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Doubling the spectrum of time-domain induced polarization: removal of non-linear self-potential drift, harmonic noise and spikes, tapered gating, and uncertainty estimation

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SUMMARY

This paper presents an advanced signal processing scheme for time-domain induced polarization full waveform data. The scheme includes several steps with an improved induced polarization (IP) response gating design using convolution with tapered windows to suppress high frequency noise, a logarithmic gate width distribution for optimizing IP data quality and an estimate of gating uncertainty. Additional steps include modelling and cancelling of non-linear background drift and harmonic noise and a technique for efficiently identifying and removing spikes. The cancelling of non-linear background drift is based on a Cole-Cole model which effectively handles current induced electrode polarization drift. The model-based cancelling of harmonic noise reconstructs the harmonic noise as a sum of harmonic signals with a common fundamental frequency. After segmentation of the signal and determining of noise model parameters for each segment, a full harmonic noise model is subtracted. Furthermore, the uncertainty of the background drift removal is estimated which together with the gating uncertainty estimate and a uniform uncertainty gives a total, data-driven, error estimate for each IP gate. The processing steps is successfully applied on full field profile data sets. With the model-based cancelling of harmonic noise, the first usable IP gate is moved one decade closer to time zero. Furthermore, with a Cole-Cole background drift model the shape of the response at late times is accurately retrieved. In total, this processing scheme achieves almost four decades in time and thus doubles the available spectral information content of the IP responses compared to the traditional processing.

Key words: Spectral induced polarization; Time-domain; Signal processing; Uncertainty estimate; Electrical properties;

INTRODUCTION

Recently, the interpretation and inversion of time-domain induced polarization (TDIP) data has changed. Research is moving from only inverting for the integral changeability to also consider the spectral information and inverting for the full induced polarization (IP) response curves. Furthermore, efforts have been made to achieve faster acquisitions and better signal-to-noise ratio (SNR) by using a 100% duty cycle current waveform, without current off-time, for TDIP measurements. However, there still remains drawbacks for the spectral TDIP

measurements, especially its limited spectral information content compared to for example laboratory frequency-domain spectral IP measurements (Revil et al., 2015). To date, only limited work has been done on increasing the spectral information content in TDIP measurement data even though recent developments in TDIP acquisition equipment have enabled access to full waveform recordings of measured potentials and transmitted current (e.g. the Terrameter LS and the Elrec pro). This paper presents a full waveform processing scheme for handling multiple issues limiting the spectral information quality and content. These issues are handled separately starting with background drift removal which is followed by identifying spikes, harmonic denoising, spike removal, tapered gating and uncertainty estimation.

DATA ACQUISITION

To be able to apply the processing scheme described in this paper it is necessary to use an instrument that is capable of recording full waveform data of the measured potentials. The required sampling rate for the full waveform depends mainly on the desired width of the shortest gate, how close it should be to the current switch and avoiding of aliasing. The data presented in this paper were acquired with a 50% duty cycle current waveform and 4s on-time using a Terrameter LS instrument for transmitting current and measuring potentials. The instrument operates at a sampling rate of 30 kHz and applies digital filtering and averaging depending on selected data rate. A data rate of 3750 Hz, corresponding to approximately 0.267 ms per sample, was used for the measurements presented in the paper. The sampling rate was chosen for being able to have the first IP gate one millisecond from the current pulse, considering that earlier gates would certainly suffer from EM-effects which we at present want to avoid, it was not judged meaningful with earlier gates. The instrument input filters were modified with a 4th order Butterworth filter with cutoff frequency of 1.5 kHz to avoid aliasing.

Two TDIP profiles (74 meter, 38 electrodes with spacing of two meter) were acquired on a grass field in Aarhus University Campus, with presence of multiple noise sources common in urban environments. The profiles were acquired with the instrument and settings as described in the previous paragraph, a multiple gradient protocol (364 quadrupoles) and acid-grade stainless steel electrodes.

