Simultaneous-source seismic data acquisition and processing with compressive sensing

Haneet Wason
Introduction

Seismic data acquisition
- marine surveys
- static vs. dynamic geometries
- time-lapse surveys
Marine seismic surveys

S : seismic source (air-gun arrays)
• : receivers (hydrophones and/or geophones)
1 : towed-streamer geometry (moving receivers => dynamic geometry)
2 : ocean-bottom geometry
3 : buried seafloor array
4 : vertical seismic profile geometry
2 - 4: fixed receivers
=> static geometries

[Caldwell and Walker]
Marine seismic source

side view of an air-gun array

schematic of air gun primed (left) and firing (right)

[Left -- Caldwell and Walker; Right -- http://www.geol.lsu.edu/jlorenzo/ReflectSeismol97/eczimmermann/WWW/eczimmermann.html]
Time-lapse (or 4D) surveys

Seismic reservoir monitoring
- compare seismic surveys re-run some time apart (order of months or years) over the same area
- monitor changes in the reservoir over time due to production

Types of gathers & trace display formats

[Left -- http://www.agilegeoscience.com/blog/2011/9/14/g-is-for-gather.html; Right -- SEG Wiki]
Types of gathers

Earth model

Receiver gather

Shot gather
Types of gathers

Earth model

Receiver gather

Shot gather
Challenges

Expensive dense and full-azimuthal sampling to produce high-resolution images of the subsurface
- deploy multiple source vessels for full azimuthal coverage
- simultaneous-source (or blended) acquisition; problem: source separation
- leads to uneven sampling: coarse source and dense receiver sampling or vice-versa

Time-lapse seismic acquisition
- repeat expensive dense acquisitions & “independent” processing
- hampered by practical challenges to ensure repetition
Our solutions

Adapt ideas from Compressive Sensing (CS)
- **design economic** (or low-cost), **randomly subsampled** acquisitions
- surveys acquired with **small** environmental **imprint**
- **recover** dense, periodically sampled data via **structure promotion**

Adapt ideas from Distributed Compressive Sensing (DCS)
- **economic**, randomly subsampled **time-lapse** acquisition
- offers possibility to **relax** insistence on survey **replicability**
- **recover** dense, periodically sampled time-lapse vintages and difference by **exploiting common information** among the vintages
The impact

Special Section: Impact of compressive sensing on seismic data acquisition and processing

640 Introduction to this special section: Impact of compressive sensing on seismic data acquisition and processing, N. Allegrar, F. J. Herrmann, and C. C. Mosher

642 Compressive sensing: A new approach to seismic data acquisition, R. G. Baraniuk and P. Stoeghs

646 Sparsity in compressive sensing, J. Ma and S. Yu


661 Operational deployment of compressive sensing systems for seismic data acquisition, C. C. Mosher, C. Li, F. D. Janiszewski, L. S. Williams, T. C. Carey, and Y. Ji


677 Highly repeatable 3D compressive full-azimuth towed-streamer time-lapse acquisition — A numerical feasibility study at scale, R. Kumar, H. Wason, S. Sharan, and F. J. Herrmann

688 Highly repeatable time-lapse seismic with distributed compressive sensing — Mitigating effects of calibration errors, F. Oghemekohwo and F. J. Herrmann
Chapters 2 & 3

Compressive sensing in seismic exploration
- simultaneous-source marine acquisition
- static acquisition geometry
Conventional vs. compressive acquisition

Conventional:
- Periodic
- Sparse
- No overlap

Jittered:
- Aperiodic
- Compressed
- Overlapping
- Irregular

Structure-promoting recovery:
- Periodic
- Dense
- No overlap

Source
Compressive sensing

Powerful sensing paradigm

- **find representations that reveal structure**
  - transform-domain sparsity (e.g., Fourier, curvelets, etc.)

