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Processing of surface-nuclear magnetic resonance data from sites with high noise levels

Jakob Juul Larsen¹ and Ahmad A. Behroozmand²

ABSTRACT

The applicability of surface nuclear magnetic resonance (NMR) in investigations of groundwater is often limited by high noise levels in many areas of interest. We have evaluated measurements from a high-noise-level area in Ristrup, Denmark, recorded with a Numis Poly instrument. Standard multichannel filtering techniques for noise reduction are inadequate for several data sets acquired in this area, and surface-NMR signals cannot be resolved from the acquired data. Based on a careful assessment of the frequency content of the data, we have determined how a model-based noise reduction approach can be generalized and used to subtract two harmonic noise components from the data. Reliable surface-NMR data can be extracted from the noise-reduced data. Moreover, we have determined the impact of the proposed processing approaches on our inversion results, and we have also developed an example in which the proposed methodology allowed us to reveal and avoid an otherwise overlooked contamination of the reference coil signals with a surface-NMR signal. No borehole data were available for the investigated sites, and the validity of the noise reduction approach was instead verified using a synthetic five-layer model embedded in noise-only records from Ristrup. Our results have determined that a careful processing of the recorded data made it possible to extract surface-NMR data in more places of interest.

INTRODUCTION

Surface nuclear magnetic resonance (NMR) is potentially an efficient method for exploration of groundwater systems in the near subsurface, i.e., within the top 100 m of the subsurface. The method

can provide depth-resolved estimates of the water content and the hydrologic properties of the geologic layers (Hertrich, 2008; Legchenko, 2013; Behroozmand et al., 2015a). Despite the vast hardware and software developments (Trushkin et al., 1994; Hertrich et al., 2005; Radic, 2006; Walsh, 2008; Jiang et al., 2011; Walsh et al., 2011; Dalgaard et al., 2012; Costabel and Müller-Petke, 2014; Larsen et al., 2014; Müller-Petke and Costabel, 2014), the applicability of the method is, however, often limited by the signal-to-noise ratio (S/N), which is often very poor due to electromagnetic noise (Legchenko, 2007; Chalikakis et al., 2008). A one-size-fits-all noise reduction strategy has yet not been obtained, and the detrimental effect of electromagnetic noise is a hurdle that must be overcome before widespread use of surface NMR becomes feasible.

One challenge of noise reduction of surface-NMR signals is the fact that the noise field affecting the measurements can be highly complex. Typically, the noise field contains components from several sources, and the noise level from each source is often nonstationary (Dalgaard et al., 2014). Analysis and discussions of the noise sources affecting surface-NMR measurements have been done by several authors (Walsh, 2008; Dlugosch et al., 2011; Dalgaard et al., 2012, 2014; Costabel and Müller-Petke, 2014; Larsen et al., 2014). The general conclusion is that surface NMR is mainly affected by two types of noise: harmonics of the fundamental powerline frequency from electrical installations and impulsive noise, known as spikes, typically originating from electric fences or thunderstorms.

Comparing the noise levels and characteristics at different sites is surprisingly difficult. First, the noise from powerline harmonics is mostly only slowly varying over short periods of time and can be classified as a power signal. Spikes are, by nature, short-time events, and they are classified as energy signals. Hence, different statistical measures are needed to describe the two noise types. Second, both types of noise can vary greatly throughout a day and among consecutive days. Third, the instruments from different manufacturers apply different analog filters to the signals and thus change the measured noise levels. Fourth, square and figure-8 coil geometries in various sizes are used in the field. A full description of the noise

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¹Aarhus University, Department of Engineering, Aarhus N, Denmark. E-mail: jjl@eng.au.dk.

²Stanford University, Department of Geophysics, Stanford, California, USA. E-mail: abehrooz@stanford.edu.

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field hence warrants detailed measurements of the statistical properties and the time dependence of the different components in the noise field. Such detailed descriptions may not be of much practical use when simple, interpretable numbers are preferred.

