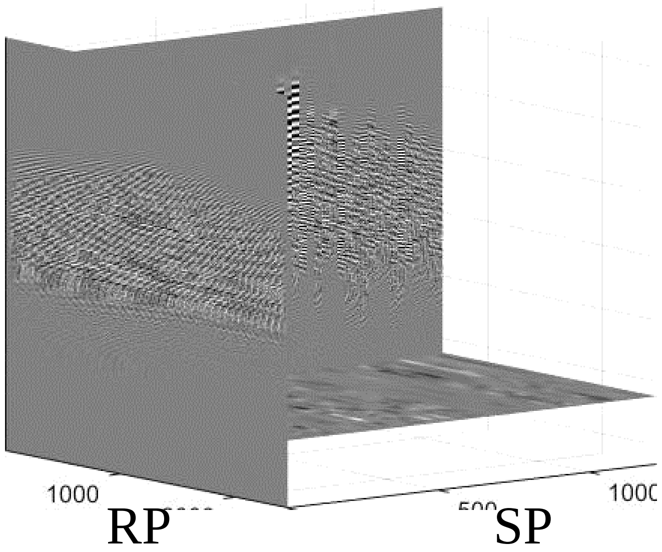


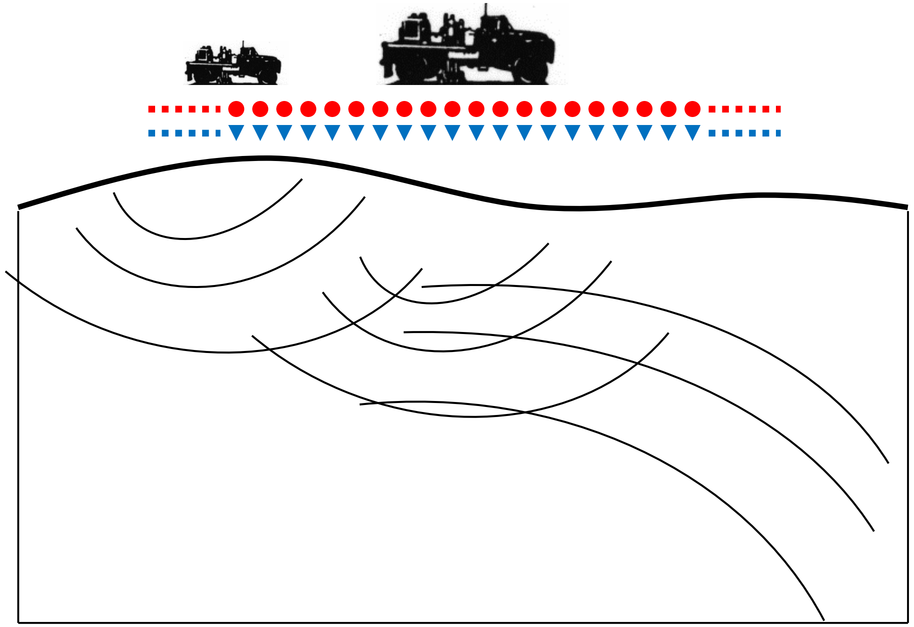
Shot-generated-wavefields interfered.

Shot-generated-wavefields frequency-banded.