- **sample to break structure**
  - randomized acquisition (e.g., time-jittered, over/under, SLO, etc.)
  - destroys sparsity

- **recover by structure promotion**
  - sparsity via one-norm minimization
Compressive sensing

Solve an underdetermined system of linear equations:

\[ b \in \mathbb{C}^n \]\n
\[ b = A \begin{bmatrix} x_0 \end{bmatrix} \]

\[ A \in \mathbb{C}^{n \times P} \]

\[ n \ll P \]

unknown \[ x_0 \in \mathbb{C}^P \]
Sampling schemes

- dense (or full) sampling
- regular (or periodic) subsampling
- uniform random subsampling

[adapted from Hennenfent and Herrmann, 2008]
Random vs. periodic subsampling

full sampling

periodic subsampling

random subsampling

[Hennenfent and Herrmann, 2008]
Adapt CS ideas to seismic acquisition

- design simultaneous-source marine acquisition
- source separation via structure ("sparsity") promotion
## Simultaneous-source marine acquisition

**random vs. periodic**

<table>
<thead>
<tr>
<th>Sampled Spatial Grid</th>
<th>Shot-Time Randomness</th>
</tr>
</thead>
<tbody>
<tr>
<td>periodic <strong>ly</strong></td>
<td>NONE</td>
</tr>
<tr>
<td>(static/dynamic acquisition geometry: conventional acquisition)</td>
<td></td>
</tr>
<tr>
<td>almost periodic <strong>ly</strong></td>
<td>SMALL</td>
</tr>
<tr>
<td>(dynamic acquisition geometry: towed arrays)</td>
<td></td>
</tr>
<tr>
<td>randomly jittered <strong>ly</strong></td>
<td>LARGE</td>
</tr>
<tr>
<td>(static acquisition geometry: OBC/OBN; “time-jittered” acquisition)</td>
<td></td>
</tr>
</tbody>
</table>
Simultaneous-source marine acquisition
random vs. periodic

“Ideal” simultaneous acquisition

Random time dithering

Periodic time dithering
Simultaneous-source sampling operators
random vs. periodic

"Ideal" simultaneous acquisition

Random time dithering

Periodic time dithering

Ns: number of sources
Nt: number of time samples
Nr: number of receivers
Measurements
– overlapping shots

“Ideal” simultaneous acquisition

Random time dithering

Periodic time dithering
Source separation via sparsity promotion

\[ d = S^H x \]
\[ \tilde{x} = \arg \min_x \|x\|_1 \quad \text{subject to} \quad Ax = b \]

- \( x \): a choice of curvelet coefficients for \( d \)
- \( S^H \): a transform domain synthesis (curvelet)
- \( A \): measurement operator: \( M S^H \), \( M \): acquisition (or mixing) operator
- \( b \): simultaneous data
- \( \tilde{x} \): estimated curvelet coefficients for source separated wavefield
- \( \tilde{d} \): \( = S^H \tilde{x} \) estimated source separated wavefield
Curvelets
Source separation
– subsampling factor = 2

“Ideal” simultaneous acquisition
Random time dithering
Periodic time dithering
Residual
– subsampling factor = 2
Conclusions

CS ideas can be **successfully** adapted to seismic data acquisition

Three **key** components:
- find representations that reveal structure, e.g., transform-domain sparsity
- sample to break structure, e.g., randomized acquisitions
- recover by structure promotion, e.g., sparsity via one-norm minimization

**Curvelets** lead to compressible representation of seismic data

**Simultaneous-source acquisition** is an instance of compressive sensing

CS offers new **design** perspectives for seismic data acquisition schemes
Chapter 4

Compressive marine seismic acquisition
- **pragmatic** simultaneous-source “time-jittered” marine
- static acquisition geometry
Sampling schemes

- **dense sampling**
- **regular subsampling**
- **uniform random subsampling**
- **jittered subsampling**

