Doubling the spectrum of time-domain induced polarization

PER-IVAR OLSSON, GIANLUCA FIANDACA, JAKOB JUUL LARSEN, TORLEIF DAHLIN, ESBEN AUKEN
Outline

- Background
- Signal processing:
  IP gating.
  Drift removal.
  Spikes.
  Harmonic noise.
  Tapered gating.
- IP gate data uncertainty.
- Conclusions.
Background

- Increase spectral information content by extending the available time range.
- Increase TDIP data reliability and quality.
- Data driven uncertainty estimates for induced polarization.
Background

**Integral chargeability**

\[ m_{\text{int}} = \frac{V_{\text{DC}} \Delta}{t_1 - t_2} \int_{t_1}^{t_2} V(t) \, dt \]

**Spectral chargeability** e.g. Cole-Cole model

\[ V_{\text{IP}}(t) = m_0 \sum_{j=0}^{\infty} (t-1)^j \left( \frac{t}{\tau} \right)^j \Gamma(1 + jc)^{-1} \]

Euler’s Gamma function:

\[ \Gamma(x) = \int_0^{\infty} y^{x-1} e^{-u} \, dy \]
IP Gating

IP response is down-sampled in windows or “gates”.

Logarithmically increasing window width to compensate for lower signal-to-noise ratio.

Gates are multiples of 20 ms to suppress harmonic noise.

BUT: We lose early time information if using long gates!
Processing today

Linear background drift removal and log-gating:

Increase of chargeability at late times due to poor performance of linear background model.

Erratic behaviour at early times while gates are <20ms due to harmonic noise.
Processing challenges

- Background drift.
- Spikes.
- Harmonic noise.
- EM coupling.

\[ u_{\text{measured}} = u_{\text{response}} + u_{\text{drift}} + u_{\text{spikes}} + u_{\text{harmonic noise}} + u_{\text{other}} \]
Background drift

Main contributor: current induced electrode polarization from previous current injections.
Background drift

Drift is estimated from averaged (20 ms) points. To reduce IP response influence, only a subset of points from end of off-time is used.

Cole-Cole drift model suitable for describing depolarization.
Spikes

Electrical fences for livestock management.

EM coupling from current pulse transients.
Spikes

Full waveform potential

High pass filter and DC-offset removal signal

Non-linear energy operator signal

Magnifications
Harmonic noise
Harmonic noise

\[ u_{\text{harmonic noise}}(n) = \sum_{m} \left( \alpha_m \cos \left( 2\pi m \frac{f_0}{f_s} n \right) + \beta_m \sin \left( 2\pi m \frac{f_0}{f_s} n \right) \right) \]

\[ E_{\text{residual}} = \sum_n \left( u_{\text{measured}}(n) - u_{\text{harmonic noise}}(n) \right)^2 \]

Minimizing \( E_{\text{residual}} \) to find parameters \( \alpha_m, \beta_m \) and \( f_0 \).
Harmonic noise

Signal is segmented so that $\alpha_m, \beta_m$ and $f_0$ variation is small.

Segment length is a trade-off between parameter accuracy and variation.
Harmonic noise

\[ f_0 \] and harmonics energy is reduced to "baseline energy".

A subset of highest harmonics is used for finding \( f_0 \).
Harmonic noise

Erratic behaviour at early times is removed.

Gates containing spikes at current pulse switches can be rejected.
Tapered gating

Gaussian windows 3.5 times wider than rectangular gate.
Same width of main lobe but 40 dB higher noise suppression!
Tapered gating

Convolution of stacked signal.
Linear fit of convoluted signal in lin-log space.
Evaluates gate value at linear fit.
Estimate uncertainty from convoluted signal and linear fit.
Uncertainty estimate

\[
STD_{total} = \sqrt{STD_{gating}^2 + STD_{drift}^2 + STD_{uniform}^2}
\]

\[
STD_{drift} = \sqrt{\frac{1}{N_{drift\ data}} \sum_{k=1}^{N_{drift\ data}} (drift\ data(k) - drift\ fit(k))^2}
\]

\[
STD_{gating} = \sqrt{\frac{1}{N_{gate\ samples}} \sum_{n=1}^{N_{gate\ samples}} (convoluted\ data(n) - linear\ fit(n))^2}
\]
Spectral information content

![Graph showing IP responses over time with Before and After markers indicating uncertainty]
### Spectral information content

<table>
<thead>
<tr>
<th>Gate #</th>
<th>Center time</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td><img src="image1.png" alt="Before" /></td>
<td><img src="image2.png" alt="After" /></td>
</tr>
<tr>
<td>9</td>
<td>17</td>
<td><img src="image3.png" alt="Before" /></td>
<td><img src="image4.png" alt="After" /></td>
</tr>
<tr>
<td>18</td>
<td>310</td>
<td><img src="image5.png" alt="Before" /></td>
<td><img src="image6.png" alt="After" /></td>
</tr>
<tr>
<td>25</td>
<td>3160</td>
<td><img src="image7.png" alt="Before" /></td>
<td><img src="image8.png" alt="After" /></td>
</tr>
</tbody>
</table>
Conclusions

- Spectral information from time domain IP surveys is doubled compared to existing procedure.
- TDIP data reliability and quality is increased.
- Data driven uncertainty estimates for individual TDIP gates.
Thank you for listening!
Spikes

\[ u_2(n) = u_{\text{measured}}(n) - u_{\text{measured}}(n - 1) \]
\[ u_3(n) = \text{abs}(u_2(n)^2 - u_2(n - 1)u_2(n + 1)) \]
Spikes

**Full waveform potential**

- **Signal**
- **Switch spikes**
- **Despike spikes**

**Magnifications**

**High pass filter and DC-offset removal signal**

- **Signal**

**Non-linear energy operator signal**

- **Signal**
- **Switch spikes**
- **Despike spikes**
- **Threshold**
Tapered gating

\[
\begin{align*}
    u_{IP,\text{stacked}}(k) &= \frac{1}{N_{\text{pulses}}} \sum_{j=1}^{N_{\text{pulses}}} (-1)^{j+1} u_{\text{processed}}(k + S_{IP}(j) - 1) \\
    u_{IP,\text{gated}}(m) &= \frac{1}{N_{\text{samples}}(m)} \sum_{i=1}^{N_{\text{samples}}(m)} u_{IP,\text{stacked}}(i + S_{\text{gate}}(m) - 1) \\
    w_m(i) &= e^{-\frac{1}{2}(\alpha \frac{i}{(N_{\text{window}}(m)-1)/2})^2} ; \quad |i| \leq (N_{\text{window}}(m) - 1)/2 \\
    u_{IP,\text{conv}}(m)(j) &= \frac{1}{N_{\text{window}}(m)-1} \sum_{i=-\frac{N_{\text{window}}(m)-1}{2}}^{\frac{N_{\text{window}}(m)-1}{2}} u_{IP,\text{stacked}}(j + S_{\text{gate}}(m) - 1 - i)w_m(i)
\end{align*}
\]
Tapered gating

Gaussian windows 3.5 times wider than gate.

40 dB noise suppression for higher frequencies!