Technology for a better society

Optimal CSEM survey design for CO_2 monitoring at Smeaheia offshore Norway

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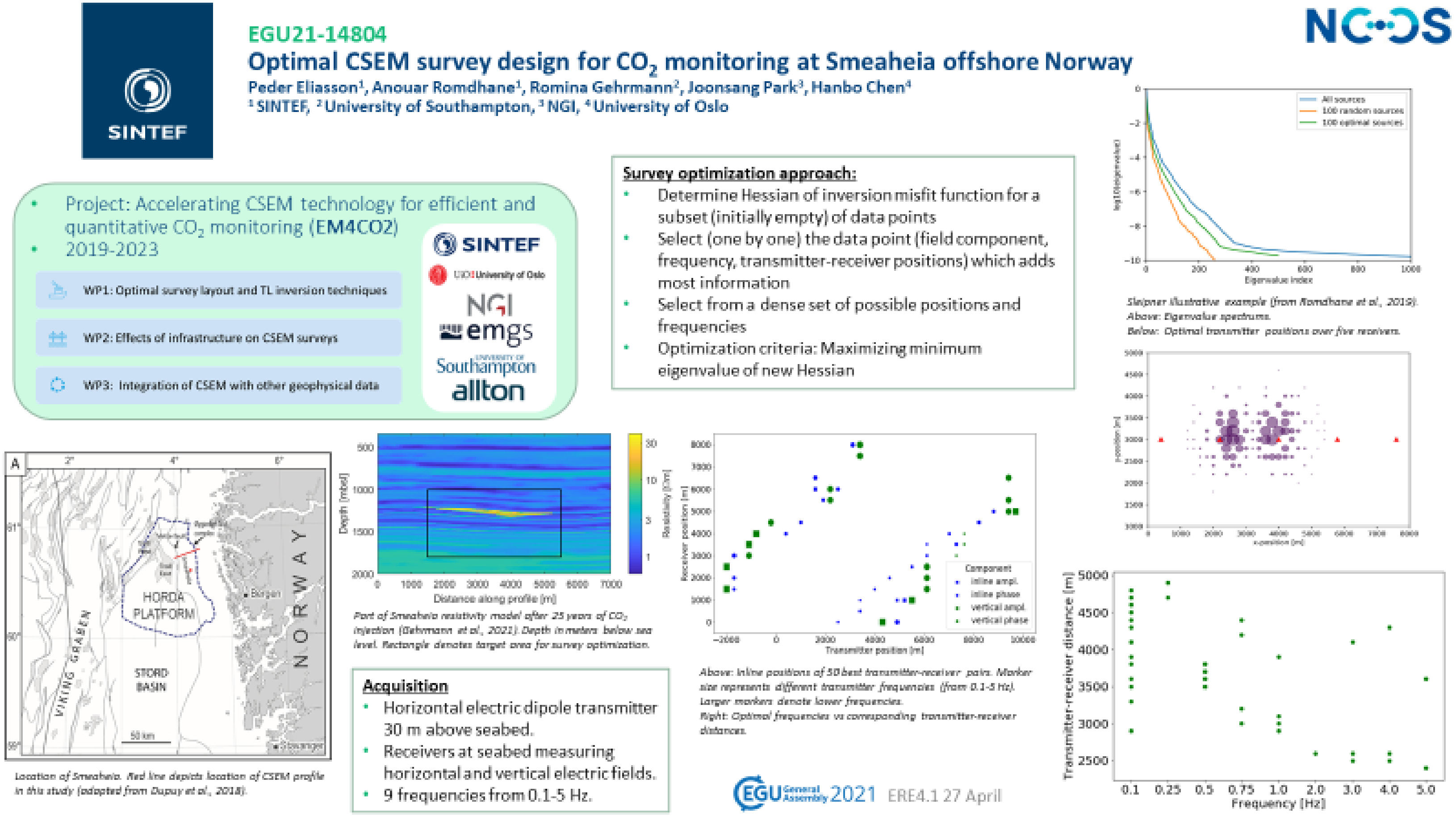

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- Project: Accelerating CSEM technology for efficient and quantitative CO_2 monitoring (EM4CO2)
- 2019-2023

WP1: Optimal survey layout and TL inversion techniques

WP2: Effects of infrastructure on CSEM surveys

WP3: Integration of CSEM with other geophysical data

Survey optimization approach:
- Determine Hessian of inversion misfit function for a subset (initially empty) of data points
- Select (one by one) the data point (field component, frequency, transmitter-receiver positions) which adds most information
- Select from a dense set of possible positions and frequencies
- Optimization criteria: Maximizing minimum eigenvalue of new Hessian

Sleipner illustrative example (from Romdhane et al., 2019).
Above: Eigenvalue spectrums.
Below: Optimal transmitter positions over five receivers.