[adapted from Hennenfent and Herrmann, 2008]
Time-jittered marine acquisition

shot-time randomness: LARGE
irregularly sampled spatial grid

continuous recording
START

ocean-bottom cable

continuous recording
STOP
Design of time-jittered shots

Low variation

10 s \( \leq \) < 1 s, 1-2 s

air-gun recovery time \quad \text{range of randomized shot time}

High variation

10 s \quad 20 s

air-gun recovery time \quad \text{range of randomized shot time}

25 m \quad 50 m

\text{assume boat speed of 2.5m/s (≈ 5 knots)}
Pragmatic compressive simultaneous acquisition

Random time dithering (non-realistic)

- Boat speed = highly irregular

Time-jittered marine (realistic)

- Boat speed ≈ constant
Restricted Isometry Property (RIP)

- indicates whether every group of \( k \) columns of \( A \) are nearly orthogonal

- restricted isometry constant \( 0 < \delta_k < 1 \) for which

\[
(1 - \delta_k)\|u\|_2^2 \leq \|A_k u\|_2^2 \leq (1 + \delta_k)\|u\|_2^2
\]
Time-jittered marine acquisition

**subsampled** shots with overlap between shot records

source fires at jittered times and jittered positions

sum

**all shots without overlap** between shot records
Conventional vs. time-jittered marine acquisition
– subsampling factor = 2
Conventional vs. time-jittered marine acquisition
– subsampling factor = 4
Compressive simultaneous acquisition

subsampling factor

\[ \eta = \frac{1}{\text{number of air-gun arrays}} \times \frac{\text{jittered spatial grid interval}}{\text{conventional spatial grid interval}} \]

for spatial sampling = 12.5 m

\[ \eta = \frac{1}{2} \times \frac{50.0 \text{ m}}{12.5 \text{ m}} = 2 \]

for spatial sampling = 6.25 m

\[ \eta = \frac{1}{2} \times \frac{50.0 \text{ m}}{6.25 \text{ m}} = 4 \]
Conventional data

Receiver gather

Shot gather
Measurements
– subsampled and overlapping shots

\[ \eta = 2 \]

\[ \eta = 4 \]
Adjoint of acquisition operator \( (M^H b) \)

\[
\eta = 2
\]

\[
\eta = 4
\]
Sparsity-promoting recovery & residual
– 2D curvelets; subsampling factor = 2

Receiver gather

Shot gather
Residual
– 2D vs. 3D curvelets; subsampling factor = 2
Residual

- 2D vs. 3D curvelets; subsampling factor = 4
Summary (S/N (dB))

\[
S/N(f, \tilde{f}) = -20 \log_{10} \frac{||f - \tilde{f}||_2}{||f||_2}
\]

<table>
<thead>
<tr>
<th></th>
<th>jittered to regular (m), subsampling ((\eta))</th>
<th>recovery with 2D FDCT*</th>
<th>recovery with 3D FDCT*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 source vessel (2 air-gun arrays)</td>
<td>50 to 12.5, 2</td>
<td>11.5</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>50 to 6.25, 4</td>
<td>4.9</td>
<td>5.7</td>
</tr>
</tbody>
</table>

* FDCT : Fast Discrete Curvelet Transform
Economic performance indicators

Improved spatial-sampling ratio (ISSR):

$$\text{ISSR} = \frac{\text{number of shots recovered via sparsity-promoting inversion}}{\text{number of shots in simultaneous-source acquisition}}$$

for $\eta = 2, 4, \text{etc.}$, gain in spatial sampling by the same factor

Survey-time ratio (STR):

$$\text{STR} = \frac{\text{time of conventional acquisition}}{\text{time of simultaneous-source acquisition}}$$

for $\eta = 2, 4, \text{etc.}$, reduction in survey time by $\frac{1}{\eta}$
Conclusions

Simultaneous-source time-jittered marine acquisition is an instance of compressive sensing
- economic acquisition with reduced environmental imprint

Jittered (sub)sampling shares the benefits of random sampling while offering control on maximum acquisition gap