IP GATE DISTRIBUTION

For retrieving spectral information close to the current pulses there is a need for gates which are shorter than the time-period of the harmonic noise (i.e. shorter than 20 ms for 50 Hz). This

is achieved by applying a log-increasing gating scheme that compensates for changes of signal-to-noise ratio throughout the IP response (Gazoty et al., 2013). When the gates are wide enough they are rounded off to multiples of the time period of the harmonic noise (Table 1, seven gates per decade). Thus, this gate distribution gives access to the IP response information more than one decade closer to the current pulse but still makes use of the efficient noise suppressing gate widths when possible.

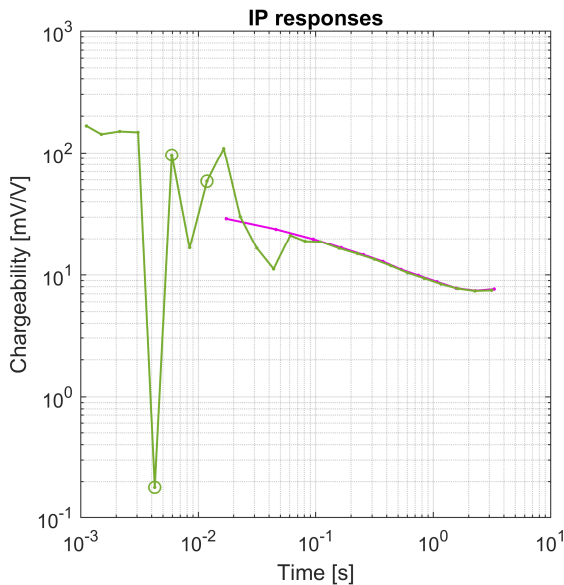


Figure 1. An IP response binned with gates that are multiples of 20 ms and delay of 10 ms (magenta, instrument output) and a re-gated IP response according to Table 1 and linear drift removal. Negative values are marked with circles.

Figure 1 shows the resulting IP response (green) after gating according to Table 1 and stacking according to the standard procedure (Fiandaca et al., 2012) when using a linear background drift estimate and the IP response retrieved from the instrument (magenta). The re-gated IP response shows similar magnitude as the instrument supplied when the gates are multiples of 20 ms. Contrastingly, it exhibits an erratic behaviour until the gate widths for both responses are multiples of 20 ms and suppress the 50 Hz harmonic noise (approximately at 60 ms). Clearly, the harmonic noise needs to be assessed to enable the use of gates shorter than 20 ms. Furthermore, the tail of both IP responses is increasing at the end as a result of the poor performance of the background drift removal when applying a linear drift model. Thus, to accurately retrieve the shape and spectral content of the IP response it is crucial to improve the drift removal by applying a more flexible drift model.

SIGNAL PROCESSING

During TDIP measurements the potential response of the injection needs to be determined. However, the potential measured in the field is composed of the sum of multiple, known and unknown, sources. The known noise sources are handled separately in the processing scheme described in this paper and applied in a sequential manner. The first processing scheme step is drift removal which is followed by identifying spike samples, harmonic denoising, spike removal, tapered gating and uncertainty estimation.

Cole-Cole model-based drift removal

The background drift removal is normally done by approximating the drift as a linear trend (Dahlin et al., 2002). The background drift caused by current-induced electrode polarization is known to be orders of magnitude larger than the signal (Dahlin, 2000) and is common during field surveys due to difficulties of designing meaningful measurement sequences that account for all recent current injections. Electrode contact tests performed before initiating the TDIP measurements is also source for current induced electrode polarization. This background drift is caused by a depolarization phenomenon which is well described by the Cole-Cole model, thus this model is especially suitable for estimating the background drift. Two background drift estimates are used in this paper: the first with a linear estimate and the second with a Cole-Cole estimate.