Location of Smeaheia. Red line depicts location of CSEM profile in this study (adapted from Dupuy et al., 2018).

Part of Smeaheia resistivity model after 25 years of CO_2 injection (Gehrmann et al., 2021). Depth in meters below sea level. Rectangle denotes target area for survey optimization.

Acquisition
- Horizontal electric dipole transmitter 30 m above seabed.
- Receivers at seabed measuring horizontal and vertical electric fields.
- 9 frequencies from 0.1-5 Hz.

Above: Inline positions of 50 best transmitter-receiver pairs. Marker size represents different transmitter frequencies (from 0.1-5 Hz). Larger markers denote lower frequencies.
Right: Optimal frequencies vs corresponding transmitter-receiver distances.

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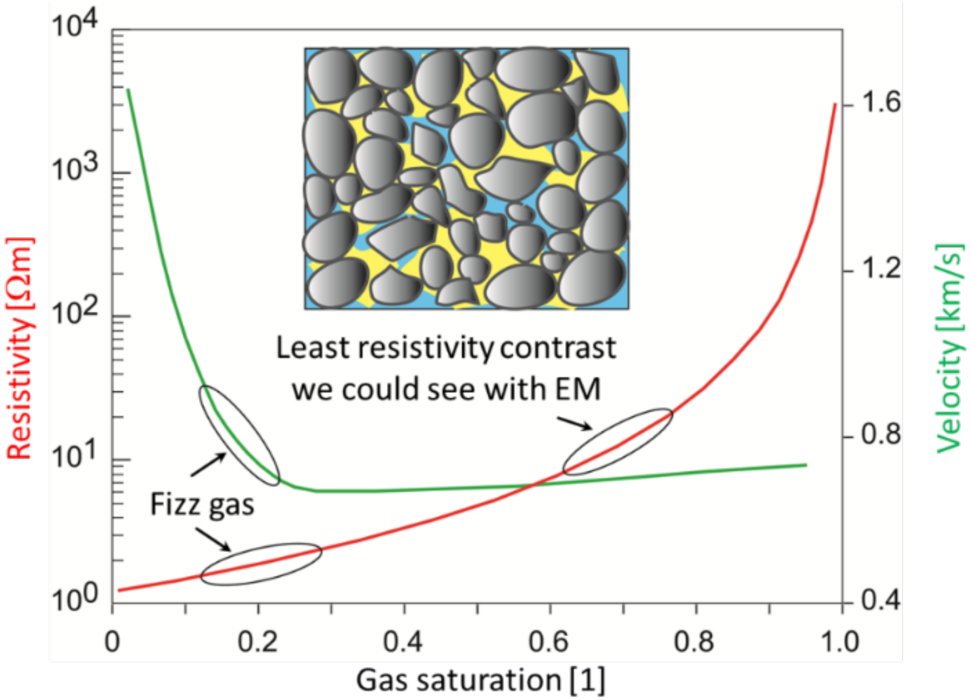
Project facts

- **EM4CO2**: Accelerating CSEM technology for efficient and quantitative CO_2 monitoring
- CLIMIT KPN (competence building project)
- Research Partners: SINTEF (coordinator), NGI, EMGS, Allton, U. Oslo, U. Southampton
- Spin-off from NCCS
- Budget: 9.2 MNOK
- Duration: 2019 - 2023