The situation is further complicated by the fact that the signal and the noise vary greatly from site to site. As an example, many of our field campaigns have been carried out in Jutland, Denmark, where the water content is generally high and the surface-NMR signals are correspondingly high. However, the noise levels are also high due to man-made electromagnetic noise, and the S/N is poor. In a recent project on investigating coastal aquifers contaminated by saltwater intrusion, surface-NMR measurements were made in the Nubariya region, northern Egypt (Behroozmand et al., 2015b). In this area, the noise levels are much lower than in Denmark, but the water content and, hence, the surface-NMR signals are much lower. Typical S/Ns are more or less identical for the two cases, but the optimum data acquisition and noise reduction strategies are different for the two cases.

In an ongoing project on improving groundwater management by integrating geology, geophysics, and hydrologic modeling (HyGEM, 2012), several geophysical and hydrologic studies have been carried out in Ristrup, near Aarhus, Denmark. Large variations in the noise levels of the acquired surface-NMR data sets were found. For low noise measurements, the surface-NMR signals were easily extracted using standard multichannel noise mitigation strategies. For the high-noise-level measurements, however, the standard methods fail to reveal surface-NMR signals. The purpose of this paper is to show how a thorough analysis of the noise field at the high-noise-level sites has enabled us to devise an efficient strategy for noise reduction. By tailoring of noise models and noise reduction strategies, valuable data have been retrieved.

The outline of the paper is as follows: In the next section, an overview of noise sources affecting surface-NMR measurements and methods for noise reduction of surface-NMR data are presented. The paper proceeds with examples of surface-NMR measurements from two high-noise sites, where multichannel Wiener filtering is found to be inadequate for noise reduction. A detailed analysis of data from one of the sites shows that the noise contains two harmonic series. A generalization of the model-based approach for harmonic noise subtraction is developed and shown to improve noise reduction. The generalized model-based approach is used on data from the second site, where it allows us to identify an otherwise overlooked contamination with NMR signal in reference coils. Inversion of field data processed with either multichannel Wiener filtering or with harmonic noise subtraction gives markedly different subsurface models. The impact of the improved noise reduction on inversion is assessed by processing of a synthetic five-layer embedded in noise-only data.

NOISE REDUCTION OF SURFACE-NMR SIGNALS

Techniques implemented in hardware and software have been devised for improving the S/N in surface NMR. One major distinction is between single channel and multichannel instruments. In single channel instruments, the NMR excitation and detection is done with one primary coil. In multichannel instruments, one or several reference coils are placed distant from the primary coil and synchronously measure the local noise field. By filtering, the noise in the reference channels can be turned into an estimate of the noise in the primary channel and subtracted to leave a noise-reduced NMR sig-

nal (Radic, 2006; Walsh, 2008; Dlugosch et al., 2011; Dalgaard et al., 2012; Müller-Petke and Costabel, 2014).

Although the subtraction of reference coil noise has been used successfully in many places, the method is inadequate in complex multi-source noise environments (Larsen et al., 2014). If the noise contains components from several sources, the optimum filters for noise reduction are different for each component. When only a single filter is applied, as current methodology enforces, the result is that the overall efficiency of the noise reduction is lowered or that only a single noise component is reduced depending on how the filter was designed.

When data sets are acquired at a site, near-stationary segments of data without surface-NMR signal and spikes can easily be identified in the late parts of the records. From these segments, root-mean-square (rms) values can be calculated and used as a simple mean to quantify the noise level. The rms noise level can easily be traced through the signal processing chain as the noise is reduced by subtraction, filtering, and stacking.

The noise reduction methods of surface-NMR data used in this paper entail removal of spikes, removal of powerline harmonic noise, and removal of other forms of correlated and uncorrelated noise as explained in the following paragraphs.

Spike identification and removal

The signal $p(k)$ from the primary channel of a surface-NMR instrument sampled at time k can be decomposed as (Larsen et al., 2014)

$$p(k) = \text{NMR}(k) + h_p(k) + \text{spikes}_p(k) + N_p(k), \quad (1)$$

where $\text{NMR}(k)$ represents the NMR signal from the protons in the subsurface water, $h_p(k)$ represents the harmonic powerline interference in the primary channel, and spikes in the primary channel signal are denoted by $\text{spikes}_p(k)$. All other noise components in the primary channel, e.g., receiver electronic noise, are collectively denoted by $N_p(k)$.

