Advances in spectral inversion of time-domain induced polarization

Gianluca Fiandaca, Esben Auken, Anders Vest Christiansen
Spectral inversion of time domain IP

- **Data Space:** \( \rho \) 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
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

GR: Rx: 5, Tx: 100, d: 5 Res: 10 M_0 : 10 \tau : 0.001 c: 0.5
Coupling

EM transient
Different IP parameterizations

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

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

with

- \( \rho = K\omega_L^{-b} \)
- \( \phi = -\frac{\pi}{2} b \)
- \( \omega_L = 10^{-5} \text{ Hz}, \text{fixed} \)
Different IP parameterizations

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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
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

\[ I_{AB} \]
\[ V_{MN} \]

\[ T_{on} \]

\[ DC \]

IP gates
Modeling of 100% duty cycle

- **Definition of pseudo-decay**

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

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

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
Focused time-lapse inversion

- Minimum support for compact anomalies in time-lapse inversions $\phi_{\text{asymmetric}}$

\begin{itemize}
  \item $\chi_{\text{ul}} = 0.79$, $\chi_{\text{TI}} = 0.54$, 9 it.
  \item $\chi_{\text{ul}} = 0.76$, $\chi_{\text{TI}} = 0.55$, 8 it.
\end{itemize}
Focused time-lapse inversion

- **Minimum support for compact anomalies in time-lapse inversions**
  - Monitoring of CO2 injection
  - Monitoring of active layer dynamics at high temporal resolution
Focused time-lapse inversion

- Minimum support for compact anomalies in time-lapse inversions

- Monitoring of CO2 injection

- Monitoring of active layer dynamics
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
Forward response for homogeneous halfspace
($\rho=100 \ \Omega m$, $m_0=10 \ mV/V$, $\tau=1 \ s$, $C=0.5$)
Jacobian of IP parameters
Jacobian of IP parameters
Jacobian of IP parameters
Sensitivity of IP parameters

- Correlation among parameters must be taken into account in the DOI computations!
- The sensitivity analysis cannot be used as it is, because for multilayer 1D/2D/3D inversions \( [G^T C_d^{-1} G]^{-1} \) 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
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