# Advances in spectral inversion of time-domain induced polarization

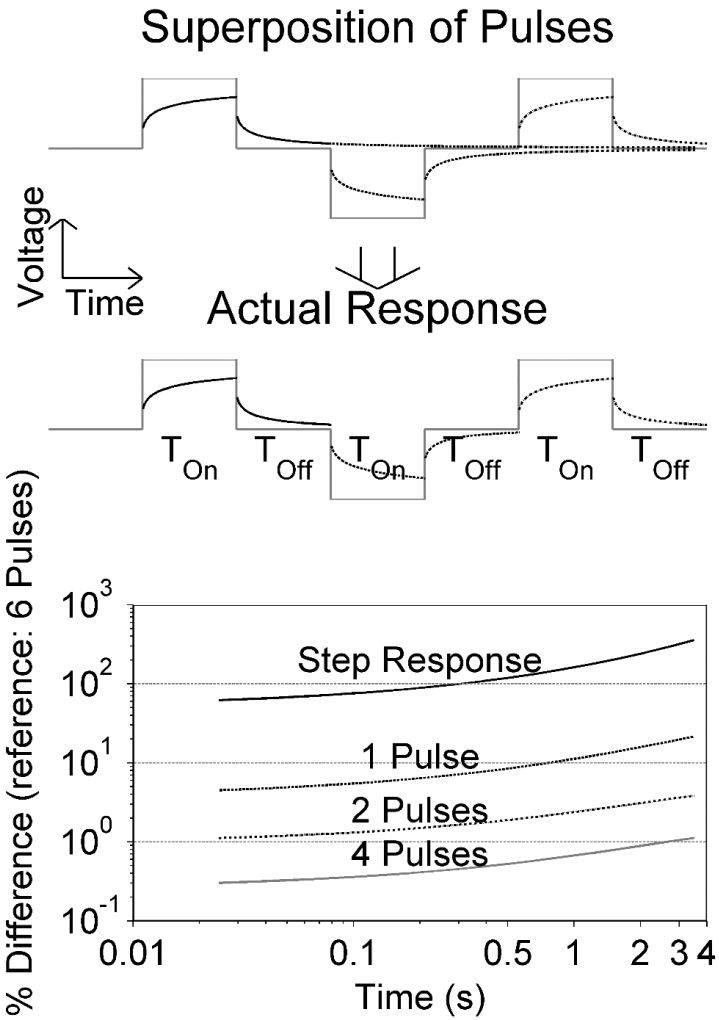
Gianluca Fiandaca, Esben Auken, Anders Vest Christiansen

AARHUS UNIVERSITY

HydroGeophysics Group
AARHUS UNIVERSITY

# Spectral inversion of time domain IP

- **Data Space: ρ values & full IP decays**
- **Model space: parameterization of the IP phenomenon**
- **Forward/Jacobian: solution in frequency domain and transformation in time domain through fast Hankel transform**
- **Transmitter waveform and receiver transfer function accounted for in the computations**
- **Quantitative spectral information from TDIP data**



# Recent advances

- **Range of acquisition “doubled”**
- **Different IP parameterizations**
- **Inversion of 100% duty cycle data**
- **Support for buried electrodes in 1D and 2D**
- **Focused time-lapse inversion**
- **MCMC inversion**
- **Depth of investigation**



# Range of acquisition “doubled”

- **Nowadays full-waveform acquisition at high sampling rate available (e.g. Terrameter LS, Abem)**
- **Processing of full-waveform data**
  - Better background removal – late times retrieval
  - Harmonic de-noising – early times down to a few milliseconds
  - Doubled acquisition range, and then spectral content
    - B03 – Doubling the spectrum of time-domain induced polarization: removal of non-linear self-potential drift, harmonic noise and spikes, tapered gating, and uncertainty estimation.



# Coupling

**Superposed to the IP decays, we may measure three types of signal that are not IP-related, all of them generically referred as coupling:**

- **The EM transient, due to the induction of the earth when we turn on/off the current**
- **The signal due to the mutual inductance of the potential and current wires**
- **The signal due to the inter-capacitance between the potential and current wires**



# Coupling

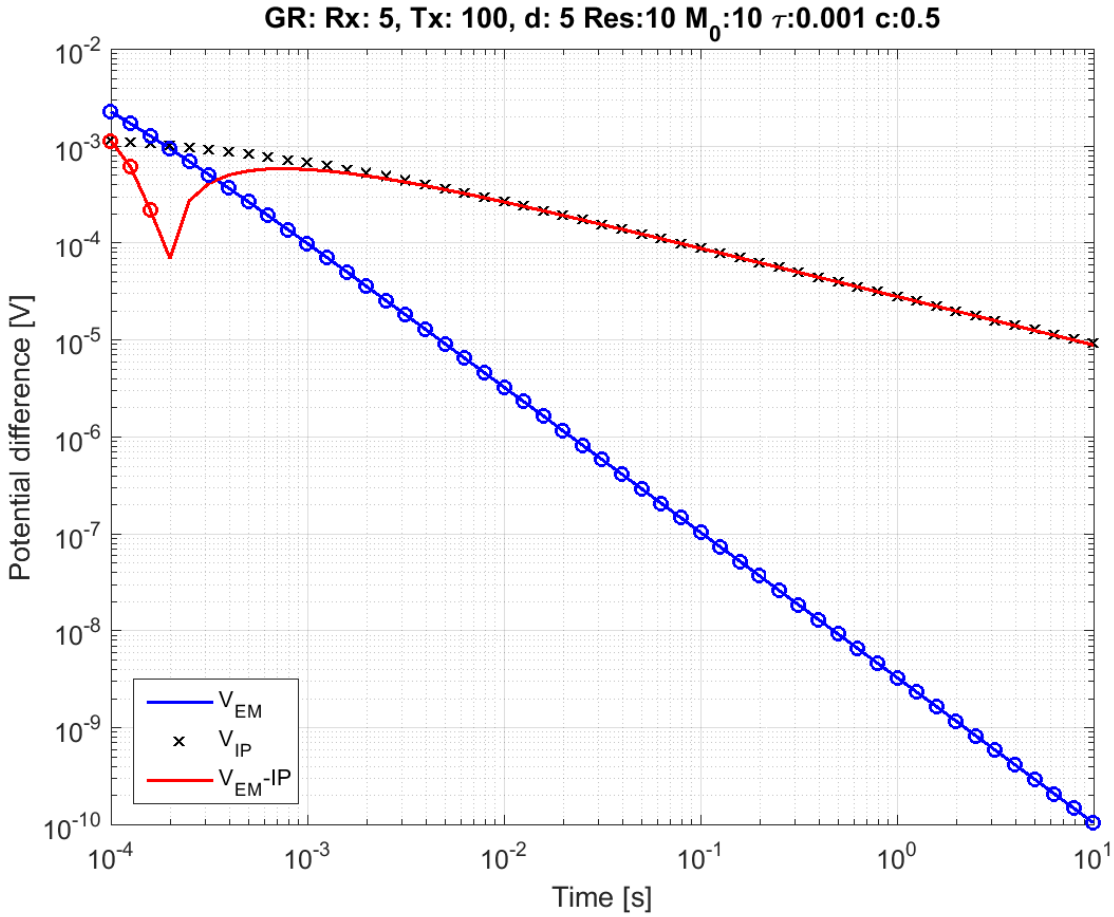
**EM transient**

- **the EM transient is unavoidable: it's the physics!**
- **usually it affects the early times**
- **but the effect last longer for:**
  - conductive medium
  - longer electrode spread