Background

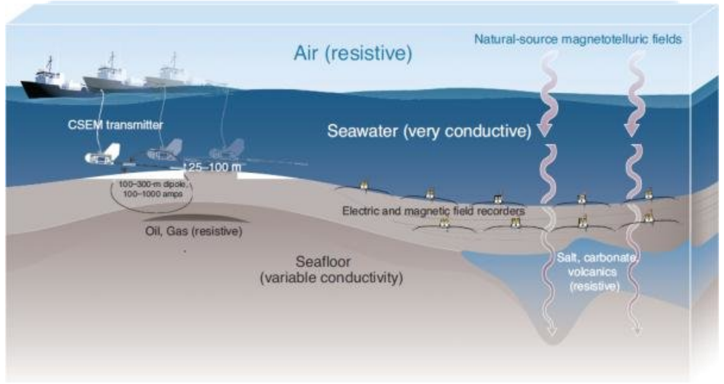
- ✓ To enable large-scale CO_2 storage, more **accurate** and **cost-efficient** monitoring methods are required
- $ Seismic is useful, seismic is expensive!
- Controlled Source Electro-Magnetics (CSEM) may be very good complement to seismic
- Potential to reduce both uncertainties and monitoring costs



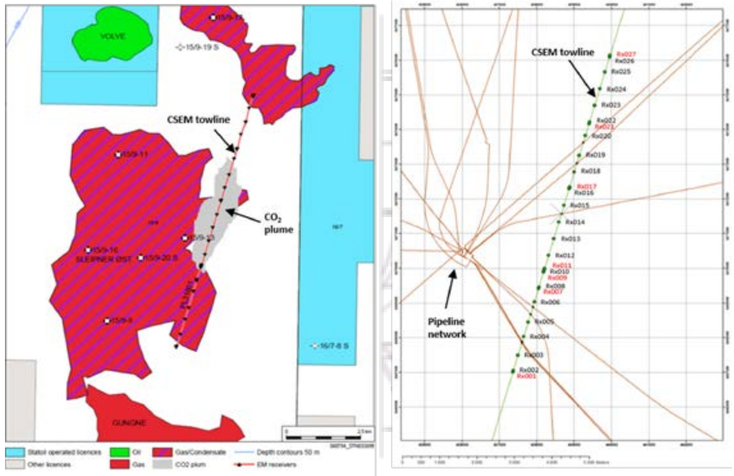
Modified from Constable (2010)

Project structure

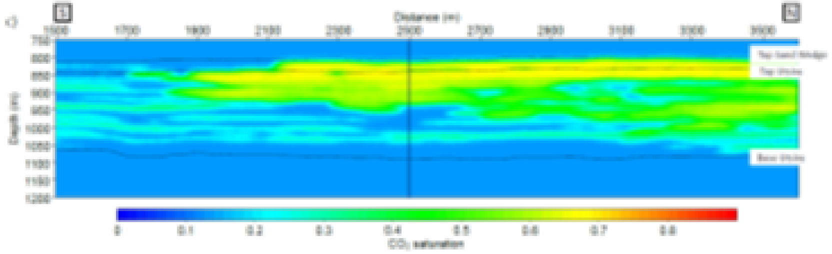
WP1: Optimal survey layout and time-lapse inversion techniques



WP2: Effects of infrastructure (well casing and pipelines)



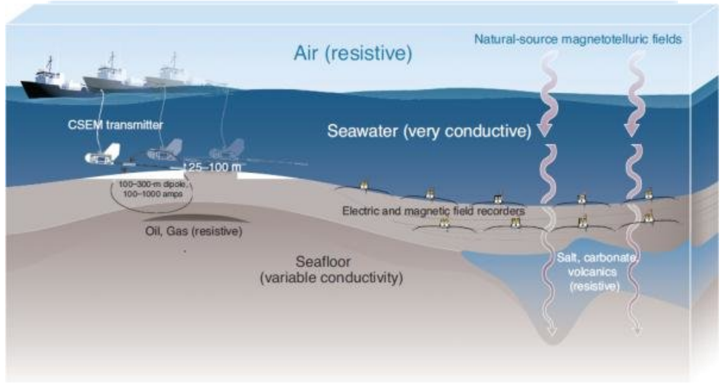
WP3: Integration of CSEM with other geophysical data



Figures from Constable (2010), Bøe et al. (2017), Subagjo et al. (2018)