In this paper, we use the method of spike identification and removal suggested by Dalgaard et al. (2012). Spikes are pre-emphasized by applying a nonlinear energy operator to the data. An ensemble-based and time-dependent threshold based on the median absolute deviation is used to locate spikes. When the spike detection is used with multichannel surface-NMR data, the results from all channels are merged; i.e., if a spike is detected in one channel, the synchronous segments in the other channels are also labeled as spikes. In the subsequent data analysis, segments containing spikes are excluded.

Modeling noise from powerline harmonics

Extending on earlier work by Butler and Russell (1993) and Legchenko and Valla (2003), we have recently proposed a surface-NMR noise reduction scheme, in which the interference from powerlines is specifically dealt with by independent modeling and subtraction (Larsen et al., 2014). On short time spans of typically 1 s or less, the harmonic noise from powerlines can be considered stationary and are modeled as

$$h(k) = \sum_m A_m \cos\left(2\pi m \frac{f_0}{f_s} k + \phi_m\right). \quad (2)$$

The amplitude and phase of each harmonic are given by A_m and ϕ_m , respectively, and all sinusoidal components are related to the same fundamental frequency f_0 . The sampling frequency is denoted by

f_s . The summation extends over all harmonic components that are excited, in most circumstances $1 \leq m \leq 100$. With the Numis Poly instrument, most of the energy is found in the frequencies near the center of the band-pass filter.

For each measurement, the model parameters for the harmonic noise are determined using least-squares fitting (Larsen et al., 2014). Afterward, the noise model is subtracted from the measurement and a data set with greatly improved S/N remains.

The signals recorded in the reference coils of multichannel instruments are modeled as

$$r_i(k) = h_i(k) + \text{spikes}_i(k) + N_i(k), \quad (3)$$

where i labels the reference coils. Similar to the above model, the powerline interference can be described as

$$h_i(k) = \sum_m A_m^i \cos\left(2\pi m \frac{f_0}{f_s} k + \phi_m^i\right). \quad (4)$$

The amplitude and phase of the harmonics are unique for each channel, and are determined independently.

The signal energy located in spikes can be comparable with or exceed the energy in the harmonic content. Segments of data with spikes are identified using the spike identification algorithm and excluded when the model parameters are determined. The harmonic model is calculated for the entire record and subtracted from all data points. The subtraction greatly enhances the visibility of spikes, and small spikes that were initially masked by harmonic noise become visible. The identification of spikes and removal of harmonic noise is, therefore, carried out in three steps. First, big spikes are located and excluded from the determination of the harmonic noise model. Second, the harmonic noise model is determined and subtracted from the data. Finally, the spike identification is run again to locate previously undetectable spikes.

The basic assumption of the powerline harmonic model is that the frequency, amplitudes, and phases remain constant throughout a signal record. This assumption is obviously invalid for long signal records, but experimentally it is found that it holds true or nearly true for all practical purposes for signal records of 1 s or less. At sites with excessive noise, nonlinear saturation and clipping of the data can occur and render the noise model inapplicable.

A potential pitfall of the model-based subtraction approach occurs if one of the harmonic frequencies is close to the Larmor frequency, $mf_0 \approx f_L$. In this case, the surface-NMR signal is incorporated into the model and partly subtracted from the data. The result is a severe distortion of the surface-NMR signal. This problem is avoided by determining the parameters of the m th harmonic on the late part of the time series where the surface-NMR signal is vanishingly small and extrapolating the noise model to the entire time series (Larsen et al., 2014).

At sites where several harmonic components with different fundamental frequencies are present, the model-based subtraction approach can be generalized. Considering the case of two harmonic components, the noise model becomes $h(k) = h_I(k) + h_{II}(k)$ with

$$h_I(k) = \sum_m A_m \cos\left(2\pi m \frac{f_0}{f_s} k + \phi_m\right) \quad (5)$$

and

$$h_{II}(k) = \sum_m B_m \cos\left(2\pi m \frac{f_1}{f_s} k + \theta_m\right). \quad (6)$$

In practice, the noise subtraction is done by fitting the harmonic components sequentially.

An important benefit of model-based subtraction of noise is that one particular noise component is selectively removed. The complexity of the resulting noise in the data is, hence, reduced. This can be advantageous for subsequent multichannel filtering, where the determination of transfer functions is less influenced by noise originating from multiple sources.