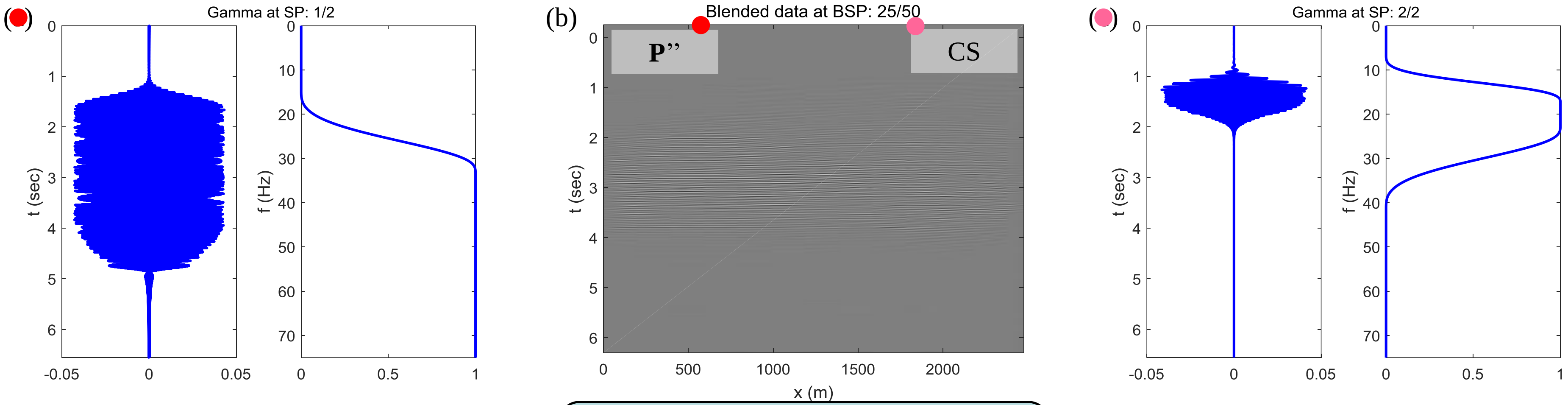
Deblending example 4

- Blended data **P**’’ from scenario 4 for land (input)
  - Inhomogeneous sweeping at the source side (3 frequency-banded vibroseises in DSA: low, mid and high) in addition to scenario 1.
  - 11 % random distribution of 100 shot points for low of 4-12 Hz; 22 % for mid of 16-24 Hz; 67 % for high of 32-96 Hz.





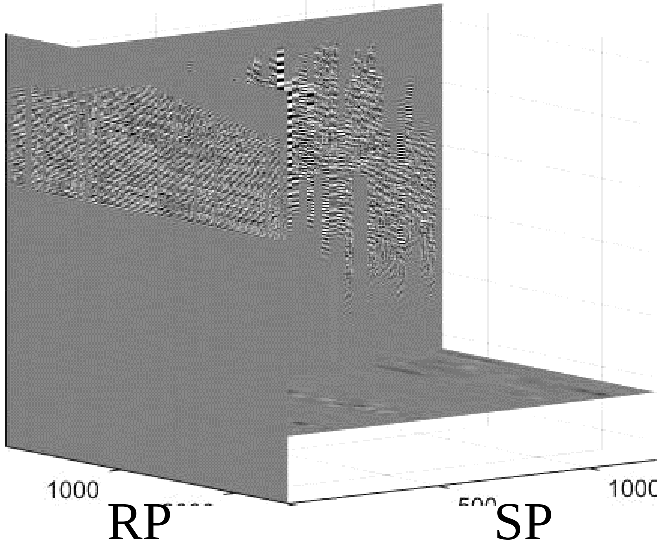
Deblending example 4

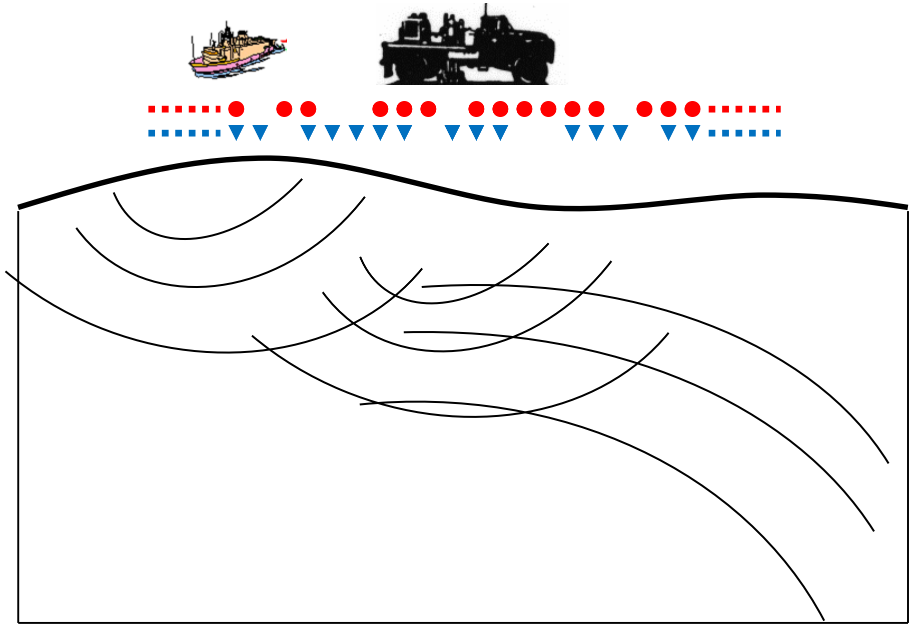


Shot-generated-wavefields with signatures stamped.