Optimal survey layout

WP1: Optimal survey layout and time-lapse inversion techniques



- EM resolution is inherently lower than seismic
- EM technology for CO_2 monitoring not sufficiently explored
- Most research efforts related to improved inversion techniques, much less attention is given to survey design strategies
- Conceptually, survey design aims at selecting the data acquisition that optimally resolve the subsurface model parameters of interest with as little uncertainty as possible → can also impact the acquisition cost

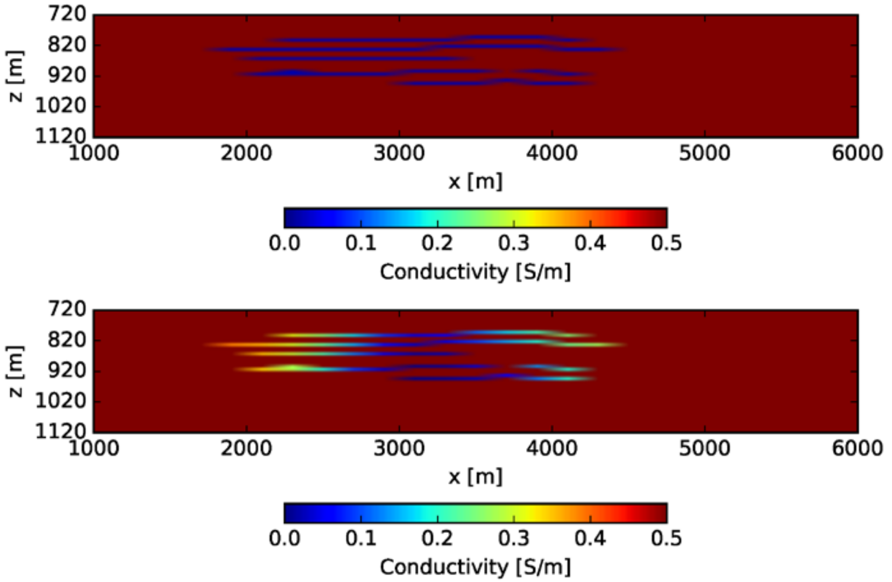
Methodology
(Optimal) acquisition design

- We quantify the goodness of a given acquisition layout through the computation of the eigenvalue spectrum of the approximate Hessian on a defined target region:

  $$\boldsymbol{H_a} = \mathrm{Re}\{\mathbf{J}^{\dagger}\mathbf{J}\}$$

  - Randomised SVD can be used for an efficient computation of the spectrum
- The target can be derived from reservoir modelling and would correspond to the spatial evolution of the plume within the storage reservoir
- Spectra corresponding to selected subsets of traces (or shots) can be analysed and compared to the reference spectrum (Maurer et al., 2010)
- General sensitivity in the dipole emitter/receiver domain can be derived.

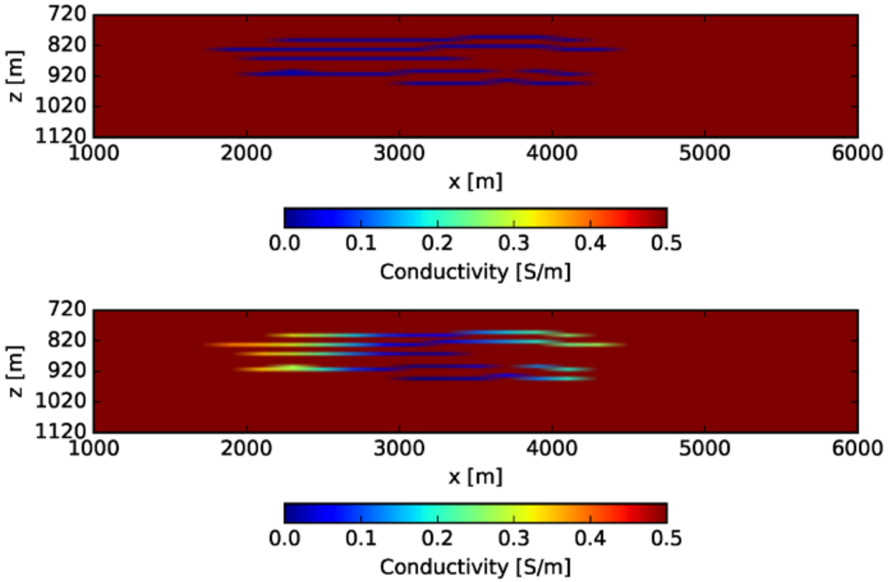
Optimal survey layout - Sleipner example



Target sections from the true conductivity model and model derived from CSEM constrained inversion assuming a homogeneous background (Romdhane and Eliasson, 2019).