3D FDCT slightly improves sparse recovery; however, its redundancy (about 24 x) renders large-scale processing extremely memory intensive, and hence impractical
Chapter 5

Compressive time-lapse seismic acquisition
- distributed compressive sensing
- static acquisition geometry
- on-the-grid marine surveys
- % overlap => exact replication of shot positions
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** subsampled acquisition, e.g., via time-jittered marine subsampling
- offers possibility to relax insistence on replicability
- exploits insights from distributed compressive sensing
Time-lapse model

**Method**

- Velocity and density model provided by BG Group, 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 time-lapse data
– time-domain finite differences

**Baseline**

**Monitor**

**4D signal**

time samples: 512
receivers: 100
sources: 100
sampling
time: 4.0 ms
receiver: 12.5 m
source: 12.5 m
Sparse structure via curvelets

significant correlation between the vintages
Distributed compressive sensing – joint recovery model (JRM)

\[
\begin{bmatrix}
A_1 & A_1 & 0 \\
A_2 & 0 & A_2 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
z_0 \\
z_1 \\
z_2
\end{bmatrix} =
\begin{bmatrix}
b_1 \\
b_2
\end{bmatrix}
\]

- different vintages share common information
- common component observed by all surveys
- invert for common component & vintages w.r.t. common component with sparse recovery

**vintages**
\[
x_1 = z_0 + z_1 \\
x_2 = z_0 + z_2
\]

**differences**
common component
Time-lapse seismic
– with & without replication

In an **ideal** world \(A_1 = A_2\)
- JRM simplifies to \((b_2 - b_1) = A_1(x_2 - x_1)\)
- expect good recovery when difference is sparse
- but relies on “exact” replicability of surveys...

In the **real** world \(A_1 \neq A_2\)
- no absolute control on surveys
- deviations in shot/receiver positions
- noise...
Synthetic seismic case study

Time-jittered marine acquisition on the grid
- % overlap => exact replication of shot positions
Conventional vs. time-jittered sources
– subsampling factor = 2 (2 source arrays)

**Conventional**
- 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 \times 10.0 = 1000.0 s

**Jittered Acquisition 1**
- (Baseline)
- Spatial subsampling factor = 2
- Increase in spatial sampling factor = 2

**Jittered Acquisition 2**
- (Monitor)
- Number of shots = 100/2 = 50 (25 per array)
- Spatial sampling: 50.0 m (jittered)
- Vessel speed: 2.50 m/s
- Recording time \approx 1000.0 \text{s}/2 = 500.0 s

**MIXING & SUBSAMPLING**
- Spatial subsampling factor = 2

**SOURCE SEPARATION & INTERPOLATION**

![Graphs comparing conventional and jittered shot gatherings](image-url)
Measurements
– subsampled and overlapping shots

Baseline

Monitor

Recording time (s)

Receiver position (km)
Monitor recovery
- Independent recovery

“on-the-grid” sampling
% overlap => “exact” replication of shot positions

100% overlap [11.6 dB]

50% overlap [11.0 dB]

25% overlap [10.3 dB]
Monitor recovery
- Joint recovery

"on-the-grid" sampling
% overlap => "exact" replication of shot positions

100% overlap
[11.6 dB]

50% overlap
[15.7 dB]

25% overlap
[18.6 dB]
Monitor residual

- Independent residual

100% overlap [11.6 dB]
50% overlap [11.0 dB]
25% overlap [10.3 dB]
Monitor residual

- Joint residual

100% overlap [11.6 dB]

50% overlap [15.7 dB]

25% overlap [18.6 dB]
4D recovery
- Independent recovery

100% overlap [10.2 dB]
50% overlap [-16.0 dB]
25% overlap [-18.5 dB]

[ colormap scale: 10 X ]
4D recovery

- Joint recovery

100% overlap
[12.8 dB]

50% overlap
[5.0 dB]

25% overlap
[2.0 dB]

