Time-jittered ocean bottom seismic acquisition

Haneet Wason and Felix J. Herrmann
Challenges

- Need for full sampling
  - wave-equation based inversion (RTM & FWI)
  - SRME/EPSI or related techniques

- Full azimuthal coverage
  - multiple source vessels
  - simultaneous/blended acquisition

- Deblending or wavefield reconstruction
  - recover unblended data from blended data
  - challenging to recover weak late events
Motivation

*Rethink marine acquisition (OBC, OBN)*
- sources (and receivers) at *random* locations
- exploit *natural* variations in the acquisition (e.g., cable feathering)
- as long as you know where sources were afterwards... *it is fine!*

*Want more for less ...*
- *shorter* survey times
- *increased* spatial sampling
Motivation

Rethink marine acquisition (OBC, OBN)
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Want more for less ...
- shorter survey times
- increased spatial sampling

How is this possible?
- (multi) vessel acquisition w/ jittered sampling & “blending” via compressed randomized intershot firing times
- sparsity-promoting recovery using $\ell_1$ constraints (“deblending”)
More for less

CONVENTIONAL

PERIODIC–SPARSE–NO OVERLAP

JITTERED

APERIODIC COMPRESSED OVERLAPPING IRREGULAR

(NO OVERLAP)

ℓ₁ RECOVERED

PERIODIC & DENSE

2X
Outline

- Measurement model & recovery strategy
- Design of jittered, ocean bottom acquisition
  - jitter in time $\Rightarrow$ jittered in space (shot locations)
- Experimental results of sparsity-promoting processing
  - wavefield recovery via “deblending” & interpolation from (coarse) jittered/irregular to (fine) regular sampling grid
Compressed Sensing

Successful sampling & reconstruction scheme

- exploit structure via sparsifying transform
- subsampling – decreases sparsity
- large scale optimization – look for sparsest solution
**Time-jittered acquisition**

Compress inter-shot times

- *random jitter in time* $\rightarrow$ *jitter in space* for a given speed
- *discrete jittering* - start by being *on the grid*
- maximum (acquisition) gap effectively controlled

**Challenges:** recover fully sampled data from *jittered* data *and* remove overlaps (but no fear..... sparse recovery is here!)

**Recent work** - use *non-uniform* grid  

[Hennenfent et.al., 2010]
Measurement model

Solve an *underdetermined* system of linear equations:

\[
\begin{align*}
\mathbf{b} \in \mathbb{C}^n & \quad \text{(data)} \\
\mathbf{x}_0 & \quad \text{(unknown)} \\
\mathbf{A} \in \mathbb{C}^{n \times P} & \quad \text{(transform matrix)} \\
\mathbf{A}^{\mathsf{H}} & \quad \text{(sampling matrix)} \\
\mathbf{b} & = \mathbf{A}\mathbf{x}_0 \quad \text{(RMS)}
\end{align*}
\]
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)

\[ b = \text{RM} \]
Exploit curvelet-domain sparsity of seismic data

Sparsity-promoting program:

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

- Support detection
- Data-consistent amplitude recovery

Sparsity-promoting solver: SPGL1 [van den Berg and Friedlander, 2008]

Recover single-source prestack data volume: \(\tilde{d} = S^H\tilde{x}\)
Outline

- Measurement model & recovery strategy

- **Design of jittered, ocean bottom acquisition**
  - jitter in *time* ⇒ jittered in *space* (*shot* locations)

- Experimental results of *sparsity*-promoting processing
  - wavefield recovery via “deblending” & interpolation from (coarse) jittered/irregular to (fine) regular sampling grid
Sampling schemes

FULL SAMPLING

REGULAR UNDERSAMPLING
(\(\eta = 4\))

UNIFORM RANDOM UNDERSAMPLING
(\(\eta = 4\))

JITTERED UNDERSAMPLING
(\(\eta = 4\))

regularly undersampled spatial grid

[Hennenfent et.al., 2008]
Conventional vs. *jittered* sources

[Speed of source vessel = 5 knots ≈ 2.5 m/s]
Conventional vs. jittered sources

[Speed of source vessel = 5 knots ≈ 2.5 m/s]
Significant spatial jittering
Simultaneous source acquisition & deblending

- A new look at simultaneous sources by Beasley et. al., ’98, ’08
- High quality separation of simultaneous sources by sparse inversion by Abma et. al., ’13
- Changing the mindset in seismic data acquisition by Berkhout, ’08
- Utilizing dispersed source arrays in blended acquisition by Berkhout et. al., ’12
- Random sampling: a new strategy for marine acquisition by Moldoveanu, ’10
- Multi-vessel coil shooting acquisition by Moldoveanu, ’10
- Simultaneous source separation by sparse radon transform by Akerberg et. al., ’08
- Simultaneous source separation using dithered sources by Moore et. al., ’08
- Simultaneous source separation via multi-directional vector-median filter by Huo et. al., ’09
- Separation of blended data by iterative estimation and subtraction of blending interference noise by Mahdad et. al., ’11
Our approach

Combination of

- multiple-source *time-jittered* acquisition
  - *random jitter* in time $\implies$ *jitter* in *space* for a constant speed
    (favours recovery compared to *periodic* sampling)
  - shorter acquisition times