- Test carried out using a synthetic 2.5D conductivity model meant to resemble the layered CO_2 plume geometry at the Sleipner field.
- CSEM inversion using a homogeneous (half-space) initial model with strong structural constraints, allowing only model updates in selected zones expected to contain CO_2.
- 39x29 sources (in x,y) 20m above sea bottom, 5 receivers on sea floor

Optimal survey layout - Sleipner example



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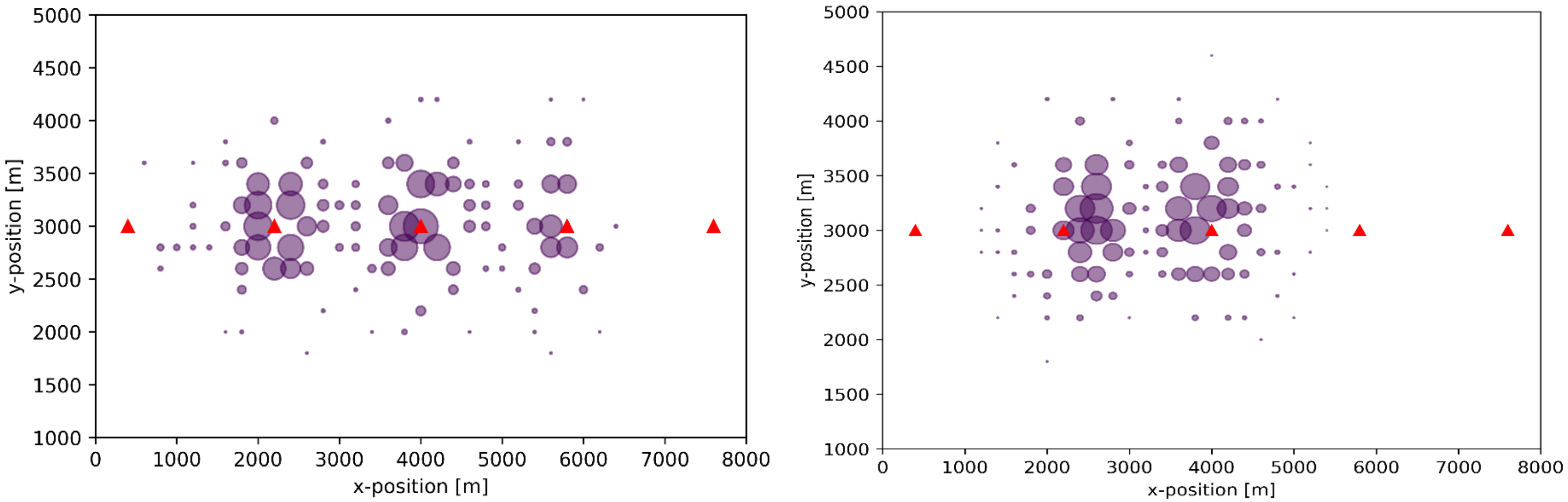
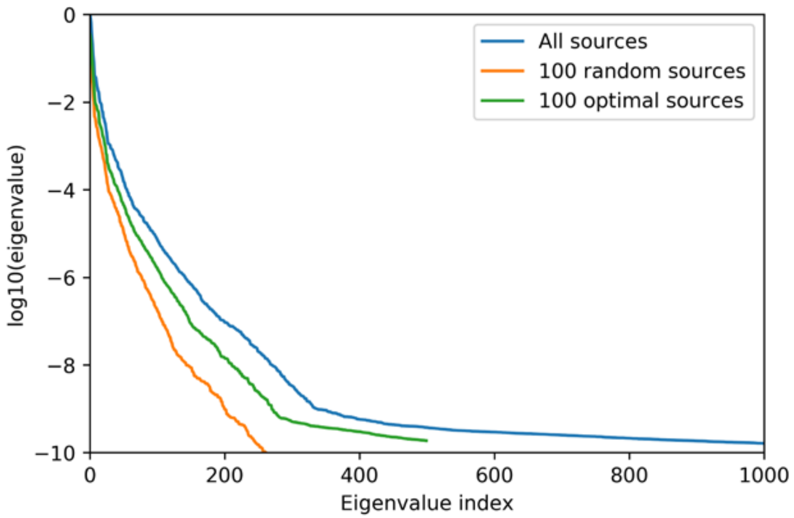
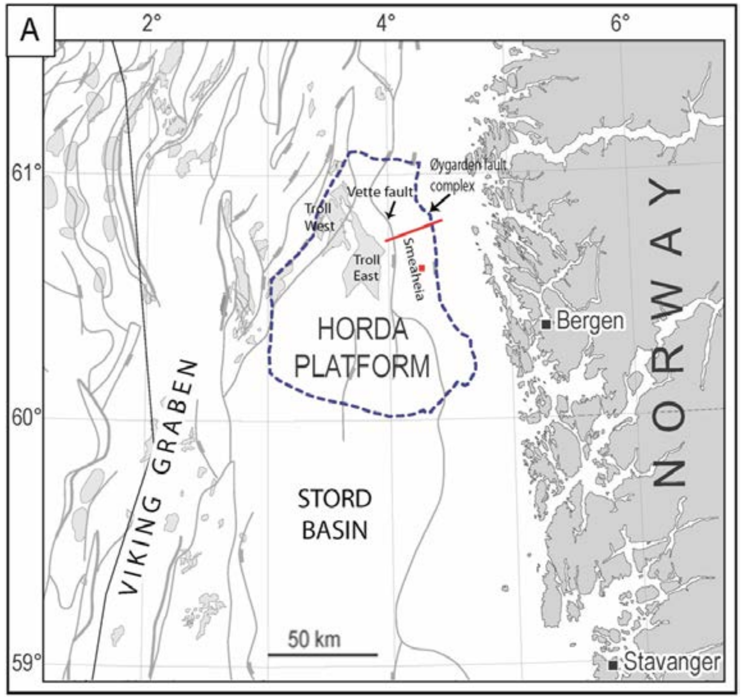