Multichannel filtering

The multichannel filtering used in this paper is based on frequency-domain Wiener filtering (Müller-Petke and Costabel, 2014). A tacit assumption of multichannel filtering is that there is no correlation between the surface-NMR signal in the primary coil and the noise in the reference coils. To ensure this and also avoid any accidental correlation from other noise sources, estimation of transfer functions is done on the last half of 1 s long signal records, where the content of the exponentially decaying surface-NMR signal is lowest. The last half of the signal records are divided into 10 segments, each 1024 samples long. Each segment is Fourier transformed, and the individual Fourier transforms are multiplied and averaged to give the cross and auto spectra, and hence, the transfer functions. Segments of data containing spikes are discarded from the averaging. The choice of 10, 1024 sample long segments is a compromise between a low uncertainty in the transfer function estimate and the frequency resolution of the transfer function (Müller-Petke and Costabel, 2014). Once the transfer functions have been estimated, the noise reduced primary coil signal is calculated by subtraction in the frequency domain followed by an inverse Fourier transform.

In our previous work on multichannel filtering, results were limited by timing jitter between channels in the Numis Poly instrument (Dalgaard et al., 2012). In this work, jitter is circumvented by estimating a new transfer function for each 1 s signal record.

Averaging of signal records and envelope detection

Following despiking, harmonic subtraction and/or multichannel filtering, remaining uncorrelated noise is suppressed by averaging of all the signal records for a given pulse moment (Legchenko and Valla, 2002). As spikes have been removed by the initial despiking, only standard averaging is used. Segments of data containing spikes are discarded in the averaging. Subsequently, the envelope of the NMR signal was extracted using the procedure described by Dalgaard et al. (2012). A low-pass filter with a 3 dB bandwidth of 2 kHz is used in the envelope detection.

FIELD EXAMPLES

Noise conditions can vary greatly from site to site. Examples of this can be found in Table 1 that present rms noise levels measured with a Numis Poly system, at different sites located outside of cities, in Jutland, Denmark.

The rms levels vary over two orders of magnitude. The lowest level of 0.003 nV/m² found in Skive is exceptionally low for Denmark. At this noise level, the surface-NMR signal is clearly visible in the raw data, and a minimum of noise reduction and averaging is

needed. Typically encountered noise levels, such as found in Norsminde, are one order of magnitude higher, and noise reduction methods are needed to extract the surface-NMR signal. The sites Ristrup-02 and Ristrup-06 have rms noise levels that are again one further order of magnitude higher. Data from these two sites are used in this paper. Ristrup is a small village and farming area close to the city of Aarhus, and it is representative for many areas of interest in Denmark.

All data presented in this paper have been collected with a Numis Poly system (Iris Instruments). The Numis Poly is a multichannel surface-NMR instrument with one primary coil for transmitting the NMR excitation signal and receiving the NMR signal from the sub-surface water. The system is equipped with up to three additional reference coils for measuring the surrounding noise field. The system uses 150 Hz wide hardware band-pass filters tuned to the Larmor frequency on all channels. For all measurements presented in this paper, a single-turn square transmit/receive coil with a size of $100 \times 100 \text{ m}^2$ was used. The transmit pulse duration is 30 ms, the instrument dead time defined as the time from the end of the transmit pulse and until the measurement starts is 20 ms. The reference coils are seven-turn square $10 \times 10 \text{ m}^2$. The 16 bit A/D converters run on a sampling frequency of 19.2 kHz.

Multichannel filtering results

Two examples of the results after applying a multichannel Wiener filtering to the data from the Ristrup-02 site are shown in Figure 1. The data in the figure are based on stacking 76 records using an excitation pulse moment of 3.26 As. The Larmor frequency is 2142 Hz. Prior to stacking, spikes have been removed from all records, and a multichannel Wiener filter was independently applied to each record.

In the data presented in Figure 1a, a surface-NMR signal is observed between 0 and 0.2 s, but the S/N is poor, and it is difficult to draw firm conclusions on the decay of the surface-NMR signal. Further, the initial amplitude is very large and exceeds 0.25 nV/m^2 . The large initial amplitude is an artifact caused by the protecting relays in the reference coil electronics. The operation of the relays can give rise to impulsive noise at the beginning of the time series with a constant amplitude independent of the pulse moment. After the hardware band-pass filter, the noise appear as an oscillating signal, which decays in 5–10 ms. When the reference coil signals are filtered and subtracted from the primary coil signals, the result is an artifact resembling a large and fast decaying NMR signal. Results similar to the data presented in Figure 1 are obtained for the other pulse moments used at this site.