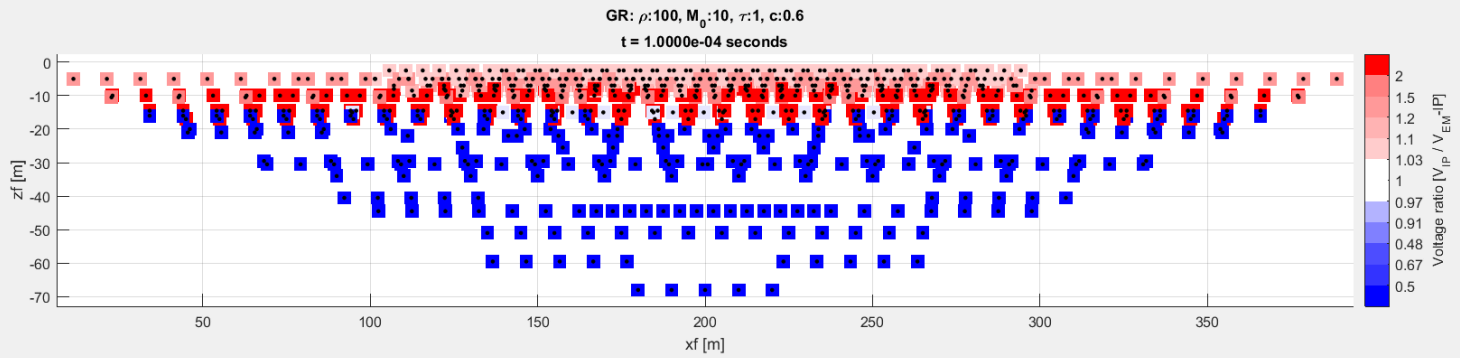
# Coupling

## EM transient



# Coupling

## EM transient



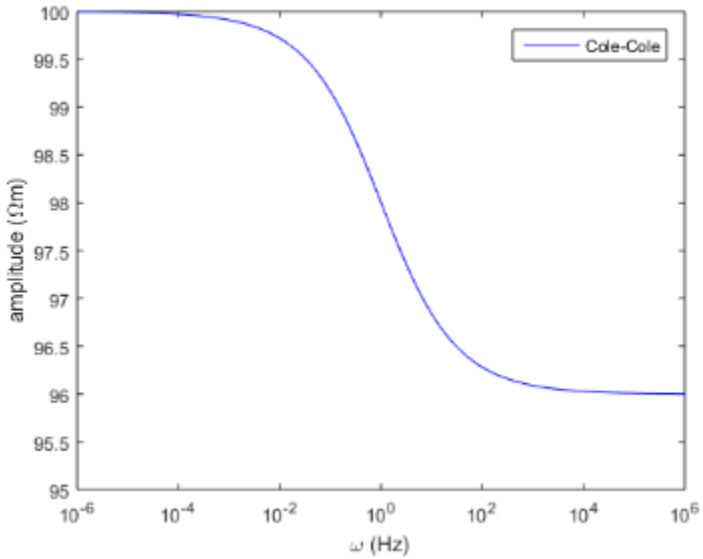
# Different IP parameterizations

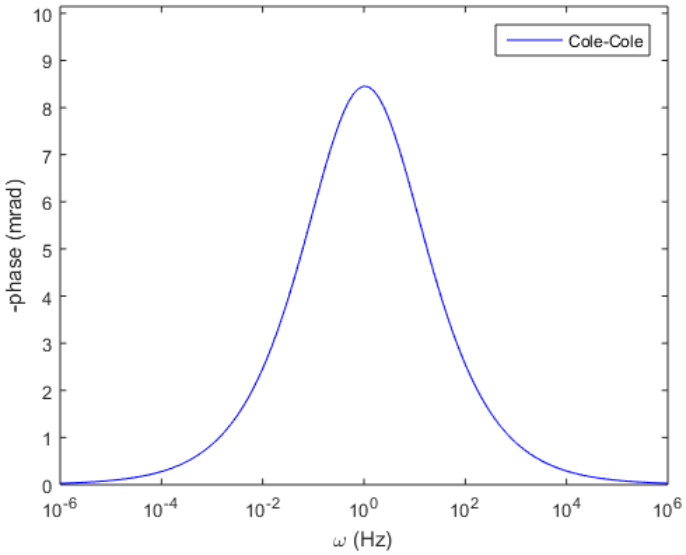
- $\zeta_{Cole-Cole} = \rho\left(1 - m_0\left(1 - \frac{1}{1+(i\omega\tau)^c}\right)\right)$

- $\zeta_{CPA} = K(i\omega + \omega_L)^{-b}$

with

- $\rho = K{\omega_L}^{-b}$
- $\varphi = -\frac{\pi}{2}b$
- $\omega_L = 10^{-5}\ Hz$, fixed



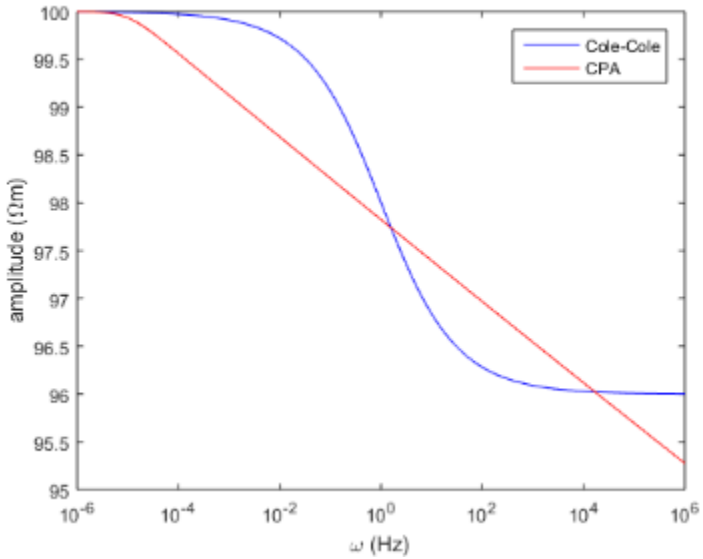
# Different IP parameterizations

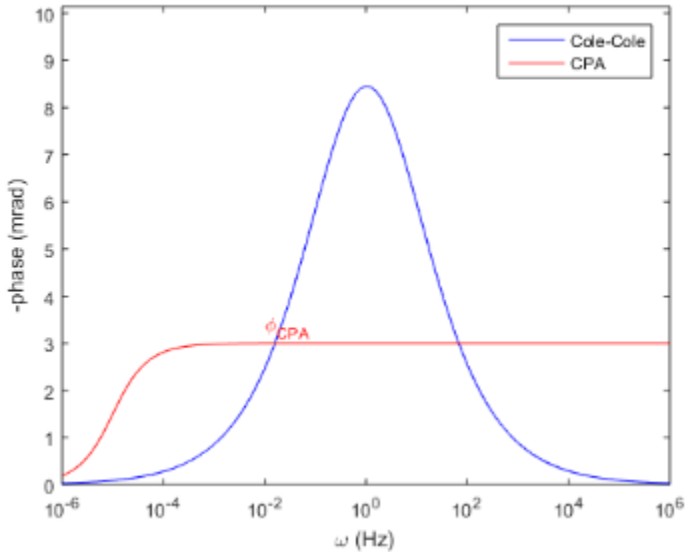
- $\zeta_{Cole-Cole} = \rho\left(1 - m_0\left(1 - \frac{1}{1+(i\omega\tau)^c}\right)\right)$

- $\zeta_{CPA} = K(i\omega + \omega_L)^{-b}$

with

- $\rho = K{\omega_L}^{-b}$
- $\varphi = -\frac{\pi}{2}b$
- $\omega_L = 10^{-5}\ Hz$, fixed