Circles representing lateral position and sensitivity (area) of optimal sources. (left): analysis with a homogenous background model, (right): analysis using CSEM inversion result. Each source is used together with all five receivers. The red triangles show the lateral position of those receivers (Romdhane and Eliasson, 2019)



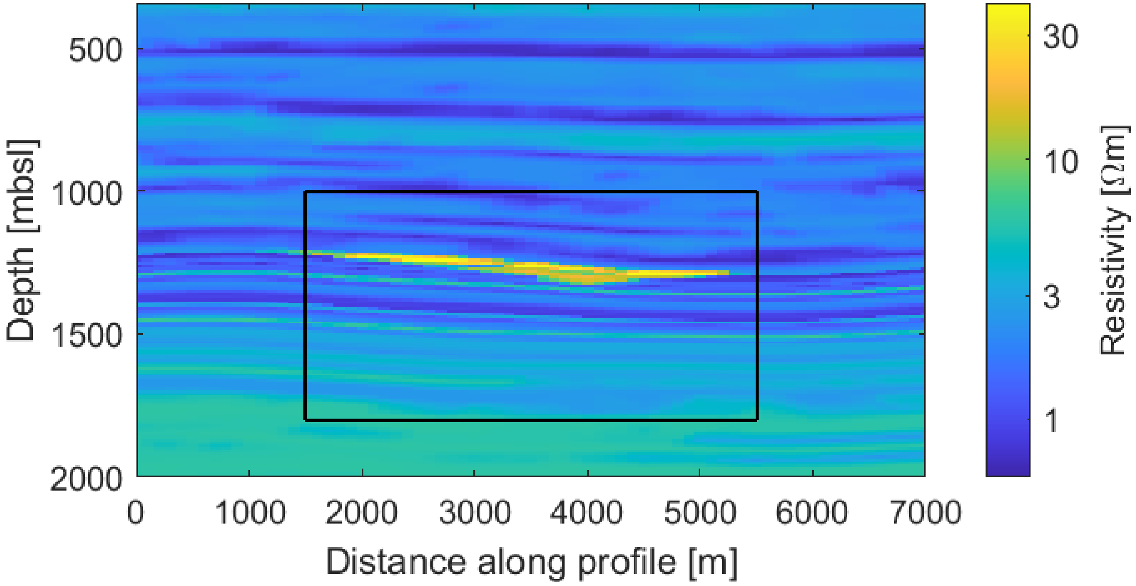
Sleipner illustrative example (Romdhane and Eliasson, 2019). Eigenvalue spectrums.