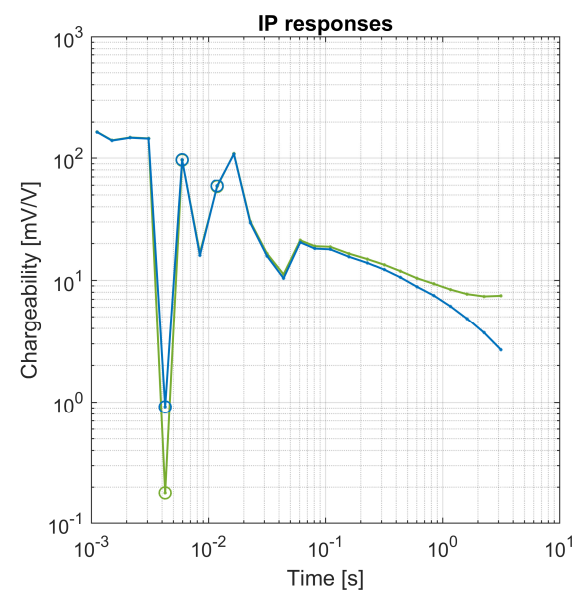
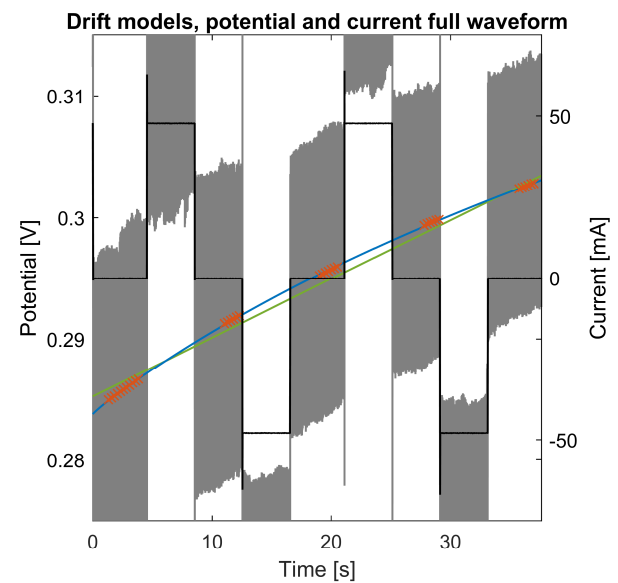


Figure 2. Top: full waveform potential (grey) and current (black), subset of the signal used for finding the drift model (orange x-marker) and background drift models (green: linear model, blue: Cole-Cole model). Bottom: resulting gated IP-response curves. Negative values are marked with circles.

To reduce the risk of any harmonic noise or IP response interfering with the drift model data, the fit is conducted for a subset of a down-sampled signal, taken at the end of the off-time period for the 50% duty-cycle and on-time period if applying a 100% duty-cycle current waveform. Fig. 2 show examples of generated drift models, as well as the resulting IP responses after gating and stacking the signal. Clearly, the linear model is not sufficient for accurately describing the drift in the full waveform potential and as a result it gives unrealistic increasing chargeability values for late gates of the IP response. Contrastingly, the Cole-Cole model shows a good fit to drift data and consequently the resulting IP response does not exhibit the erroneous behavior at late gates. In total, it is clear that a linear drift model gives incorrect IP responses, especially at late times when signal-to-noise ratio is smaller and that a more advanced drift model such as the Cole-Cole is needed.

Model-based cancelling of harmonic noise

The processing approach applied in this paper is similar to the processing successfully applied on data from other geophysical methods, for example magnetic resonance soundings (Larsen et al., 2013) and seismoelectrics (Butler and Russell, 1993) but it has in this case been adapted to be applicable for data from TDIP measurement. The method takes a model-based approach for processing the TDIP full waveform potential by describing the harmonic noise in terms of a sum of harmonic signals. The different harmonic signals have frequencies given by a common fundamental frequency (f_0) multiplied with an integer (m) to describe the different harmonics but have independent amplitudes (α_m and β_m) for each harmonic m :

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

for sample index n and sampling frequency f_s . The reader is referred to the mentioned references for details.

