Economic time-lapse seismic acquisition and imaging - Reaping the benefits of randomized sampling with distributed compressive sensing

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Ph.D. Final Oral Defense
10th August 2017
Outline

**Introduction:**
- basic concepts - seismic, time-lapse etc.
- compressive sensing & impact
- motivation

**Time-lapse seismic:**
- current challenges & existing solutions
- overview of my contribution
- main message
Outline

Theory:
- compressive sensing in seismic
- randomized acquisition in marine
- time-lapse formulation
- DCS & joint recovery model

Applications:
- time-lapse marine acquisition - Chapters 2, 3 & 4
- time-lapse seismic imaging - Chapter 5

Conclusions
Marine seismic survey

**Principle:**
- Airgun fires shot
- Reflections from subsurface
- Recorded by receivers
- Generates data (shot records)
- Repeat after “t” seconds
Marine seismic data

Shot Gather (Raw)

**Shot records:**
- Non-overlapping
- Contain coherent events
- Reflections
- Function of time & offset
- Record many shots

FIG. 3.6-3. Selected common-shot gathers from an offshore survey just after demultiplexing. (Data courtesy Dovrol Babgray, Kongsberg Geophysical.)
Seismic method

Workflow:
- *data acquisition*
- preprocessing
  - sorting, noise removal etc.
  - multiple removal
  - velocity analysis
  - NMO correction
- *postprocessing*
  - stacking
  - noise suppression
  - migration (imaging)
  - other enhancements
Principle of time-lapse

**Principle:**
- 1st - Baseline
- 2nd - Monitor
- Difference = Baseline - Monitor
- Quantify changes
- Fluid sat., temp., pressure etc.

**Current acquisition paradigm:**
- *repeat expensive dense* acquisitions & “independent” processing
- compute *differences* between baseline & monitor survey(s)
- *hampered by practical* challenges to ensure repetition

http://www.geoexpro.com/articles/2009/05/4d-geophysical-data
Compressive sensing

Consider the following (severely) underdetermined system of linear equations:

$$\begin{align*}
\text{data} & \;\quad \rightarrow \quad \begin{bmatrix} b \\ A \end{bmatrix} \\
\text{(measurements/} & \quad \text{observations} \\
\text{/simulations)} & \\
\text{unknown} & \;\quad \uparrow \\
\text{is it possible to recover } \mathbf{x}_0 \text{ accurately from } \mathbf{b}? \\
\text{The field of Compressive Sensing attempts to answer this.}
\end{align*}$$
Compressive sensing

Signal model

\[ b = Ax_0 \quad \text{where} \quad b \in \mathbb{R}^n \]

and \( x_0 \) \( k \)-sparse

Sparse one-norm recovery

\[
\tilde{x} = \arg \min_x ||x||_1 \overset{\text{def}}{=} \sum_{i=1}^{N} |x[i]| \quad \text{subject to} \quad b = Ax
\]

with \( n \ll N \) where \( N \) is the ambient dimension
Impact of CS

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Impact:

- Industry uptake e.g. ConocoPhillips.
- Reported improvement in efficiency & economics - up to 10-fold improvements
- Planned time-lapse surveys
Sim. src (jittered) blended shots
– instance of compressive sensing

subsampling shots with overlap between shot records

source fires at jittered times and jittered positions

sum

all shots without overlap between shot records
Context

Time-lapse surveys

- are expensive
- require strict repeat surveys
- repetition of surveys is difficult

Solution:

- cheap surveys based on CS
- less reliance on survey repetition
Objective

- Reduce cost of time-lapse surveys
- Improve quality of the prestack vintages
- Less reliance on high degrees of survey replicability

Method:
- design low-cost surveys based on CS
- leverage the shared information in time-lapse recordings
Thesis contributions

Time-lapse & CS:
- *first* attempt to investigate feasibility
- focus on impact of survey *replication*
- implications for *repeatability*
- impact of *calibration errors*

Main message:
- Do not attempt to *replicate* time-lapse surveys
- Recover surveys “jointly” w/ the proposed JRM
Time-lapse: current practice/methods