The relay induced noise can be removed by deleting the first part of each record prior to processing. This increase of the instrument dead time is effective in suppressing the relay noise as shown in

Table 1. Comparison of rms noise levels for different sites in Denmark. All data are recorded with a $100 \times 100 \text{ m}$ square coil and normalized by the area.

Site	rms (noise) (nV/m^2)
Skive	0.003
Norsminde	0.03
Ristrup-02	0.25
Ristrup-06	0.3

Figure 1b, where 20 ms dead time was added. For both cases, the rms level of noise is decreased from approximately 0.25 in the raw recordings to 0.12 nV/m^2 in the filtered records and further to 0.015 nV/m^2 after stacking. The envelopes of the data sets are fitted to monoexponentials and plotted as gray lines (Table 2).

Model-based noise reduction

The poor performance of multichannel Wiener filtering to improve the S/N and extract a surface-NMR signal can be understood by a thorough analysis of the data. In Figure 2a, a representative raw time series from Ristrup-02 for 3.26 As pulse moment is plotted. The raw data from this site are only lightly influenced by impulsive noise, and less than one visible spike is found per second of data. In Figure 2b, the power spectral density (PSD) of the same data is shown. The spectrum is calculated as a periodogram to achieve the best possible frequency resolution. It is evident from the spectrum

Figure 1. Plot of the resulting surface-NMR signal after despiking, multichannel Wiener filtering, and stacking of 76 records from the Ristrup-02 site for a pulse moment of 3.26 As. (a) The entire records are used, the initial amplitude of the NMR signal is distorted by the multichannel filter and exceeds 0.25 nV/m^2 . (b) The 20 ms of data time has been deleted prior to processing to remove this noise component. The resulting rms noise levels are approximately 0.015 nV/m^2 in both cases. The gray lines show monoexponentially fitted envelopes. The insets show the spectrum of the signal and the remaining noise components. The Larmor frequency is 2142 Hz.

that the signal contains many harmonic components from 50 Hz to more than 5 kHz. A magnification on the frequency axis is shown in Figure 2c. In typical data from Denmark, the harmonic components would all be a multiple of the fundamental 50 Hz powerline frequencies and would be located at 2000, 2050 Hz, etc. Such components, marked with circles, are observed in the spectrum, but many more components are also observed. An analysis of the additional frequencies observed in the spectrum, marked with diamonds, shows that a second harmonic series with a fundamental frequency of approximately 51 Hz is present. The origin of this second series is currently unknown. Note also that special attention is needed for this series as the 42nd harmonic will be close to the 2142 Hz Larmor frequency.

Table 2. Comparison of rms noise levels and monoexponential fitting parameters using multichannel Wiener filtering, multichannel Wiener filtering with 20 ms extra dead time, or harmonic subtraction. The MSEs of the fits are given in relative numbers.

Method	rms (nV/m ²)	A (nV/m ²)	T_2^* (ms)	MSE
Wiener (standard)	0.015	0.078 ± 0.001	83 ± 1	3.8
Wiener (+20 ms dead time)	0.015	0.070 ± 0.001	108 ± 2	2.7
Harmonic subtraction	0.007	0.105 ± 0.001	80 ± 1	1

Figure 2. Typical results from site Ristrup-02. (a) Time series, (b) PSD, and (c) magnification on PSD. The 50 Hz harmonic series is labeled with black circles. A second 51 Hz harmonic series is labeled with diamonds.

If the two different harmonic series have different spatial distributions, the transfer functions that are optimal for canceling one series is suboptimal for the other series and vice versa. The frequency resolution of the used transfer functions cannot be made high enough to provide good reduction of both series simultaneously, and the result is a suboptimum noise reduction.