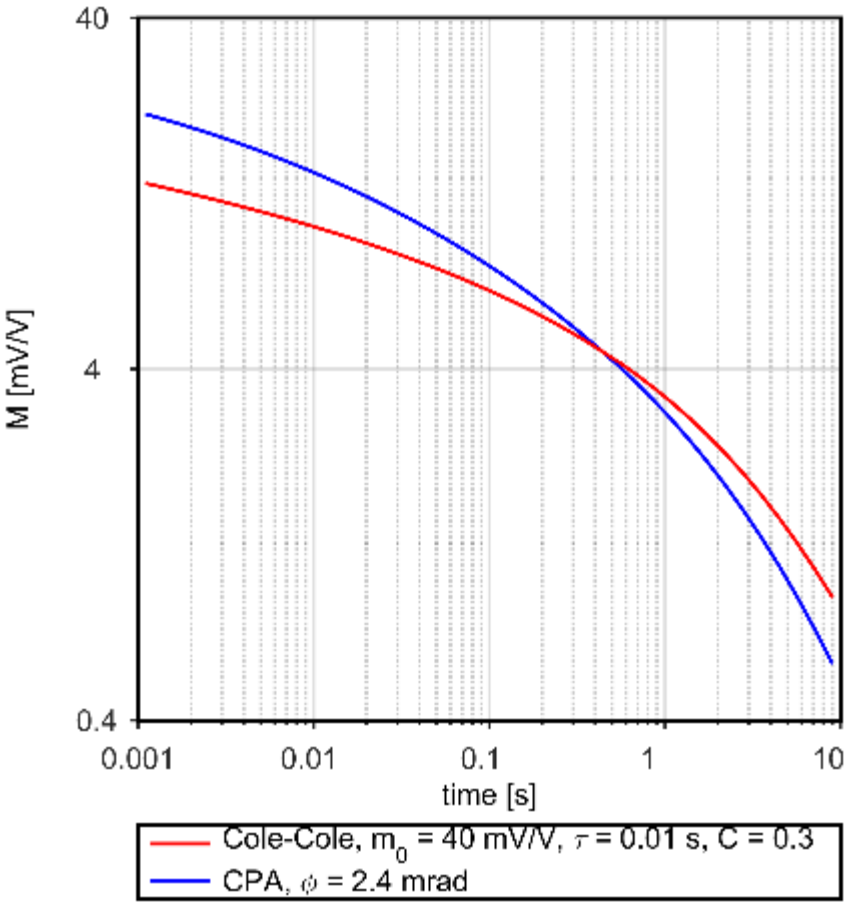



# Different IP parameterizations

**CPA vs Cole-Cole:**

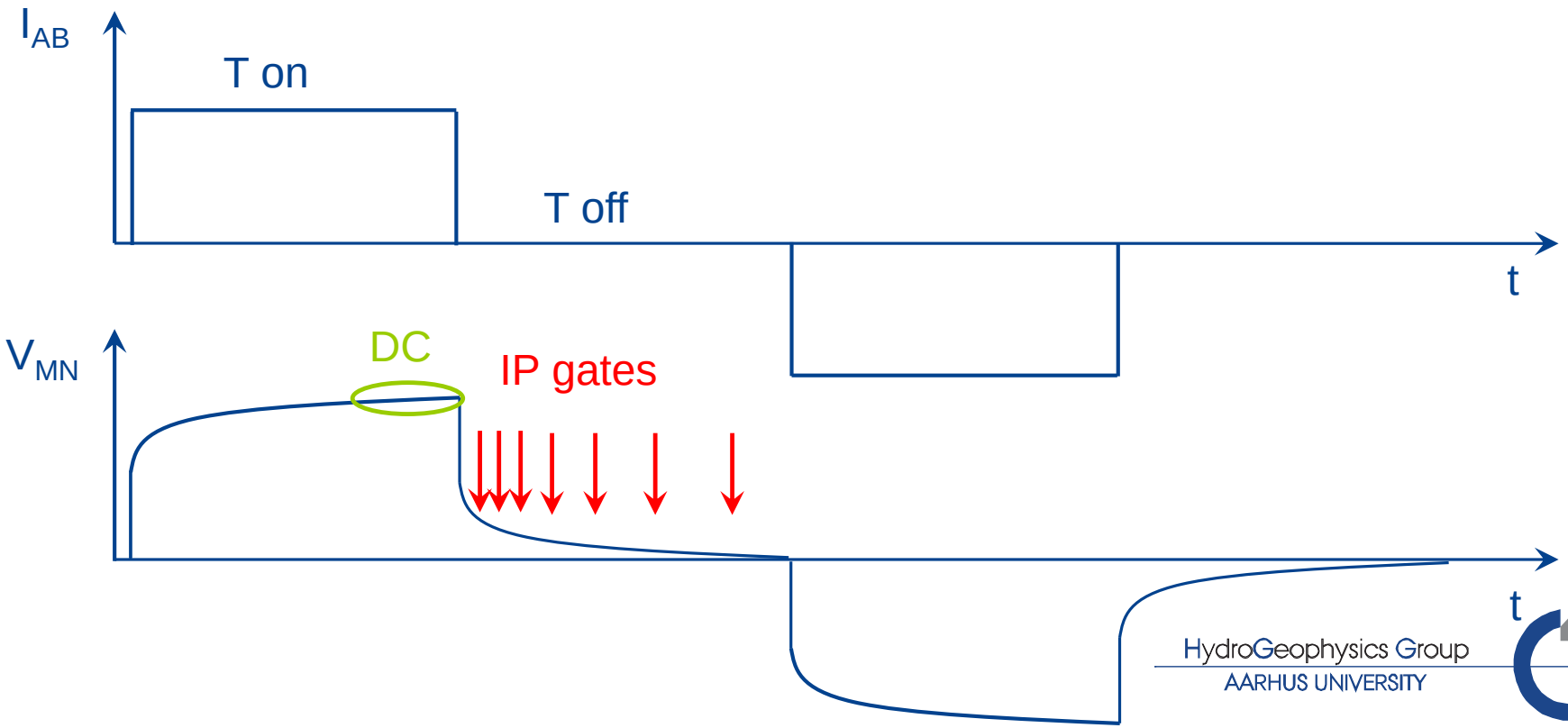
- **Less parameters (2 instead of 4)**
  - Faster computation
- **Less powerful in fitting data**
- **Details in B09**

  Comparison of Cole Cole and CPA modeling in TDIP



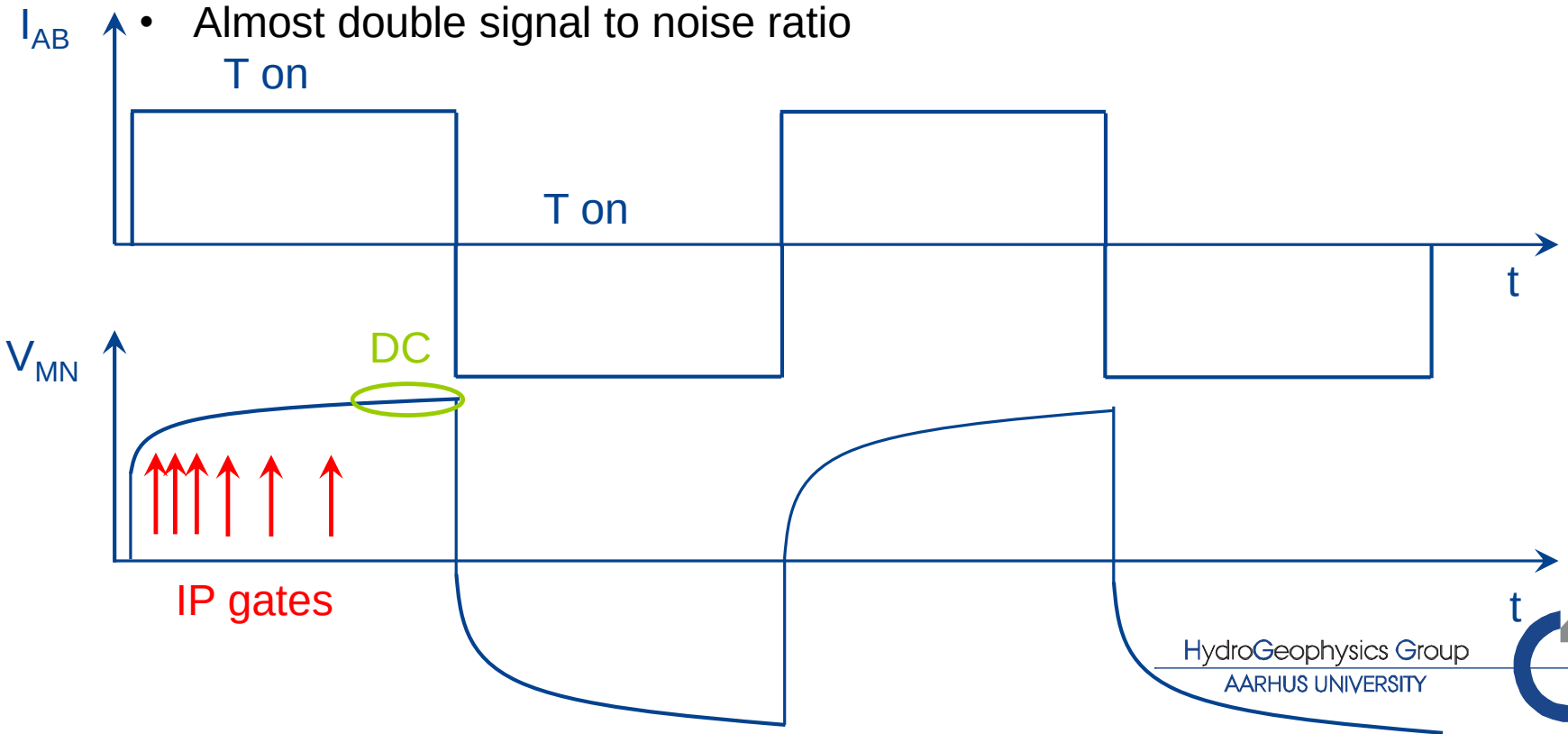
# Modeling of 100% duty cycle data

- **Classically, 50% duty cycle acquisition**
  - 50% of the time the current is On
  - 50% of the time the current is Off



# Modeling of 100% duty cycle

- **But it also possible to measure the IP signal during the potential rise**
  - 100% of the time the current is on
  - Acquisition twice faster
  - Almost double signal to noise ratio

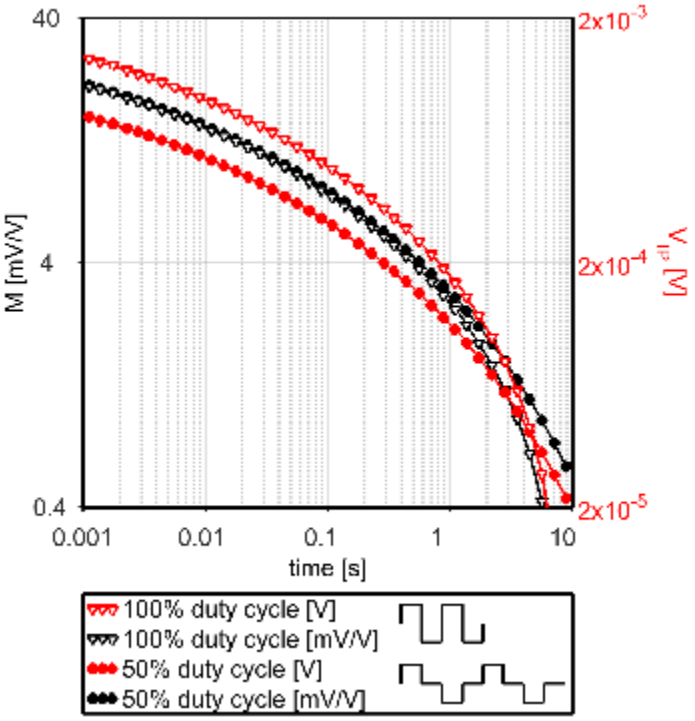


# Modeling of 100% duty cycle

- **Definition of pseudo-decay**

$$M_i^{50\,\%} = \frac{1}{V_{DC}.[t_i - t_{i-1}]} \int_{t_{i-1}}^{t_i} V_{ip}\, dt$$

