Doubling the spectrum of time-domain induced polarization

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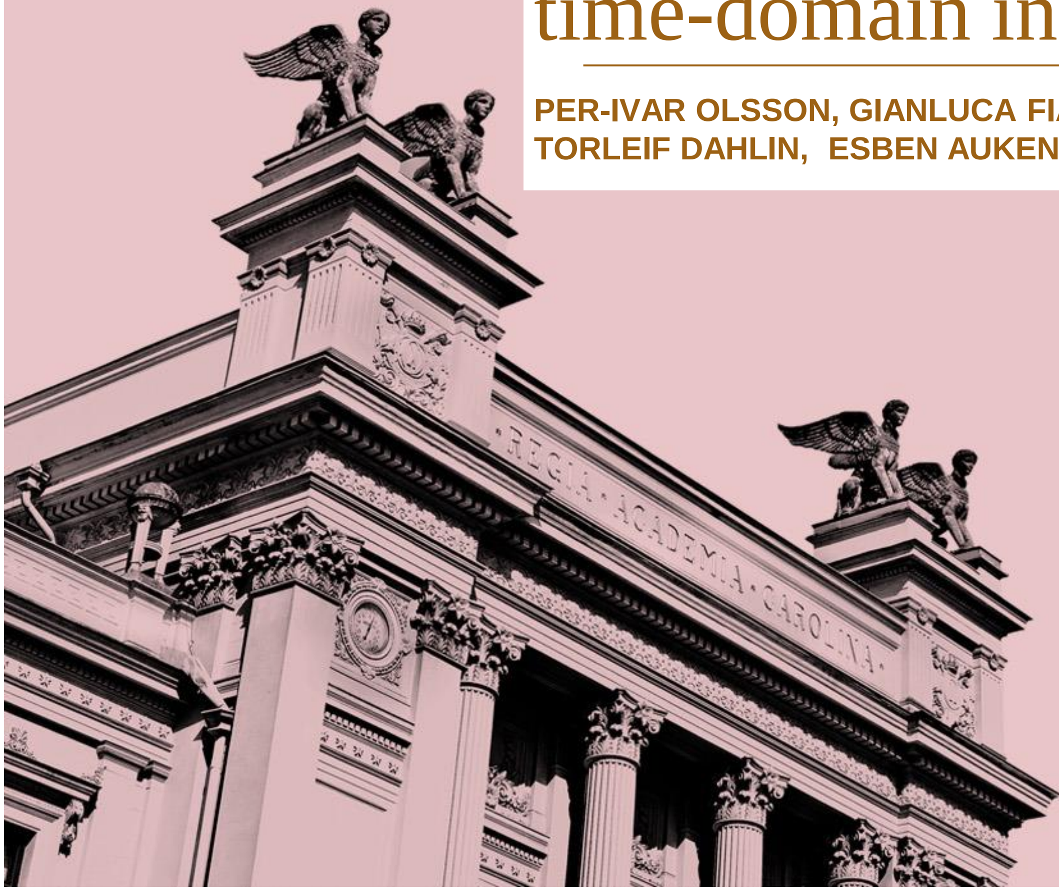
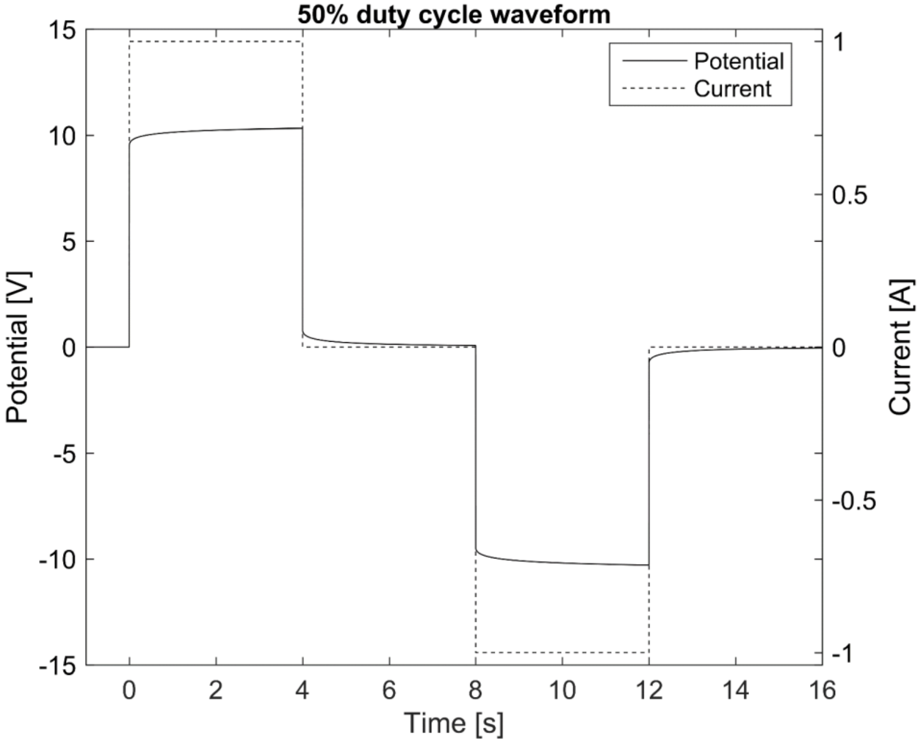


Outline

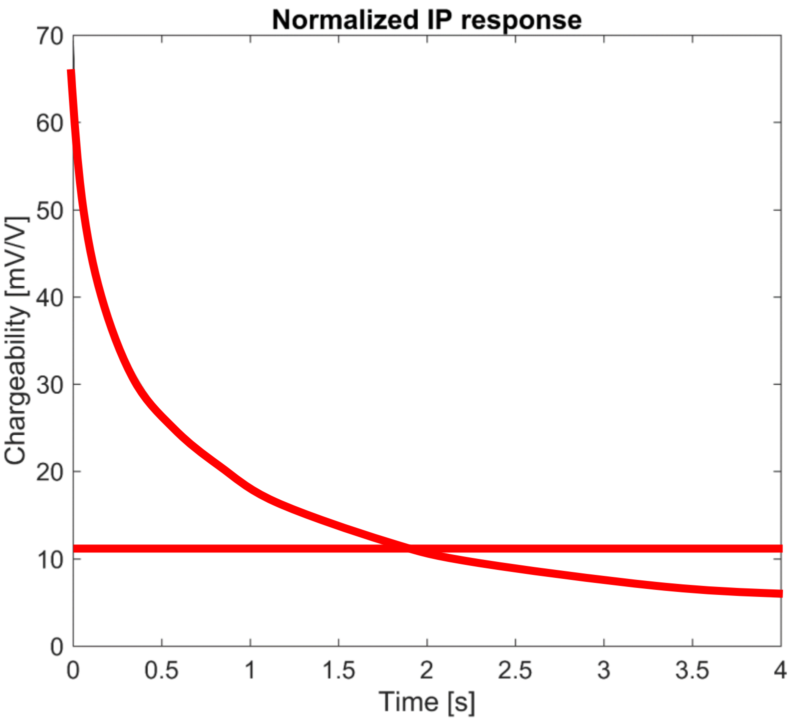
- Background
- Signal processing:
  IP gating.
  Drift removal.
  Spikes.
  Harmonic noise.
  Tapered gating.
- IP gate data uncertainty.
- Conclusions.