Turning instead to the generalization of the model-based subtraction approach better results are obtained. The top plot of Figure 3 shows the PSD of the raw signal for the 3.26 As pulse moment. In the middle plot, the harmonic series related to the fundamental 50 Hz powerline signal have been subtracted. Under optimum circumstances, the powerline harmonic signal is completely removed; i.e., the component at 2250 Hz is reduced by 40 dB and no remnants can be seen. In the bottom plot of Figure 3, the second harmonic series with a frequency just less than 51 Hz has been subtracted. Nearly, complete attenuation is observed for most components. For the example presented here, the rms value of the noise is decreased from 0.25 to 0.13 nV/m² by the first subtraction and further decreased to 0.06 nV/m² by the second subtraction. This noise level is still very high, but it can be further reduced by subsequent multichannel filtering and stacking of the 76 records. Using this approach, the rms level of the noise is reduced to values in the range of 0.025–0.040 nV/m². As discussed above, the relays in the reference coil receivers can add an additional noise component to the first part of each record that will appear as a surface-NMR signal in the processed data. For this particular experiment, the effect of the relay noise was an overestimation of the initial amplitude by a factor of two to three. To avoid this problem, the multichannel filtering was discarded and instead the primary channel, harmonic noise subtracted

Figure 3. An example of removal of multiple harmonic series by model-based subtraction. (a) Spectrum of original signal, (b) spectrum after subtraction of 50 Hz series, and (c) spectrum after subtraction of 50 and 51 Hz series.

signal was averaged. The lack of multichannel filtering increases the rms level of the noise in the range of 0.040–0.080 nV/m², but it significantly increases the fidelity of the signal. A compromise solution can be found by discarding the distorted first part of the time series before processing. This will add an additional dead time to the measurements but increase the S/N. It is noteworthy that for data acquired at the Ristrup-02 site, the rms level of noise after model-based subtraction of harmonic components and stacking is a factor of two lower than when multichannel filtering and stacking was used.

The results for the 3.26 As pulse moment and a monoexponential envelope fit to the data are shown in Figure 4. The figure is based on the data used for Figure 1, and the plots are directly comparable. The inset shows the PSD of the signal on the same scale as the spectra presented in Figure 3. The presence of a NMR signal with initial amplitude of 0.1 nV/m² is now immediately evident. An overview of the rms noise levels and the monoexponential fitting parameters for the three different noise reduction methods is given in Table 2. The mean square error (MSE) of the fit is significantly reduced by using the model-based noise subtraction instead of multichannel Wiener filtering.

Contamination of reference coil signals

In the preceding section, it was demonstrated that following model-based subtraction of harmonic components, the rms noise level can be further decreased by multichannel filtering. However, when the harmonic noise components have been removed from the primary coil signal and the reference coil signals by subtraction, the results of subsequent multichannel filtering become more sensitive to possible contamination of the signal in the reference coils with surface-NMR signal. A clear example of this is found in data from the Ristrup-06 site, where two harmonic series with fundamental frequencies of 50 and 51 Hz are also observed.

Data from Ristrup-06 were noise reduced with model-based subtraction, and a subsequent multichannel filtering was attempted. The first 20 ms of the data records with relay noise are discarded before the processing. Results for a pulse moment of 5.4 As are presented in Figure 5.

Figure 4. Plot of the resulting surface-NMR signal after despiking, model-based subtraction, and stacking of 76 records from the Ristrup-02 site for a pulse moment of 3.26 As. The resulting rms noise level is approximately 0.007 nV/m². The inset shows the spectrum of the processed signal.

The top plot shows the result after despiking, model-based subtraction, stacking of 150 records, and envelope detection. The bottom plot shows the result when multichannel Wiener filtering has been applied in between model-based subtraction and stacking. The additional multichannel filtering gives a reduction of the rms noise level from approximately 0.050 to 0.030 nV/m². Monoexponential decays have been fitted to the data. Significant differences are observed between the two fitted models. The amplitude is increased by 29% from 0.077 ± 0.001 to 0.099 ± 0.001 nV/m², and the decay time is reduced by 12% from 154 ± 1 to 135 ± 1 ms by the multichannel filtering.

The discrepancy is caused by a small amount of surface-NMR signal being recorded by the reference coils. This is evident from Figure 6, where one of the reference coil signals is shown after despiking, model-based subtraction, and stacking. The reference coil signal contains an exponentially decaying signal with a frequency of 2142 Hz equal to the Larmor frequency at the site. The initial amplitude of the signal is approximately 0.7 ± 0.2 pV/m², and the decay time is 270 ± 50 ms.