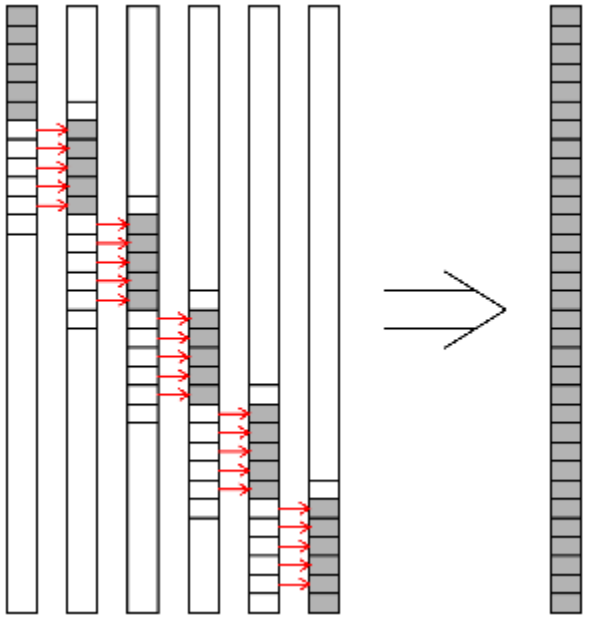
$$M_i^{100\,\%} = \frac{n_{pulses}}{2\,n_{pulses} - 1} \frac{1}{V_{DC}.[t_i - t_{i-1}]} \int_{t_{i-1}}^{t_i} (V_{DC} - V_{ip})\, dt$$




Olsson P.-I., Dahlin T., Fiandaca G. & Auken E., 2015. Measuring time-domain spectral induced polarization in the on-time: decreasing acquisition time and increasing signal-to-noise ratio, Journal of Applied Geophysics, 123, 316-321. 10.1016/j.jappgeo.2015.08.009.

# Support for buried electrodes in 1D/2D

- **1D**
  - AP15 – Mapping the lythotypes using the in-situ measurement of time domain induced polarization: El-log

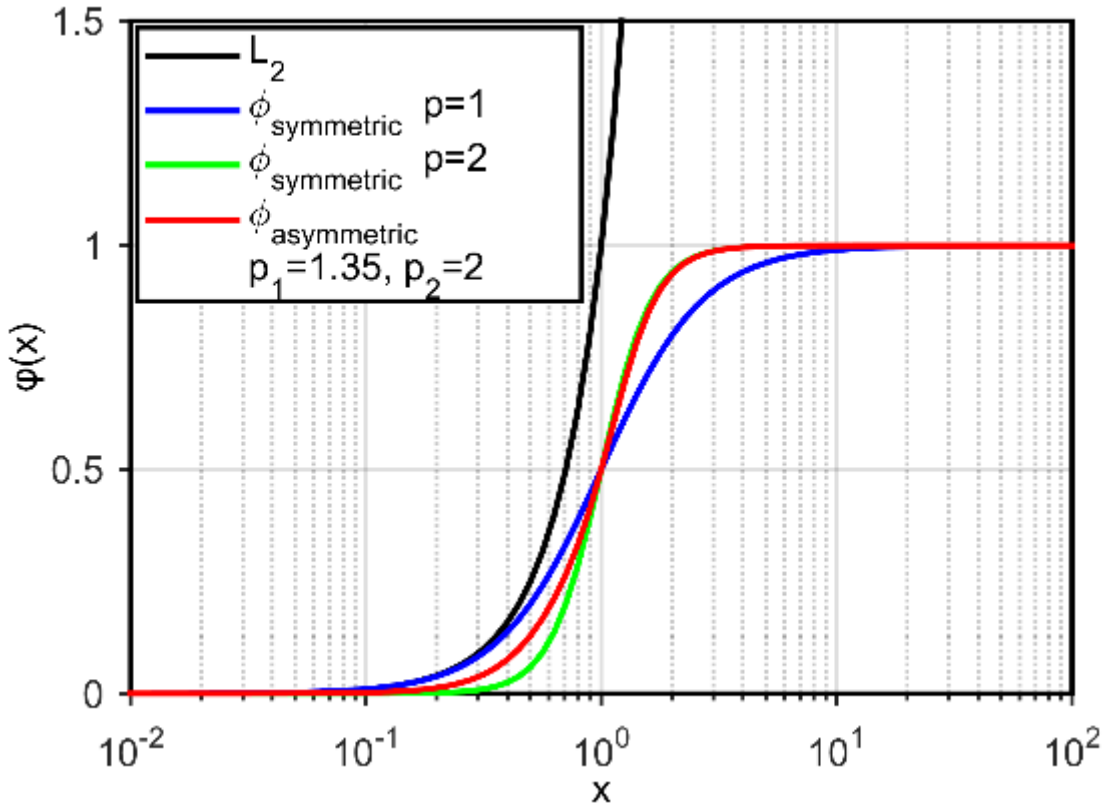


- **2D**
  - BP16 – Mapping possible flowpaths of contaminants through surface and cross-borehole spectral time-domain induced polarization



# Focused time-lapse inversion

- **Minimum support for compact anomalies in time-lapse inversions**



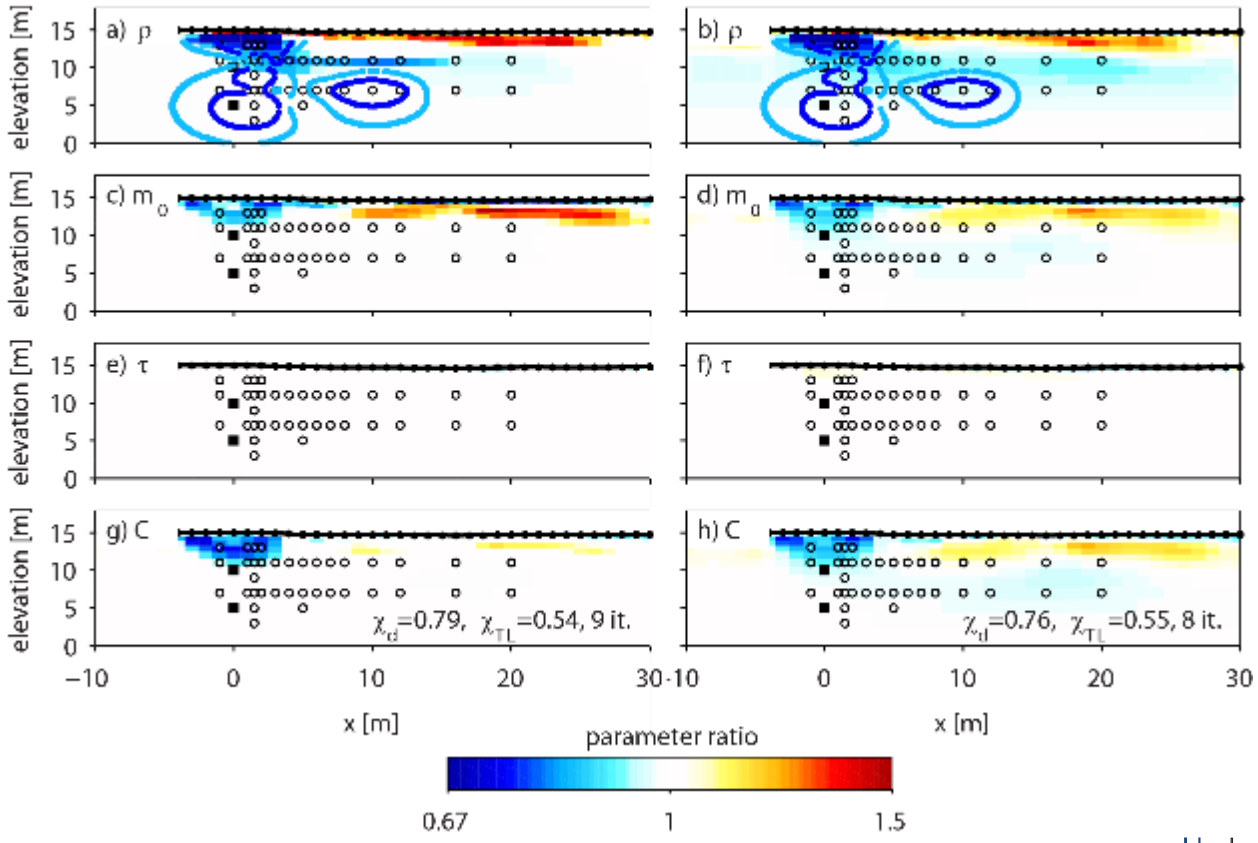
# Focused time-lapse inversion

- **Minimum support for compact anomalies in time-lapse inversions**
  - Monitoring of CO2 injection through time domain IP
    - Fiandaca G., Doetsch J., Vignoli G. & Auken E., 2015. Generalized focusing of time-lapse changes with applications to direct current and time-domain induced polarization inversions, Geophysical Journal International, 203, 1101-1112. 10.1093/gji/ggv350.