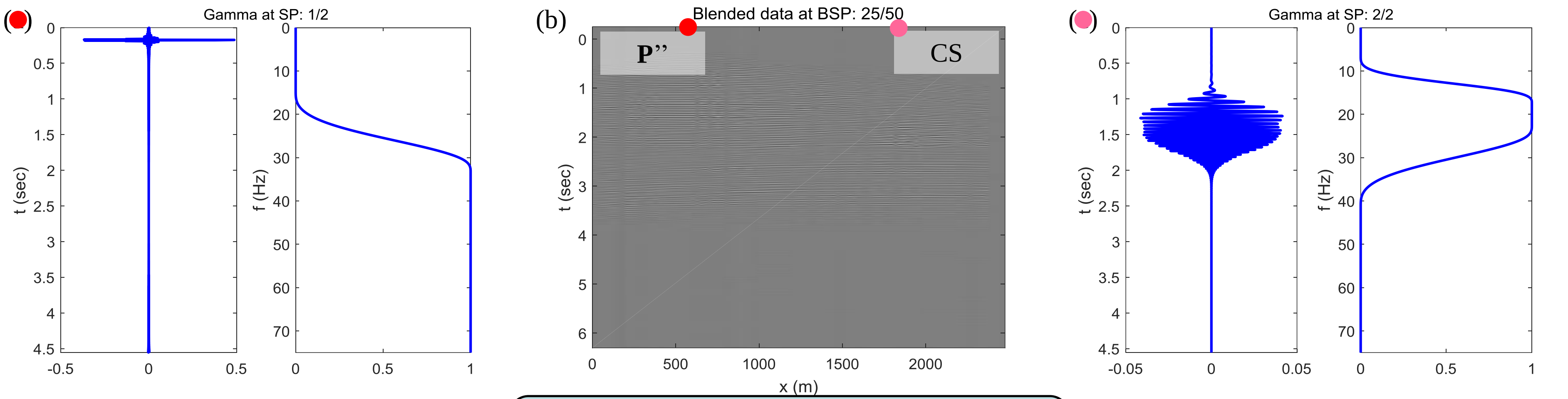
Deblending example 5

- Blended data **P**'' from scenario 5 for TZ (input)
  - Fully generalized case with scenarios 1, 2 and 4, and non-uniform and under sampling both at the source and receiver sides.
  - 50 % random distribution of 100 shot points for air-guns; 50 % for vibroseises.
  - About 9 % random decimation each at the source and receiver side; consequently about 25 % in total.





Deblending example 5



Shot-generated-wavefields non-uniformly and under sampled.