[ colormap scale: 10 X]
Stacked sections

Baseline

4D signal
Stacked sections

- 100% overlap in acquisition matrices

IRS
[21.4 dB]

JRM
[23.4 dB]
Stacked sections

- **50% overlap** in acquisition matrices

**IRS**

[9.1 dB]

**JRM**

[20.2 dB]
Stacked sections
- **25% overlap** in acquisition matrices

**IRS**
- [7.8 dB]

**JRM**
- [18.0 dB]
### SNR (dB) for stacked sections
- average of 100 experiments

<table>
<thead>
<tr>
<th>overlap</th>
<th>baseline</th>
<th>monitor</th>
<th>4D signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IRS</td>
<td>JRM</td>
<td>IRS</td>
</tr>
<tr>
<td>100%</td>
<td>23.1 ± 1.2</td>
<td>24.8 ± 1.2</td>
<td>23.1 ± 1.3</td>
</tr>
<tr>
<td>50%</td>
<td>23.1 ± 1.2</td>
<td><strong>32.8 ± 1.6</strong></td>
<td>23.4 ± 1.2</td>
</tr>
<tr>
<td>25%</td>
<td>23.1 ± 1.2</td>
<td><strong>35.3 ± 1.5</strong></td>
<td>22.0 ± 1.1</td>
</tr>
</tbody>
</table>
Conclusions

Seismic synthetics show that we do not necessarily have to insist on full replication of surveys depending on the recovery of the vintages.

Processing time-lapse data jointly leads to improved recovery of the vintages with little variability in the time-lapse difference.

Recall: we are still on the grid => exactly replicated (subsampled) shot locations ...... not realistic!
Chapter 6

Compressive time-lapse marine acquisition
- static acquisition geometry
- off-the-grid (or irregular) marine surveys
- with & without deviations in shot positions
Sampling schemes

- **Dense sampling**
- **Regular subsampling**
- **Jittered subsampling**

**ON THE GRID**

- **Regularly subsampled spatial grid**

**OFF THE GRID**

- **Jittered subsampling**
- **Jittered subsampling ("exact" replication)**
- **Jittered subsampling (deviations: 0-1, 2, 3...m)**

*In the real world*

[adapted from Hennenfent and Herrmann, 2008]
4D time-jittered marine acquisition

\[
\text{deviation} \approx 1.0 \text{ m}
\]

\[
\text{deviation} \approx 1.4 \text{ m}
\]
Conventional vs. compressive acquisition

Conventional

- periodic–sparse–no overlap
- source

Jittered

- aperiodic
- compressed
- overlapping
- irregular

Structure-promoting recovery

- periodic–dense–no overlap

Separation + regularization + interpolation

4X
BG Compass model
– contains gas cloud

Baseline

Monitor

Time-lapse difference
Simulated time-lapse data
– time-domain finite differences

Baseline

Monitor

4D signal

time samples: 512
receivers: 260
sources: 260

time: 4.0 ms
receiver: 12.5 m
source: 12.5 m
Measurements
– subsampled, overlapping and irregular shots
FDCT vs. NFDCT

**Fast Discrete Curvelet Transform (FDCT)**

\[
\begin{align*}
\text{Input} & \quad \xrightarrow{2D \text{ FFT}} \quad f \\
\text{curvelet tilling} & \quad \xrightarrow{2D \text{ IFFT}} \quad \text{curvelet coefficients}
\end{align*}
\]

**Nonequispaced Fast Discrete Curvelet Transform (NFDCT)**

\[
\begin{align*}
\text{Input} & \quad \xrightarrow{1D \text{ NFFT on } x} \quad f \\
\text{curvelet tiling} & \quad \xrightarrow{1D \text{ INFFT on } k} \quad \text{curvelet coefficients}
\end{align*}
\]
4D recovery