**Acquisition/Processing:**
- *effort to repeat* **expensive dense** acquisitions & “*independent*” processing
- mostly static receivers to minimize differences
- “*cross-equalization*” to address some non-repeatability effects

**Imaging/Inversion:**
- different methods (data/image domain) depending on non-repeatability effects
- *Parallel WI, DDWI, SeqFWI, AltFWI, IDWT*

Watanabe et al., 2004; Denli and Huang, 2009; Zheng et al., 2011; Asnaashari et al., 2012; Raknes et al., 2013; Shragge et al., 2013; Maharramov et al., 2014; Yang et al., 2014.
CS formulation in time-lapse

Sampling

\[ A_1 x_1 = b_1 \]
\[ A_2 x_2 = b_2 \]

subsampling baseline data

subsampling monitor data

Sparsity-promoting recovery

\[ \tilde{x} = \arg \min_x \|x\|_1 \quad \text{subject to} \quad A x = b \]

recovered data: \[ \tilde{d} = S^H \tilde{x} \]
Aim

- *Reduce cost of time-lapse surveys*
- *Improve quality of the prestack vintages*
- *Avoid repetition*

**Method:**

- *economic randomized sampling based on CS*
- *sparsity-promoting data recovery*
- *leverage the shared information in time-lapse recordings*
Distributed compressed sensing
– joint recovery model (JRM)

\[ \begin{align*}
\mathbf{x}_1 &= \mathbf{z}_0 + \mathbf{z}_1 \\
\mathbf{x}_2 &= \mathbf{z}_0 + \mathbf{z}_2 \\
\end{align*} \]

differences

\[ \begin{bmatrix}
\mathbf{A}_1 & \mathbf{A}_1 & 0 \\
\mathbf{A}_2 & 0 & \mathbf{A}_2 \\
\end{bmatrix} \begin{bmatrix}
\mathbf{z}_0 \\
\mathbf{z}_1 \\
\mathbf{z}_2 \\
\end{bmatrix} = \begin{bmatrix}
\mathbf{b}_1 \\
\mathbf{b}_2 \\
\end{bmatrix} \]

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
Joint recovery model (JRM)

sparsity-promoting minimization:

\[ \tilde{z} = \arg \min_{z} \|z\|_1 \quad \text{subject to} \quad Az = b \]

support detection \hspace{1cm} \text{data-consistent amplitude recovery}

\[ \tilde{z} = \begin{bmatrix} \tilde{z}_0 \\ \tilde{z}_1 \\ \tilde{z}_2 \end{bmatrix} \]

Key idea:
- invert for common components & innovation w.r.t. common components with sparse recovery
- common component observed by all surveys
Seismic application
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**
- **4-D signal**

- time samples: 512
- receivers: 100
- sources: 100
- sampling time: 4.0 ms
- receiver: 12.5 m
- source: 12.5 m
Evaluation

Signal to noise ratio:

$$\text{SNR}(d, \tilde{d}) = -20 \log_{10} \frac{\|d - \tilde{d}\|_2}{\|d\|_2}$$

Repeatability as NRMS (normalized root mean square): [Kragh and Christie (2002)]

$$\text{NRMS}(\tilde{d}_1, \tilde{d}_2) = \frac{200 \times \text{RMS}(\tilde{d}_1 - \tilde{d}_2)}{\text{RMS}(\tilde{d}_1) + \text{RMS}(\tilde{d}_2)}$$

$$\text{RMS}(d) = \sqrt{\frac{\sum_{t=t_1}^{t_2} (d[t])^2}{N}}$$

$N$ is the number of samples in the interval $t_1$ to $t_2$

$d[t]$ is a sample recorded at time $t$
Conventional vs. *time-jittered* sources
– subsampling ratio = 2, 2 source arrays

**“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

**“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

**[BLENDING & SUBSAMPLING]**
- spatial subsampling factor = 2
- spatial sampling *increase* factor = 2

**[DEBLENDING & INTERPOLATION]**
Measurements
– subsampled and blended

Baseline

Monitor

Recording time (s)

Receiver position (m)
CS formulation in time-lapse

Sampling

\[ A_1 x_1 = b_1 \]
\[ A_2 x_2 = b_2 \]