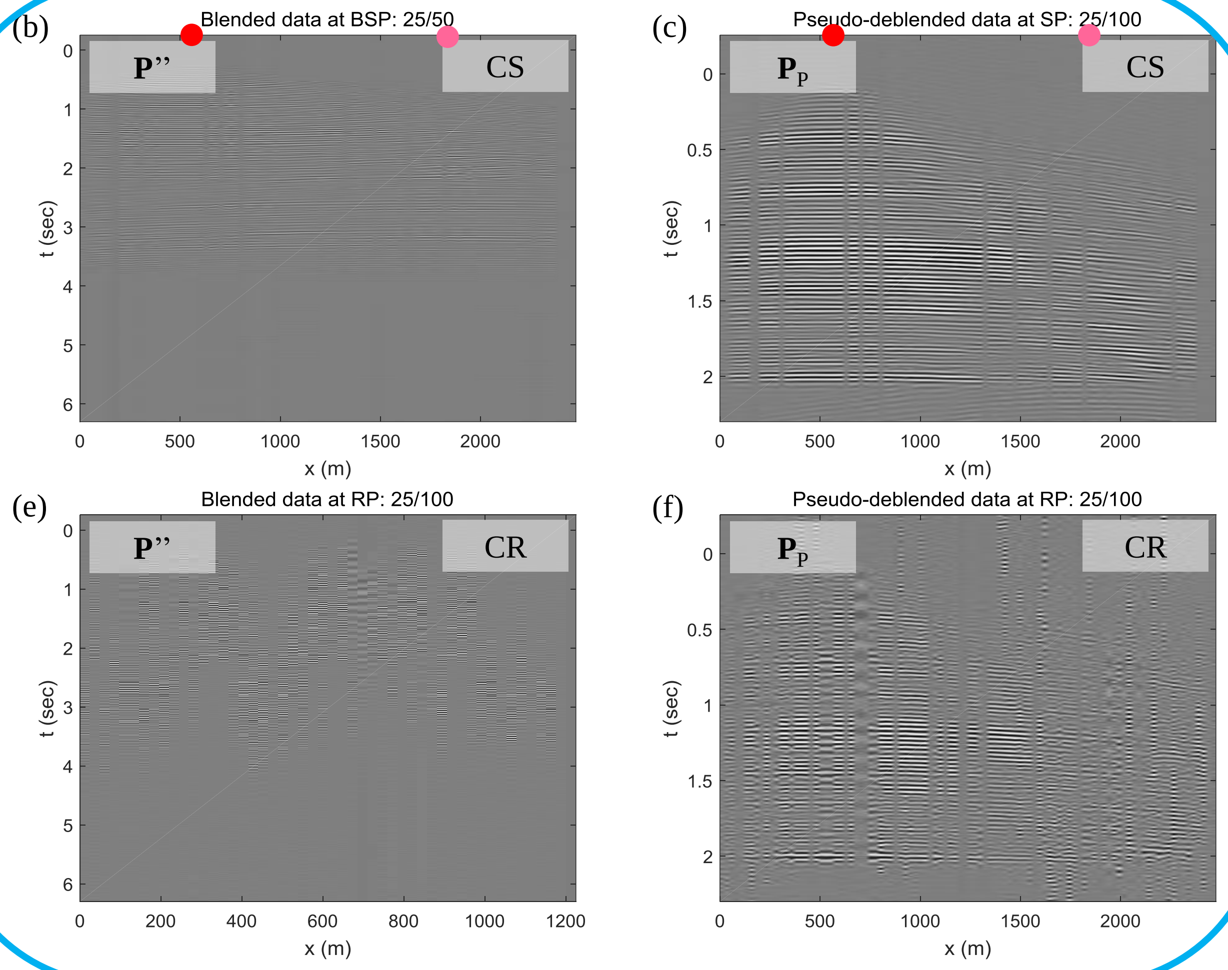
Deblending example 5

Blended-signal coherency promoted in the pseudo-deblended and CR domain.

See source-dependent frequency-banded contribution in the CR domain.

See source-dependent sweep pattern in the CR domain.

See non-uniform and under sampling both in the CS and CR domain.



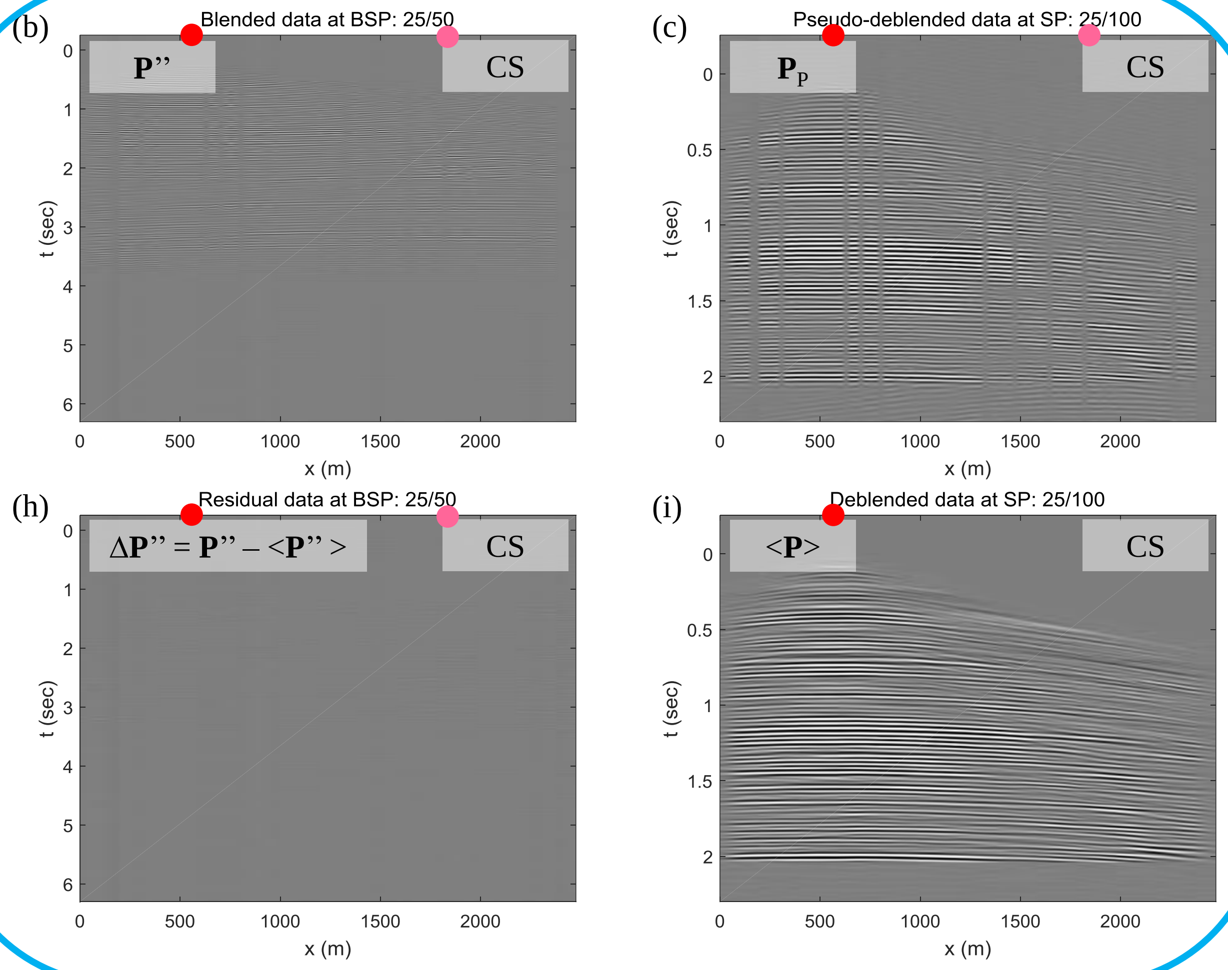
Deblending example 5

Shot-generated-wavefields separated.