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

$$m_{int} = \frac{1}{V_{DC}\Delta t}\int_{t_1}^{t_2} V(t)\,dt$$

Spectral chargeability

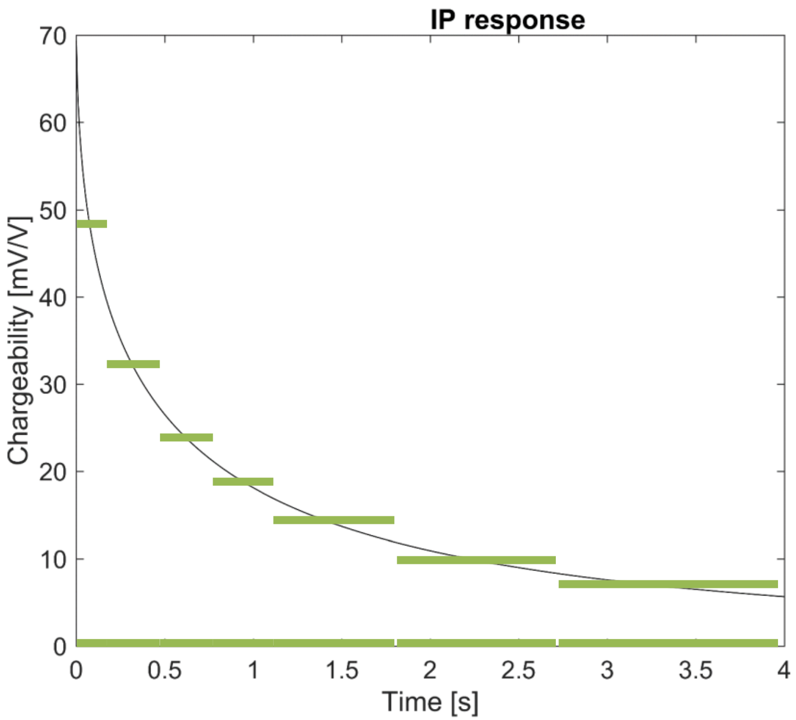
e.g. Cole-Cole model

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

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!

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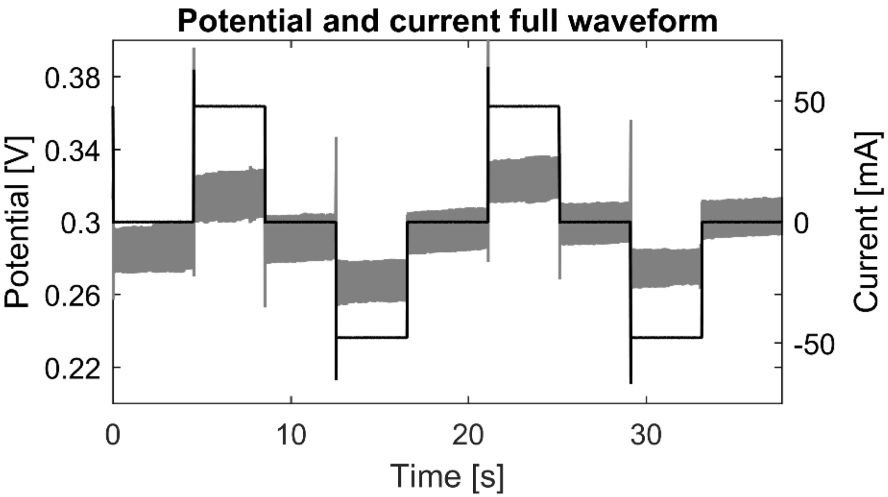
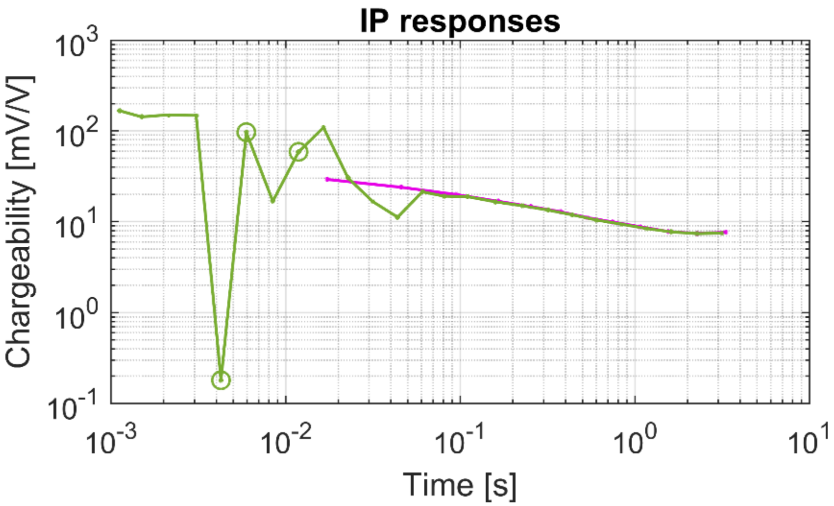
Processing today





Linear background drift removal and log-gating:

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

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

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Processing challenges

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

$$u_{measured} = u_{response} + u_{drift} + u_{spikes} + u_{harmonic\,noise} + u_{other}$$