The amplitude of the surface-NMR signal is in this case increased by multichannel filtering. The reason for this result is that the transfer functions are estimated on the remaining noise in the last half of the signal records where surface-NMR signals are absent. Hence, the transfer functions are optimized for reducing this remaining noise component, and the effect on the contaminating surface-NMR signal is uncontrolled. In this particular case, the sign of the transfer function causes NMR signal to be added. It should also be noted that the applicability of multichannel filtering is limited by a low correlation between the remaining noise in the primary and the reference coils. Coherence values of 0.5 or less are observed (Bendat and Piersol, 2010).

Contamination with surface-NMR signal is normally not evident in standard multichannel filtering, where the signals recorded in the primary and the reference coils are dominated by spikes and harmonic noise components. After removal of these components, the sensitivity of multichannel filtering to contamination with NMR signal is significantly increased. In this particular case, the distance between corner of the primary coil and the reference coils was approximately 55 m dictated by the feed-in cable length of the Numis Poly system. A distance of two to three times the loop size, i.e., more

Figure 5. Ristrup-06 surface-NMR signal (a) without multichannel filtering and (b) with multichannel filtering. The gray lines are monoexponential fits with parameters as indicated. The difference in the retrieved surface-NMR signal is due to the contamination with surface-NMR signal in the reference coils.

than 200 m for a $100 \times 100 \text{ m}^2$ coil, is typically considered as the sensitive zone for numerical modeling of surface-NMR signal (Dlugosch et al., 2011).

Figure 6. Plot of the signal in a reference channel after despiking, model-based subtraction of harmonics, and stacking of 150 records. A small contamination with a decaying signal is evident in the time series. The contamination is identified as surface-NMR signal from the peak at the Larmor frequency at 2142 Hz in the spectrum.

Figure 7. Inversion results at site Ristrup-02: the fit through observed data resulting from (a) the Wiener-only and (b) subtraction-only approaches. The gray dots and error bars denote time-gated observed data and associated standard deviations. The black lines denote simulated data from the final estimated models.

Inversion procedure

In the following sections, results from inversion of the Ristrup-02 data are presented to assess the impact of the noise reduction schemes. The data set is processed using the two approaches mentioned above: (1) the standard approach consisting of despiking, multichannel Wiener filtering, and stacking (hereafter called Wiener-only) and (2) the approach proposed in this study consisting of despiking, model-based subtraction of the harmonics, and stacking (hereafter called subtraction-only). For the Wiener-only data, the first 10 ms of the data containing noise from the relays are discarded.

The entire data set (so-called QT data) was used for inversion because it provides improved determination of the model parameters and helps to improve discrimination of layers with different water contents and decay times (Müller-Petke and Yaramanci, 2010; Behroozmand et al., 2012a). The free induction decays (FIDs) were integrated over 12 logarithmically spaced time gates (Behroozmand et al., 2012b) as shown in Figure 7. The mean of the samples within each gate is calculated as the gated value, and the standard deviation is scaled by the square root of the number of samples in each gate. The Wiener-only and subtraction-only data, together with their associated standard deviations, used for inversion are depicted as gray dots and error bars in Figure 7a and 7b, respectively. The black curves in Figure 7 show simulated forward responses using the final estimated model. For the Wiener-only data, oscillatory-like deviations are seen for some pulse moments. This is caused by insufficient removal of the closest harmonic component, which causes beating with the NMR signal.

Figure 8. Inversion results from the Ristrup-02 site with the (a) Wiener-only and (b) subtraction-only approaches. The models are estimated in terms of (left) water content and (right) decay time values as a function of depth.