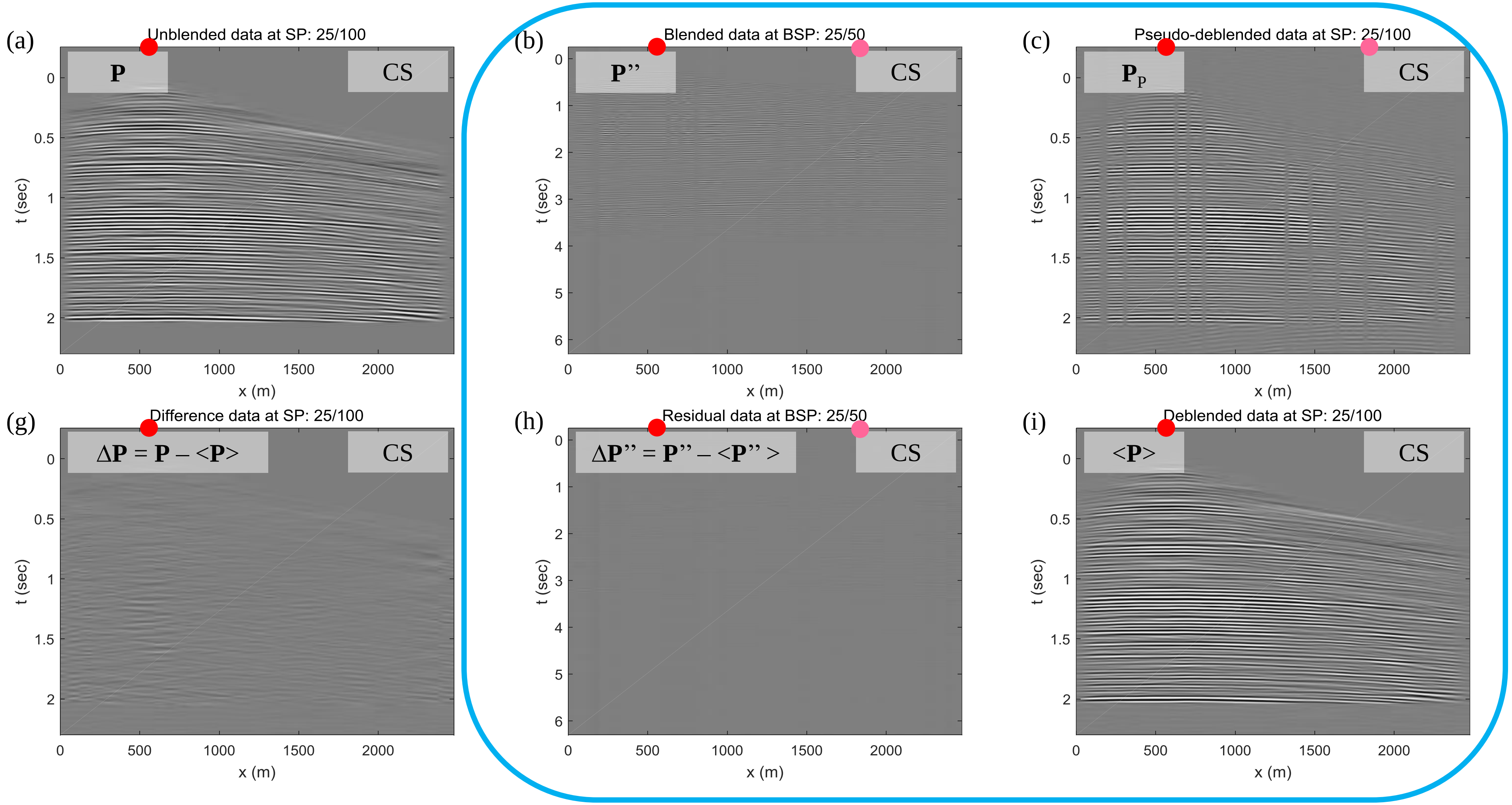
Shot-generated-wavefields full-frequency-balanced.

Shot-generated-wavefields designatured.

Shot-generated-wavefields regularized and interpolated.