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Background drift

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

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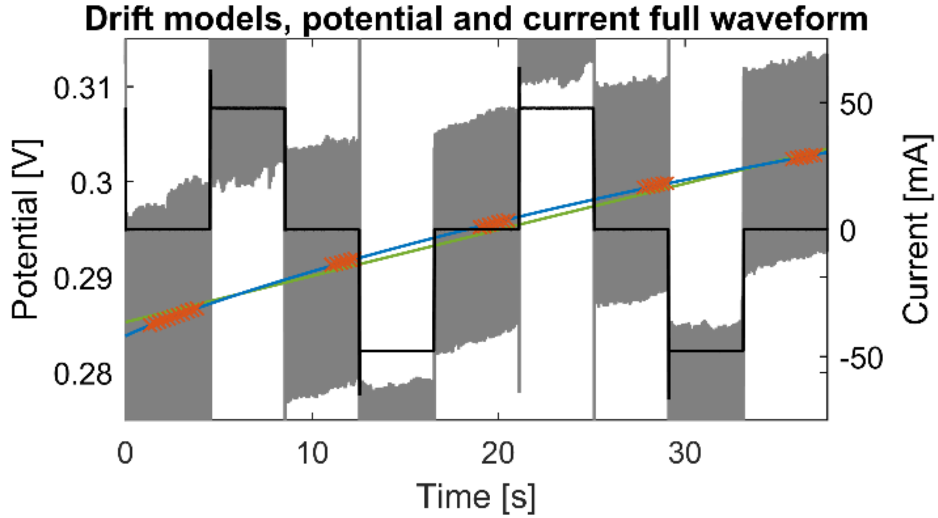
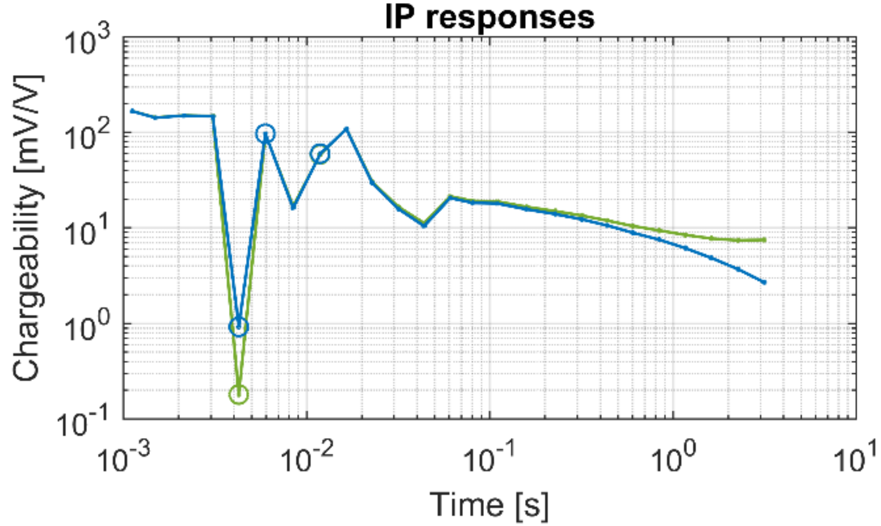
Background drift





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.

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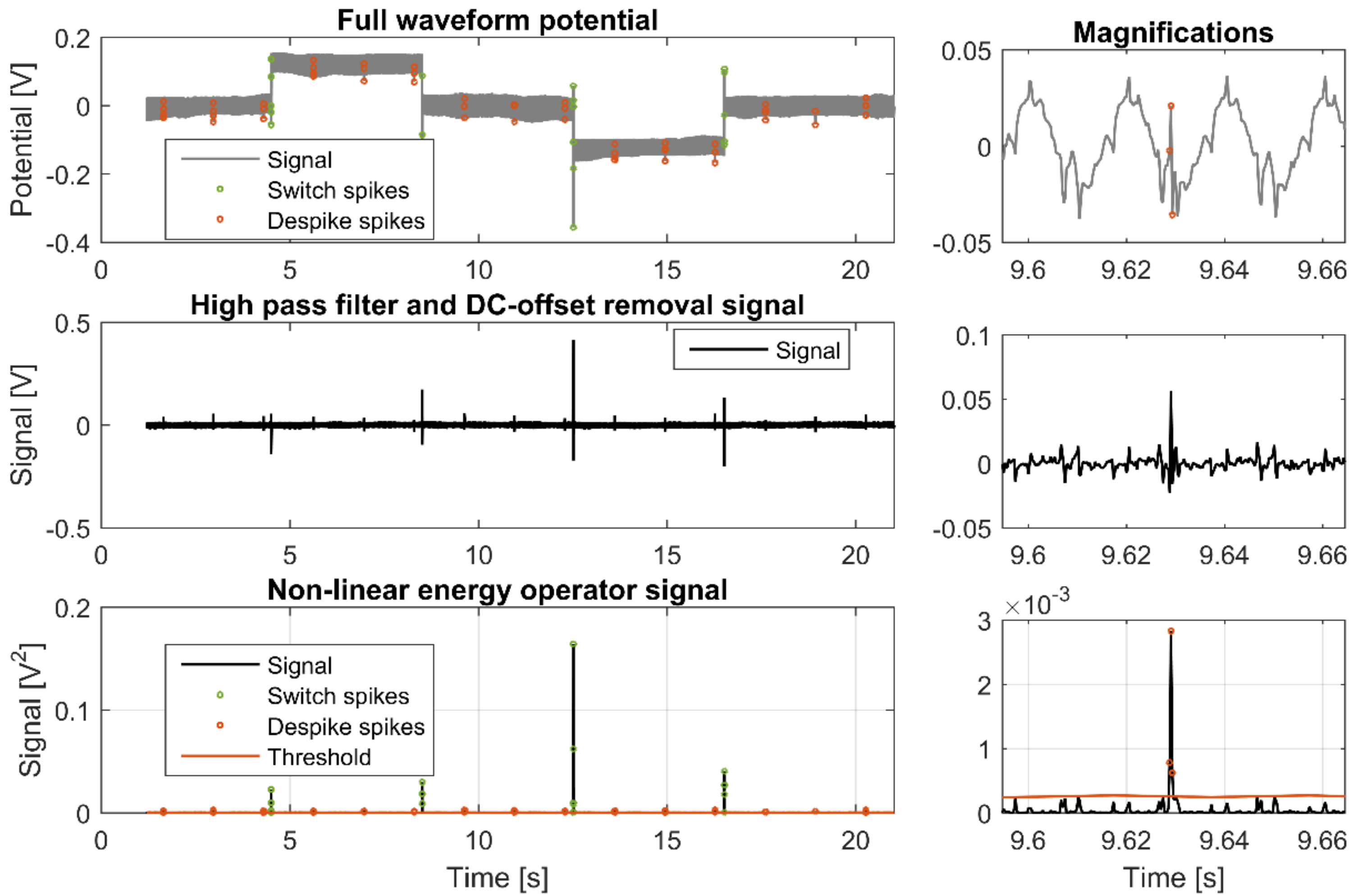
Spikes

Electrical fences for livestock management.