# Focused time-lapse inversion

- **Minimum support for compact anomalies in time-lapse inversions** $\varphi_{asymmetric}$ L2

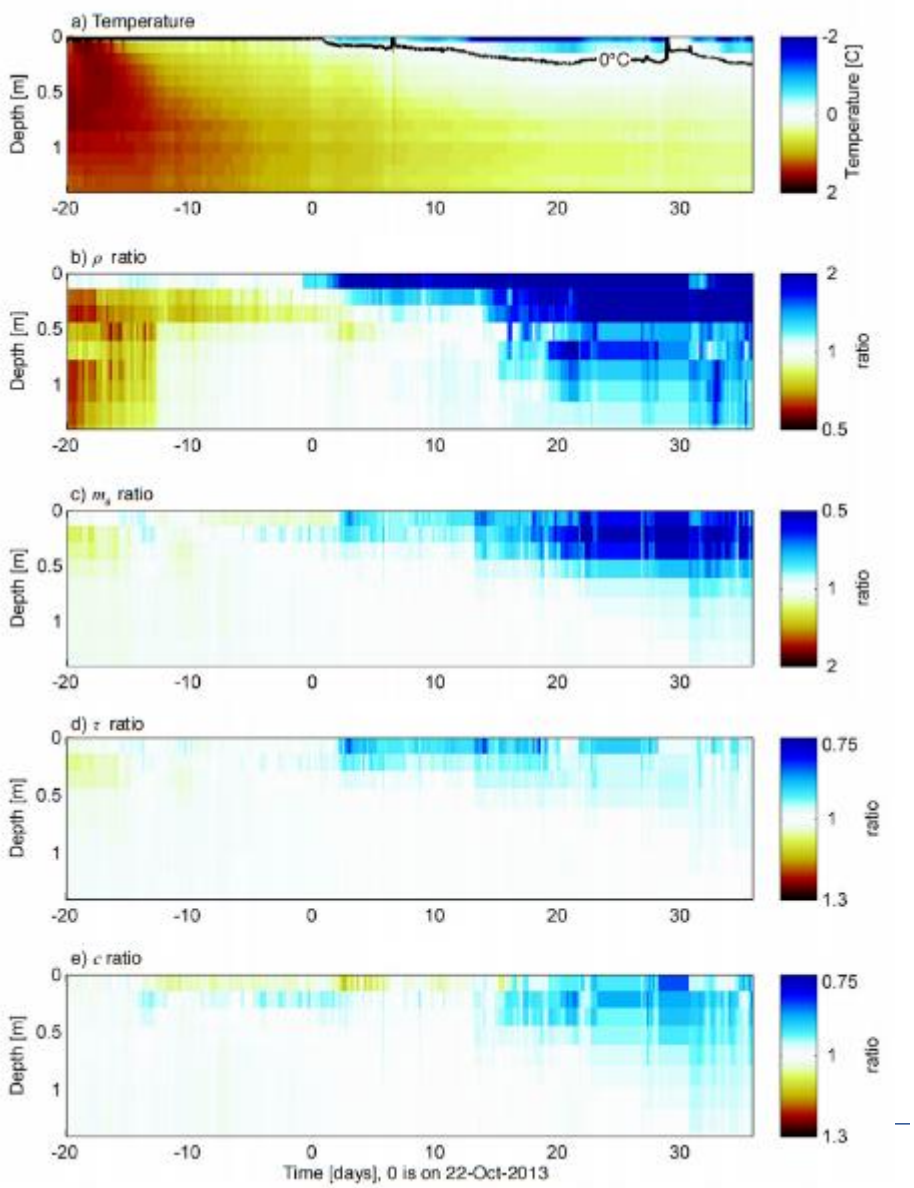


# Focused time-lapse inversion

- **Minimum support for compact anomalies in time-lapse inversions**
  - Monitoring of CO2 injection
    - Fiandaca G., Doetsch J., Vignoli G. & Auken E., 2015. Generalized focusing of time-lapse changes with applications to direct current and time-domain induced polarization inversions, Geophysical Journal International, 203, 1101-1112. 10.1093/gji/ggv350.
  - Monitoring of active layer dynamics at high temporal resolution
    - Doetsch J., Ingeman-Nielsen T., Christiansen A.V., Fiandaca G., Auken E. & Elberling B., 2015. Direct current (DC) resistivity and induced polarization (IP) monitoring of active layer dynamics at high temporal resolution, Cold Regions Science and Technology, 119, 16-28. 10.1016/j.coldregions.2015.07.002.

# Focused time-lapse inversion

- **Minimum support for compact a inversions**
  - Monitoring of CO2 injection
    - Fiandaca G., Doetsch J., Vignoli G of time-lapse changes with applica induced polarization inversions, G 1101-1112. 10.1093/gji/ggv350.
  - Monitoring of active layer dynamic
    - Doetsch J., Ingeman-Nielsen T., C Elberling B., 2015. Direct current (IP) monitoring of active layer dyn Regions Science and Technology, 10.1016/j.coldregions.2015.07.00



# MCMC inversion

- **Markov chain Monte Carlo 1D inversion**
  - For comparison to the linearized approach
  - B04 – An analysis of Cole-Cole parameters for IP data using Markov chain Monte Carlo



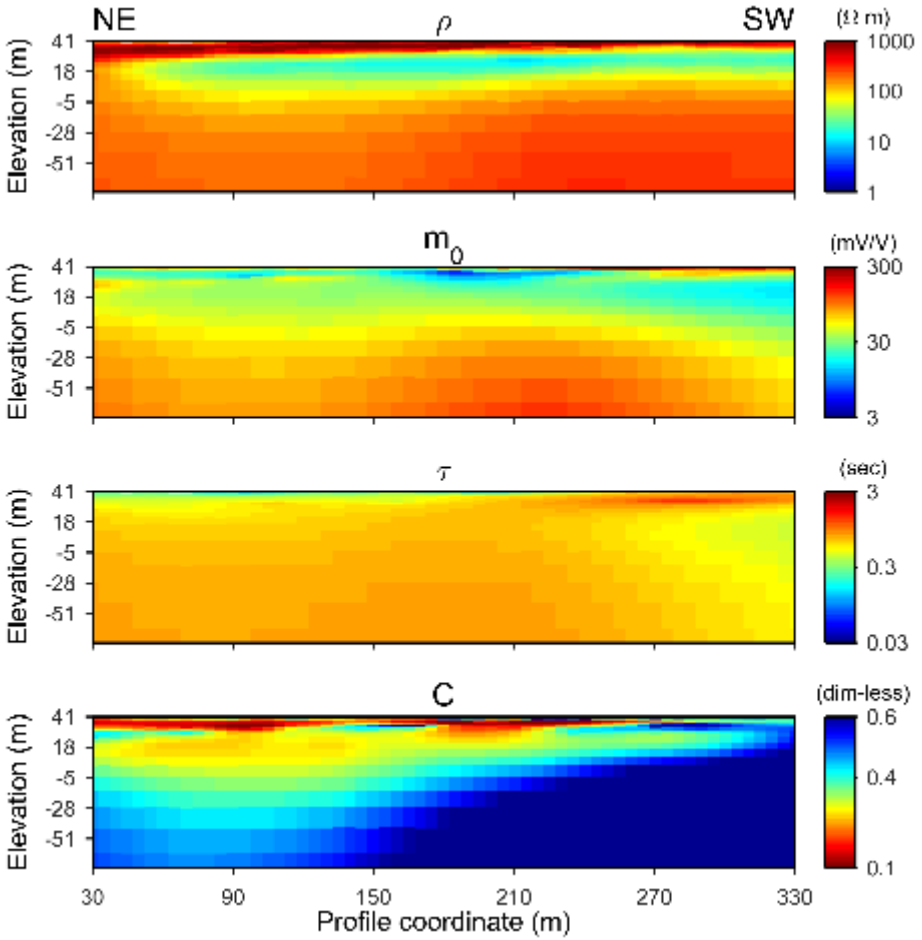
# Depth Of Investigation (DOI)
# Global DOI – Christiansen and Auken

- **Tested and currently used for several E&EM methods, e.g.:**
  - Airborne EM surveys
  - Groundbased TEM and GCM data
  - DC methods