Sparsity-promoting recovery

\[ \tilde{x} = \arg \min_x \|x\|_1 \quad \text{subject to} \quad A x = b \]

recovered data: \[ \tilde{d} = S^H \tilde{x} \]
Recovery (independently)

25% overlap [10.3 dB]
Structure - curvelet representation
Recovery (jointly) via JRM

Monitor

25% overlap
[18.6 dB]

Residual
Monitor recovery

- Independent recovery

100% overlap
[11.6 dB]

50% overlap
[11.0 dB]

25% overlap
[10.3 dB]
Monitor recovery

- Joint recovery

100% overlap
[11.6 dB]

50% overlap
[15.7 dB]

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

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

- Joint recovery

100% overlap
[12.8 dB]

50% overlap
[4.0 dB]

25% overlap
[-1.9 dB]
Observations

In the given context of randomized subsampling,

- Independent surveys bring extra information
- “Exactly” repeated surveys do not add any new information
- For different surveys, independent processing degrades recovery quality of vintages and time-lapse difference
- With joint recovery, we observe improvement in recovery quality of the vintages for completely independent surveys

Our joint recovery model exploits the shared information in time-lapse data, improving the repeatability of the vintages.

“Exact” replicability of the surveys seems essential for good recovery of the time-lapse signal
Summary

With decrease in survey replication i.e. overlap in shot positions,

- quality of recovered vintages improves significantly
- small variability in quality of the recovered time-lapse signal

Recovered prestack vintages can serve as input to poststack processes.

Results hold for processes with/without regularization (Chapter 2 & 3)

Focus on knowing the exact shot positions i.e. postplots, rather than striving to replicate the time-lapse surveys.
What is the impact of calibration errors?

\[(A_1 \neq A_2)\]
4-D time-jittered marine acquisition

Baseline

Monitor

periodic-dense-no overlap

separation + regularization
+ interpolation

True ★ Baseline post-plot ★ Monitor post-plot ★
Recovery & repeatability
Summary

- High-cost densely sampled surveys give best quality & repeatability in the absence of calibration errors.
- Quality of dense surveys decay rapidly in presence of small errors.
- Independently recovering the CS-based surveys leads to the worst recovery quality and repeatability.
- Low-cost randomized surveys show modest decay in quality and repeatability when recovered with the joint recovery model.

Recovery with the JRM is stable with respect to calibration errors.
Time-lapse seismic imaging

**Challenges:**
- non-repeatability effects e.g. via acquisition differences
- overburden complexity
- weak 4D signal in complex areas

**Objectives:**
- investigate the role of DCS & the JRM
- compare data-domain versus image-domain
- migration & FWI
Assuming similar geometry, “good” starting model
Assuming similar geometry, “poor” starting model

Parallel w/ initial model

SNR: -3.32

Joint w/ initial model

SNR: 2.61

Sequential w/ inverted base

SNR: -2.01

Joint w/ inverted base

SNR: 5.80
Observations

A good initial model drives the inversion results for the vintages and time-lapse model

**Sequential** FWI is better than **parallel** FWI, however **joint** inversion with JRM is better than both approaches

Significant attenuation of the artifacts in the time-lapse model using JRM, which exploits the shared information in time-lapse
General conclusions

**Time-lapse seismic acquisition:**
- Randomize acquisition & do not bother with “exact” repetition
- Processing: recover high-quality vintages & time-lapse using the joint-recovery model (JRM)
- Advantageous to have precise information on acquisition specs.

**Impact of calibration error in (time-lapse) CS:**
- Robust recovery using the JRM
- Avoid independent processing & expensive conventional dense surveys
- Shot timing errors need to be minimized, less so for spatial errors.
General conclusions

*Time-lapse seismic imaging with DCS:*

- Independent time-lapse inversions do not exploit the common information in the vintages
- Model differences due to different inversions can mask true time-lapse changes
- Inversions leveraging the JRM yield images (or models) with better quality for both the vintages and time-lapse difference.
- Inversions with JRM attenuates artifacts observed with separate inversions, minimizing the risk of false time-lapse changes


Thank you!!!

To:
- my advisor
- committee
- sponsors of SLIM
- members of SLIM

To:
- family
- friends