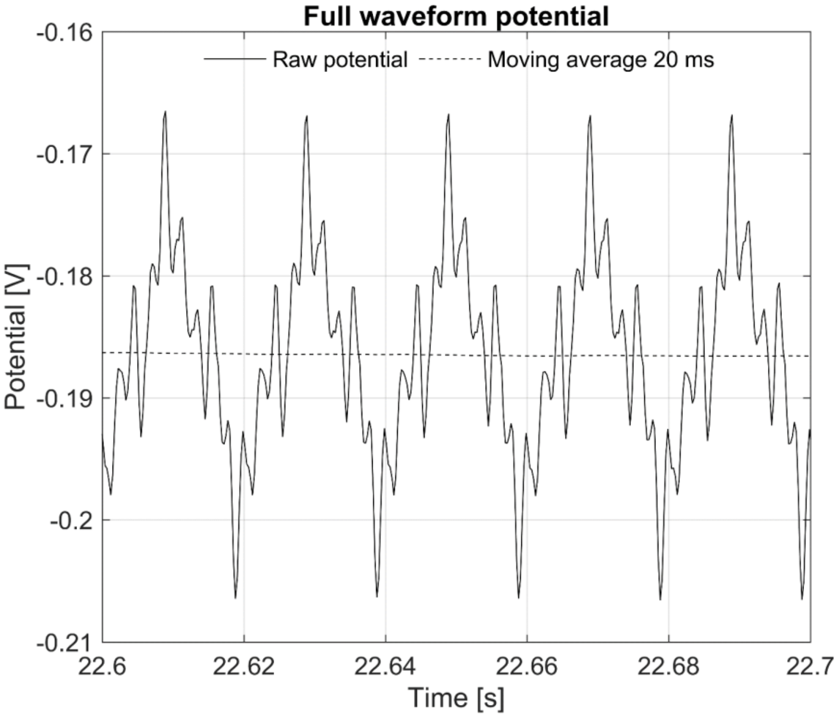
EM coupling from current pulse transients.

Spikes



Full waveform potential
Potential [V]
Signal
Switch spikes
Despike spikes
Magnifications
High pass filter and DC-offset removal signal
Signal [V]
Signal
Non-linear energy operator signal
Signal [V^2]
Signal
Switch spikes
Despike spikes
Threshold
×10^-3
Time [s]
Time [s]

Harmonic noise



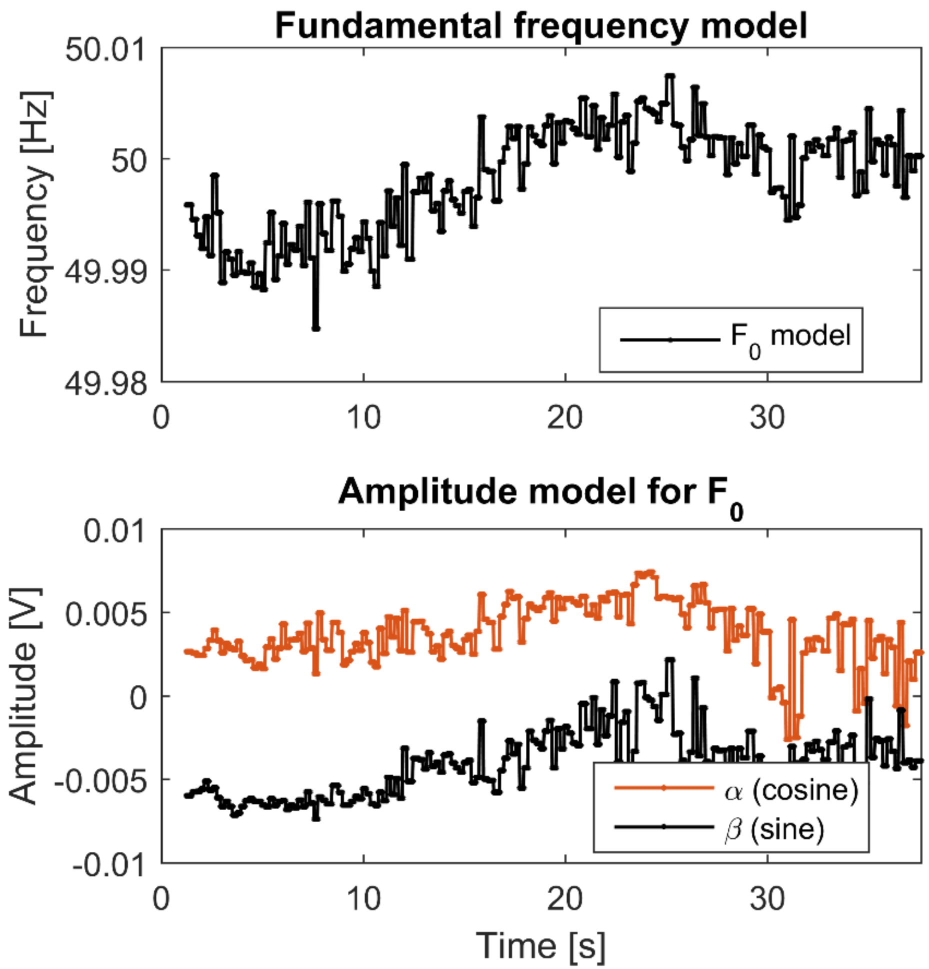
Harmonic noise

$$u_{harmonic\,noise}(n) = \sum_m \left(\alpha_m \cos\left(2\pi m \frac{f_0}{f_s} n\right) + \beta_m \sin\left(2\pi m \frac{f_0}{f_s} n\right)\right)$$

$$E_{residual} = \sum_n \left(u_{measured}(n) - u_{harmonic\,noise}(n)\right)^2$$

Minimizing $E_{residual}$ to find parameters α_m, β_m and f_0.

Harmonic noise



Signal is segmented so that α_m, β_m and f_0 variation is small.