Optimal survey layout - Smeaheia example



Location of Smeaheia. Red line depicts location of CSEM profile in this study (adapted from Dupuy et al., 2018).

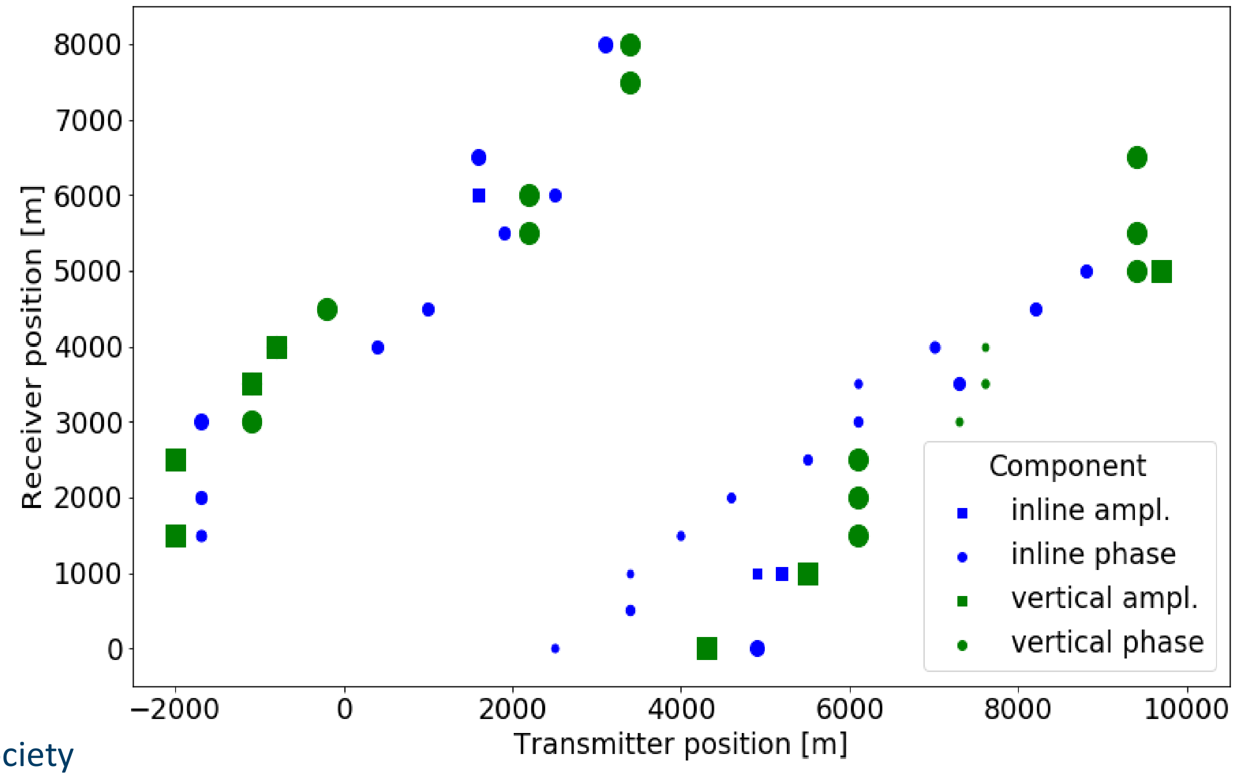
- Optimization of Smeaheia CSEM survey layout subject to following constraint:
  - Horizontal electric dipole transmitter 30 m above seabed.
  - Receivers at seabed measuring horizontal and vertical electric fields.
  - 9 frequencies from 0.1-5 Hz.