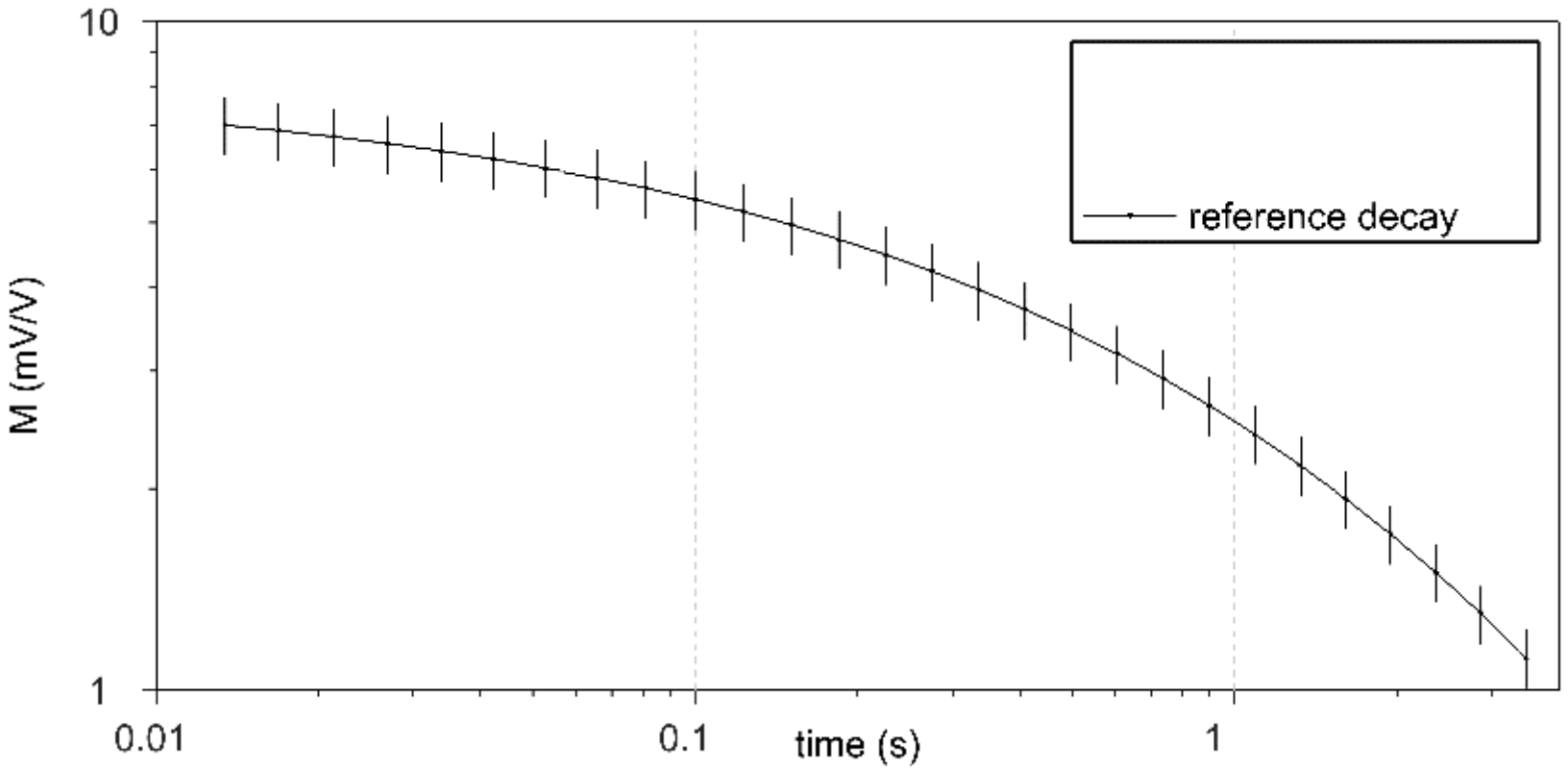
- **But…**
  - Not performing well for induced polarization (IP) and magnetic resonance sounding (MRS), i.e. for multi-parametric inversions
  - Unrealistic (too deep) DOI values are retrieved