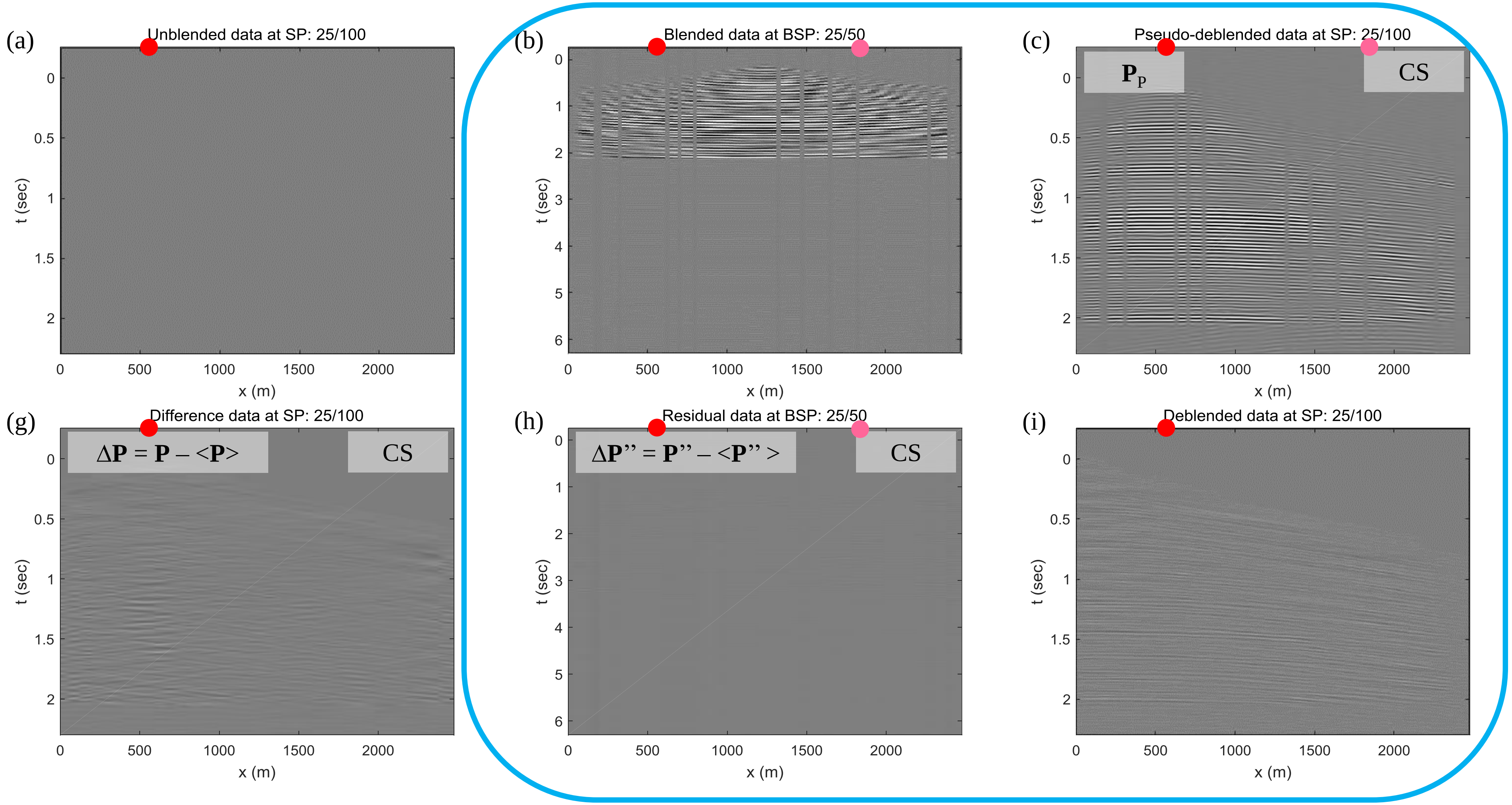


Deblending example 5



- Deblended data <**P**> (output)
  - The residual (**ΔP**''/**P**'') of –46 dB down; the S/N (**P**/**ΔP**) of 34 dB up.

Deblending example 5



- Deblended data <**P**> (output)
  - The residual (**ΔP**''/**P**'') of –46 dB down; the S/N (**P**/**ΔP**) of 34 dB up.

Application to time-lapse seismic monitoring

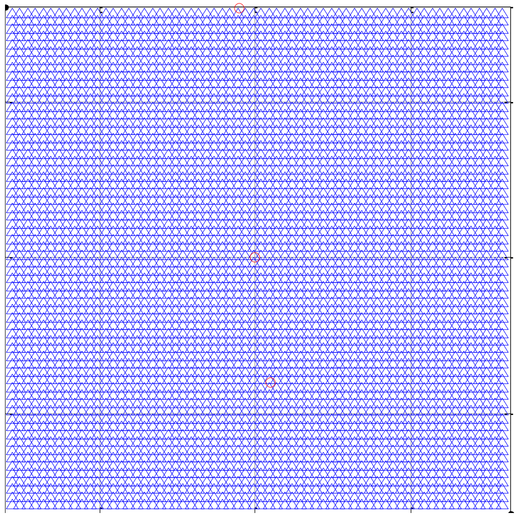
- Suppose that:
  - Unblended data, **P**, are from a traditional baseline survey;
  - Blended data, **P**’’, are from a generalized monitor survey.