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

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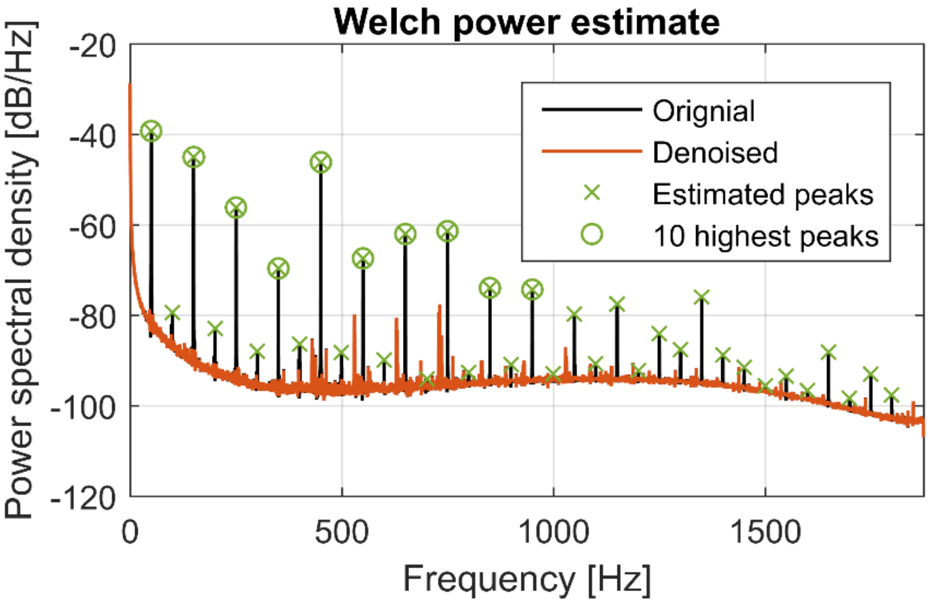
Harmonic noise



f_0 and harmonics energy is reduced to “baseline energy”.

A subset of highest harmonics is used for finding f_0.

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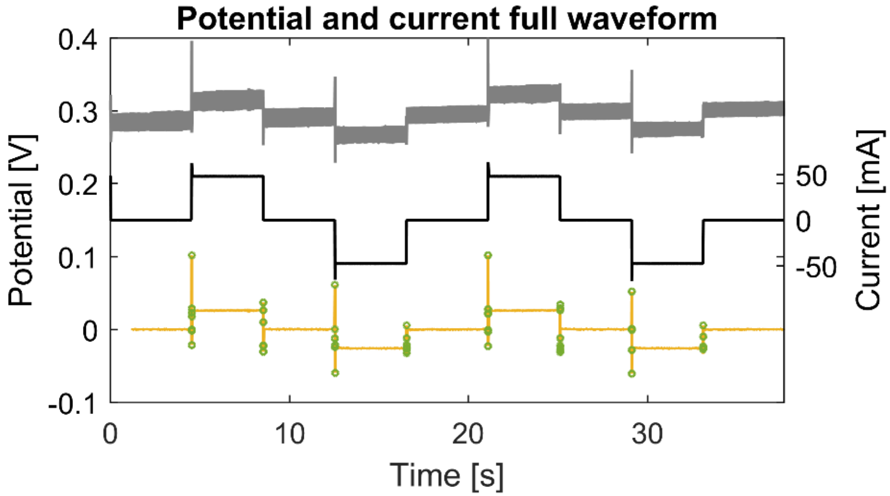
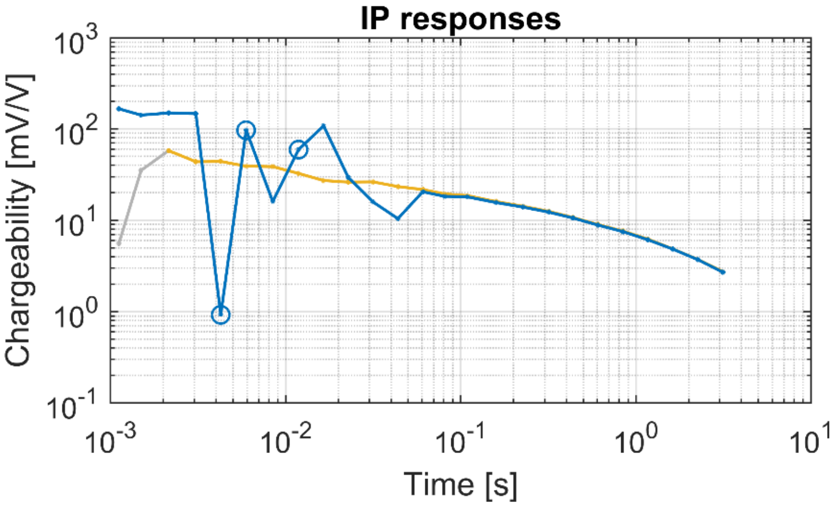
Harmonic noise