# The time-domain IP inversion problem

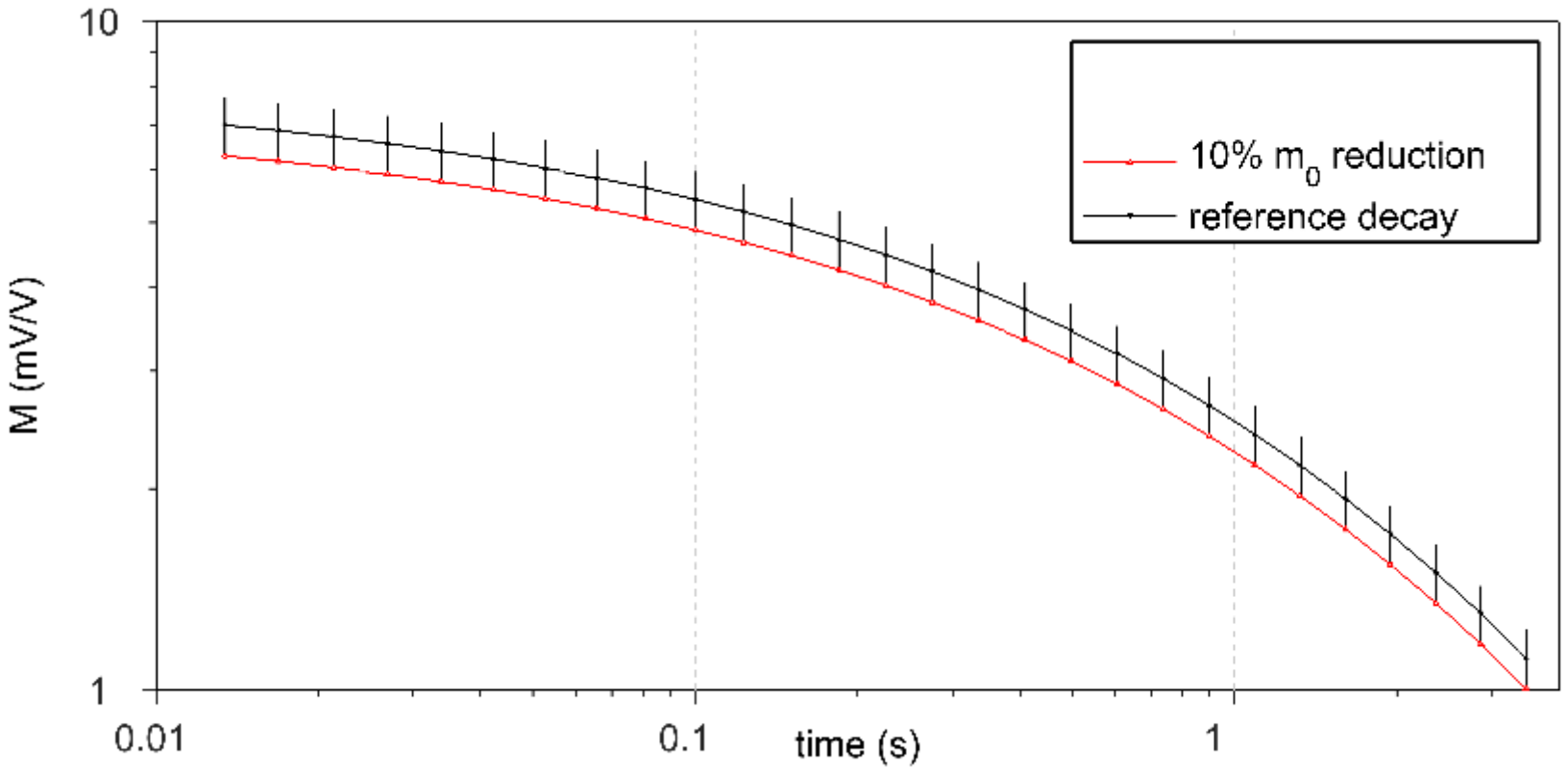


# Jacobian of IP parameters

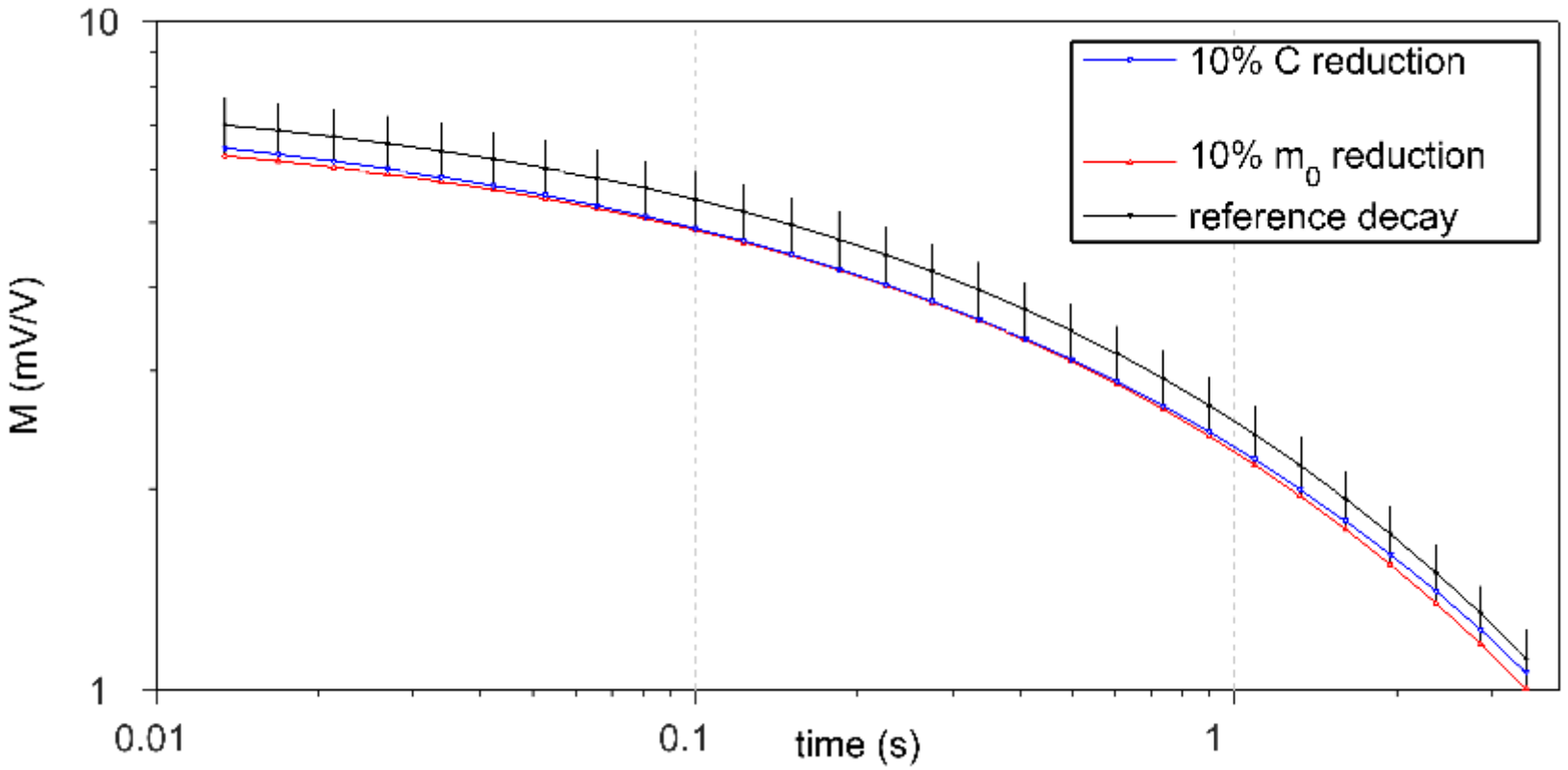



Forward response for homogeneous halfspace
($\rho$=100 Ωm, $m_0$=10 mV/V, $\tau$=1 s, C=0.5)

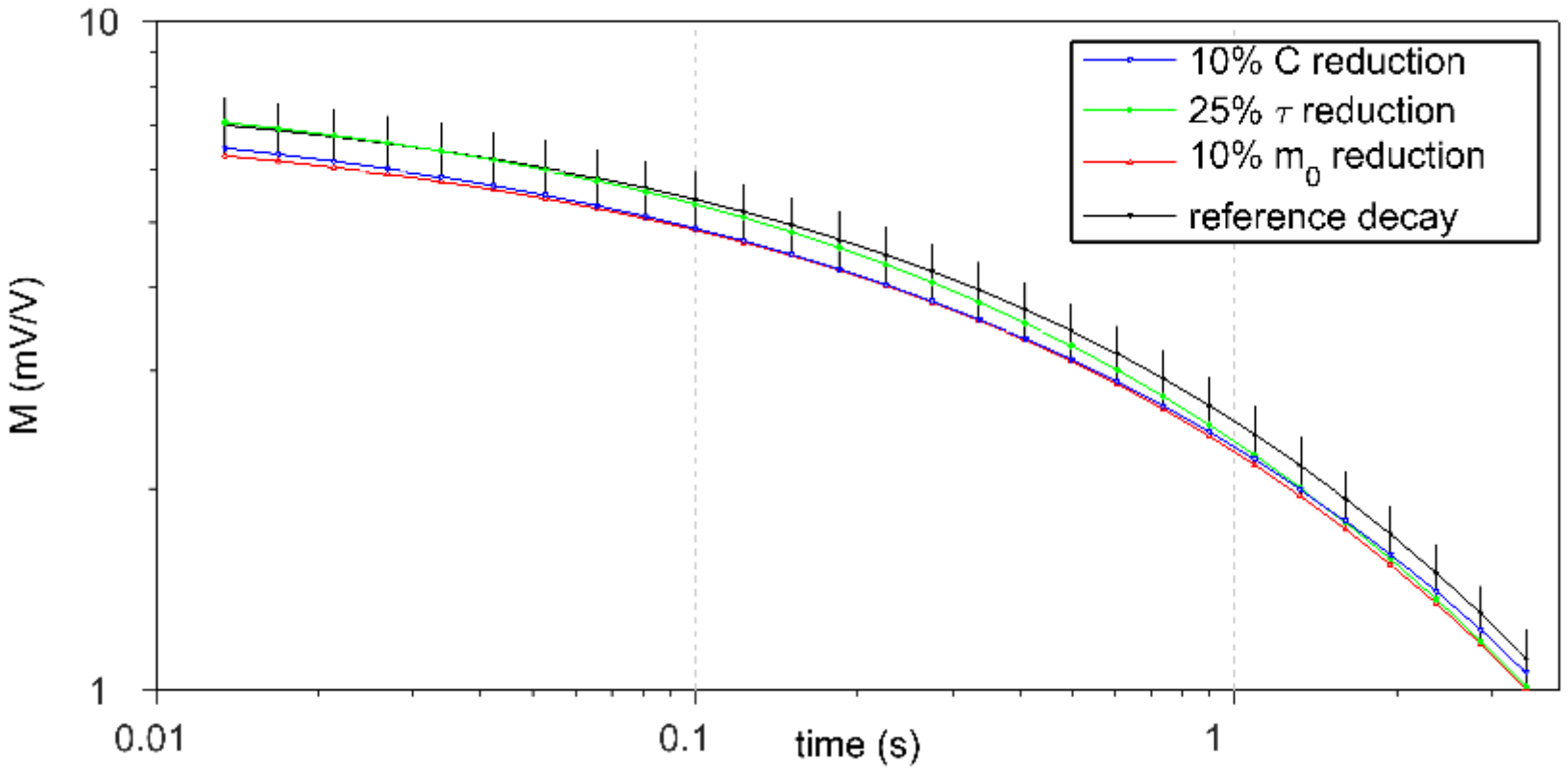
# Jacobian of IP parameters



# Jacobian of IP parameters



# Jacobian of IP parameters



# Sensitivity of IP parameters

- **<u>Correlation among parameters must be taken into account in the DOI computations!</u>**
- **The sensitivity analysis cannot be used as it is, because for multilayer 1D/2D/3D inversions $\left[G^T {C_d}^{-1} G\right]^{-1}$ is singular**
- **We want a cumulated information below the DOI**

