Controlled-source electromagnetic survey design for geothermal applications

EasyGO Training: EM Modelling

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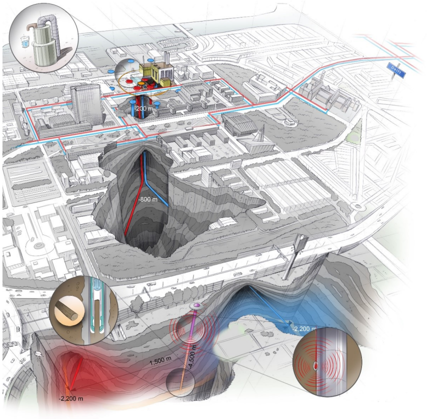

TU Delft

Course info

https://github.com/emsig/easygo-training-em

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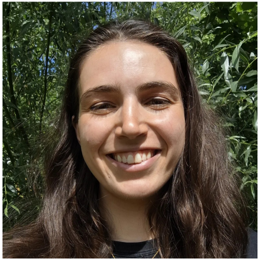

Learning Objectives

What would you like to learn?

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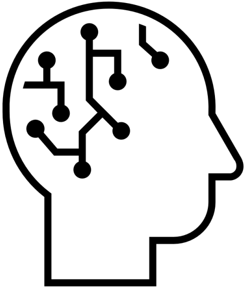
- **Relate** the electromagnetic geophysical method to the field setup and aim of investigation for geothermal monitoring
- **Use** *empymod* and *emg3d* to model electromagnetic data
- **Design** a field plan using controlled-source electromagnetics to monitor a near-surface geothermal project



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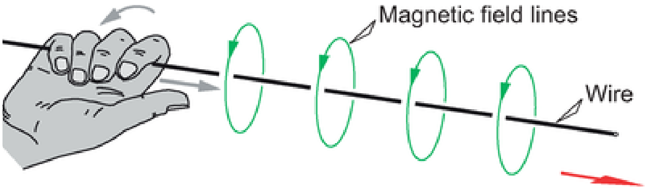
Electromagnetism (EM)



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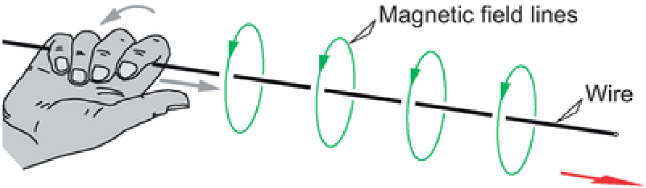
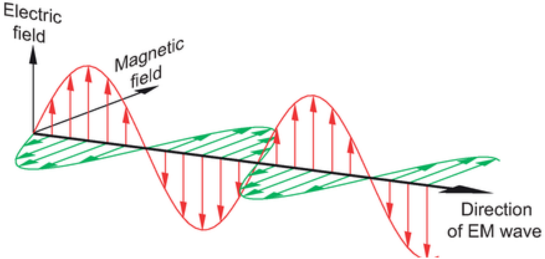
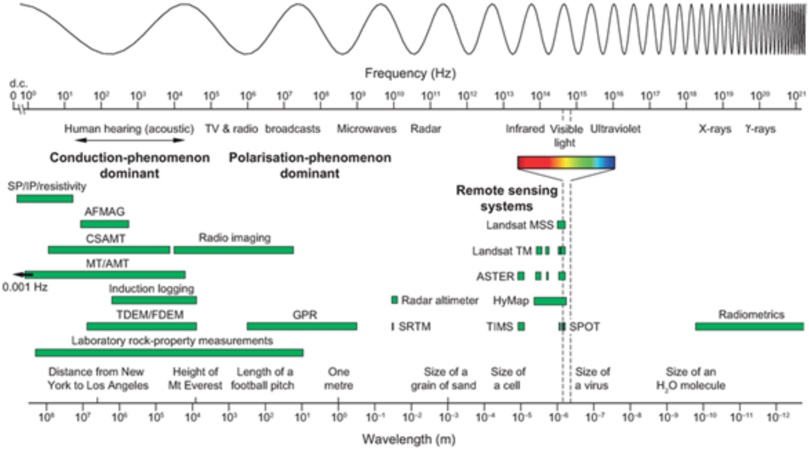