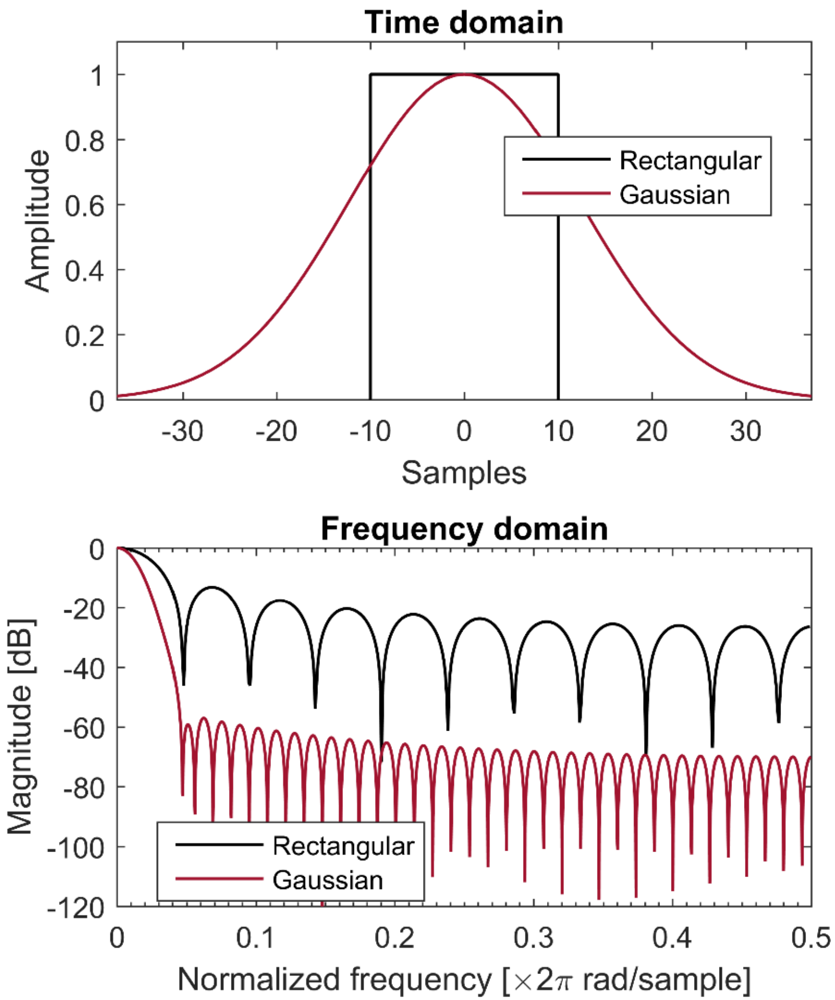




Erratic behaviour at early times is removed.

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!

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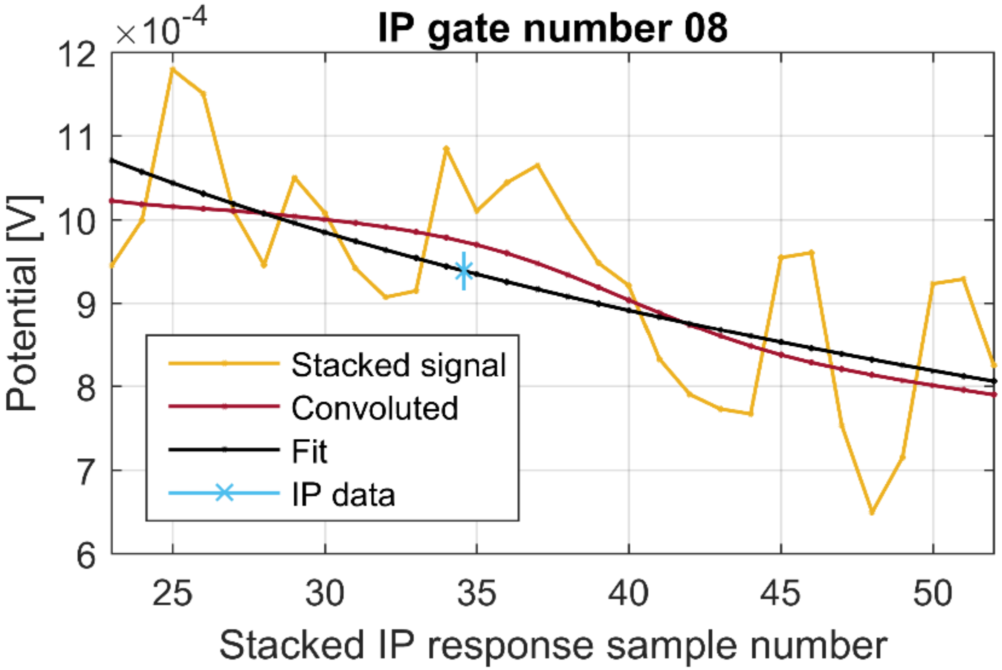
Tapered gating



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.

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Uncertainty estimate

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

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

$$STD_{gating} = \sqrt{\frac{1}{N_{gate\ samples}} \sum_{n=1}^{N_{gate\ samples}} (convoluted\ data(n) - linear\ fit(n))^2}$$

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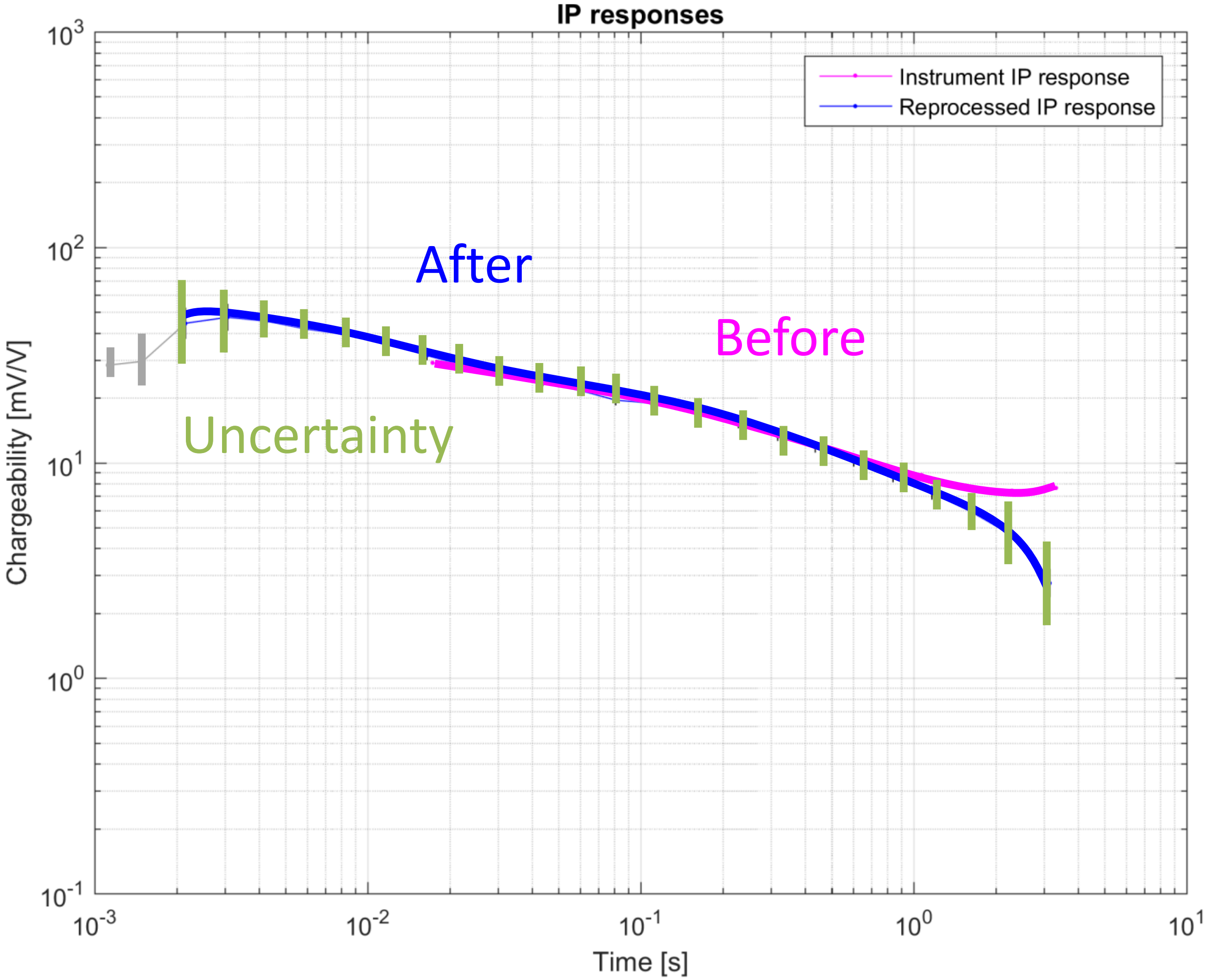
Spectral information content



