Laboratory-scale monitoring of CO2 sequestration using complex electrical conductivity and seismic property changes derived from seismic interferometry

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The strategy to reduce greenhouse gas emission must combine:

1. Increased Energy Efficiency
2. More renewable energy production (incl. wind, solar, geothermal)
3. A wise implementation of Carbon Capture and Storage (CCS)

(Bellona Report, 2007)
Three storage options:

1. Deep unminable coal seams
2. Depleted oil and gas reservoirs
3. Deep saline aquifers
Reasons/Need for monitoring:
1. For process efficiency (for site development, track the migration)
2. For storage verification (containment: mass balance, saturation)
3. For safety (seal or cap rock integrity, leakage)
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Monitoring techniques:

1. Direct sampling methods (chemical sensors, monitoring in wells)
2. Remote sensing methods (spaceborne satellites, geophysical methods)
Geophysical methods for monitoring CCS:

- Seismic
- Electromagnetic
- Gravity
- Geodetic
Seismic methods have the broadest applicability!

Sleipner Field, North Sea
(Chadwick et al., 2009)

Frio Formation, Texas
(Daley et al., 2008)
Four major issues that remain unresolved are:

1. Inability to monitor CO2 phases
2. Difficulty to monitor quantitatively CO2 saturation
3. Removal of the effect of overburden in seismics
4. Minimize seismic source-related variations
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CCS monitoring: use of complex electrical measurements
We measure frequency-dependent impedance: amplitude $|Z|$ and phase $\phi$:

We estimate effective complex permittivity:

We get effective complex conductivity:

\[ \text{and} \quad \text{are related as:} \]
CCS monitoring: use of complex electrical measurements

The diagram shows a phase diagram with axes labeled 'Pressure [bar]' and 'Temperature [°C]'. The phase regions are color-coded and labeled as 'Liquid', 'Dense fluid', and 'Vapor'. The diagram includes arrows indicating the transition from one phase to another, with annotations '1' and '2'.
CCS monitoring: use of complex electrical measurements

a)  

b)
CCS monitoring: use of complex electrical measurements

Complex Impedance

Amplitude

Phase
CCS monitoring: use of complex electrical measurements

Equivalent circuit representation for CO2 and brine saturation: 

(Kavian et al., 2012)

To estimate the fitting parameters, minimize the residual $R$:

![Graphs showing frequency response of Zr and Zj](image-url)
CCS monitoring: use of complex electrical measurements

Graphs showing frequency response of impedance plots with various parameters.
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CCS monitoring: use of “ghost” arrivals in seismic interferometry

Wapenaar and Fokkema, 2006
However, in case of a lossy medium and/or one sided illumination, spurious events will appear → nonphysical or “ghost” events!
CCS monitoring: use of “ghost” arrivals in seismic interferometry

Model of Sleipner CCS Field, North Sea
CCS monitoring: use of “ghost” arrivals in seismic interferometry

Synthetic Model of Sleipner CCS Field, North Sea

SI Retrieval with Max 15 m Source Error

Base Survey

Monitor Survey
CCS monitoring: use of “ghost” arrivals in seismic interferometry

Synthetic Model of Sleipner CCS Field, North Sea

Brine-to-CO2 saturation ratio:
(using Gassmann’s equation)

Base: 0.98  Monitor: 0.80 →  Input Model
Base: 0.97  Monitor: 0.77 →  From SI Ghosts
CCS monitoring: use of “ghost” arrivals in seismic interferometry

Diagram showing the setup of seismic interferometry with labels for first and second series, distances in millimeters, and positions of receivers and sources.
- Aim: to monitor velocity changes in a reservoir during displacement of brine by ethanol

- Using retrieved ghost reflections

- (In practice the events can be identified using a vertical well or the difference in expected arrival times of reflections from the cap rock and the reservoir)
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CCS monitoring: use of “ghost” arrivals in seismic interferometry

Recorded arrivals and their interpretation

- Arr1 – P-wave reflection from bottom of epoxy
- Arr2 – converted-wave reflection
- Arr3 – free-surface multiple of Arr1
- Arr4 – S-wave reflection from bottom of epoxy
- Arr5 – P-wave reflection from bottom of sandstone
CCS monitoring: use of “ghost” arrivals in seismic interferometry

Results from SI by CC

![Graph showing normalized amplitude vs. two-way travel time for different ethanol concentrations (100% brine, 1/3 ethanol, 2/3 ethanol, and 3/3 ethanol). Arrows indicate changes in amplitude.]
CCS monitoring: use of “ghost” arrivals in seismic interferometry
CCS monitoring: use of “ghost” arrivals in seismic interferometry

Results from transmission measurements

Normalized amplitude

Two-way travel time (ms)

100 % brine
1/3 ethanol
2/3 ethanol
3/3 ethanol
<table>
<thead>
<tr>
<th>Method</th>
<th>100 % brine: velocity (m/s)</th>
<th>1/3 ethanol injected: velocity (m/s)</th>
<th>2/3 ethanol injected: velocity (m/s)</th>
<th>3/3 ethanol injected: velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghost reflection</td>
<td>2544</td>
<td>2558</td>
<td>2611</td>
<td>2616</td>
</tr>
<tr>
<td>Transmission</td>
<td>2520</td>
<td>2607</td>
<td>2594</td>
<td>2596</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>0.95</td>
<td>1.88</td>
<td>0.66</td>
<td>0.77</td>
</tr>
</tbody>
</table>

CCS monitoring: use of “ghost” arrivals in seismic interferometry
CCS monitoring using ghosts in SI

- Layer-specific changes in velocity monitored using ghost reflections retrieved from SI by cross-correlation of reflection measurements
- The effect of overburden and source positioning error minimized
- Good saturation estimates
Conclusions

CCS monitoring using complex electrical measurements

- Real part of complex permittivity is clearly sensitive to CO$_2$ phase changes
- Both the amplitude and phase of the phase of complex impedance shows significant sensitivity to CO$_2$/brine saturation $\rightarrow$ inversion
- Ongoing work: upscaling the results to field

CCS monitoring using ghosts in seismic interferometry

- Layer-specific changes in velocity can be monitored using ghost reflections retrieved from SI by CC between reflection measurements
- The effect of overburden and source positioning error can be minimized
- Saturation estimates are quite accurate
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