[1] Dentith, M., & Mudge, S. T. (2014)

EM Geophysics



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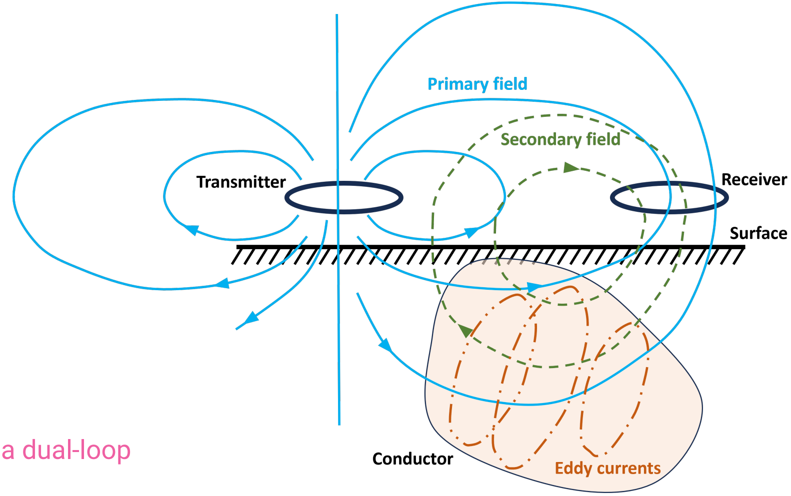
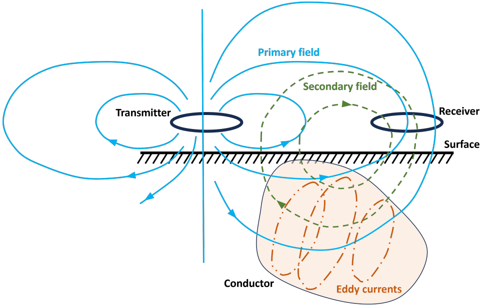
EM Geophysics



Play with a dual-loop

EM Geophysics



Play with a dual-loop

Maxwell's equations with a time dependency of $e^{i\omega t}$ in frequency-domain:

$$\nabla \times E = -i\omega\mu H \quad \text{(Faraday's law)}$$

$$\nabla \times H = \left(\frac{1}{\rho} + i\omega\varepsilon\right)E + J_p \quad \text{(Ampère's law)}$$

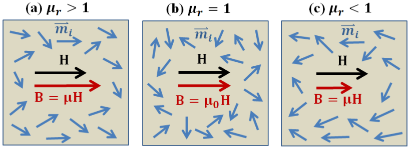
$$\nabla \cdot (\varepsilon E) = q \quad \text{(Gauss' law)}$$

$$\nabla \cdot \mu H = 0,$$

ω: angular frequency [rad/s]
E: electric field [V/m]
H: magnetic field [A/m]
J_p: impressed current density of the source
q: volume electric charge density [C/m^3]
i: imaginary unit

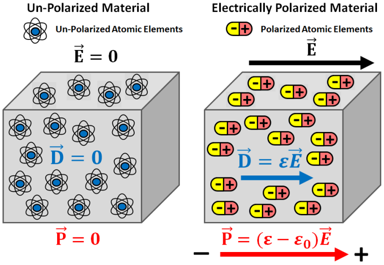
Physical properties

Magnetic permeability μ



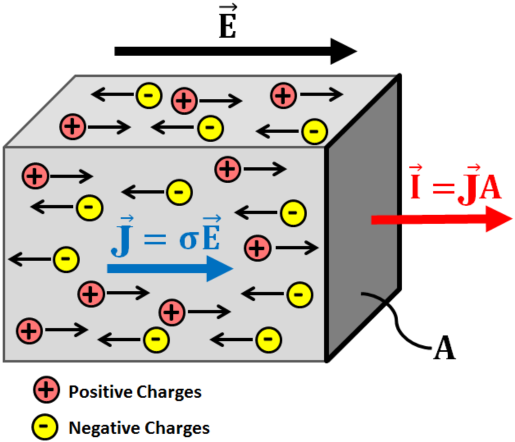
Characterises the degree of induced magnetism a material experiences under the influence of an external magnetic field.