The data were inverted using AarhusInv (Auken et al., 2014). Complex rotated amplitude data were used for inversion (Müller-Petke et al., 2011). The first data point represents the measurement effective dead time consisting of half of the transmitter pulse (to consider relaxation during the pulse; Walbrecker et al., 2009), the instrument dead time, and the processing dead time (Dlugosch et al., 2011; Walsh et al., 2011). The inversion started from a homogeneous half-space model for all parameters, and we used the stretch-exponential relaxation-time distribution model within the layers (Behroozmand et al., 2012b). Finally, we inverted the data for smooth models, in which fixed-layer boundaries are assumed and vertical smoothing constraints (here 1) are applied to the model parameters. Figure 8 shows the inversion results as water content (left) and decay time (right) values as a function of depth. Figure 8a and 8b corresponds to the Wiener- and subtraction-only processed data, respectively. The black lines represent the estimated models, and the gray area indicates the 68% confidence intervals. The surface-NMR data were inverted jointly with transient electromagnetics (TEM) data (Behroozmand et al., 2012a), by which the resistivity models are also provided (not shown).

Inversion results

As seen in Figure 7, a much better agreement between the observed and simulated data is observed, and a better data fit is obtained

Figure 9. Inversion results for the five-layer synthetic model embedded in noise-only records from Ristrup-02. The fit through observed data resulting from the (a) Wiener-only and (b) subtraction-only approaches. The gray dots and error bars denote time-gated observed data and associated standard deviations. The black lines denote simulated data from the final estimated models.

for the subtraction-only data with a total weighted data residual of 1.1 versus 1.3 for the Wiener-only data. Moreover, smaller errors associated with the subtraction-only data provide smaller uncertainties associated with the model parameters because the error is mapped from data to model parameters during the inversion. The inversion of the two data sets estimates significantly different models (Figure 8) in terms of the water content and decay times.

Synthetic model and results

Because no borehole data are available for the two Ristrup sites, the above results cannot be compared with independent measurements. The results are instead verified by numerical experiments, where synthetic NMR data are embedded in noise-only records from Ristrup-02 and retrieved using the subtraction-only and the Wiener-only approaches. The data were simulated using conditions similar to the Ristrup-02 field setup, i.e., loop size, pulse moments, etc. A five-layer model, consisting of two aquifers, was used for data simulation. A fixed homogeneous half-space resistivity model, with a resistivity value of 100 Ωm , was used during inversion. Similar to Figure 7, the processed synthetic data are shown in Figure 9. Again, a much better data fit is obtained for the subtraction-only data, and smaller errors are associated with the data. The total weighted data residuals are 0.8 and 1.2 for subtraction-only and Wiener only, respectively. We note that the subtraction-only data are slightly overfitted; however, the goal here is to show how well the two approaches fit the FIDs. Figure 10 shows inversion results as water content (left) and decay time (right) values as a function of depth for Wiener-only (Figure 10a) and sub-

Figure 10. Inversion results for the five-layer synthetic model embedded in noise-only records from the Ristrup-02 site processed with the (a) Wiener-only and (b) subtraction-only approaches. The models are estimated in terms of (left) water content and (right) decay time values as a function of depth.

traction-only (Figure 10b) processed data. The true five-layer model is shown by dotted lines, and the estimated multilayer models are shown by solid black lines, the 68% confidence intervals are shown as gray area. The results of the subtraction-only data are clearly advantageous because they give a superior retrieval of the true model.

CONCLUSIONS

We presented surface-NMR measurements from two sites in a high noise area and showed how the data were distorted by two harmonic series, which could not be adequately suppressed by multichannel Wiener filtering. A generalization of the model-based approach for noise reduction to include two harmonic noise component was proposed and shown to be efficient in removing the harmonic components from the data by subtraction, hence, making the surface-NMR signal more obtainable. Data processed with either standard multichannel Wiener filtering or the generalized model-based approach were compared, and the advantages of using the model-based approach were discussed. The model-based approach also revealed an otherwise overlooked contamination of surface-NMR signal in reference coil data from one of the sites. If undetected, such contamination can lead to erroneous estimates of water content and decay times. In future measurements, contamination can be avoided, and a further decrease in noise levels is possible by combining the two noise reduction methods.

Inversion of field data showed significant differences in the retrieved models using the two different noise reductions methods. The effectiveness of the generalized model-based subtraction over multichannel Wiener filtering on data from the Ristrup site was established through the processing and inversion of a synthetic five-layer model embedded in noise-only data. Here, it was shown that model-based subtraction was much better in retrieving the synthetic model.

The impact of this work lies in the fact that a careful processing of the surface-NMR data based on the generalized model-based subtraction approach enable us to extract invertible data that are otherwise impossible to obtain.

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