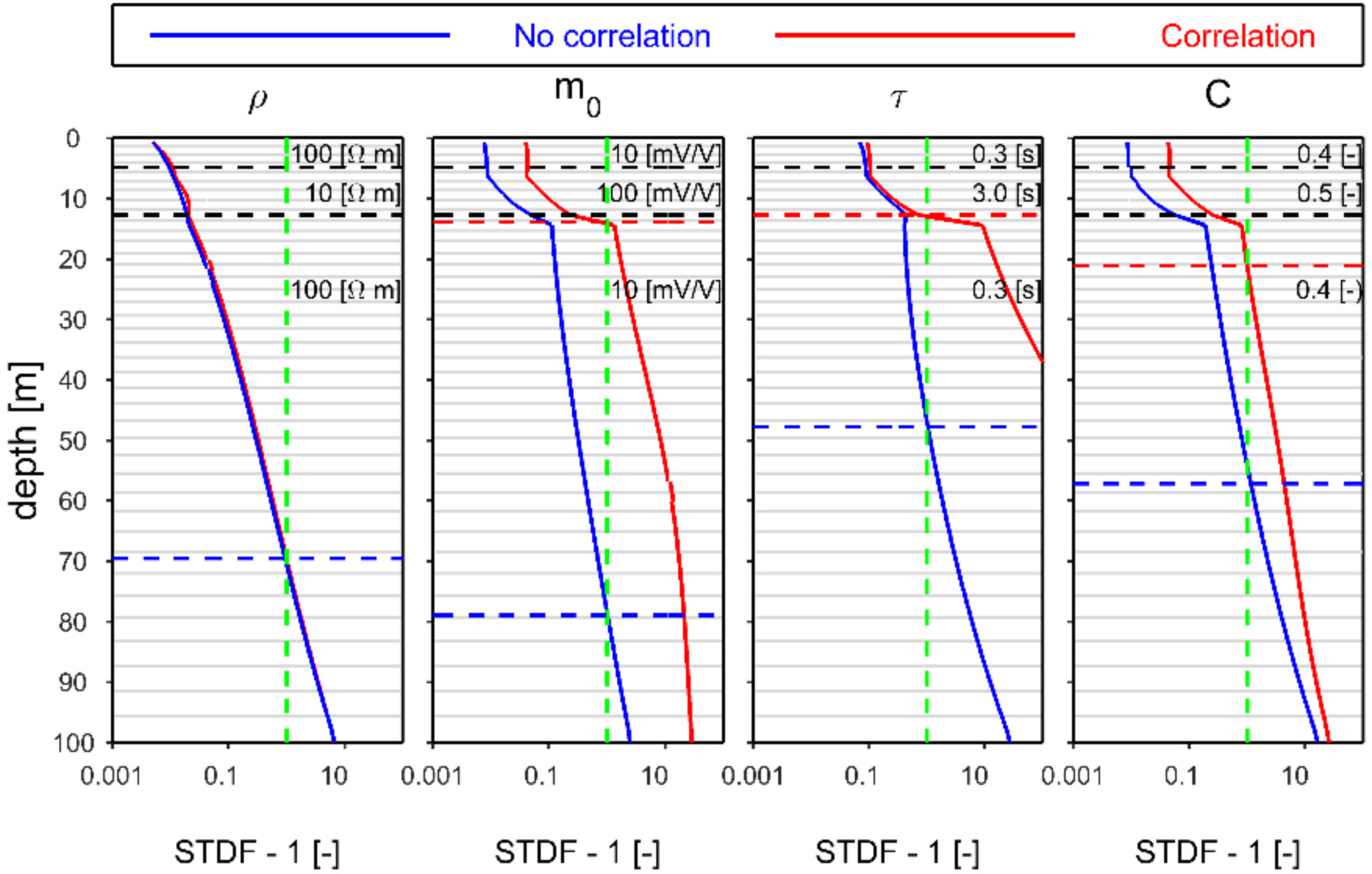


# DOI Challenge solution - *Cumulated approximate analysis*

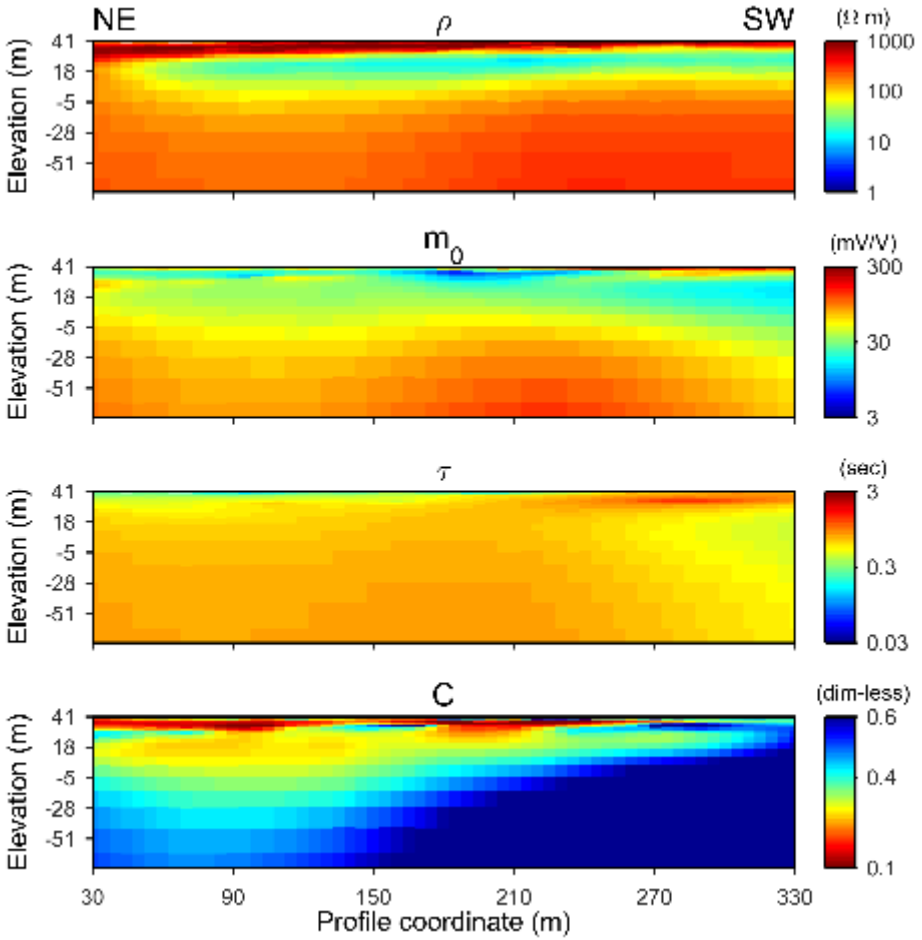
- **Jacobian matrix based**
  - Based on actual model
  - Uses actual data and system parameters
  - Includes noise
  - Cumulates the sensitivities of the layers
- **Correlation taken into account**
  - Approximate analysis performed to account for correlation



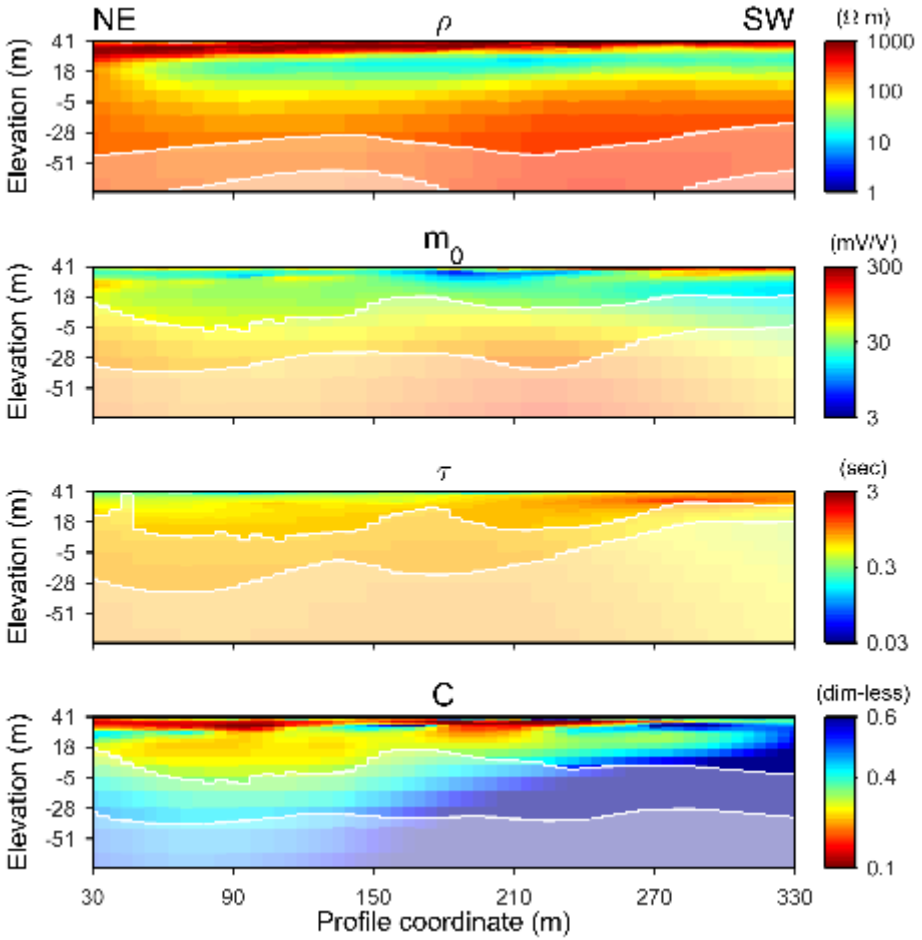
# New DOI implementation



# DOI – field example



# DOI – field example




Fiandaca G., Christiansen A. & Auken E., 2015. Depth of Investigation for Multi-parameters Inversions, Near Surface Geoscience 2015-21st European Meeting of Environmental and Engineering Geophysics, 1-4. 10.3997/2214-4609.201413797.

# Conclusions

- **The spectral inversion of time domain IP has reached maturity**
- **Increased potential of time domain IP in hydrogeophysical applications**
  - B06 – Lithological characterization of a contaminated site using Direct Current resistivity and time domain induced polarization
- **Quantitative interpretation of field data - directly comparable with laboratory results?**
- **AarhusInv is available and free for the scientific community**

**… and the IP inversion has also been implemented in Aarhus Workbench**