Dielectric permittivity ϵ



Defines how strongly a material becomes electrically polarised under the influence of an electric field.

Electrical resistivity ρ



Source: https://em.geosci.xyz

ρ [Ωm]

- Quantifies how easily electrical charges move through a given material when subjected to an applied electric field.
- Is the inverse of conductivity σ.
- Determines - in combination with the source current frequency and measurement geometry - the depth of investigation.
- ρ of a subsurface material depends on its mineralogy and pore-water properties.

Controlled-source Electromagnetics (CSEM)

Investigating the electric and magnetic properties of the Earth by measuring electric and magnetic fields generated by a transmitter and the conductive subsurface.

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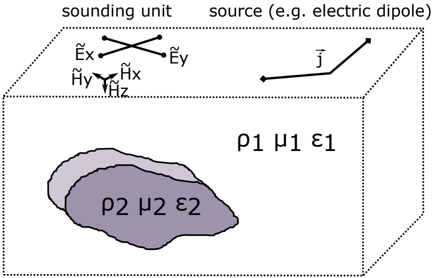

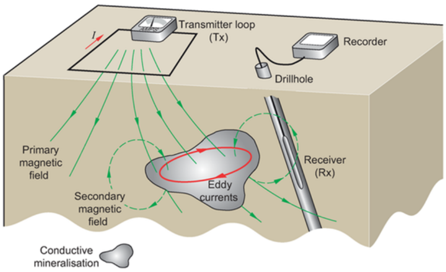

$\tilde{E}$: electric field component
$\tilde{H}$: magnetic field component

Modelling

Total-field formulation for the electric field E in frequency domain with time dependence $e^{i\omega t}$:

$$\nabla \times \frac{1}{\mu} \nabla \times E + i\omega \frac{1}{\rho} E - \omega^2 \epsilon E = -i\omega J_p \quad \text{in} \quad \Omega,$$

$$\hat{n} \times E = 0 \quad \text{on} \quad \partial\Omega$$

$\mathbf{J}_p$: source ($\approx 10^{-1} - 10^{4}$ Hz)

ω: angular frequency
ρ: electrical resistivity
ε: dielectric permittivity
μ: magnetic permeability

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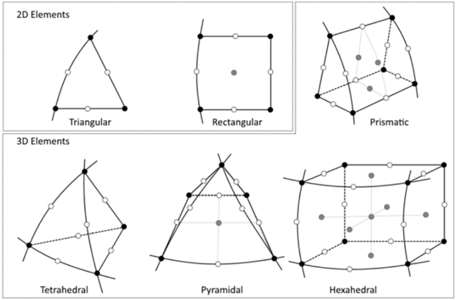
Discretisation



https://www.comsol.com

Modelling

Layered-Earth modelling with empymod using empymod.ipynb

Aquifer Thermal Energy Storage (ATES) in Delft

To account for seasonal supply and demand fluctuations, seasonal shallow heat storage will be connected to continuous deep geothermal exploration.

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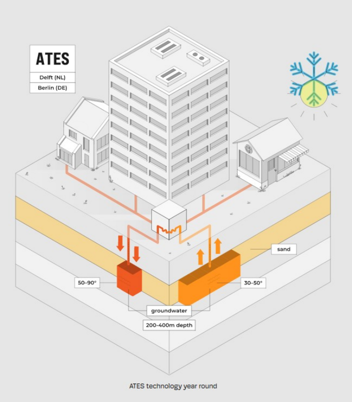
To account for seasonal supply and demand fluctuations, seasonal shallow heat storage will be connected to continuous deep geothermal exploration.