- Suggest that:
  - Deblended data, <**P**>, are fully reconstructed from the monitor survey, which is comparable with the unblended data from the baseline survey.

  ➢ This should reduce the repeatability problem because reconstructing deblended data is much more realistic and reliable than positioning sources and receivers of monitor surveys exactly as the baseline survey.

Application to time-lapse seismic monitoring

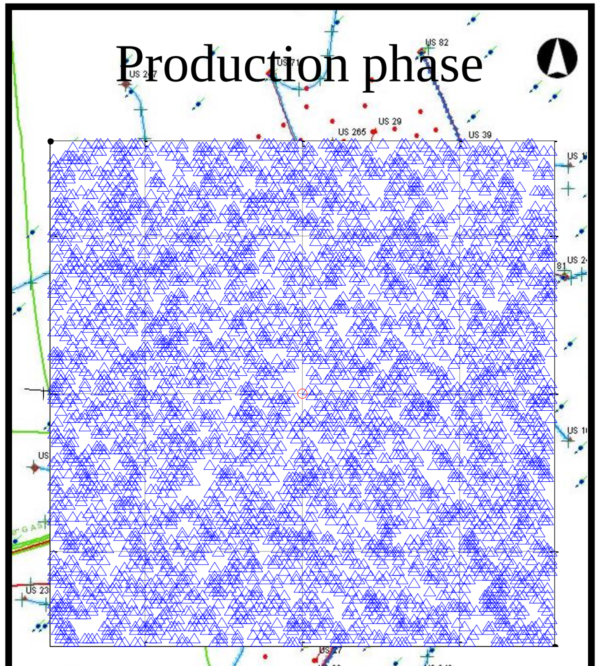
Exploration phase



Baseline survey

Time-lapse

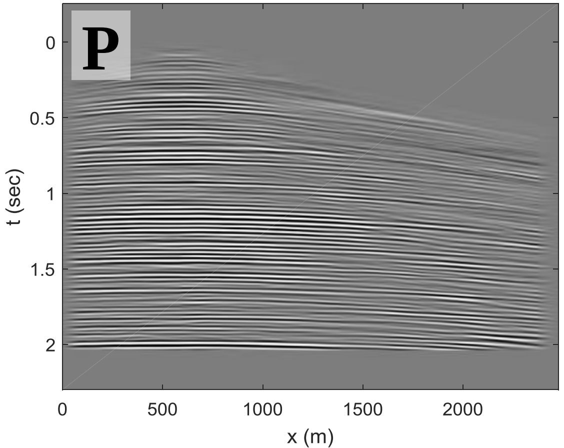
Production phase

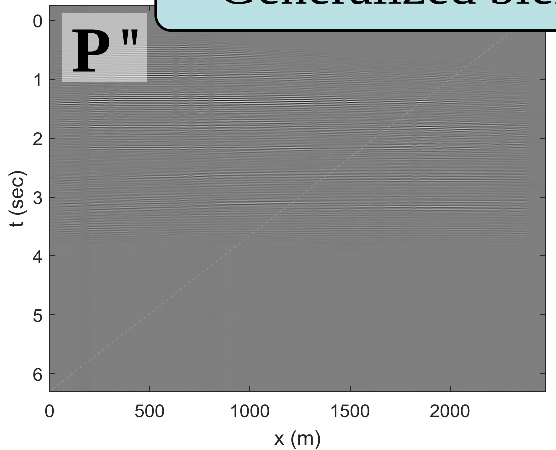


Monitor survey

Generalized blended.