Part of Smeaheia resistivity model after 25 years of CO_2 injection (Gehrmann et al., 2021). Depth in meters below sea level. Rectangle denotes target area for survey optimization.

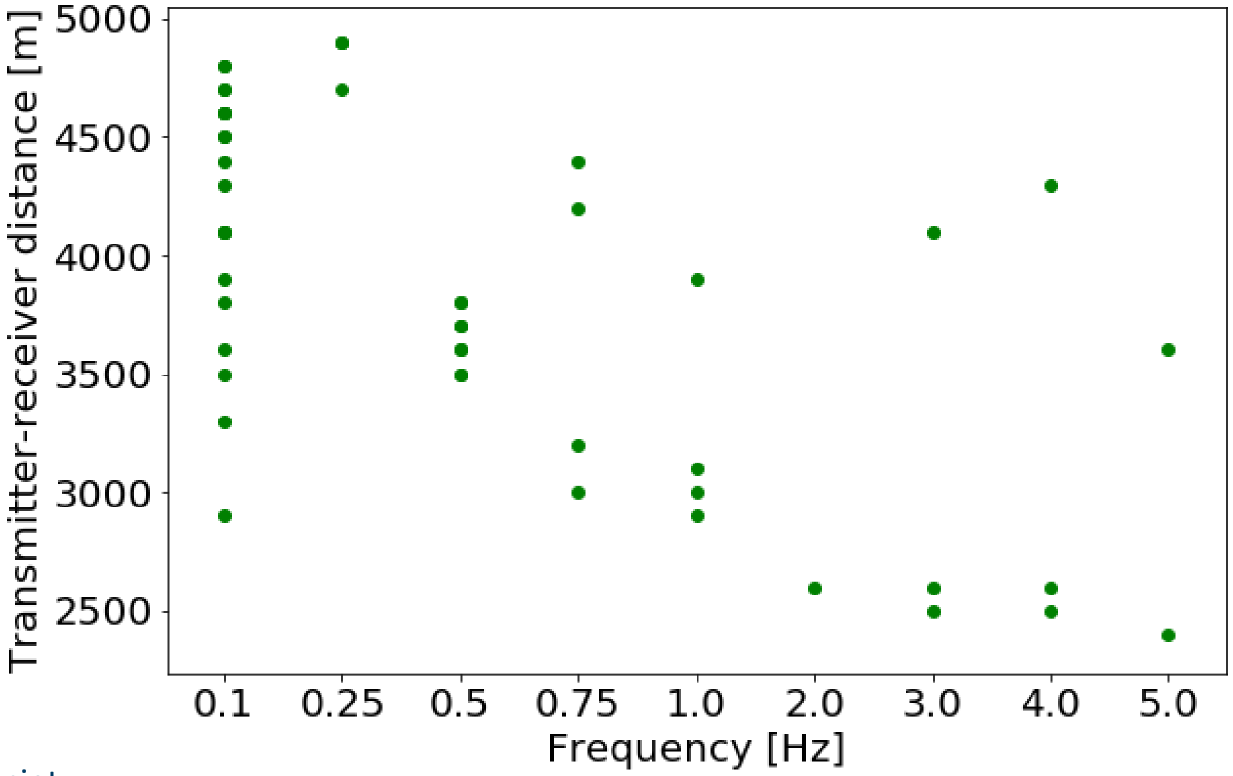
Optimal survey layout - Smeaheia example

- Inline positions of 50 best transmitter-receiver pairs. Marker size represents different transmitter frequencies (from 0.1-5 Hz). Larger markers denote lower frequencies.



Optimal survey layout
- Smeaheia example

- Optimal frequencies vs corresponding transmitter-receiver distances.



Observations and conclusions

- Optimal survey design shows that highest sensitivity to the storage target region is achieved for transmitter-receiver offsets between 2500 and 5000 m
- Phase data contains more information than amplitude data, emphasizing the requirement for accurate time logging during surveying
- Lower frequencies (in the 0.1 – 5 Hz range) are preferred, especially for long offsets

- Sophisticated optimal survey design important for reliable and cost-efficient monitoring
- Further studies required to verify inversion results for optimized surveys
- Survey cost vs information value to be balanced using a VOI framework

Acknowledgements

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