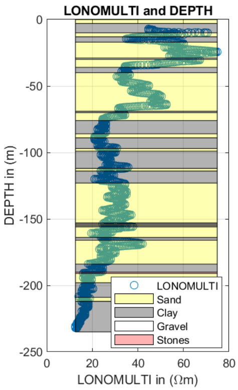
- Store heat surplus in summer and supply this heat in winter, thereby reducing the need for fossil fuel energy to meet peak heat demand
- Monitoring changes in subsurface temperatures due to heat injection and extraction operations

PUSH IT

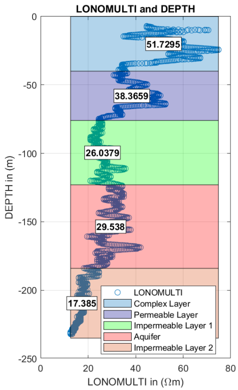


https://www.push-it-thermalstorage.eu/technologies/#ates

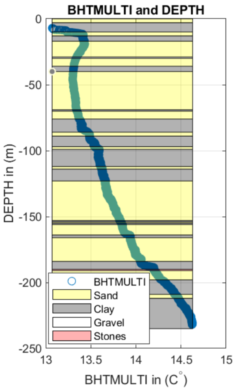
ATES site: Subsurface Structure



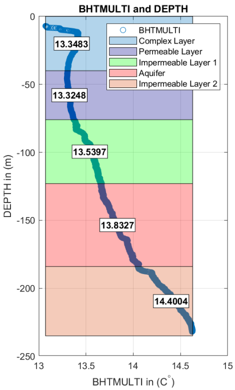
Stratigraphy with long-normal resistivity log [3]



Averaged resistivities [3]

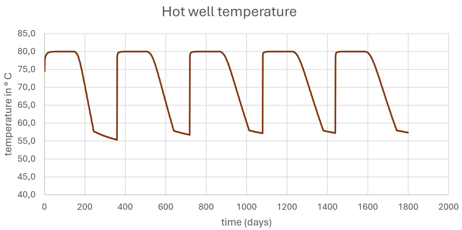


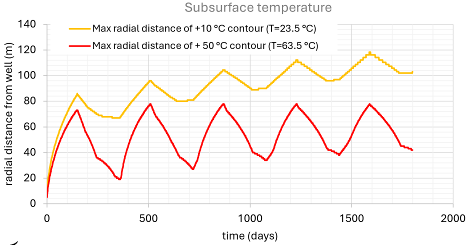
Stratigraphy with temperature log [3]

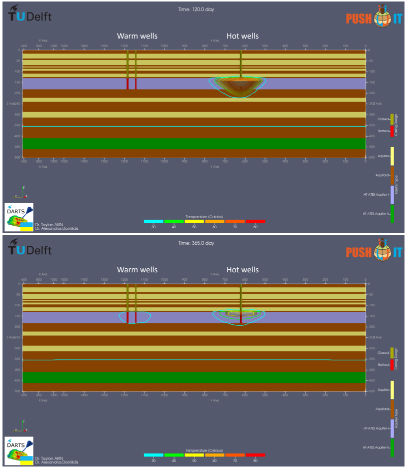


Averaged temperatures [3]

ATES site: Heat Propagation Simulations







after 120 & 365 days, simulated with *openDARTS* [4]

Source: Pers. Comm. Stijn Beernink

Geothermal Characterisation and Monitoring with CSEM

Base line: Characterising geoelectric structure before operations.
Monitoring: Aquifer temperature variations result in resistivity changes during operations.

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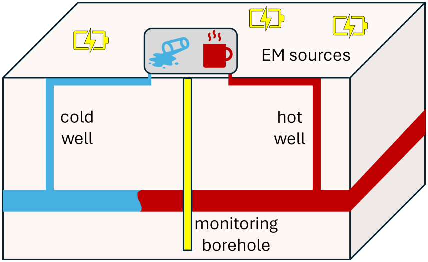
Base line: Characterising geoelectric structure before operations.
Monitoring: Aquifer temperature variations result in resistivity changes during operations.