Spectral information content

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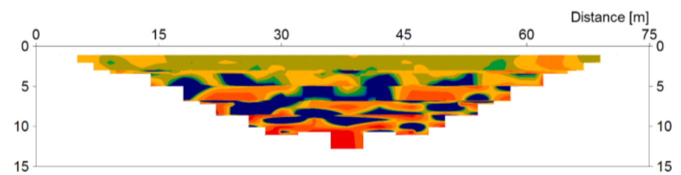
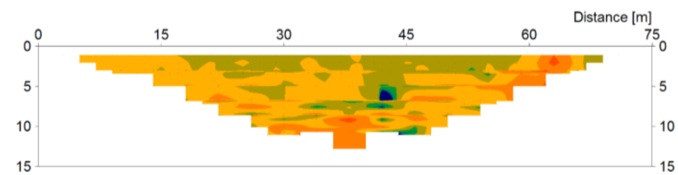
<tr><td>3</td><td>2</td><td>
</td><td>
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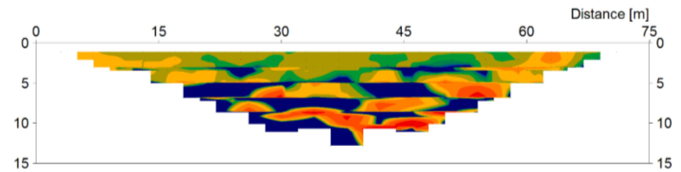
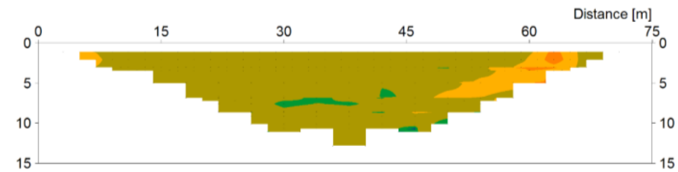
<tr><td>9</td><td>17</td><td>
</td><td>
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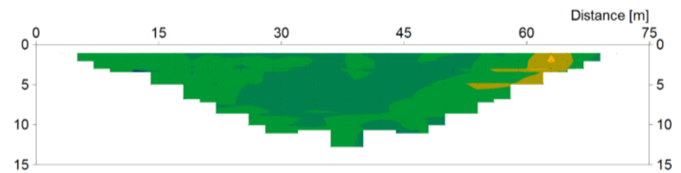
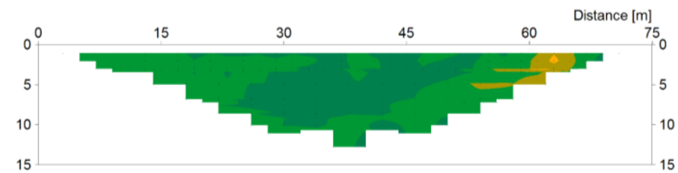
<tr><td>18</td><td>310</td><td>
</td><td>
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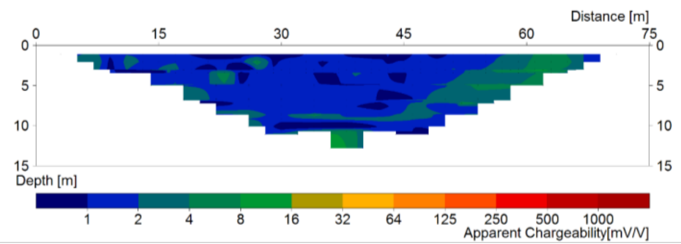
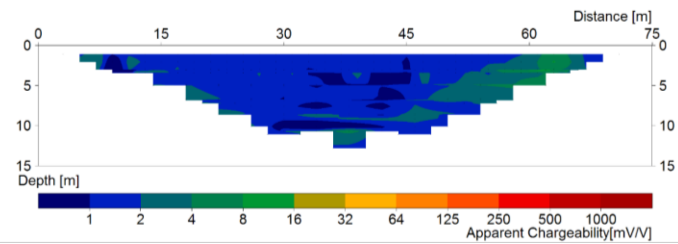
<tr><td>25</td><td>3160</td><td>
</td><td>
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Conclusions

- 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.

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Thank you for listening!

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Spikes

$$u_2(n) = u_{measured}(n) - u_{measured}(n-1)$$
$$u_3(n) = abs(u_2(n)^2 - u_2(n-1)u_2(n+1))$$

