FULL-WAVEFORM INVERSION FOR CO2 QUANTIFICATION – APPLICATION TO REAL DATA AT SLEIPNER

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Outline

- Principle of Full-waveform inversion (FWI)
- Full-waveform inversion for CO$_2$ imaging
- Synthetic example at the Sleipner field
- Results using Sleipner real data (2006 and 2008 datasets)
  - Pre-processing
  - Initial velocity model
  - Results
- Conclusions
Principle of Full-Waveform Inversion

- Introduced in the 1980s (A. Tarantola, 1984)
- Exploits the complete information in the waveforms of seismograms
- Finds the “best” model that minimises the misfit between the observed and the computed seismic data (amplitude and phase)

Formulation in
- Time Domain (Tarantola, 84)
- Frequency Domain (Pratt et al., 90)
- Laplace domain (Shin, 2008)
Principle of Full-Waveform Inversion

Full-waveform iteration loop

Initial velocity model \( m_0 \)

**Step 1:** Full-waveform modelling by Finite differences in the initial model

**Step 2:** Residuals \( \delta d \) = difference between observed and computed data

**Step 3:** Perturbation model that minimizes \( \delta d \)

**Step 4:** Compute step \( \alpha \) and new model \( m = m_0 + \delta m \)
Application to the Sleipner field

- CO₂ monitoring at Sleipner
  - CO₂ injection in a saline reservoir at Sleipner (North Sea) since 1996
  - 3D seismic monitoring to follow the CO₂ plume migration
  - CO₂ appears as clear reflectors on post-injection seismic
  - CO₂ accumulations under intra shales layers within the Utsira sand

- Challenges:
  - CO₂ accumulations within extremely thin layers (~10 meters)
  - Low velocity inversions (1300 m/s)
  - Inter-bed and surface multiples
  - Limited range of offsets

- Apply FWI to better characterise thickness and Vp velocity at Sleipner
  - Synthetic test
  - 2006 real dataset
  - 2008 real dataset
Synthetic example on the Sleipner field

- Synthetic 2D velocity model from TNO
- Model 3.3 km x 1.2 km
- Regular square grid of 3 m
- CO₂ layers of 10-20 m thick
- CO₂ layers with velocities of 1500 m/s
Synthetic example on the Sleipner field

- Ocean Bottom acquisition
- 3.2 km acquisition
- Smoothed initial model

- 10 Hz initial frequency
- 15 frequencies every 5 Hz component
- Maximum frequency of 80 Hz
Conclusions form the synthetic tests

- Well constrained Vp velocity model
- Reconstructed low velocity layers (16 to 20 m thickness)
- Good estimation of the velocity in the CO₂ accumulations down to 0.9 km depth
- Layers with thickness about 9 meters requires sources with a high frequency content
- Application to real data should give interesting results if they are not too noisy
Application to real data

- 2006 and 2008 datasets
- Extracted a 2D line from both 3D datasets
- Post-swell processed data
- Maximum offset of 1.8 km
- Frequency content of the data is from 6 Hz to 80 Hz
- CO$_2$ accumulations are visible on the near offset section
Specific pre-processing

- Removed $t^2$ gain
- Mute before first-arrivals
- Data with offset larger than 420 m
- Time shift to get causal signal
- 3D to 2D conversion
- Multiples still in the data

Same pre-processing for 2006 and 2008 datasets
Initial velocity model

- Stacking velocities converted into interval velocities in depth
- Velocity model is 6 km long
- Model defined on a regular 3m squared grid
- Validity checked by finite difference modelling
Full-waveform inversion of the real Sleipner data

- Invert for 6 frequencies between 10 and 20 Hz
- Inversion is performed frequency by frequency: from low to high frequencies to reduce the non-linearity of the inverse problem
- 10 iterations per frequency
- Invert for the source wavelet
- Released the smoothing constraints during inversion
Velocity models derived from FWI (2006 dataset)
Extraction of 1D velocity profiles (2006 dataset)
Velocity models derived from FWI (2008 dataset)
Extraction of 1D velocity profiles (2008 dataset)
Velocity models derived from FWI

2006 dataset
Results of FWI

- Improved image of the velocity in the CO₂ plume
- 2-3 layers with velocities of about 1480 m/s and thickness of about 40-60 m
- Better data explanation (frequency and time)
- Same pre-processing for 2006 and 2008 datasets
- Inversion is converging toward possible solutions in both cases
Conclusions

- FWI is a promising method to better characterise thickness and Vp velocity at Sleipner

- Synthetic case:
  - Capability of the method
  - Imaging of thin CO2 layers can be performed using
    - Reasonable initial frequency (10Hz)
    - Good initial model
    - Classic acquisition geometry

- Results on real data (2006 and 2008 datasets):
  - Improved low frequency velocity image within CO2 plume
  - Consistent models with 2006 and 2008 datasets
  - Velocity changes of CO2 layers

- Future work:
  - Higher frequency inversion (> 20 Hz)
  - Initial velocity model
  - Pre-processing of the data
  - Effects on the migrated image (using RTM)
  - 3D inversion
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Synthetic example on the Sleipner field

- Better results with 3.2 km offset
- Model derived with 1.8 km offset is still well constrained
- With less offset range more frequency components need to be inverted
Data fit in the initial velocity model

- First-arrivals for the first offset in phase but not amplitude
- First-arrivals at larger offsets
- Does not explain reflections associated with CO₂ plume
- Model is correct but probably not optimal
Data fit in the time domain
Comparison with migrated image in initial model
Velocity models derived from FWI

2008 dataset

2006 dataset