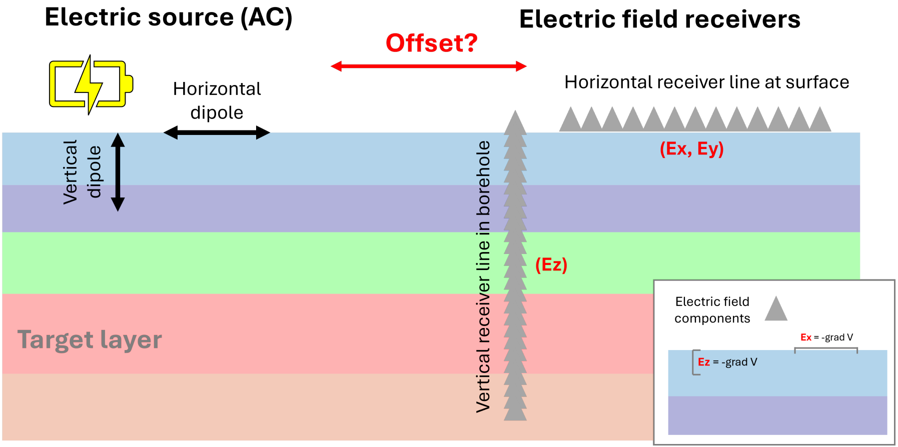
Monitoring aquifer temperature variations ΔT through resistivity changes $\Delta\rho$ [2] as

$$\rho(T_{hot}) = \rho(T_{cold})\,[1 + 0.025(T_{hot} - T_{cold})]^{-1}.$$



For example, ΔT from 14°C to 75°C results in $\Delta\rho$ from 29.5 Ωm to 11.7 Ωm.

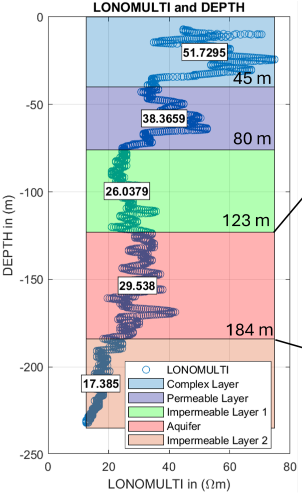
Survey configurations and field components

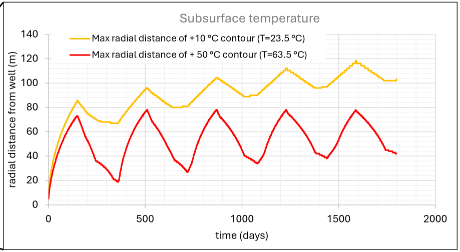


Magnetic field components could be measured with receiver coils.

Modelling

Design a CSEM survey for monitoring the ATES site using empymod_ATES.ipynb



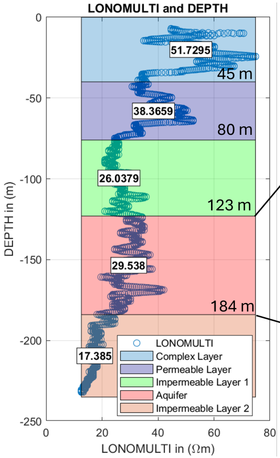


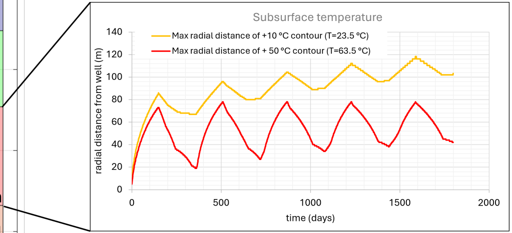
3D Modelling

3D modelling with *emg3d* using emg3d.ipynb.

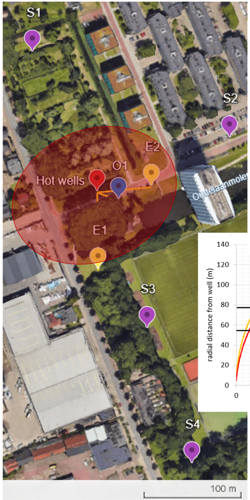
3D Modelling

Improve your CSEM survey design for monitoring the ATES site using emg3d_ATES.ipynb and including different hot plume sizes.