Removal of full waveform spikes

Despiking of the measured full waveform signal is done for two main reasons. The first reason is that spikes in the full waveform data can corrupt the integrated values for IP gates, especially for short gates consisting of a few samples when only part of the spike falls within the gate thus having large effect on the integrated value. The second reason is related to the modelling of the harmonic noise and how the finding of noise model parameters is implemented in this paper which is known to be sensitive to spikes in data (Larsen et al., 2013).

The method for finding the spikes used in this paper employs several steps to enhance the spikes in the signal and defines a data-driven, automatic threshold limit based on a Hampel filter (Pearson, 2002) to determine if a sample index is to be considered as spike or not. By applying the filters in this manner an automatic data-driven threshold variable along the full-waveform acquisition is defined. All the samples above the threshold are marked as spikes and are neglected when performing the calculations for the residual energy in the harmonic denoising procedure. After harmonic denoising are the spike sample values replaced by the mean of their non-spike neighbours in the denoised signal.

Tapered gate design and error estimation

Today, the standard procedure for gating IP is to average the data within the predefined IP gates, corresponding to a discrete and normalized convolution with a rectangular window. In other geophysical methods (e.g. electromagnetic) a gate method applying different kinds of tapered windows have been used since decades (Macnae et al., 1984). Tapered window functions are superior in suppressing high frequency noise compared to

the rectangular counterpart. Furthermore, the tapered windows allow the use of wider gates which has higher noise suppression, without distorting the signal. In this paper, a Gaussian window with 3.5 times the width of the traditional rectangular window width was applied before evaluating the IP gate values. With this window, the main frequency response lobe of both windows cuts at approximately the same normalized frequency but the side lobes of the Gaussian window have around 40 dB higher frequency suppression.

Uncertainty estimation of the data for individual IP gates cannot be retrieved by directly comparing the individual IP stacks because each individual stack is different due to superposition from previous pulses (Fiandaca et al., 2012), hence other approaches are needed. It is also desirable that an uncertainty estimate make use of the advantage of applying the convolution with tapered gates as described in this paper. If enough gates per decade are used for gating the data, the signal variability is almost linear within the gates and for IP signals the linearity is more evident in lin-log space. Thus, it is possible to use a linear fit of the convoluted gate in lin-log space for estimating the gate uncertainty by taking the difference between the fit and the convoluted gate data. The difference gives a measure of the noise content within the gate after the convolution.

FULL FIELD PROFILE PROCESSING EXAMPLE

The processing scheme presented in this paper has been successfully applied to the entire test datasets with substantial improvements in spectral information content, data reliability and quality. One of the datasets is presented here as an illustration. Figure 4 shows IP responses from instrument processing and the redesigned processing scheme presented by this paper. The spurious IP increase present at late times in the response retrieved by the instrument is removed in the reprocessed IP response as a result of the improved drift removal. At the same time, the harmonic denoising processing enables to retrieve reliable IP data already 2.2 ms after the current switch, one decade closer to time zero compared to instrument IP processing.