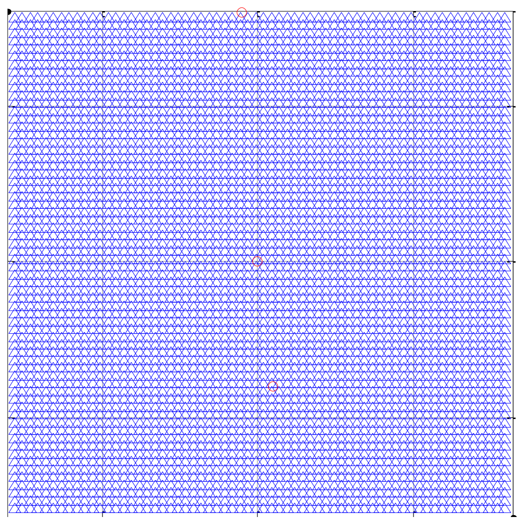
Unblended data at SP: 25/100





Application to time-lapse seismic monitoring

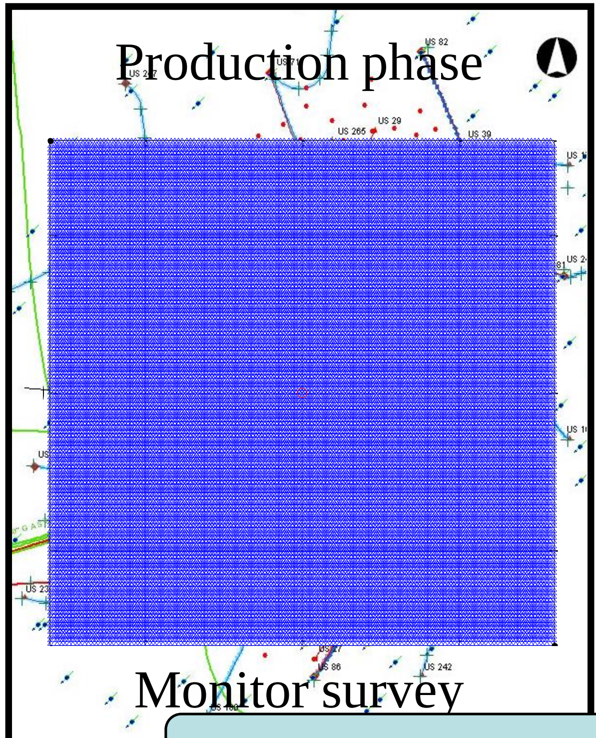
Exploration phase



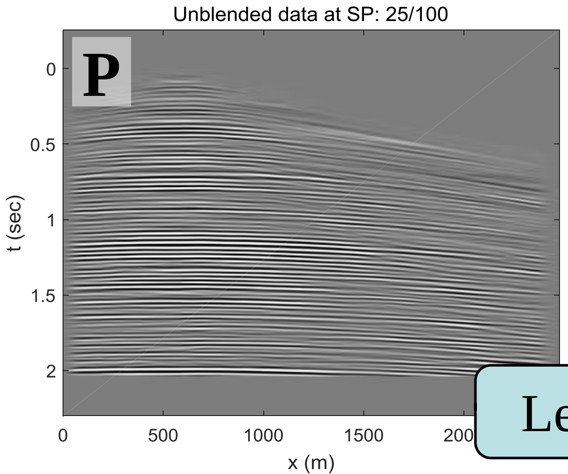
Baseline survey

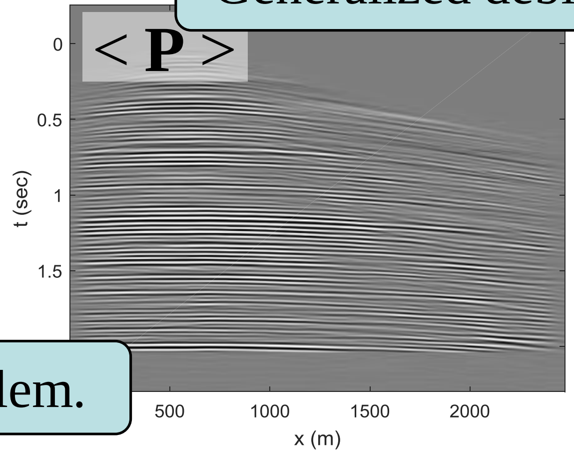
Time-lapse

Production phase



Monitor survey





Generalized deblended.

Less repeatability problem.

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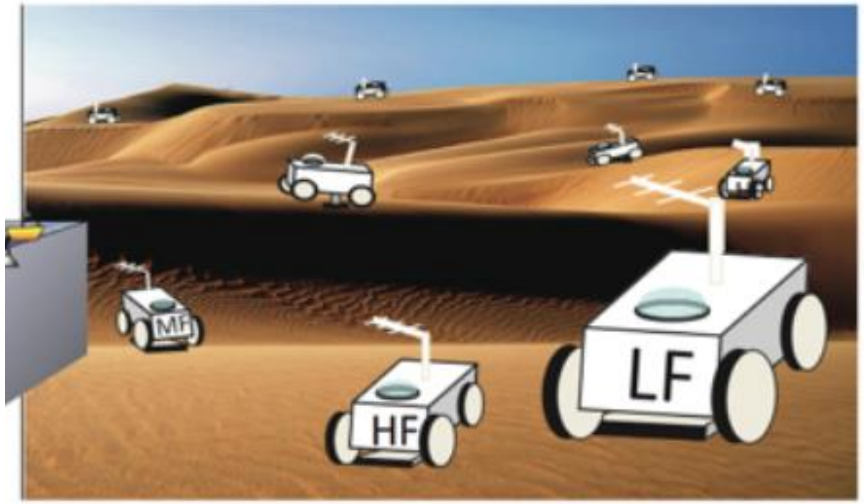

Conclusions

– We fully generalized blending and deblending models, which are quite practical and can handle real-life situations in any surveys.

– Our deblending method succeeded to fully reconstruct deblended data from the fully generalized blended data.

– Our methodology is highly applicable to time-lapse seismic monitoring as it ensures high repeatability of the surveys.

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