ATES 3D EM Simulations

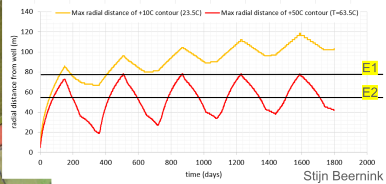


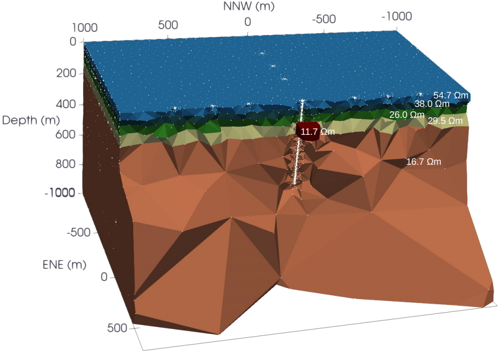
Potential EM borehole locations: E1 & E2

Potential EM source locations 10 m HEDs (150 m or 300 m distant from hot wells)

Hot wells: center steel-cased injection wells

O1: Observation borehole

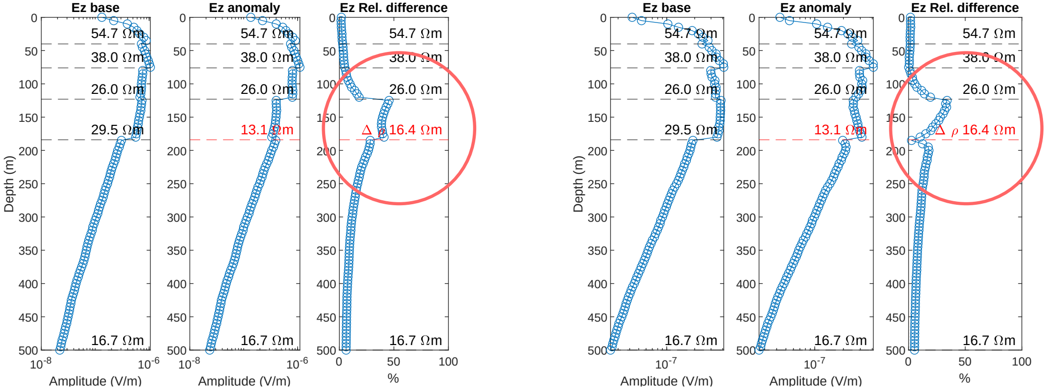




3D finite-element model: averaged layer resistivities, oval conductive heat-plume, sensor locations and radially distributed electric dipole sources

ATES 3D EM Simulations

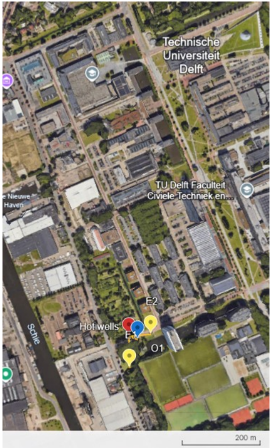
Densely (5 m) sampled E_z field components along borehole simulated with elfe3D [5].
Electric dipole source at the surface. Aquifer at 123 - 184 m depth.



Source: 150 m North, borehole location E2

Source: 150 m North, borehole location E1

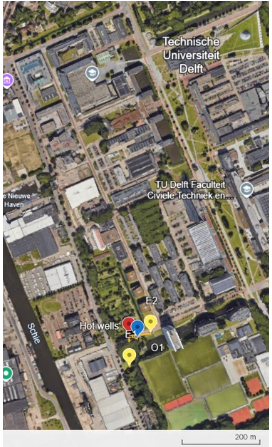
ATES 3D EM Simulations: Infrastructure



ATES location on TU Delft campus

Infrastructure, particularly power lines and metallic objects, represents a significant source of "cultural noise" in electromagnetic geophysics, interfering with the measurement of subsurface electrical properties.