- **Joint recovery**: subsampling factor = 2

<table>
<thead>
<tr>
<th>Overlap</th>
<th>Time (s)</th>
<th>Shot position (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% overlap</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100% ± 1.0 m</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>100% ± 2.0 m</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>100% ± 3.0 m</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>&lt; 15% overlap</td>
<td>3.5</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (dB)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4 dB</td>
<td>10.4 dB</td>
<td>10.7 dB</td>
</tr>
<tr>
<td>10.7 dB</td>
<td>11.1 dB</td>
<td>10.8 dB</td>
</tr>
</tbody>
</table>

< 15% overlap

Subsampling factor = 2
4D residual

- **Joint recovery;** subsampling factor = 2

<table>
<thead>
<tr>
<th>Overlap</th>
<th>Maximum Error (m)</th>
<th>[dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>± 1.0 m</td>
<td></td>
<td>10.4</td>
</tr>
<tr>
<td>± 2.0 m</td>
<td></td>
<td>10.7</td>
</tr>
<tr>
<td>± 3.0 m</td>
<td></td>
<td>11.1</td>
</tr>
</tbody>
</table>

- `< 15% overlap [10.8 dB]`
position deviations **improve** recovery of the vintages
Monitor recovery

- **Joint recovery**: subsampling factor = 2

100% overlap
[19.0 dB]

100% ± 1.0 m
[19.6 dB]

100% ± 2.0 m
[20.2 dB]

100% ± 3.0 m
[20.8 dB]

< 15% overlap
[24.6 dB]
Monitor residual

- **Joint recovery; subsampling factor = 2**

<table>
<thead>
<tr>
<th>Overlap</th>
<th>Distance (m)</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% overlap</td>
<td></td>
<td>19.0 dB</td>
</tr>
<tr>
<td>100% ± 1.0 m</td>
<td>1.0</td>
<td>19.6 dB</td>
</tr>
<tr>
<td>100% ± 2.0 m</td>
<td>2.0</td>
<td>20.2 dB</td>
</tr>
<tr>
<td>100% ± 3.0 m</td>
<td>3.0</td>
<td>20.8 dB</td>
</tr>
<tr>
<td>&lt; 15% overlap</td>
<td></td>
<td>24.6 dB</td>
</tr>
</tbody>
</table>
**SNR (dB) for data recovered via JRM**
– average of 10 experiments; **subsampling factor = 2**

<table>
<thead>
<tr>
<th>overlap ± deviation</th>
<th>Baseline</th>
<th>Monitor</th>
<th>4D signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>19.1 ± 0.9</td>
<td>19.0 ± 0.9</td>
<td>9.4 ± 1.8</td>
</tr>
<tr>
<td>100% ± 1.0 m</td>
<td>19.7 ± 0.7</td>
<td>19.6 ± 0.7</td>
<td>10.4 ± 1.3</td>
</tr>
<tr>
<td>100% ± 2.0 m</td>
<td>20.3 ± 1.5</td>
<td>20.2 ± 1.5</td>
<td>10.7 ± 1.9</td>
</tr>
<tr>
<td>100% ± 3.0 m</td>
<td>21.0 ± 1.5</td>
<td>20.8 ± 1.5</td>
<td>11.1 ± 1.8</td>
</tr>
<tr>
<td>&lt; 15 % *</td>
<td><strong>24.8 ± 1.8</strong></td>
<td><strong>24.6 ± 1.7</strong></td>
<td><strong>10.8 ± 0.9</strong></td>
</tr>
</tbody>
</table>

* least possible overlap range > 0% and < 15% (depends on simultaneous acquisition design and subsampling factor)
### SNR (dB) for data recovered via JRM
- average of 10 experiments; **subsampling factor = 4**