- *sparsity*-promoting processing
  - *data* is sparse in *curvelets*
  - *optimization*: use $\ell_1$ constraints

Address two challenges - *overlap* and *jittered sampling* (regularize & interpolate)
Outline

- Measurement model & recovery strategy
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  - wavefield recovery via “deblending” & interpolation from (coarse) jittered/irregular to (fine) regular sampling grid
Time-jittered OBC acquisition

[1 source vessel, speed = 5 knots, underlying grid: 25 m]

[no. of jittered source locations is half the number of sources in ideal periodic survey w/o overlap]
Sparsity-promoting recovery on the grid (14.2 dB)
[“deblending” + interpolation from jittered 50m grid to regular 25m grid]
Sparsity-promoting recovery on the grid (14.2 dB)
[“deblending” + interpolation from jittered 50m grid to regular 25m grid]
(difference)
FDCT vs. NFDCT

**FAST DISCRETE CURVELET TRANSFORM**

Input $t$  

$2$-D FFT  

$\rightarrow$  

curvelet tilling $k$  

$2$-D IFFT  

$\rightarrow$  

curvelet coefficients

**NON-EQUISPACED FAST DISCRETE CURVELET TRANSFORM**

Input $t$  

$1$-D FFT on $t$  

$1$-D NFFT on $x$  

$\rightarrow$  

curvelet tilling $k$  

$1$-D IFFT on $f$  

$1$-D INFFT on $k$  

$\rightarrow$  

curvelet coefficients
NFFT-generated data

Receiver Gather

Shot Gather
Recovery with FDCT (‘binning’)

[“deblending” + interpolation from jittered 50m grid to regular 25m grid]
Recovery with FDCT (‘binning’) 
[“deblending” + interpolation from jittered 50m grid to regular 25m grid]
Sparsity-promoting recovery on irregular grid with NFDCT (17.6 dB)
[“deblending” + interpolation from jittered 50m grid to regular 25m grid]
Sparsity-promoting recovery on *irregular* grid with NFDCT (17.6 dB)

[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]
Sparsity-promoting recovery on *irregular* grid with NFDCT (17.6 dB)

[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]  (difference)
Performance

Improvement spatial sampling ratio

\[
= \frac{\text{no. of spatial grid points recovered from jittered sampling via sparse recovery}}{\text{no. of spatial grid points in conventional sampling}}
\]

\[
= \frac{128}{64} = 2
\]
Multiple source vessels

- *improves* recovery – *shorter* times lead to better *spatial* sampling at the expense of *more* overlap

- better *azimuthal* coverage
Time-jittered OBC acquisition

[2 source vessels, speed = 5 knots, underlying grid: 25 m]

[no. of jittered source locations is half the number of sources in ideal periodic survey w/o overlap]
Sparsity-promoting recovery on *irregular* grid with NFDCT (21.5 dB)
[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]
Sparsity-promoting recovery on *irregular* grid with NFDCT (21.5 dB)

[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]
Sparsity-promoting recovery on *irregular* grid with NFDCT (21.5 dB)

[“deblending” + interpolation from *jittered* 50m grid to *regular* 25m grid]  

(difference)
Time-jittered OBC acquisition

[2 source vessels, speed = 5 knots, underlying grid: 12.5 m]

[no. of jittered source locations is one-fourth the number of sources in ideal periodic survey w/o overlap]
Sparsity-promoting recovery on \textit{irregular} grid with NFDCT (16.8 dB)

[“deblending” + interpolation from \textit{jittered} 50m grid to \textit{regular} 12.5m grid]
Sparsity-promoting recovery on *irregular* grid with *NFDCT* (16.8 dB)

[“deblending” + interpolation from *jittered* 50m grid to *regular* 12.5m grid]
Sparsity-promoting recovery on \textit{irregular} grid with \textit{NFDCT} (16.8 dB)

[“deblending” + interpolation from \textit{jittered} 50m grid to \textit{regular} 12.5m grid] (difference)
Performance

Improvement spatial sampling ratio

\[
\text{Improvement spatial sampling ratio} = \frac{\text{no. of spatial grid points recovered from jittered sampling via sparse recovery}}{\text{no. of spatial grid points in conventional sampling}}
\]

\[
= \frac{128}{32} = 4
\]
<table>
<thead>
<tr>
<th></th>
<th>deblend + interpolate (jittered (m) to regular (m))</th>
<th>sparsity-promoting recovery with <strong>NFDCT</strong> [SNR (dB)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 source vessel</td>
<td>50 to 25</td>
<td>17.6</td>
</tr>
<tr>
<td>(2 airgun arrays)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 to 12.5</td>
<td>12.7</td>
</tr>
<tr>
<td>2 source vessels</td>
<td>50 to 25</td>
<td>21.5</td>
</tr>
<tr>
<td>(2 airgun arrays per vessel)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>50 to 12.5</td>
<td>16.8</td>
</tr>
</tbody>
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Observations

- *Time-jittered* marine acquisition is an instance of *compressed sensing*

- With *sparsity*-promoting recovery we can:
  - *deblend* – recover the wavefield, and
  - *regularize* from a *jittered/irregular* to a *regular* grid
  - *interpolate* from a *coarse jittered* (50m) grid to a *fine regular* grid (25m, 12.5m, and finer)
Acknowledgements

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Thank you!