ATES 3D EM Simulations: Infrastructure



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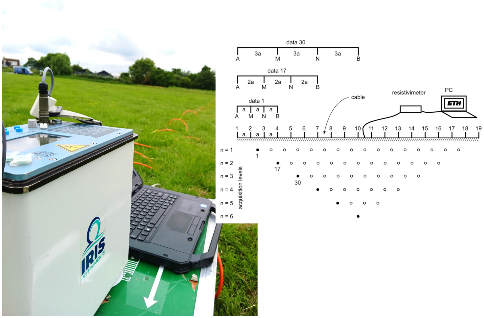
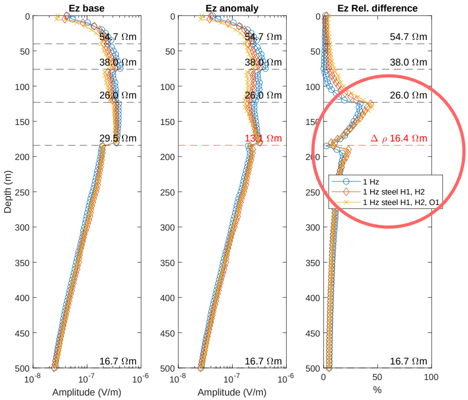
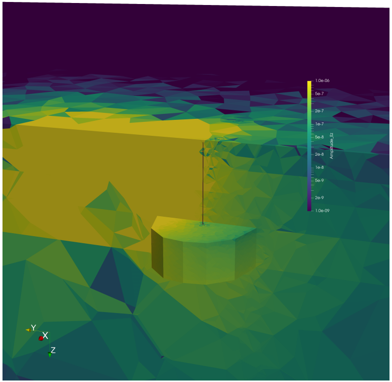


ATES 3D EM Simulations: Steel casings

Densely (5 m) sampled E_z field components along borehole simulated with elfe3D [5]. Electric dipole source at the surface. Aquifer at 123 - 184 m depth, 73 m thermal radius.

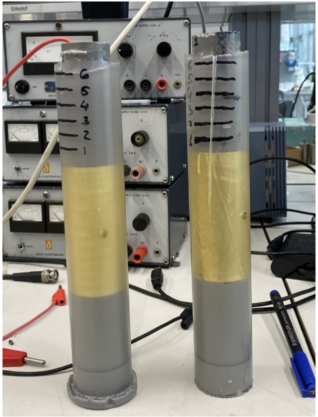


Source: 150 m North, borehole location E1



Ez field amplitudes in the domain

Borehole Electrodes



Lab-test to develop zero-resistance ammeter with Integrator.

Casings with capacitive electrodes.

Capacitively coupled copper electrodes and non-corrosive casings [6]

- Combination makes long-term downhole monitoring possible.
- Crucial to minimise the capacitive effect of the cables to make SNR levels of galvanic and capacitive electrodes comparable.

Q&A

Questions & Feedback

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References

1 Dentith, M., & Mudge, S. T. (2014). Geophysics for the Mineral Exploration Geoscientist. Cambridge: Cambridge University Press.

2 Keller, G. V., & Frischknecht, F. C. (1966). Electrical Methods in Geophysical Prospecting. Oxford: Pergamon Press Inc.

3 Bortolotti, M. (2024). Optimal Placement of Capacitive Electrodes in a Monitoring Borehole for the Campus Geothermal Project at TU Delft. BSc thesis. TU Delft.

4 Voskov et al. (2024). open Delft Advanced Research Terra Simulator (open-DARTS). Journal of Open Source Software, 9(99), 6737, https://doi.org/10.21105/joss.06737

5 Rulff, P. (2025). elfe3D v1.0.1: Modelling with the total electric field approach using finite elements in 3D. Journal of Open Source Software, 10(110), 7949.

6 Drijkoningen, G. et al. (2024). Capacitively coupled EM sensors integrated in non-corrosive casings for long-term CSEM monitoring. 85th EAGE Annual Conference & Exhibition.