<table>
<thead>
<tr>
<th>overlap ± deviation</th>
<th>Baseline</th>
<th>Monitor</th>
<th>4D signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>14.1 ± 0.7</td>
<td>13.9 ± 0.7</td>
<td>6.1 ± 0.8</td>
</tr>
<tr>
<td>100% ± 1.0 m</td>
<td>14.5 ± 0.8</td>
<td>14.3 ± 0.8</td>
<td>5.6 ± 0.8</td>
</tr>
<tr>
<td>100% ± 2.0 m</td>
<td>15.6 ± 0.7</td>
<td>15.5 ± 0.7</td>
<td>6.4 ± 0.7</td>
</tr>
<tr>
<td>100% ± 3.0 m</td>
<td>16.2 ± 0.7</td>
<td>16.0 ± 0.7</td>
<td>6.0 ± 0.6</td>
</tr>
<tr>
<td>&lt; 5 % *</td>
<td>18.0 ± 0.9</td>
<td>17.7 ± 0.8</td>
<td>5.2 ± 0.5</td>
</tr>
</tbody>
</table>

*least possible overlap range > 0% and < 5% (depends on simultaneous acquisition design and subsampling factor)*
SEAM Phase 1 model
– time-lapse difference via fluid substitution

Baseline

Monitor

Time-lapse difference
Simulated time-lapse data
– time-domain finite differences

Baseline

Monitor

4D signal

time samples: 2048
receivers: 330
sources: 330

sampling
time: 4.0 ms
receiver: 12.5 m
source: 12.5 m
Monitor recovery & residual

- **Joint recovery**: subsampling factor = 2

100% overlap [19.5 dB] 

< 15% overlap [30.2 dB]
4D recovery & residual
- Joint recovery; subsampling factor = 2
Conclusions

In the given context of randomized subsampling, position deviations
- have **little variability** on recovery of the time-lapse **difference**
- **improve** recovery of the **vintages**

Should we repeat compressive randomized time-lapse surveys?
- **Irregular sampling is inevitable in the real world** => “exact” replicability of surveys is naturally not possible
- Better to focus on knowing the shot positions post acquisition

**Embrace** natural **randomness** in the field or better purposefully randomize acquisitions to maximize collection of information
Main contributions

Design of **pragmatic** simultaneous-source **time-jittered marine** acquisition

Adaptation of **NFDCT** for simultaneous-source acquisition and source separation

Design of **pragmatic** simultaneous-source **time-jittered time-lapse marine** acquisition with different overlaps between baseline & monitor surveys
Main conclusions

CS ideas can be **successfully** adapted to seismic data acquisition

CS offers new **design** perspectives for seismic data acquisition schemes

Three **key** components:
- find representations that reveal structure, e.g., transform-domain sparsity
- sample to break structure, e.g., randomized acquisitions
- recover by structure promotion, e.g., sparsity via one-norm minimization

**Simultaneous-source acquisition** is an instance of compressive sensing
- **economic** acquisitions with **reduced** environmental **imprint**
Main conclusions

Time-lapse seismic

- **processing** time-lapse data **jointly** leads to improved recovery of the vintages with little variability in the time-lapse difference
- **irregular** sampling is **inevitable** in the real world => better to focus on knowing the shot positions post acquisition

**Embrace** natural **randomness** in the field or better purposefully randomize acquisitions to maximize collection of information
Summary of publications

Journal papers


Conference proceedings


**Source-separation via SVD-free rank minimization in the hierarchical semi-separable representation**, Haneet Wason, Rajiv Kumar, and Felix. J. Herrmann, SEG Annual Meeting 2014.


Future research directions

Develop a computationally faster and memory efficient implementation of 2D & 3D curvelet transforms

Improve recovery of weak late-arriving events with weighted one-norm minimization

Develop robust algorithms to use simultaneous-source data directly in imaging and inversion

Improve sparse time-lapse data recoveries with $\gamma$-weighted one-norm formulation for DCS:

$$\tilde{z} = \arg\min_z \gamma_0 z_0 + \gamma_1 |z_1|_1 + \gamma_2 |z_2|_1 \quad \text{subject to} \quad y = Az$$
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