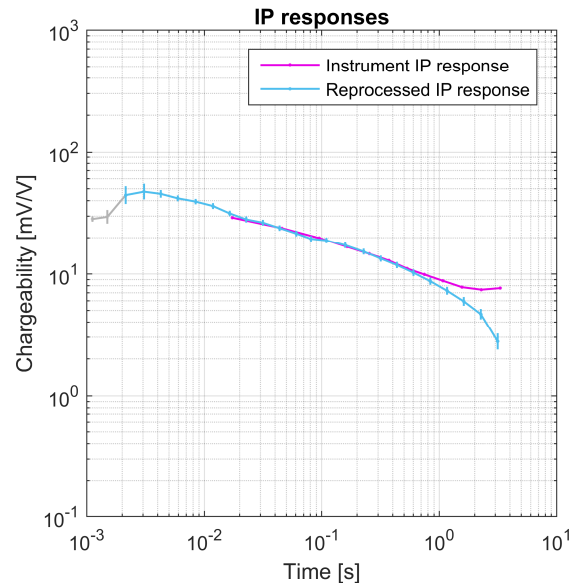


Figure 4. IP responses from instrument processing (magenta, instrument output) and the redesigned processing scheme presented by this paper (light blue) with error bars corresponding to one STD. Gates rejected by processing for containing spikes are marked in grey.

Figure 5 shows pseudosections for a full data set acquired on the same profile as the previous data example was extracted from. It shows gates for IP responses generated by the full signal processing routine and corresponding pseudosections for the same gates but only applying the linear background drift removal. For the early gates which are not a multiple of the time period of the harmonic noise there is a clear improvement with much smoother pseudosection from gate 3 and higher. Contrastingly, IP gate number 18 which is little affected by the background drift removal shows very similar pseudosections for the two processing examples. However, the pseudosections for the last IP gate (25) show some difference due to the sensitivity of the late gates for background drift estimates where the linear drift model sometimes causes the IP responses to increase at late times. Again, the improved processing with Cole-Cole drift estimate shows smoother variation in the pseudosection, especially on the left side.

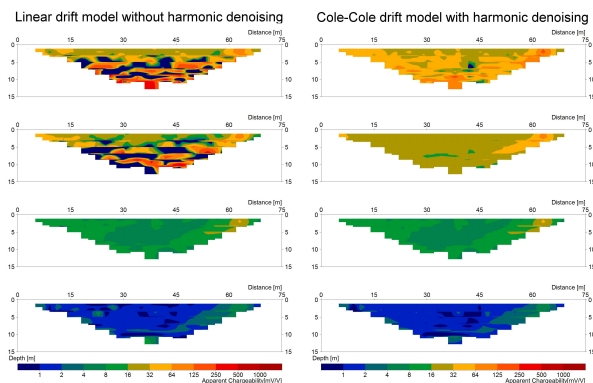


Figure 5. Pseudosections for IP gates 3, 9, 18 and 25 (from top-down) for processed data without harmonic denoising and linear drift removal (left) and with harmonic denoising and Cole-Cole drift removal (right) of full waveform data.

CONCLUSIONS

The TDIP signal processing scheme described in this paper significantly improves the handling of background drift, spikes and harmonic noise superimposed on the potential response in the measured full waveform potential. The Cole-Cole background drift removal substantially increases the accuracy of the drift model for non-linear drift cases and recovers the shape of the IP response at late times. The reliability of early IP response times, down to a few ms, is generally increased with a flexible data-driven despiking algorithm and model-based harmonic denoising. Furthermore, the improved gate distribution and tapered design gives access to early spectral IP response information and overall increases the signal-to-noise ratio by applying tapered and overlapped gates without distorting the IP response. Additionally, the data driven uncertainty estimates of the individual IP gate values provides valuable information for assessing data quality and for succeeding spectral inversion. In total, this processing moves the first gate one decade closer to time zero, recovers the late gates with reduced bias and supplies valuable estimates of IP gate uncertainty. These improvements double the usable spectral information of the IP response, achieving almost four decades in time, compared to instrument processing procedure.

Table 1. Duration of delay time and IP gates for the processed field data corresponding to seven gates per decade. Note that the width of the gates from 13 and higher are multiples of 20 ms.

Gate number	Delay	1	2	3	4	5	6	7	8	9	10	11	12
Width [ms]	1	0.26	0.53	0.80	1.06	1.33	2.13	2.93	4	5.33	7.46	10.4	14.4
Gate number	13	14	15	16	17	18	19	20	21	22	23	24	25
Width [ms]	20	20	40	60	60	120	120	180	300	360	540	780	1020

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