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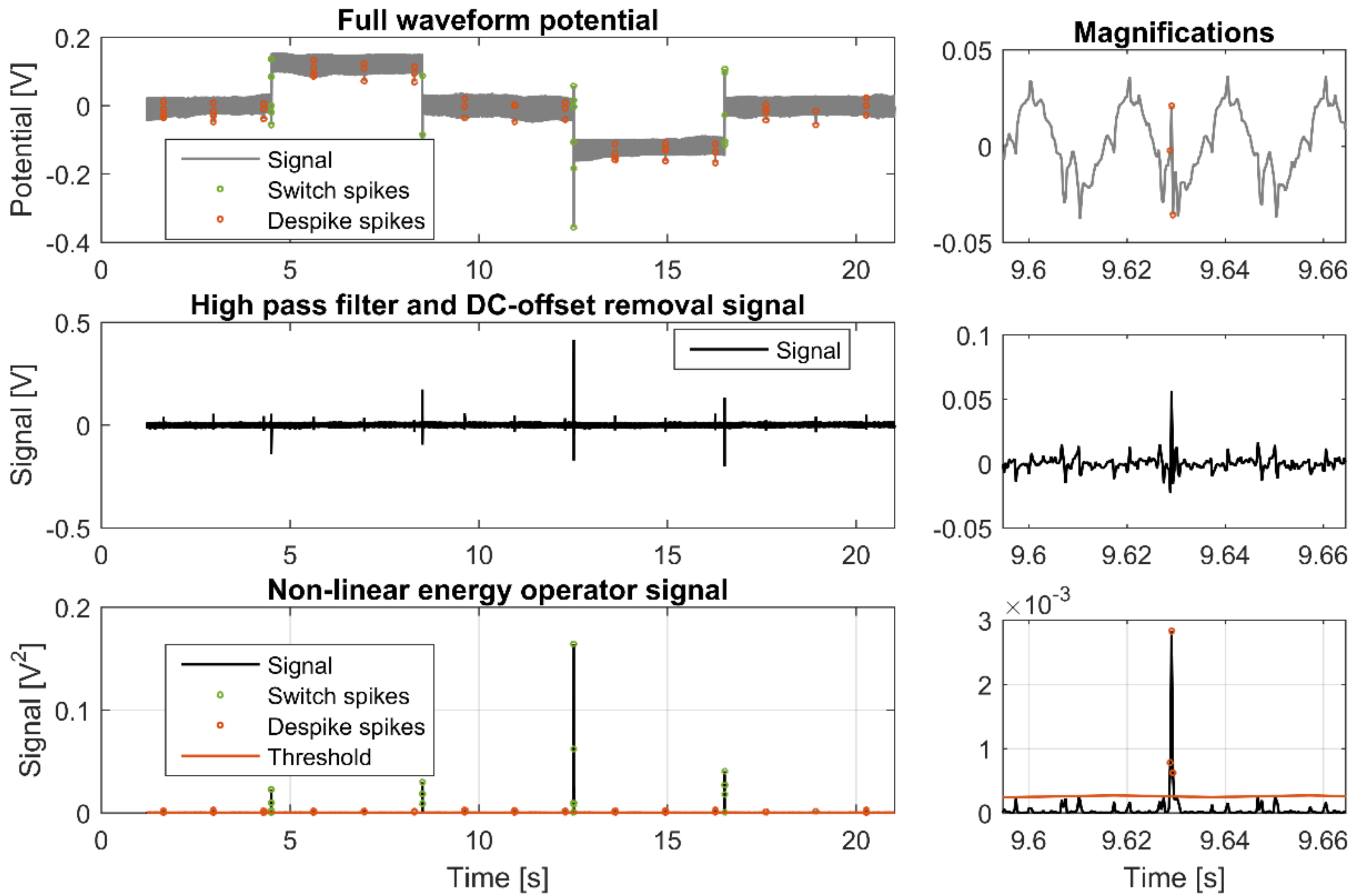
Spikes


Full waveform potential
Potential [V]
Signal
Switch spikes
Despike spikes
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High pass filter and DC-offset removal signal
Signal [V]
Signal
Non-linear energy operator signal
Signal [V^2]
Signal
Switch spikes
Despike spikes
Threshold
$\times 10^{-3}$
Time [s]
Time [s]

Tapered gating

$$u_{IP,stacked}(k) = \frac{1}{N_{pulses}} \sum_{j=1}^{N_{pulses}} (-1)^{j+1} u_{processed}(k + S_{IP}(j) - 1)$$

$$u_{IP,gated}(m) = \frac{1}{N_{samples}(m)} \sum_{i=1}^{N_{samples}(m)} u_{IP,stacked}\left(i + S_{gate}(m) - 1\right)$$

$$w_m(i) = e^{-\frac{1}{2}\left(\alpha \frac{i}{(N_{window}(m)-1)/2}\right)^2}; \quad |i| \le (N_{window}(m) - 1)/2$$

$$u_{IP,conv(m)}(j) = \frac{1}{\sum w_m} \sum_{i=-\frac{N_{window}(m)-1}{2}}^{\frac{N_{window}(m)-1}{2}} u_{IP,stacked}(j + S_{gate}(m) - 1 - i) w_m(i)$$

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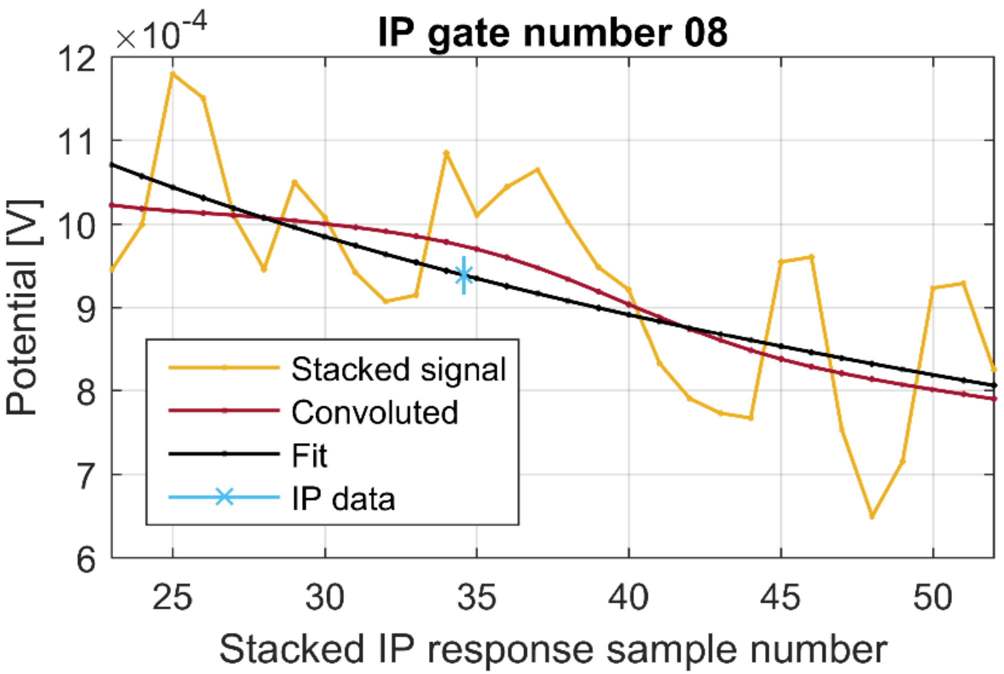
Tapered gating



Gaussian windows 3.5 times wider than gate.

40 dB noise suppression for higher frequencies!

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